Augmented reality in minimally invasive partial nephrectomy

DISSERTATION

zur Erlangung des akademischen Grades

Doktoringenieur (Dr.-Ing.)

angenommen durch die Fakultät für Informatik

der Otto-von-Guericke-Universität Magdeburg

von Fabian Joeres, M.Sc.

geb. am 19.01.1988 in Mönchengladbach

Gutachter:innen

Prof. Dr. Christian Hansen

Prof. Dr. Thomas Neumuth

Prof. Dr. Stefanie Speidel

Magdeburg, den 13.12.2021

Acknowledgments

The research reported in this dissertation was conducted at the Otto-von-Guericke-University Magdeburg and the Research Campus STIMULATE in Magdeburg (Germany). The work was funded by the European Union and the federal state of Saxony-Anhalt (Germany) under grant number ZS/2016/10/81684.

Zusammenfassung

Die laparoskopische und robotergestützte Chirurgie bietet diverse klinische Vorteile für Patientinnen und Patienten. Hierbei spielen insbesondere die kleineren Wunden und das insgesamt geringere chirurgische Trauma eine Rolle. Dabei enstehen neue und zusätzliche physische und kognitive Herausforderungen für Chirurginnen und Chirurgen. Das Forschungsfeld der computerassistierten Chirurgie versucht unter anderem, Chirurginnen und Chirurgen bei diesen zusätzlichen Herausforderungen zu unterstützen. Die minimalinvasive Nierenteilresektion ist eine Operation, die von diesen Herausforderungen betroffen ist und die aufgrund ihrer chirurgischen Komplexität nur von spezialisierten und erfahrenen chirurgischen Urologinnen und Urologen durchgeführt werden kann. Ziel der minimalen Nierenteilresektion ist die laparoskopische oder robotergestützte Resektion von Nierentumoren unter Erhaltung einer möglichst hohen Nierenfunktion.

In den letzten Jahrzehnten ist eine Vielzahl von Forschungsarbeiten in der computerassistierten, minimalinvasiven Chirurgie erstellt worden. Viele dieser Arbeiten nutzen augmentierte Realität (AR), um intraoperativ relevante Informationen zur Verfügung zu stellen. Diese Ansätze haben zum Ziel, die entsprechende Operation sicherer, effektiver oder effizienter zu machen. Dabei fokussiert sich die Mehrheit dieser Arbeiten auf technische Systemaspekte, wie etwa die Genauigkeit und Zuverlässigkeit chirurgischer AR-Systeme. Allerdings stellt die nutzerzentrierte Betrachtung solcher Systeme eine Voraussetzung für die Entwicklung sicherer und effektiver chirurgischer Assistenzsysteme dar. Diese Dissertation führt eine nutzerzentrierte Untersuchung der folgenden übergreifenden Forschungsfrage durch: *Wie kann AR-Navigation die chirurgische Behandlung von Nierentumoren unterstützen?* Die erste Frage, die sich in diesem Kontext stellt, ist: Welche zusätzlichen Informationen braucht die Chirurgin oder der Chirurg? Daher nutzt diese Dissertation die minimalinvasive Nierenteilresektion als beispielhafte Fallstudie für die folgende zweite Forschungsfrage: *Kann eine gezielte Untersuchung der Informationsbedürfnisse neue Forschungsfelder für die chirurgische Navigationsassistenz eröffnen?*

Zu diesem Zweck wurden die Informationsbedürfnisse, die während der minimalinvasiven Nierenteilresektion auftreten, mit Methoden der kognitiven Aufgabenanalyse untersucht. Die Ergebnisse wurden mithilfe eines systematischen Literaturreviews mit dem aktuellen Forschungsstand verglichen. In diesen Analysen wurden drei chirurgische Phasen der minimalinvasiven Teilresektion identifiziert, die besonders von AR-Assistenz profitieren können: Die Präparation und Versorgung der Nierenblutgefäße vor der Tumorresektion, die Tumorresektion selbst und die Versorgung der Resektionswunde. In dem systematischen Literaturreview wurden keine dedizierten Lösungen für die Assistenz während der Resektionswundenversorgung gefunden. Während dieser Phase treten einige spezielle technologische Herausforderungen für die Entwicklung von AR-Systemen auf.

Im Rahmen dieser Dissertation wurden daher ein AR-Registrierungsprozess für diese Phase, sowie allgemeine interaktive Registrierungsmethoden für laparoskopische AR entwickelt. Zusätzlich wurde ein interaktives, audiovisuelles AR-Konzept für die Navigation während der Resektionswundenversorgung entwickelt. Diese Lösungskonzepte wurden im Rahmen früher Forschungsprototypen implementiert und in laborbasierten Nutzerstudien getestet. Die in dieser Dissertation berichteten Arbeiten eröffnen ein neues Anwendungsfeld für AR-Navigation in der minimalinvasiven Nierenteilresektion und stellen Lösungskonzepte für diese Anwendung vor. Weitere Arbeiten sind erforderlich, um diese Lösungskonzepte in einem weiterentwickelten Assistenzsystem zu integrieren und dieses, letztendlich, zum Wohle von Patientinnen und Patienten einsetzbar zu machen.

Abstract

Laparoscopic or robot-assisted surgery bears great clinical benefits for the patients due to their minimal invasiveness and the associated reduced surgical trauma. However, they can be taxing for the operating surgeon and introduce additional physical and cognitive challenges. The field of surgical computer assistance aims to alleviate these challenges. One operation that is affected by these challenges and that is, due to its surgical complexity, limited to specialised and experienced surgical urologists, is laparoscopic / robot-assisted partial nephrectomy (LRPN). LRPN describes the minimally invasive resection of kidney tumours while preserving as much healthy kidney tissue as possible.

A wide range of research has been conducted on computer assistance in minimally invasive surgery (including LRPN) over the past few decades. Many of these research approaches use augmented reality (AR) to provide surgeons with intraoperative information in convenient ways. These computer assistance approaches aim to make the surgery safer, more effective, more efficient, or to reduce the surgeon's workload. The majority of this research focuses on technological aspects, such as the accuracy and reliability of surgical augmented reality (AR) systems. However, user-centred considerations have been shown to be essential in creating safe and effective computer assistance solutions. The work reported in this dissertation takes a user-centred approach to the overall research question: *How can AR navigation aid the surgical treatment of kidney cancer?* The first question to be asked in this context is, what information does the surgeon need. Thus, this dissertation uses LRPN as a case study example for its second overall research question: *can a dedicated investigation of information needs advance novel research areas for surgical navigation assistance?*

These information needs that arise during LRPN were investigated with cognitive task analysis methods. The results were compared against the field's state of the art by means of a systematic literature review. These analyses revealed three surgical phases that can particularly benefit from AR assistance: the management of renal vessels before the tumour resection, the tumour resection itself, and the repair of the resection wound. No dedicated assistance concepts for the third phase could be identified. A number of specific technological challenges for AR systems arise during this phase.

Therefore, this dissertation introduces a registration workflow and interactive registration techniques that may be useful for AR assistance during the resection wound repair. Moreover, an interactive, audiovisual AR prototype has been developed. These solution concepts were implemented in early-stage prototypes and evaluated in laboratory-based user studies. The work reported in this dissertation revealed a novel application for AR assistance in LRPN and early-stage solution concepts were generated for this application. Further work is required to mature these concepts into an integrated surgical assistance system and, ultimately, introduce them to the patient.

Contents

Acronyms

3D	three-dimensional
ACTA	Applied Cognitive Task Analysis
ANOVA	analysis of variance
AR	augmented reality
CDM	Critical Decision Method
CT	computed tomography
CTA	cognitive task analysis
DoF	degrees of freedom
FoV	field of view
GUI	graphical user interface
HMD	head-mounted display
HTA	hierarchical task analysis
ICG	indocyanine green
ICP	Iterative Closest Point
LPN	laparoscopic partial nephrectomy
LRPN	laparoscopic / robot-assisted partial nephrectomy
MRI	magnetic resonance imaging
NASA-TLX	NASA Task Load Index
OPN	open partial nephrectomy
PN	partial nephrectomy
RCC	renal cell carcinoma
RPN	robot-assisted partial nephrectomy
SUS	System Usability Scale
TCT	task completion time
TRE	target registration error

1 Introduction

Synopsis

This chapter introduces the field of augmented reality (AR) and image guidance in laparoscopic oncological surgery. It motivates the user-centred research and development of techniques and technologies for intraoperative surgical assistance and briefly introduces the exemplary application of laparoscopic / robot-assisted partial nephrectomy (LRPN). A summary of the research approach that arises from this motivation is provided and the aspired contribution of this dissertation is derived from it. Finally, this chapter provides an overview of the dissertation's overall structure.

1.1 Motivation

How can AR navigation aid the surgical treatment of kidney cancer? This is the first and initial overall research question that underlies and motivates this dissertation. Globally, approximately 430,000 patients develop renal cancer each year [1]. This accounts for 5% of cancer diagnoses in men and 3% of cancer diagnoses in women [2]. The surgical removal of the tumour is the only known curative treatment option [3]. It, therefore, plays a crucial role in the management of renal cancer cases. Historically, this surgical treatment entailed the removal of the entire affected kidney in an open surgery. In recent years, the standard methods have shifted to either removing the affected kidney in a minimally invasive approach or to only removing the tumour itself while preserving as much healthy kidney tissue as possible. This partial nephrectomy (PN) is also increasingly being conducted laparoscopically or with laparoscopic robot-assistance [3].

Laparoscopic surgery is generally less invasive and causes reduced surgical trauma for the patient when compared to open surgery. Meanwhile, it can be taxing for the operating surgeon [4]. The challenging factors include the spatial perception and orientation [5], physical stress [6], and instrument manipulation [7]. These challenges and the surgical complexity of PN make LRPN a procedure that is limited to specifically trained and experienced surgeons[1] and to selected urological centres [3]. These problems do not only limit the spread of LRPN but are, beyond that, endemic to laparoscopic surgery in general. Alleviating these challenges has been the objective of a wide range of research on surgical computer assistance.

Surgical computer assistance mostly aims to support the preoperative surgical planning process and the intraoperative surgical performance [8]. A majority of perioperative clinical errors occur intraoperatively [9]. Moreover, the mental fusion of preoperative plans with the laparoscopic view of the surgical site is one of the error-prone cognitive tasks in laparoscopic surgery [10]. One popular approach to address these intraoperative challenges is the use of AR in laparoscopic surgery [11]. AR allows the integration of surgical planning data or other relevant anatomical, pathological, or clinical information into the view of the surgical site without requiring the surgeon to search the information elsewhere and mentally fuse it with the surgical site [8, 11]. Such computer assistance systems have demonstrated the potential to improve patient safety and surgeon performance [12], and to reduce surgery duration [8].

However, reviews of the relevant literature have found that the majority of research focuses on primarily technological system aspects, such as system accuracy and reliability [13]. Meanwhile, a reduced focus has been put on the intended users' (i.e. the surgeons') clinical needs and the constraints and conditions that are inherent in the intended use environment [12, 14]. This consideration of the user, however, is essential because the surgical computer assistance (e.g. AR) system is directly interacted with by the surgeon. It affects the surgeon's workload, situation awareness, and skill acquisition (and loss) processes and, thereby, indirectly affects the intended outcomes of patient safety, surgical efficacy, and surgical efficiency [12]. In fact, surgical AR assistance can even harm the surgeon's performance by occluding the direct surgical view [10] or by affecting the surgeon's allocation of attention [15, 16].

[1] LRPN is commonly performed by surgical urologists. Since this dissertation alternatingly discusses both, LRPN-specific and more general surgical matters, the more general term *surgeon* is used throughout the document.

The key questions to be asked in the user-centred research and development of surgical computer assistants can be phrased as:

1. What information should be displayed to the surgeon?
2. When should it be displayed?
3. How should it be displayed? [13]

While many AR publications investigate the second and third aspects, little systematic research has been published that examines the first question. A majority of the usability research on medical AR investigates the performance of and with finalised prototypes [17]. The first question of the user-centred research process, however, requires an investigation of the surgical tasks to be assisted and the surgical circumstances, prior to the solution development and prototyping phase. Therefore, this dissertation investigates a second and more general overall research question. The specific surgery of LRPN serves as a suitable case study scenario for this question: *can a dedicated investigation of information needs advance novel research areas for surgical navigation assistance?*

1.2 Contribution

The contribution of this dissertation is framed by the two overall research questions posed above. The herein reported work demonstrates a research approach for the investigation and identification of surgeons' information needs. In the context of this document, information needs describe any information that may aid the surgeons in making the surgery safer, more effective, more efficient, or that can help to reduce the workload for the surgeon. This research is based on existing cognitive task analysis (CTA) methods and allows for the identification of relevant surgical challenges and the information that may help to alleviate these. A systematic literature research of image guidance (including AR) in LRPN provides a comprehensive overview of existing approaches for *what* information should be made available to the surgeon and *when* it should be made available.

The remainder of the research reported in this dissertation is based on the comparison of the information needs and the relevant literature on assistance in LRPN. Specifically, the comparison reveals a potential benefit of AR assistance during the surgical phase of repairing the resection wound [18]. The surgical conditions during this phase entail specific technological challenges for the AR registration and visualisation. This dissertation proposes a dedicated registration workflow that is intended to address the former. A prototypical implementation of this workflow is reported along with a laboratory user study for its evaluation. Moreover, this dissertation further explores the field of user interaction for laparoscopic AR registration. Two novel interaction methods are introduced and evaluated. Finally, a dedicated interactive audiovisual AR concept is introduced that aims to address the specific challenges arising during the phase of resection wound repair. A proof-of-concept evaluation by means of a laboratory-based user study is reported for this concept.

1.3 Structure

The remainder of this dissertation is structured as follows:

- **Chapter 2** provides the clinical and technical background for the research activities that are reported in this dissertation. Its first part focuses on the clinical context of this work. The chapter's second part gives an introduction to AR. Following a brief and general overview of the AR technology and its applications, the components of surgical AR systems are introduced.
- **Chapter 3** investigates the question: what information do surgeons need during LRPN to make the surgery safer, more effective, more efficient, or to reduce the workload for the surgeon. It reports a study that systematically investigated these information needs in a CTA-based interview study with nine senior urological surgeons.
- A range of surgical computer assistance and image guidance methods and solutions for LRPN have been published in the literature. **Chapter 4** reports a systematic review of the relevant literature. The chapter reports the identification of a research gap during the surgical phase of the resection wound repair. This phase entails multiple surgical challenges with no published, dedicated image guidance or computer assistance solutions. The chapter is concluded by identifying the technological challenges around the AR registration, visualisation, and interaction that arise during this phase.
- **Chapter 5** investigates the challenges that arise for the registration of AR content during the resection wound repair phase. A dedicated registration workflow is introduced that aims to address the phase specific challenges reported in Chapter 4. A laboratory-based user study is reported in which the registration pipeline has been evaluated.
- The field of laparoscopic AR registration is further explored in **Chapter 6**. The chapter examines the field of interactive or manual registration of AR content. Two novel interaction concepts are introduced and evaluated that aim to employ natural interaction metaphors and to achieve a minimal invasiveness to the surgical workflow.
- Beyond the registration-related challenges, Chapter 4 reports some technological challenges that affect the visualisation of and user interaction with laparoscopic AR content during the resection site repair phase of LRPN. **Chapter 7** introduces an interactive, audiovisual AR concept that aims to address these challenges. A proof-of-concept user study for the concept is reported.
- Finally, **Chapter 8** concludes the dissertation. It discusses the research contribution and its limitations, and summarises the future work objectives that arise from them.

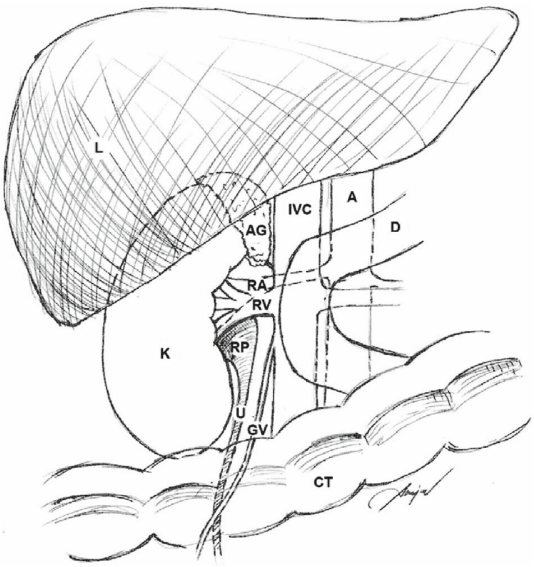
2

Background

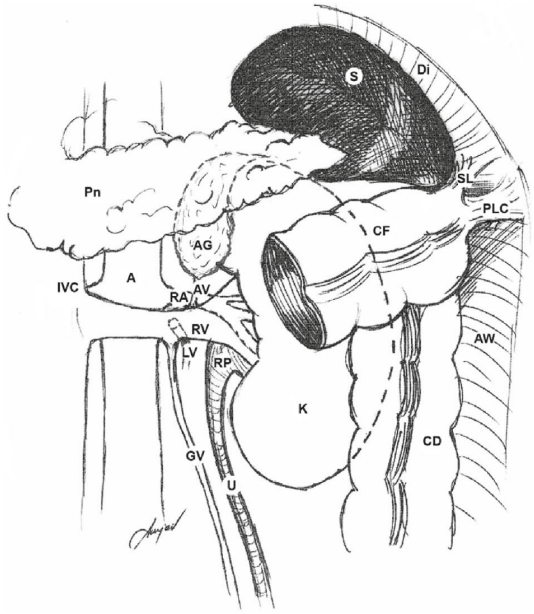
Synopsis

The first part of this chapter provides the medical background for the research reported in this dissertation. The pathology, epidemiology, and treatment options of renal cancer are briefly summarised and the surgical treatment options are further discussed. The section also gives an introduction to laparoscopic and robot-assisted surgical techniques, and briefly discusses their limitations that motivate the research of technological assistance solutions. The second part gives an introduction to surgical AR for intraoperative assistance. An overview of the components that constitute a functioning AR system is provided and the components are further examined one by one.

2.1 Clinical context: renal cancer and minimally invasive partial nephrectomy



(a) Anatomical position and context of the right kidney. Figure from Guillonneau et al. [19] and reprinted by permission from Springer Nature.



(b) Anatomical position and context of the left kidney. Figure from Guillonneau et al. [19] and reprinted by permission from Springer Nature.

Figure 2.1: Anatomical positions and context of the right and left kidney. The drawings are from the anterior perspective. A: Aorta; **AG: Adrenal gland**; AV: Adrenal vein; AW: Lateral abdominal wall; CD: Descending colon; CF: Colonic flexure; CT: Transverse colon; D: Duodenum; DI: Diaphragm; GV: Gonadal vessel; IVC: Inferior vena cava; **K: Kidney**; L: Liver; LV: Lumbar vein; PCL: Phrenocolonic ligament; Pn: Pancreas; **RA: Renal artery**; **RP: Renal pelvis**; **RV: Renal vein**; S: Spleen; SL: Splenocolonic ligament; **U: Ureter** [19].

2.1.1 The kidney's anatomy and physiology

The kidney is a bilateral organ that is situated in the retroperitoneal space [19]. The anatomical positions of the left and right kidney are shown in Figure 2.1. The kidneys are perfused by the left and right renal artery and vein, which branch off the aorta and the vena cava, respectively. Adult human kidneys are approximately 11-12cm long and 5-6cm wide with an approximate weight of 150g [20]. The kidney has multiple functions for the human organism, including the regulation of the water and electrolyte balance and blood pressure. Further functions include the preservation and management of the acid-base balance, calcium concentration, and phosphate concentration, as well as the filtration and disposal of water soluble toxins. [21].

The kidney comprises two main anatomical structures: the renal hilum and the parenchyma (Figure 2.2). The renal artery and renal vein enter the kidney and the ureter

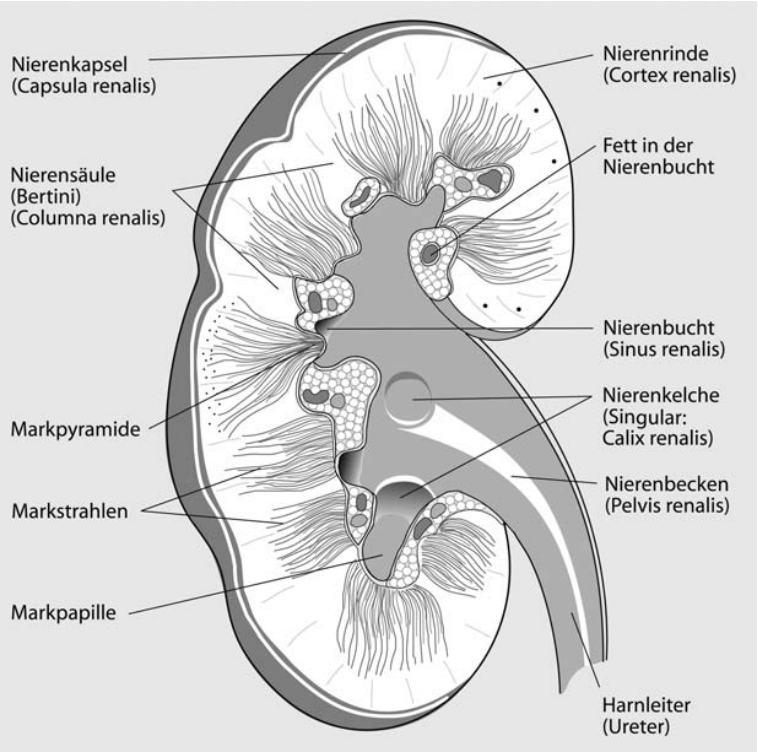


Figure 2.2: Renal anatomy. Figure from Nowack et al. [20] and reprinted by permission from Springer Nature. The German labelling is used due to copyright limitations.

exits the kidney at the hilum that is oriented towards the medial plane. The renal artery and vein split up into segmental branches, which branch into smaller structures up to capillary blood vessels in the renal cortex that is the outer part of the parenchyma. The ureter transports the urine that is collected in the renal pelvis (which is also situated in the hilum) to the bladder [21]. The superior and inferior ends of the kidney (top and bottom in Figure 2.2) are referred to as the kidney poles. The kidney is surrounded by fatty tissue and encapsuled in the Gerota fascia.

The renal parenchyma includes the inner medulla and the peripheral cortex [21]. It contains the kidney's main functional structures, the nephrons. The nephrons perform the blood filtration and urine production. They consist of the glomeruli that are situated in the cortex, and the tubuli. Initial filtration and the production of primary urine are performed in the glomeruli. The primary urine is then processed through the tubuli. Additional filtration and re-absorption processes in the tubuli convert the primary urine to the finally expelled urine. The tubuli that merge into larger collecting tubes and, finally, into the medulla's papillae. These merge into the renal calyces, which transport the urine to the renal pelvis. The glomeruli are filled and the tubuli are surrounded by capillaries that allow for the filtration and re-absorption processes that are required during the urine production [21]. The blood vessels that branch into these capillaries run primarily through the renal columns.

2.1.2 Renal cell carcinoma

Renal cancer is the 11th most common cancer diagnosis in women (2.3%) and the 9th most common cancer diagnosis in men (3.6%) in Germany [22]. Overall, approximately 14.500 cases were reported in Germany in 2016 [22]. As the occurrence rate indicates, the incidence is higher in men than in women with risk ratios being reported between 1.5:1 [3] and 2:1 [23]. The global peak incidence rate for sporadic (as opposed to hereditary) cases lies between 60 and 70 years [2], whereas the mean age of diagnosed patients in Germany, Austria, and Switzerland has been reported as 65 to 70 for men and over 70 for women [23]. Apart from hereditary factors, risk factors for renal cancer include high blood pressure, smoking, and a high body mass index [24]. In women, diabetes has also been correlated with a higher risk for renal cancer [25]. In correlation with the prevalence of these risk factors, renal cancer incidence is particularly high in economically developed societies in Western Europe and North America [2].

The majority (approximately 75%) of renal tumours are made up by sporadic clear-cell renal cell carcinoma (RCC). Sporadic means that the causal genetic mutation was not inherited but that it occurred spontaneously. These tumours are usually located in the renal cortex. Five per cent of renal tumours are renal oncocytoma, which orginate from the papillae. These are classified as benign and rarely metastate but are hardly distinguishable from RCC in current imaging techniques. They are, therefore, indicated for the same treatment options and identified histologically [3].

RCC are smooth and soft tumours that are encapsuled by a stable pseudo-capsule [3]. They are commonly located near the kidney poles [26]. In later stages, tumour thrombi of RCC can extend into the venous system. These thrombi can reach into the renal vein, the vena cava, or even the right atrium [3].

Most RCC, however, are detected during earlier stages of the disease. More than 50% of RCC are detected in the examination of unspecific abdominal symptoms [3]. Usually, RCC do not cause specific symptoms during their early growth but later-stage symptoms include abdominal pain, hematuria, and a palpable tumour. Only 6-10% of RCC are detected based on these symptoms [3]. The staging of RCC is classified following the Union for International Cancer Control's TNM classification [27]. The TNM stages are listed in Table 2.1. Due to the commonly early detection, up to 90% of the patients diagnosed with RCC are diagnosed during the T1 or T2 stages [3], i.e. while the tumour is limited to the kidney from which it originated.

The diagnosis itself is primarily conducted with anatomical ultrasound and contrast enhanced abdominal computed tomography (CT) or magnetic resonance imaging (MRI). MRI is generally inferior to CT in RCC differentiation but can help identify and classify venal thrombi in advanced stages [3]. Ultrasound imaging is mostly sufficient for differentiation of RCC and renal cysts and CT imaging allows for the identification of the tumour type and the TNM classification [3]. Due to the high diagnostic value of this imaging combination, biopsies are commonly not required. The existence of multiple distributed tumours poses an exception to this. In this case, pathological biopsy data can help determine whether the renal tumour is the primary tumour or a metastasis from a different origin [3].

Table 2.1: TNM classification of renal tumours as per the Union for International Cancer Control [27].

T - Primary tumour	
Tx	Primary tumour cannot be assessed
T0	No evidence of primary tumour
T1	Tumour 7cm or less in greatest dimension, limited to the kidney
T2	Tumour more than 7 cm in greatest dimension, limited to the kidney
T3	Tumour extends into major veins or perinephric tissues but not into the ipsilateral adrenal gland and not beyond Gerota fascia
T4	Tumour invades beyond Gerota fascia (including contiguous extension into the ipsilateral adrenal gland)
N - Regional lymph nodes	
Nx	Regional lymph nodes can not be assessed
N0	No regional lymph node metastasis
N1	Metastasis in regional lymph node(s)
M - Distant metastasis	
M0	No distand metastasis
M1	Distant metastasis

2.1.3 Treatment options for renal cell carcinoma

Patients with early stage detection of RCC have a good prognosis with a five year survival rate of 70-90% for T1/T2 cases [26] in TNM classification (Table 2.1). The primary treatment algortihm that is recommended by the German Society for Haematology and Clinical Oncology is depicted in Figure 2.3 [23]. The recommended algorithm illustrates that surgical treatment is the clearly preferred approach for RCC. This is because surgical treatment is the only known curative treatment for RCC [3]. In fact, approximately 90% of T1 RCC cases can be definitively cured by nephrectomy or PN.

These procedures constitute the standard treatment approach for RCC: laparoscopic nephrectomy has been described as the gold standard treatment [3] with a recent trend towards PN in T1 and T2 cases [28]. During nephrectomy, the entire affected kidney is resected. Laparoscopic surgery describes a minimally invasive surgical approach in which the surgeon accesses the surgical site through small incisions in the abdominal wall. It is discussed in more detail in the next section. For smaller tumours or tumours that are located distally from the hilum, PN poses a viable alternative [3]. In PN, the tumour is resected from the kidney while sparing as much healthy renal tissue as possible. The recurrence and survival rates are identical in partial and radical nephrectomy (i.e. resection of the entire kidney) but patients show lower rates of later renal insufficiency and related cardiovascular diseases after PN [3]. Beyond cases with small tumours, PN may also be indicated in cases with a high likelihood for renal insufficiency due to comorbidities or in cases with a high likelihood of tumour recurrence, such as hereditary tumour risk factors [3].

The laparoscopic approach to PN, however, is gaining more and more importance [19, 29]. More recently, this approach has been augmented by the use of laparoscopic surgical robots [30, 31]. These LRPN approaches are the focus of this dissertation and are discussed in further detail in the next sections.

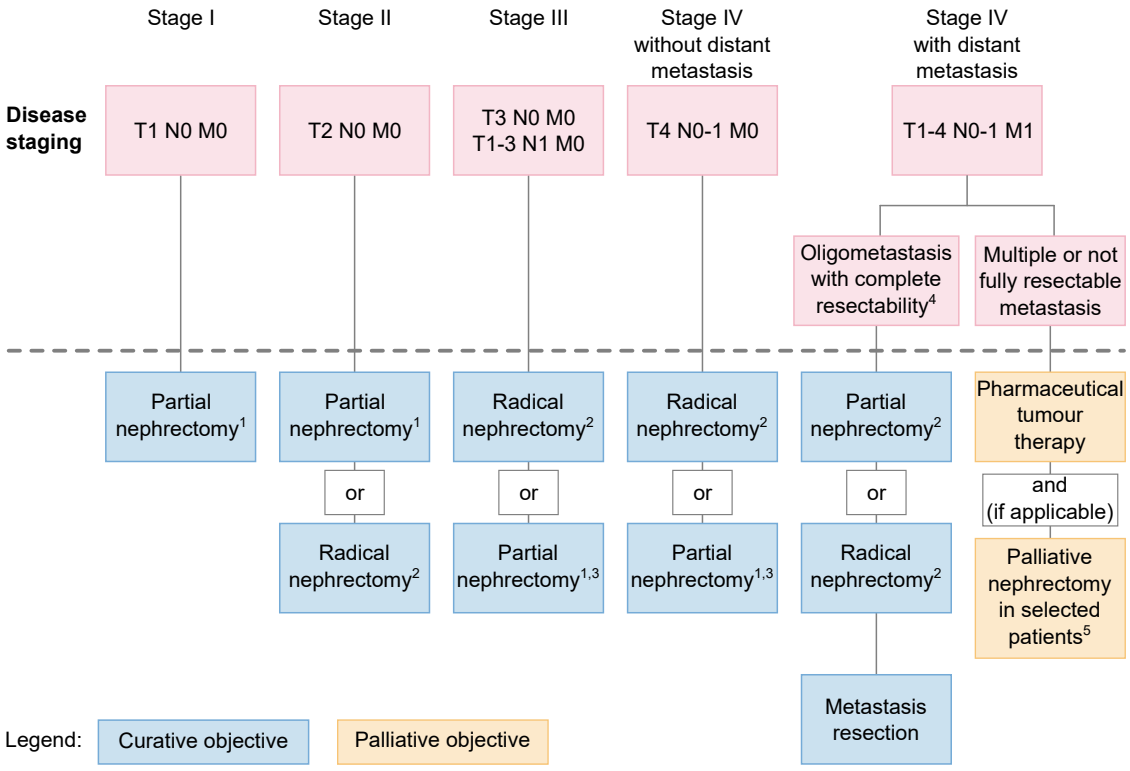


Figure 2.3: Treatment algorithm for RCC as per the German Society for Haematology and Clinical Oncology's guidance. Notes: [1]if surgically feasible; [2]laparoscopic if possible; [3]in particular cases; [4]indication depends on general patient state, risk profile, tumour histology, and other factors; [5]no benefit from surgery for intermediate and high risk patients. Figure adapted and translated from Bergmann et al. [23]. For the TNM tumour classification, see Table 2.1.

Finally, non-surgical treatments play only a secondary role in the treatment of RCC. Radiation has not been shown to considerably improve local tumour control or overall survival rates. It is, therefore, mainly applied in palliative care [3]. Pharmaceutical therapy is primarily indicated for disease control after the tumour has metastated. It is mostly applied complementarily to the surgical route, rather than as an alternative [3].

2.1.4 Laparoscopic and robot-assisted surgery

Laparoscopic surgery describes a minimally invasive surgical approach in which the surgical site is accessed through small incisions in the abdominal wall. The required working space is established by insufflating the abdominal cavity with pressurised CO_2. The resulting space is called the pneumoperitoneum. The surgical team gains visual access to the surgical site with a monoscopic or stereoscopic camera, the laparoscope (Figure 2.4). The laparoscopic camera head that is inserted into the pneumoperitoneum combines two functions: it transmits light from an external light source and it contains a camera objective that transmits the optical input to a camera unit. The laparoscopic video is streamed to a screen and used for the duration of the surgery. Further access points are created for the required surgical instruments (Figure 2.4). Each access port is established by a small incision in the abdominal wall and the placement of a trocar (Figures 2.4, 2.5). The trocars grant laparoscope and tool access while preserving the pneumoperitoneal pressure. The number and placement of these trocars depends on the surgical procedure and approach.

The key benefit of laparoscopic surgery lies in the reduced invasiveness of a given procedure, including the smaller wounds and lower overall surgical morbidity [32]. Laparoscopic surgery was initially proposed for appendectomies but has gained popularity across multiple surgical domains since the 1980s [33]. Surgical domains that benefit from the laparoscopic approach include urology [19], gastroenterology [33], gynecology [34],and hepatology [35].

Beside the clinical benefits for the patient, laparoscopic surgery causes a number of challenges for the operating surgeon. The first challenge lies in the unintuitive hand-eye coordination that arises from the camera position and the associated perspective of the surgical site. Another challenging factor is the impaired depth perception of the surgical field. In monoscopic laparoscopic surgery, the surgeon lacks all binocular depth cues [5]. However, even in stereoscopic laparoscopy, the surgeon's depth perception is affected by the camera's constraints: both, the field of view and the range for camera motion are very limited, reducing the amount of spatial context information that is available. Moreover, the placement of the camera port is restricted by anatomical and surgical constraints. This limits the choice of perspective on the surgical site. Finally, the light emission and the camera objective on the laparoscopic camera head are located very close to each other. This means that, from the camera's perspective, the surgical site is nearly shadowless, which reduces the available depth cues even further [5].

In addition to the spatial perception issues, the instrument handling poses additional cognitive challenges: the instrument's motion is restricted by the positions of the trocars [7]. The instruments' possible motion can be described as a rotation around the point where the trocar crosses the abdominal wall. In addition to this rotation, the instruments can be moved along their own longitudinal axis, i.e. in and out of the surigcal space, and rotated around that axis. This means that an instrument tip's spatial

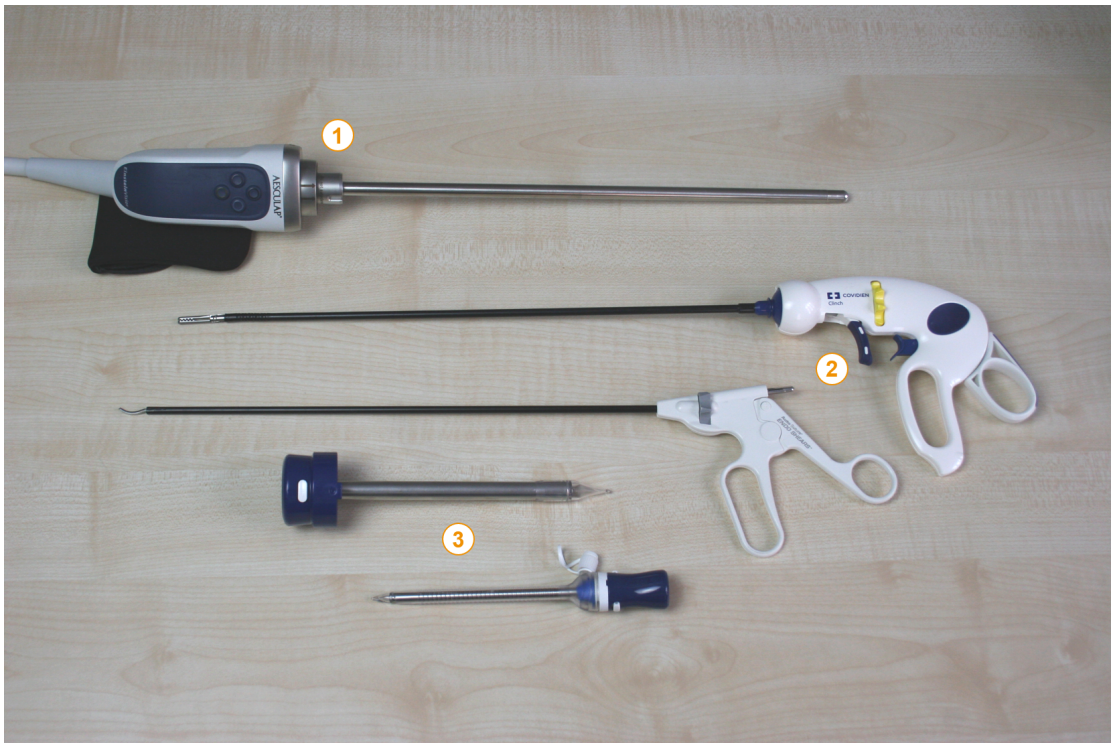


Figure 2.4: Laparoscopic camera head (1), instruments (2), and trocars (3).

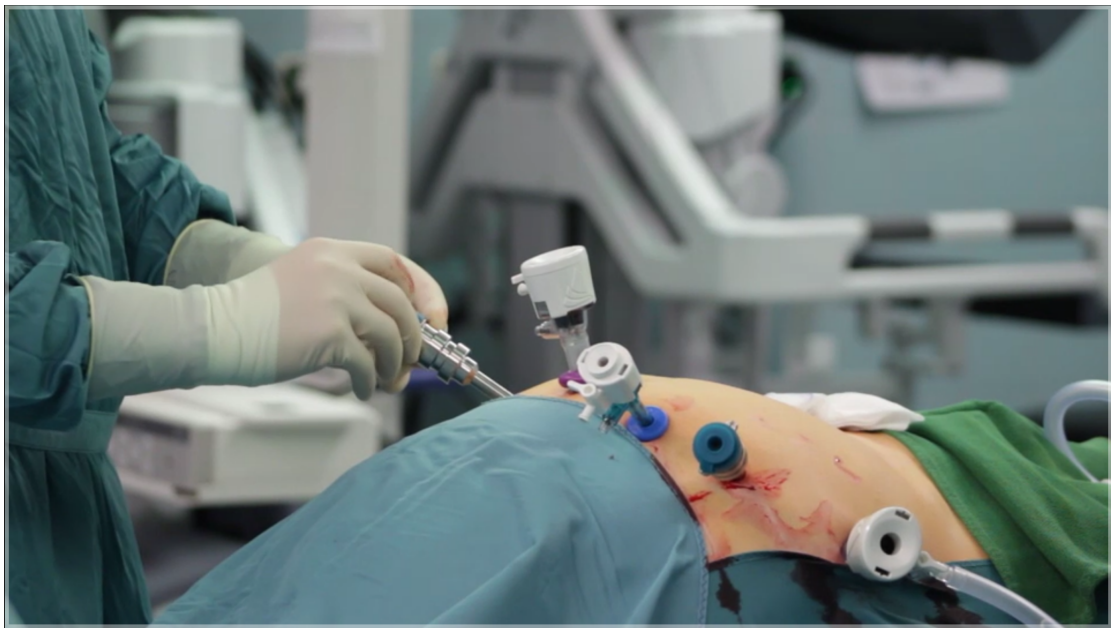


Figure 2.5: Insufflated abdomen with trocars in place. This photograph is from a robot-assisted laparoscopic surgery. Image courtesy of Prof. Martin Schostak, University Hospital Magdeburg.

orientation at any given point within its reach is determined by the vector from the trocar port to that point. This can hinder the use of some instruments in some areas of the surgical site. Moreover, the rotation around the trocar port causes the so-called 'fulcrum' effect. This describes the fact that the surgeon's hand and the instrument tip move in opposite directions for all motion components that are perpendicular to the tool axis [7]. For motion along the tool axis, however, the fulcrum effect does not apply. Finally, the surgeon receives reduced haptic information in laparoscopic surgery as compared to open surgery. This applies to haptic feedback on his or her own actions and to haptic information about the consistency of anatomical or pathological structures [7].

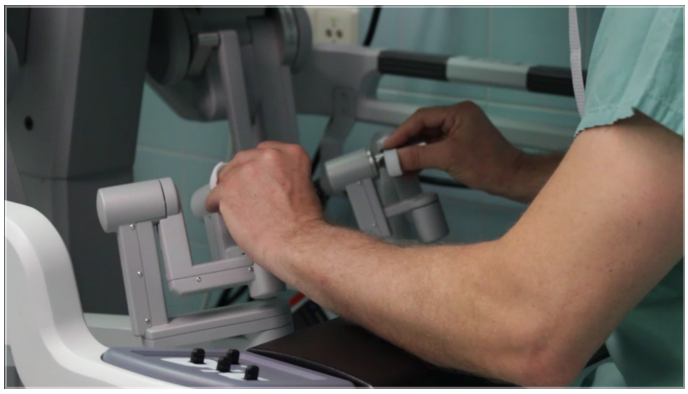
These challenges in spatial perception and instrument manipulation can lead to increased mental stress for the surgeon [4]. This increased stress, in turn, can impair surgical performance and, ultimately, affect patient safety or the surgery's efficacy [36]. Finally, the laparoscopic surgical setup can require the surgical team to work in unergonomic postures over prolongued periods. This can cause physical upper body stress for the surgical team [6].

The introduction of robot-assisted surgery has aimed to mitigate some of these challenges and drawbacks of manual laparoscopic surgery [37]. Robot-assisted surgery has been introduced in multiple (minimally invasive and open) surgical domains, including orthopaedics, neurosurgery, urology, cardiothoracics, general surgery, and gynaecology [38]. For the scope of this dissertation, however, the term refers to robot-assisted *laparoscopic* surgery. The commonly used term robot-assisted surgery is somewhat misleading because the so-called robot is not an autonomous agent in the surgery but rather a telemanipulator that is controlled by the surgeon in real time. Nonetheless, the term robot is used throughout this dissertation to maintain consistency with the common terminology convention.

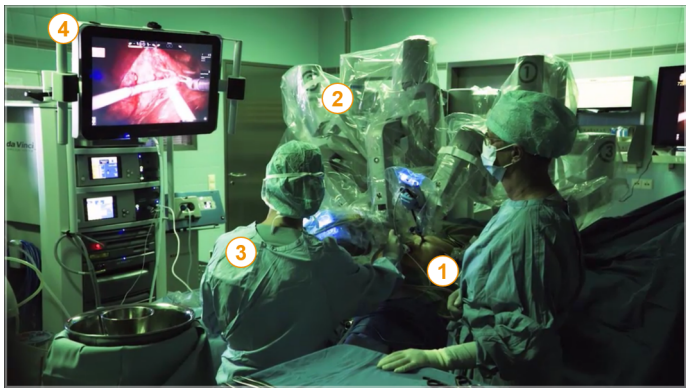
The currently dominating system for robot-assisted laparoscopic surgery is the da Vinci system (Intuitive Surgical, Sunnyvale, CA, USA). Its first generation was first used in 1998 and cleared commercial approval in the USA in 2000 [38]. The surgical interface of current da Vinci robots includes the surgeon console and the bedside cart. The surgeon console (Figure 2.6a) provides a stereoscopic display of the surgical site and a set of bespoke controllers (Figure 2.6b) for real time manipulation of the instruments that are attached to the robot arms and inserted into the surgical area. The bedside cart (Figure 2.6c) contains four arms that implement the surgeon's actions inside the surgical site. The required instruments are attached to these arms by surgical assistants. Additional, competitor laparoscopic robot systems are being developed. One example that has recently been introduced to the clinical market is the *Versius* robot (CMR Surgical, Cambridge, UK).

This robotic approach has been shown to improve the instrument manipulation by increasing the range of instrument motion, elimination of the fulcrum effect, and neutralisation of surgeon tremor [37], and to accelerate novices' technical skill learning curve [39]. Moreover, an additional joint at the instrument tip eliminates the tip orientation constraint that is introduced to manual laparoscopic surgery by the rigid instrument axis. However, robot-assisted surgery requires specialised surgical training.

(a) Surgeon console of the da Vinci robot. Image courtesy of Prof. Martin Schostak, University Hospital Magdeburg.



(b) Instrument controllers of the da Vinci robot. Image courtesy of Prof. Martin Schostak, University Hospital Magdeburg.



(c) Bedside view of the da Vinci robot during surgery, including the patient (1), the bedside cart with the robot arms (2), the bedside assistant (3), and the assistants' view of the laparoscopic video stream (4). Image courtesy of Prof. Martin Schostak, University Hospital Magdeburg.

Figure 2.6: Components of the da Vinci robot's surgical interface.

Table 2.2: Summarised overview of the workflow in LRPN [18]. The development of this workflow description was a part of the work reported in this dissertation and is documented in Chapter 3.

Task	Task summary
[...]	
2 Initiate operation	Establish pneumoperitoneum and place ports
3 Navigation to operative site	Navigate to and mobilise kidney
4 Intraop. planning	Dissection of surgical site and incision line planning
5 Manage renal vessels	Clamp dedicated vessels
6 Excise tumour	Resect tumour while supervising navigation
7 Repair renal defects	Close vessel lesions and overall resection wound
8 Unclamp	Remove vessel clamps
9 Extract tumour	Remove tumour with specimen bag
10 Conclude operation	Repair extrarenal defects and close ports
[...]	

2.1.5 Laparoscopic and robot-assisted partial nephrectomy

The first laparoscopic partial nephrectomy (LPN) was performed by Winfield et al. in 1993 [29]. Four years after the introduction of robot-assisted surgery, Gettman et al. performed the first robot-assisted partial nephrectomy (RPN) in 2004 [30]. Both these approaches have since gained significant popularity and importance in the treatment of RCC [40]. The general goal of LRPN can be summarised with the complete removal of the tumour while preserving as much functioning renal tissue as possible.

Generally, LPN and RPN follow an equivalent workflow. A systematic analysis of this workflow is a part of this dissertation and reported in detail in Chapter 3. A summarised overview of the workflow is provided in Table 2.2: after surgery initialisation, the surgeon navigates to the kidney and mobilises it. The hilum and the necessary parts of the kidney surface are dissected and the incision line is planned. The surgeon then applies the required artery clamps and resects the tumour. After the tumour has been resected, the resection wound is closed and the clamps are removed as soon as possible during this renorrhaphy process. Finally, the tumour is removed from the surgical site and the surgery is concluded. There are some stratetic surgical decisions that affect the detailed surgical steps that occur throughout this workflow. The two predominant decisions are the surgical access direction and the renal vessel management.

The kidney and surgical site can be accessed transperitoneally [29] or retroperitoneally [41]. This decision affects the patient positioning and port placement. Moreover, less working space is available in the retroperitoneal approach. The decision is primarily based on the tumour position.

The second strategic decision affects the clamping strategy for the renal blood vessels. Traditionally, the renal artery and vein are clamped off at the hilum [42]. The suppression of renal perfusion allows for a more precise tumour excision and more effective repair of the resection wound. Criteria for a successful resection wound repair include watertight suture repair of the pelvicalyceal urinary collecting system and full parenchymal haemostasis [43]. However, the intention of LRPN is to preserve as much functional renal tissue as possible. Renal ischemia (i.e. the suppression of renal tissue perfusion) damages the parenchymal tissue and affects the postoperative renal function [44]. Complete clamping of the renal

vessels can, therefore, be counterproductive to the surgery's objectives. Alternative solutions include the clamping of segmental arterial branches to only suppress perfusion in the affected kidney area [45] and super-selective, 'zero-ischemia' clamping [46]. In zero-ischemia clamping, the arterial branches are micro-dissected and only the branches that directly supply the tumour are severed and closed. Finally, Guillonneau et al. proposed imitating the renal cooling that is applied during open partial nephrectomy (OPN) by applying a cooling agent via a catheter [47]. This aimed to reduce the damaging effects of the so-called warm ischemia that is standard in LRPN with arterial clamping.

The general clinical benefits of laparoscopic surgery over open surgery are reflected in the comparison literature between laparoscopic and open partial nephrectomy. This is particularly evident in the lower blood loss during LPN [48, 49] (including a lower blood transfusion rate [49]) and shorter hospitalisation time [48, 50]. This was achieved at comparable oncological results [48, 50, 49], renal functional outcomes [48, 50, 49], and intraoperative complication rates [48, 50]. The laparoscopic approach, however, does exhibit some apparent drawbacks. Gill et al. found the postoperative complication rate to be higher in their LPN cohort, despite the OPN cohort including more patients with higher tumour staging and a higher overall risk profile [48]. Moreover, two studies found the ischemia duration to be longer in LPN than in OPN. In contrast, Marszalek et al. found ischemia times to be longer in OPN [50]. However, they cooled the kidney during the open approach's ischemia phase. This may have reduced the time pressure during this phase and led to the observed longer ischemia duration.

Comparison between LPN and RPN shows that these drawbacks can be partially mitigated by using the robot-assisted approach. Two meta-analyses [51, 52] indicate overall superiority for the RPN approach. At the time of writing this dissertation, the more recent meta-analysis by Zhou et al. [52] was only available as an unreviewed preprint. Both meta-analyses found shorter ischemia times, better postoperative renal function, and lower rates of conversion to OPN or radical nephrectomy for RPN. Oncological results, blood loss, and postoperative complication rates were found to be equivalent in LPN and RPN. Moreover, Zhou et al. found RPN to perform with shorter surgery duration, and lower intraoperative complication rates at comparable hospitalisation duration [52]. Meanwhile, Choi et al. identified comparable surgery durations for LPN and RPN with shorter hospitalisation stays after RPN [51].

Direct comparison between RPN and OPN is required to assess whether these improvements suffice to compensate for the LPN approach's drawbacks. However, little work has been conducted to directly compare these strategies. Lucas et al. compared all approaches and found equivalent performance for LPN and RPN, which both performed with lower blood loss and shorter hospitalisation than OPN but with longer operation and ischemia times [40]. A direct comparison between RPN and OPN found that the key benefits of laparoscopic surgery (i.e. reduced blood loss, shorter hospitalisation, lower overall surgical morbidity) could be achieved with RPN [53]. Moreover, RPN exhibited fewer severe postoperative complications. These benefits could be achieved at comparable oncological and renal functional results, overall intraoperative and postoperative complication rates, and ischemia times. Solely the overall surgery duration was found to be longer in RPN than in OPN. These findings indicate the overall suitability of minimally invasive approaches for partial nephrectomy (i.e. LRPN).

2.2 Technical background: surgical augmented reality

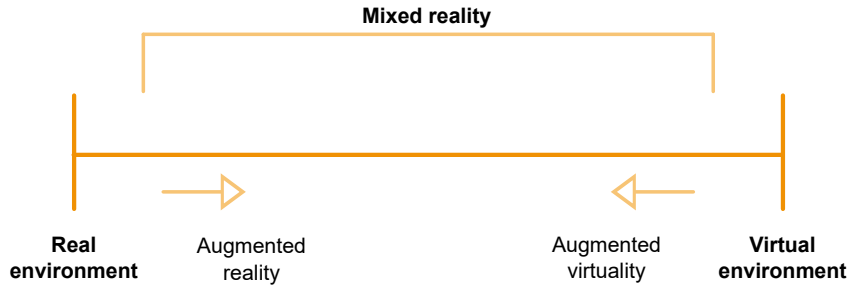


Figure 2.7: Mixed reality continuum. Figure adapted from Milgram et al. [54].

2.2.1 Introduction to augmented reality

AR describes the extension of a human's physical surroundings by adding virtual information, objects, or other content to his or her perceived environment. Following the commonly used definition by Azuma [55], the presented virtual content in AR environments is interactive and rendered in real time. Another characterising attribute is that the content is registered in the real three-dimensional (3D) space. This means that it is presented as if it was stationary (or its motion defined) in the physical space. AR is viewed as a part of the mixed reality continuum [54]. The mixed reality continuum describes the degree to which a human's perceived environment is defined by his or her physical environment on the one hand and by virtual content on the other hand (Figure 2.7). One end of this spectrum is defined by an entirely real (physical) environment. The other end is defined by fully immersive virtual environments. AR comprises environments, which are predominantly defined by the human's physical environment but augmented by context-relevant virtual content.

Generally, the environment's augmentation can target most human senses; including the visual, auditory, haptic, olfactory, and gustatory perception. Most AR applications, however, focus on the visual presentation of virtual content [56]. This dissertation and, therefore, this introduction to AR also focuses on visual AR displays. Three major categories of visual AR display solutions have been developed for the integration of virtual content in the user's physical environment: optical see-through, video see-through, and projective or spatial AR displays [57]. Optical see-through solutions display the virtual content on a semitransparent screen. This means that the user directly observes his or her environment through that screen, and the rendered virtual content is displayed as an overlay on that direct view. Video see-through displays do not rely on the user's direct view of the environment. Instead, the environment is captured with a video camera. The video is then overlaid with the virtual content and streamed to the user in real time. Finally, projective AR utilises the physical surfaces in the user's environment. These systems display the virtual content by projecting it onto the available surfaces [57].

2.2.2 Augmented reality applications

Conceptual precursors of AR can be traced back as far as World War II: some British airplane windshields were superimposed with a radar screen and information about

which nearby aircraft were friendly and which belonged to enemy nations [58]. In 1968, Sutherland published the '*head-mounted three dimensional display*' [59] that is now seen as the first AR display [56]. The system comprised an optical see-through head-mounted display (HMD) that could be tracked in space by an ultrasound or a mechanical tracking system. This early system aimed to display wireframe graphics without a dedicated applied functionality. The term *augmented reality* itself was finally coined by Caudell and Mizell [60] in 1992 [56]. Caudell and Mizell introduced an optical see-through AR assistant for wire assembly.

Since then, AR has been incorporated in many technology domains and applications [57]. These domains include AR for educational purposes [61], for the aeroscpace domain [62], for consumer retail [63], for novel gaming concepts [63], for industrial maintenance and repair [64], and multiple others [57]. Following this dissertation's overall research objectives, however, the remainder of this chapter keeps a focus on AR applications and technologies in the medical domain [65, 63].

Within the medical domain, AR is commonly used in patient therapy and in the training and education of students and junior clinical staff [65]. The primary application of AR for medical training is in surgical training [65]. Surgical training with AR can include the simulation and training of surgical scenarios [66] or the remote mentoring and consultation by senior surgeons [67]. Generally, AR has been shown to improve the effectiveness of surgical training [8]. Beyond the surgical training domain, AR is used in the context of anatomical education and anaesthesia training [68].

While the use of AR includes applications for non-surgical patient treatment [69] or for patient rehabilitation [70], it is most commonly used in surgical contexts [65]. Within the surgical context, AR is mostly used for preoperative planning or for intraoperative navigation [8]. Many surgical AR planning and navigation solutions rely on preoperative data about the surgical target and risk structures. They are, therefore, sensitive to the anatomy deformations that may occur. Thus, surgical planning and, even more so, navigation are particularly well suited for surgical domains that focus on rather rigid structures. Therefore, its use is more common in neurosurgery, head-and-neck surgery, and orthopedic surgery than in other surgical disciplines [8].

Many solutions in conventional (open) surgery navigation rely on optical see-through AR [71] or projective AR [10]. This maintains the key benefit of AR support that the surgeon does not have to divert his or her visual attention from the surgical scene. In laparoscopic (and robot-assisted) surgery, however, the surgeon can only see the surgical scene through a video camera's (i.e. the laparoscope's) real time video stream. Therefore, laparoscopic AR support is primarily implemented in video see-through solutions [11]. Some concepts exist that use optical see-through AR [72] or employ small projector probes to generate projective AR visualisations in the laparoscopic field [73]. Nevertheless, the remainder of this chapter primarily focuses on the technical background and prerequisuites of video see-through AR in laparoscopic and robot-assisted surgery.

2.2.3 Augmented reality system components

Multiple generic framework descriptions for the generation of AR visualisations have been published in the relevant literature. Broll defines a simplified production pipeline with five steps [57]:

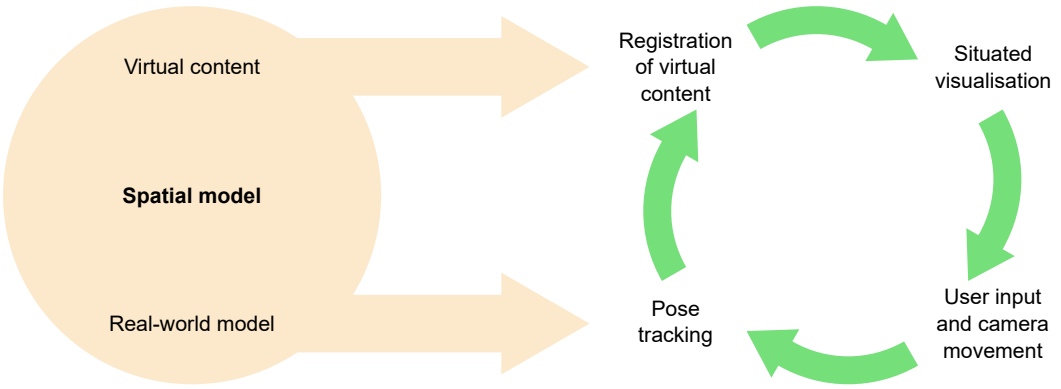


Figure 2.8: Feedback loop between the AR system and the user. Figure adapted from Schmalstieg and Höllerer [56].

1. Video capture (only in video see-through AR),
2. Tracking,
3. Registration,
4. Rendering,
5. Display.

Video capture is required in video see-through AR solutions to provide a video stream of the environment on which the virtual content can be overlaid. Tracking means the spatial tracking of the observer's position and orientation. The observer can either be the video camera (in video see-through AR solutions) or the user him or herself (in optical see-through and projective AR environments). The observer's position and orientation are required for accurate registration and rendering of the virtual content. Registration describes the determination and application of the correct coordinate transformation between the virtual content space and the real environment. Based on the tracking and registration information, the virtual content can then be rendered in the correct direction (i.e. position) and orientation from the observer's (i.e. the camera's or the user's) perspective. Finally, the rendered content is displayed on the selected output device (e.g., video screen, head-mounted display, or projector) [57].

A similar framework is proposed by Schmalstieg and Höllerer [56] and is replicated in Figure 2.8. This perspective adds the aspect of active user inputs to the overall framework. Moreover, it distinguishes between the apects that are primarily centred in the physical space (user actions and pose tracking) and the virtual content's registration and rendering that enable and rely on the combination of the physical and the virtual space. Finally, the framework emphasises the feedback loop characteristic of AR systems that is inherent in the real-time rendering and interactivity.

The *Data, Visualisation, View* taxonomy for mixed reality surgical guidance [14] adds the data component to the architectural considerations. This aspect describes the type of virtual content that is to be visualised in a given AR application. Figure 2.9 depicts a combined architectural framework that aims to encapsulate the components introduced above: the video stream of the real environment provides a basis for video see-through

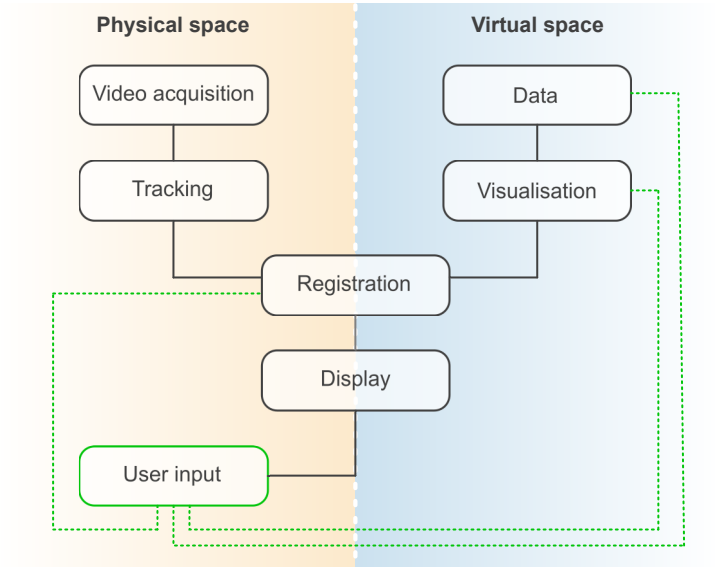


Figure 2.9: AR system framework. The video acquisition is only required in video see-through AR systems.

AR visualisations and tracking of the observer's physical motion is required for their generation. The virtual content of the intended AR product comprises the data to be visualised and the visualisation methods that are applied to them. The registration uses the tracking data and the visualised content to correctly overlay the video stream. The resulting AR visualisation can be displayed to and interacted with by the user. The next sections provide a brief introduction to each of these components.

2.2.4 Video acquisition

The video stream that provides the basis for video see-through AR can be recorded with a single camera (monoscopic video) or with a stereo camera setup (stereoscopic video) [56]. The latter allows the stereoscopic display of the user's physical environment and the integration of stereoscopically rendered virtual content. Video see-through AR is often applied in handheld devices like smartphones or tablet computers [57]. These commonly have an integrated, monoscopic camera. Another application vor video see-through AR with HMDs [74] enables the stereoscopic recording of the user's surrounding.

In the context of laparoscopic AR, the camera that provides the video stream is the laparoscope itself. Laparoscopic cameras (and displays) are available in monoscopic and stereoscopic models and modes. The da Vinci robot that represents the current standard in robot-assisted surgery also provides a stereoscopic video stream. Stereoscopic laparoscopy has been shown to particularly improve performance for novice surgeons [75] whereas limited improvements have been shown for expert surgeons. Figure 2.10 shows an example of a laparoscopic video snapshot.

The immersive display of virtual content in a video see-through AR setting requires rendering the virtual objects as if they were captured by the actual video camera. This means that the rendering needs to imitate the physical camera's optical properties (e.g. the field of view). The video stream itself is subjected to the camera lense's optical

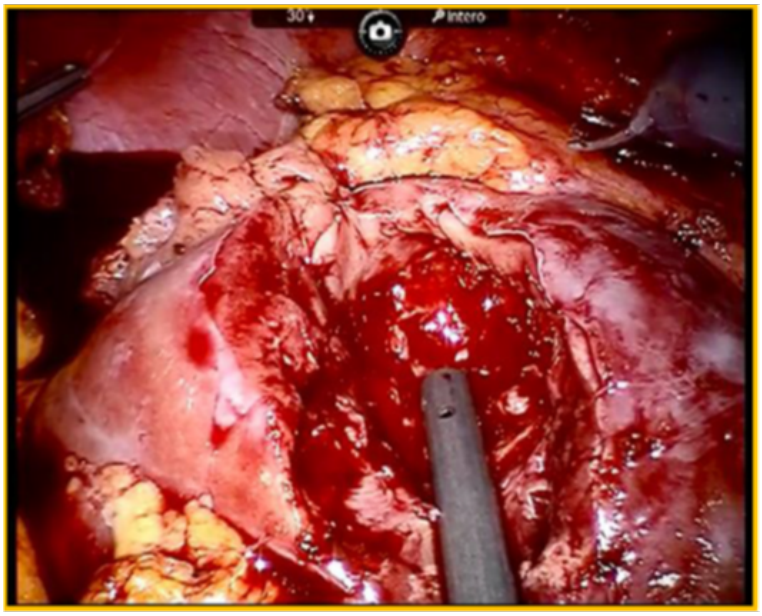


Figure 2.10: Monoscopic video snapshot of a resection wound in RPN. Figure reprinted from Porpiglia et al. [76] with permission from Elsevier.

distortion. There are two options to account for this: either the video stream's distortion is corrected or the same distortion is applied to the virtual content's rendering [56]. The camera's geometric and optical parameters constitute the camera's internal parameters. These internal parameters' identification requires a camera calibration. A commonly applied calibration algorithm by Zhang is based on the idealised pinhole camera model [77, 78]. For this purpose, a known geometry is captured with the camera and the resulting, distorted image allows for the reconstruction of the camera's internal parameters that describe its optical properties (e.g. focus length, field of view, distortion parameters). This algorithm is available in the widely used OpenCV library [79].

2.2.5 Tracking

The correct perspective rendering requires knowledge about the observer's (i.e. the camera's or the user's) position and orientation. This is achieved by spatial tracking. The data for the tracking calculations can be acquired by sensors that are attached to the tracked object. This approach is referred to as inside-out tracking. The alternative approach (outside-in tracking) comprises methods in which external sensors that are often fixed in the environment measure the target object's tracking data in relation to the fixed environment [57]. This section focuses on tracking methods that are applicable and applied in a (laparoscopic) surgical context. Generally, a wider range of tracking options is available that are neglected here, such as GPS tracking in outdoor AR applications.

The most common tracking approaches in laparoscopic surgery are optical outside-in tracking and electromagnetic tracking [11]. Optical outside-in tracking relies on the coordinated images of at least two cameras that trace dedicated objects. One common, concrete solution to this generalised concept is the integration of two calibrated cameras in one tracking device (e.g. NDI Polaris, Northern Digital Inc., Waterloo, Canada; see

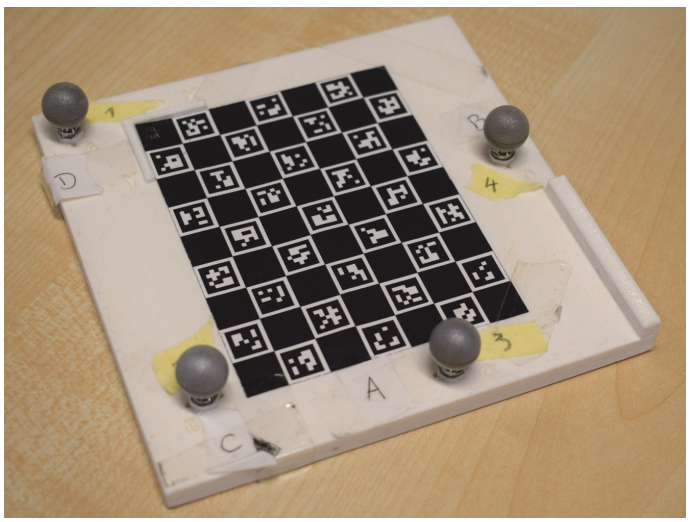
Figure 2.11a). This integrated tracking camera films ifrared marker objects that either actively emit or passively reflect infrared light. The markers are arranged in a unique geometry on dedicated marker shields, which, in turn, are attached to the object to be tracked (Figure 2.11b). Triangulation of the single markers' positions in the separate camera frames enables the calculation of the marker shield's position and orientation in space [56]. One limitation to this method is that it requires free line of sight between the tracking camera and the tracking markers, which may limit the surgical team's movement [11].

The tracked marker body is attached to a part of the tracked object that is located outside the patient to maintain visibility. However, the object of interest (e.g. the laparoscopic camera lens) is located inside the patient. This means that a spatial calibration step is required to determine the target object's position and orientation in relation to the tracked marker geometry. For camera tracking, this spatial calibration is called hand-eye calibration [11]. One option to achieve this for the laparoscopic camera is the use of calibration geometries that integrate a known optical pattern and marker geometry in a defined spatial constellation (Figure 2.11c). The pattern's acquisition allows for camera pose reconstruction and the camera marker geometry's position and orientation can be tracked in relation to the calibration body. This enables the reconstruction of the spatial transformation (position and orientation) of the camera in the marker geometry's reference system [80]. Similarly, if any surgical instruments are tracked for interaction with the AR system, their tooltip positions also need to be calibrated to their marker geometries. One commonly used solution to this is pivot calibration in which the tooltip is placed in one fixed point and the tool is rotated around that point [81]. The distance between the marker geometry and the tracked object (the camera or tooltip) can increase the tracking error [11]. This is because the marker geometry is rigidly mounted to the tracked object. This means that, at larger distances, the tracked object's position measurement depends on the marker geometry's orientation tracking [82]. The rigid transformation between the marker geometry and the tracked object also means that this tracking method is limited to rigid objects [11].

An alternative tracking technology is electromagnetic tracking. In this approach, a dynamic magnetic field with a defined geometry is generated in the surgical site by means of dedicated coil arrangements. This induces electric currents in small sensors that can be attached to the tracked objects. The currents are measured and enable the calculation of the object's position and orientation [11]. This method is better suited for flexible laparoscopic tools because the sensors can be attached to the tooltip and inserted in the surgical site [11]. Moreover, electromagnetic tracking solves the line-of-sight limitation of optical tracking. However, it has been shown to be less accurate than optical tracking [83]. Two further relevant tracking options are optical inside-out tracking and kinematic tracking. In optical inside-out tracking [84], the camera view of known geometries is used to calculate the camera's pose in relation to the scene. In laparoscopic surgery, this method is limited by the availability of unique, recognisable geometries [11]. Kinematic tracking can use (translational and rotational) acceleration sensors to calculate the motion and pose of an object. This, however, is subject to error accumulation over time because the overall position and orientation are calculated from the temporal integration of measured accelerations [84]. In robot-assisted surgery, the robotic arms' kinematic data can be directly extracted from the robot. These can be used for camera or instrument tracking [85].

(a) *NDI Polaris* infrared tracking camera.

(b) Passive infrared tracking markers on a unique geometry marker shield (Cascination AG, Bern, Switzerland). The marker shield is mounted to a laparoscopic camera head.



(c) Calibration body for the laparoscope's hand-eye calibration.

Figure 2.11: Components of an optical infrared tracking system for laparoscopic AR.

2.2.6 Data

Kersten-Oertel et al. provide a comprehensive overview of the data types that may underlie surgical mixed reality systems [14]: the data types are generally classified as patient specific data and visually processed data. The patient specific data include non-spatial data, such as patients' demographic information or relevant clinical scores. The patient specific data category also includes raw imaging data (e.g. CT, MRI, or ultrasound imaging). These imaging data may be obtained preoperatively or intraoperatively.

If these raw imaging data are processed in some visualisation or analysis pipeline, they are assigned to the visualisable data category as 'analysed data'. Further, abstracted data can be derived from these and other sources. These 'derived data' include information like labels, uncertainty levels, or measurements. Finally, generic data that are not based on a given patient may be useful in aiding surgery. Such 'prior knowledge data' may be anatomical atlases, surgical guidelines, or information about the surgical tools [14].

Overall, visualisable data can be further distinguished by their semantic, which may be strategic, operational, or anatomical. Strategic data are associated with surgical planning and guidance, while operational data refer to a specific task (e.g. indicating a tool state). Finally, anatomical data include information about the patient's anatomy, physiology, or pathology (e.g. locations of target or risk structures) [14]. Anatomical data are the most commonly employed type of visualisable data in surgical mixed reality systems [13].

2.2.7 Visualisation

Following the *Data, Visualisation, View* taxonomy [14], the visualisation step comprises the '*specific techniques or transformations performed on the data to achieve the best visual representation of the data for a particular task at a given surgical step.*' [13]. The best suited visualisation for a given application depends on the type of the data. The most commonly visualised data type are anatomical data from medical imaging modalities like CT or MRI. The two main classes of visualisation techniques for these (volumetric) data are indirect volume rendering and direct volume rendering [86].

Indirect volume rendering relies on the segmentation of the raw image data. Segmentation describes the (manual or semi-automatic) assignment of volumes within the image data to objects of interest or to the image background. This means, each voxel is given a label that assigns it to an object of interest or to the background. The border geometries of these objects can then be detected and converted to surface mesh models. These surface models can then, in turn, be visualised for surgical assistance [86] (e.g. Figure 2.12). The surface models are often displayed semi transparently to alleviate the problem of surgical scene occlusion. Surface rendering is the most commonly applied visualisiation approach for laparoscopic AR visualisation of anatomical data [13].

Direct volume rendering does not require prior processing or analysis of the volumetric imaging data but rather generates visualisations from the voxel data. The most common approach for this is a range of ray casting methods. The rays are cast through the volume and each voxel emits or absorbs a certain intensity. The resulting intensity for each pixel is then mapped to a colour value by a dedicated transfer function [86]. While no prior processing (e.g. segmentation) is required in direct volume rendering, it tends to be more computationally expensive than indirect volume rendering [11]. Moreover,

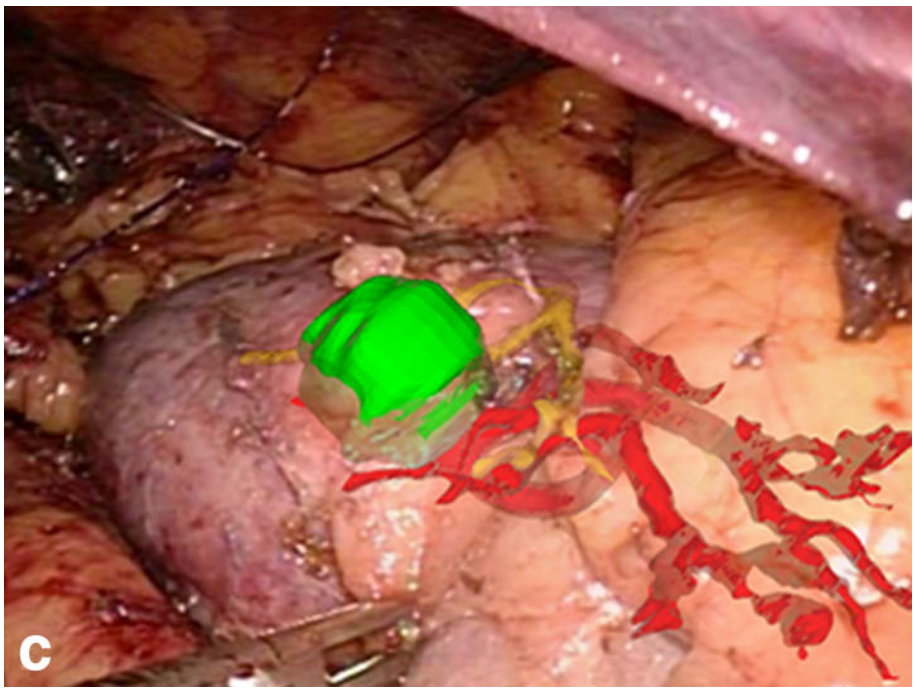


Figure 2.12: AR display of a surface rendered model of the tumour and tumour supplying vessels in a partial nephrectomy. Figure reprinted from Chen et al. [87] with permission from Springer Nature.

the lack of prior definition of objects of interest makes it difficult to specifically visualise the relevant structures [13]. Generally, direct volume rendering is not very commonly used in laparoscopic AR applications [13].

Beside the volumetric anatomical data, two-dimensional ultrasound data may also be useful in surgical AR assistance [11]. These data can be overlaid in real time as a planar image in the laparoscopic scene. Visual aids like perspective distortion or virtual windows can be used to convey the spatial orientation of the currently displayed ultrasonic plane [88].

One challenge in the display of spatial virtual objects within a surgical scene is the correct communication of depth information [13]. Specifically, virtual objects often appear in front of physical objects and structures in the surgical scene while, geometrically, they are located behind or inside these structures. Common methods for the visualisation of spatial object arrangement are object transparancy or lighting [13]. Another option is the detection of physical objects and the occlusion of virtual object pixels that lie behind the surface of these physical objects [89]. Colour manipulation has also been applied to convey depth information, e.g. for vascular structures. The chromadepth [90] and pseudo-chromadepth methods [91, 92] encode depth information in colour hues. Kersten-Oertel et al. found that a combination of colour hue and saturation manipulation is effective in encoding depth information for vascular structures. Finally, dedicated illustrative visualisations have been developed for the display of derived depth data for the relevant structures [10] (e.g. Figure 2.13).

Other, derived and abstracted information can be visualised in various illustrative

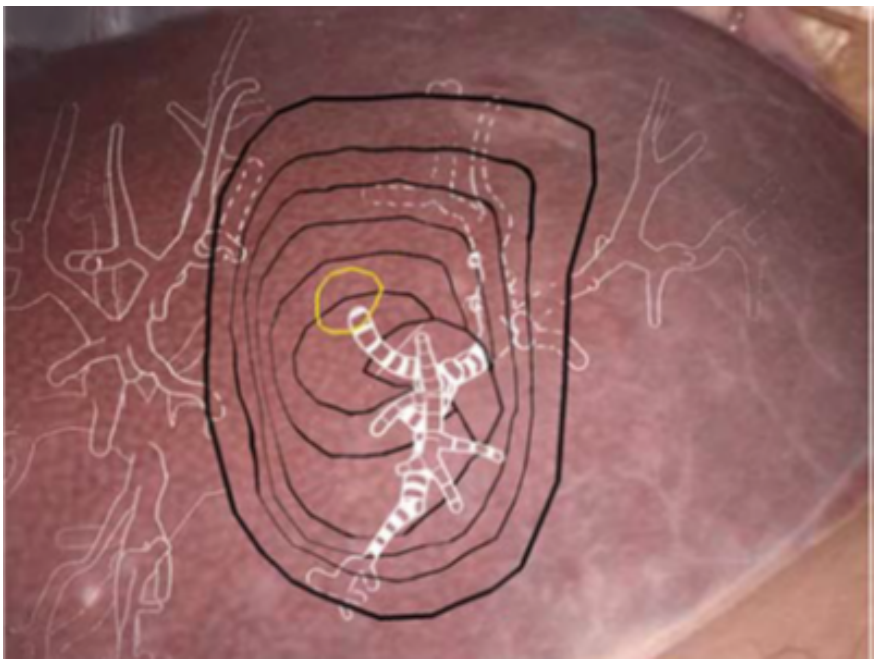


Figure 2.13: Illustrative visualisation of hepatic vessels and a planned resection plane in partial hepatectomy. The illustration conveys the spatial relationship between these structures. Figure reprinted from Hansen et al. [10] with permission from Springer Nature.

ways. One example illustrates uncertainty levels of the estimated tumour boundaries [94] by colour coding a projection of the tumour border. In terms of the data type, this example visualises derived information about the segmentation process and results are included in the visualisation of anatomical data. Another example visualises the spatial relationship between the surgical instruments and the tumour position [95] by rendering abstracted wireframe models of the tooltips and the tumour. This example visualises real time geometric information that is derived from the spatial tracking system.

2.2.8 Registration

Registration describes the determination and application of the correct coordinate transformation between the (navigation content's) virtual space and the patient space. Within the context of this dissertation, the patient space describes the laparoscopic space. For laparoscopic AR systems that use preoperative imaging data, this means that the image data set's coordinate system is registered to the laparoscopic camera coordinate system. (Rigid) registration transformations consist of a coordinate translation, rotation, and scaling component. Due to the likely organ deformation between the time of preoperative data acquisition and its application in surgical navigation, some methods for non-rigid registration have been developed. For AR systems that employ intraoperative imaging data, the intraoperative imaging sensor's coordinate system is registered to the laparoscopic camera's coordinate system. Bernhardt et al. [11] distinguish four categories of registration methods: interactive methods, point-based methods, surface-based methods, and volume-based methods.

Interactive registration methods allow the user to set some or all of the nine degrees of freedom (DoF) (three translational DoF, three rotational DoF, and three scaling DoF) by manual input [11]. One example is the manual rotation and translation of a 3D model until it correctly matches a recent screenshot of the laparoscopic image [87]. Another approach determines the translational part of the registration by identifying one landmark in the virtual content [96]. The use of landmarks is further explained below. This landmark is then located by identifying it in both images of the stereoscopic laparoscope view and triangulating its position. The rotation is conducted manually, using a trackball interface. One advantage of predominantly manual registration methods lies in their technological simplicity that makes certification of a medical product easier than for a highly automated solution. However, these solutions are potentially invasive to the workflow and the registration accuracy is dependent on the interacting operator's performance [11]. The latter aspects are influenced by the interaction concept employed.

Paired point-based registration determines the registration transformation based on the positions of a set of paired landmark points. Landmark points can be anatomical or artificial landmarks, as well as external or internal landmarks [11]. Anatomical landmarks are characteristic points in the patient's natural anatomy. Artificial landmarks are fiducials that are attached to the patient. External landmarks are on the patient's skin, whereas internal landmarks are located in or near the surgical site itself. The geometric positions of each of the landmark points needs to be identified in the virtual and physical space to determine the spatial transformation required for virtual content registration [97]. The number of points depends on the application [98] but as few as four paired points have been successfully used in laparoscopic surgery navigation [99]. Hayashi et al. [100] propose using anatomical landmarks that are naturally relevant for the surgical workflow in order to make the process of point acquisition more efficient.

Surface based registration methods use an intraoperatively acquired point cloud from an anatomical surface for registration to the geometrical information of the pre-operative virtual data [101]. Overall, four steps of surface based registration can be distinguished [11]:

1. Extraction of geometrical surface information on the virtual model,
2. Reconstruction of a surface patch (point cloud) on the physical organ,
3. Initial rigid registration of the two point clouds,
4. Rigid or non-rigid refinement.

The first task is trivial if the virtual model has been previously segmented. A point cloud from the real organ's surface can be acquired by use of a tracked laparoscopic tool (e.g. a stylus) [102]. A second option is the use of passive laparoscopic image processing methods. Finally, active light casting methods (e.g. light pattern projections or time of flight measurement) can be employed for measuring the organ's surface [11]. The most common algorithm for surface-based registration is the Iterative Closest Point (ICP) method [103]. This method requires a rough initial registration (Task 3). Interactive or paired-point methods can be applied to this end. It then optimises this initial registration to a (usually) local or global optimum. Su et al. [104] employ the ICP algorithm in a navigation system for LPN. They combine it with a manual initial registration. Various

characteristics of the surface from which the point cloud is acquired affect the performance of surface-based registration. Benincasa et al. [105] investigate two key factors, using the ICP algorithm. The first examined factor is the size of the surface patch from which points are sampled. The second factor is the surface curvature within this patch. The observed registration accuracy was better for bigger surface patches and patches with areas of higher curvature. Independent of curvature, the registration was found to be accurate for patches that include 28% of the kidney's surface or more. Multiple non-rigid optimisation solutions have been developed in the past few years [11], which aim to mitigate the organ deformation that occurs in abdominal organs. This deformation can arise between the time of the acquisition of preoperative images (that often underlie the virtual AR models) and the time of surgery. Intraoperative factors can also contribute to the deformation. Non-rigid registration, however, is beyond the scope of this dissertation.

Volume registration methods rely on intraoperatively acquired volumetric imaging in hybrid operating theatres [11]. They are, therefore, particularly well suited for the registration of intraoperatively recorded navigation content [106]. However, due to the added need for intraoperative imaging and the resulting equipment requirements, volumetric registration is out of this dissertation's scope.

AR registration aims to determine the (rigid or non-rigid) coordinate transformation between the virtual and the physical space as accurately as possible. The most common accuracy measure for the registration is the target registration error (TRE) [107]. The TRE describes the distance between a surgically relevant point (e.g. the centre of a target or risk structure) and its virtual equivalent after the registration has been completed. The TRE cannot be directly measured in the clinical application but only estimated [108]. Some AR navigation assistants aim to visualise the estimated TRE to communicate some registration uncertainty information to the operating surgeon [109, 110].

2.2.9 Display

The main distinction between AR display types is the distinction of video see-through, optical see-through, and projective AR displays that has been explained above [57]. Another important distinction is the dimensionality of the real world's and the virtual content's display [56]. In optical see-through and projective AR, the real environment is typically perceived three-dimensionally. In video see-through, the environment may be recorded monoscopically or stereoscopically and displayed to the user accordingly [56]. Video and optical see-through displays may be monocular or binocular. For binocular display devices, the virtual content display may be monoscopic or stereoscopic, enabling a spatial perception of the virtual content [56]. Projective displays are usually monoscopic although some concepts exist for stereoscopic AR projection [111].

The display location is another characterising factor of AR display devices. Schmalstieg and Höllerer [56] characterise displays based on the distance between the display and the eyes and state four overall categories: HMDs, handheld displays, stationary displays, and projective displays. For surgical AR, the perceived location of the virtual content can be further specified as being on the patient him or herself, on a display device, on a surgical tool, or in the further environment [14]. Generally, the conditions and setup of the operating theatre constrain the perceived and physical location of the AR content [13].

This makes laparoscopy an interesting application in which the abovementioned classifications can become somewhat blurry. The primary information source for the

surgeon is the laparoscopic video stream itself [13]. This means that video see-through AR displays of anatomical data may be physically displayed on a stationary monitor but yet be perceived to be located in the patient him or herself. Similarly, the video stream makes video see-through AR an intuitive route for displaying relevant content. Nevertheless, laparoscopic projective probes allow the use of projective AR [73]. The already augmented scene is then captured by the laparoscopic camera and fed to the video display.

2.2.10 User input

User input methods in AR systems can be reviewed regarding their virtual function or regarding their physical input modalities and the associated input device(s) [14]. User input is primarily required for the selection of the data that is to be displayed and for controlling the visualisation of those data [13]. Visualisation settings may include objects' position, rotation, clipping planes, or colour [13]. However, user input may also be required in the AR registration process [11]. This is obvious in interactive registration approaches [112, 113] but user input is also often required in other registration approaches. For example, point-based registration may require the interactive acquisition of fiducial positions [99] or surface-based registration may require the interactive recording of surface point clouds [114].

The physical input modalities and devices cover a range as broad as input modalities and devices for human computer interaction in general. This spectrum includes classic input devices (e.g. mouse, keyboard, touchscreen) [13] and spatial and haptic input devices (e.g. 'Space Mice' with six DoF [13] or virtual reality hand controllers [115]). Beyond these conventional input modalities, more natural user input methods have also been applied in surgical AR contexts. These include input modalities like head movement [72], hand and foot gestures [115], voice control [116], or eye tracking [84]. The latter modalities bear the particular benefit that that they can be implemented as touchless input methods, which are not constrained by the surgical sterility requirements [8]. Finally, AR enables the integration of tangible objects that are already a part of the workflow as input devices for the AR system. The acquisition of geometric data for AR registration with laparoscopic instruments [99] or robotic instruments [114] are examples for this concept.

The interaction with virtual objects in surgical AR is very similar to the 3D manipulation of objects in virtual reality [117]. There has been ample research on interaction methods for this that may inform the development of suitable interaction techniques for AR object interaction and manipulation.

3

Surgeon information needs in LRPN

Synopsis

What information do surgeons need during LRPN to make the surgery safer, more effective, more efficient, or to reduce the workload for the surgeon? This chapter reports a study that systematically investigated these information needs. To this end, the surgical workflow was examined in a literature-based task analysis. Based on this, a CTA interview study was conducted with nine senior surgical urologists to identify surgical challenges and the strategies, cues, and information that are used or could be useful to overcome these challenges. The study identified three main challenging phases of LRPN: the hilar and vascular management, the tumour resection and the intraoperative planning thereof, and the resection wound repair. Specific challenges and information needs were identified that arise during each of these phases.

About this chapter

Parts of this chapter have been published in: Joeres, F., Schindele, D., Luz, M., Blaschke, S., Russwinkel, N., Schostak, M., and Hansen, C. (2019). 'How well do software assistants for minimally invasive partial nephrectomy meet surgeon information needs? A cognitive task analysis and literature review study'. In: *PloS one* 14.7 *[18]*.

3.1 Introduction

The first question to be asked in the user centred development of novel assistance systems in general and, more specifically, of navigation aids for surgeons has been phrased as: what information does the user (i.e. the surgeon) need [13, 118]? In complex procedures that may especially benefit from software assistance, the answer to this question depends on the phase or stage of the operation. The question can, therefore, be extended to include: what information does the surgeon need and at what point in the procedure does he or she need it [13, 119]? The present chapter aims to answer this question with the example of LRPN. In this context, information needs are defined as any information that, if provided to the surgeon, can help make the procedure safer, more effective, more efficient, or that can help to reduce the workload for the surgeon.

Providing useful information in the surgical stages in which it is needed requires the understanding of two factors: firstly, the surgical workflow itself. The research field of surgical process modelling [120] has developed numerous methods to understand and model surgical workflows. An overview of the respective techniques is given below. Secondly, the challenges within that workflow need to be understood and possible routes to alleviating these challenges need to be identified.

Thus, the research reported in this chapter followed a process with two distinct phases and the chapter is structured accordingly: first, the surgical workflow at hand (LRPN) was investigated and formalised. This provided a basic understanding of the user task structure and served as a basis for the information need investigation that followed. Next, a CTA was conducted in the form of a qualitative, semi-structured interview study. Within this study, particularly challenging or risk-associated parts of the workflow were identified by experienced urologists. These parts were then discussed in detail to identify information that may help surgeons to conduct these challenging parts of the workflow, i.e., intraoperative information needs. This phase provided the data to answer the above research question.

This chapter's contribution is threefold: firstly, it provides a systematic workflow description of LRPN. Secondly, it reports surgical challenges and information needs that arise during this operation. Finally, it can serve as a case study for a novel research approach to facilitate the insights that are summarised in the above contributions.

3.2 Workflow analysis

3.2.1 Related work

Multiple approaches exist for the generation and documentation of formalised surgical workflow and process models. These models aim to identify the common states and activities that occur in a certain type of surgical procedure despite the fact that every patient's surgery is individual to some degree [121]. These modelling approaches can be classified as top-down or bottom-up methods [122]: while top-down methods start with an overall process objective and deconstruct activities and steps that need to be taken to achieve this objective, the bottom-up methods rely on highly granular data from the operating theatre and integrate these to represent broader, higher-level tasks. Bottom-up methods allow for highly precise, flexible models, which may contain quantitative representations of relevant workflow aspects. However, they require complex data from

multiple sources for their creation and may reach high model complexitities. Top-down methods, on the other hand, allow the break down of complex processes to a desired level of complexity and can be based on more abstract data sources [122].

A widely-used top-down method for investigating and reporting workflows in human-machine systems is the hierarchical task analysis (HTA) [123]. This method has been used, modified, and extended over the past five decades. In 2006, Stanton [124] provided a comprehensive review of variations and extensions of the HTA approach. In the HTA method, the user's goals and activities are systematically deconstructed into their subgoals and task steps. These subgoals and steps are then further desconstructed and so on. One major challenge lies in identifying the end point for this deconstruction, i.e., defining the desired granularity of goals and activities. Within the surgical domain, Sarker et al. [125] recommend defining the end point of task deconstruction such that the tasks and steps required for the achievement of the surgical goal are well defined, but the individual technique and tools applied by the surgeon are not implied.

While a wide range of methods have been applied to model a broad field of surgical applications [121], no dedicated model or description of the workflow of partial nephrectomy exists. Various informal descriptions of the surgical workflow in LRPN exist. These descriptions are either published in the form of surgical educational literature (e.g. [19]) or published as reports of new surgical techniques (e.g. [46, 31]). However, these procedure descriptions do not aim to systematically describe a generic workflow across various surgical strategies and schools of thought.

3.2.2 Methods

A literature-based HTA approach was selected to investigate the LRPN workflow. An informal literature search was conducted on Google Scholar to identify eligible surgical procedure descriptions of LRPN. The search terms "laparoscopic partial nephrectomy", "laparoscopic partial nephrectomy segmental clamping", and "robot assisted partial nephrectomy" were used for this search. The results were informally screened by one investigator (the author). Forward and backward searches were applied for relevant results. The results of this literature search were combined with relevant scientific publications and surgical textbook literature that were already known to the involved investigators [18]. Clinical publications and teaching literature were selected from the overall search results by the following criteria:

- Publications were included that describe the surgical procedure of LRPN at a high level of detail.
- Publications were selected such that laparoscopic and robot-assisted procedure descriptions were included.
- Publications were selected such that different vascular management strategies were included (i.e., total clamping, selective clamping, and zero ischaemia approaches).

The publications were chosen such that the authorship overlap between the publications in the selection was kept to a minimum. This was done to prevent bias towards one surgical centre or school of thought.

The surgical procedure described in each publication was reviewed and formalised into a separate HTA by one investigator (the author). The granularity of working steps was

set to represent the tasks and steps required to achieve the respective sub-goals without implying the individual technique or tools [125]. The sub-goals were not explicitly listed as they are implied in the surgical tasks and steps. The tasks and steps of each HTA were then compared to identify equivalencies and workflow parts that depend on the surgical approach. Based on this, the HTAs were merged into one generic HTA, which included tasks and steps from all separate HTA with removed redundancies.

Four additional surgical publications were then selected to validate the generic HTA. These followed the same selection criteria as the first set of publications, except that no authorship overlap with any of the original publications or with each other was accepted. Separate HTAs were created for each of these additional publications. These HTAs were compared to the generic HTA to confirm whether they contained any additional tasks or steps that had been omitted in the generic HTA.

3.2.3 Results

Five surgical publications [30, 46, 19, 31, 45] were selected for the initial generic HTA. One author contributed to two of these [46, 19]; no further authorship overlaps occurred. From these publications, 12 tasks comprising 43 surgical steps were identified constituting the initial generic HTA of the LRPN surgical procedure. The resulting HTA is reported in Table 3.1.

Four publications were selected for the validation [42, 126, 127, 41]. The validation yielded no further surgical tasks, but three additional steps were identified, as highlighted in Table 3.1.

It is important to note that the steps do not have to be and will not always be conducted in the order and frequency in which they are listed here. Some steps will only be conducted in some surgical approaches. For example, step '8.2: Open / remove clamps' is only performed in cases in which vascular clamping is applied in the first place. Moreover, some steps may be conducted only once whereas others may be conducted repeatedly. For example, vessel cauterisation and tissue resection are performed continuously and iteratively during tumour resection.

Table 3.1: Workflow of LRPN in HTA format.

Surgical Task	Surgical Steps
1 Prepare operation	**1.1** Preoperative plannning **1.2** Patient preparation
2 Initiate operation	**2.1** Stretch retroperitoneal space[1] (*only in retroperitoneal approach*) **2.2** Insufflate operative space **2.3** Place camera port **2.4** Place working ports
3 Navigate to operative site	**3.1** Navigate to renal fascia **3.2** Mobilise kidney **3.3** Dissect hilum

[1] These steps were identified during validation. Table continues on the next page.

Table 3.1 – continued from the previous page

Surgical Task	Surgical Steps
4 Intraoperative examination and planning	**4.1** Remove renal fat from tumour area **4.2** Examine tumour **4.3** Search for further tumours **4.4** Plan and mark excision site **4.5** Confirm plan with ultrasound **4.6** Position kidney for excision[1] **4.7** Confirm that all materials required during resection and renorrhaphy are prepared **4.8** Administer diuretics before clamping
5 Manage renal vessels	**5.1** Clamp renal artery or segmental arteries **5.2** Clamp renal vein or segmental veins **5.3** Confirm that no relevant branches have been missed **5.4** Start clock to monitor ischaemia time
6 Excise tumour	**6.1** Navigate within excision site **6.2** Cut renal tissue **6.3** Cauterise vessels **6.4** [if not clamped] Reduce blood pressure after renal cortex has been cut through **6.5** [if not clamped] Identify and clamp intrarenal vessels **6.6** [if not clamped] Monitor continued renal perfusion under reduced blood pressure **6.7** Place excised tumour next to kidney **6.8** Take biopsy from tumour bed[1]
7 Repair renal defects	**7.1** Close entries to collecting system and major intrarenal vessels **7.2** Confirm lower repairs **7.3** Repair parenchyma
8 Unclamp	**8.1** Administer diuretics **8.2** Open / remove clamps **8.3** Assess haemostasis **8.4** Repair remaining bleeding vessels **8.5** [if not removed in 8.2] Remove clamps
9 Extract tumour with specimen bag	-
10 Conclude operation	**10.1** Repair extrarenal defects **10.2** Place wound drain **10.3** Inspect operative site after deflation to confirm haemostasis **10.4** Remove trocars and close ports
11 Administer postoperative care	-
12 Communication with other operation room staff	**12.1** Communicate with assistant **12.2** Communicate with anaesthesist **12.3** Communicate with nurse staff

[1] These steps were identified during validation.

3.2.4 Discussion

The HTA, as presented in Table 3.1, aims to represent a generic workflow description of LRPN. Thus, its creation and validation are based on nine independent procedure

descriptions. This approach was taken in order to make the HTA valid for a broad range of surgical strategies and schools of thought. Thus, it includes steps that may only be applicable in some of these approaches (e.g., different clamping strategies will affect which exact steps of vascular management will have to be taken). It should be noted that further surgical tasks or steps may exist for additional strategies for LRPN. However, the fact that the HTA validation yielded no further tasks and only few minor steps, indicates that the reported HTA is likely to give a comprehensive overview of the tasks and steps that occur during the operation.

The HTA does not formally describe how many times a given step is performed or in which order the steps are conducted. This information is commonly represented as plans in HTA [17]. These plans were not formalised in this project because the HTA was intended to serve as a basis for discussion in the subsequent interview study. Thus, the workflow description was kept as simple as possible in order to avoid unnecessary complexity for the participants. Moreover, formalised plans were not expected to provide additional benefit for the research objectives at hand.

Beyond literature-based workflow investigation, other methods are available to inform an HTA (e.g., structured observation, interviews, etc. [122]). Depending on the purpose of the investigation, on the domain investigated, and on the available literature, these may be helpful or even required to further inform the HTA. In the present investigation, the observation of multiple cases in multiple surgical centres would have been required to achieve the intended generic scope and independence for the generic HTA. Since sufficient relevant literature was available for the given research objective, this was not considered necessary in this project.

3.3 Surgeon information needs

To further determine users' information needs for a surgical assistance system in LRPN, the challenging aspects of the previously documented workflow were identified and investigated using a CTA method.

3.3.1 Related work

Generally, CTA pursues the objective of eliciting and understanding the (conceptual and procedural) knowledge, cognitive processing, and decision making that experts utilise in complex tasks [128]. Besides numerous methods for behavioural and cognitive research, several CTA methods have been proposed and applied to inform the design of trainings or assistance systems for complex tasks. Roth & Mumaw's Function-Based Cognitive Task Analysis [129], as well as Ormerod & Shepards Sub-Goal Template Analysis [130] aim to understand user needs for human-machine interaction. Specifically, they aim to understand which information expert systems can provide to support users in complex tasks. However, both methods primarily target monitoring and controlling tasks (e.g., in industrial plants or anaesthetic monitoring). These are structurally different from process-oriented and operator-driven tasks like surgery.

In contrast, the Workflow Integration Matrix [119] has been developed to understand surgical information needs. Specifically, it aims to ensure that useful information is provided to the surgeon at the appropriate time. It has been succesfully used for the clinical application of surgical needle navigation [131]. However, the method requires

the structured observations of multiple interventions in combination with surgeon focus groups. This requires a level of availability of eligible surgeon participants that seems unrealistic for a challenging operation like LRPN that is conducted by only a few surgeons. The number of interventions to be observed and deconstructed would also be further increased by the objective of covering multiple surgical approaches and schools of thought in the present project. Moreover, the resulting complexity of the surgical process representation seems unfeasible for the complexity of LRPN.

The Applied Cognitive Task Analysis (ACTA) method [132] offers a less detailed approach to understanding the knowledge and information sources that are applied in complex tasks. However, this approach bears a lower logistical threshold as it relies on verbal interviews with experts. Meanwhile, it aims to elicit information that yields design recommendations for the design of expert trainings and support systems.

Finally, the Critical Decision Method [133] investigates the information sources and reasoning that experts utilise in critical, non-routine situations. This offers a perspective for including the investigation of information needs during surgical complications. The present project, however, aimed to elicit information needs that arise during the intended surgical process of LRPN.

No work has been published on these (or similar) methods being applied in the fields of minimally invasive kidney surgery or laparoscopic surgery.

3.3.2 Methods

A qualitative CTA study with two phases was conducted with experienced surgical urologists. In the first phase, a written questionnaire was administered to identify surgical steps that the urologists deemed particularly challenging and/or associated with risks. This was followed by a semi-structured interview employing an adapted form of the ACTA method to further understand the surgical challenges and the information needs that arise from these steps. The following sections report the specific methods applied in these phases.

Identification of challenging tasks

A written questionnaire (Appendix A) was administered that included a list of the 46 previously identified surgical steps (see Table 3.1). Participants were asked to mark the following:

- Two to five steps, which they deemed particularly challenging when performing the operation themselves,
- Two to five steps, which they deemed particularly challenging for novice colleagues, and
- Two to five steps, which they deemed particularly associated with perioperative risks.

Based on the participants' assessment, two or three steps were selected per participant for in-depth discussion: any steps that were marked as challenging *and* risky by a given participant were selected for discussion with that participant. Beyond that, steps were selected such that the number of participants with whom a step was discussed, reflected

the number of participants who marked the step as challenging or risky. This approach aimed to discuss steps with more participants if they were rated challenging or risky by a higher number of participants. This could not be systematically ensured because many participants completed their written questionnaires after the first interviews had already been conducted. Steps 1.1 and 11 (see Table 3.1) were excluded in this analysis because they represent preoperative or postoperative activities.

Identification of surgical challenges and corresponding information needs

The study's objective could be broken down into three partial objectives: first, to identify challenges that participants encounter when performing LRPN. Second, to understand the strategies and cues used by the participants to address these challenges. Finally, to identify potential information needs in LRPN where additional software assistance may be particularly helpful. This section reports the interview techniques applied to collate the data for the first two objectives. The information needs were extracted from these data during data analysis (fulfilling the third objective).

Two categories of interview prompts were used to elicit the information that was required to meet the abovementioned objectives: first, an adapted version of the ACTA's [132] knowledge audit technique was applied. This technique aims to elicit the specific knowledge that domain experts apply and call on (conciously or unconciously) for their performance in complex tasks. The knowledge audit relies on six basic interview probes and two optional ones. Each probe is followed up by in-depth discussion. Five of the basic probes were used in this interview (the *Job Smarts* probe was omitted). These probes were augmented by using the optional *Anomalies* prompt and an explicit prompt on unmet information needs. This additional prompt was phrased as: 'Are there situations in this surgical step in which you would wish for additional information? That is, information that currently either is not available at all or is not available during the step.' The prompts for each discussed surgical step were applied in randomised order.

Second, a list of potential intraoperative decisions was used as interview prompts. Prior to study commencement, a brainstorming activity was conducted between two clinical experts and two human factors experts. This brainstorming activity aimed to identify decisions, which surgeons may have to make during any given surgical step. A total of 340 potential decisions was identified (between two and 20 decisions per surgical step). The potential decisions for the respective step under discussion were read out loud to participants as decision questions. Participants were asked to judge if these were relevant decisions and, if so, to describe what information helps them to make these decisions. The decision questions for each discussed surgical step were presented and discussed in a randomised order.

Each prompt from either category was followed by unstructured in-depth probing to ensure that all challenges, strategies, and cues described by the participants were sufficiently understood by the interviewer.

Study sample recruitment

Twenty-three (23) German hospitals that were known to the author to conduct LPN and/or RPN were contacted by telephone. LRPN experienced surgical urologists from 14 hospitals expressed their interest in participating (one urologist from each hospital).

It was not possible to find suitable time slots with five of them. Thus, nine interview partners participated in the study. Participants volunteered their time and were not paid or otherwise rewarded for their participation.

Study execution

All interviews were conducted by one investigator. Participants could choose between a personal interview and an interview by telephone. Six interviews were conducted by telephone and three interviews were conducted in person. All interviews were conducted in German.

Participants' informed consent for participation was confirmed orally at the times of recruitment and of interview commencement. Prior to the agreed interview date, participants were sent the written questionnaire by e-mail and were asked to complete it and submit the filled-in questionnaire by e-mail. At the beginning of the interview, participants were reminded about the study's objectives, and the interviewer collected data on their relevant surgical experience.

Two or three surgical steps were then discussed in detail. First, the interviewer asked the participants why they rated the step under discussion as challenging and/or risky. The steps were then further discussed using the prompts and in-depth probing that are described above. If time permitted, additional surgical steps were briefly discussed. Brief discussion comprised two prompts: 1) Why did the participant rate a step as challenging and/or risky, and 2) the prompt on unmet information needs otherwise used as part of the modified ACTA method. Each interview lasted between 60 and 90 minutes.

Data recording and analysis

Questionnaire data from each participant were tallied as soon as they were received. Prior to each participant's interview, the data were used to select surgical steps for the discussion as outlined above. During the first interviews it became clear that the answers to the second questionnaire question (*Which steps do you deem challenging for novice colleagues?*) had a very strong overlap with the first question. Moreover, where the answers to these two question diverged, it became clear that the second question was misleading to some participants. Therefore, the selection of discussion points was based on the first and third question only.

During the interview, the interviewer took notes of relevant participant comments, and the interviews were audio-recorded. The recordings were saved locally and only accessible to the interviewer to guarantee participant anonymity. Following the interviews, the interviewer compared the notes to the recordings to ensure that all relevant participant comments were incorporated in the subsequent analysis.

The interview notes were then analysed qualitatively by one investigator. First, the notes were filtered for specific challenges. They were then filtered for strategies and cues that participants reported to employ when facing these challenges. Explicit information needs that were expressed by participants were also assigned to the challenges from which they were understood to arise.

These data were collated across participants and, where applicable, clustered across participants. Finally, surgeon information needs were extracted from this data. Information needs were defined as information, which, if provided to the surgeon, might help

face the challenges identified. To extract information needs, the strategies, cues, and explicit information needs were reviewed for each challenge. This approach procured information needs based on three types of information:

1. Information, which was explicitly requested by participants (hereafter referred to as explicit needs),
2. Anatomical or pathological structures that were named as relevant for a given challenge,
3. Information, which participants reported to usually have to recall from memory or judge by experience and gut feeling.

3.3.3 Results

Participant background

Nine participants were interviewed. Three participants had experience with RPN only, two participants had experience with LPN only, and four participants were experienced with both procedures. Overall, LPN experience ranged from 20 to 300 procedures (median: 125) and RPN experience ranged from 10 to 300 procedures (median: 50). One participant who was experienced with only LPN did not provide the number of procedures he/she had conducted.

Identification of challenging tasks

Figure 3.1 provides an overview of the number of participants who rated each surgical step as challenging or risk-associated. The most frequently rated steps included hilum dissection (3.3), vascular clamping (5.1), excision plane navigation (6.1), and the repair of the collecting system and vascular lesions (7.1). Figure 3.2 shows the number of participants with whom each surgical step was discussed. This selection aimed to approximately reflect the distribution of participant votes in the questionnaire data. No participant rated more than three steps as challenging *and* risky. Thus, the objective of discussing all steps that a participant had rated challenging and risky was achieved.

Identification of surgical challenges and information needs

Overall, 21 full in-depth discussions and 11 brief discussions of surgical steps were conducted across the nine interviews (see Figure 3.2). The sample size and applied method do not allow for a quantitative inferential analysis. However, the questionnaire data and interview indicate a consistent trend: it seems that most steps that were rated as challenging or risky, can be classified into one of three surgical phases:

1. Hilar and vascular management (steps 3.3, 5.1, 5.3),
2. Tumour excision (steps 6.1, 6.2, 6.3, 6.5),
3. Repair of renal defects (steps 7.1, 7.2, 7.3, 8.2, 8.3, 8.4, 8.5).

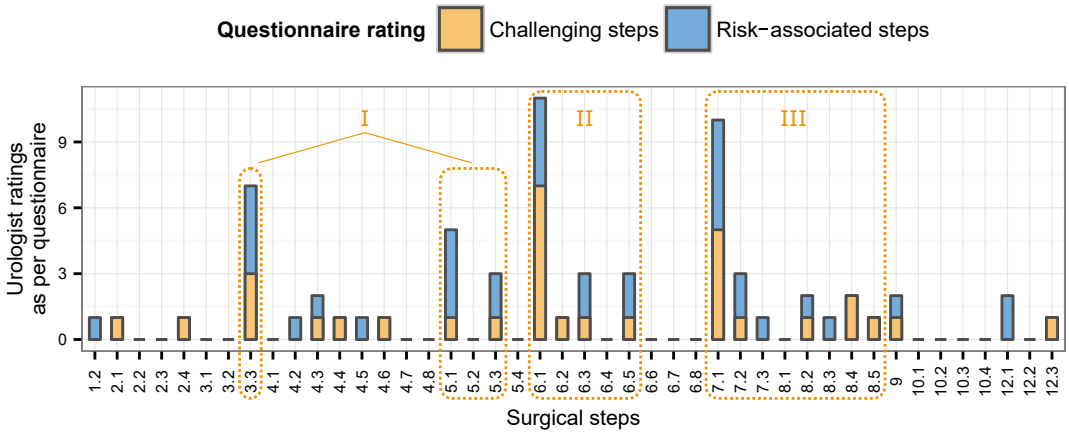


Figure 3.1: Results of the written questionnaire for surgical step selection. Values greater than nine are due to participants rating a given step as challenging *and* risk-associated. The surgical steps are reported in Table 3.1. The numbers I, II, and III indicate the surgical steps that belong to the respective challenging surgical phase.

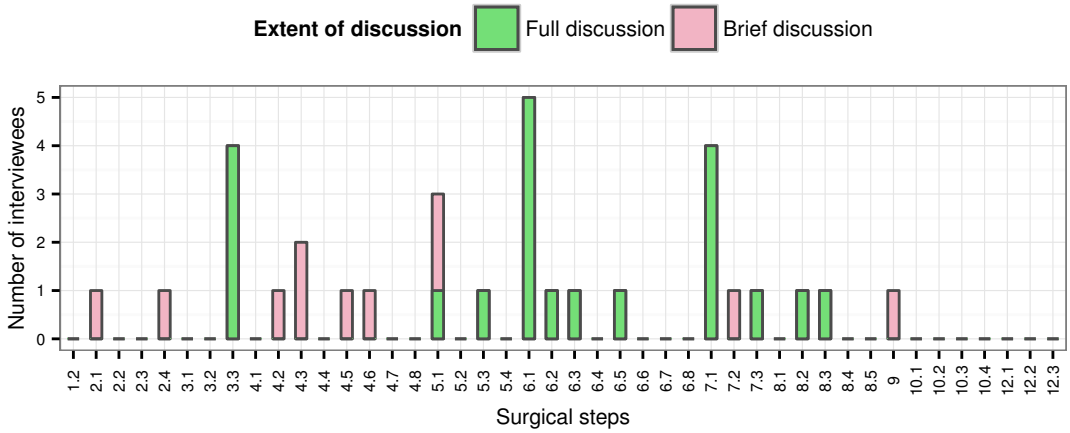


Figure 3.2: Number of participants with whom each step was discussed in the in-depth interviews. Full discussion and brief discussion are defined above. The surgical steps are reported in Table 3.1.

The interview results supported the identity of these three surgical phases: participants who selected different steps from a given surgical phase tended to describe very similar challenges, strategies, cues, and information needs. Discussion with the participants often led to covering other surgical steps within the same phase. In this study, five participants were interviewed about at least one step in surgical phase I, seven were interviewed about at least one step in phase II, and five were interviewed about at least one step in phase III.

During data analysis, 25 challenging surgical decisions, activities, or circumstances were identified (hereafter summarised as challenges), which had been brought up by at least one participant. Twenty-one (21) of these challenges could be assigned to the three surgical phases described above. For most of these challenges, participants reported a range of strategies and/or cues. Table 3.2 lists the reported challenges and the information needs derived from the reported strategies, cues, and explicit information needs.

Most challenges reported by the participants involve spatial navigation in the surgical site, including the identification and localisation of target or risk structures (14 challenges: I.2, I.3, II.1, II.2, II.4, II.6, II.7, III.1, III.3, III.4, III.5, IV.1, IV.2, IV.3). Other challenges include the detection of lesions or complications (4: II.5, II.8, III.2, III.6), strategic decisions (3: I.1, II.3, II.9), and the intraoperative assessments of the successful completion of safety-critical surgical steps (2: I.4, II.10). Two challenges fit none of these categories (III.7, IV.4). A full account of the strategies, cues, and explicit information needs reported by participants is documented in Appendix B.

The type of data collected in this study does not allow for quantitative analysis. However, some trends are visible in the data. Summarising these trends aims to provide an overview of the data reported in Appendix B: the key relevant anatomical structures included the hilum, tumour supplying vessels, large non-tumour related vessels, collecting system, and the tumour(s). The interview data suggest that, unsurprisingly, visual inspection of the surgical site and preoperative CT or MRI data (and processed versions thereof) are the most commonly used information sources. Multiple participants reported using laparoscopic ultrasound (including Doppler ultrasound) and Intuitive Surgical's Firefly^{TM} (Intuitive Surgical Inc., Sunnyvale, CA, USA) indocyanine green fluorescence imaging as intraoperative imaging modalities. Most information needs that were expressed by participants or identified during data analysis involved the intraoperative visualisation of relevant anatomical structures.

Table 3.2: Challenges and information needs for the most risky and challenging surgical phases.

Surgical phase	Challenge	Information needs
I Hilar management	**I.1** Decision: Is clamping required and, if so, which vessels require clamping?	Information about tumour size, position, and tumour supplying vasculature.
	I.2 Hilar dissection in highly variable individual patient anatomy.	Information about ureter, major extrarenal vessels, renal vascular tree, and highlighting of inferior pole.

Table continues on the next page.

Table 3.2 – continued from the previous page

Surgical phase	Challenge	Information needs
	I.3 Identify, localise, and dissect all relevant vascular branches.	Intraoperative availability of preoperative imaging data (and processed versions thereof). Highlighting of occluded vessels. Information about instrument proximity to major arteries.
	I.4 Decision: Have all relevant vascular branches been clamped?	Information about segmental perfusion. Confirmation that clamps are fully closed.
II Tumour excision	**II.1** Localise and navigate to tumour.	Intraoperative availability of preoperative imaging data (and processed versions thereof). Information about tumour position.
	II.2 Find the ideal resection plane.	Intraoperative availability of preoperative imaging data (and processed versions thereof), endophytic parts of tumour, tumour depth, spatial relationship between tools and tumour, preoperative excision plan.
	II.3 Decision: Can the tumour be enucleated?	-
	II.4 Identify current resection plane and surrounding tissue.	-
	II.5 React to unexpected anatomy or pathology.	-
	II.6 Identify, localise, and protect risk structures (vessels, collecting systems).	Information about, or highlighting of parenchyma, major tumoursupplying vessels, collecting system. Intraoperative availability of preoperative imaging data. Highlighting of major occluded vessels.
	II.7 Preserve perfusion to the remaining renal tissue.	Information about segmental perfusion.
	II.8 Detect and manage lesions to risk structures (vessels, collecting system).	nformation about lesions of the collecting system. Information about tumour tissue in the resection plane.
	II.9 Decision: Is retroactive clamping required?	Information about segmental perfusion.
	II.10 Decision: Was the resection oncologically successful?	Information about tissue type in resection bed.
III Repair of renal defects	**III.1** Apply correct positioning, strength, and distance of sutures.	Information about arteries and tissue, which may be in the needle path.
	III.2 Identify, localise, and manage collecting system lesions.	Information about collecting system lesions.
	III.3 Identify, localise, and manage major vessel lesions.	Information about vessels crossing the resection area.
	III.4 Prevent and manage visibility issues due to profuse bleeding.	Information about major blood vessels intraoperatively. Information about source of bleeding.

Table continues on the next page.

Table 3.2 – continued from the previous page

Surgical phase	Challenge	Information needs
	III.5 Distinguish vessels that require individual suturing from those, which do not.	Information about arteries. Quantification and visualisation of strength of bleeding.
	III.6 Problem: Undetected lesions of collecting system or vasculature.	-
	III.7 Problem: In deep incision sites, the first suture can contract the resection too far to apply further sutures.	-
IV Other	**IV.1** *Step 2.1*: Trocar placement is challenging in retroperitoneal approach due to very limited space.	-
	IV.2 *Step 2.4*: Trocar placement is patient-individual and challenging due to robot arm trajectories and constraints.	Support in placement decision making to maximise surgical access and minimise interference of robot arms.
	IV.3 *Step 4.3*: Intraparenchymal tumours are difficult to detect intraoperatively, despite the use of ultrasound. No solution reported.	-
	IV.4 *Step 4.6*: The kidney may have to be fully mobilised. In laparoscopic surgery, holding the kidney in position binds one of the available tools (and arms) for the duration of the procedure.	-

3.3.4 Discussion

Discussion of the study methods and results

The CTA interview study results identified three key surgical phases during which most reported challenges occur. The three phases were discussed with a similar number of participants. Within these phases, a range of challenges were identified and participants reported a variety of strategies and cues, which they employ to meet those challenges. From these, a range of information needs could be identified. These phases were identified through the interviews. Clinical investigation and structured observation may be necessary to confirm whether a majority of complications and clinical risks arise from these three phases.

The research approach in this study included a mixture of methods, including a bespoke questionnaire, an adapted version of the ACTA, and additional, decision-based interview prompts. The questionnaire was successfully used to select surgical steps for an in-depth discussion with participants. Although not all questionnaire responses had been received by the time that the first interviews were conducted, it was, overall, possible to approximately reflect the questionnaire ratings in the surgical step selection for interview discussion.

The approach of selecting only a few steps for in-depth discussion made the interviews more efficient. This was helpful in the investigation of a procedure, which requires a high level of expertise, as this limits the population of potential interview partners.

However, due to the available number of participants, it is not guaranteed that all relevant challenges, strategies, and cues could be identified. This approach is, therefore, a compromise between the feasibility of a study with a highly experienced and limited expert population and the objective to draw a full picture of a complex procedure. This study and its results may be affected by the surgical techniques applied by the recruited interview participants and by the information sources that are currently available to them.

The LRPN procedure's complexity may have affected this work in two ways. Firstly, discussion with the participants was limited to a few surgical steps per participant. Secondly, due to the small population of surgeons who are experienced with this procedure, the number of recruited participants was also limited. It is possible that including more surgeons in the study would have revealed additional surgical challenges and, thus, information needs. It is difficult to define a minimum number of participants needed for this type of qualitative study. One may argue that the duplication of interview replies may be an indicator for the completeness of the results. That is, when all data points have been reported by at least two participants, this may indicate that nearly all relevant and obtainable data points have been recorded. Following this criterion, additional participants might have broadened this study's results because a range of the challenges and information needs were only reported by one participant each. However, in this study, the availability of experienced surgeons constituted a limiting factor.

Surgeons may also not be aware of information needs, as they may have learned to compensate for missing information in their clinical routine. While CTA aims to compensate for this, there may be additional information needs that were not revealed with the methods applied here. Generally, focusing on specific surgical steps is likely to have helped to make the discussion tangible and concrete, as intended in the ACTA method. Interestingly, the overall challenging phases still manifested in the data. In future work, these phases could be used to improve the HTA of LRPN further. They may also be helpful in the future development of trainings and training material for LRPN.

The ACTA method enabled a good understanding of the specific expertise applied in this procedure as well as the limits of this expertise. However, the discussion in this interview study was primarily focused on the regular, routine completion of LRPN. Some participants mentioned possible complications during the interviews. In those cases, the information that is used to detect and manage those complications was discussed as intended within the scope of the interview. However, the interview methods did not specifically target complications or non-routine emergency situations. Additional information needs may arise during these rare situations that were not covered in this study. One possible method for investigating those emergency situations in future research could be the Critical Decision Method (CDM) [133].

Applicability of the research methods to other procedures

An interview-based CTA method was used to detect surgeons' information needs during LRPN. This method identified a range of information needs across three surgical phases that may be suitable to being addressed with intraoperative software assistance. The method proved to be successful with the intended objectives. It may well be transferable to investigating other complex surgical procedures. However, the approach has limitations,

and some adaptations may be useful or required when applied to other procedures.

One such aspect is how the initial workflow description was developed. Ample literature is available for LRPN, which was sufficient to generate the HTA reported in this chapter. If this is not available, other data may be more efficient or even necessary to generate a valid and complete workflow description. For example, in some procedures, observational techniques or structured interviews may be more effective or efficient methods to document the surgical workflow. It may also be sufficient to base the workflow definition on a smaller number of clinical publications if the procedure at hand has a smaller range of surgical strategies across the surgical community, or if only one such strategy is of interest. Namely, the second and third inclusion criteria (i.e., coverage of laparoscopic and robotic approaches as well as coverage of different clamping strategies) are specific to LRPN and may be omitted or modified for other surgical procedures. In some surgical tasks, it may be useful to further detail and formalise the task analysis (e.g., by formalising plans).

Another aspect, which may affect the applicability of this approach, is the complexity of the task under investigation. Depending on the task complexity, further limitation of the interview scope may be required. This may lead to greater sample size requirements, which, at some point, may make this approach impractical. In those cases, the first part of the approach (i.e., applying task analysis and identifying critical steps via a questionnaire) may help to identify critical task phases, which can then be investigated in detail. On the other hand, if the approach is applied to a simpler surgical procedure or shorter parts of a procedure, this selection process may not be required at all.

Another potential research focus might lie in intraoperative complications and supporting the surgeon in addressing those. This was not within the scope of this work and may require an adaptation of the technique that is used to identify workflow parts and scenarios to take into focus in the CTA interviews (e.g., CDM [133]).

3.4 Conclusion

This chapter reports a study that investigated the surgeons' information needs that arise during LRPN. This investigation intends to inform the future development of intraoperative software assistance solutions. The approach that was taken involved understanding the surgical workflow at hand, identifying challenging and / or risky phases within this workflow, and understanding in depth the challenges that occur, as well as the strategies and cues that surgeons apply to address these challenges. For the surgical procedure under investigation (LRPN), this approach yielded useful results to further develop the field of intraoperative software assistance. Three surgical phases were identified during which software assistance may be particularly useful: the hilar and vascular management (phase I), the tumour excision (phase II), and the resection wound repair (phase III). Moreover, the results indicate what information may be particularly useful to the surgeons in each surgical phase.

This study did not take into account which of these information needs can realistically be addressed with intraoperative software assistants. Moreover, it did not cross-reference the information needs with software assistance solutions that have already been reported in the literature. The next step, therefore, lies in reviewing the existing software assistance literature for LRPN. This review and a comparison against the information needs can reveal potential gaps in this field and opportunities for the research and

development of novel, surgically beneficial surgical software assistants. Finally, future work is required to generate similar data for other procedures, which may lead to the detection of information needs that occur across multiple procedures or even surgical domains.

4

Review of image guidance in LRPN

Synopsis

This chapter reports a systematic literature review on image guidance and intraoperative software assistance in LRPN. A literature search was conducted to identify relevant articles published between 2008 and 2020. The included image guidance solutions were reviewed for the information they aim to provide to the surgical team and for the data on which this information relies. They were then compared against the information needs previously identified in Chapter 3. Fourty-nine (49) publications were included in the review. The majority of these propose image guidance solutions for the first two challenging surgical phases, i.e. vascular management and tumour resection. This finding revealed a research gap in the current literature regarding image guidance for the resection wound repair as the third challenging surgical phase.

About this chapter

Parts of this chapter have been published in: Joeres, F., Schindele, D., Luz, M., Blaschke, S., Russwinkel, N., Schostak, M., and Hansen, C. (2019). 'How well do software assistants for minimally invasivepartial nephrectomy meet surgeon information needs? A cognitive task analysisand literature review study'. In: *PloS one* 14.7 *[18]*.

4.1 Introduction

The field of image guidance and AR assistance for laparoscopic and / or urological surgery has inspired a broad field of research and publications over the past two decades. This includes various navigation and support solutions for laparoscopic or robot-assisted oncological surgery [11] in general and for LRPN specifically. This chapter's first objective is to provide a comprehensive review of image guidance and AR assistance for LRPN. The review's focus is on the information that the various assistance solutions provide to the operating surgeon. The purpose of this is to compare these proposed solutions against the surgical information needs that arise during LRPN (see Chapter 3). Thus, the second objective of this chapter is to review which surgical information needs have been addressed in previously published work.

4.2 Related work

Following the multitude of scientific literature in this field, multiple dedicated literature reviews have been published in the past few years. Two comprehensive and extensive reviews investigate the use of AR in laparoscopic surgery [11] and robot-assisted surgery [134]. Both these reviews cover a wide scope of clinical applications and target organs and, therefore, have limited focus on LRPN. Similarly, Rassweiler et al. [135] provide an overview of image guidance solutions in wider urological surgery with limited emphasis on the information solutions in LRPN.

Detmer et al. [136] investigate in greater detail which information is presented to surgeons in AR solutions for various urological interventions including LRPN and the data on which this information is based. However, this review is limited to AR-based concepts and excludes other image guidance approaches. Similarly, one review specifically examines intraoperative imaging solutions for PN [137].

Two articles review the use of AR assistance and 3D printed models across the perioperative treatment process for the treatment of kidney or prostate cancer [138] or, more specifically, for RPN [139]. Due to the scope of reviewing solutions for the wider treatment pipeline (including surgical planning, patient education, and surgical simulation), these reviews provide limited detail on the information provided to surgeons intraoperatively. Other, more specific reviews of image guidance in LRPN, focus primarily on the aspects of registration and tracking [102] or the quality of image guidance evaluation studies [140].

One comprehensive review that includes the clinical objectives and solutions for image guidance in renal and hepatic surgery reviewed publications from a time period between 2000 and 2011 [141]. The results, therefore, do not cover recent, relevant findings within the field. Finally, multiple review papers exist that provide introductory overviews of image guidance for the fields of general minimally invasive surgery [142], minimally invasive urological surgery [143, 144], or LRPN [145] without providing an in-depth analysis of the information that is provided to the surgeons.

4.3 Methods

This section reports the search method, publication selection process, and analysis approach of the literature review.

4.3.1 Literature search and selection

The search process comprised three phases. In the first phase, a PubMed and Google Scholar search was conducted with the following search terms:

(((‘computer’ AND ‘assisted’) OR ((‘augmented’ OR ‘virtual’) AND ‘reality’) OR (‘image’ AND (‘guided’ OR ‘guidance’)) OR ‘navigation’) AND ‘nephrectomy’)

The search was conducted in June 2019 and was limited to publications that were published in or after 2008. In addition, publications were selected from concurrent, relevant literature reviews [136, 137, 102]. The second search phase was conducted in January 2021 to update and extend the initial search results. The search employed the same search terms and platforms and was limited to publications that were published in 2019 or later. During this update, the *Publish or Perish* software [146] was used to conduct the Google Scholar search. In the third phase, all publications that were selected for inclusion in the first two phases were submitted to a forward-backward search. In addition, all relevant review papers that were identified in the first two phases were included in this forward-backward search. The Scopus database was used to collate the references and citations of all previously selected publications. The overall search results of each phase iteratively underwent the selection process that is reported below.

Publications were included that fulfilled the following inclusion criteria:

- Publications that refer to image guidance or software assistance for LPN or RPN.
- Publications that present an image guidance or software assistance approach for intraoperative use.
- Publications that report the information presented to the surgeon.

Publications were excluded if they presented software assistance for preoperative planning only or if they mainly focused on technical challenges (e.g., image registration or medical imaging techniques). Case studies were also excluded when they employed software assistance approaches that were also described in other publications. In cases where research teams published several iterations of the same system, the most recent publication was selected that fulfilled the inclusion criteria. Finally, publications were excluded that were not written in English.

During the first phase, two reviewers independently conducted a title and abstract-based screening of the PubMed search results, following the inclusion and exclusion criteria listed above. One reviewer conducted an equivalent title and abstract screening of the Google Scholar search results. All publications that were deemed to potentially match the criteria by at least one reviewer underwent a subsequent full-text review by one reviewer. Final inclusion or exclusion was determined based on this full-text review and the criteria listed above. The same selection process was applied to the search results of the second and third phase, respectively. All selection steps were conducted by one reviewer for these phases.

4.3.2 Data analysis

The selected publications were reviewed for the clinical purpose pursued. This included the surgical phase that they aimed to support, the clinical objective (if reported), and the information that was proposed to be presented to the surgeon. Moreover, the type of data was recorded on which the proposed image guidance solutions were based (e.g., the medical imaging modality).

The publications were then clustered by surgical phase. Finally, the publications were assigned to the previously identified challenges in order to review how the identified information needs are addressed by the proposed solutions. This analysis was conducted by one reviewer.

4.4 Results

4.4.1 Literature search and selection

An overview of the quantitative results of the search and selection process is provided in Figure 4.1. During the first search phase (conducted in 2019), the PubMed search yielded 340 publications of which 49 underwent full text review. The Google Scholar search yielded 2,750 results. The results were sorted by relevance and the first 595 results underwent a title and abstract-based review. The last identified eligible entry was the 345th entry in the list of search results. Another 250 entries were screened without further eligible results. Thus, the screening was terminated after 595 entries. Out of these 595 search results, four publications that had not been identified in the PubMed search or previous reviews underwent full-text review. Twenty-six (26) publications were included for analysis from the PubMed and Google Scholar search. Eight additional publications were identified from previous reviews [136, 137, 102], resulting in a total number of 34 publications to be included in the review.

The second phase's PubMed search yielded 33 publications that had not been previously screened. Out of these 33 publications, nine proceeded to full text review. The Google Scholar search yielded 973 new results. Nineteen (19) of these underwent full text review. After reviewing these 28 full texts, five were included in the review.

The 39 publications that were identified during the first two search phases were included in the forward-backward search. In addition, 14 review papers were included that had been found in the first two search phases [11, 140, 142, 139, 136, 145, 137, 143, 102, 141, 144, 134, 135, 138]. Three publications were not listed in the Scopus database. Therefore, the backward search was conducted manually and the forward search was conducted using Google Scholar. The remaining 50 publications were entered in the Scopus database and the references and citations were exported. The forward-backward search yielded 1306 eligible results (publications in English and published in or after 2008). Of these, 26 underwent full text review and 11 were finally included in the review. The forward-backward search yielded an updated version of a previously included article [147, 148]. The original publication [148] was, thefore, replaced. Thus, 49 publications in total were included in the review.

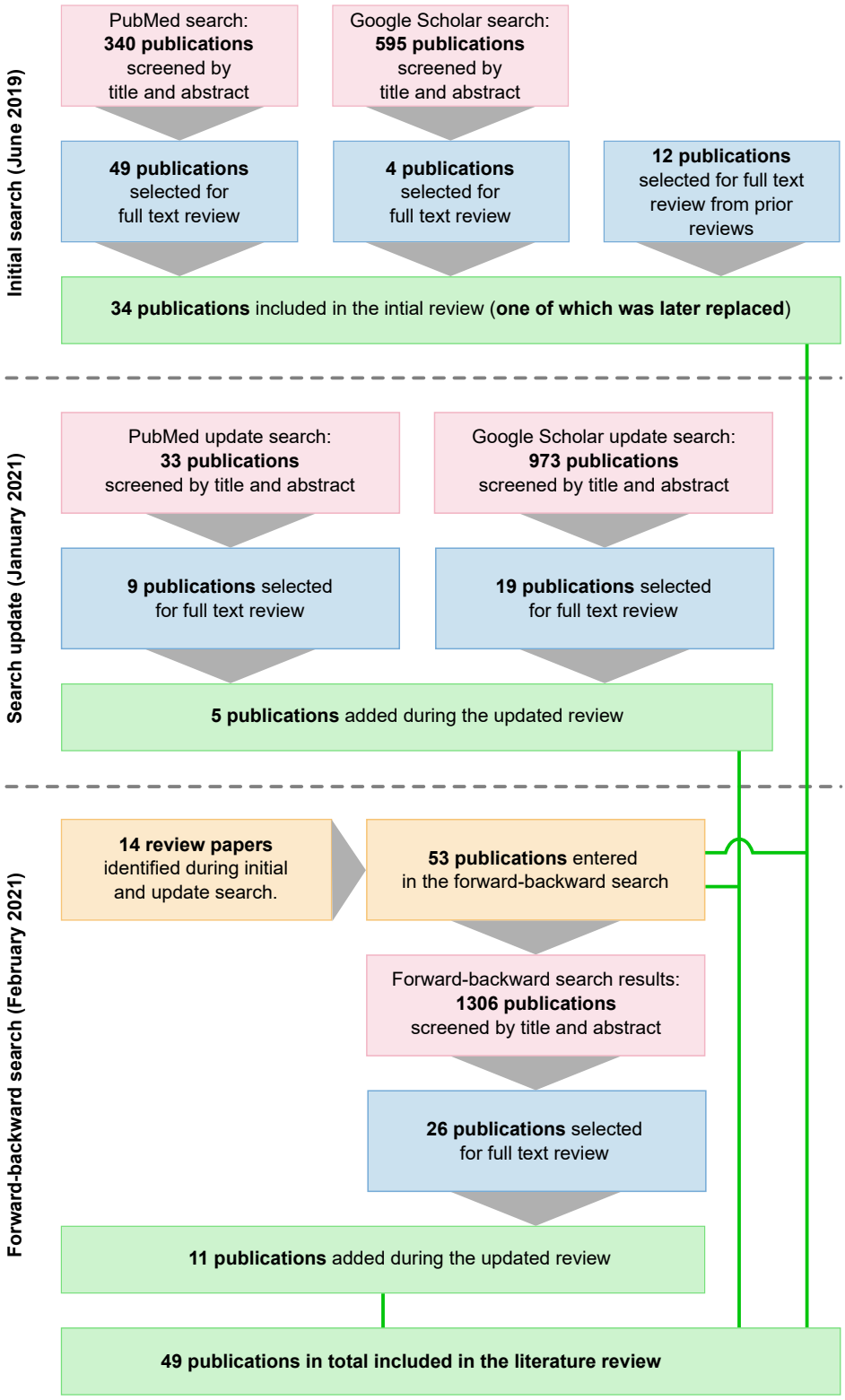


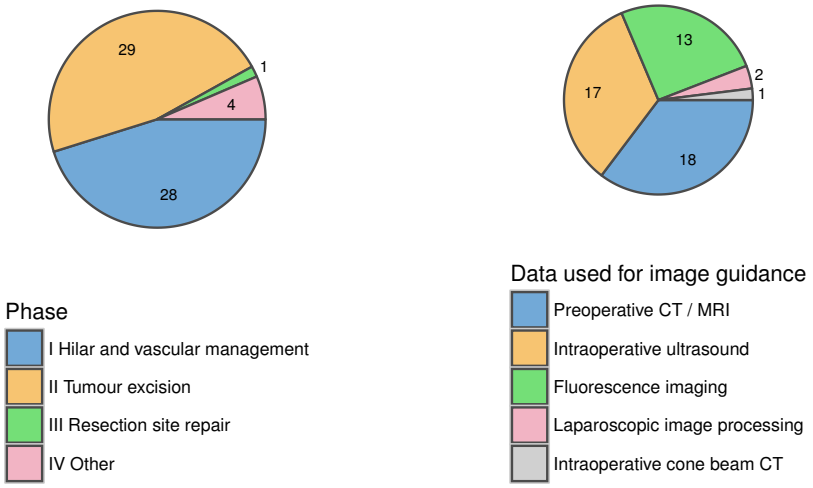
Figure 4.1: Literature search and selection process with its quantitative results. The first search phase's results have been previously published [18].

4.4.2 Software assistance solutions by surgical phase

The included image guidance solutions were categorised by the challenging surgical phase that they supported:

1. Phase I: Hilar and vascular management,
2. Phase II: Tumour excision,
3. Phase III: Repair of renal defects,
4. Other clinical objectives.

Thirty-seven (37) publications could be assigned to one category and ten publications were assigned to two categories each. Two publications [76, 149] aimed to support a major portion of the overall surgery and were, therefore, assigned to three of the four categories each. An overview of this clinical objective classification is provided in Figure 4.2a and summarised below.



(a) Distribution of image guidance solutions across the surgical phases.

(b) Modalities of the data on which image guidance is based.

Figure 4.2: Overview of the quantitative literature review results.

Twenty-eight (28) publications aimed to support the hilar and vascular management phase (phase I) and 30 published solutions aimed to support the tumour excision (phase II). One publication reported the intent to support surgeons during the resection site repair (phase III). Finally, four publications were intended to support surgeons during post-resection perfusion assessment. This is not covered by the challenging phases that were identified in the previous chapter.

Most published solutions employed preoperative CT or MRI imaging data (18 publications) and/or intraoperative ultrasound data (17) (one solution used both of these

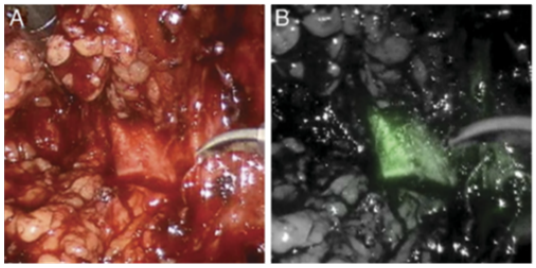
modalities). Another group of publications used fluorescence imaging (13), of which one combined fluorescence imaging and preoperative CT/MRI imaging. The remaining solutions used real-time laparoscopic image processing (2) or intraoperative cone-beam CT (1) as their data basis. Figure 4.2b provides an overview of this distribution. The reported data modalities refer to the data sources for the information provided to the surgeon.

Image guidance for hilar and vascular management

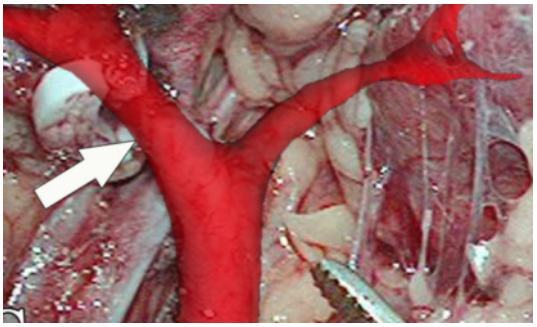
Various approaches have been introduced to support this surgical phase and the steps it comprises. The first group of approaches support the surgeon in the localisation of and navigation towards the renal hilum. These solutions help the surgeon identify the renal artery and vein via AR visualisation of the hilar vasculature [96, 113], via Doppler ultrasound [150, 151], or via real-time colour component analysis of the laparoscopic video stream [152]. Another solution for localising the renal artery (and, thereby, the renal hilum) is the intravenous administration of indocyanine green (ICG) [149, 153]. ICG is a near-infrared fluorescent that can be detected through the arterial walls (Figure 4.3a). Finally, this group of approaches includes the hilum localisation with standard laparoscopic ultrasound [154].

The second group of systems support the surgeon in identifying and localising vessels for clamping during the vascular management phase. This includes a group of publications that propose providing the surgeon with virtual 3D models of the patient's vascular anatomy (including the tumour location) [155, 156, 157, 158, 159, 160]. These models are made available during the operation. They aim to serve as a roadmap for vessel selection and localisation in selective or super-selective clamping. Five further systems take a similar approach but allow the surgeon to overlay the 3D models onto the surgical scene in an AR visualisation (e.g. Figure 4.3b) [85, 161, 76, 113, 162]. Other solutions utilise intraoperative data to support the surgeon during this task. One such approach uses Doppler ultrasound to detect hidden intrarenal vessels [163]. Alternatively, ICG has been proposed to detect hidden vessels [149] or to localise the arteries that are targeted for clamping [164, 149]. In a third approach, the laparoscopic image is analysed in real-time for tissue, which subtly pulsates at approximate heart rate frequency to detect hidden arteries [165].

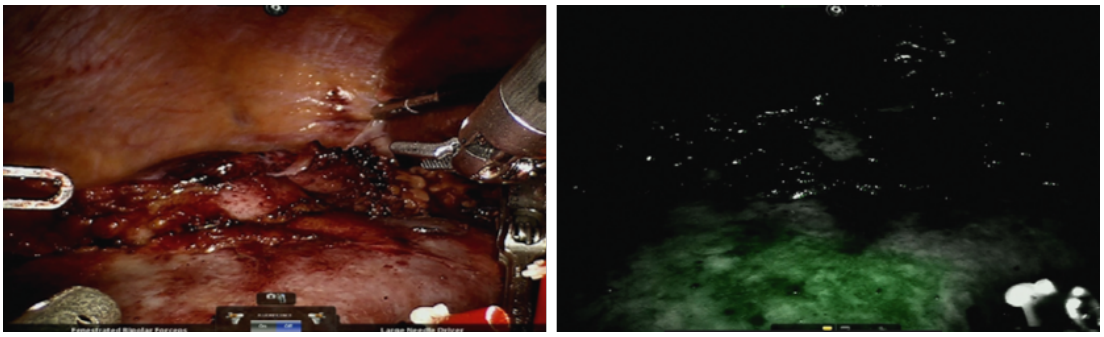
Various approaches have been proposed to help the surgeon with confirming whether all arteries that require clamping have been clamped. One proposed method uses Doppler ultrasound to confirm if the targeted kidney segment is still perfused (in selective clamping) [163, 154, 166] or if the overall kidney is still perfused (in full clamping) [167]. Rao et al. [158] propose using the sonographic contrast agent SonoVue^{TM} (Bracco International, Milan, Italy) to confirm segmental perfusion. In a similar approach, the same contrast agent is used repeatedly to iteratively correct clamp placement [168]. The previously listed strategy of laparoscopic colour component analysis has also been shown to distinguish perfused from ischemic renal tissue [152], enabling the visualisation of segmental perfusion. Finally, five solutions propose administering ICG to visualise the segmental perfusion of the kidney (Figure 4.3c) [147, 169, 170, 171, 113]. ICG is administered after clamping and permeates into the perfused parenchymal tissue. The perfused tissue's near-infrared fluorescence distinguishes it from the ischemic tissue that was previously perfused by the clamped arteries.



(a) ICG visualisation of the hilar renal artery. Figure reprinted from Tobis et al. [149] with permission from Wolters Kluwer Health, Inc.



(b) AR overlay of a targeted artery branch. Figure reprinted from Wang et al. [162] with permission from Springer Nature.



(c) Visualisation of segmental perfusion with ICG fluorescence. Figure reprinted from Gadus et al. [170] under CC-BY license.

Figure 4.3: Selected examples of image guidance solutions for hilar and vascular management during LRPN.

Table 4.1: Anatomical and pathological structures included in different image guidance models.

References	AR visualisation	Structures					
		Parenchyma	Tumour	Hilum	Intrarenal vessels	Extrarenal vessels	Collecting system
Chauvet et al. (2018) [172]	x	x	x				
Hughes-Hallett et al. (2014) [85]		x	x	x	x	x	x
Chen et al. (2014) [87]		x	x	x	x	x	
Porpiglia et al. (2019) [76]	x	x	x	x	x		x
Pratt et al. (2012) [96]	x	x	x	x		x	
Schiavina et al. (2020) [113]	x	x	x	x	x	x	x
Sengiku et al. (2017) [173]	x	x	x	x	x	x	x
Teber et al. (2009) [174]	x	x	x		x		x

Image guidance for tumour excision

A large number of image guidance solutions aim to support the intraoperative planning and execution of the tumour resection. To this end, multiple research groups propose providing the surgeon with 3D models of the patient anatomy and pathology intraoperatively to support tumour localisation [87, 85]. Moreover, means of overlaying these 3D models on the surgical scene in AR visualisations have been introduced (e.g. Figure 4.4a) [172, 76, 96, 113, 173, 174]. A similar reported strategy involves the intraoperative generation of 3D models (using cone-beam CT imaging) and visualising them in a software assistance setting [175]. All of these models include the segmented tumour and overall parenchyma. However, the scope of other structures and information differs between the publications. Table 4.1 provides an overview of the structures included in each publication's navigation solution.

A second cluster of proposed solutions aims to visualise information about the required resection margins and the resulting ideal incision line during the resection planning. Ukimura and Gill [106] propose rendering colour-coded resection margins around the tumour. Another solution visualises the planned incision path in an AR visualisation [96]. This approach has been further pursued for completely endophytic tumours: Chauvet et al. [172] use the position of the resection tool port to project the tumour contours onto the kidney surface from the perspective of this port (Figure 4.4b). This serves to support the identification of an optimal incision path. One further AR-based solution displays colour-coded uncertainty margins around the estimated tumour contours [94]. The uncertainty visualisation encodes the segmentation uncertainty of preoperative probabilistic segmentation results.

Other publications employ intraoperative, laparoscopic ultrasound to provide information about intrarenal structures. This includes multiple publications that localise the tumour using ultrasound probes [176, 177, 178, 175, 154, 166]. Cheung et al. [179] and Pratt et al. [88] propose overlaying the intraoperative ultrasound images onto the

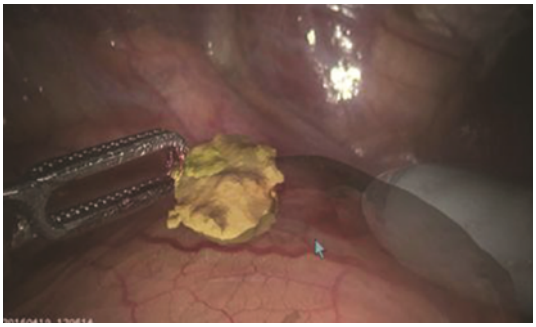
laparoscopic view by tracking the ultrasound probe and laparoscope. The latter solution further augments this overlay with a virtual window animation to provide visual guidance with regards to the displayed ultrasound plane (Figure 4.4c). Kawahara et al. [180] introduce a real-time segmentation solution that automatically detects tumorous tissue in intraoperative ultrasound frames. A similar solution uses the segmentation of intraoperative ultrasound data for projective AR guidance. The segmented tumour is projected onto the kidney surface with a visually tracked, laparoscopic projector [73]. Finally, one publication reports the intra-corporeal ultrasound examination of the resected volume after it has been stored in a saline-filled retrieval bag. This examination investigates and aims to confirm the presence of negative tumour margins [181].

The fourth cluster of solutions proposes the use of fluorescent agents to support the intraoperative planning and execution of the tumour resection. ICG at the right dosage permeates into the parenchymal tissue but not to the same extent into the tumour tissue. It can, therefore, be used to distinguish healthy parenchymal tissue from tumour tissue [182] (see Figure 4.4e). Two research groups report employing this method for the intraoperative resection planning for (partially) exophytic tumours [149, 153]. A modified version of this approach has been reported by Tobis et al. [183]. This approach employs an AR overlay of the fluorescence image onto the regular laparoscopic video stream for resection margin planning. Two other research groups propose an intermittant use of ICG during the resection itself [164, 184]. This serves to progressively localise and develop the resection plane and ensure that it remains within healthy (i.e., fluorescent) tissue. One publication proposes a different, orally administered fluorescent that marks tumour tissue (5-aminolevulinic acid) [185]. This fluorescent agent is used to inspect the resected volume and the resection bed in order to assess the presence of tumourous tissue in the resection plane. Remaining fluorescence in the resection plane indicates positive margins and, therefore, implies that further resection is required.

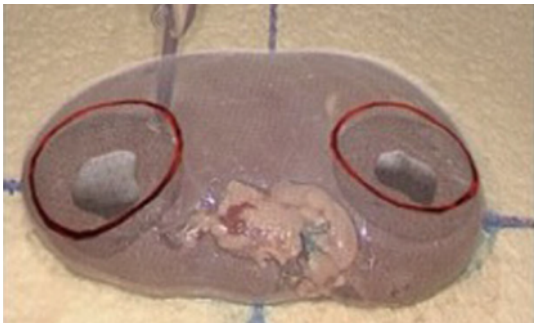
Finally, two solutions focus on conveying the spatial relationship between the laparoscopic instruments and the tumour during the resection phase. Singla et al. [95] utilise visual instrument tracking and real-time segmented ultrasound data for this purpose (Figure 4.4d). Similarly, Simpfendörfer et al. [175] use real-time segmented fluoroscopy data. Both groups visualise the spatial relationship between the instruments and the tumour in dedicated views rather than employing AR visualisation. Both these solutions aim to support the preservation of negative margins throughout the resection.

Image guidance for resection wound repair and other objectives

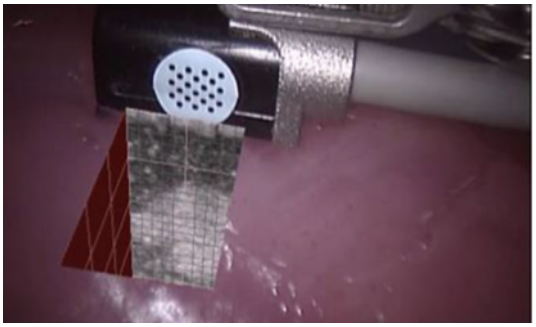
While most of the identified image guidance solutions can be assigned to one of the first two challenging surgical phases as reported above, some solutions' objectives lie outside these phases. The review did not identify any dedicated image guidance solutions that were developed to support the resection wound repair phase of LRPN. However, the AR display of intrarenal structures has been reported to have been applied during this phase in one instance [76]. The authors report displaying the anatomical model of the intrarenal vasculature and the collecting system after the resection for the identification of potential lesions in these structures. Beyond the resection site repair, four publications propose the use of ICG fluorescence imaging to confirm the expected perfusion of the remaining kidney tissue after renorrhaphy is completed [147, 186, 184, 149]. One of these further explores the use of ICG in non-oncological, pediatric LPN [186].



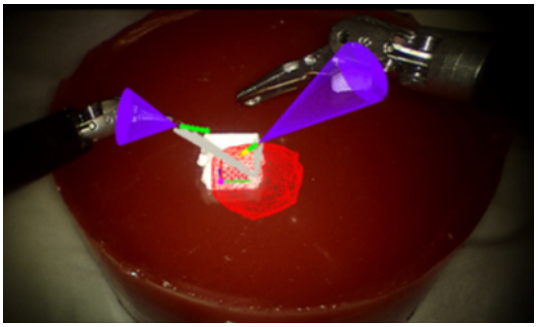
(a) AR overlay of a tumour and kidney model on the laparoscopic view. Figure reprinted from Sengiku et al. [173] with permission from Springer Nature.



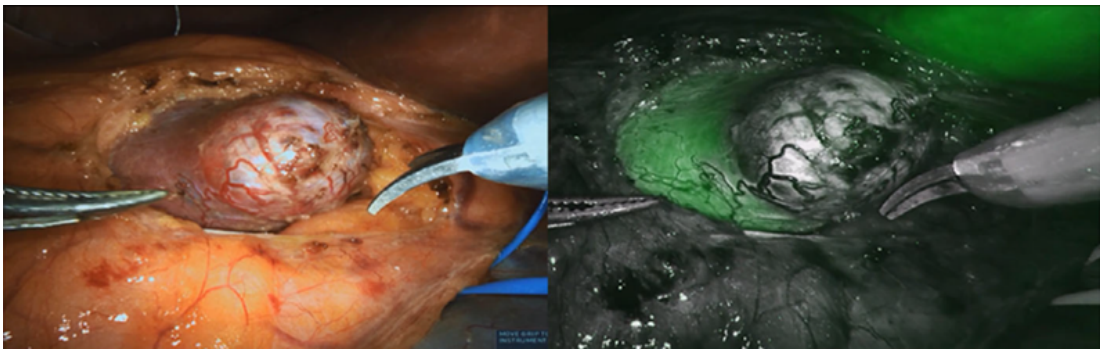
(b) Projection of the tumour margins for incision path estimation. Figure reprinted from Chauvet et al. [172] with permission from Springer Nature.



(c) AR overlay of the laparoscopic ultrasound with virtual window visualisation. Figure reprinted from Pratt et al. [88] with permission from Springer Nature.



(d) AR visualisation of the spatial relationship between the instruments and the tumour. Figure reprinted from Singla et al. [95] under CC-BY license.



(e) ICG fluorescence-based distinction of healthy tissue (fluorescent) and tumour (hypo-fluorescent). Figure reprinted from Sentell et al. [182] with permission from Wiley and Sons.

Figure 4.4: Selected examples of image guidance solutions for the intraoperative planning and execution of the tumour excision.

4.4.3 Software assistance and surgical information needs

The literature review yielded publications proposing various solutions for a range of surgical challenges. An overview of the comparison and assignment between the proposed solutions and the previously identified challenges is provided in Table 4.2. The results suggest a clear trend of solutions primarily supporting the challenging surgical phases of hilar and vascular management (I) and tumour excision (II). The third challenging surgical phase of repairing the renal defects (III) is currently not addressed by dedicated image guidance solutions in the literature.

Within phases I and II, some surgical challenges were identified for which currently no software assistance concepts exist. One such challenge is the intraoperative decision if the tumour can be enucleated, or needs to be resected with greater margins (II.3). There are also no current solutions that help the surgeon to react to unexpected anatomies or pathologies (II.5). No dedicated solutions have been reported for the challenges of preserving the perfusion for the remaining kidney tissue (II.7) and for the decision whether retroactive clamping is required during the resection (II.9). However, multiple publications report visualisations of segmental kidney perfusion (see challenge I.4). These solutions may also be applicable during the resection phase. Based on the number of identified publications, a primary focus of research seems to lie in the identification and localisation of the tumour and the intraoperative resection planning (II.1, II.2).

Concerning the visualised structures, most publications focus on the kidney, tumour, and vasculature (with varying degrees of detail). Only five solutions that are based on general virtual 3D models of the kidney addressed the collecting system. While a preoperative planning system has been published, which supports the surgeon in protecting the collecting system [187], the review did not find any intraoperative software assistance solutions primarily dedicated to the collecting system.

Table 4.2: LRPN image guidance literature compared against the surgical challenges and information needs previously identified (see Chapter 3).

Challenge	Information needs	Proposed solutions
Phase I: Hilar and vascular management		
I.1 Decision: Is clamping required and, if so, which vessels require clamping?	Information about tumour size, position, and tumour supplying vasculature.	Preoperatively created models of the vascular anatomy / pathology [155, 156, 157, 158, 159, 160], AR visualisation of the hilar anatomy [96, 113], AR visualisation of the vascular anatomy / pathology [85, 161, 76, 113, 162].
I.2 Hilar dissection in highly variable individual patient anatomy.	Information about ureter, major extrarenal vessels, renal vascular tree, and highlight inferior pole.	Preoperatively created models of the vascular anatomy / pathology [155, 156, 157, 158, 159, 160], AR visualisation of the hilar anatomy [96, 113], AR visualisation of the vascular anatomy / pathology [85, 161, 76, 113, 162], Ultrasound exploration of the hilar configuration [154], Localisation of the renal vessels with Doppler ultrasound [150, 151], ICG [153], or laparoscopic image processing [152].

Table continues on the next page.

Table 4.2 – continued from the previous page

Challenge	Information needs	Proposed solutions
I.3 Identify, localise, and dissect all relevant vascular branches.	Intraoperative availability of preoperative imaging data (and processed versions thereof). Highlighting of occluded vessels. Information about instrument proximity to major arteries.	Preoperatively created models of the vascular anatomy / pathology [155, 156, 157, 158, 159, 160], AR visualisation of the vascular anatomy / pathology [85, 161, 76, 113, 162], Localisation of target artery with ICG [164], Detection of hidden vessels with Doppler ultrasound [163], ICG [149], or laparoscopic image processing [165].
I.4 Decision: Have all relevant vascular branches been clamped?	Information about segmental perfusion. Confirmation that clamps are fully closed.	Inspection of segmental parenchymal perfusion with ICG [147, 169, 170, 171, 113], Doppler ultrasound [163, 167, 154, 166], ultrasonographic contrast agent *SonoVue*^{TM} [168, 158], or laparoscopic image processing [152].
Phase II: Tumour excision		
II.1 Localise and navigate to tumour.	Intraoperative availability of preoperative imaging data (and processed versions thereof). Information about tumour position.	Display of 3D models of the overall kidney, tumour, hilum, and extrarenal vessels [87, 85], AR display of the overall kidney [172, 76, 96, 113, 173, 174], the tumour [94, 172, 76, 96, 113, 173, 174, 106], the hilum [76, 96, 113, 173], and the extrarenal vessels [96, 113, 173], Tumour detection and localisation with ultrasound [176, 177, 178, 175, 154, 166], AR overlay of ultrasound images onto laparoscopic video [179] with virtual window visualisation [88], Automatic tumour slice detection in real-time ultrasound frames [180].
II.2 Find the ideal resection plane.	Intraoperative availability of preoperative imaging data (and processed versions thereof), endophytic parts of tumour, tumour depth, spatial relationship between tools and tumour, preoperative excision plan.	Display of 3D models of the overall kidney, tumour, intrarenal vessels [87, 85], and collecting system [85] AR display of the overall kidney [172, 76, 96, 113, 173, 174], the tumour [94, 172, 76, 96, 113, 173, 174, 106], the intrarenal vessels [76, 113, 173, 174], and collecting system [76, 113, 173, 174] Intraoperative cone beam CT segmentation and AR overlay of the tumour and renal blood vessels [175], AR visualisation of the tumour contours with segmentation uncertainty [94], safety margins [106], planned incision path [96], or a calculated incision path based on the tool position [172], AR overlay of ultrasound images onto laparoscopic video [179] with virtual window visualisation [88], Ultrasound-based projective AR visualisation of the tumour [73],

Table continues on the next page.

Table 4.2 – continued from the previous page

Challenge	Information needs	Proposed solutions
		Automatic tumour slice detection in real-time ultrasound frames [180], ICG highlighting of partially exophytic tumour tissue [182, 149, 153] with optional AR overlay of the fluorescence image onto the laparoscopic video [183].
II.3 Decision: Can the tumour be enucleated?	-	-
II.4 Identify current resection plane and surrounding tissue.	-	Display of 3D models of the overall kidney, tumour, intrarenal vessels [87, 85], and collecting system [85] AR display of the overall kidney [172, 76, 96, 113, 173, 174], the tumour [94, 172, 76, 96, 113, 173, 174, 106], the intrarenal vessels [76, 113, 173, 174], and collecting system [76, 113, 173, 174] Real-time visualisation of the spatial relationship between the tumour and the instruments based on tracked ultrasound [95] or real-time fluoroscopy [175], Intermittant ICG administration to distinguish tumour tissue [164, 184]
II.5 React to unexpected anatomy or pathology.	-	-
II.6 Identify, localise and protect risk structures (vessels, collecting systems).	Information about or highlighting of parenchyma, major tumour-supplying vessels, collecting system. Intraoperative availability of preoperative imaging data. Highlighting of major occluded vessels.	Display of 3D models of the intrarenal vessels [87, 85] and collecting system [85] AR display of the intrarenal vessels and collecting system [76, 113, 173, 174]
II.7 Preserve perfusion to the remaining renal tissue.	Information about segmental perfusion.	*The solutions for segmental perfusion visualisation that have been proposed for Challenge I.4 may be applicable here but have not been reported in the literature to be used at this point during the operation. ICG imaging has, however, been used to confirm segmental perfusion after the completion of the resection (see below).*

Table continues on the next page.

Table 4.2 – continued from the previous page

Challenge	Information needs	Proposed solutions
II.8 Detect and manage lesions to risk structures (vessels, collecting system).	Information about lesions of the collecting system. Information about tumour tissue in the resection plane.	Intermittant ICG administration to distinguish tumour tissue [164, 184]
II.9 Decision: Is retroactive clamping required?	Information about segmental perfusion.	*The solutions for segmental perfusion visualisation that have been proposed for Challenge I.4 may be applicable here but have not been reported in the literature to be used for this point during the operation.*
II.10 Decision: Was the resection oncologically successful?	Information about tissue type in resection bed.	Fluorescent-based inspection of the resected volume and resection bed for the detection of remaining tumour tissue [185], Intracorporeal, ex-vivo ultrasound inspection of the resected volume [181].
Phase III: Repair of renal defects		
Various potentially targeted challenges (III.1, III.2, III.3, III.5, III.6)	Information about intrarenal vessels and collecting system.	AR visualisation of preoperative models of the intrarenal vessels and collecting system. [76]
IV: Other solutions		
-	-	ICG fluorescence inspection of the perfusion in the remaining kidney after the resection is complete. [147, 186, 184, 149].

4.5 Discussion

4.5.1 Discussion of the literature review

The literature review that is reported in this chapter aimed to provide a comprehensive overview of previously reported or proposed image guidance solutions for LRPN. The search can be seen as mainly successful within this scope. However, the necessary definition of a search scope, inclusion criteria, exclusion criteria, and data analysis approach may have entailed some limitations for the results. The greatest limiting factor among the inclusion and exclusion criteria is the focus on the operation itself, i.e. LRPN. Numerous further image guidance concepts exist for other minimally invasive surgical interventions [11]. However, the profile of surgical challenges is likely to vary for different surgeries. While particular challenges (e.g., localisation of target vessels or risk structures) is common across surgical domains, the particular combination and sequence of challenges is likely to be unique to each surgery. Within the domain of LRPN, the search did not differentiate between LPN and RPN. This is due to the fact that the overall workflow and the available information are similar in both approaches (see Chapter 3).

The second major selection criterion is the limitation to intraoperative navigation

solutions. The research and development of assistance systems for patient-specific preoperative planning is a very closely related field [188, 189]. There is an overlap between the fields of preoperative planning and intraoperative navigation because many preoperatively created plans will be consulted during the surgery, thus assisting the surgeon. For the purpose of a clearly defined scope, this review excluded publications on preoperative planning if they did not specify how, when, or for what purpose the resulting plan would be accessed during the surgery. Without this information, the assignment of preoperative plans to a surgical phase or challenge would have been highly speculative.

Besides the literature selection criteria, the approach for data analysis and information extraction poses a major scope characteristic. The herein reported literature review primarily focused on the information that different solutions present to the surgeon and clinical purpose that the information serves. The review did not investigate how advanced the development of the identified solutions was and, thereby, how close they were to application in the clinical use case. Some solutions can already be viewed as common clinical practice. For example, multiple participants in the previously reported interviews reported using ICG fluorescence for the assessment of segmental perfusion or using ultrasound for the localisation of the tumour. Other solutions have been reported at earlier development stages (e.g. the automatic estimation and visualisation of incision paths [172]). This aspect will require further investigation to assess which challenges have been addressed (and potentially solved) by clinically viable solutions and for which challenges there are initial ideas in the research community. A similar question has been investigated for urological AR solutions in general [140]. Bertolo et al. investigated the level and quality of clinical evaluations for various AR solutions. More generally, the method of evaluation and its degree of clinical realism are listed as key characteristics of image guidance systems [14]. Taking this aspect into account poses a potentially valuable extension and follow-up of this review. However, the review (in combination with the previously conducted interview study) was able to detect some surgical challenges that have not been addressed in the current literature. These research gaps may offer valuable opportunities to improve LRPN and they are discussed in detail in the next section.

4.5.2 Current research gap

Table 4.2 and Figure 4.2a illustrate that a clear majority of the identified image guidance solutions address challenges that arise during the first two challenging surgical phases. Within these, the localisation of the tumour (challenge II.1) and the planning of and navigation within the resection plane (challenges II.2, II.4) seem to have attracted particular attention from the research community. There are two challenges (as per Chapter 3) that none of the identified solutions can be clearly assigned to: firstly, the intraoperative assessment and decision whether the tumour can be enucleated (II.3) and, secondly, the surgical demand to react to unexpected anatomy or pathology (II.5). Moreover, no clear information needs were identified for these challenges. One AR solution was reported to have aided the decision for enucleation by supporting the ultrasound-based assessment of the tumour-supplying vasculature [76]. Speculatively, it is also possible that real-time processing of intraoperative imaging may present effective approaches for these challenges. However, further research is required to investigate whether and how technical assistance like image guidance can support the surgeons with

facing these challenges.

Ensurance and post-resection assessment of the perfusion of the remaining, healthy kidney tissue (II.7, II.9) have also not been explicitely addressed in the LRPN image guidance literature. However, various solutions for perfusion assessment during other surgical challenges have been reported. Clinical research may indicate whether these solutions can also aid the perfusion assessment during and immediately after the resection.

The most significant gap lies in the lack of dedicated image guidance support assistance for the resection wound repair in LRPN (phase III). One identified AR solution reported aiding the identification of severed urinary and blood vessels by overlaying the overall anatomical model [76]. However, this model display does not reflect the removal of tissue and intrarenal structures in the model. One source of information to support suture placement may lie in the anticipation and visualisation of the endophytic needle trajectory [190]. However, no such applications have been identified in the review. Dedicated preoperative planning assistance solutions for the prediction of severed risk structures have been published [187]. However, there are multiple design and engineering challenges that may have prevented the use or adaptation of the general image guidance concepts identified in this review for the phase of resection wound repair. These challenges are discussed in the next section.

Finally, the interview study reported in Chapter 3 identified four distinct surgical challenges that were outside the three main challenging surgical phases. Two of these challenges arise during the position planning and placement of the trocars. The *ARssist* [191] assistance concept aims to support the first assistant in the operating theatre by means of a HMD AR solution. One of the *ARssist*'s objectives is the support during the trocar planning and placement. This solution was not included in the systematic literature review because it is not specific to LRPN (or explicitely aimed at LRPN). However, the concept is likely to be transferrable to LRPN.

Another challenge was reported to lie in the identification of additional, intraparenchymal tumours (IV.3). This is a challenging problem as it specifically affects tumours that were not preoperatively identified. One potential alleviation may lie in the automatic real-time segmentation of ultrasound frames [180]. However, this is speculative and does not address isoechoic tumour tissue. Further research is, therefore, required to identify potential solutions for this challenge.

The final challenge that was identified is the occupation of one robot arm or access port for tools that hold the kidney in case of full mobilisation (IV.4). This is primarily a logistical problem that is unlikely to be directly addressable through image guidance or software assistance. It may be possible to reduce the required degree of mobilisation with optimised resection planning or substitution of visual access by image guidance solutions. However, this general approach is speculative and likely to require a combination of the various challenges and solutions that have been previously discussed. Therefore, reducing the need for mobilisation may be considered an additional, latent objective for assistance solutions that primarily target other surgical challenges.

4.5.3 Challenges for image guidance during resection wound repair

The development of a navigation concept for the resection site repair phase faces a number of specific challenges. Firstly, a geometrically undefined tissue volume has been removed from the kidney at this stage. While preoperative plans for the resection volume

exist, the actual resection plane often deviates from them due to unexpected anatomy. Therefore, the preoperative data and models provide limited information about the position of intrarenal risk structures in relation to the resection plane. Secondly, the phase of tending to the resection wound is conducted under significant time pressure. The reason for this time pressure depends on the vascular clamping strategy that is applied in a given case: if the renal artery has been clamped, then any delay increases the risk of ischemia-induced kidney damage [44]. If the artery has not been clamped, then the renorrhaphy phase is conducted with bleeding, causing an increased blood loss [47]. Therefore, intraoperative re-acquisition of images (e.g., cone beam CT) is not feasible during this time. Due to the obstacles to utilising real-time data, some dedicated AR visualisation of preoperative data may be useful to aid surgeons during the repair of the resection wound. This, however, requires the spatial registration of the navigation relevant content. The last two challenges concern the use of pre-resection AR registration: the kidney is moved considerably during the resection. Finally, the kidney geometry is deformed during the resection. Existing tracking methods for maintaining AR registration have not been shown to be sufficiently robust against these changes [192, 193].

Thus, a solution to these challenges may be a dedicated AR visualisation that is based on preoperative or pre-resection information and takes the unknown resected volume into account. Moreover, a means for fast registration of the relevant content is required in the post-resection phase.

4.6 Conclusion

This chapter reports a systematic review of the current literature on image guidance in LRPN. The relevant publications were identified throughout three iterative search phases. They were then analysed primarily to extract the clinical purpose that the reported image guidance and AR solutions aim to address and the information that is provided to the surgeons. The review was conducted with a strong focus on intraoperative support in LRPN. Related publications for peri-operative support (e.g. in planning or patient education) were excluded to facilitate the in-depth comparison against the information needs identified in Chapter 3.

The comparison of the assisting information against the information needs provided a comprehensive overview about which surgical phases have been addressed more or less intensely by the current literature. The predominant research gap that was identified in this analysis is the lack of image guidance concepts for aiding the resection wound repair after tumour resection (challenging phase III). Specific technical challenges arise for image guidance solutions that address this phase. Dedicated AR solutions may be a promising approach. The research objectives arising from this analysis lie in the development of dedicated AR visualisation and registration methods for the support of resection wound repair. The following chapters introduce initial AR solution concepts that address these specific challenges.

5

Registration for post-resection AR navigation

Synopsis

This chapter reports a dedicated registration pipeline that addresses the specific challenges that arise during post-resection AR navigation. The registration method requires two distinct registration stages: one before, and one after the tumour resection. The primary registration is used to place and define artificial, non-invasive fiducials that are recorded after the resection for fast re-registration. The registration method was tested in a simulated use evaluation to assess concept viability. The results indicate that the method is faster and potentially more accurate than registration with anatomical landmarks.

About this chapter

Parts of this chapter have been published in: Joeres, F., Mielke, T., and Hansen, C. (2021). 'Laparoscopic augmented reality registration for oncological resection site repair'. In: *International Journal of Computer Assisted Radiology and Surgery*, pp. 1–10. *[194].*

Portions of the work reported in this chapter were conducted as part of the Bachelor's thesis project of Ms Tonia Mielke (thesis title: Entwicklung eines Registrierungskonzepts für laparoskopische Augmented Reality). Ms Mielke's Bachelor's thesis project was supervised by the author of this dissertation.

5.1 Introduction

The previous chapters have demonstrated a particular research gap in the context of AR navigation for LRPN. This gap lies in supporting the surgeons during the resection wound repair phase after the tumour has been removed from the kidney. Moreover, it has been discussed in the previous chapters that this may potentially be beneficial beyond the specific surgery of LRPN.

Chapter 4 has also discussed the specific challenges that arise during this phase for the design and development of an image guidance or AR navigation system: the resection wound repair is conducted under time pressure; an unknown tissue volume has been removed with the tumour; and the organ has been moved and deformed during the resection process. The first two challenges affect the availability of navigation data and the visualisation or general presentation of those data. All four challenges affect the registration of AR navigation content. Therefore, two separate studies were undertaken to, firstly, address the AR registration and to, secondly, address the AR navigation data presentation. This chapter reports the registration approach that was developed to address these challenges. A dedicated AR concept is reported in Chapter 7.

The first challenge is that the resection wound repair is conducted under time pressure because it is either conducted under ischemic conditions (if the renal blood vessels have been clamped for resection) or under blood loss conditions (if the vessels have not been clamped). This means that any unnecessary delay increases the risk of renal function loss or blood loss [47, 44]. One potential solution for this might be conducting the registration before the resection and then tracking the kidney during the resection. However, the kidney is moved and manipulated considerably during the resection process itself. Current organ tracking techniques [192, 193] have not been shown to be robust against resection of major volumes from an organ or loss of sight of the organ surface. Both of these scenarios are realistic during the tumour resection. Moreover, if vascular clamping is applied, the registration should ideally be conducted before the blood supply is interrupted. The clamping, however, causes an overall deformation of the organ that affects the overall registration accuracy [195]. Due to these reasons, it is unlikely that pre-resection registration results can be directly used for AR navigation during the resection wound repair.

Therefore, a registration pipeline has been developed that aims to address these specific challenges and compromises registration speed and accuracy during the time critical surgical phase after the tumour resection. This method uses internal, artificial landmarks that allow for fast point acquisition. The intraoperative placement of artificial markers traditionally requires intraoperative CT [196, 197] or MRI scans [198]. This need has been eliminated in the herein presented registration method by using a primary, elaborate registration for the definition of artificial fiducials that is conducted before the tumour resection. This chapter reports the registration concept and a simulated use evaluation of its prototypical implementation. The evaluation compares the method's accuracy and speed against the reference method of using anatomical landmarks for registration.

5.2 Related work

Generally, registration methods can be classified as either manual, point-based, surface-based, or volume-based methods [11]. Manual (e.g. [96]) and volume-based methods [199] are not suitable for the resection wound repair phase because they require too much time. While recent laparoscopic AR registration concepts for LPN/RPN tend to rely on surface point cloud acquisition [200, 201], this method requires general integrity of the organ surface. This means that it has not been shown to be robust against the resection of an organ volume. The use of anatomical landmarks as paired point references [99] may be robust against the removal of tissue if landmarks are chosen that lie outside the resected area. However, laboratory-based simulations of this task can take multiple minutes [202]. Another approach makes use of artificial fiducials on the organ [197], which require intraoperative imaging like computed tomography (CT). The solution reported in this chapter aims to minimise the registration time during the resection wound repair phase without the need for intraoperative imaging. A recent approach has been published that also uses fiducials, which are defined after an initial registration has been completed [203]. Due to the temporal and conceptual overlap with the work reported in this chapter, the concept's relevance and the parallels between the results are examined in the *Discussion* section of this chapter.

5.3 Registration method

5.3.1 Registration concept

The overall two-stage registration procedure is summarised in Figure 5.1: a primary registration process is completed before the resection is started, but after the intraoperative resection planning is complete. The primary registration should be conducted before vessel clamping in order to reduce the time pressure on this registration procedure. The focus for this registration lies in the accuracy rather than the speed. This can be conducted by any established means, as described in the literature.

In the implementation reported in this chapter, the primary registration consists of two steps: an initial alignment and a surface-based refinement step. The initial alignment is achieved with the paired point method, using four anatomical landmarks on or around the kidney [204]. The ICP algorithm [103] is used for surface-based refinement. In the clinical application, this may be further refined by non-rigid deformation adaptation. However, this was outside of this work's scope for reasons discussed further below. Other registration methods may also be used for this primary registration.

After the primary registration is complete, the process is continued under the assumption that the virtual and physical kidneys are registered as accurately as possible. The surgeon then places four artificial markers around the planned incision path and, consequentially, around the intended resection area. It is important that these markers remain on the kidney during the resection. Adhesive markers [197] are a well-suited, non-invasive option for this. These markers' positions are recorded by touching them with an optically tracked pointing tool. The recorded positions are stored in the virtual model for later re-registration. It should be noted that the recorded positions of the tracked pointing tool are situated slightly above the organ surface. This is because the adhesive markers are not thin slices but rather of unknown thickness. The position is

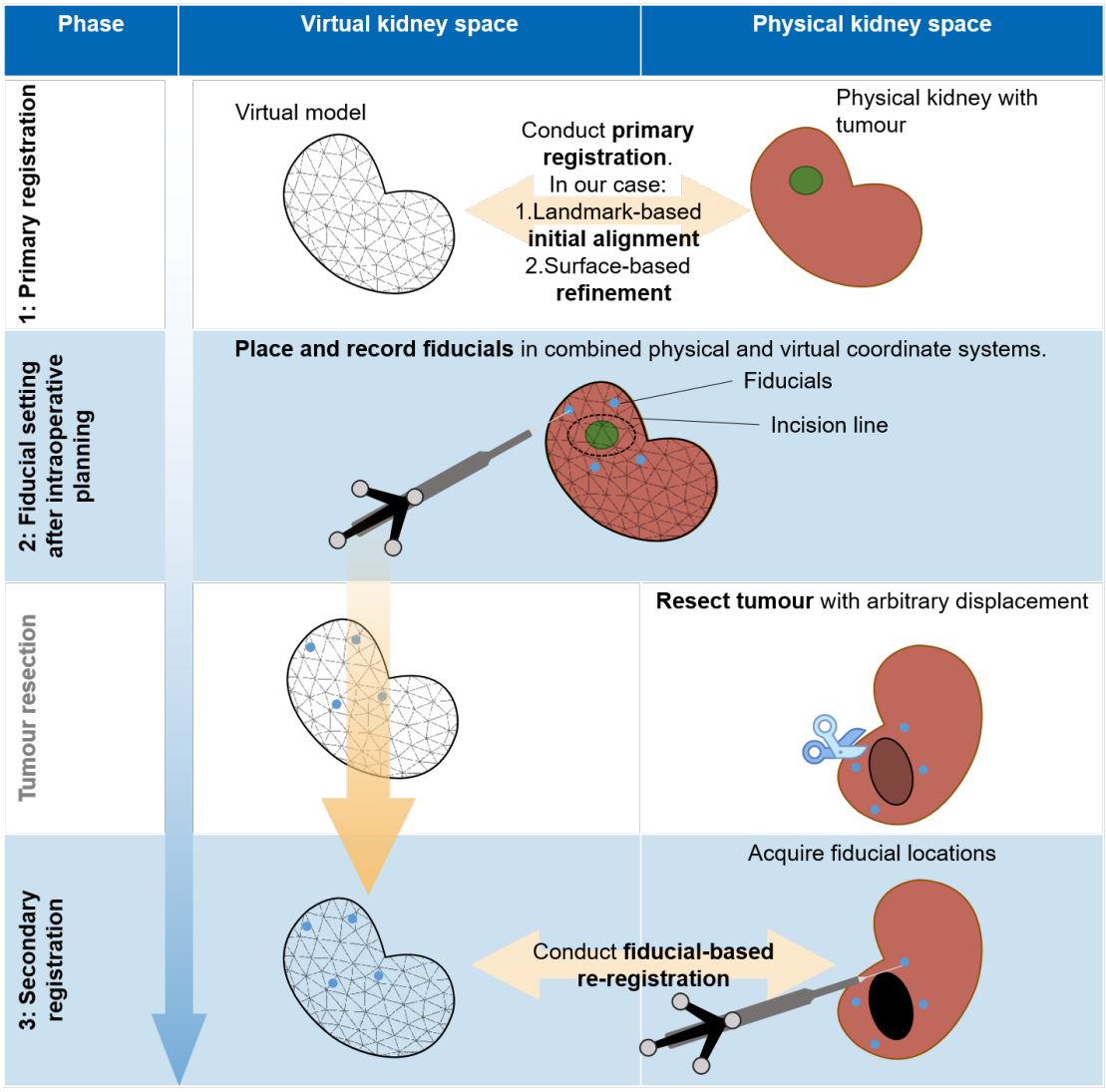


Figure 5.1: Overview of the proposed two-stage registration procedure.

stored as it is recorded, i.e., slightly above the virtual organs's surface. Due to any remaining registration errors from the primary registration, the recorded point may be located *below* the virtual model's surface. In that case, the point is also stored as it is recorded. After this step, the surgeons can proceed with the tumour resection while the artificial markers remain in place. No specific tracking measures or precautions are required during the resection.

When the resection is completed, the secondary registration is conducted by the surgeon. At this point, the system's graphical user interface (GUI) displays the virtual model with the previously recorded points. Following the order that is instructed by the GUI, the surgeon records the artificial markers with the tracked pointing tool. In the concept's current implementation, the re-acquired points are then used for a rigid re-registration. The aim of providing the artificial landmarks during the secondary registration is to increase the speed and accuracy of the landmark identification and, thereby, the point acquisition, compared to the 'naive' acquisition of anatomical landmarks.

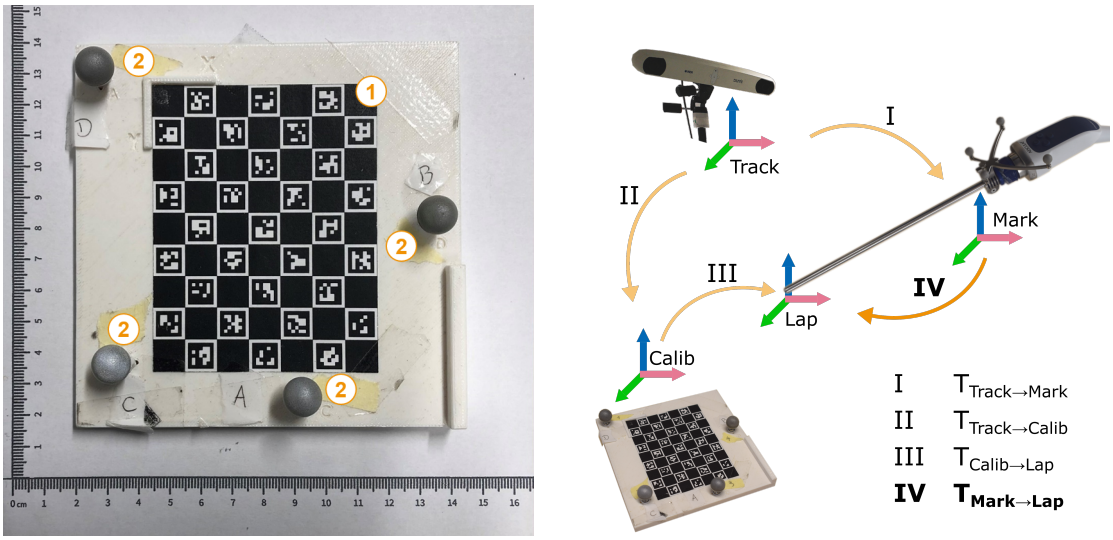
5.3.2 Prototype implementation

Augmented reality infrastructure

The general AR infrastructure reported in this section was used for the prototypes and experiments in this chapter and in the next two chapters (see Chapters 6 and 7). The overall software prototype was developed in Unity 2018 (Unity Software, San Francisco, USA). The laparoscopic video stream was generated with an Einstein Vision© 3.0 laparoscope (B. Braun Melsungen AG, Melsungen, Germany) with a 30° optic in monoscopic mode. A standard laparoscopic grasper was used as a pointing tool. The pointing tool was used for different purposes in the separate prototypes and studies but the general technical solution for the pointing tool that is reported here was applied in all cases.

The laparoscopic camera head and the tool were spatially tracked with a NDI Polaris Spectra infrared tracking camera (Northern Digital Inc., Waterloo, Canada). In addition, a stationary object was tracked to provide a reference coordinate system and ensure robustness against accidental movement of the tracking camera.

The laparoscopic camera calibration was based on a pinhole model [77] as implemented in the OpenCV library [79]. Within this prototype, the commercially available *OpenCV for Unity* package (Enox Software, Japan) was used. The optical camera parameters were determined by use of ChArUCo markers [205]. The hand-eye calibration (i.e. translation vector and rotation between the laparoscope's tracking marker shield and the camera) was conducted by attaching the ChArUCo pattern to a bespoke, spatially tracked calibration board (Figure 5.2a). The transformation of the calibration pattern in the tracking camera's reference space $T_{\text{Track}\rightarrow\text{Calib}}$ was tracked by means of this calibration board. The pose transformation between the calibration board and the laparoscopic camera itself ($T_{\text{Calib}\rightarrow\text{Lap}}$) was one of the results of the pinhole calibration method. Finally, the camera head's marker body's transformation in the tracking camera's reference space ($T_{\text{Track}\rightarrow\text{Mark}}$) was directly tracked. The transformation between the camera's marker body and the camera, $T_{\text{Mark}\rightarrow\text{Lap}}$, could then be determined as follows (Equation 5.1; see also Figure 5.2b):



(a) Bespoke calibration board with ChArUCo pattern (1) and passive tracking markers (2).

(b) Coordinate transformations for the external camera head calibration.

Figure 5.2: Overview of the camera calibration board and coordinate transformations.

$$T_{\text{Mark}\to\text{Lap}} = T_{\text{Calib}\to\text{Lap}} \cdot T_{\text{Track}\to\text{Calib}} \cdot (T_{\text{Track}\to\text{Mark}})^{-1} \tag{5.1}$$

The resulting transformation was combined with the real-time tracking data for the camera head to control a virtual camera within the Unity prototype to render any virtual content from the correct perspective. The virtual camera's view was then distorted with the laparoscope's optical calibration parameters and overlaid on the laparoscopic camera stream. The display arrangement of the resulting AR-overlaid video stream was different for each prototype and study (see also Chapters 6 and 7). In the prototype that is reported in this chapter, a 24 inch medical LCD monitor (Sony Corporation, Minato, Japan) was placed opposite the user (Figure 5.3). This screen displayed the unaltered laparoscopic video stream. A second 24 inch standard monitor was positioned to the right and showed either the laparoscopic video with the AR overlay or the GUI, depending on the current state of the workflow.

The translation vector between the tool's tracking markers' coordinate system and its tip was determined with pivot calibration using the NDI Toolbox software (Northern Digital Inc., Waterloo, Canada). The rotational transformation between the tool's tracking markers and the tool axis was measured with the calibration body.

Registration interface and workflow

The prototype for the registration pipeline was implemented in the general AR infrastructure that is reported above. In this prototype setup, the laparoscopic grasper was used as a pointing tool to record information about the fiducial positions and for the surface point cloud acquisition. Beyond its function as the pointing tool, the grasper was also used to manipulate the artificial fiducials.

An overview of the prototypical workflow implementation is provided in Figure 5.4.

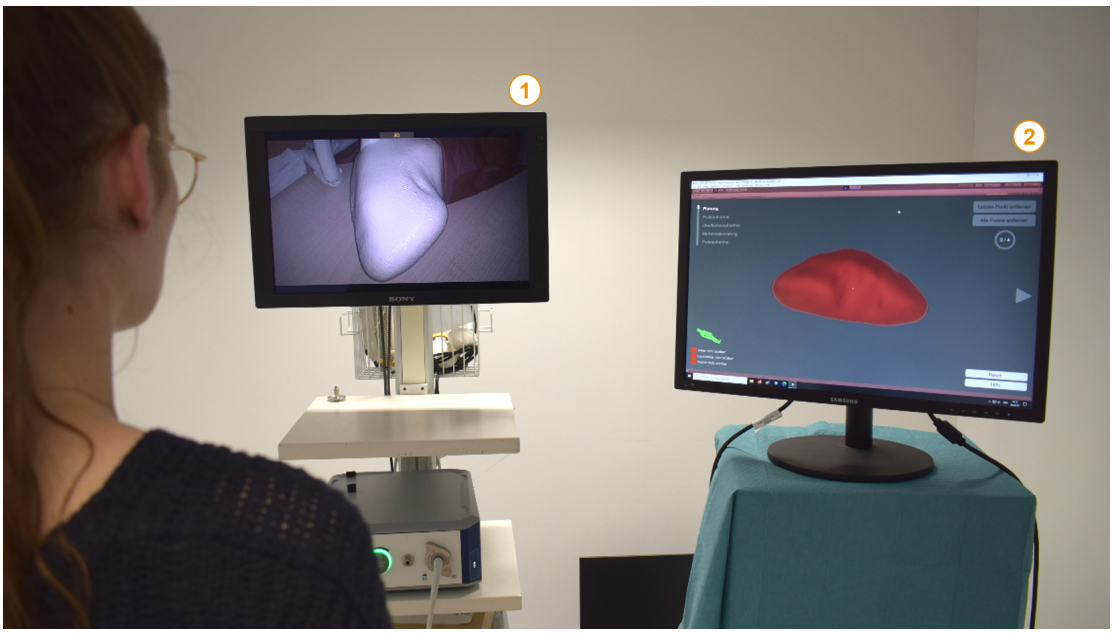


Figure 5.3: Display setup of the AR prototype. The left display (1) shows the laparoscopic stream. The right display (2) is currently displaying the registration GUI.

For the initial landmark-based registration, the user was provided with a GUI displaying the virtual model. The model view could be rotated, panned, and zoomed in or out with a mouse. The user was required to select four characteristic points on the organ surface with a mouse, as currently applied in clinically used AR systems [99]. Participants were instructed to select characteristic points that they would recognise on the phantom. After this, the points were highlighted one after the other and the user was required to record the points' positions with the spatially tracked pointing tool. The points were highlighted in three colours (Figure 5.4): the point that was to be recorded next was highlighted in blue. A green colour marked points that were already recorded. The points that were yet to be addressed were marked in red. After all four points had been recorded, the registration transformation was calculated based on the resulting two paired point clouds [97].

The surface point cloud acquisition was conducted with the same tactile pointing tool: the user was required to trace it across the phantom surface while activating point acquisition with a foot pedal. Points were recorded along this path at 2mm distance while the foot pedal was being pressed. After at least 200 points had been recorded, the user could trigger the ICP-based registration. There is no optimal number of points reported in the literature. However, a range of 40-200 points has been reported for neurosurgery [206]. This step completed the primary registration.

The next step required users to attach simulated adhesive artificial markers to the kidney phantom. These markers aimed to simulate adhesive surgical markers as reported by Wild et al. [197]. No specific location instructions were given to the participants. In the clinical application, the markers would need to be placed around the intended resection area. Upon completion, the marker positions were recorded and stored in the virtual model by touching them with the spatially tracked pointing tool. This concluded

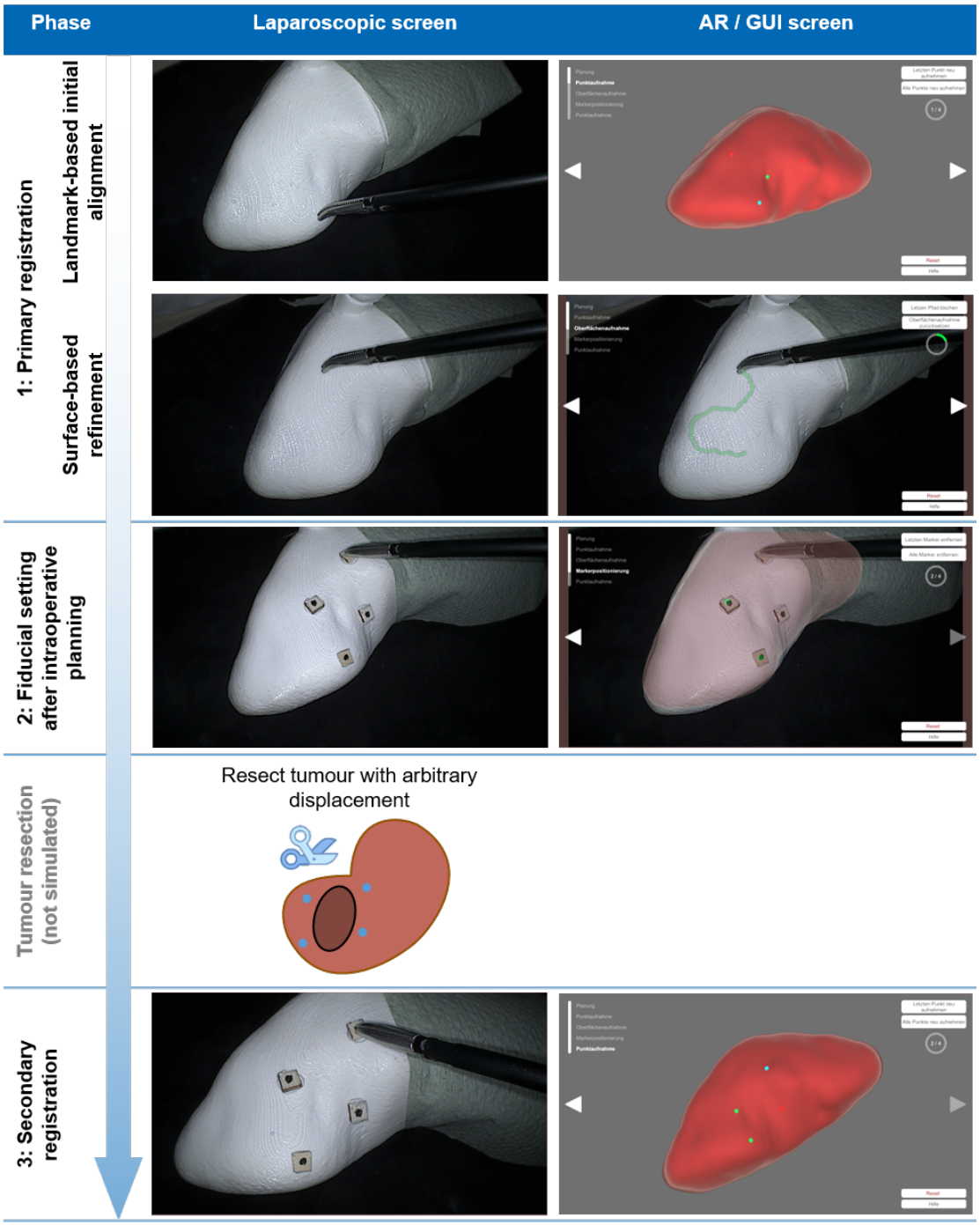


Figure 5.4: Overview of the prototypical workflow implementation. Participants in the evaluation study always saw both screens simultaneously.

the simulated workflow that would be expected prior to the resection.

The secondary registration is meant to be conducted after the tumour resection and during the resection wound repair phase. In the secondary registration, the GUI displayed the recorded points on the virtual model, highlighting them in the order in which they were previously recorded. The user was required to record the position of the fiducial that corresponded to each highlighted point in the virtual model by touching them with the tracked pointing tool. The highlighting was equivalent to the point acquisition during the initial alignment. The registration was then completed based on the two paired point clouds [97]. This concluded the secondary registration process.

5.4 Evaluation methods

The two-stage registration concept was evaluated in a simulated use study. The study aimed to investigate two aspects: firstly, to evaluate whether the method would improve registration speed and accuracy during the time critical phase as compared to the naive use of anatomical landmarks. Secondly, the study aimed to assess the magnitude of the accuracy loss between the surface-based primary registration and the secondary registration.

5.4.1 Study design

Regarding the first study objective, the registration performance was compared between the initial alignment, based on anatomical landmarks, and the secondary registration, based on the artificial adhesive fiducials. This means that the performance was recorded and compared at two different stages of the same registration procedure. The independent variable in this aspect was the method applied at the respective stage of the registration process.

Four points were defined around each kidney pole that were used as simulated, virtual surgical targets. The first dependent variable was the registration accuracy for these four points, which was operationalised as the mean TRE for these targets. The second dependent variable was the task completion time that was required for identifying and recording the landmark points / fiducial positions. Regarding the second study objective, the TRE difference was assessed that occurred between the completed primary registration's mean TRE and the mean TRE after the completed secondary registration of the same workflow.

5.4.2 Sample design

Eighteen (18) participants took part in the study. The participants were medical students in their fourth and fifth year of training. Participants' age ranged from 21 years to 27 years (median 23.5 years). Twelve participants reported having between 0.5h and 14h (median = 3h) of previous experience with laparoscpoic procedures (either in clinical applications or in simulators or trainers). Some laparoscopic training tasks were administered to mitigate the different levels of prior experience (see *Study procedure*). The participants were paid 20 EUR for participation.

5.4.3 Study setup

The surgical site was simulated with a partially occluded phantom. This phantom was created from the CT dataset of a healthy, adult left kidney from a public database [207]. The parenchymal surface was segmented using *3D Slicer* [208] and printed with the deposition modelling method. The virtual surface model was used in the GUI display. The physical phantom was equipped with an adapter in order to spatially track it from outside the simulated surgical site (see Figure 5.5a).

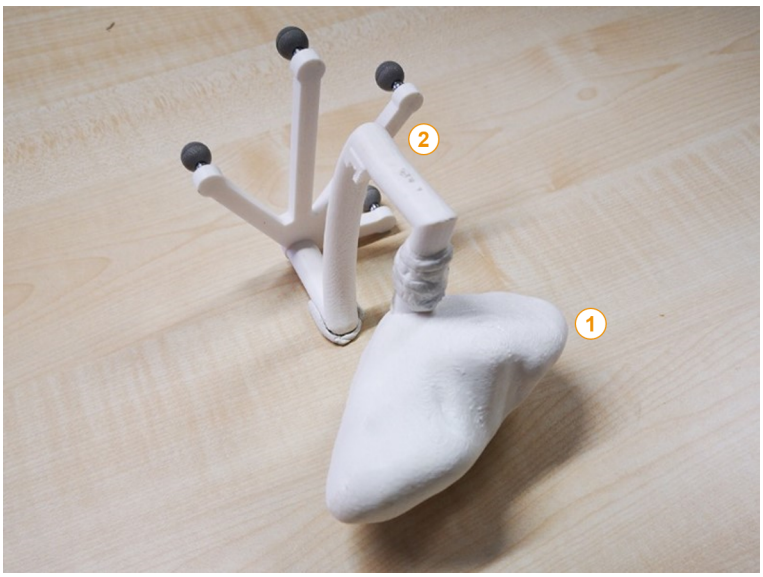
The phantom was placed inside a cardboard box that occluded the simulated surgical site to simulate a laparoscopic workspace. The site could be accessed with the tracked laparoscope and pointing tool through six holes in the box (Figure 5.5b). The organ motion that would occur during the resection in real surgery was simulated by varying the holes through which the workspace was accessed. When the simulated surgical target was on the upper pole (to the participant's left), holes one and three were used during the primary registration and holes two and four were used for the secondary registration. When the simulated target was on the lower pole (to the participant's right), holes three and five were used during the primary registration and holes four and six were used for the secondary registration.

Approximately half of the phantom was covered with a cloth in each registration procedure. The cloth extended from one of the kidney poles to the phantom adapter (Figure 5.5c). The registration was conducted on the non-covered half of the phantom. This aimed to simulate the fact that not the entire renal surface would be revealed during intraoperative dissection. Standard, commercial adhesive putty was used to simulate the adhesive marker paste. Figure 5.5c also displays the simulated adhesive markers that were applied in the study. The simulated surgical environment and the interaction tools were placed on a height-adjustable table and the participants stood in front of this table. The resulting overall study setup is shown in Figure 5.6.

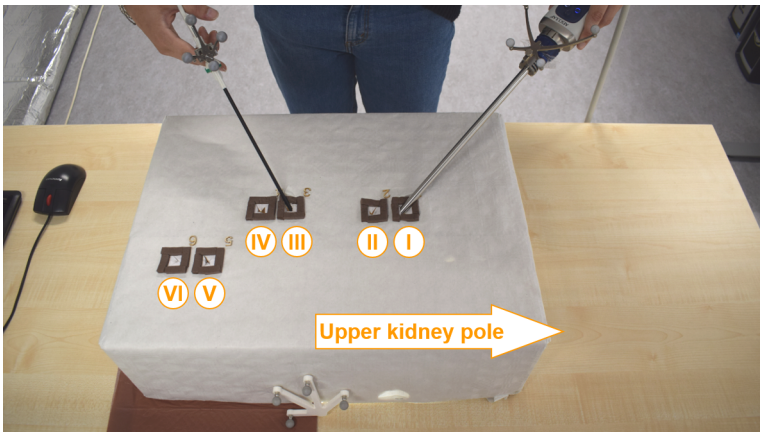
5.4.4 Study procedure

Participants' written informed consent and demographic information were collected before the main experiment. Participants were asked to complete two laparoscopic training tasks to practise the particular hand-eye coordination and spatial understanding that are required in laparoscopic interaction. The training tasks were self-built versions of the 'bean drop' and 'checkerboard drill' tasks [209]. These two tasks require the targeted, coordinated motion of the laparoscope and a laparoscopic tool, but are not more complex than necessary for the simulated task. Each task was performed once by every participant. The training performance was not measured or recorded.

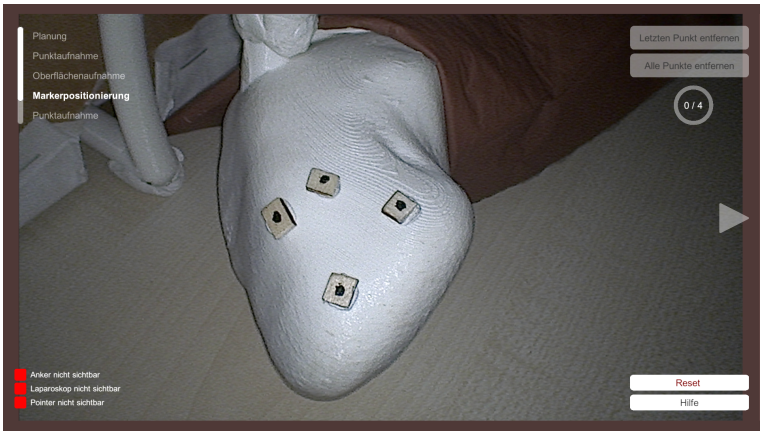
Following this training, participants conducted the registration process for the first time with step-by-step instructions from the experimenter. They then conducted a second training trial without explicit instructions but with the opportunity to ask questions. After all questions had been answered, the experimenter exchanged the targeted kidney pole (by moving the cloth). Finally, participants performed the registration process in a test trial in which the required data were recorded. This concluded the experiment.



(a) 3D printed kidney phantom (1) with tracking adapter (2).



(b) Simulated laparoscopic space with six access points (I-VI).



(c) Partially occluded phantom with the simulated adhesive markers. The image also shows the GUI that is displayed while the user first records the marker positions.

Figure 5.5: Components of the simulated surgical scene.

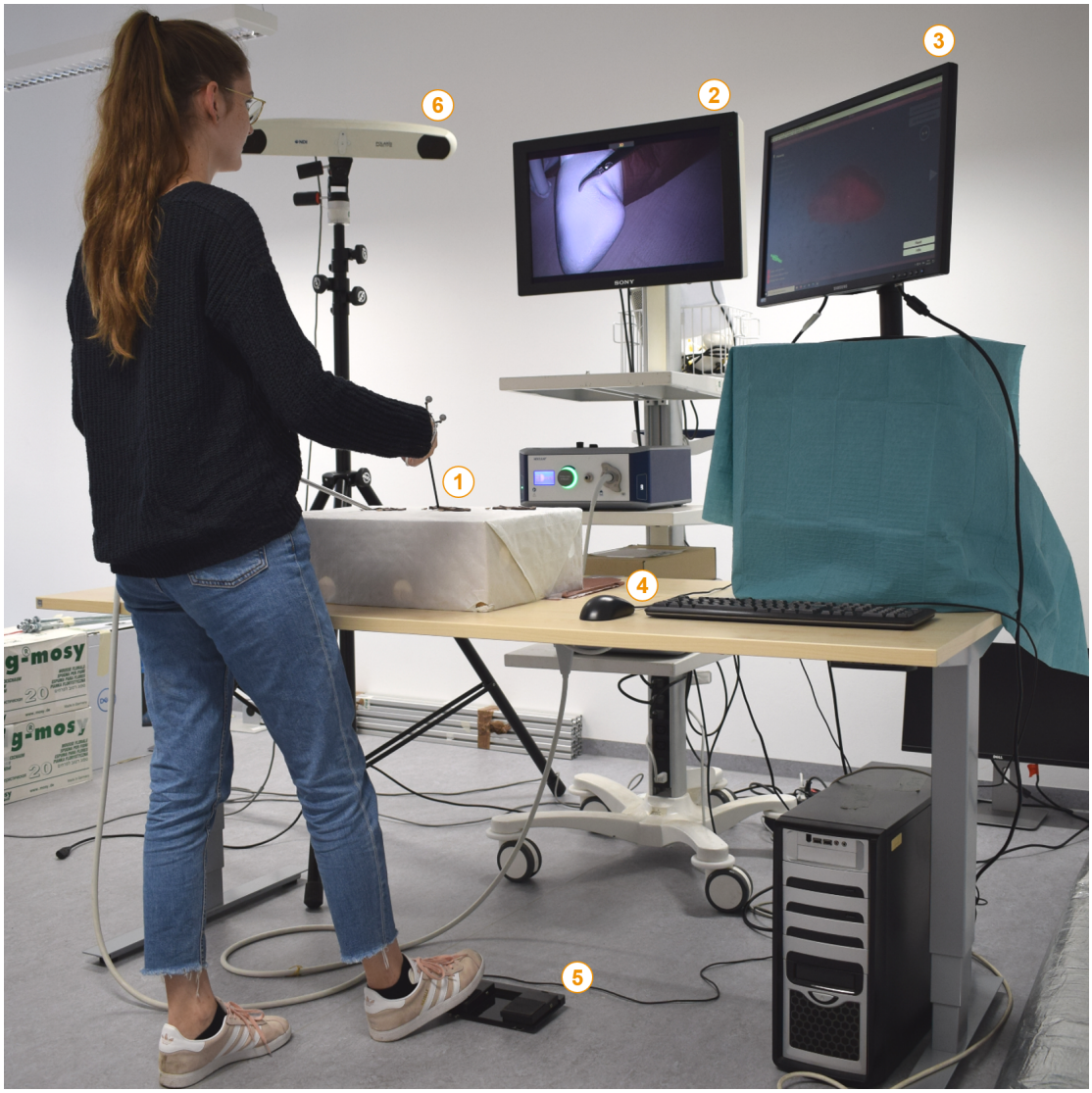


Figure 5.6: Overall study setup: (1) Simulated laparoscopic environment, including the phantom, camera head, and grasper; (2) Laparoscopic screen; (3) AR / GUI screen; (4) Mouse for registration planning; (5) Foot pedal; (6) Optical tracking camera.

Table 5.1: Registration speed and accuracy results for the full sample. SD: standard deviation, TCT: task completion time in seconds, TRE: target registration error in mm.

Registration step	TCT mean	TCT SD	TRE mean	TRE SD
Initial alignment	**42.72**	11.81	**11.83**	5.35
ICP	N/A	N/A	**9.01**	4.28
Secondary registration	**38.52**	8.83	**11.36**	6.24

5.4.5 Hypotheses and data analysis

One-sided, paired t-tests were conducted for the TRE and task completion time (TCT). The tests compared data from the initial, landmark-based alignment (prior to surface-based refinement) and the secondary registration with the alternative hypotheses:

$$H_{1,\text{TRE}} : TRE_{\text{secondary registration}} < TRE_{\text{initial alignment}} \tag{5.2}$$

$$H_{1,\text{TCT}} : TCT_{\text{secondary registration}} < TCT_{\text{initial alignment}} \tag{5.3}$$

It is inherent in this registration concept that the TRE will systematically increase between the refined primary registration and the secondary registration. This is because the latter builds on the former and the registration errors from the primary registration propagate throughout the secondary registration. Therefore, significance tests for this difference were not conducted. Rather, the 95% confidence interval was calculated to provide an estimate for the magnitude of the accuracy loss during the secondary registration. Modified post-hoc tests were conducted as reported in the *Results* section.

5.5 Results

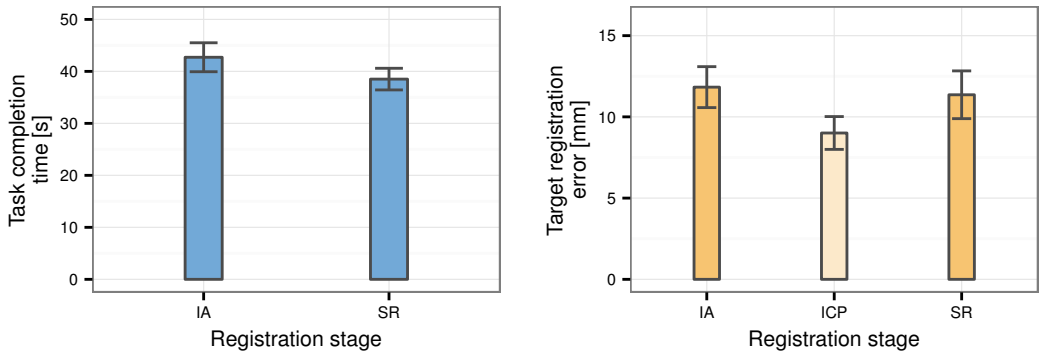
5.5.1 Speed and accuracy results

A descriptive summary of the performance results is provided in Table 5.1. The point acquisition phase could be conducted significantly faster during the secondary registration than during the initial alignment ($T = 1.80$, $p = 0.045$, Fig 5.7a). The registration accuracy was not significantly higher across the full sample ($T = .025$, $p = 0.402$, Fig 5.7b). The mean TRE difference between the primary surface-based registration and the secondary registration amounted to 2.35mm ($\text{CI}_{95} = [0.47\text{mm}, 4.23\text{mm}]$).

5.5.2 Data exclusion and post-hoc analysis

The surface-based registration step is conducted to refine the landmark-based initial alignment. It is generally expected to increase registration accuracy [210, 211]. However, data analysis showed that six of the participants produced a higher TRE during surface-based refinement than during the initial landmark-based alignment.

This registration error increase during what is intended to be a registration refinement step is likely to be caused by a number of use errors that are detailed in the *Discussion* section below. These errors are unlikely to be encountered by experienced surgeons,



(a) Speed results

(b) Accuracy results

Figure 5.7: Performance results for the *full sample*. The error bars represent the standard error. IA: initial alignment; ICP: iterative closest point refinement; SR: secondary registration.

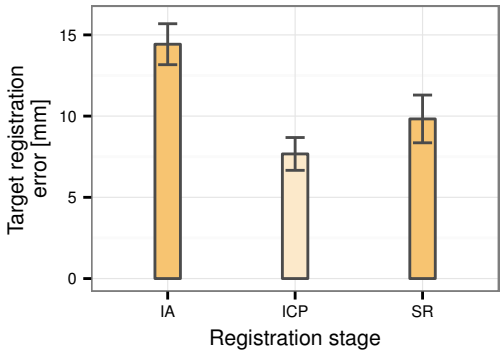


Figure 5.8: Accuracy results of the post-hoc analysis for the *reduced sample*. The error bars represent the standard error. IA: initial alignment; ICP: iterative closest point refinement; SR: secondary registration.

i.e. the intended user population for systems like this. Therefore, a post-hoc analysis was conducted in which these six participants were excluded. The post-hoc analysis comprised a repetition of the paired t-test for the TRE with the reduced sample. When excluding these cases, the TRE was significantly lower after secondary registration than after the initial alignment step ($T = 4.00, p = 0.001$, Fig 5.8).

5.6 Discussion

5.6.1 Discussion of the results

The results indicate that the two-stage registration solution can improve registration speed and may be able to improve the accuracy for laparoscopic AR applications in time critical surgical phases. The speed improvement that was measured in this study appears to be only gradual (42.7s for point acquisition in the initial alignment and 38.5s

in the secondary registration). However, the time for the initial alignment is based on the assumption that no further planning or definition of the landmarks is required. This assumption may not be accurate for the post-resection phase: only parts of the kidney surface are usually exposed during LRPN. Sufficiently characteristic landmarks that can be defined prior to resection and that are still available / accessible after the resection may be difficult to find. Therefore, additional registration planning may be required with the naive method. This would considerably increase the speed benefit of the secondary registration with artificial fiducials. The artificial fiducials' placement is less constrained and can be selected by the surgical team regardless of the availability of characterisic natural landmarks. In cases in which new anatomical landmarks have to be defined after the resection, the speed benefit grows considerably because the overall registration process with anatomical landmarks can take more than three minutes to complete [202] (see also Chapter 6).

One limitation of the registration accuracy results is the unusually low overall accuracy of the surface-based primary registration. There are two potential reasons for this: firstly, the required point clouds were recorded with a pivot-calibrated standard laparoscopic grasper. This instrument was chosen because it is readily available in the operating theatre. However, it is rather flexible and bends easily under mechanical load. This affects the tooltip tracking because the result of the pivot calibration is a rigid transformation. An interesting follow-up objective of the work reported in this chapter may lie in the measurement and quantification of this tool deformation and its contribution to the overall registration error. This has not yet been systematically investigated and reported in the literature. Secondly, the participants had very limited experience with handling laparoscopic tools. It was anecdotally observed in the experiment that several participants accidentally recorded some points after the tooltip had slipped off the phantom surface. Participants also applied high pressure when tracing the instrument across the phantom surface, which increased the issue of instrument deformation. Moreover, it was difficult for some participants to keep the tooltip rather than the side of the tool on the surface because of the typically constrained tooltip motion. These difficulties are likely to have contributed to the high inaccuracy that was observed in the surface-based registration for some participants. It seems unlikely that experienced laparoscopic surgeons would experience these specific difficulties. The assumption that these difficulties are caused by the participants' limited experience and are unlikely to occur with the intended user population motivated the post-hoc analysis that has been reported above.

Inaccuracies in the surface-based primary registration are passed onto the secondary registration. This is because the fiducial location in the virtual model is determined after and based on the primary registration. Thus, there is a discrepancy between the physical fiducial's position on the kidney and the fiducial's recorded position on the virtual model. This 'fiducial storage error' is caused by two components: firstly, the registration error that persists after the primary registration is complete. The second contributor to the fiducial storage error is the placement inaccuracy that occurs when the user records each fiducial's position. This fiducial storage error is added to the fiducial localisation error that occurs during the secondary point acquisition. The impact of the resulting accuracy loss (fiducial storage error plus fiducial localisation error) has been quantified with a TRE growth of approximately 0.47mm to 4.23mm (95% confidence interval). Improvement of the accuracy in the surface-based primary registration, therefore, leads to increased accuracy in the secondary registration. This is illustrated by the results of

the post-hoc analysis of the reduced sample.

5.6.2 General discussion

While this chapter presents a successful proof-of-concept evaluation for the two-stage registration method, it does not yet demonstrate clinical applicability or benefit. The obvious follow-up question for the results is whether the method's speed and accuracy are sufficient to make AR support feasible and useful during the time critical phase of resection wound repair. Specifically, three questions arise: firstly, is the added registration task with an estimated duration of 40 seconds during a time critical phase justified by the clinical benefit? That is, can the resection wound repair either be accelerated enough to compensate for the additional 40 seconds or does the additional information make the process more safe and effective? This entails the investigation of further process acceleration by supporting the user in the fiducial acquisition. For example, the fiducials could be detected and highlighted in the video stream. The second follow-up question is: is the registration accurate enough to provide meaningful information about the position of risk structures? Finally, the study participants' experience does not reflect the skill level of the experienced surgeons that would use the system in a real application. The different levels of experience may influence users' abilities to recognise landmarks / fiducials due to a better understanding of the surgical site and to record those landmarks / fiducials / surface point clouds due to a higher skill level at using the laparoscopic tools. The third question is, therefore: which accuracy levels can experienced surgeons achieve with this approach? These questions remain to be answered in future work.

Besides the study participants' skill level, the greatest limitation to the study's external validity lies in the experimental setup and the simulated surgical environment. In particular, the organ deformation that occurs during the tumour resection was not considered in the experimental setup. Organ deformation in abdominal AR registration is a major limiting challenge and an active field of research [212, 195]. Promising concepts exist in the literature to mitigate this by applying biomechanical models to the virtual content and, thereby, simulating the physical organ's deformation. One approach [192] informs a biomechanical model via fiducial marker locations and is, therefore, promising for the herein reported method as it is also based on fiducial positions. However, current biomechanical models [192, 193] assume that the kidney is deformed but structurally intact. In the application of post-resection AR navigation, however, the kidney is additionally deformed from its preoperative state by removing an unknown tissue volume. Some data have been published on the surface deformation caused by a single straight-line incision [212]. However, a biomechanical model for this application would also have to consider the intrarenal structure deformation that is caused by the removal of a tissue volume. While this requires further research, a deformation study for the liver [213] has shown that intraoperative deformation is very limited on a local scale. Thus, within the area of the four fiducials and resection wound, rigid registration may even prove to be sufficient. This needs to be further investigated in more realistic circumstances (e.g. with ex vivo human or porcine kidney phantoms).

The two conditions that were compared in the evaluation study were measured in a fixed order. This may have led to training effects between the two stages of the registration process. Specifically, participants were more familiar with the surgical object (in this case, the phantom) during the secondary registration than during the primary

registration. A part of the fiducial acquisition acceleration may be attributed to this fact. However, this familiarisation process with the surgical site can be considered to be realistic and, therefore, does not affect the validity of the results.

Overall, registration accuracy in a clinical setting may be higher due to better surface-acquisition methods, or it may be lower due to organ deformation. Thus, the absolute TRE values from the study are of limited external validity. However, the effects indicate that the registration concept may be a viable approach for AR support during the resection wound repair phase of LRPN. Future research is required to investigate whether the general two-stage registration concent may be suitable for other image guided surgery applications in which the registration process is conducted under time pressure or in which the opportunities for intraoperative imaging or preoperative fiducial placing are limited.

Finally, an equivalent approach for re-registration with fiducial points [203] was published approximately simultaneously with the article on which this chapter is based[1] [194]. Kavoussi et al. propose the same strategy for AR registration in RPN. They report using the robot's kinematic tracking information for point acquisition and the fiducials for re-registration are drawn onto the kidney surface with surgical ink. The resulting accuracy loss between primary and secondary registration (as measured in a phantom study) is reported at approximately 1.7mm and, thereby, slightly lower than the mean of 2.35mm that was observed in this study. The main reason for this is likely to be found in the higher accuracy of the primary registration itself: Kavoussi et al. report a mean TRE of 2.5mm and 4.9mm respectively for two phantoms whereas this study found a primary registration TRE of 9.0mm for the full sample (Figure 5.7b) and 7.7mm in the post-hoc analysis (Figure 5.8). The primary registration error propagates through to the fiducial recording error and, thereby, affects the secondary registration accuracy. The probable reasons for this relatively low accuracy have been discussed above. Moreover, the fiducial design may have further contributed to the difference in accuracy: surgical ink dots may be recorded and re-acquired more accurately and reliably than volumentric putty-like fiducials. However, the volumentric shape and potential fluorescence of the herein used marker concept may increase visibility and, thereby, speed in a clinical setting. Overall, the simultaneous development of the two very similar methods for laparoscopic and for robot-assisted PN and the two studies' similar results highlight the potential benefit of this re-registration method. Moreover, the results of Kavoussi et al. support the feasibility of using rigid re-registration after the resection has been completed.

5.7 Conclusion

The work reported in this chapter introduced and evaluated a two-stage registration method with artificial adhesive fiducials for AR support during the post-resection phase of LRPN. Specifically, the method aims to reduce the required registration time for AR support during this surgical phase. The concept was successfully implemented and tested in a simulated use evaluation. The results indicate that the method is faster and has the

[1] The article authored by Kavoussi et al. [203] was published online on 11th Nov 2020 with a first peer reviewed pre-print available online on 12th Oct 2020. The article authored by Joeres et al. [194] was initially submitted for publication on 29th Oct 2020 and published online on 2nd April 2021. The Bachelor's thesis was submitted on 02nd Sep 2020.

potential to be more accurate than a state of the art landmark-based method, and that it is faster than the surface-based registration. While the results do not conclusively demonstrate clinical applicability, they represent a promising proof-of-concept evaluation for the two-stage registration method. Further research is required to investigate the tissue deformation during tumour resection in order to achieve valid clinical feasibility for any (rigid or non-rigid) post-resection registration approach. This chapter focused on the challenges for AR registration during the resection site repair phase. Further challenges arise with regards to the display and interaction with the navigation content. Chapter 7 introduces a dedicated display and interaction concept. Finally, future work will be needed to investigate whether the two-stage registration method can be used in other laparoscopic AR applications that require a fast registration of the navigation content with limited availability of intraoperative imaging capabilities. Overall, the results indicate that a two-step registration approach may be a promising route for AR navigation for resection site repair.

6

Interaction methods for interactive AR registration

Synopsis

This chapter introduces two interaction methods for the manual registration of laparoscopic AR content or the general manipulation of virtual objects in the laparoscopic AR space. One method uses the spatially tracked laparoscopic camera head and aims to minimise the hardware that is introduced to the workflow for the registration. The other method uses a spatially tracked surgical instrument as a pointing tool and aims to make the manipulation more natural by employing realistic interaction metaphors. Both methods were comparatively tested in a user study. They were tested against a landmark-based registration method as a reference. The results showed that the laparoscope-based method is inferior to the reference method. The instrument-based method did not outperform the reference method. However, potential design improvements were identified and are briefly introduced in this chapter. The findings indicate that this method may be a promising approach after the implementation of these improvement measures.

About this chapter

Parts of this chapter have been published in: Joeres, F., Heinrich, F., Schott, D., and Hansen, C. (2020). 'Towards natural 3D interaction for laparoscopic augmented reality registration'. In: *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization* 189.194, pp. 1–8. *[202].*

6.1 Introduction

Effective (laparoscopic) AR navigation requires an accurate and efficient AR registration process. Chapter 5 has introduced a complete registration pipeline for the specific scenario of laparoscopic AR navigation during the surgical phase after a tumour resection in LRPN. A broader range of solutions has been proposed for the general field of laparoscopic AR registration, as outlined in Chapter 2. While rigid or non-rigid surface-based methods for accurate registration refinement are an important and potentially the most promising area in laparoscopic AR registration research [105, 193, 201, 214, 215], they require an initial transformation to build upon. Initial registration means that no prior rough alignment is required. Generally, multiple methods for initial registration have been proposed in the literature. Amongst these methods, one can distinguish between static and interactive methods [11]. Landmark-based methods, being a popular static approach, calculate the registration transformation (consisting of translation, rotation, and scale) on the basis of anatomical or artificial landmarks. Interactive methods allow the user to set some, or all of these, parameters manually. These interactive methods allow the user to conduct the registration iteratively and correct minor registration errors [216]. Most current research prototypes for AR in LRPN that have reached the stage of clinical testing seem to rely on manual or interactive registration methods [76, 113, 173]. Nevertheless, little research has been conducted to investigate and design dedicated interaction methods for this task. This chapter investigates interactive registration for virtual kidney models.

Interactive AR registration is an application of manual manipulation of virtual 3D objects. The interactive manipulation of virtual 3D objects has been well researched in the field of virtual reality, particularly for the case of objects in the user's peripersonal space. The most promising approach seems to lie in mimicking natural interaction with real objects [117, 217, 218]. These approaches have shown to be highly effective in 3D object manipulation tasks [219]. In laparoscopic surgery, the natural interaction with physical objects occurs via the laparoscopic instruments and video stream. This chapter, therefore, introduces two interaction methods that aim to apply the simulated natural interaction approach to the laparoscopic domain. This is achieved by controlling the virtual content by gestures that are performed with a tracked laparoscopic instrument or the laparoscopic camera head. The interaction methods were comparatively evaluated against a landmark-based reference method in a simulated registration task.

6.2 Related work

One common initial registration approach determines the registration transformation from the positions of a set of paired landmark points. Landmark points can be anatomical or artificial landmarks, as well as external or internal landmarks [11]. Conrad et al. [99] use four internal anatomical landmarks. These are manually selected in the preoperative virtual model and then recorded with a tracked pointing tool. This is the method that was also used in the work reported in Chapter 5 [194]. A similar approach that aims to reduce the impact on the surgical workflow uses landmarks that are relevant to the surgical procedure anyway [100]. A different static approach is the use of laparoscopic (stereoscopic) still images with camera tracking. Characteristic landmarks are selected

in the left and right camera's images and on the virtual model. Triangulation is used to determine the registration transformation [162].

Interactive registration methods allow the user to set some or all of the up to seven degrees of freedom by manual input [11]. This can increase the cognitive workload for the operator and the resulting accuracy depends on the operator's skills [136]. On the other hand, interactive approaches allow for an iterative approach and real-time adjustments of the registration [216]. One example is the manual rotation and translation of a 3D model until it correctly matches a recent screenshot of the laparoscopic image screen using a classic desktop interface [87] or a 3D input device [113]. Another approach [96] determines the translational part of the registration by identifying and recording one landmark and then setting the rotation manually. For the closely related field of intraoperatively correcting registration in video see-through AR, Léger et al. [112] provide a manual input interface on the AR display device (a tablet computer). Finally, 3D joysticks have been used to adjust the display of virtual models to the laparoscopic video stream in robot-assisted laparoscopic surgery [220].

Multiple approaches exist that aim to introduce intuitive three-dimensional manipulation to the interactive registration process: for 2D/3D registration of x-ray images, Gong et al. [221] propose using hand gestures to spatially manipulate the virtual model relative to the screen's coordinate system. In their second approach, a virtual tool is placed next to the virtual model. A corresponding tracked tool is then placed next to the physical structure. By moving the tracked, physical tool, the virtual model can be manipulated to match the 2D image. In a similar approach, Thompson et al. [222] track a tool relative to the screen's coordinate system and manipulate the overlaid 3D model accordingly.

6.3 Interaction methods

Two interactive registration methods were developed: the Instrument Control method (hereafter *InstControl*) and the Laparoscope Control (*LapControl*) method. Both of these methods are rigid registration methods that do not currently accommodate means for scaling the virtual content.

6.3.1 InstControl registration method

In the InstControl method, the user sets the virtual model's translational and rotational degrees of freedom manually. The concept is based on the idea of natural interaction in virtual reality and transfers this idea to the laparoscopic working space. It aims to simulate natural manipulation of the virtual content as if it were located in the laparoscopic surgical space. Moreover, this concept aims to reduce the invasiveness of the additional registration task to the surgical workflow. This is achieved by utilising only devices that are already present in the workflow. Thus, the InstControl method enables the user to 'grab' and manipulate the virtual object with a spatially tracked laparoscopic instrument or pointing tool. This registration method employs two interaction devices: one optically tracked laparoscopic pointing tool and an input device with at least four buttons. In the clinical application scenario, this could be the laparoscopic camera head or a separate input device that is combined with the surgical tool. In summary, this approach aims to mimic natural interaction with the virtual object as realistically

as possible. This is attempted by using the same instrument that would be used to manipulate a real object.

The registration workflow is initiated by pressing a Start button, which places (i.e. displays) the virtual model 100mm in front of the pointing tool. The start button is then repurposed for later confirmation to be used again when the registration is completed. The user now has three modes at his or her disposal that can be activated by holding down one of the three remaining buttons: the *translation mode*, the *axis rotation mode*, and the *free rotation mode*. Each mode includes specific interaction gestures for controlling the virtual model (Figure 6.1).

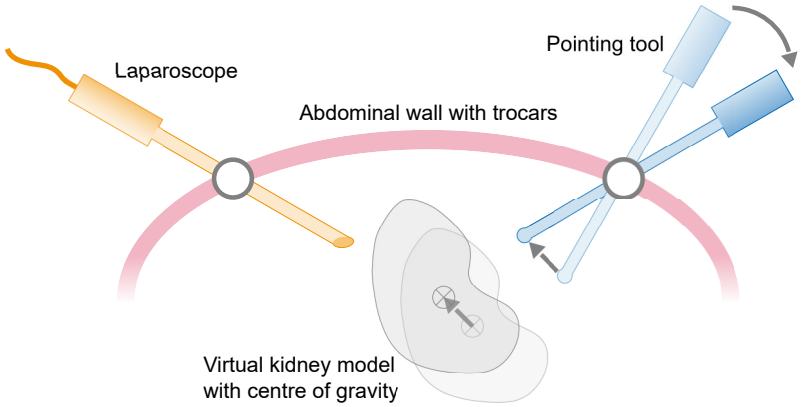
In the translation mode (Figure 6.1a), the user can grab the virtual model with the pointing tool and move it by moving the pointing tool. The model then imitates the tool tip's trajectory while maintaining the same orientation. In the axis rotation mode (Figure 6.1b), the user can rotate the virtual model around the pointing tool's axis by rotating the pointing tool itself. In the free rotation mode (Figure 6.1c), the user can rotate the object around any axis that is perpendicular to the tool's axis by moving the tool tip. The free rotation is applied to the model on each frame t. It is defined by the rotation between the vector $\vec{MT}_{\text{t-1}}$ and the vector $\vec{MT}_{\text{t}}$, where $\vec{MT}$ is the vector from the model's centre of gravity to the the pointing tool tip. This applies the metaphor of grabbing the virtual model by the surface point that is close to the pointing tool. The hereby determined rotation is scaled up by the factor of two to accelerate the rotation process and make it more convenient for the user. Additional acceleration or deceleration can be applied by the user because any given tool motion between two frames will cause a greater rotation of the model if the motion is conducted closer to the model's centre of gravity. Finally, the user can conclude the registration by holding down the confirmation button for two seconds.

6.3.2 LapControl registration method

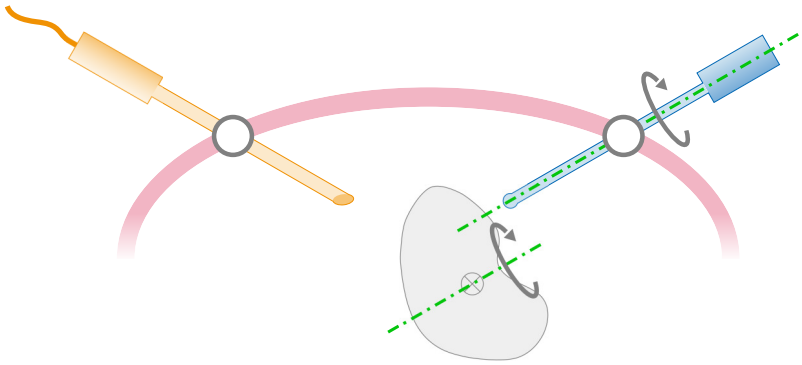
The LapControl method also allows the user to perform the registration manually. This method further reduces the number of devices with which the user interacts: the laparoscope's camera head itself is used to manipulate the virtual model. Thus, while moving slightly away from highly realistic 3D manipulation, this method's key benefit lies in minimising the number of required devices to just the laparoscope itself.

This registration method requires the user to interact with the laparoscope and an input device with four buttons. Again, the camera head's own four buttons can potentially be repurposed for this.

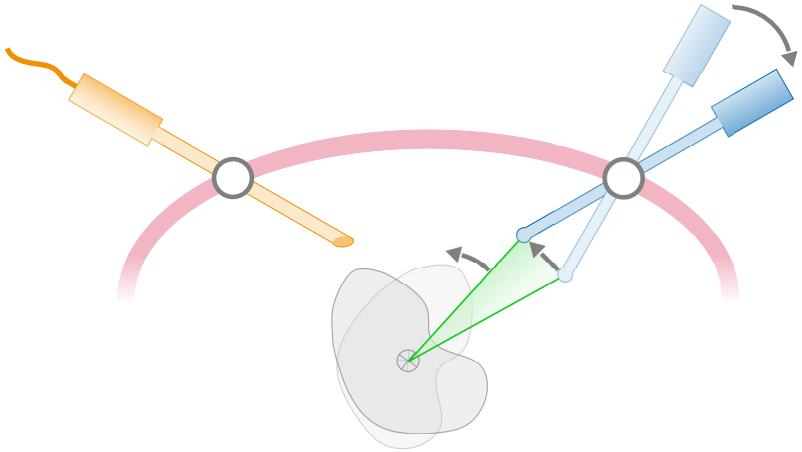
The registration workflow is equivalent to the InstControl workflow. Upon the initialisation button press, the virtual model is displayed 150mm in front of the laparoscope. A larger distance is chosen for this method to provide the required overview. The user can then translate and rotate the virtual model as described above and as shown in Figure 6.1. However, the laparoscopic camera's position is used for the translation mode and for the free rotation mode. The objective's axis instead of the pointing tool's axis is used in the axis rotation mode. One difference between this method's implementation and the InstControl method is that the free rotation scaling is doubled to the factor four in this method. This accounts for the greater distance that needs to be kept between the camera and the virtual model in order to maintain a sufficient overview.



(a) Translation mode for position setting.



(b) Axis rotation mode for the rotation setting around the axis parallel to the pointing tool's axis.



(c) Free rotation mode. The rotation of the vector between the model and the tooltip is scaled up.

Figure 6.1: Interaction gestures in the InstControl manual registration concept. Each mode is activated by the associated button press.

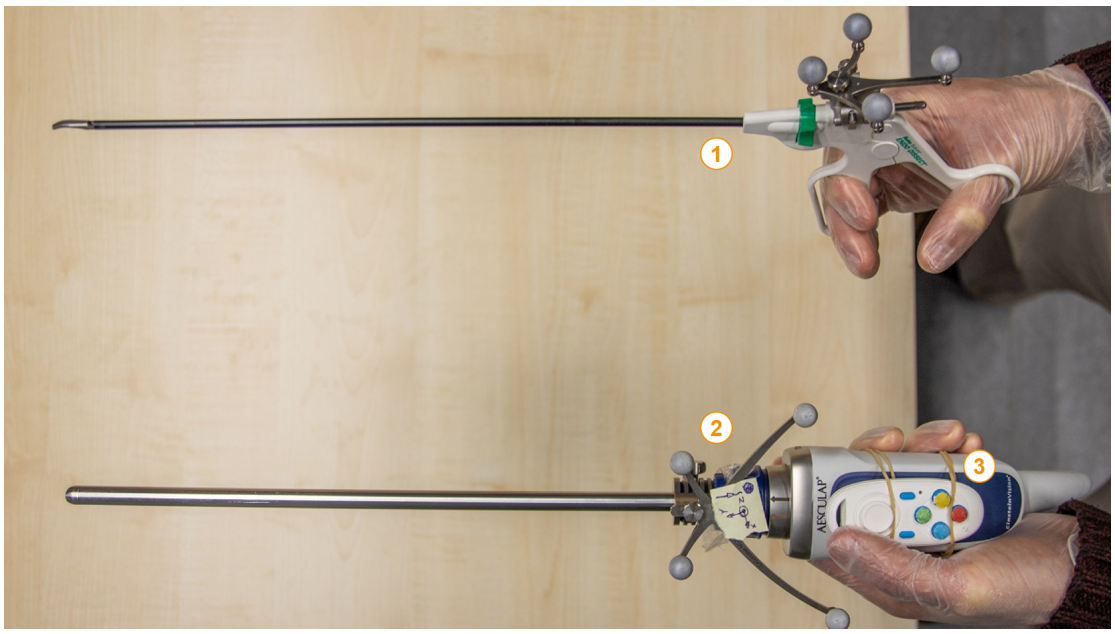


Figure 6.2: Pointing tool (1) and laparoscopic camera head (2). A mini gamepad with colour-coded buttons is mounted to the camera head (3).

6.3.3 Paired point registration method

A landmark-based solution was implemented as a reference method to compare to the proposed interactive methods. This method requires the user to interact with a mouse or touchscreen interface for registration planning. The user then uses the tracked laparoscopic pointing tool and an input device with at least one button. This method utilises anatomical, internal landmarks. During an initial planning phase, the user identifies and marks four characteristic points on the virtual model. These points are then recorded in the patient space by touching them with the tracked pointing tool. The virtual model's position and orientation are then determined based on the two paired point clouds [97]. This method is identical to the initial alignment step of the primary registration described in Chapter 5 and the implementation was equivalent.

6.3.4 Prototype implementation

The methods were implemented in the same AR infrastructure that was previously reported in Chapter 5. The InstControl method required a calibration of the pointing tool and the LapControl method required a calibration of the laparoscopic camera's position and orientation in their respective tracking marker reference systems. The calibrations for the tooltip and the camera's position were conducted as previously reported in Chapter 5. The camera objective's longitudinal axis was assumed to be equivalent to its marker shield's longitudinal axis. A mini gamepad was mounted to the laparoscope's camera head to simulate repurposing the camera head's four buttons for the registration methods (Figure 6.2). The mini gamepad's buttons were colour-coded for the clear assignment of GUI functions.

A GUI was developed for assisting the user in the two manual methods (Figure 6.3).

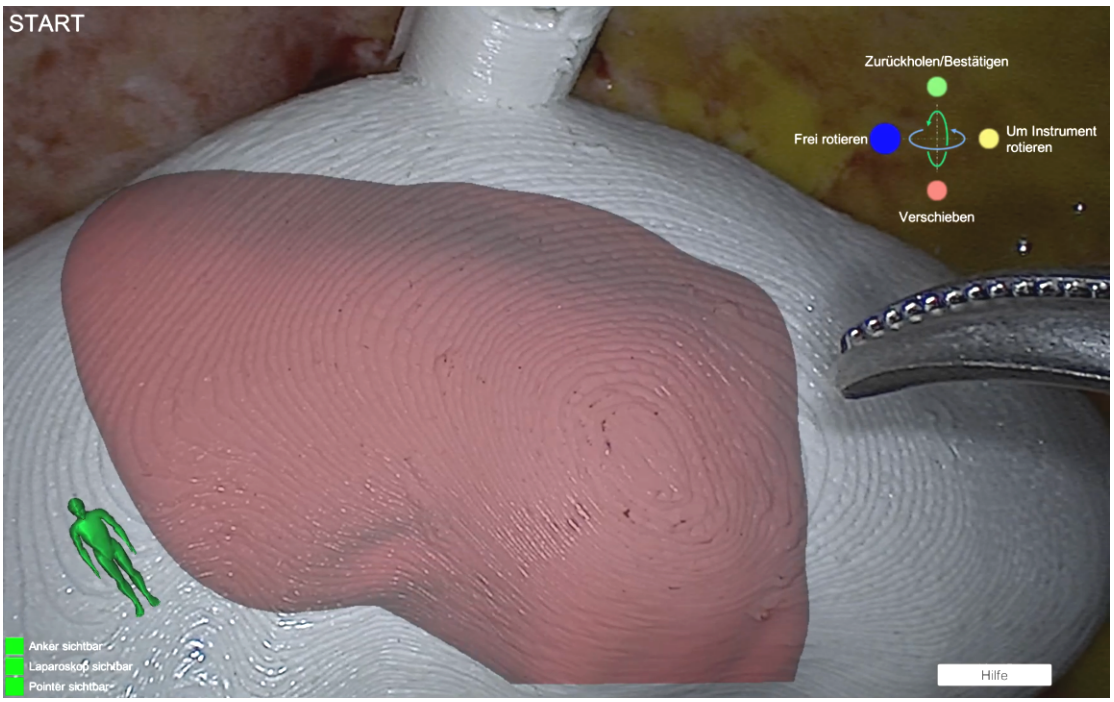


Figure 6.3: Registration GUI for the InstControl method. The free rotation mode is currently activated.

The main GUI element consisted of an overview of the availabe functions and their assignments to the four buttons. When one of the three manipulation modes was activated, the respective button's icon was highlighted and a descriptive graphical icon was displayed. In addition, a small mannequin was displayed in the bottom corner of the screen and rotated with the virtual model. This served to convey an overview of the model's approximate anatomical orientation. The landmark-based reference method and its GUI were implemented as previously reported in Chapter 5.

6.4 Evaluation methods

The three registration methods were comparatively evaluated in a user study with a simulated intraoperative registration task. The registration methods were compared with regards to three evaluation criteria: registration accuracy, registration speed, and participants' subjective usability perception.

6.4.1 Study design

The study was conducted in a within-subject repeated measures design. The applied registration method was the independent variable with three levels. Each participant performed all three registration tasks in a counterbalanced order.

The evaluation criteria were operationalised into four dependent variables: the translation error was measured as the translational offset between the registered virtual model's and physical model's centres of gravity. Rotation error was measured as the rotational

offset between the virtual and physical models in degrees. Registration speed was measured as the time that was required to complete the registration process (task completion time, TCT). The time measurement started when the start button was pressed in the InstControl and LapControl methods and when the planning was started in the paired point method. The TCT ended when participants concluded the registration with the confirmation button in the InstControl and LapControl methods, or by recording the last landmark point in the paired point method. Participants' usability perception was measured using the System Usability Scale (SUS) questionnaire by Brooke [223]. The questionnaire was translated to German by a native speaker. The translated version is included in Appendix C. In addition, participants' qualitative opinion on the registration methods was collected in an open interview format.

6.4.2 Sample design

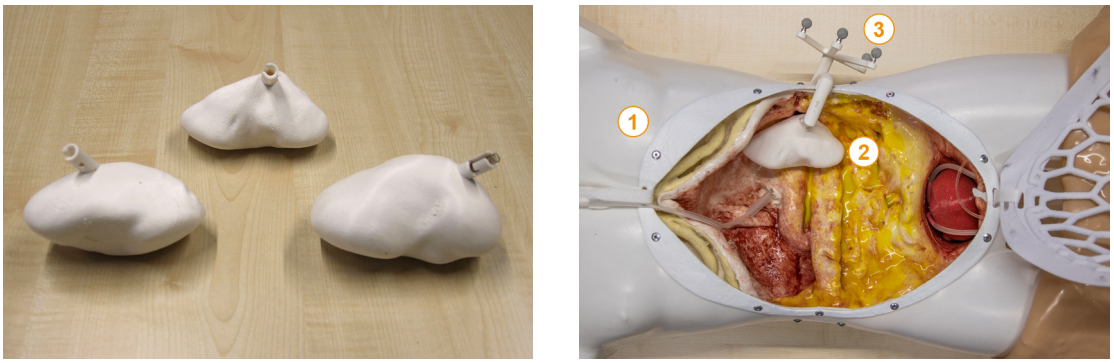
Twelve (12) participants were recruited for the study. The inclusion criteria were a medical background (medical students and physicians) and initial experience with laparoscopy. Training experience with a simulator was sufficient for participation because it provides experience with the particular hand-eye coordination that is required when working laparoscopically. Participants were paid 40 EUR for participation. Two participants were excluded from the data analysis during the initial data exploration (see the *Results* section for details). The following demographic data describe the remaining sample of 10 participants (five males, five females). The participants were 23 years to 36 years old (median = 24.5 years). Eight were medical students in their fourth and fifth year and two were physicians with two and nine years professional experience, respectively. One physician reported approximately 200 hours experience with operating laparoscopically; the remaining participants reported between one to 20 hours of laparoscopic trainer experience (median = 2h).

6.4.3 Study setup

The kidney models for the simulated registration task were created from a public CT database [207]. Three cases with a tumour-free kidney were selected and their healthy kidneys' parenchymal surface was manually segmented using *3D Slicer* [208]. The segmentations were reviewed by a senior urologist and converted to surface mesh models. The selected models included two left kidneys and one right kidney and are shown in Figure 6.4a. One of the models was the same model that has been previously described in Chapters 5. All three models were equipped with a mounting structure for a tracking marker geometry (see also Chapter 5, Figure 5.5a) and printed with the fused deposition modelling method.

A simulated laparoscopic operating environment was created with a torso model for laparoscopic surgical training (EasyLap training system, HumanX GmbH, Wildau, Germany). One kidney phantom at a time was mounted into the torso (Figure 6.4b). It should be noted that the anatomical position was more superior than would be anatomically correct. This was due to the fixed structures inside the torso model.

The torso model was then closed up and the simulated surgical site was made accessible with two 12mm trocars. The trocars were placed slightly contralaterally but close to the medial plane. The surgical site could then be accessed with the laparoscope and



(a) Kidney phantoms.

(b) Torso (1) with kidney phantom (2). The kidney phantom is mounted via the spatially tracked adapter geometry (3).

Figure 6.4: Components of the simulated surgical environment.

the laparoscopic grasper. It was not specified which trocar should be used for which tool. The simulated surgical environment and the interaction tools were placed on a height-adjustable table and the participants stood in front of this table. The resulting overall study setup is shown in Figure 6.5.

6.4.4 Study procedure

The experiment started with an introduction to the study. The participants' written informed consent and demographic information were collected during this introduction. This was followed by one trial block for each registration method (i.e. three blocks overall). The order in which the registration methods were performed was counterbalanced across participants. Each registration method was performed with a separate kidney model. The order of the kidney models was fixed, thus counterbalancing the assignment between registration methods and kidney models.

At the beginning of each trial block, the experimenter briefly explained the general principle of the respective registration method to the participant. The participant then performed a first practise trial (i.e. the registration process) with step-by-step instructions from the experimenter. Following this, the participant performed a second practise trial independently but with the freedom to ask questions. After all questions were answered, the experimenter exchanged the kidney phantom and virtual model for new ones. The participant then conducted a final test trial on the new model. The data were recorded during this test trial. Finally, the participant completed the SUS questionnaire for the tested registration method. After the completion of all three blocks, the experimenter conducted a brief interview with the participant. This interview aimed to elicit participants' qualitative feedback on the three registration methods.

6.4.5 Data analysis

A one-factorial, repeated-measures analysis of variance (ANOVA) was conducted for each of the four dependent variables. Data sphericity was tested with Mauchly's Test. Greenhouse-Geisser (GG) correction was applied in case of sphericity violation. In case of

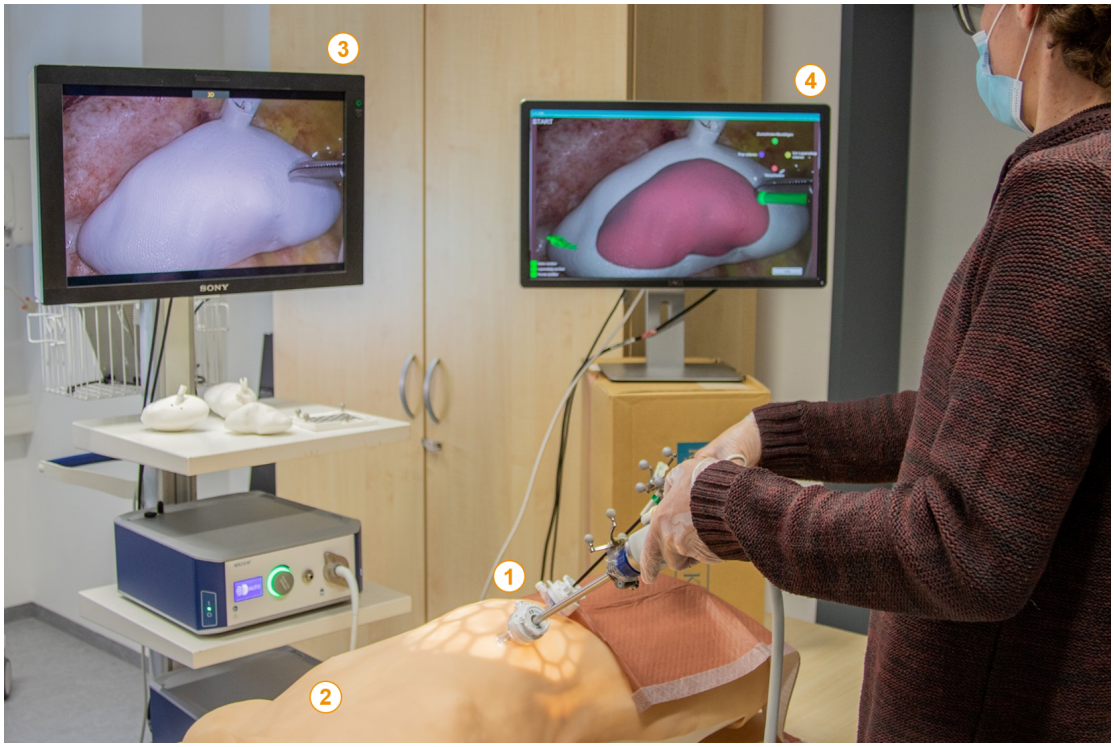


Figure 6.5: Overall study setup. The laparoscopic tools are inserted in the trocar ports (1) of the torso model (2). The left screen (3) displays the unaltered laparoscopic video. The right screen (4) is currently showing the InstControl GUI. The optical tracking camera is to the top left, outside the photograph's field of view and the mouse is located behind the torso model (to the user's right).

Table 6.1: Descriptive results for all dependent variables with $N = 10$. All entries are in the format: <mean value (standard deviation)>

Method	TCT [s]	Translation error [mm]	Rotation error [°]	SUS rating
InstControl	224.68 (89.70)	11.74 (4.91)	23.77 (18.82)	63.25 (18.41)
LapControl	270.39 (128.11)	12.44 (4.76)	29.73 (19.39)	49.75 (21.71)
PairedPoint	207.57 (75.19)	11.12 (4.78)	12.87 (6.46)	77.75 (11.27)

Table 6.2: ANOVA results for the registration method's effects on all dependent variables.

Variable	Sphericity violated	GG Correction	Test statistic	p	η^2
TCT	Yes	Yes ($\varepsilon = .573$)	$F(1.15, 10.31) = 1.21$	0.306	0.072
Translation error	No	No	$F(2, 18) = 0.171$	0.844	0.014
Rotation error	No	No	$F(2, 18) = 2.682$	0.096	0.174
SUS	No	No	$F(2, 18) = 11.82$	< 0.001*	0.317

significant findings in an ANOVA, post-hoc pairwise T-tests with Bonferroni correction were conducted. Participants' comments during experiment performance or from the interview were labelled, clustered and qualitatively analysed by one investigator.

6.5 Results

6.5.1 Data exclusion

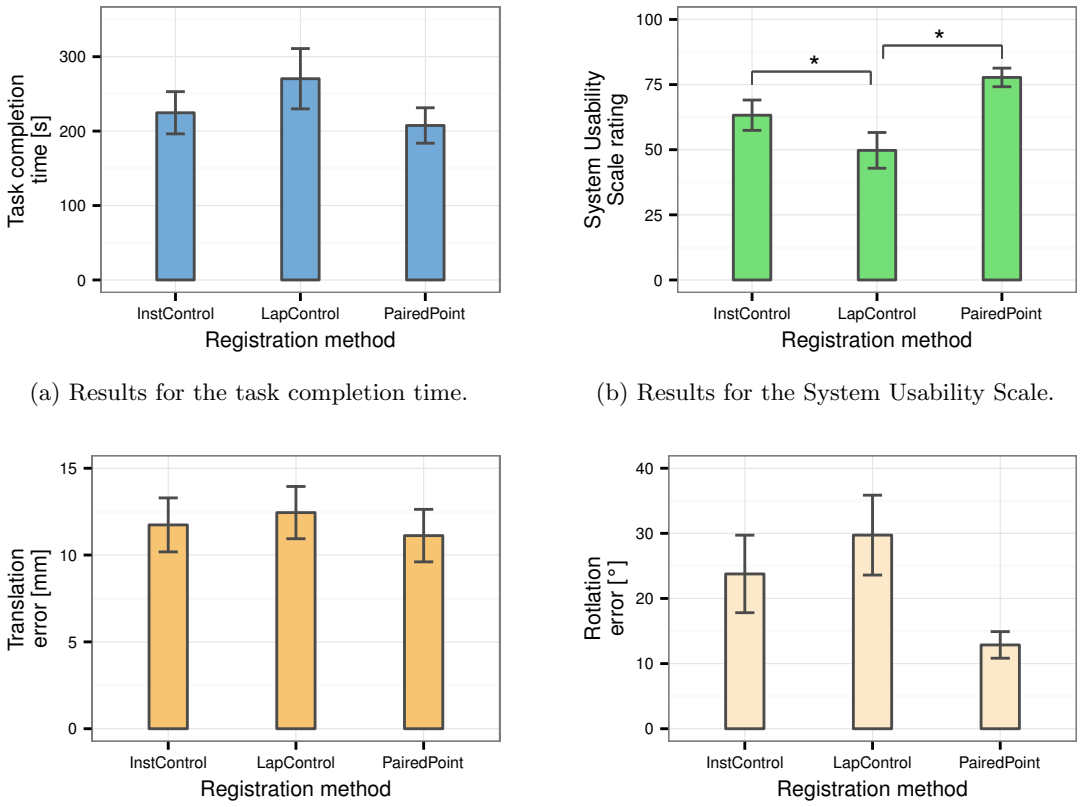
Two participants were excluded from the data analysis: one participant performed with a rotation error of 142.8° in the paired point condition, which equivalates to a z-score of 4.15. This indicates that they exchanged the upper and lower kidney pole. The second participant had a translation error of 30.5mm ($z = 3.24$) in the paired point condition. This indicates that at least one highly inaccurate point was selected. These are likely to be visualisation issues rather than interaction issues.

6.5.2 Quantitative results

The experiment's descriptive results are listed in Table 6.1. The ANOVA results for all dependent variables are shown in Table 6.2. No significant results were found for the TCT (see also Figure 6.6a), translation error (Figure 6.6c), and rotation error (Figure 6.6d). A significant effect was found for the participants' SUS rating (Figure 6.6b). The post-hoc pairwise t-tests found significant differences between the LapControl method and the InstControl method ($p = 0.047$), as well as between LapControl and the paired point method ($p = 0.01$). The difference between the InstControl method and the paired point condition was not statistically significant ($p = 0.077$).

6.5.3 Qualitative participant feedback

Nine general categories of participant comments emerged during qualitative data analysis. These included comments about the methods' general impression, their clinical



(a) Results for the task completion time.

(b) Results for the System Usability Scale.

(c) Results for the position accuracy.

(d) Results for the orientation accuracy.

Figure 6.6: Statistical results for all dependent variables. The error bars show standard errors. The asterisks in (b) indicate pairwise significance in the post-hoc t-tests.

applicability, the interaction devices, interaction handedness, characteristic landmark use, camera use, translation manipulation, rotation manipulation, and interaction metaphors. The comments for each interaction method are summarised below. These data are qualitative and no conclusions should be drawn from the reported numbers. These are not necessarily representative due to the open interview question format.

Instrument control

Participants found this method to be particularly well suited for adjustment and correction of registration results. One participant was concerned about potential 'false positives', i.e. false confidence in an incorrect registration. Three participants criticised that the method required bimanual interaction with the laparoscope and its buttons in one hand and the pointing instrument in the other hand. However, three other participants gave positive feedback on this aspect as it provides a 'division of labour' between both hands. Two participants commented that the translation setting with this method was simple, but they and three others reported that rotation was not intuitive. The first reason was that the instrument's own axis was not aligned with the image plane. The second reason

was that the model's behaviour was difficult to predict in free rotation - particularly when the instrument tip was outside the field of view (FoV). Two participants commented that the grasp-and-manipulate metaphor was generally realistic and intuitive.

Laparoscope control

Three participants commented that the system is too 'compressed' because the entire workflow is completed with one hand. They stated that they would usually hold the laparoscope with their non-dominant hand. The two main points of criticism expressed by participants concerned the FoV and the rotation mode: four participants criticised that the FoV's continuous motion during the process affected their sense of direction and repeatedly removed the area of interest from the FoV. One participant said that the motion might make them feel dizzy over time. The free rotation was perceived to be rather unpredictable, but one participant said that the axial rotation was easier to imagine than in the InstControl method. Finally, one participant stated that the interaction metaphor was rather unrealistic because the camera usually does not directly interact with objects in the surgical site.

Paired point registration

Overall, four participants stated that they found this method to be the easiest and 'most trustworthy' one. However, it was mentioned that a second person might be needed in a clinical setting to perform the planning. One participant also criticised that the method would not allow for corrections. Two participants reported that they were very used to using mouse-and-screen interfaces and that this was, therefore, easy to them. However, two participants mentioned that point acquisition required them to monitor the laparoscopic screen and the recording progress bar on the second screen at the same time.

6.6 Discussion

6.6.1 Discussion of the results

The evaluation results indicate that the LapControl method may not be well suited for the task at hand. No statistically significant inferiority was found for the TCT and accuracy parameters. However, the descriptive results suggest that this method did not perform well in these measures. Moreover, participants provided rather negative feedback on this method - both quantitatively and qualitatively. The main issue seems to be the FoV's instability when moving the camera as an input device. This effect is exacerbated by the fact that targeted laparoscope motion is often distinctly used to gain a better spatial understanding [5]. Using the LapControl method was likely made more difficult by using a laparoscope with a tilted camera because this offsets the tool axis from the optical axis. However, this is a realistic (and likely worst-case) application scenario and therefore a suitable testing scenario. The method grants qualitative benefits by limiting the interaction to one device that is naturally present in the workflow. Nevertheless, these benefits seem to be outweighed by the usability drawbacks that the study exposed.

The InstControl method was rated significantly more usable than the LapControl method by the participants. The data also showed trends that it may perform better with

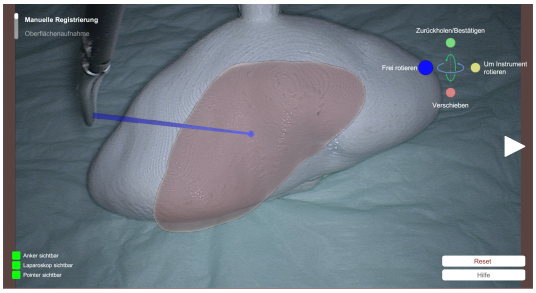
regards to TCT and accuracy. However, descriptive results suggest that, in its current form, it may not perform as well as the paired point method. This potential deficit is particularly evident for the rotation accuracy and the subjective feedback. The qualitative feedback suggests that this may have been caused by unintuitive model behaviour during the free rotation, whereas the position setting seems to have performed similarly to the paired point method. Moreover, the descriptively observed TCT difference between the InstControl method and the paired point method is only small (approximately 17s, no statistical significance). This time difference is likely to be caused by the confusion that participants (observably and reportedly) experienced with the manual rotation setting. This drawback requires further research as it can be largely mitigated with adjustments to the interaction technique. These potential adjustments are discussed in the following section.

6.6.2 General discussion

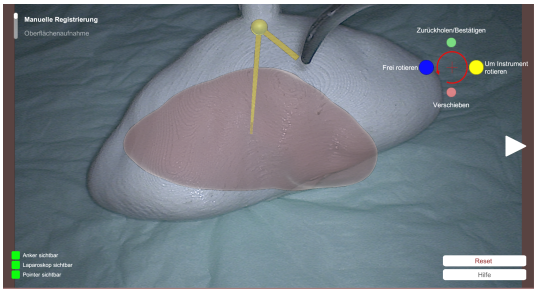
The evaluation study's results indicate that the LapControl method is likely to be inferior to current methods for initial registration. In contrast, the InstControl method may be a promising approach but requires further design iteration for the rotation setting interaction. The first approach for this may lie in improving the interaction with the current metaphors: firstly, the free rotation may become more intuitive by implementing auxiliary visualisations. One such visualisation could show the vector between the manipulation tool and the model's centre, visualising the point where the resulting line crosses the model surface (Figure 6.7a). An additional benefit of this visualisation concept is that it highlights the pivot point around which the model is rotated. This information may convey a better understanding of the spatial relationship and make the free rotation more predictable for users. Equivalently, the rotation axis could be displayed during the axis rotation mode (Figure 6.1b). A different approach to making the free rotation more intuitive could be restricting when it can be applied. This could either be restricted to situations when the pointing tool is within a maximum distance from the model, or it could be restricted to situations in which the tool is in the camera's FoV. The latter restriction would have the additional benefit of preventing tissue damage from tool motion outside the FoV. However, the issue of using the manipulation tool outside the FoV is unlikely to occur in the real application: anecdotal observation during the study indicated that experienced users primarily used the tool when in FoV.

Alternative interaction concepts for the manual rotation setting may also improve the registration method's overall usability. One option may be the restriction of the rotation setting to the axes of a defined coordinate system. Figure 6.7c shows a potential solution concept that uses the surgical tool's screen motion (as calculated from the tracking data) to rotate the model around the axes of a camera or screen-based coordinate system. This mirrors more conventional object manipulation with mouse or touchscreen interfaces [112]. Another option could be the bimanual rotation setting with two tracked surgical tools (Figure 6.7d). This requires a registration mode activation with foot pedals or alternative input devices and allows the rotation manipulation by tracking the vector between the two instruments' tooltips.

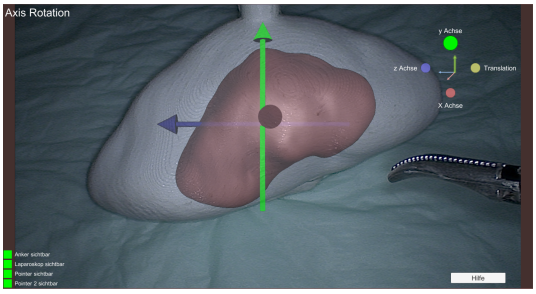
Besides the necessity of improving the rotation setting interaction, there is a practical issue with the herein reported implementation of the InstControl method. The interaction buttons are currently located on the laparoscope's camera head. In surgical scenarios,



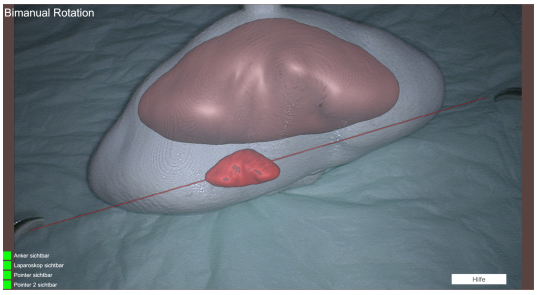
(a) Visualisation of the controlling vector $\vec{MT}_t$ for the free rotation mode.



(b) Visualisation of the rotation axis for the axis rotation mode.



(c) Screen-based coordinate system for a restricted rotation setting concept.



(d) Visualisation aid for a bimanual rotation setting concept.

Figure 6.7: Interaction and visualisation concepts for improving the InstControl rotation setting.

the laparoscope is often guided by an assistant. Therefore, an alternative means of interaction might be useful. This might either include moving the buttons to the pointing tool or implementing a touchless interaction technique, such as gesture or speech control.

In addition to these concept-related issues, there are some limitations concerning the evaluation study itself. The evaluation setup aimed to simulate a realistic surgical scenario. However, several design aspects are not representative of real surgery and may have influenced the results: the kidney phantoms were placed openly in the surgical site. Thus, the entire surface of one kidney side was visible to the participants. In contrast, surgeons only dissect the kidney surface parts that need to be accessed. The trocar setup was another deviation from a realistic surgical environment. Two 12mm-trocars were used to enable participants to choose which one to use for the laparoscope and which one to use for the pointing tool. Some participants used this setup to migrate the laparoscope back and forth between the trocars during a trial to gain a better spatial understanding. This is not realistic during surgery. Finally, the participants' experience with laparoscopic instruments was very limited and their performance was recorded in only one trial for each method. This may have influenced the difficulty of interacting with the laparoscopic surgical space.

It stands to be investigated how the depth perception limitations in the study may have affected the outcome. The interactive registration methods relied solely on optical, monoscopic depth cues. Even more so when the manually operated pointing tool was outside of the FoV and, therefore, unusable as a reference. The paired point method, however, provided additional haptic feedback when recording the points on the physical kidney phantom. This may have increased the level of difficulty of the interactive methods. Stereoscopic display and the constraint to have the tool in the FoV may help to mitigate this impact.

The two interaction methods have been evaluated as means for the initial alignment of the virtual AR content. Another potential application may lie in intraoperative registration correction (e.g. after organ movement or deformation). Future research is required to investigate whether this is a feasible application. This slightly altered application may even mitigate some of the drawbacks of the LapControl method because the required alignment changes would be only gradual and not as extensive as in this experiment.

Finally, one important scope limitation should be discussed: the interactive methods were compared to a landmark-based method. This reference method was selected because landmark-based methods seem to be a well-established standard approach for initial registration. However, the evident follow-up questions arising from this, are: firstly, how do the methods compare to previous interactive methods? Secondly, how do existing interactive methods compare to landmark-based methods? Future comparative research will need to show which overall approach is more suitable.

6.7 Conclusion

This chapter introduces two interaction methods for initial AR registration in laparoscopic surgery. One interaction method, the InstControl method, aimed to facilitate natural interaction metaphors for the object manipulation. The LapControl method aimed to minimise the hardware that needs to be introduced to the workflow specifically for

the registration. The interaction methods were compared to each other as well as to a reference landmark-based registration method in a simulated laparoscopy environment. The user study's results show that the LapControl method is inferior to the reference method and they provide a detailed explanation for this apparent inferiority. These findings can lay the groundwork for the development of future interaction methods for laparoscopic AR systems. The InstControl method did not outperform the reference method. However, the study yielded a number of findings that will help improving natural interaction with virtual objects in laparoscopic AR settings.

Three immediate follow-up research activities arise from the herein reported results. Firstly, the improvement measures concluded from the findings need to be integrated into the InstControl method and tested to determine if and how they improve the effectiveness, efficiency, and usability of this method. Secondly, it should be investigated how interactive methods generally compare against landmark-based methods for initial registration. Finally, the improved InstControl method should be compared to other interactive methods.

In the wider scope, some follow-up questions arise about the interaction method's more general applicability. This includes the applicability in other laparoscopic interventions with AR navigation support. It also includes the investigation of using the interaction method for the registration correction throughout the intervention. Finally, the method can be converted to robot-assisted applications where the input of the surgeon console controls could even be directly used for natural object manipulation without having to physically move a tool inside the surgical space.

Overall, this chapter does not present a finalised solution for manual registration or, more generally, natural manipulation of virtual objects in the laparoscopic space. However, this work generated valuable findings that can help to improve the overall registration process for laparoscopic AR and, thereby, to extend its applicability.

7

Audiovisual AR concept for resection wound navigation

Synopsis

This chapter reports a visual AR and an auditory navigation concept. Both concepts aim to support surgeons in laparoscopic subsurface structure navigation during the resection wound repair phase of LRPN. Both concepts are controlled by the user with an optically tracked surgical instrument. The concepts were evaluated in a simulated use study. The results indicate potential aptitude of the navigation concepts but further research, particularly into the auditory display, is required.

About this chapter

Parts of this chapter have been published in: Joeres, F., Black, D., Razavizadeh, S., and Hansen, C. (2021). 'Audiovisual AR Concepts for Laparoscopic Subsurface Structure Navigation'. In: Proceedings of Graphics Interface 2021 (Virtual event), pp. 224–230. *[224].*

Portions of the work reported in this chapter were conducted as part of the Master's thesis project of Mr Seyedsina Razavizadeh (thesis title: Virtual torchlight / stethoscope: An augmented reality tool for resection site repair phase during laparoscopic partial nephrectomy). Mr Razavizadeh's Master's thesis project was supervised by the author of this dissertation. Significant conceptual input towards the auditory display development was provided by David Black.

7.1 Introduction

Chapter 4 has identified a potential benefit from navigation aids during the resection site repair phase of LRPN. This phase bears some particular challenges for the design and development of AR navigation solutions. While Chapter 5 has investigated the implications for AR registration, two of these challenges specifically affect the availability and presentation of navigation-relevant data: firstly, the resection wound repair is conducted under time pressure and, secondly, an unknown tissue volume has been removed with the tumour. This chapter reports an audiovisual AR concept for navigation content presentation during the resection wound repair.

The audiovisual AR concept reported in this chapter aims to support the surgeons in the identification and localisation of intrarenal structures that have either been severed during the tumour resection or that lie immediately under the newly created resection surface. The former are relevant because they may require individual suturing if the lesion is too big to be closed by the general wound closure. The latter are relevant for the placement of the general wound closing suture. The structures of interest may be interarenal blood vessels or branches of the urinary collecting system.

Due to the time pressure during resection wound repair, the proposed system relies on preoperatively created virtual models of the structures of interest. Beside the time pressure, the second specific issue to be considered is the unknown position and geometry of the resection wound surface. This means that, in the preoperative model, it is not possible to identify which (urinary or blood) vessel branches either cross or lie close to the resection plane. The proposed solution to this is a data presentation that is interactively controlled by the surgeon by means of a spatially tracked tool. The tool can be moved along the resection surface and only structures that lie in front of the tool can be included in the (auditory or visual) display.

Finally, this chapter reports a laboratory-based simulated use study with a simplified task that provided a proof-of-concept evaluation for the audiovisual AR concept's prototypical implementation. The AR registration was omitted in this study and has been previously investigated in Chapter 5.

7.2 Related work

An overview of the relevant literature on image guidance and AR in LRPN has been reported in Chapter 4. No dedicated solutions exist in the current literature to support surgeons during the resection wound repair phase. One application has been reported in which the general AR model of the intrarenal structures was used during renorrhaphy [76]. This approach, however, does not address the unknown resection wound surface geometry and potential occlusion issues. It was also not specifically evaluated for its suitability during resection wound care.

Multiple solutions have been proposed to visualise intrarenal vascular structures. These include solutions in which a preoperative model of the vascular structures is rendered in an AR overlay [85, 161, 76, 113, 162]. This may be less informative after an unknown tissue volume has been resected. Other methods rely on real-time detection of subsurface vessels [165, 163, 164, 149]. However, these are unlikely to perform well when the vessels are clamped (suppressing blood flow and pulsation) or when the organ surface is occluded

by blood.

Outside of LPN/RPN, such as in angiography exploration, visualisation methods have been developed to communicate the spatial arrangement of vessels. These include the chromadepth [90] and pseudo-chromadepth methods [91, 92], which map vessel depth information to colour hue gradients. Kersten-Oertel et al. [93] showed that colour hue mapping, along with contrast grading, performs well in conveying depth information for vascular structures.

One strategy to make a visualisation independent from the knowledge about resected tissue geometries may be the interactive control of visualisations with phsical instruments. The visualisation of structures based on tool position has inspired work both inside and outside of the field of LRPN: Singla et al. [95] and Simpfendörfer et al. [175] proposed visualising the tool position in relation to the tumour during the intraoperative resection planning in LRPN. Multiple visualisations have been proposed for the spatial relationship between intracorporeal needles and the surrounding vasculature [225]. These visualisations are intended for minimally-invasive needle interventions in interventional radiology where the instrument is moving between the structures of interest. This is not possible in the given application because the structures of interest are below the organ's surface. Another example for tool-based AR visualisation is the virtual window technique for displaying real-time ultrasound [88]. However, direct ultrasound visualisation in LRPN has only been reported for tumour localisation and not for vessel identification.

In addition to visual approaches to supporting LRPN and other navigated applications, surgical tasks can be augmented and aided by auditory feedback. Relevant geometrical or surgical information can be classified or quantified and mapped to parameters of sounds that are synthesised in real time. A commonly known example for the principle of parameter mapping is the parking assistance in cars where the sound's rhythm encodes the distance between the vehicle and an obstacle. Similar approaches have been developed for navigational use in medical interventions. A comprehensive overview has been provided by Black et al. [226]. Applications include robot-assisted neurosurgery [227], needle placement for tumour ablation [228], bone drilling in otologic surgery [229], skull base surgery [230], open liver surgery [231], endoscopic, and force feedback substitution in robot-assisted surgical suturing [232]. These approaches have demonstrated increased spatial awareness and accuracy while, on the other hand, increasing task completion times.

7.3 Navigation methods

Two routes were pursued to provide navigation content to the operating surgeon: the first approach is the AR visualisation of preoperative anatomical information in a video-see through setting. The second approach is an auditory display.

7.3.1 AR visualisation

The AR concept aims to provide information about intrarenal risk structures to the surgeons. The visualisation is based on preoperative 3D image data of the intrarenal vasculature and collecting system. These were segmented and exported as surface models. The resection volume and resulting wound geometry are preoperatively unknown. Simply overlaying the preoperative models onto the laparoscopic video stream would include all

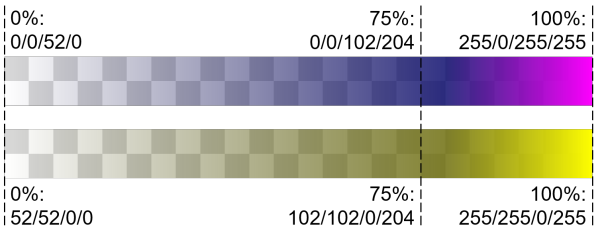


Figure 7.1: Colour spectrum for blood vessels (top) and urinary tract (bottom). The colour values are in RGBA format.

risk structures that were resected with the resection volume. Therefore, a tool-based visualisation is applied that allows the user to interactively adjust the visualised volume of interest. In this concept, only information about risk structures in front of a pointing tool are rendered and overlaid onto the video stream. To this end, the surgeon can place a spatially tracked pointing tool on the newly created organ surface (i.e. resection ground) and see a representation of the risk structures beneath: a virtual circular plane is placed around the tooltip. This plane is perpendicular to the tool axis with a diameter of 20mm. The structures in front of this plane (following the tool axis direction) are projected orthogonally onto the plane and rendered accordingly.

The visualisation encodes the structures' type, size, and distance from the rendering plane. The two different structure types are visualised with two different colour scales (Figure 7.1). The scales visualise the distance between a given structure and the plane. The scale ends are equivalent to a minimum and maximum probing depth that can be set for different applications. The scale hues were selected based on two criteria: firstly, the hues were selected for the maximisation of contrast visibility in front of laparoscopic videos. Secondly, the choice of yellow for urinary tracts and blue-magenta for blood vessels is consistent with conventions in anatomical illustrations and should be intuitive for medical professionals.

For the urinary tract, colour brightness and transparency are changed across the spectrum. For the blood vessels, colour hue, brightness, and transparency are used. These colour spectrums aim to combine the colour gradient and fog concepts that were identified as promising approaches by Kersten-Oertel et al. [93]. An example for the resulting visualisation (using a printed kidney phantom) is provided in Figure 7.2. The blue line marks the measured tool axis and the green circle delimits the circular detection and visualisation plane.

7.3.2 Audio navigation

The audio navigation concept is based on the principle of parameter mapping. The volume for which navigation feedback is provided is a half sphere around the tooltip, pointing forward along the tool axis. Three parameters are encoded for the relevant model structures inside the volume: the strucutre type, an artificial structure density variable, and structure distance from the tooltip. After three preliminary designs were evaluated informally with 12 test users, an auditory display consisting of two contrasting sounds was developed to represent the different structure types. The sound of running water represents the presence of collecting system branches and a synthesised tone

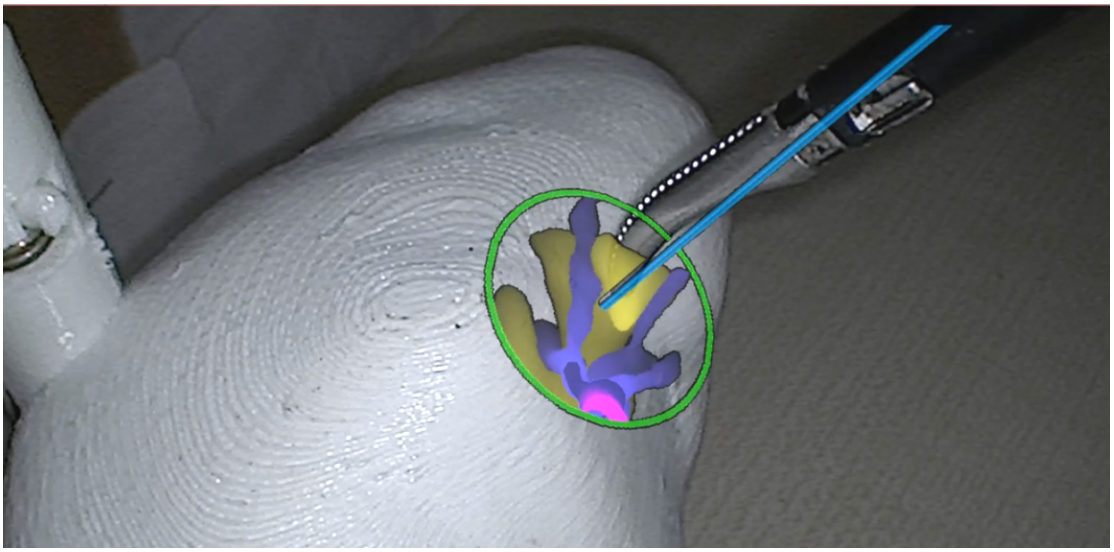


Figure 7.2: Laparoscopic view of a printed kidney phantom with the visual AR overlay.

represents blood vessels. The size and number of the vessels in the scanning area are encoded in a three-level *density* score. The density score is determined separately for each structure type. The density is then mapped to the water sound's pitch for the collecting system, symbolising a higher water pressure, and to the synthetic tone's pitch for blood vessels. Higher pitch indicates a higher structure density. Finally, the rhythm of each tone represents the distance between the instrument tip and the closest point on the targeted structure, with a faster rhythm representing lesser distance. The distance variable is also categorised in three distance categories: distant, near, and inside the vessel.

7.3.3 Prototype implementation

The prototype was implemented in the AR infrastructure that was previously described in Chapter 5. The display setup was slightly altered: the user was presented with the AR stream on a standard 24 inch LCD monitor that was located where the laparoscopic video monitor would normally be placed. A second standard 24 inch LCD monitor was placed to the participant's right. This second monitor displayed the experiment's GUI. For the prototype reported in this chapter, AR registration was outside of the project scope. The kidney registration was based on the predefined spatial transformation between the kidney phantom and its tracking markers (see *Study setup* section).

AR visualisation implementation

The circular plane was placed at the tooltip and perpendicular to the tool's axis as provided by the real-time tracking data. The registration between the visualisation (i.e. the tooltip location) and the camera was provided by the abovementioned tool and camera calibration and the real-time tracking data. The plane was then overlaid with a mesh with a rectangular vertex arrangement. The vertices had a density of 64 pts/mm^2 and served as virtual pixels. Repeated ray-casting requests along the tool axis

direction were conducted for each vertex. For each ray that hit the surface mesh of the structures in the virtual navigation model, the respective vertex was coloured according to the structure type and ray collision distance of that structure. The visualisation was permanently activated in the study prototype. Interactive activation and deactivation would be required in a clinical prototype or in the real clinical application.

Auditory display implementation

The synthesic tone qualitatively contrasted the water sound to ensure distinction between the structure types. The synthesised sound was created from the base frequencies of 65.4 Hz, 130.8 Hz, and 261.6 Hz (C2, C3, and C4 notes) and harmonised by each frequency's first to eighth harmonics, creating a complex tone. The blood vessel density was encoded in this pitch, representing low, medium, and high density, respectively. For the urinary vessels, three water sounds were devised that imitated water running at three different pressures - also representing three density stages. The repetition time of the tones expressed the distance between the instrument tip and the closest point on the targeted vessel. A continuous tone represented a far-away vessel, while a close vessel was heard as the tone being repeated every 500 ms with a duration of 400ms. Being inside the vessel triggered an alert sound, playing every 125 ms accompanied by the tone every 250 ms. The auditory display was implemented using Pure Data [233].

7.4 Evaluation methods

A simulated use proof-of-concept evaluation study was conducted with N=11 participants to investigate whether the concepts can effectively support the surgeons in locating subsurface structures in laparoscopic surgery.

7.4.1 Study task

The specific challenges of identifying relevant subsurface structures in resection wound repair are difficult to replicate in a laboratory setting. A study task was devised that aimed to imitate the identification of specific structures beneath an organ surface: participants were presented with a printed kidney phantom in a simulated laparoscopic environment. A 3D model of the same kidney was displayed on a 24 inch screen. This virtual model included surface meshes of the vessel tree and collecting system inside that kidney (Figure 7.3). Participants could manipulate the view of that model by panning, rotating, and zooming. For each study trial, a point on the internal structures (a blood or urine vessel) was marked in the virtual model with a red dot (Figure 7.3). The target points were arranged into four clusters to prevent familiarisation with the target structures throughout the experiment. The participants were then asked to point the surgical tool at the location of that subsurface point in the physical phantom as accurately and as quickly as possible by placing the tool on the surface and orienting it such that the tool's direction pointed towards the internal target point.

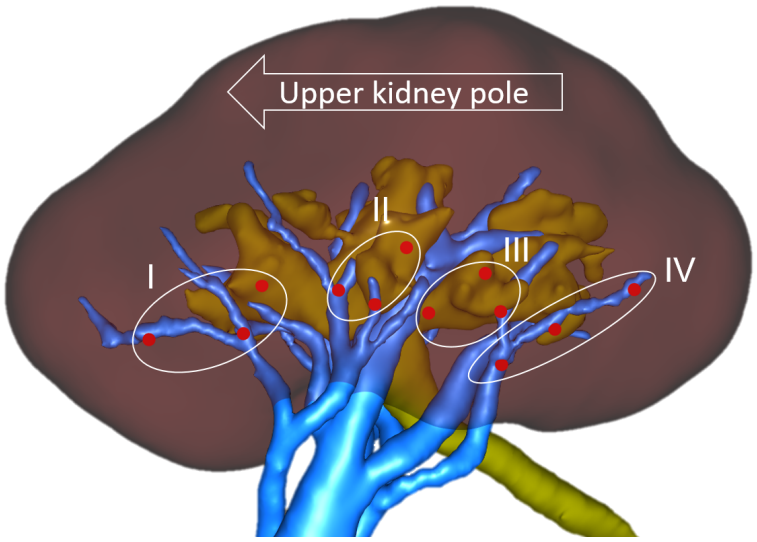


Figure 7.3: Virtual kidney model with the target point clusters. The model is shown from a medial-anterior perspective, corresponding to the participant's position.

7.4.2 Study design

The study investigated the impact of the visual and auditory support on the performance and perceived workload of the navigation task. Two independent variables were examined with two levels each (2×2 design): the presence or absence of the visual support and the presence or absence of the auditory support. The condition in which neither support modality was present was the control condition. Three dependent variables were measured and analysed: firstly, the task completion time was measured. Time started counting when the target point was displayed in the 3D model. It stopped when participants gave a verbal cue that they were confident they were pointing at the target as accurately as possible. Secondly, the tool pointing accuracy was measured. Accuracy was measured as the closest distance between the tool's axis and the target point (point-to-ray distance). Finally, the NASA Task Load Index (NASA-TLX) [234] questionnaire was used as an indicator for the subjectively perceived workload. The NASA-TLX questionnaire is based on six contributing dimensions of subjectively perceived workload. Participants weighted the scores by relevance in pairwise rankings and the weighted scores were combined into an overall workload score.

7.4.3 Study sample

Eleven (11) participants took part in the study (six females, five males). All participants were medical students between their third and fifth year of training. Participants were aged between 24 and 33 years (median = 25 years). All participants were right-handed. Four participants reported between one and five hours of experience with laparoscopic interaction (median = 3h) and seven participants reported between one and 15 hours of AR experience (median = 2h). Finally, eight participants reported to be trained in playing a musical instrument. No participants reported any untreated vision or hearing impairments. The participants were paid 20 EUR for participation.

7.4.4 Study setup

The virtual kidney model and its physical phantom were created from a public database of abdominal computed tomography imaging data [207]. A healthy left kidney was segmented using 3D Slicer [208]. The parenchymal surface, the vessel tree, and the urinary collecting system were exported as separate surface models. The parenchymal surface model was printed with the fused deposition modeling method and equipped with an adapter for passive tracking markers (see also Chapter 5; Figure 5.5a). The resulting rigid phantom had a length of 112mm from pole to pole (original scaling). The phantom was placed in a cardboard box to simulate a laparoscopic working environment (Figure 7.4a). The screen with the laparoscopic video stream was placed opposite the participant and the screen with the virtual model viewer was placed to the participant's right. A mouse was provided to interact with the model viewer and a standard commercial multimedia speaker was included for the auditory display. The simulated surgical environment and the interaction tools were placed on a height-adjustable table and the participants stood in front of this table. The overall study setup is shown in Figure 7.4b.

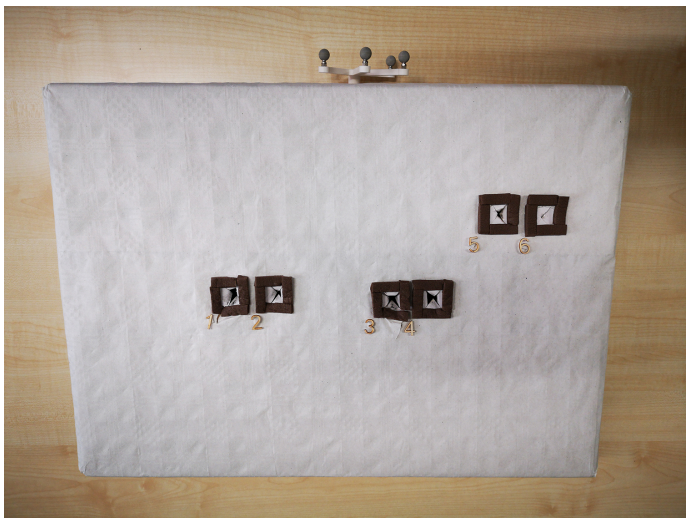
7.4.5 Study procedure

Participants' written consent and demographic data were collected upon arrival. The participants then received an introduction to the visualisation and auditory display of the navigation information. Participants conducted one trial block per navigation method (i.e. four overall blocks). In each trial block, they were asked to locate the three points of one cluster, with one trial per point. After each trial block, one NASA-TLX questionnaire was completed for the respective navigation method. The order of the navigation methods and the assignment between the point clusters and the navigation methods were counterbalanced. The order in which the points had to be located within each trial block was permutated across the participants.

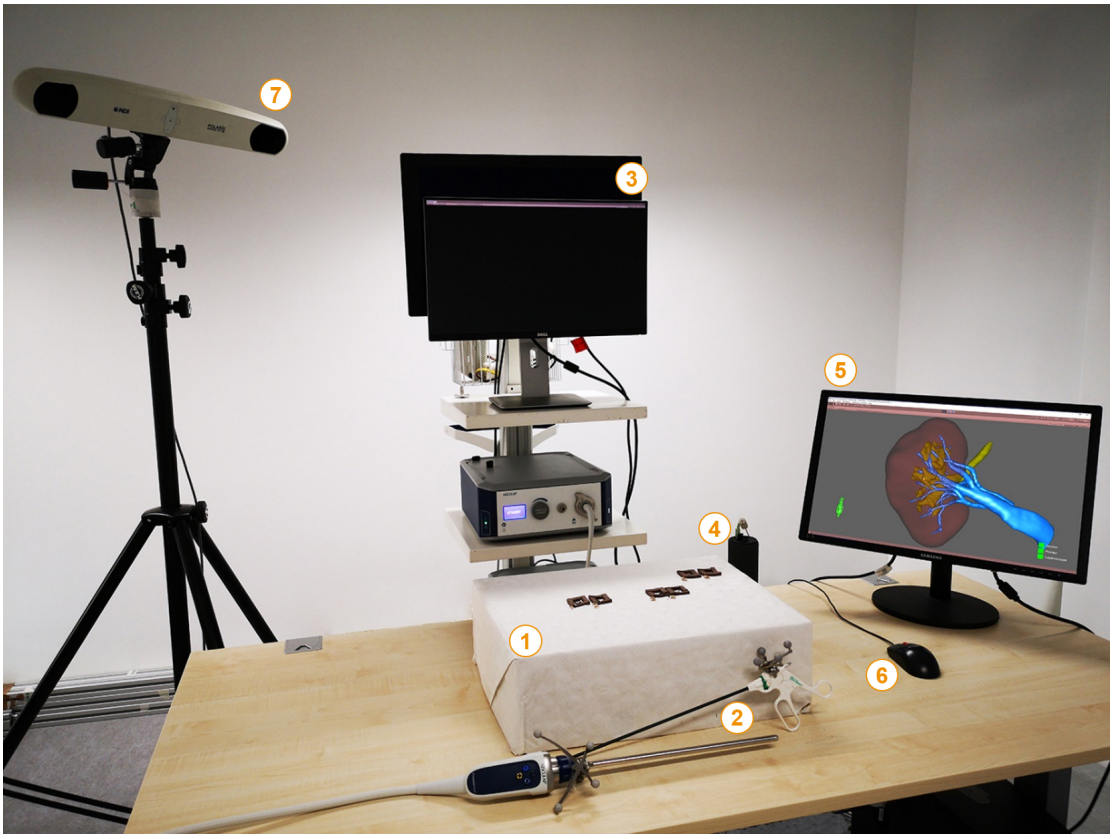
7.5 Results

During the initial data exploration, a trend became apparent that participants took more time to complete the first trial they conducted with each method than in the second and third trials (Figure 7.5). Therefore, the first trial for each method and participant was regarded as a training trial and excluded from the analysis. The data (time and accuracy) from the remaining two trials from each block were averaged and a repeated-measures two-way ANOVA was conducted for each dependent variable.

The descriptive results for the three dependent variables are listed in Table 7.1 and an overview of the data is plotted in Figure 7.6. The ANOVA results are listed in Table 7.2. Two significant main effects were found in the ANOVA. The presence of the visual display was shown to significantly reduce the pointing error ($p < 0.001$) and the and the NASA-TLX rating ($p = 0.03$). The significant effects are plotted in Figure 7.7.



(a) Simulated laparoscopic environment with access holes for the laparoscopic camera head and the pointing tool.



(b) Overall study setup, including the simulated laparoscopic environment (1), the laparoscope and pointing tool (2), the AR screen (3), the speaker (4), the GUI screen (5), the mouse for model manipulation (6), and the optical tracking camera (7).

Figure 7.4: Study setup components.

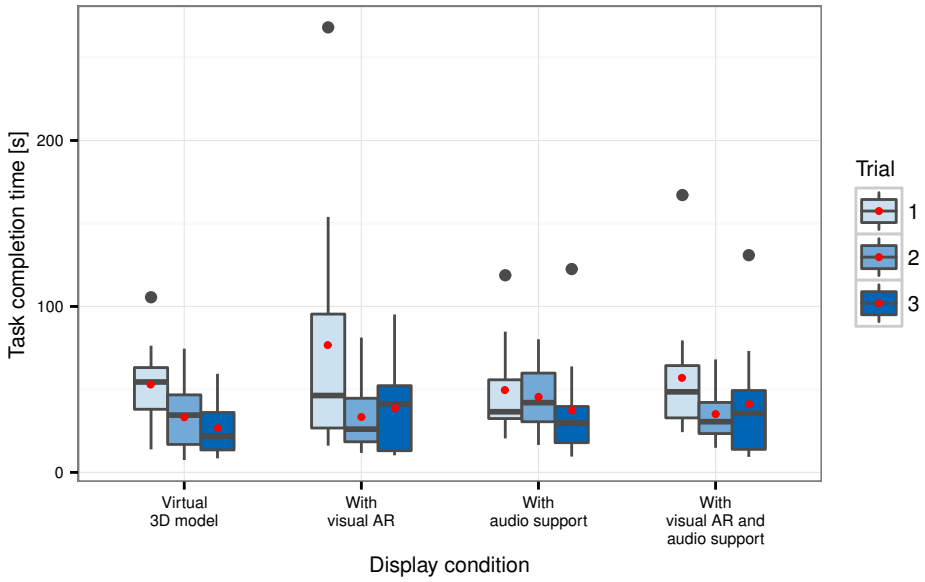
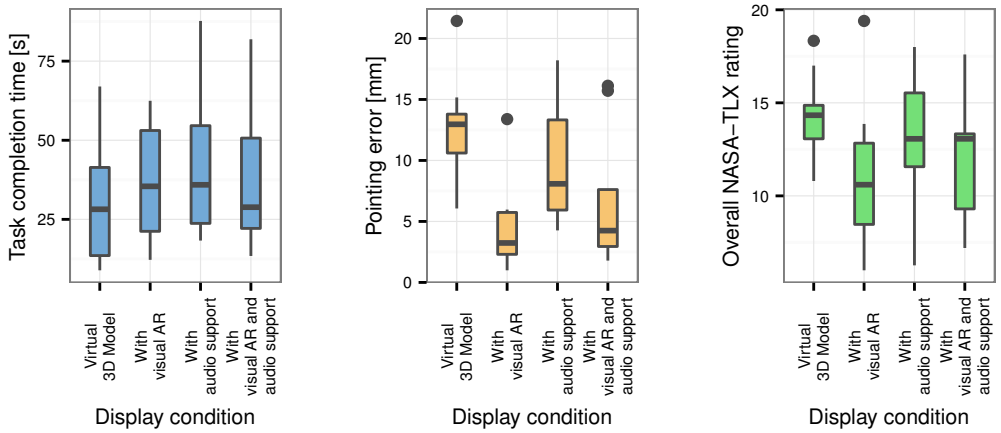


Figure 7.5: Task completion times during the first, second, and third trials for each display condition. The red points indicate the mean values.

Table 7.1: Descriptive results for all dependent variables. All entries are in the format <mean value (standard deviation)>.

Navigation condition	Task completion time [s]	Accuracy [mm]	NASA-TLX
Virtual 3D model	29.92 (18.59)	12.54 (4.21)	14.14 (2.18)
With visual AR	36.02 (19.21)	4.39 (3.49)	10.87 (3.86)
With audio support	41.44 (22.9)	9.69 (5.14)	12.93 (3.46)
With visual AR and audio support	38.12 (22.48)	6.45 (5.08)	11.93 (3.3)



(a) Task completion time data.

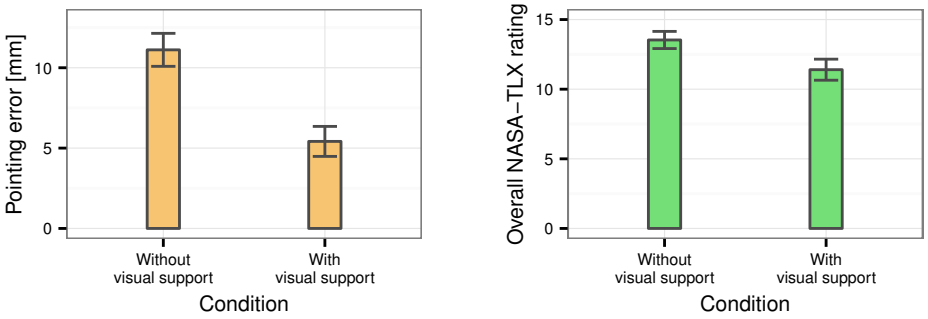
(b) Pointing accuracy data.

(c) NASA-TLX rating data.

Figure 7.6: Overview of the experimental data for all navigation display conditions.

Table 7.2: ANOVA results for all variables. AD: auditory display, VD: visual display. All cells are in the format: <F value (degrees of freedom); p value>.

Dependent variable	Main effect AD	Main effect VD	Interaction AD:VD
Task completion time	1.41(1,10); 0.263	0.17(1,10); 0.688	1.47(1,10); 0.253
Accuracy	0.11(1,10); 0.748	**28.01(1,10); <0.001***	2.67(1,10); 0.133
NASA TLX	0.01(1,10); 0.911	**6.35(1,10); 0.03***	1.47(1,10); 0.253



(a) Visual display main effect on the pointing accuracy.

(b) Visual display main effect on the NASA-TLX rating.

Figure 7.7: Significant ANOVA main effects. The error bars represent standard errors.

7.6 Discussion

7.6.1 Discussion of the results

The most evident result from the evaluation is that the visual display increases the accuracy and reduces the perceived workload of identifying subsurface vascular and urinary structures in the tested, simplified task. At the same time, the visual display method did not reduce the task completion time. Generally, there were non-significant trends that all tested conditions with visual or auditory display performed more accurately and tended to cause a lower perceived workload. However, the navigation support conditions tended to perform less quickly than the control condition. This may be due to the fact that the required mental spatial transformations are reduced, but a greater amount of information needs to be processed by the participants.

This explanation is also supported by the result that the combined auditory and visual display performed worse than the visual-only condition within the sample. While this trend is not statistically significant, it poses a question: were the auditory display designs somewhat misleading or distracting, or is the combination of multimodal channels for the *same* information in itself potentially hindering in this task? The trend of auditory support performing slightly better than the control condition within the study sample (no significance) may indicate that the latter explanation is more likely. Another aspect may be users' lower familiarity with auditory navigation than visual cues. The descriptive exploration of the task completion times across the trial order (Figure 7.5) shows that the

performance speed continued to improve across all three trials for the control condition (Virtual 3D model) and for the audio support condition. This may also indicate that participants were still undergoing a training process and that three trials may have been too few to reach ideal performance in these conditions. This means that the effect of the visual AR may be smaller with more training. However, this also means that the audio support concept may be more effective with additional training. Thus, greater participant experience may reduce the difference between the visual and auditory navigation aids.

The AR visualisation was well suited for the abstracted task in the proof-of-concept evaluation. In the clinical context, a semi-transparent display of the visualisation may be better suited to prevent occlusion of the relevant surgical area. This occlusion issue can further be reduced by providing a means to interactively activate or deactivate the visualisation.

Finally, the absolute values reported for the dependent variables are less meaningful than the comparative effects that were found. Multiple design factors limit the clinical validity of the study that are discussed in the next section. This means that the absolute task time or pointing error may well deviate from the reported results.

7.6.2 General discussion

The evaluation study generated preliminary but successful proof-of-concept results for the audiovisual AR support for laparoscopic subsurface structure navigation during resection wound repair. The results indicate that audio guidance may be helpful but no statistically significant evidence for this benefit was found within the study sample. There are some limitations to the clinical validity of the prototypes and the study setup.

First and foremost, the study task is an abstraction of the actual surgical task: the surgical task requires not only the identification of major subsurface structures but also the judgment and selection of a suture path. This task limitation went along with an abstract laparoscopic environment and surgical site: the kidney phantom imitated an in-vivo kidney only in its geometric properties. The colour, biomechanical behavior, and surgical surroundings did not resemble their real clinical equivalents. Moreover, the phantom was simplified in that it was based on an intact kidney rather than containing a resection wound. While this simplification is an additional limitation to the study's clinical validity, introducing a phantom with a resection bed will only be meaningful in combination with a more complex simulated task. This is because, in a realistic setting, the surgeon will be familiar with the wound and aware of potential landmarks (like intentionally severed vessels) that may help the navigation. This would not have been the case in the simplified task and for the study participants. One further step in improving the phantom for increased realism may be the simulation of the deformation that occurs. This may be achieved by producing one preoperative phantom and one intraoperative phantom based on simulated intraoperative deformation (e.g. using the Simulation Open Framework Architecture [235])

As discussed above, a more realistic task could also contribute to an increased clinical validity for the evaluation. The most valid performance parameter, however, would be the frequency of suture setting errors. Because these are not very frequent, the study would require a large sample consisting of experienced surgeons. This is logistically challenging. The reported approximation can, therefore, be regarded as a good first indication for the aptitude of the navigation support methods. Future evaluation with a

more realistic phantom and task should also include the AR overlay of structure models on the simulated resection wound as an (additional) reference condition.

The study participants were medical students with limited laparoscopic experience: they were less trained in the spatial cognitive processes that are involved in laparoscopic navigation than the experienced surgeons who would be the intended users for such a navigation support system. Thus, the navigation methods presented in this chapter will need to be further evaluated in clinically realistic settings with a more realistic user demographic. This may include testing on an in-vivo or ex-vivo human or porcine kidney phantom. This, however, requires an effective AR registration that is compromised by the time pressure (for in-vivo phantoms) or post-mortem deformation in ex-vivo phantoms.

AR registration was excluded from this study's scope to focus the investigation on the tested information presentation methods. A dedicated registration method for post-resection AR is reported in Chapter 5. This could be combined with the dedicated AR concepts reported in this chapter for future, high-fidelity evaluation and development stages.

The study task simplification in combination with the novelty of the clinical application for audiovisual navigation limit the comparability of the results with other solutions reported in the literature. Evaluation work with a higher task and setup fidelity may investigate system performance in comparison to AR solutions like the one proposed by Porpiglia et al. [76]. A pre-clinical audiovisual navigation concept for skull base surgery reported similar effects on the subjectively perceived workload [230]. However, the study task in that evaluation included the full simulation of a surgery and no performance parameters were recorded. Thus, further evaluation work is required under more realistic conditions in order to assess the concepts' performance in relation to other solutions reported in the literature.

Beyond more clinically valid evaluation, some other research questions arise from the work reported in this chapter: firstly, some design iteration and comparison should be implemented to evaluate whether the limited success of the tested auditory display was due to the specific designs or due to a limited aptitude of the auditory modality for such information. Secondly, further visualisations should be developed and compared with this initial proposal to identify an ideal information visualisation. Finally, it should be investigated whether other procedures with soft tissue resection (e.g., liver or brain surgery) may benefit from similar navigation support systems for the resection wound repair.

7.7 Conclusion

This chapter introduces an audiovisual AR concept to support surgeons during the resection wound repair phase in LRPN. This concept was preliminarily evaluated in a laboratory-based study with a highly abstracted task. Although the results only represent a proof-of-concept evaluation, they indicate the potential benefits of the presented concepts.

Two follow-up work objectives arise from this: the first objective is the further investigation and iteration of the auditory and visual display designs. This investigation includes the question whether the limited performance of the audio display is due to

the specific design or due to a general inaptitute of the auditory modality for this task. Moreover, further design iteration is required for the visual AR display.

The second follow-up objective is the integration of the dedicated registration method that was reported in Chapter 5. The combined system then requires evaluation in a high fidelity test environment and surgical simulation to assess whether the overall system may bring clinical benefit to the surgical phase of resection wound repair in LRPN.

8

Conclusion

Synopsis

This chapter summarises the contribution and the limitations of the research reported in this dissertation and assesses the overall scientific contribution. It recapitulates the specific future work objectives that were identified throughout Chapters 3 - 7. Further, more general research perspectives for AR in LRPN and laparoscopic surgery are discussed. An examination of the challenges and potential strategies in this future work concludes the chapter and this dissertation.

8.1 Research contribution

The laparoscopic surgical approach bears multiple clinical benefits to the patient due to its minimal invasiveness and the associated low surgical trauma. However, it entails additional challenges for the operating surgeon that include perceptual, cognitive, and manipulative obstacles. While robot-assistance can alleviate some of the (primarily physical) challenges, the broad field of image guidance and AR assistance aims to support the surgeon in meeting the perceptual and cognitive challenges. This dissertation investigated - for the application of LRPN - the usefulness of a user needs centred approach to these AR assistance systems.

Overall, the research reported in this dissertation revealed a new application for AR assistance in LRPN: the navigation during the resection wound repair. This new application represents a new result to the initial research question: *how can AR navigation aid the surgical treatment of kidney cancer?* Moreover, this demonstrates that - within this case study - the selected research approach has widened the research field of AR navigation assistance for this surgery. This successful case study provides evidence towards the second overall research question: *can a dedicated investigation of information needs advance novel research areas for surgical navigation assistance?*

To this end, a literature-based workflow analysis of the surgical procedure of LRPN was conducted (Chapter 3). The results of this workflow analysis served as the basis for a qualitative interview study with nine senior urologists that employed CTA methods. The study identified the surgical phases that are perceived to be particularly challenging and risk-associated by the clinicians: these were the hilar and vascular management (phase I), the tumour excision (phase II), and the resection wound repair (phase III). Moreover, the specific challenges, strategies, and information needs that arise during these phases were identified. This was the first reported, dedicated analysis of this kind for a laparoscopic surgery.

The second contribution aimed to put the identified surgical information needs in the context of the existing relevant literature. A sytematic literature review of image guidance literature in LRPN identified an open research gap (Chapter 4). This gap lies in the surgical navigation during the resection wound repair phase of LRPN. Specifically, the surgeon has to identify blood and urinary vessels that lie close to the newly created resection surface and that have either been severed or need to be considered in the suture placement. Chapter 4 also defines the technological challenges that arise from the surgical conditions during this phase:

1. An unknown tissue volume has been removed at this point, leaving behind an undefined resection bed.

2. The resection wound repair is performed under time pressure, leaving little time for the required AR registration and the navigation itself.

3. The kidney has been moved during the resection process.

4. The kidney has been deformed during the resection process.

While the first two challenges affect both, the AR visualisation and registration, the last two primarily affect the registration. Chapter 1 introduced the three question items

to be asked in the user centred development of surgical AR systems: *what* information should be displayed to the surgeon *when*, and *how*? [13]. The findings summarised above provide answers to the first two of these questions. Moreover, they analyse the specific challenges that arise in answering the third question: *how* can and should the information be displayed?

This dissertation does not report an integrated AR navigation solution that can answer this third question by solving all four issues. However, Chapters 5 and 7 report a registration concept and an interactive audiovisual AR navigation concept that aim to address these four challenges. These concepts have been implemented and tested in early stage proof-of-concept settings. This prototyping level entails multiple limitations for their external validity that are discussed in the next section.

Finally, the dissertation introduces a novel interaction technique for the interactive AR registration in laparoscopic surgery (Chapter 6). This technique is not limited to the previously discussed application of resection wound repair in LRPN. However, it may complement the registration pipeline introduced in Chapter 5. Moreover, it may be useful in other laparoscopic surgeries. The transferrability of this dissertation's overall results is a matter for future research as discussed in the next section.

8.2 Research limitations

The main limitations of the research reported in this dissertation fall into three major categories: the first category comprises the surgical application scope of the information needs and their potential solutions. While LRPN served as a successful case study for the user needs centred approach, the results do not provide sufficient evidence to assess whether the identified needs and solutions may be applicable beyond LRPN. The second group of limitations concern the external validity of the prototypes and evaluations for the concepts introduced in Chapters 5 - 7. Finally, this dissertation observes LRPN as blanket term for LPN and RPN. In a clinical context, however, different detailed design requirements may arise in LPN and RPN for AR navigation systems. These limitation categories are discussed in detail below.

The challenges identified in Chapter 3 may be generalisable to other laparoscopic surgeries. Specifically, they may arise in other surgeries in which an organ is partially resection (e.g. partial hepatectomy [236]). The data collected in the reported interview study, however, do not permit any conclusions to this end. Moreover, the research approach was taylored to the complexity of LRPN. Specifically, a workflow-based written questionnaire was used to preselect discussion topics with each interviewee. The study results indicate that this approach was successful in this context. However, there are two open methodological issues: firstly, some surgical tasks were discussed with only one or two interviewees. While the interview was able to reveal novel information needs previously unaddressed, further information needs may still remain undidentified. Secondly, other surgeries may require an adaptation of the method. They may be simpler and not require the preselection step. Or they may be even more surgically complex and require further filtering or selection steps. This case study is not sufficient for any conclusions about a general scoping and filtering technique for the application of this method to other surgeries.

Regarding the evaluation validity for the research prototypes reported in Chapters 5 - 7,

there are three main factors to be considered: the simulated surgical environment, the study task, and the sample design. The potentially biggest limitation to the evaluation validity is the neglect of organ deformation in the surgical site. Organ deformation affects the registration [11] (i.e. the prototypes presented in Chapters 5 and 6), and, consequently, will affect the accuracy of the navigation information displayed in the proposed navigation concept (Chapter 7). Multiple factors affect the deformation of the kidney during laparoscopic surgery. These include the motion of the kidney between the preoperative imaging and the intraoperative situation [237], the loss of turgor after the suppression of perfusion by arterial clamping [195], the pneumoperitoneal pressure [238], and the surgical organ manipulation [212]. The most relevant deformation factor for the investigated resection wound repair phase is likely to be the removal of a tissue volume. This deformation factor, however, has not been systematically investigated in the literature. While Altamar et al. [212] investigated the surface deformation that is caused by a linear incision, the experiment did not include the kidney's inner deformation when a whole volume is resected from the organ. Multiple non-rigid registration approaches exist for laparoscopic kidney surgery that aim to apply the real organ's deformation to its virtual counterpart [215, 239]. However, these, too, do not account for the resection of tissue volumes. Therefore, further biomechanical research into this matter is required before it can be incorporated into a resection wound repair assistance system.

The study task factor primarily applies to the solutions for assistance during the resection wound repair phase (Chapters 5 and 7). The two tasks that are relevant for the novel concepts are the re-registration after the tumour resection and the navigation in the resection wound. The experiments reported in this dissertation did not simulate the resection of a tumour or any other tissue volume. This alteration affects both tasks: the resection would constrain the pre-resection placement options for the adhesive fiducials in the registration task. It is trivial that the resection wound navigation is affected by the presence or absence of a simulated resection wound. The decision to simulate both tasks with an intact kidney phantom was closely related with the final study validity factor, i.e. the sample design. The user studies were conducted with medical students with some basic laparoscopic training. The intended users, however, are highly experienced surgeons because LRPN is a complex surgery that is primarily performed by senior staff. The simulation of a tissue resection (both, in the registration study and the navigation study) would have required participants with extensive surgical knowledge about the procedure. The navigation study could have hypothetically been conducted with a phantom with a simulated resection wound. However, the process of planning, understanding, and executing the resection gives the operating user extensive context knowledge about the kidney at hand, its anatomy, and the resection geometry. This knowledge could not have been validly simulated with the participants that were available. Therefore, the resection was not simulated in the proof-of-concept evaluations reported in Chapters 5 and 7. The simulation of the resection process itself would also require an advanced kidney phantom. The three factors of study phantom (resectable and deformable), study task (including the resection), and study sample (senior urological surgeons) are, therefore, strongly intertwined. It is challenging to improve the realism of one of the factors in a valid way without improving the other two factors at the same time.

The study sample factor also affected the evaluation study for the interactive registration concepts introduced in Chapter 6. The participants had limited experience with the spatial orientation and motor challenges that arise in laparoscopic interaction. Generally,

the study participants' limited experience and the resulting deviation from the intended users diminishes the aspiration for a user centred research approach that was derived in Chapter 1. This overall limitation was owed to the logistical challenge of recruiting senior surgical staff who are truly representative of the intended user population. This requires (temporal and financial) ressources that were out of the scope of what was appropriate for the early stage of the tested research prototypes.

Finally, the research reported in this dissertation did not strongly distinguish between the application of AR navigation in LPN and in RPN. The literature (Chapter 4) suggests that there is an overlap in the surgical information needs that may arise during these two surgical approaches to PN. However, different requirements may arise in a more detailed observation. The effect that this has on the research results' validity is different for the various research activities reported throughout Chapters 3 - 7. These potential effects are discussed below.

The interview study reported in Chapter 3 included urologists who perform both surgical approaches. No clear differences in their needs arose from the qualitative discussions. The sample size of N=9 was too small to draw any conclusions from quantitative analysis, particularly because the various surgical steps were only discussed with subgroups of the overall study sample. It is likely that the overall information needs would not be invalidated by a more distinguished investigation of LPN andRPN. Chapter 5 introduced the two-stage registration pipeline and evaluated it in a simulated laparoscopic setting. The approximately concurrent publication of an equivalent, successful approach for robotic surgery [203] indicates that the concept is equally viable in the robotic surgical approach. The interactive registration approach in Chapter 6 is specific to the interaction with laparoscopic instruments. Its transferrability to the robotic approach is likely to be limited. While it may be realistic to use the robotic instruments in a similar fashion, more intuitive dedicated solutions are imaginable. For example, the robotic controllers' signal could be directly used for interactive registration input. The concept, therefore, seems primarily applicable to manual laparoscopic surgery. Finally, the audiovisual AR navigation prototype that was introduced in Chapter 7 is likely to be applicable in RPN although it was only tested in a simulated laparoscopic setting. It may be even easier to use in the robotic approach because the additional joint at the tooltip (da Vinci *EndoWrist* technology) would offer the user more freedom in controlling the visualisation.

8.3 Future research objectives

Three groups of future work objectives arise from the research that has been described in this dissertation. The first group comprises the immediate follow-up questions from the activities reported throughout Chapters 3 - 7. These research questions have already been discussed in the respective chapters and are summarised below. The second group arises from the limitations that have been discussed in the previous section. Additional work is required to address these limitations and increase the scope and validity of the reported work. The third group includes research questions and objectives that generally advance the results obtained during this work.

There are two immediate follow-up questions from the interview study reported in Chapter 3: the first issue concerns the three challenging surgical phases of LRPN. The identification of these phases may be useful in the future design of training material for

LRPN. Future work is required to investigate how the identified challenges and solutions can be used to better prepare junior surgeons for this surgery. The second open extension of this work is the inclusion of non-routine scenarios in the investigation. One potential method for this may be the Critical Decision Method. The literature review in Chapter 4 identified multiple research gaps in the context of AR in LRPN. The biggest gap was in the support of the resection wound repair phase. This gap has been further investigated in this dissertation. However, two more relevant challenges were identified that have not been addressed in the literature: the placement of the trocars and the identification of additional parenchymal tumours. These require further investigation in the future. The results of Chapter 5 include the speed and accuracy of the registration process. These results require further investigation of the speed and accuracy performance that is required to provide a meaningful and beneficial AR assistance for the resection wound repair in LRPN. This, however, requires further research on more realistic test conditions as discussed in the previous section. The follow-up objectives of the work reported in Chapters 6 and 7 primarily concern design decisions: the interactive registration method InstControl (Chapter 6) requires further design iteration. The reported concepts need to be implemented and tested. The audiovisual AR concept (Chapter 7) showed limited performance for the auditory display. Further research is required to determine whether this was due to the specific design or whether the auditory display is an inapt modality for the task at hand. Moreover, the tested AR visualisation is an initial design that may require further iteration and comparative evaluation against other visualisation methods.

The second cluster of research objectives arise from the limitations discussed above. The first major limitation is the generalisability of the information needs analysis findings (Chapter 3). Similar studies are required for other laparoscopic procedures to investigate whether equivalent information needs arise. If this is the case, it may be possible to develop navigation solutions that can be applied across different interventions or even surgical domains (e.g. liver surgery).

Another major limitation lies in the external validity of the evaluation studies for the proposed registration and visualisation solutions. A more valid evaluation of the concepts requires four study design factors to be improved: firstly, the prototypes themselves should be integrated into one navigation system. This should follow the design iteration steps that were previously discussed.

The second factor limiting the study validity is the surgical environment and, particularly, the kidney phantom on which the surgery was simulated. Ultimately, a test in live surgery should be the goal, either in human patients or in an animal specimen. This allows for considerably higher external evaluation validity. However, it does reduce the control over the test conditions and is logistically and ethically complex [12]. Therefore, further phantom testing is preferrable for the continued development of a navigation assistance for resection wound repair. The key challenge is the simulation of the kidney's biomechanical behaviour (i.e. its deformation behaviour). This may require the use of human or animal ex-vivo specimens. This behaviour then needs to be integrated in existing deformation methods for the virtual model. Moreover, the question needs to be investigated, whether the deformation needs to be included in the registration process. Research about the liver's deformation during hepatic resection has shown that the local deformation is so small that it can be neglected for some surgical AR registration applications [213]. The kidney is considered to be slightly more rigid than the liver [11]. Therefore, future research should also investigate whether sufficient registration accuracy

can be achieved with a rigid registration as proposed in Chapter 5. Finally, the study task and the testing participants' qualification should be improved to better represent the clinical application scenario.

The third major limitation of this work is the simultaneous investigation of LPN and RPN. Future work is required to analyse the differences that arise in the detailed solution design requirements. This may include an extension of the information needs interview study, including enough surgeons from each surgical approach to allow for a systematic comparison. Potential, more detailed design requirements may also arise for the audiovisual AR concept. The increased number of DoF in the instrument manipulation may open more design opportunities for the visualisation and the interaction. Moreover, dedicated interactive registration concepts are required for robot-assisted surgery, as the solutions reported in Chapter 6 specifically rely on interaction with laparoscopic instruments.

The ultimate objective should be the experimental integration of a matured prototype for AR assistance in the resection wound repair phase of LRPN. Multiple technical challenges are yet to be overcome until this can be achieved as discussed above. Beyond these technical challenges, a scientific challenge lies in the generation of clinically valid evaluation data for academic research prototypes like this [140]. Further methodological research is required to generate unbiased clinical evidence for the benefit of AR navigation asssitance during all challenging phases of LRPN.

8.4 Conclusion

This dissertation set out to generate findings towards two overall research questions:

- *How can AR navigation aid the surgical treatment of kidney cancer?*
- *Can a dedicated investigation of information needs advance novel research areas for surgical navigation assistance?*

Three surgical phases were identified during which AR assistance may be particularly useful. These include the vascular management, the tumour excision, and the resection wound repair. While multiple solutions exist for the first two phases, this dissertation proposes initial solution concepts for AR assistance during the third phase. Much research and development remain to be completed before these concepts can be introduced to the clinical workflow. Nevertheless, these findings can be seen as an overall contribution towards the first research question. LRPN served as an examplary case study towards the second research question. The methods applied in this work identified a new potentially beneficial application area for AR assistance within this surgery. This indicates that the user information needs centred approach may benefit the scientific field of surgical computer assistance by revealing novel research areas. An application of this or similar methods to other (laparoscopic) surgical domains may enable the systematic comparison of user needs in different interventions and domains. This may, one day, facilitate the development of generalised navigation solutions that benefit patients and surgeons across multiple surgical disciplines.

Bibliography

[1] Sung, H., Ferlay, J., Siegel, R. L., Laversanne, M., Soerjomataram, I., Jemal, A., and Bray, F. (2021). 'Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries'. eng. In: *CA: a cancer journal for clinicians* 71.3, pp. 209–249. DOI: 10.3322/caac.21660. eprint: 33538338.

[2] Capitanio, U., Bensalah, K., Bex, A., et al. (2019). 'Epidemiology of Renal Cell Carcinoma'. eng. In: *European urology* 75.1, pp. 74–84. DOI: 10.1016/j.eururo.2018.08.036. eprint: 30243799.

[3] Hautmann, R. and Gschend, J., eds. (2014). *Urologie*. 5th ed. Springer. ISBN: 9783642343186.

[4] Berguer, R., Smith, W. D., and Chung, Y. H. (2001a). 'Performing laparoscopic surgery is significantly more stressful for the surgeon than open surgery'. En;en. In: *Surgical Endoscopy* 15.10, pp. 1204–1207. DOI: 10.1007/s004640080030.

[5] Bogdanova, R., Boulanger, P., and Zheng, B. (2016). 'Depth Perception of Surgeons in Minimally Invasive Surgery'. eng. In: *Surgical innovation* 23.5, pp. 515–524. DOI: 10.1177/1553350616639141. eprint: 27009686.

[6] Berguer, R., Forkey, D. L., and Smith, W. D. (2001b). 'The effect of laparoscopic instrument working angle on surgeons' upper extremity workload'. En;en. In: *Surgical Endoscopy* 15.9, pp. 1027–1029. DOI: 10.1007/s00464-001-0019-1.

[7] White, A. D., Mushtaq, F., Giles, O., Wood, M. L., Mole, C., Culmer, P. R., Wilkie, R. M., Mon-Williams, M., and Lodge, J. P. A. (2016). 'Laparoscopic Motor Learning and Workspace Exploration'. eng. In: *Journal of surgical education* 73.6, pp. 992–998. DOI: 10.1016/j.jsurg.2016.05.001. eprint: 27321983.

[8] Vávra, P., Roman, J., Zonča, P., Ihnát, P., Němec, M., Kumar, J., Habib, N., and El-Gendi, A. (2017). 'Recent Development of Augmented Reality in Surgery: A Review'. eng. In: *Journal of healthcare engineering* 2017, p. 4574172. DOI: 10.1155/2017/4574172. eprint: 29065604.

[9] Gawande, A. A., Zinner, M. J., Studdert, D. M., and Brennan, T. A. (2003). 'Analysis of errors reported by surgeons at three teaching hospitals'. eng. In: *Surgery* 133.6, pp. 614–621. DOI: 10.1067/msy.2003.169. eprint: 12796727.

[10] Hansen, C., Wieferich, J., Ritter, F., Rieder, C., and Peitgen, H.-O. (2010). 'Illustrative visualization of 3D planning models for augmented reality in liver surgery'. eng. In: *International journal of computer assisted radiology and surgery* 5.2, pp. 133–141. DOI: 10.1007/s11548-009-0365-3. eprint: 20033519.

[11] Bernhardt, S., Nicolau, S., Soler, L., Doignon, C., and Nicolau, S. A. (2017). 'The status of augmented reality in laparoscopic surgery as of 2016'. eng. In: *Medical Image Analysis* 37, pp. 66–90. DOI: 10.1016/j.media.2017.01.007. eprint: 28160692.

[12] Luz, M., Strauss, G., and Manzey, D. (2016). 'Impact of image-guided surgery on surgeons' performance: a literature review'. In: *International Journal of Human Factors and Ergonomics* 4.3/4, p. 229. DOI: 10.1504/IJHFE.2016.083516.

[13] Kersten-Oertel, M., Jannin, P., and Collins, D. L. (2013). 'The state of the art of visualization in mixed reality image guided surgery'. eng. In: *Computerized medical imaging and graphics : the official journal of the Computerized Medical Imaging Society* 37.2, pp. 98–112. DOI: 10.1016/j.compmedimag.2013.01.009. eprint: 23490236.

[14] Kersten-Oertel, M., Jannin, P., and Collins, D. L. (2012). 'DVV. A taxonomy for mixed reality visualization in image guided surgery'. eng. In: *IEEE transactions on visualization and computer graphics* 18.2, pp. 332–352. DOI: 10.1109/TVCG.2011.50. eprint: 21383411.

[15] Dixon, B. J., Daly, M. J., Chan, H., Vescan, A. D., Witterick, I. J., and Irish, J. C. (2013). 'Surgeons blinded by enhanced navigation. The effect of augmented reality on attention'. eng. In: *Surgical endoscopy* 27.2, pp. 454–461. DOI: 10.1007/s00464-012-2457-3. eprint: 22833264.

[16] Hughes-Hallett, A., Mayer, E. K., Marcus, H. J., Pratt, P. J., Mason, S., Darzi, A. W., and Vale, J. A. (2015). 'Inattention blindness in surgery'. eng. In: *Surgical endoscopy* 29.11, pp. 3184–3189. DOI: 10.1007/s00464-014-4051-3. eprint: 25582962.

[17] Dey, A., Billinghurst, M., Lindeman, R. W., and Swan, J. E. (2018). 'A Systematic Review of 10 Years of Augmented Reality Usability Studies: 2005 to 2014'. In: *Frontiers in Robotics and AI* 5, p. 161. DOI: 10.3389/frobt.2018.00037.

[18] Joeres, F., Schindele, D., Luz, M., Blaschke, S., Russwinkel, N., Schostak, M., and Hansen, C. (2019). 'How well do software assistants for minimally invasive partial nephrectomy meet surgeon information needs? A cognitive task analysis and literature review study'. eng. In: *PloS one* 14.7, e0219920. DOI: 10.1371/journal.pone.0219920. eprint: 31318919.

[19] Guillonneau, B., Gill, I. S., Janetschek, G., and Tuerk, I. A. (2009). *Laparoscopic Techniques in Uro-Oncology*. eng. London: Springer London. ISBN: 978-1-84628-521-9. DOI: 10.1007/978-1-84628-789-3.

[20] Nowack, R., Birck, R., and Weinreich, T. (2009). *Dialyse und Nephrologie für Fachpersonal*. ger. 3. Aufl. s.l.: Springer-Verlag. 391 pp. ISBN: 3540723226. URL: http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10346865.

[21] Klingele, M. and Brodmann, D., eds. (2017). *Einführung in die Nephrologie und Nierenersatzverfahren. Für Pflegende, Medizinstudenten und Assistenzärzte*. ger. Berlin, Heidelberg and s.l.: Springer. 25364 pp. ISBN: 9783662545829. DOI: 10.1007/978-3-662-54583-6.

[22] Robert-Koch-Institut and Gesellschaft Der Epidemiologischen Krebsregister In Deutschland E.V., eds. (2019). *Krebs in Deutschland 2015/2016*. de. DOI: 10.25646/5977.2. (Visited on 05/21/2021).

[23] Bergmann, L., Bauernhofer, T., Bokemeyer, C., et al. (2020). *Nierenzellkarzinom (Hypernephrom). Empfehlungen der Fachgesellschaft zur Diagnostik und Therapie hämatologischer und onkologischer Erkrankungen*. Deutsche Gesellschaft für Hämatologie und Medizinische Onkologie e.V. URL: https://www.onkopedia.com/de/onkopedia/guidelines/nierenzellkarzinom-hypernephrom/@@guideline/html/index.html (visited on 05/21/2021).

[24] Macleod, L. C., Hotaling, J. M., Wright, J. L., Davenport, M. T., Gore, J. L., Harper, J., and White, E. (2013). 'Risk factors for renal cell carcinoma in the VITAL study'. eng. In: *The Journal of Urology* 190.5, pp. 1657–1661. DOI: 10.1016/j.juro.2013.04.130. eprint: 23665301.

[25] Joh, H.-K., Willett, W. C., and Cho, E. (2011). 'Type 2 diabetes and the risk of renal cell cancer in women'. eng. In: *Diabetes care* 34.7, pp. 1552–1556. DOI: 10.2337/dc11-0132. eprint: 21602426.

[26] Gasser, T. (2015). *Basiswissen Urologie*. 6., überarb. Aufl. 2015. Springer-Lehrbuch. Berlin: Springer Berlin. 280 Seiten in 1 Teil. ISBN: 9783662451304.

[27] Brierley, J., Gospodarowicz, M. K., and Wittekind, C., eds. (2017). *TNM classification of malignant tumours*. eng. Eighth edition. Chichester, West Sussex, UK and Hoboken, NJ: John Wiley & Sons Inc. 253 pp. ISBN: 9781119263562.

[28] Deutsche Krebsgesellschaft, Deutsche Krebshilfe, AWMF (2020). *Diagnostik, Therapie und Nachsorge des Nierenzellkarzinoms. Langversion 2.0*. URL: https://www.leitlinienprogramm-on-kologie.de/leitlinien/nierenzellkarzinom/ (visited on 07/19/2021).

[29] Winfield, H. N., Donovan, J. F., Godet, A. S., and Clayman, R. V. (1993). 'Laparoscopic Partial Nephrectomy: Initial Case Report for Benign Disease'. EN. In: *Journal of Endourology* 7.6, pp. 521–526. DOI: 10.1089/end.1993.7.521.

[30] Gettman, M. T., Blute, M. L., Chow, G. K., Neururer, R., Bartsch, G., and Peschel, R. (2004). 'Robotic-assisted laparoscopic partial nephrectomy. Technique and initial clinical experience with DaVinci robotic system'. eng. In: *Urology* 64.5, pp. 914–918. DOI: 10.1016/j.urology.2004.06.049. eprint: 15533477.

[31] Kaouk, J. H., Khalifeh, A., Hillyer, S., Haber, G.-P., Stein, R. J., and Autorino, R. (2012). 'Robot-assisted laparoscopic partial nephrectomy. Step-by-step contemporary technique and surgical outcomes at a single high-volume institution'. eng. In: *European urology* 62.3, pp. 553–561. DOI: 10.1016/j.eururo.2012.05.021. eprint: 22658759.

[32] Agha, R. and Muir, G. (2003). 'Does laparoscopic surgery spell the end of the open surgeon?' eng. In: *Journal of the Royal Society of Medicine* 96.11, pp. 544–546. DOI: 10.1258/jrsm.96.11.544. eprint: 14594961.

[33] Carus, T. (2014). *Operationsatlas Laparoskopische Chirurgie*. Berlin, Heidelberg: Springer. ISBN: 978-3-642-31245-8. DOI: 10.1007/978-3-642-31246-5.

[34] Gomes-da-Silveira, G. G., da Silveira, G. P. G., and Pessini, S. A., eds. (2018). *Minimally Invasive Gynecology. An Evidence Based Approach*. eng. Cham: Springer International Publishing. 387 pp. ISBN: 9783319725925. DOI: 10.1007/978-3-319-72592-5.

[35] Liu, R. (2017). *Laparoscopic Liver Resection. Theory and Techniques*. eng. Dordrecht: Springer. 111 pp. ISBN: 9789401797351.

[36] Arora, S., Sevdalis, N., Nestel, D., Woloshynowych, M., Darzi, A. W., and Kneebone, R. (2010). 'The impact of stress on surgical performance: A systematic review of the literature'. en. In: *Surgery* 147.3, 318–330.e6. DOI: 10.1016/j.surg.2009.10.007.

[37] van der Schatte Olivier, R. H., Van't Hullenaar, C. D. P., Ruurda, J. P., and Broeders, I. A. M. J. (2009). 'Ergonomics, user comfort, and performance in standard and robot-assisted laparoscopic surgery'. eng. In: *Surgical endoscopy* 23.6, pp. 1365–1371. DOI: 10.1007/s00464-008-0184-6. eprint: 18855053.

[38] Yates, D. R., Vaessen, C., and Roupret, M. (2011). 'From Leonardo to da Vinci: the history of robot-assisted surgery in urology'. en. In: *BJU international* 108.11, pp. 1708–1713. DOI: 10.1111/j.1464-410x.2011.10576.x.

[39] Chandra, V., Nehra, D., Parent, R., Woo, R., Reyes, R., Hernandez-Boussard, T., and Dutta, S. (2010). 'A comparison of laparoscopic and robotic assisted suturing performance by experts and novices'. eng. In: *Surgery* 147.6, pp. 830–839. DOI: 10.1016/j.surg.2009.11.002. eprint: 20045162.

[40] Lucas, S. M., Mellon, M. J., Erntsberger, L., and Sundaram, C. P. (2012). 'A comparison of robotic, laparoscopic and open partial nephrectomy'. eng. In: *JSLS : Journal of the Society of Laparoendoscopic Surgeons* 16.4, pp. 581–587. DOI: 10.4293/108680812X13462882737177. eprint: 23484568.

[41] Zheng, J.-H., Xu, Y.-F., Peng, B., Zhang, H.-M., Yan, Y., Gao, Q.-R., Meng, J., and Huang, J.-H. (2009). 'Retroperitoneal laparoscopic partial nephrectomy for renal-cell carcinoma in a solitary kidney. Report of 56 cases'. eng. In: *Journal of Endourology* 23.12, pp. 1971–1974. DOI: 10.1089/end.2008.0653. eprint: 19916753.

[42] Cáceres, F., Núñez-Mora, C., Cabrera, P. M., García-Mediero, J. M., García-Tello, A., and Angulo, J. C. (2011). 'Laparoscopic partial nephrectomy'. In: *Actas Urológicas Españolas (English Edition)* 35.8, pp. 487–493. DOI: 10.1016/j.acuroe.2011.03.013.

[43] Desai, M. M., Gill, I. S., Ramani, A. P., Spaliviero, M., Rybicki, L., and Kaouk, J. H. (2005). 'The impact of warm ischaemia on renal function after laparoscopic partial nephrectomy'. eng. In: *BJU international* 95.3, pp. 377–383. DOI: 10.1111/j.1464-410X.2005.05304.x. eprint: 15679798.

[44] Thompson, R. H., Lane, B. R., Lohse, C. M., Leibovich, B. C., Fergany, A., Frank, I., Gill, I. S., Blute, M. L., and Campbell, S. C. (2010). 'Every minute counts when the renal hilum is clamped during partial nephrectomy'. eng. In: *European urology* 58.3, pp. 340–345. DOI: 10.1016/j.eururo.2010.05.047. eprint: 20825756.

[45] Shao, P., Qin, C., Yin, C., Meng, X., Ju, X., Li, J., Lv, Q., Zhang, W., and Xu, Z. (2011). 'Laparoscopic partial nephrectomy with segmental renal artery clamping. Technique and clinical outcomes'. eng. In: *European urology* 59.5, pp. 849–855. DOI: 10.1016/j.eururo.2010.11.037. eprint: 21146917.

[46] Gill, I. S., Eisenberg, M. S., Aron, M., Berger, A., Ukimura, O., Patil, M. B., Campese, V., Thangathurai, D., and Desai, M. M. (2011). 'Zero ischemia partial nephrectomy. Novel laparoscopic and robotic technique'. eng. In: *European urology* 59.1, pp. 128–134. DOI: 10.1016/j.eururo.2010.10.002. eprint: 20971550.

[47] Guillonneau, B., Bermúdez, H., Gholami, S., et al. (2003). 'Laparoscopic Partial Nephrectomy for Renal Tumor: Single Center Experience Comparing Clamping and No Clamping Techniques of the Renal Vasculature'. In: *Journal of Urology* 169.2, pp. 483–486. DOI: 10.1016/S0022-5347(05)63939-0.

[48] Gill, I. S., Kavoussi, L. R., Lane, B. R., et al. (2007). 'Comparison of 1,800 laparoscopic and open partial nephrectomies for single renal tumors'. eng. In: *Journal of Urology* 178.1, pp. 41–46. DOI: 10.1016/j.juro.2007.03.038. eprint: 17574056.

[49] Park, H., Byun, S.-S., Kim, H. H., et al. (2010). 'Comparison of Laparoscopic and Open Partial Nephrectomies in T1a Renal Cell Carcinoma: A Korean Multicenter Experience'. en. In: *Korean Journal of Urology* 51.7, p. 467. DOI: 10.4111/kju.2010.51.7.467.

[50] Marszalek, M., Meixl, H., Polajnar, M., Rauchenwald, M., Jeschke, K., and Madersbacher, S. (2009). 'Laparoscopic and open partial nephrectomy: a matched-pair comparison of 200 patients'. eng. In: *European urology* 55.5, pp. 1171–1178. DOI: 10.1016/j.eururo.2009.01.042. eprint: 19232819.

[51] Choi, J. E., You, J. H., Kim, D. K., Rha, K. H., and Lee, S. H. (2015). 'Comparison of Perioperative Outcomes Between Robotic and Laparoscopic Partial Nephrectomy: A Systematic Review and Meta-analysis'. en. In: *European Urology* 67.5, pp. 891–901. DOI: 10.1016/j.eururo.2014.12.028.

[52] Zhou, J.-B., Xiao, X., Shi, T.-L., Huang, X.-H., and Jiang, Y.-L. (2021). *Comparison of Robotic Versus Laparoscopic Partial Nephrectomy For Renal Tumors With A RENAL Nephrometry Score≥7: A System Review and Meta-Analysis*. Preprint before peer review. DOI: 10.21203/rs.3.rs-443733/v1. (Visited on 05/29/2021).

[53] Vittori, G. (2014). 'Open versus robotic-assisted partial nephrectomy: a multicenter comparison study of perioperative results and complications'. eng. In: *World journal of urology* 32.1, pp. 287–293. DOI: 10.1007/s00345-013-1136-x. eprint: 23913095.

[54] Milgram, P., Takemura, H., Utsumi, A., and Kishino, F. (1995). 'Augmented reality: a class of displays on the reality-virtuality continuum'. In: *Telemanipulator and Telepresence Technologies*. Photonics for Industrial Applications (Boston, MA). Ed. by H. Das. SPIE Proceedings. SPIE, pp. 282–292. DOI: 10.1117/12.197321.

[55] Azuma, R. T. (1997). 'A Survey of Augmented Reality'. In: *Presence: Teleoperators and Virtual Environments* 6.4, pp. 355–385. DOI: 10.1162/pres.1997.6.4.355.

[56] Schmalstieg, D. and Höllerer, T. (2016). *Augmented Reality. principles and practice*. New Jersey: Addison-Wesley. 528 pp. ISBN: 978-0-321-88357-5.

[57] Broll, W. (2019). 'Augmentierte Realität'. In: *Virtual und Augmented Reality (VR/AR)*. Ed. by R. Dörner, W. Broll, P. Grimm, and B. Jung. Berlin, Heidelberg: Springer, pp. 315–356. ISBN: 978-3-662-58860-4. DOI: 10.1007/978-3-662-58861-1_8.

[58] Vaughan-Nichols, S. J. (2009). 'Augmented Reality: No Longer a Novelty?' In: *Computer* 42.12, pp. 19–22. DOI: 10.1109/MC.2009.380.

[59] Sutherland, I. E. (1968). 'A head-mounted three dimensional display'. In: *Proceedings of the December 9-11, 1968, fall joint computer conference, part I on - AFIPS '68 (Fall, part I)* (San Francisco, California). New York, New York, USA: ACM Press, p. 757. DOI: 10.1145/1476589.1476686.

[60] Caudell, T. P. and Mizell, D. W. (1992). 'Augmented reality: an application of heads-up display technology to manual manufacturing processes'. In: *Hawaii International Conference on System Sciences, 25th*. Los Alamitos: IEEE Computer Society Press. DOI: 10.1109/hicss.1992.183317.

[61] Garzón, J., Pavón, J., and Baldiris, S. (2019). 'Systematic review and meta-analysis of augmented reality in educational settings'. In: *Virtual Reality* 23.4, pp. 447–459. DOI: 10.1007/s10055-019-00379-9.

[62] Safi, M., Chung, J., and Pradhan, P. (2019). 'Review of augmented reality in aerospace industry'. In: *Aircraft Engineering and Aerospace Technology* 91.9, pp. 1187–1194. DOI: 10.1108/AEAT-09-2018-0241.

[63] Parekh, P., Patel, S., Patel, N., and Shah, M. (2020). 'Systematic review and meta-analysis of augmented reality in medicine, retail, and games'. eng. In: *Visual computing for industry, biomedicine, and art* 3, p. 21. DOI: 10.1186/s42492-020-00057-7. eprint: 32954214.

[64] Palmarini, R., Erkoyuncu, J. A., Roy, R., and Torabmostaedi, H. (2018). 'A systematic review of augmented reality applications in maintenance'. In: *Robotics and Computer-Integrated Manufacturing* 49, pp. 215–228. DOI: 10.1016/j.rcim.2017.06.002.

[65] Eckert, M., Volmerg, J. S., and Friedrich, C. M. (2019). 'Augmented Reality in Medicine: Systematic and Bibliographic Review'. eng. In: *JMIR mHealth and uHealth* 7.4, e10967. DOI: 10.2196/10967. eprint: 31025950.

[66] Leblanc, F., Champagne, B. J., Augestad, K. M., Neary, P. C., Senagore, A. J., Ellis, C. N., and Delaney, C. P. (2010). 'A Comparison of Human Cadaver and Augmented Reality Simulator Models for Straight Laparoscopic Colorectal Skills Acquisition Training'. en. In: *Journal of the American College of Surgeons* 211.2, pp. 250–255. DOI: 10.1016/j.jamcollsurg.2010.04.002.

[67] Shenai, M. B., Dillavou, M., Shum, C., Ross, D., Tubbs, R. S., Shih, A., and Guthrie, B. L. (2011). 'Virtual Interactive Presence and Augmented Reality (VIPAR) for Remote Surgical Assistance'. In: *Operative Neurosurgery* 68.suppl_1, ons200–ons207. DOI: 10.1227/NEU.0b013e3182077efd.

[68] Gerup, J., Soerensen, C. B., and Dieckmann, P. (2020). 'Augmented reality and mixed reality for healthcare education beyond surgery: an integrative review'. eng. In: *International journal of medical education* 11, pp. 1–18. DOI: 10.5116/ijme.5e01.eb1a. eprint: 31955150.

[69] Mewes, A., Heinrich, F., Hensen, B., Wacker, F., Lawonn, K., and Hansen, C. (2018). 'Concepts for augmented reality visualisation to support needle guidance inside the MRI'. eng. In: *Healthcare technology letters* 5.5, pp. 172–176. DOI: 10.1049/htl.2018.5076. eprint: 30464849.

[70] Mousavi Hondori, H., Khademi, M., Dodakian, L., Cramer, S. C., and Lopes, C. V. (2013). 'A spatial augmented reality rehab system for post-stroke hand rehabilitation'. In: *Medicine Meets Virtual Reality 20. NextMed / MMVR20*. Ed. by J. D. Westwood, S. W. Westwood, L. Felländer-Tsai, R. S. Haluck, R. A. Robb, S. Senger, and K. G. Vosburgh. Studies in health technology and informatics v. 184. Amsterdam and Washington, D.C.: IOS Press.

[71] Yoon, J. W., Chen, R. E., Kim, E. J., et al. (2018). 'Augmented reality for the surgeon: Systematic review'. eng. In: *The international journal of medical robotics + computer assisted surgery : MRCAS* 14.4, e1914. DOI: 10.1002/rcs.1914. eprint: 29708640.

[72] Heinrich, F., Huettl, F., Schmidt, G., Paschold, M., Kneist, W., Huber, T., and Hansen, C. (2021). 'HoloPointer: a virtual augmented reality pointer for laparoscopic surgery training'. En;en. In: *International Journal of Computer Assisted Radiology and Surgery* 16.1, pp. 161–168. DOI: 10.1007/s11548-020-02272-2.

[73] Edgcumbe, P., Singla, R., Pratt, P. J., Schneider, C., Nguan, C., and Rohling, R. (2018). 'Follow the light: projector-based augmented reality intracorporeal system for laparoscopic surgery'. eng. In: *Journal of medical imaging (Bellingham, Wash.)* 5.2, p. 021216. DOI: 10.1117/1.JMI.5.2.021216. eprint: 29487888.

[74] Schott, D., Saalfeld, P., Schmidt, G., et al. (2021). 'A VR/AR Environment for Multi-User Liver Anatomy Education'. In: *2021 IEEE Virtual Reality and 3D User Interfaces (VR)* (Lisboa, Portugal), pp. 296–305. DOI: 10.1109/VR50410.2021.00052.

[75] Schoenthaler, M., Schnell, D., Wilhelm, K., Schlager, D., Adams, F., Hein, S., Wetterauer, U., and Miernik, A. (2016). 'Stereoscopic (3D) versus monoscopic (2D) laparoscopy: comparative study of performance using advanced HD optical systems in a surgical simulator model'. eng. In: *World journal of urology* 34.4, pp. 471–477. DOI: 10.1007/s00345-015-1660-y. eprint: 26242728.

[76] Porpiglia, F., Checcucci, E., Amparore, D., et al. (2019). 'Three-dimensional Augmented Reality Robot-assisted Partial Nephrectomy in Case of Complex Tumours (PADUA ≥10): A New Intraoperative Tool Overcoming the Ultrasound Guidance'. eng. In: *European urology* 78.2, pp. 229–238. DOI: 10.1016/j.eururo.2019.11.024. eprint: 31898992.

[77] Zhang, Z. (2000). 'A Flexible New Technique for Camera Calibration'. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 22, pp. 1330–1334.

[78] Burger, W. (2016). 'Zhang's camera calibration algorithm: in-depth tutorial and implementation'. In: *HGB* 16.5, pp. 1–6.

[79] Bradski, G. (2000). 'The OpenCV Library'. In: *Dr. Dobb's Journal of Software Tools* 25, pp. 120–125.

[80] Tsai, R. Y. and Lenz, R. K. (1989). 'A new technique for fully autonomous and efficient 3D robotics hand/eye calibration'. In: *IEEE Transactions on Robotics and Automation* 5.3, pp. 345–358. DOI: 10.1109/70.34770.

[81] Yaniv, Z. R. (2015). 'Which pivot calibration?' In: SPIE Medical Imaging (Orlando, Florida, United States). Ed. by R. J. Webster and Z. R. Yaniv. SPIE Proceedings. SPIE, p. 941527. DOI: 10.1117/12.2081348.

[82] Wiles, A. D., Thompson, D. G., and Frantz, D. D. (2004). 'Accuracy assessment and interpretation for optical tracking systems'. In: *Medical Imaging 2004: Visualization, Image-Guided Procedures, and Display*. Medical Imaging 2004 (San Diego, CA). Ed. by J. L. Galloway. SPIE Proceedings. SPIE, p. 421. DOI: 10.1117/12.536128.

[83] Franz, A. M., Haidegger, T., Birkfellner, W., Cleary, K., Peters, T. M., and Maier-Hein, L. (2014). 'Electromagnetic tracking in medicine–a review of technology, validation, and applications'. eng. In: *IEEE transactions on medical imaging* 33.8, pp. 1702–1725. DOI: 10.1109/TMI.2014.2321777. eprint: 24816547.

[84] Grimm, P., Broll, W., Herold, R., and Hummel, J. (2019). 'VR/AR-Eingabegeräte und Tracking'. In: *Virtual und Augmented Reality (VR/AR)*. Ed. by R. Dörner, W. Broll, P. Grimm, and B. Jung. Berlin, Heidelberg: Springer, pp. 117–162. ISBN: 978-3-662-58860-4. DOI: 10.1007/978-3-662-58861-1_4.

[85] Hughes-Hallett, A., Pratt, P. J., Mayer, E. K., Martin, S., Darzi, A. W., and Vale, J. (2014a). 'Image guidance for all–TilePro display of 3-dimensionally reconstructed images in robotic partial nephrectomy'. eng. In: *Urology* 84.1, pp. 237–242. DOI: 10.1016/j.urology.2014.02.051. eprint: 24857271.

[86] Bartz, D. and Preim, B. (2010). 'Visualization and Exploration of Segmented Anatomic Structures'. en. In: *Biomedical Image Processing*. Springer, Berlin, Heidelberg, pp. 379–401. DOI: 10.1007/978-3-642-15816-2_15.

[87] Chen, Y., Li, H., Wu, D., Bi, K., and Liu, C. (2014). 'Surgical planning and manual image fusion based on 3D model facilitate laparoscopic partial nephrectomy for intrarenal tumors'. eng. In: *World journal of urology* 32.6, pp. 1493–1499. DOI: 10.1007/s00345-013-1222-0. eprint: 24337151.

[88] Pratt, P. J., Jaeger, A., Hughes-Hallett, A., Mayer, E. K., Vale, J., Darzi, A. W., Peters, T., and Yang, G.-Z. (2015). 'Robust ultrasound probe tracking. Initial clinical experiences during robot-assisted partial nephrectomy'. eng. In: *International Journal of Computer Assisted Radiology and Surgery* 10.12, pp. 1905–1913. DOI: 10.1007/s11548-015-1279-x. eprint: 26302723.

[89] Fuchs, H., Livingston, M. A., Raskar, R., et al. (1998). 'Augmented reality visualization for laparoscopic surgery'. In: *Medical image computing and computer-assisted intervention - MICCAI '98. First international conference, MA, USA, October 11-13, 1998 : proceedings*. Ed. by W. M. Wells. Vol. 1496. Lecture Notes in Computer Science 1496. Berlin [etc.]: Springer, pp. 934–943. DOI: 10.1007/BFb0056282.

[90] Steenblik, R. A. (1987). 'The Chromostereoscopic Process: A Novel Single Image Stereoscopic Process'. In: OE LASE'87 and EO Imaging Symp (January 1987, Los Angeles) (Los Angeles, CA). Ed. by D. F. McAllister and W. E. Robbins. SPIE Proceedings. SPIE, p. 27. DOI: 10.1117/12.940117.

[91] Joshi, A., Qian, X., Dione, D. P., Bulsara, K. R., Breuer, C. K., Sinusas, A. J., and Papademetris, X. (2008). 'Effective visualization of complex vascular structures using a non-parametric vessel detection method'. eng. In: *IEEE transactions on visualization and computer graphics* 14.6, pp. 1603–1610. DOI: 10.1109/TVCG.2008.123. eprint: 18989016.

[92] Ropinski, T., Steinicke, F., and Hinrichs, K. (op. 2006). 'Visually Supporting Depth Perception in Angiography Imaging'. In: *Smart graphics. 6th International Symposium, SG 2006 : Vancouver, Canada, July 23-25, 2006 : proceedings*. Ed. by A. Butz. Vol. 4073. Lecture Notes in Computer Science 4073. Berlin: Springer, pp. 93–104. DOI: 10.1007/11795018_9.

[93] Kersten-Oertel, M., Chen, S. J.-S., and Collins, D. L. (2014). 'An evaluation of depth enhancing perceptual cues for vascular volume visualization in neurosurgery'. eng. In: *IEEE transactions on visualization and computer graphics* 20.3, pp. 391–403. DOI: 10.1109/TVCG.2013.240. eprint: 24434220.

[94] Amir-Khalili, A., Nosrati, M. S., Peyrat, J.-M., Hamarneh, G., and Abugharbieh, R. (2013). 'Uncertainty-Encoded Augmented Reality for Robot-Assisted Partial Nephrectomy. A Phantom Study'. In: *Augmented Reality Environments for Medical Imaging and Computer-Assisted Interventions*. Ed. by D. Hutchison, T. Kanade, J. Kittler, et al. Vol. 8090. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, pp. 182–191. DOI: 10.1007/978-3-642-40843-4_20.

[95] Singla, R., Edgcumbe, P., Pratt, P. J., Nguan, C., and Rohling, R. (2017). 'Intra-operative ultrasound-based augmented reality guidance for laparoscopic surgery'. eng. In: *Healthcare technology letters* 4.5, pp. 204–209. DOI: 10.1049/htl.2017.0063. eprint: 29184666.

[96] Pratt, P. J., Mayer, E. K., Vale, J., Cohen, D., Edwards, E., Darzi, A. W., and Yang, G.-Z. (2012). 'An effective visualisation and registration system for image-guided robotic partial nephrectomy'. eng. In: *Journal of robotic surgery* 6.1, pp. 23–31. DOI: 10.1007/s11701-011-0334-z. eprint: 27637976.

[97] Arun, K. S., Huang, T. S., and Blostein, S. D. (1987). 'Least-squares fitting of two 3-d point sets'. eng. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 9.5, pp. 698–700. DOI: 10.1109/tpami.1987.4767965. eprint: 21869429.

[98] Yaniv, Z. R. (2008). 'Rigid Registration'. In: *Image-Guided Interventions*. Ed. by T. Peters and K. Cleary. Vol. 9. Boston, MA: Springer US, pp. 159–192. ISBN: 978-0-387-73856-7. DOI: 10.1007/978-0-387-73858-1_6.

[99] Conrad, C., Fusaglia, M., Peterhans, M., Lu, H., Weber, S., and Gayet, B. (2016). 'Augmented Reality Navigation Surgery Facilitates Laparoscopic Rescue of Failed Portal Vein Embolization'. eng. In: *Journal of the American College of Surgeons* 223.4, e31–4. DOI: 10.1016/j.jamcollsurg.2016.06.392. eprint: 27450989.

[100] Hayashi, Y., Misawa, K., Hawkes, D. J., and Mori, K. (2016). 'Progressive internal landmark registration for surgical navigation in laparoscopic gastrectomy for gastric cancer'. eng. In: *International journal of computer assisted radiology and surgery* 11.5, pp. 837–845. DOI: 10.1007/s11548-015-1346-3. eprint: 26811079.

[101] dos Santos, T. R., Seitel, A., Kilgus, T., et al. (2014). 'Pose-independent surface matching for intra-operative soft-tissue marker-less registration'. eng. In: *Medical Image Analysis* 18.7, pp. 1101–1114. DOI: 10.1016/j.media.2014.06.002. eprint: 25038492.

[102] Hughes-Hallett, A., Mayer, E. K., Marcus, H. J., Cundy, T. P., Pratt, P. J., Darzi, A. W., and Vale, J. A. (2014b). 'Augmented reality partial nephrectomy. Examining the current status and future perspectives'. eng. In: *Urology* 83.2, pp. 266–273. DOI: 10.1016/j.urology.2013.08.049. eprint: 24149104.

[103] Besl, P. J. and McKay, N. D. (1992). 'A method for registration of 3-D shapes'. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 14.2, pp. 239–256. DOI: 10.1109/34.121791.

[104] Su, L.-M., Vagvolgyi, B. P., Agarwal, R., Reiley, C. E., Taylor, R. H., and Hager, G. D. (2009). 'Augmented reality during robot-assisted laparoscopic partial nephrectomy. Toward real-time 3D-CT to stereoscopic video registration'. eng. In: *Urology* 73.4, pp. 896–900. DOI: 10.1016/j.urology.2008.11.040. eprint: 19193404.

[105] Benincasa, A. B., Clements, L. W., Herrell, S. D., and Galloway, R. L. (2008). 'Feasibility study for image-guided kidney surgery. Assessment of required intraoperative surface for accurate physical to image space registrations'. eng. In: *Medical physics* 35.9, pp. 4251–4261. DOI: 10.1118/1.2969064. eprint: 18841875.

[106] Ukimura, O. and Gill, I. S. (2008). 'Imaging-assisted endoscopic surgery. Cleveland Clinic experience'. eng. In: *Journal of Endourology* 22.4, pp. 803–810. DOI: 10.1089/end.2007.9823. eprint: 18366316.

[107] Fitzpatrick, J. M., West, J. B., and Maurer, C. R. (1998). 'Predicting error in rigid-body point-based registration'. eng. In: *IEEE transactions on medical imaging* 17.5, pp. 694–702. DOI: 10.1109/42.736021. eprint: 9874293.

[108] Datteri, R. D. and Dawant, B. M. (2012). 'Estimation and Reduction of Target Registration Error'. eng. In: *Medical image computing and computer-assisted intervention : MICCAI ... International Conference on Medical Image Computing and Computer-Assisted Intervention* 15.0 3, pp. 139–146. eprint: 23286124.

[109] Linte, C. A., Moore, J., Wiles, A. D., Lo, J., Wedlake, C., and Peters, T. M. (2009). 'In vitro cardiac catheter navigation via augmented reality surgical guidance'. In: Medical Imaging 2009: Visualization, Image-Guided Procedures, and Modeling. 7261. International Society for Optics and Photonics, 72610O. DOI: 10.1117/12.813829.

[110] Risholm, P., Pieper, S., Samset, E., and Wells, W. M. (2010). 'Summarizing and visualizing uncertainty in non-rigid registration'. eng. In: *Medical image computing and computer-assisted intervention : MICCAI ... International Conference on Medical Image Computing and Computer-Assisted Intervention* 13.Pt 2, pp. 554–561. DOI: 10.1007/978-3-642-15745-5_68. eprint: 20879359.

[111] Schmidt, S., Bruder, G., and Steinicke, F. (2017). 'Moving Towards Consistent Depth Perception in Stereoscopic Projection-based Augmented Reality'. In: *International Conference on Artificial Reality and Telexistence & Eurographics Symposium on Virtual Environments (ICAT-EVGE)*. Ed. by R. W. Lindeman, G. Bruder, and D. Iwai, pp. 161–168. URL: https://sreal.ucf.edu/wp-content/uploads/2019/01/schmidt2017b.pdf.

[112] Léger, É., Reyes, J., Drouin, S., Collins, D. L., Popa, T., and Kersten-Oertel, M. (2018). 'Gesture-based registration correction using a mobile augmented reality image-guided neurosurgery system'. eng. In: *Healthcare technology letters* 5.5, pp. 137–142. DOI: 10.1049/htl.2018.5063. eprint: 30800320.

[113] Schiavina, R., Bianchi, L., Chessa, F., et al. (2020). 'Augmented Reality to Guide Selective Clamping and Tumor Dissection During Robot-assisted Partial Nephrectomy: A Preliminary Experience'. eng. In: *Clinical genitourinary cancer*. DOI: 10.1016/j.clgc.2020.09.005. eprint: 33060033.

[114] Ferguson, J. M., Cai, L. Y., Reed, A., Siebold, M., De, S., Herrell, S. D., and Webster, R. J. (2018). 'Toward image-guided partial nephrectomy with the da Vinci robot: exploring surface acquisition methods for intraoperative re-registration'. In: *Medical Imaging 2018*. Image-Guided Procedures, Robotic Interventions, and Modeling (Houston, United States). Ed. by B. Fei. Proceedings of SPIE 10576. Bellingham, Washington: SPIE, p. 8. DOI: 10.1117/12.2296464.

[115] Heinrich, F., Bornemann, K., Lawonn, K., and Hansen, C. (2020). 'Interacting with Medical Volume Data in Projective Augmented Reality'. en. In: International Conference on Medical Image Computing and Computer-Assisted Intervention. Springer, Cham, pp. 429–439. DOI: 10.1007/978-3-030-59716-0_41.

[116] Dias, A., Männle, D., Balkenhol, T., et al. (2021). 'Augmented Reality during Parotid Surgery: Real-Life Evaluation of Voice Control and User-Experience'. In: *100 Jahre DGHNO-KHC. Wo kommen wir her? Wo stehen wir? Wo gehen wir hin?* (Estrel Congress Center Berlin). Ed. by Deutsche Gesellschaft für Hals-Nasen-Ohren-Heilkunde, Kopf- und Hals-Chirurgie e.V., Bonn. Laryngo-Rhino-Otologie. Georg Thieme Verlag KG. DOI: 10.1055/s-0041-1727676.

[117] Mendes, D., Caputo, F. M., Giachetti, A., Ferreira, A., and Jorge, J. A. (2019). 'A Survey on 3D Virtual Object Manipulation: From the Desktop to Immersive Virtual Environments'. In: *Computer Graphics Forum* 38.1, pp. 21–45. DOI: 10.1111/cgf.13390.

[118] Malaka, R., Dylla, F., Freksa, C., Barkowsky, T., Herrlich, M., and Kikinis, R. (2017). 'Intelligent Support for Surgeons in the Operating Room'. In: *Anticipation and Medicine*. Ed. by M. Nadin. Vol. 2. Cham: Springer International Publishing, pp. 269–277. ISBN: 978-3-319-45140-4. DOI: 10.1007/978-3-319-45142-8_16.

[119] Jalote-Parmar, A. and Badke-Schaub, P. (2008). 'Workflow Integration Matrix: a framework to support the development of surgical information systems'. In: *Design Studies* 29.4, pp. 338–368. DOI: 10.1016/j.destud.2008.03.002.

[120] Stauder, R., Ostler, D., Vogel, T., Wilhelm, D., Koller, S., Kranzfelder, M., and Navab, N. (2017). 'Surgical data processing for smart intraoperative assistance systems'. In: *Innovative Surgical Sciences* 2.3, pp. 145–152. DOI: 10.1515/iss-2017-0035.

[121] Lalys, F. and Jannin, P. (2014). 'Surgical process modelling: a review'. eng. In: *International Journal of Computer Assisted Radiology and Surgery* 9.3, pp. 495–511. DOI: 10.1007/s11548-013-0940-5. eprint: 24014322.

[122] Neumuth, T. (2017). 'Surgical process modeling'. In: *Innovative Surgical Sciences* 2.3, pp. 123–137. DOI: 10.1515/iss-2017-0005.

[123] Annett, J., Duncan, K. D., Stammers, R. B., and Gray, M. J. (1971). 'Task analysis. Department of employment training information paper 6'. In: *HMSO, London. Artman, H.(2000). Team situation assessment and information distribution. Ergonomics* 43.8, pp. 1076–1095.

[124] Stanton, N. A. (2006). 'Hierarchical task analysis: developments, applications, and extensions'. eng. In: *Applied ergonomics* 37.1, pp. 55–79. DOI: 10.1016/j.apergo.2005.06.003. eprint: 16139236.

[125] Sarker, S. K., Chang, A., Albrani, T., and Vincent, C. (2008). 'Constructing hierarchical task analysis in surgery'. eng. In: *Surgical endoscopy* 22.1, pp. 107–111. DOI: 10.1007/s00464-007-9380-z. eprint: 17483993.

[126] Patel, M. N., Bhandari, M., Menon, M., and Rogers, C. G. (2009). 'Robotic-assisted partial nephrectomy'. eng. In: *BJU international* 103.9, pp. 1296–1311. DOI: 10.1111/j.1464-410X.2009.08584.x. eprint: 19402830.

[127] Phillips, C. K., Taneja, S. S., and Stifelman, M. D. (2005). 'Robot-assisted laparoscopic partial nephrectomy. The NYU technique'. eng. In: *Journal of Endourology* 19.4, 441–5, discussion 445. DOI: 10.1089/end.2005.19.441. eprint: 15910252.

[128] Clark, R. E., Feldon, D. F., Merrienboer, J., Yates, K. A., and Early, S. (2011). 'Cognitive Task Analysis'. In: *Handbook of research on educational communications and technology*. Ed. by J. M. Spector. 3rd ed. New York and London: Routledge, pp. 577–593. ISBN: 978-0-415-96338-1.

[129] Roth, E. M. and Mumaw, R. J. (1995). 'Using Cognitive Task Analysis to Define Human Interface Requirements for First-of-A-Kind Systems'. In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 39.9, pp. 520–524. DOI: 10.1177/154193129503900918.

[130] Ormerod, T. C. and Shepherd, A. (2003). 'Using task analysis for information requirements specification: the Sub-Goal Template (SGT) method'. In: *The Handbook of Task Analysis for Human-Computer Interaction*. Ed. by D. Diaper and N. Stanton. CRC Press, p. 347. ISBN: 9780429228230.

[131] Jalote-Parmar, A., Badke-Schaub, P., Ali, W., and Samset, E. (2010). 'Cognitive processes as integrative component for developing expert decision-making systems: a workflow centered framework'. eng. In: *Journal of biomedical informatics* 43.1, pp. 60–74. DOI: 10.1016/j.jbi.2009.07.001. eprint: 19607934.

[132] Militello, L. G. and Hutton, R. J. (1998). 'Applied cognitive task analysis (ACTA): a practitioner's toolkit for understanding cognitive task demands'. eng. In: *Ergonomics* 41.11, pp. 1618–1641. DOI: 10.1080/001401398186108. eprint: 9819578.

[133] Klein, G. A., Calderwood, R., and MacGregor, D. (1989). 'Critical decision method for eliciting knowledge'. In: *IEEE Transactions on Systems, Man, and Cybernetics* 19.3, pp. 462–472. DOI: 10.1109/21.31053.

[134] Qian, L., Wu, J. Y., DiMaio, S. P., Navab, N., and Kazanzides, P. (2020). 'A Review of Augmented Reality in Robotic-Assisted Surgery'. In: *IEEE Transactions on Medical Robotics and Bionics* 2.1, pp. 1–16. DOI: 10.1109/TMRB.2019.2957061.

[135] Rassweiler, J. J., Rassweiler, M.-C., Müller, M., Kenngott, H. G., Meinzer, H.-P., and Teber, D. (2014). 'Surgical navigation in urology: European perspective'. eng. In: *Current opinion in urology* 24.1, pp. 81–97. DOI: 10.1097/MOU.0000000000000014. eprint: 24280651.

[136] Detmer, F. J., Hettig, J., Schindele, D., Schostak, M., and Hansen, C. (2017). 'Virtual and Augmented Reality Systems for Renal Interventions. A Systematic Review'. eng. In: *IEEE reviews in biomedical engineering*, pp. 78–94. DOI: 10.1109/RBME.2017.2749527. eprint: 28885161.

[137] Hekman, M. C. H., Rijpkema, M., Langenhuijsen, J. F., Boerman, O. C., Oosterwijk, E., and Mulders, P. F. A. (2018). 'Intraoperative Imaging Techniques to Support Complete Tumor Resection in Partial Nephrectomy'. eng. In: *European urology focus*. DOI: 10.1016/j.euf.2017.04.008. eprint: 28753888.

[138] Wake, N., Nussbaum, J. E., Elias, M. I., Nikas, C. V., and Bjurlin, M. A. (2020). '3D Printing, Augmented Reality, and Virtual Reality for the Assessment and Management of Kidney and Prostate Cancer: A Systematic Review'. eng. In: *Urology* 143, pp. 20–32. DOI: 10.1016/j.urology.2020.03.066. eprint: 32535076.

[139] Checcucci, E., Cillis, S. de, and Porpiglia, F. (2020). '3D-printed models and virtual reality as new tools for image-guided robot-assisted nephron-sparing surgery: a systematic review of the newest evidences'. eng. In: *Current opinion in urology* 30.1, pp. 55–64. DOI: 10.1097/MOU.0000000000000686. eprint: 31725000.

[140] Bertolo, R., Hung, A., Porpiglia, F., Bove, P., Schleicher, M., and Dasgupta, P. (2019). 'Systematic review of augmented reality in urological interventions: the evidences of an impact on surgical outcomes are yet to come'. eng. In: *World journal of urology* 38.9, pp. 2167–2176. DOI: 10.1007/s00345-019-02711-z. eprint: 30826888.

[141] Najmaei, N., Mostafavi, K., Shahbazi, S., and Azizian, M. (2013). 'Image-guided techniques in renal and hepatic interventions'. eng. In: *The international journal of medical robotics + computer assisted surgery : MRCAS* 9.4, pp. 379–395. DOI: 10.1002/rcs.1443. eprint: 22736549.

[142] Catellani, M., Cordima, G., Cobelli, O. de, et al. (2020). 'Augmented and Virtual Reality in Minimally Invasive Surgery, State of the Art and Future Prospects'. In: *XV Mediterranean Conference on Medical and Biological Engineering and Computing - MEDICON 2019. Proceedings of MEDICON 2019, September 26-28, 2019, Coimbra, Portugal*. Ed. by J. Henriques, N. Neves, and P. de Carvalho. Vol. 76. IFMBE Proceedings volume 76. Springer International Publishing. Cham: Springer International Publishing, pp. 1590–1595. DOI: 10.1007/978-3-030-31635-8_196.

[143] Hongo, F. and Ukimura, O. (2019). 'Navigation in Laparoscopic and Robotic Urologic Surgery'. In: *Endourology progress. Technique, technology and training*. Ed. by E. S.-y. Chan and T. Matsuda. Singapore: Springer, pp. 297–302. ISBN: 978-981-13-3464-1. DOI: 10.1007/978-981-13-3465-8_38.

[144] Pervez, A., Ahmed, K., Thompson, S., Elhage, O., Khan, M. S., and Dasgupta, P. (2014). 'Image guided robotic surgery: current evidence for effectiveness in urology'. eng. In: *Archivio italiano di urologia, andrologia : organo ufficiale [di] Societa italiana di ecografia urologica e nefrologica* 86.4, pp. 245–248. DOI: 10.4081/aiua.2014.4.245. eprint: 25641443.

[145] Hamada, A., Sawada, A., Kono, J., et al. (2020). 'The Current Status and Challenges in Augmented-Reality Navigation System for Robot-Assisted Laparoscopic Partial Nephrectomy'. In: *Human-Computer Interaction. Human Values and Quality of Life. Thematic Area, HCI 2020, Held as Part of the 22nd International Conference, HCII 2020, Copenhagen, Denmark, July 19-24, 2020, Proceedings, Part III*. Ed. by M. Kurosu. Vol. 12182. Information Systems and Applications, incl. Internet/Web, and HCI 12183. Cham: Springer International Publishing and Imprint: Springer, pp. 620–629. DOI: 10.1007/978-3-030-49062-1_42.

[146] Harzing, A.-W. (2007). *Publish or Perish*. URL: https://harzing.com/resources/publish-or-perish (visited on 03/18/2021).

[147] Bjurlin, M. A., McClintock, T. R., and Stifelman, M. D. (2015). 'Near-infrared fluorescence imaging with intraoperative administration of indocyanine green for robotic partial nephrectomy'. eng. In: *Current urology reports* 16.4, p. 20. DOI: 10.1007/s11934-015-0495-9. eprint: 25698588.

[148] Bjurlin, M. A., Gan, M., McClintock, T. R., Volpe, A., Borofsky, M. S., Mottrie, A., and Stifelman, M. D. (2014). 'Near-infrared fluorescence imaging: emerging applications in robotic upper urinary tract surgery'. eng. In: *European urology* 65.4, pp. 793–801. DOI: 10.1016/j.eururo.2013.09.023. eprint: 24099660.

[149] Tobis, S., Knopf, J. K., Silvers, C., Yao, J., Rashid, H., Wu, G., and Golijanin, D. (2011). 'Near infrared fluorescence imaging with robotic assisted laparoscopic partial nephrectomy: initial clinical experience for renal cortical tumors'. eng. In: *The Journal of Urology* 186.1, pp. 47–52. DOI: 10.1016/j.juro.2011.02.2701. eprint: 21571337.

[150] Hyams, E. S., Kanofsky, J. A., and Stifelman, M. D. (2008). 'Laparoscopic Doppler technology: applications in laparoscopic pyeloplasty and radical and partial nephrectomy'. eng. In: *Urology* 71.5, pp. 952–956. DOI: 10.1016/j.urology.2007.11.062. eprint: 18455632.

[151] Sethi, A. S., Regan, S. M., and Sundaram, C. P. (2009). 'The use of a Doppler ultrasound probe during vascular dissection in laparoscopic renal surgery'. eng. In: *Journal of Endourology* 23.9, pp. 1377–1382. DOI: 10.1089/end.2009.0397. eprint: 19698037.

[152] Crane, N. J., Gillern, S. M., Tajkarimi, K., Levin, I. W., Pinto, P. A., and Elster, E. A. (2010). 'Visual enhancement of laparoscopic partial nephrectomy with 3-charge coupled device camera: assessing intraoperative tissue perfusion and vascular anatomy by visible hemoglobin spectral response'. eng. In: *The Journal of Urology* 184.4, pp. 1279–1285. DOI: 10.1016/j.juro.2010.06.010. eprint: 20723937.

[153] Yamasaki, T., Tamada, S., Kato, M., Otoshi, T., Tanaka, H., Iguchi, T., and Nakatani, T. (2018). 'Near infrared fluorescence imaging system for laparoscopic partial nephrectomy'. eng. In: *The Canadian journal of urology* 25.6, pp. 9606–9613. eprint: 30553287.

[154] Wang, X.-Z., Yu, Z.-X., Guo, R.-J., and Xing, N.-Z. (2014). 'Application of laparospic ultrasonography in surgery of small renal cell carcinoma'. eng. In: *Asian Pacific journal of cancer prevention : APJCP* 15.21, pp. 9113–9116. DOI: 10.7314/apjcp.2014.15.21.9113. eprint: 25422187.

[155] Furukawa, J., Miyake, H., Tanaka, K., Sugimoto, M., and Fujisawa, M. (2014). 'Console-integrated real-time three-dimensional image overlay navigation for robot-assisted partial nephrectomy with selective arterial clamping. Early single-centre experience with 17 cases'. eng. In: *The international journal of medical robotics + computer assisted surgery : MRCAS* 10.4, pp. 385–390. DOI: 10.1002/rcs.1574. eprint: 24615844.

[156] Kobayashi, S., Cho, B., Huaulmé, A., Tatsugami, K., Honda, H., Jannin, P., Hashizumea, M., and Eto, M. (2019). 'Assessment of surgical skills by using surgical navigation in robot-assisted partial nephrectomy'. eng. In: *International journal of computer assisted radiology and surgery*. DOI: 10.1007/s11548-019-01980-8. eprint: 31119486.

[157] Porpiglia, F., Fiori, C., Checcucci, E., Amparore, D., and Bertolo, R. (2018). 'Hyperaccuracy Three-dimensional Reconstruction Is Able to Maximize the Efficacy of Selective Clamping During Robot-assisted Partial Nephrectomy for Complex Renal Masses'. eng. In: *European urology* 74.5, pp. 651–660. DOI: 10.1016/j.eururo.2017.12.027. eprint: 29317081.

[158] Rao, A. R., Gray, R., Mayer, E. K., Motiwala, H., Laniado, M., and Karim, O. (2013). 'Occlusion angiography using intraoperative contrast-enhanced ultrasound scan (CEUS): a novel technique demonstrating segmental renal blood supply to assist zero-ischaemia robot-assisted partial nephrectomy'. eng. In: *European urology* 63.5, pp. 913–919. DOI: 10.1016/j.eururo.2012.10.034. eprint: 23116657.

[159] Ukimura, O., Nakamoto, M., and Gill, I. S. (2012). 'Three-dimensional reconstruction of renovascular-tumor anatomy to facilitate zero-ischemia partial nephrectomy'. eng. In: *European urology* 61.1, pp. 211–217. DOI: 10.1016/j.eururo.2011.07.068. eprint: 21937162.

[160] Wang, F., Zhang, C., Guo, F., Ji, J., Lyu, J., Cao, Z., and Yang, B. (2019). 'Navigation of Intelligent/Interactive Qualitative and Quantitative Analysis Three-Dimensional Reconstruction Technique in Laparoscopic or Robotic Assisted Partial Nephrectomy for Renal Hilar Tumors'. eng. In: *Journal of Endourology*. DOI: 10.1089/end.2018.0570. eprint: 30565487.

[161] Nakamura, K., Naya, Y., Zenbutsu, S., et al. (2010). 'Surgical navigation using three-dimensional computed tomography images fused intraoperatively with live video'. eng. In: *Journal of Endourology* 24.4, pp. 521–524. DOI: 10.1089/end.2009.0365. eprint: 20218887.

[162] Wang, D., Zhang, B., Yuan, X., Zhang, X., and Liu, C. (2015). 'Preoperative planning and real-time assisted navigation by three-dimensional individual digital model in partial nephrectomy with three-dimensional laparoscopic system'. eng. In: *International Journal of Computer Assisted Radiology and Surgery* 10.9, pp. 1461–1468. DOI: 10.1007/s11548-015-1148-7. eprint: 25577366.

[163] Hyams, E. S., Perlmutter, M., and Stifelman, M. D. (2011). 'A prospective evaluation of the utility of laparoscopic Doppler technology during minimally invasive partial nephrectomy'. eng. In: *Urology* 77.3, pp. 617–620. DOI: 10.1016/j.urology.2010.05.011. eprint: 21109296.

[164] Krane, L. S., Manny, T. B., and Hemal, A. K. (2012). 'Is near infrared fluorescence imaging using indocyanine green dye useful in robotic partial nephrectomy: a prospective comparative study of 94 patients'. eng. In: *Urology* 80.1, pp. 110–116. DOI: 10.1016/j.urology.2012.01.076. eprint: 22607949.

[165] Amir-Khalili, A., Hamarneh, G., Peyrat, J.-M., Abinahed, J., Al-Alao, O., Al-Ansari, A., and Abugharbieh, R. (2015). 'Automatic segmentation of occluded vasculature via pulsatile motion analysis in endoscopic robot-assisted partial nephrectomy video'. eng. In: *Medical Image Analysis* 25.1, pp. 103–110. DOI: 10.1016/j.media.2015.04.010. eprint: 25977157.

[166] Yang, F., Liu, S., Mou, L., Wu, L., Li, X., and Xing, N.-Z. (2019). 'Application of intraoperative ultrasonography in retroperitoneal laparoscopic partial nephrectomy: A single-center experience of recent 199 cases'. eng. In: *Endoscopic ultrasound* 8.2, pp. 118–124. DOI: 10.4103/eus.eus_15_19. eprint: 31006707.

[167] Mues, A. C., Okhunov, Z., Badani, K., Gupta, M., and Landman, J. (2010). 'Intraoperative evaluation of renal blood flow during laparoscopic partial nephrectomy with a novel Doppler system'. eng. In: *Journal of Endourology* 24.12, pp. 1953–1956. DOI: 10.1089/end.2010.0171. eprint: 20846005.

[168] Alenezi, A., Motiwala, A., Eves, S., et al. (2017). 'Robotic assisted laparoscopic partial nephrectomy using contrast-enhanced ultrasound scan to map renal blood flow'. eng. In: *The international journal of medical robotics + computer assisted surgery : MRCAS* 13.1. DOI: 10.1002/rcs.1738. eprint: 26948671.

[169] Borofsky, M. S., Gill, I. S., Hemal, A. K., Marien, T. P., Jayaratna, I., Krane, L. S., and Stifelman, M. D. (2013). 'Near-infrared fluorescence imaging to facilitate super-selective arterial clamping during zero-ischaemia robotic partial nephrectomy'. eng. In: *BJU international* 111.4, pp. 604–610. DOI: 10.1111/j.1464-410X.2012.11490.x. eprint: 23253629.

[170] Gadus, L., Kocarek, J., Chmelik, F., Matejkova, M., and Heracek, J. (2020). 'Robotic Partial Nephrectomy with Indocyanine Green Fluorescence Navigation'. eng. In: *Contrast media & molecular imaging* 2020, p. 1287530. DOI: 10.1155/2020/1287530. eprint: 32410919.

[171] Lee, H. J., Chen, K., Molchanov, R., Schwentner, C., and Sim, A. S. P. (2018). 'Feasibility of utilizing near-infrared fluorescence imaging with indocyanine green for super-selective arterial clamping in pure laparoscopic partial nephrectomy'. eng. In: *International journal of urology : official journal of the Japanese Urological Association* 25.4, pp. 382–383. DOI: 10.1111/iju.13525. eprint: 29388263.

[172] Chauvet, P., Collins, T., Debize, C., Novais-Gameiro, L., Pereira, B., Bartoli, A., Canis, M., and Bourdel, N. (2018). 'Augmented reality in a tumor resection model'. eng. In: *Surgical endoscopy* 32.3, pp. 1192–1201. DOI: 10.1007/s00464-017-5791-7. eprint: 28812157.

[173] Sengiku, A., Koeda, M., Sawada, A., et al. (2017). 'Augmented Reality Navigation System for Robot-Assisted Laparoscopic Partial Nephrectomy'. In: *Design, user experience, and usability. Theory, methodology, and management : 6th International Conference, DUXU 2017, held as part of HCI International 2017, Vancouver, BC, Canada, July 9-14, 2017, proceedings*. Ed. by W. Wang and A. Marcus. Vol. 10289. Lecture Notes in Computer Science 10288-10290. International Conference on Human-Computer Interaction. Cham: Springer, pp. 575–584. DOI: 10.1007/978-3-319-58637-3_45.

[174] Teber, D., Guven, S., Simpfendörfer, T., Baumhauer, M., Güven, E. O., Yencilek, F., Gözen, A. S., and Rassweiler, J. J. (2009). 'Augmented reality. A new tool to improve surgical accuracy during laparoscopic partial nephrectomy? Preliminary in vitro and in vivo results'. eng. In: *European urology* 56.2, pp. 332–338. DOI: 10.1016/j.eururo.2009.05.017. eprint: 19477580.

[175] Simpfendörfer, T., Gasch, C., Hatiboglu, G., Müller, M., Maier-Hein, L., Hohenfellner, M., and Teber, D. (2016). 'Intraoperative Computed Tomography Imaging for Navigated Laparoscopic Renal Surgery: First Clinical Experience'. eng. In: *Journal of Endourology* 30.10, pp. 1105–1111. DOI: 10.1089/end.2016.0385. eprint: 27530774.

[176] Dong, D., Ji, Z., Li, H., Yan, W., and Zhang, Y. (2016). 'Laparoscopic Nephron Sparing Surgery Assisted with Laparoscopic Ultrasonography on Centrally Located Renal Tumor - Single Center Experience'. eng. In: *Urologia internationalis* 97.2, pp. 195–199. DOI: 10.1159/000446026. eprint: 27160301.

[177] Gunelli, R., Fiori, M., Salaris, C., Salomone, U., Urbinati, M., Vici, A., Zenico, T., and Bertocco, M. (2016). 'The role of intraoperative ultrasound in small renal mass robotic enucleation'. eng. In: *Archivio italiano di urologia, andrologia : organo ufficiale [di] Societa italiana di ecografia urologica e nefrologica* 88.4, pp. 311–313. DOI: 10.4081/aiua.2016.4.311. eprint: 28073200.

[178] Reeves, J. J., Forauer, A., Seigne, J. D., and Hyams, E. S. (2015). 'Image-Guided Embolization Coil Placement for Identification of an Endophytic, Isoechoic Renal Mass During Robotic Partial Nephrectomy'. eng. In: *Journal of endourology case reports* 1.1, pp. 59–61. DOI: 10.1089/cren.2015.0022. eprint: 27579392.

[179] Cheung, C. L., Wedlake, C., Moore, J., Pautler, S. E., and Peters, T. M. (2010). 'Fused Video and Ultrasound Images for Minimally Invasive Partial Nephrectomy. A Phantom Study'. In: *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2010*. Ed. by D. Hutchison, T. Kanade, J. Kittler, et al. Vol. 6363. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, pp. 408–415. DOI: 10.1007/978-3-642-15711-0_51.

[180] Kawahara, J., Peyrat, J.-M., Abinahed, J., Al-Alao, O., Al-Ansari, A., Abugharbieh, R., and Hamarneh, G. (2014). 'Automatic labelling of tumourous frames in free-hand laparoscopic ultrasound video'. eng. In: *Medical image computing and computer-assisted intervention : MICCAI ... International Conference on Medical Image Computing and Computer-Assisted Intervention* 17.Pt 2, pp. 676–683. eprint: 25485438.

[181] Doerfler, A., Oitchayomi, A., and Tillou, X. (2014). 'A simple method for ensuring resection margins during laparoscopic partial nephrectomy: the intracorporeal ultrasonography'. eng. In: *Urology* 84.5, pp. 1240–1242. DOI: 10.1016/j.urology.2014.07.025. eprint: 25239259.

[182] Sentell, K. T., Ferroni, M. C., and Abaza, R. (2020). 'Near-infrared fluorescence imaging for intraoperative margin assessment during robot-assisted partial nephrectomy'. eng. In: *BJU international* 126.2, pp. 259–264. DOI: 10.1111/bju.15089. eprint: 32320124.

[183] Tobis, S., Knopf, J. K., Silvers, C., Messing, E., Yao, J., Rashid, H., Wu, G., and Golijanin, D. (2012). 'Robot-assisted and laparoscopic partial nephrectomy with near infrared fluorescence imaging'. eng. In: *Journal of Endourology* 26.7, pp. 797–802. DOI: 10.1089/end.2011.0604. eprint: 22250958.

[184] Simone, G., Tuderti, G., Anceschi, U., et al. (2018). '"Ride the Green Light": Indocyanine Green-marked Off-clamp Robotic Partial Nephrectomy for Totally Endophytic Renal Masses'. eng. In: *European urology* 75.6, pp. 1008–1014. DOI: 10.1016/j.eururo.2018.09.015. eprint: 30262342.

[185] Hoda, M. R. and Popken, G. (2009). 'Surgical outcomes of fluorescence-guided laparoscopic partial nephrectomy using 5-aminolevulinic acid-induced protoporphyrin IX'. eng. In: *The Journal of surgical research* 154.2, pp. 220–225. DOI: 10.1016/j.jss.2008.12.027. eprint: 19375717.

[186] Esposito, C., Coppola, V., Del Conte, F., et al. (2020). 'Near-Infrared fluorescence imaging using indocyanine green (ICG): Emerging applications in pediatric urology'. eng. In: *Journal of pediatric urology* 16.5, pp. 700–707. DOI: 10.1016/j.jpurol.2020.07.008. eprint: 32747308.

[187] Ueno, D., Makiyama, K., Yamanaka, H., Ijiri, T., Yokota, H., and Kubota, Y. (2014). 'Prediction of open urinary tract in laparoscopic partial nephrectomy by virtual resection plane visualization'. eng. In: *BMC urology* 14, p. 47. DOI: 10.1186/1471-2490-14-47. eprint: 24927795.

[188] Bianchi, L., Barbaresi, U., Cercenelli, L., et al. (2020). 'The Impact of 3D Digital Reconstruction on the Surgical Planning of Partial Nephrectomy: A Case-control Study. Still Time for a Novel Surgical Trend?' eng. In: *Clinical genitourinary cancer* 18.6, e669–e678. DOI: 10.1016/j.clgc.2020.03.016. eprint: 32354617.

[189] Fujisaki, A., Takayama, T., Yamazaki, M., et al. (2020). 'Utilization of a three-dimensional printed kidney model for favorable TRIFECTA achievement in early experience of robot-assisted partial nephrectomy'. eng. In: *Translational andrology and urology* 9.6, pp. 2697–2704. DOI: 10.21037/tau-20-927. eprint: 33457241.

[190] Nageotte, F., Zanne, P., Doignon, C., and Mathelin, M. de (2009). 'Stitching Planning in Laparoscopic Surgery: Towards Robot-assisted Suturing'. In: *The International Journal of Robotics Research* 28.10, pp. 1303–1321. DOI: 10.1177/0278364909101786.

[191] Qian, L., Deguet, A., and Kazanzides, P. (2018). 'ARssist: augmented reality on a head-mounted display for the first assistant in robotic surgery'. eng. In: *Healthcare technology letters* 5.5, pp. 194–200. DOI: 10.1049/htl.2018.5065. eprint: 30800322.

[192] Kong, S.-H., Haouchine, N., Soares, R., et al. (2017). 'Robust augmented reality registration method for localization of solid organs' tumors using CT-derived virtual biomechanical model and fluorescent fiducials'. eng. In: *Surgical endoscopy* 31.7, pp. 2863–2871. DOI: 10.1007/s00464-016-5297-8. eprint: 27796600.

[193] Zhang, X., Wang, J., Wang, T., Ji, X., Shen, Y., Sun, Z., and Zhang, X. (2019). 'A markerless automatic deformable registration framework for augmented reality navigation of laparoscopy partial nephrectomy'. eng. In: *International journal of computer assisted radiology and surgery* 14.8, pp. 1285–1294. DOI: 10.1007/s11548-019-01974-6. eprint: 31016562.

[194] Joeres, F., Mielke, T., and Hansen, C. (2021a). 'Laparoscopic augmented reality registration for oncological resection site repair'. In: *International Journal of Computer Assisted Radiology and Surgery*, pp. 1–10. DOI: 10.1007/s11548-021-02336-x.

[195] Ong, R. E., Herrell, S. D., Miga, M. I., and Galloway, J. L. (2008). 'A kidney deformation model for use in non-rigid registration during image-guided surgery'. In: *Medical Imaging 2008: Visualization, Image-guided Procedures, and Modeling*. Medical Imaging (San Diego, CA). Ed. by M. I. Miga and K. R. Cleary. SPIE Proceedings. SPIE, 69180W. DOI: 10.1117/12.771669.

[196] Baumhauer, M., Simpfendörfer, T., Müller-Stich, B. P., Teber, D., Gutt, C. N., Rassweiler, J. J., Meinzer, H.-P., and Wolf, I. (2008). 'Soft tissue navigation for laparoscopic partial nephrectomy'. In: *International Journal of Computer Assisted Radiology and Surgery* 3.3-4, pp. 307–314. DOI: 10.1007/s11548-008-0216-7.

[197] Wild, E., Teber, D., Schmid, D., Simpfendörfer, T., Müller, M., Baranski, A.-C., Kenngott, H. G., Kopka, K., and Maier-Hein, L. (2016). 'Robust augmented reality guidance with fluorescent markers in laparoscopic surgery'. eng. In: *International journal of computer assisted radiology and surgery* 11.6, pp. 899–907. DOI: 10.1007/s11548-016-1385-4. eprint: 27177759.

[198] Tsutsumi, N., Tomikawa, M., Uemura, M., et al. (2013). 'Image-guided laparoscopic surgery in an open MRI operating theater'. eng. In: *Surgical endoscopy* 27.6, pp. 2178–2184. DOI: 10.1007/s00464-012-2737-y. eprint: 23355150.

[199] Stolka, P. J., Keil, M., Sakas, G., McVeigh, E., Allaf, M. E., Taylor, R. H., and Boctor, E. M. (2010). 'A 3D-elastography-guided system for laparoscopic partial nephrectomies'. In: SPIE Medical Imaging (San Diego, California, USA). SPIE Proceedings. SPIE, p. 76251I. DOI: 10.1117/12.844589.

[200] Edgcumbe, P., Pratt, P. J., Yang, G.-Z., Nguan, C., and Rohling, R. (2015). 'Pico Lantern: Surface reconstruction and augmented reality in laparoscopic surgery using a pick-up laser projector'. eng. In: *Medical Image Analysis* 25.1, pp. 95–102. DOI: 10.1016/j.media.2015.04.008. eprint: 26024818.

[201] Ferguson, J. M., Pitt, E. B., Remirez, A. A., Siebold, M. A., Kuntz, A., Kavoussi, N. L., Barth, E. J., Herrell, S. D., and Webster, R. J. (2020). 'Toward Practical and Accurate Touch-Based Image Guidance for Robotic Partial Nephrectomy'. In: *IEEE Transactions on Medical Robotics and Bionics* 2.2, pp. 196–205. DOI: 10.1109/TMRB.2020.2989661.

[202] Joeres, F., Heinrich, F., Schott, D., and Hansen, C. (2020). 'Towards natural 3D interaction for laparoscopic augmented reality registration'. In: *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization* 189.194, pp. 1–8. DOI: 10.1080/21681163.2020.1834877.

[203] Kavoussi, N. L., Pitt, E. B., Ferguson, J. M., et al. (2021). 'Accuracy of Touch-Based Registration During Robotic Image-Guided Partial Nephrectomy Before and After Tumor Resection in Validated Phantoms'. eng. In: *Journal of Endourology*. DOI: 10.1089/end.2020.0363. eprint: 33040602.

[204] Horn, B. K. P. (1987). 'Closed-form solution of absolute orientation using unit quaternions'. In: *Journal of the Optical Society of America A* 4.4, p. 629. DOI: 10.1364/JOSAA.4.000629.

[205] Garrido-Jurado, S., Muñoz-Salinas, R., Madrid-Cuevas, F. J., and Marín-Jiménez, M. J. (2014). 'Automatic generation and detection of highly reliable fiducial markers under occlusion'. In: *Pattern Recognition* 47.6, pp. 2280–2292. DOI: 10.1016/j.patcog.2014.01.005.

[206] Eggers, G., Mühling, J., and Marmulla, R. (2006). 'Image-to-patient registration techniques in head surgery'. eng. In: *International journal of oral and maxillofacial surgery* 35.12, pp. 1081–1095. DOI: 10.1016/j.ijom.2006.09.015. eprint: 17095191.

[207] Heller, N., Sathianathen, N., Kalapara, A., et al. (2019). *The KiTS19 Challenge Data: 300 Kidney Tumor Cases with Clinical Context, CT Semantic Segmentations, and Surgical Outcomes*. URL: http://arxiv.org/pdf/1904.00445v1.

[208] Fedorov, A., Beichel, R., Kalpathy-Cramer, J., et al. (2012). '3D Slicer as an image computing platform for the Quantitative Imaging Network'. eng. In: *Magnetic resonance imaging* 30.9, pp. 1323–1341. DOI: 10.1016/j.mri.2012.05.001. eprint: 22770690.

[209] Scott, D. J., Bergen, P. C., Rege, R. V., et al. (2000). 'Laparoscopic training on bench models: better and more cost effective than operating room experience?11No competing interests declared'. In: *Journal of the American College of Surgeons* 191.3, pp. 272–283. DOI: 10.1016/S1072-7515(00)00339-2.

[210] Serej, N. D., Ahmadian, A., Mohagheghi, S., and Sadrehosseini, S. M. (2015). 'A projected landmark method for reduction of registration error in image-guided surgery systems'. En;en. In: *International Journal of Computer Assisted Radiology and Surgery* 10.5, pp. 541–554. DOI: 10.1007/s11548-014-1075-z.

[211] Sugano, N., Sasama, T., Sato, Y., Nakajima, Y., Nishii, T., Yonenobu, K., Tamura, S., and Ochi, T. (2001). 'Accuracy Evaluation of Surface-Based Registration Methods in a Computer Navigation System for Hip Surgery Performed Through a Posterolateral Approach'. In: *Computer Aided Surgery* 6.4, pp. 195–203. DOI: 10.3109/10929080109146083.

[212] Altamar, H. O., Ong, R. E., Glisson, C. L., Viprakasit, D. P., Miga, M. I., Herrell, S. D., and Galloway, R. L. (2011). 'Kidney deformation and intraprocedural registration. A study of elements of image-guided kidney surgery'. eng. In: *Journal of Endourology* 25.3, pp. 511–517. DOI: 10.1089/end.2010.0249. eprint: 21142942.

[213] Heizmann, O., Zidowitz, S., Bourquain, H., Potthast, S., Peitgen, H.-O., Oertli, D., and Kettelhack, C. (2010). 'Assessment of intraoperative liver deformation during hepatic resection: prospective clinical study'. eng. In: *World journal of surgery* 34.8, pp. 1887–1893. DOI: 10.1007/s00268-010-0561-x. eprint: 20372896.

[214] Guan, S.-Y., Wang, T.-M., Meng, C., and Wang, J.-C. (2018). 'A Review of Point Feature Based Medical Image Registration'. In: *Chinese Journal of Mechanical Engineering* 31.1, p. 642. DOI: 10.1186/s10033-018-0275-9.

[215] Zhang, X., Wang, T., Zhang, X., Zhang, Y., and Wang, J. (2020). 'Assessment and application of the coherent point drift algorithm to augmented reality surgical navigation for laparoscopic partial nephrectomy'. eng. In: *International journal of computer assisted radiology and surgery* 15.6, pp. 989–999. DOI: 10.1007/s11548-020-02163-6. eprint: 32361857.

[216] Nicolau, S., Soler, L., Mutter, D., and Marescaux, J. (2011). 'Augmented reality in laparoscopic surgical oncology'. eng. In: *Surgical oncology* 20.3, pp. 189–201. DOI: 10.1016/j.suronc.2011.07.002. eprint: 21802281.

[217] Araújo, B. R. de, Casiez, G., Jorge, J. A., and Hachet, M. (2013). 'Mockup Builder: 3D modeling on and above the surface'. In: *Computers & Graphics* 37.3, pp. 165–178. DOI: 10.1016/j.cag.2012.12.005.

[218] Song, P., Goh, W. B., Hutama, W., Fu, C.-W., and Liu, X. (2012). 'A handle bar metaphor for virtual object manipulation with mid-air interaction'. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. the 2012 ACM annual conference (Austin, Texas, USA). Ed. by J. A. Konstan. ACM Digital Library. New York, NY: ACM, p. 1297. DOI: 10.1145/2207676.2208585.

[219] Bowman, D. A., McMahan, R. P., and Ragan, E. D. (2012). 'Questioning naturalism in 3D user interfaces'. In: *Communications of the ACM* 55.9, p. 78. DOI: 10.1145/2330667.2330687.

[220] Volonté, F., Buchs, N. C., Pugin, F., Spaltenstein, J., Schiltz, B., Jung, M., Hagen, M., Ratib, O., and Morel, P. (2013). 'Augmented reality to the rescue of the minimally invasive surgeon. The usefulness of the interposition of stereoscopic images in the Da Vinci™ robotic console'. eng. In: *The international journal of medical robotics + computer assisted surgery : MRCAS* 9.3, e34–8. DOI: 10.1002/rcs.1471. eprint: 23239589.

[221] Gong, R. H., Güler, Ö., Kürklüoglu, M., Lovejoy, J., and Yaniv, Z. R. (2013). 'Interactive initialization of 2D/3D rigid registration'. eng. In: *Medical physics* 40.12, p. 121911. DOI: 10.1118/1.4830428. eprint: 24320522.

[222] Thompson, S., Totz, J., Song, Y., et al. (2015). 'Accuracy validation of an image guided laparoscopy system for liver resection'. In: *Medical Imaging 2015: Image-Guided Procedures, Robotic Interventions, and Modeling*. SPIE Medical Imaging (Orlando, Florida, United States). Ed. by R. J. Webster and Z. R. Yaniv. Vol. 9415. SPIE Proceedings. SPIE, p. 941509. DOI: 10.1117/12.2080974.

[223] Brooke, J. (2014). 'SUS-A quick and dirty usability scale'. In: *Usability Evaluation In Industry*. Ed. by P. W. Jordan. London and Bristol, PA: CRC Press LLC and CRC Press, p. 189. ISBN: 0748403140.

[224] Joeres, F., Black, D., Razavizadeh, S., and Hansen, C. (2021b). 'Audiovisual AR Concepts for Laparoscopic Subsurface Structure Navigation'. In: *Proceedings of Graphics Interface 2021* (Virtual event), pp. 224–230. DOI: 10.20380/GI2021.34.

[225] Heinrich, F., Schmidt, G., Jungmann, F., and Hansen, C. (2019). 'Augmented Reality Visualisation Concepts to Support Intraoperative Distance Estimation'. In: *Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology*. VRST '19. New York, NY, USA: ACM. DOI: 10.1145/3359996.3364818.

[226] Black, D., Hansen, C., Nabavi, A., Kikinis, R., and Hahn, H. K. (2017a). 'A Survey of auditory display in image-guided interventions'. eng. In: *International journal of computer assisted radiology and surgery* 12.10, pp. 1665–1676. DOI: 10.1007/s11548-017-1547-z. eprint: 28275890.

[227] Black, D., Lilge, S., Fellmann, C., Reinschluessel, A. V., Kreuer, L., Nabavi, A., Hahn, H. K., Kikinis, R., and Burgner-Kahrs, J. (2019). 'Auditory Display for Telerobotic Transnasal Surgery Using a Continuum Robot'. In: *Journal of Medical Robotics Research* 04.02, p. 1950004. DOI: 10.1142/S2424905X19500041.

[228] Black, D., Hettig, J., Luz, M., Hansen, C., Kikinis, R., and Hahn, H. K. (2017b). 'Auditory feedback to support image-guided medical needle placement'. eng. In: *International journal of computer assisted radiology and surgery* 12.9, pp. 1655–1663. DOI: 10.1007/s11548-017-1537-1. eprint: 28213646.

[229] Cho, B., Oka, M., Matsumoto, N., Ouchida, R., Hong, J., and Hashizume, M. (2013). 'Warning navigation system using real-time safe region monitoring for otologic surgery'. eng. In: *International journal of computer assisted radiology and surgery* 8.3, pp. 395–405. DOI: 10.1007/s11548-012-0797-z. eprint: 23161169.

[230] Dixon, B. J., Daly, M. J., Chan, H., Vescan, A. D., Witterick, I. J., and Irish, J. C. (2014). 'Augmented real-time navigation with critical structure proximity alerts for endoscopic skull base surgery'. eng. In: *The Laryngoscope* 124.4, pp. 853–859. DOI: 10.1002/lary.24385. eprint: 24122916.

[231] Hansen, C., Black, D., Lange, C., Rieber, F., Lamadé, W., Donati, M., Oldhafer, K. J., and Hahn, H. K. (2013). 'Auditory support for resection guidance in navigated liver surgery'. eng. In: *The international journal of medical robotics + computer assisted surgery : MRCAS* 9.1, pp. 36–43. DOI: 10.1002/rcs.1466. eprint: 23192891.

[232] Kitagawa, M., Dokko, D., Okamura, A. M., and Yuh, D. D. (2005). 'Effect of sensory substitution on suture-manipulation forces for robotic surgical systems'. eng. In: *The Journal of thoracic and cardiovascular surgery* 129.1, pp. 151–158. DOI: 10.1016/j.jtcvs.2004.05.029. eprint: 15632837.

[233] Puckette, M. (1996). 'Pure Data: Another integrated computer music environment'. In: *Proceedings of the second intercollege computer music concerts* 1, pp. 37–41.

[234] Hart, S. G. and Staveland, L. E. (1988). 'Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research'. In: *Human mental workload*. Ed. by P. A. Hancock and N. Meshkati. Online-ausg. Vol. 52. Advances in Psychology 52. Amsterdam, New York, and New York, N.Y., U.S.A: North-Holland, pp. 139–183. ISBN: 9780444703880. DOI: 10.1016/S0166-4115(08)62386-9.

[235] Faure, F., Duriez, C., Delingette, H., et al. (2012). 'SOFA: A Multi-Model Framework for Interactive Physical Simulation'. In: *Soft Tissue Biomechanical Modeling for Computer Assisted Surgery*. Ed. by Yohan Payan. Vol. 11. Studies in Mechanobiology, Tissue Engineering and Biomaterials. Springer, pp. 283–321. DOI: 10.1007/8415_2012_125.

[236] Kaneko, H., Takagi, S., and Shiba, T. (1996). 'Laparoscopic partial hepatectomy and left lateral segmentectomy: Technique and results of a clinical series'. In: *Surgery* 120.3, pp. 468–475. DOI: 10.1016/S0039-6060(96)80065-1.

[237] Schneider, C., Nguan, C., Longpre, M., Rohling, R., and Salcudean, S. (2013). 'Motion of the kidney between preoperative and intraoperative positioning'. eng. In: *IEEE transactions on bio-medical engineering* 60.6, pp. 1619–1627. DOI: 10.1109/TBME.2013.2239644. eprint: 23322758.

[238] Figueroa-Garcia, I., Peyrat, J.-M., Hamarneh, G., and Abugharbieh, R. (2014). 'Biomechanical kidney model for predicting tumor displacement in the presence of external pressure load'. In: *2014 IEEE International Symposium on Biomedical Imaging. Tuesday, 29 April - Friday, 2 May 2014 : Renaissance Beijing Capital Hotel, Beijing, China*. 2014 IEEE 11th International Symposium on Biomedical Imaging (ISBI 2014) (Beijing, China). Piscataway, NJ.: IEEE, pp. 810–813. DOI: 10.1109/ISBI.2014.6867994.

[239] Jing, M., Cui, Z., Fu, H., and Chen, X. (2021). 'Real-Time Deformation Simulation of Kidney Surgery Based on Virtual Reality'. In: *Journal of Shanghai Jiaotong University (Science)* 26.3, pp. 290–297. DOI: 10.1007/s12204-021-2295-3.

List of Figures

Publication List

[1] Chheang, V., Saalfeld, P., Joeres, F., Boedecker, C., Huber, T., Huettl, F., Lang, H., Preim, B., and Hansen, C. (2021). 'A Collaborative Virtual Reality Environment for Liver Surgery Planning'. In: *Computers & Graphics* in print. DOI: 10.1016/j.cag.2021.07.009.

[2] Joeres, F., Black, D., Razavizadeh, S., and Hansen, C. (2021a). 'Audiovisual AR Concepts for Laparoscopic Subsurface Structure Navigation'. In: *Proceedings of Graphics Interface 2021* (Virtual event), pp. 224–230. DOI: 10.20380/GI2021.34.

[3] Joeres, F., Mielke, T., and Hansen, C. (2021b). 'Laparoscopic augmented reality registration for oncological resection site repair'. In: *International Journal of Computer Assisted Radiology and Surgery*, pp. 1–10. DOI: 10.1007/s11548-021-02336-x.

[4] Schott, D., Saalfeld, P., Schmidt, G., et al. (2021). 'A VR/AR Environment for Multi-User Liver Anatomy Education'. In: *2021 IEEE Virtual Reality and 3D User Interfaces (VR)* (Lisboa, Portugal), pp. 296–305. DOI: 10.1109/VR50410.2021.00052.

[5] Wagner, S., Belger, J., Joeres, F., Thöne-Otto, A., Hansen, C., Preim, B., and Saalfeld, P. (2021). 'iVRoad: Immersive virtual road crossing as an assessment tool for unilateral spatial neglect'. In: *Computers & Graphics* 99.5, pp. 70–82. DOI: 10.1016/j.cag.2021.06.013.

[6] Gulamhussene, G., Joeres, F., Rak, M., Pech, M., and Hansen, C. (2020). '4D MRI: Robust sorting of free breathing MRI slices for use in interventional settings'. eng. In: *PloS one* 15.6, e0235175. DOI: 10.1371/journal.pone.0235175. eprint: 32569335.

[7] Heinrich, F., Schwenderling, L., Joeres, F., Lawonn, K., and Hansen, C. (2020). 'Comparison of Augmented Reality Display Techniques to Support Medical Needle Insertion'. eng. In: *IEEE transactions on visualization and computer graphics* 26.12, pp. 3568–3575. DOI: 10.1109/TVCG.2020.3023637. eprint: 33006930.

[8] Joeres, F. (July 14, 2020). *Intraoperative software assistance in minimally invasive partial nephrectomy. FIN Doktorandentag 2020.* Magdeburg, Germany: OvGU.

[9] Joeres, F., Heinrich, F., Schott, D., and Hansen, C. (2020). 'Towards natural 3D interaction for laparoscopic augmented reality registration'. In: *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization* 189.194, pp. 1–8. DOI: 10.1080/21681163.2020.1834877.

[10] Schott, D., Hatscher, B., Joeres, F., Gabele, M., Hußlein, S., and Hansen, C. (2020). 'Lean-Interaction: passive image manipulation in concurrent multitasking'. In: *Proceedings of Graphics Interface 2020* (Toronto, Canada), pp. 404–412. DOI: 10.20380/GI2020.40.

[11] Heinrich, F., Joeres, F., Lawonn, K., and Hansen, C. (2019a). 'Comparison of Projective Augmented Reality Concepts to Support Medical Needle Insertion'. eng. In: *IEEE transactions on visualization and computer graphics* 25.6, pp. 2157–2167. DOI: 10.1109/TVCG.2019.2903942. eprint: 30892210.

[12] Heinrich, F., Joeres, F., Lawonn, K., and Hansen, C. (2019b). 'Effects of Accuracy-to-Colour Mapping Scales on Needle Navigation Aids visualised by Projective Augmented Reality'. In: *Proceedings of the Annual Meeting of the German Society of Computer- and Robot-Assisted Surgery (CURAC)*. Reutlingen, Germany, pp. 217–222.

[13] Joeres, F., Schindele, D., Luz, M., Blaschke, S., Russwinkel, N., Schostak, M., and Hansen, C. (2019). 'How well do software assistants for minimally invasive partial nephrectomy meet surgeon information needs? A cognitive task analysis and literature review study'. eng. In: *PloS one* 14.7, e0219920. DOI: 10.1371/journal.pone.0219920. eprint: 31318919.

[14] Wagner, S., Joeres, F., Gabele, M., Hansen, C., Preim, B., and Saalfeld, P. (2019). 'Difficulty factors for VR cognitive rehabilitation training. Crossing a virtual road'. In: *Computers & Graphics* 83, pp. 11–22. DOI: 10.1016/j.cag.2019.06.009.

[15] Smieszek, H., Joeres, F., and Russwinkel, N. (2015). 'Workload of airport tower controllers: empirical validation of a macro-cognitive model'. In: *Online Journal Kognitive Systeme* 2.1. URL: https://duepublico2.uni-due.de/servlets/mcrfilenodeservlet/duepublico_derivate_00038598/ks_vol2_2015_1_smieszek_joeres_russwinkel.pdf.

[16] Joeres, F. and Russwinkel, N. (2014a). 'Introduction of an ACT-R based modeling approach to mental rotation'. In: *Cognitive Processing* 15.1, pp. 112–114.

[17] Joeres, F. and Russwinkel, N. (2014b). 'Object-Related Learning Effects in Mental Rotation'. In: *Spatial Cognition 2014: Poster Presentations* (Bremen, Germany), pp. 56–59.

[18] Smieszek, H. and Joeres, F. (2013). 'Prospective decision making in a macro-cognitive model of airport traffic control system (MaTriCS) based on coloured petri nets'. In: *Tagungsband der 10. Berliner Werkstatt Mensch-Maschine-Systeme. Grundlagen und Anwendungen der Mensch-Maschine-Interaktion* (Berlin, Germany), pp. 500–507.

Appendices

Appendix A

Questionnaire for the identification of challenging and risk-associated surgical steps in LRPN (Chapter 3). The questionnaire is in German as used in the study.

Herzlichen Dank für die Unterstützung dieser Untersuchung!

Einführung

Herzlichen Dank für Ihre Teilnahme an der Interviewstudie zu minimalinvasiven Nierenteilresektionen. Die Studie dient dazu, den Operationsablauf und die auftretenden Herausforderungen minimalinvasiver Nierenteilresektionen zu untersuchen und besser zu verstehen. Im Rahmen der Studie bitte ich Sie zunächst, den vorliegenden Fragebogen (wenn möglich bis zum 20.07.2018) auszufüllen, danach findet das Interview statt. Dieser Fragebogen hilft uns dabei, Ihr persönliches Interview optimal vorzubereiten. Der Fragebogen wird etwa **10 Minuten** in Anspruch nehmen.

Erläuterung der Fragebogenstruktur

Auf den folgenden Seiten ist eine **Workflowbeschreibung für minimalinvasive Nierenteilresektionen** aufgeführt. Sechsundvierzig Arbeitsschritte wurden identifiziert und sind im Fragebogen aufgelistet. Zum besseren Verständnis der Workflowbeschreibung beachten Sie bitte folgende Punkte:

- Einige der beschriebenen Arbeitsschritte werden nur in bestimmten Kliniken, unter bestimmten Bedingungen oder bei der Anwendung bestimmter Techniken durchgeführt – sind also **nicht immer Bestandteil** der OP.
- Die Arbeitsschritte werden nicht unbedingt in der **aufgeführten Reihenfolge** durchgeführt.
- Einige Arbeitsschritte können sich **wiederholen** oder sogar während der gesamten OP immer wieder auftreten.

Instruktion Fragebogen

Bitte führen Sie die folgenden vier Schritte durch, um den Fragebogen auszufüllen:

1. Bitte **lesen Sie die vollständige Workflowbeschreibung**, bevor Sie fortfahren.
2. Bitte identifizieren Sie **2-5 Arbeitsschritte**, die Sie **selbst** als **besonders herausfordernd** empfinden und markieren Sie diese durch Ankreuzen in **Spalte (A).**
3. Bitte identifizieren Sie **2-5 Arbeitsschritte**, die Sie für **besonders herausfordernd für Anfänger/Innen** halten und markieren Sie diese durch Ankreuzen in **Spalte (B).**
4. Bitte identifizieren Sie **2-5 Arbeitsschritte**, von denen Sie glauben, dass sie besonders mit **intra- oder postoperativen Risiken** behaftet sind und markieren Sie diese durch Ankreuzen in **Spalte (C).**

Allgemeine Hinweise

Ich möchte Sie bitten, den Fragebogen wie oben beschrieben auszufüllen und bis zum **20.07.2018** zurückzusenden, an:

E-Mail: ***fabian.joeres@ovgu.de*** oder:

Fax: **0391/67-41164** (Bei Fax bitte diese Deckblattseite mitsenden und Absender kenntlich machen).

Bei Fragen stehe ich gerne jederzeit unter der oben genannten E-Mail-Adresse oder unter **0391/67-19349** zur Verfügung.

Herzlichen Dank für Ihre Hilfe!

Fabian Joeres

Computer-Assisted Surgery Group (FIN-ISG)
Otto-von-Guericke-Universität Magdeburg
www.cas.ovgu.de

(A) Für Sie herausfordernder Schritt	(B) Herausfordernd für Anfänger/Innen	(C) Risikobehafteter Schritt	(D) Arbeitsschritt	(E) Details
			1 Operationsvorbereitung	
			1.1 Präoperative Planung	*Bildgebung, Diagnostik, Entscheidung operative Herangehensweise*
☐	☐	☐	1.2 Patientenvorbereitung	*Klinische Patientenvorbereitung, Harnkatheter legen, Patienten rasieren und desinfizieren, Patienten lagern und sichern, Tisch einstellen*
			2 Operationseinleitung	
☐	☐	☐	2.1 Retroperitonealraum dehnen	*Nur bei retroperitonealem Ansatz*
☐	☐	☐	2.2 CO_2-Eintrag zur Weitung des Operationsraums	
☐	☐	☐	2.3 Kamera-Trokar setzen	
☐	☐	☐	2.4 Arbeitstrokare setzen	
			3 Navigation zum Operationsfeld	
☐	☐	☐	3.1 Navigation zur Nierenfaszie	*Leber / Milz und Pankreas zurückziehen, Peritoneum einschneiden und Darm mobilisieren, Verbindungen von der Nierenfaszie zur Milz und Leber lösen*
☐	☐	☐	3.2 Niere mobilisieren	*Nierenfaszie identifizieren und öffnen, Niere innerhalb der Faszie mobilisieren, Tumor identifizieren und offenlegen*
☐	☐	☐	3.3 Hilus präparieren	*Zum Hilus navigieren, abzuklemmende Gefäße identifizieren, Gefäße zum Abklemmen mobilisieren und präparieren* *Kommentar: Präparation ist abhängig von der gewählten Klemmstrategie*
			4 Intraoperative Untersuchung und Planung	
☐	☐	☐	4.1 Fettgewebe abseits des Tumors entfernen	
☐	☐	☐	4.2 Tumor untersuchen	
☐	☐	☐	4.3 Weitere Tumore suchen	
☐	☐	☐	4.4 Schnittebene planen und Einschnitt mit Kauterisation markieren	
☐	☐	☐	4.5 Geplante Schnittebene mit Ultraschall bestätigen	
☐	☐	☐	4.6 Niere für Tumorresektion positionieren	
☐	☐	☐	4.7 Bestätigen, dass alle Materialien, die während der Ischämie benötigt werden, bereit liegen	

(A) Für Sie herausfordernder Schritt	(B) Herausfordernd für Anfänger/Innen	(C) Risikobehafteter Schritt	(D) Arbeitsschritt	(E) Details
☐	☐	☐	└ 4.8 Diuretikum verabreichen (30 Minuten vor Abklemmen der Nierenblutgefäße)	
			5 Sperren der Nierenblutgefäße	
☐	☐	☐	└ 5.1 Nierenarterie oder segmentäre Arterie abklemmen	
☐	☐	☐	└ 5.2 Nierenvene oder segmentäre Vene abklemmen	
☐	☐	☐	└ 5.3 Überprüfen, ob relevante Blutgefäße ausgelassen wurden	*Überwachung während der gesamten Ischämie notwendig*
☐	☐	☐	└ 5.4 Uhr für Ischämie-Dauer starten	
			6 Tumorresektion	
☐	☐	☐	└ 6.1 Navigation innerhalb der Schnittebene	*Schritte 6.1, 6.2 und 6.3 werden mehrfach in unterschiedlicher Reihenfolge wiederholt, bis der Tumor vollständig vom übrigen Nierengewebe getrennt ist.*
☐	☐	☐	└ 6.2 Gewebe schneiden	
☐	☐	☐	└ 6.3 Blutgefäße kauterisieren	
☐	☐	☐	└ 6.4 [*Wenn nicht geklemmt*] Arteriellen Druck senken, nachdem Nierenrinde durchschnitten wurde	*Nur wenn die Operation ohne Abklemmen der Blutgefäße durchgeführt wird.*
☐	☐	☐	└ 6.5 [*Wenn nicht geklemmt*] Intrarenale Gefäße identifizieren und veröden	*Nur wenn die Operation ohne Abklemmen der Blutgefäße durchgeführt wird.*
☐	☐	☐	└ 6.6 [*Wenn nicht geklemmt*] Dauerhafte Durchblutung unter verringertem arteriellem Druck überprüfen	*Nur wenn die Operation ohne Abklemmen der Blutgefäße durchgeführt wird.*
☐	☐	☐	└ 6.7 Tumor neben der Niere ablegen	
☐	☐	☐	└ 6.8 Biopsie des Schnittbettes entnehmen	
			7 Reparatur des Nierendefekts	
☐	☐	☐	└ 7.1 Kelchsystem und größere intrarenale Gefäße schließen	
☐	☐	☐	└ 7.2 Vollständige Reparatur der tieferen Defekte bestätigen	*Visuellen Indikator durch Katheter geben, um Verschluss des Kelchsystems zu prüfen, arteriellen Druck auf Normalniveau anheben (wenn Druck zuvor gesenkt wurde), verbleibende blutende Nierengefäße identifizieren und reparieren*
☐	☐	☐	└ 7.3 Parenchym schließen	*Hämostatische Medikamente oder Polster aufbringen, Parenchym über Polster schließen, Niere in anatomische Position zurückbewegen*

(A) Für Sie herausfordernder Schritt	(B) Herausfordernd für Anfänger/Innen	(C) Risikobehafteter Schritt	(D) Arbeitsschritt	(E) Details
			8 Entsperren der Nierenblutgefäße	
☐	☐	☐	8.1 Diuretika verabreichen (5-10 Minuten vor Ausklemmen)	*Wird nicht in allen Kliniken verabreicht*
☐	☐	☐	8.2 Klemmen öffnen oder entfernen	• *So früh wie möglich – wenn möglich, schon vor Schritt 7.3, um Ischämie so kurz wie möglich zu halten* • *Öffnen / entfernen abhängig vom verwendeten Klemmentyp*
☐	☐	☐	8.3 Hämostase prüfen	*Unter reduziertem Peritonealdruck*
☐	☐	☐	8.4 [*Wenn nötig*] Verbleibende Blutgefäße schließen	
☐	☐	☐	8.5 [*falls nicht in 8.2 geschehen*] Klemmen entfernen	
☐	☐	☐	**9 Entfernung des Tumors mit Schutzbeutel**	
			10 Abschluss der Operation	
☐	☐	☐	10.1 Extrarenale Defekte reparieren	*Schnittwunde mit Zellulose und Versiegelung bedecken, Nierenfaszie schließen, Übrige Strukturen/ Organe in anatomische Position zurückbringen*
☐	☐	☐	10.2 Wunddrainage legen	
☐	☐	☐	10.3 Nephrektomiebett 5-10 Minuten nach Deflation der Bauchhöhle prüfen und Hämostase bestätigen	
☐	☐	☐	10.4 Trokare entfernen und Bauchhöhle schließen	
			11 Postoperative Behandlung	
			12 Kommunikation mit anderen Team-Mitgliedern im OP	
☐	☐	☐	12.1 Kommunikation mit Assistenzarzt/-ärztin	*z.B. Anweisung zum Werkzeugwechsel, Anweisung zum Absaugen (Aufklärung des Sichtfelds), Anweisung zum Aufbringen von, Anweisung zum Säubern des Endoskops, Anweisungen zum Ändern des Sichtfelds (z.B. Position, Winkel und Vergrößerung des Endoskops)*
☐	☐	☐	12.2 Kommunikation mit Anästhesie	*z.B. Präoperatives Briefing mit Anästhesie, Patientenstatus an Anästhesie melden oder empfangen, Status der Operation an Anästhesie melden*
☐	☐	☐	12.3 Kommunikation mit Pflegepersonal	*z.B. Anweisung, welche Materialien vorzubereiten sind*

Appendix B

Comprehensive account of the strategies, cues, and explicit information needs that were reported throughout the interview reported in Chapter 3.

Surgical phase	Challenge	Strategies [S], cues [C], and explicitly expressed information needs [E]
I Hilar management	**I.1** Decision: Is clamping required and, if so, which vessels require clamping?	[**S**] Initial decision based on CT data. [**C**] Knowledge-based recognition of tumour-supplying vasculature based on surgical site, anatomical knowledge and imagery data. [**C**] CT data on tumour size and position.
	I.2 Hilar dissection in highly variable individual patient anatomy.	[**S**] Dissection from multiple directions. [**C**] Landmarks for hilar dissection: ureter, large vessels (aorta, v. cava), renal vein, inferior pole. [**C**] Vascular tree complexity is criterion for clamping strategy. [**C**] Dissection is complete when sufficient space for bulldog clamp has been created.
	I.3 Identify, localise and dissect all relevant vascular branches.	[**S**] Dissect renal artery centrally and follow to branches that are more distal. [**S**] If expected vessels cannot be found: dissection from different direction or total clamping. [**C**] Anatomical knowledge as basis for navigation. [**C**] Preoperative use of CT imaging data. [**C**] Preoperative and intraoperative use of three-dimensional reconstructed models based on imaging data. [**C**] Anatomical circumstances in the surgical site. [**C**] Doppler US to identify hidden vessels. [**E**] Picture-in-picture of the CT data. [**E**] AR display of CT-based 3D model with highlighted blood vessels during navigation to hilum. [**E**] Proximity alarm when dissection instrument gets close to major arteries.
	I.4 Decision: Have all relevant vascular branches been clamped?	[**S**] Block renal or segmental vein. If the vein expands, relevant arterial branch has been missed. [**C**] *Firefly*™ (Intuitive Surgical Inc., California, USA) fluorescence imaging to visualise renal segment perfusion. (*Reported by* DaVinci *(Intuitive Surgical Inc., California, USA) users.*) [**C**] Unexpected bleeding during resection retrospectively indicates missed arterial branches. [**E**] Electronic control of clamp being closed.
II Tumour excision	**II.1** Localise and navigate to tumour.	[**C**] General and patient-specific anatomical knowledge (remembering three-dimensional anatomy reconstruction from CT data). [**C**] Compare surgical site and mental transformation of CT imaging data. [**C**] Intraoperative laparoscopic ultrasound. [**E**] Picture-in-picture access to CT data.
	II.2 Find the ideal resection plane.	[**S**] Resect (perpendicular to the kidney surface) around the contour of the tumour until estimated depth of tumour has been reached. Then switch to resection parallel to kidney surface to remove the resected volume. [**S**] Start resecting in healthy tissue and then move towards tumour. In less clearly distinguishable tumour tissue, keep greater margins. [**S**] Open multiple resection planes based on resection plane visibility and accessibility. [**C**] Optical recognition of tissue in resection site. Landmarks: Tumour capsule, collecting system. Unexpected early or late appearance of structures indicates deviation from previously planned resection plane. [**C**] Memory of CT data and three-dimensional patient-specific reconstruction. Shape and size of resected volume is compared to the expected geometry.

Surgical phase	Challenge	Strategies [S], cues [C], and explicitly expressed information needs [E]
		[**C**] Ultrasound [*Participant comment: Ultrasound is too slow under ischaemia time pressure*]
		[**C**] Mental extrapolation of the visible extra-parenchymal tumour surface curvature to estimate intra-parenchymal geometry.
		[**E**] Ultrasound is too slow during ischaemia but faster alternatives are not around.
		[**E**] Visualise tumour depth / display tumour dimensions.
		[**E**] Display distance from tumour.
		[**E**] AR visualisation tumour.
		[**E**] Display planned resection plane in virtual three-dimensional model.
	II.3 Decision: Can the tumour be enucleated?	[**C**] Criteria: solid tumour capsule, which can be bluntly dissected from renal tissue?
	II.4 Identify current resection plane and surrounding tissue.	[**C**] Visual tissue recognition (colour and texture).
		[**C**] Haptic feel and elasticity of parenchymal tissue is recognisable.
		[**C**] Frozen section analysis.
	II.5 React to unexpected anatomy or pathology.	[**S**] Preoperative review of imagery data with radiologist and review of three-dimensional reconstructed model.
		[**C**] Visual tissue recognition.
		[**C**] Intraoperative ultrasound.
	II.6 Identify, localise and protect risk structures (vessels, collecting systems).	[**S**] If possible, orient dissection away from hilum.
		[**S**] When hazard to risk structure is suspected, open new resection plane.
		[**S**] Occasionally pull back laparoscope to prevent injuries outside field of view.
		[**S**] Cut major tumour-supplying vessels last.
		[**C**] Preoperative and intraoperative review of CT data.
		[**C**] Visual tissue recognition (parenchyma, vasculature, collecting system).
		[**C**] Review hilum to identify unclamped vessels.
		[**C**] Identification of vessels with *Firefly*™ fluorescence imaging.
		[**C**] Track current incision depth into kidney.
		[**C**] *Hypothetically*: Administer dye into collecting system to detect leakage. [*All participants who mentioned this stated that they were aware of the possibility but usually do not use this technique.*]
		[**E**] Visualise distinction between blood and collecting system vessels.
		[**E**] Display proximity to blood vessels and collecting system.
	II.7 Preserve perfusion to the remaining renal tissue.	[**S**] Try to avoid renorrhaphy close to the hilum to prevent affecting vessels supplying other than the resected segments.
		[**C**] Test perfusion after clamping and after renorrhaphy, using *Firefly*™ fluorescence imaging or Doppler ultrasound.
	II.8 Detect and manage lesions to risk structures (vessels, collecting system).	**[S]** If possible, treat bleeding vessels with compression or sutures.
		[**C**] Strong, unexpected bleeding indicates injuries.
		[**C**] Colour and pressure of bleeding indicate type of injured vessel.
		[**C**] Visual tissue recognition and urine leakage indicate collecting system injury.
		[**C**] Visual tumour tissue recognition indicates negative margins.
		[**E**] Visualise collecting system lesions.
	II.9 Decision: Is retroactive clamping required?	[**C**] Where is the border of the currently clamped segment and what is the expected resection volume?
		[**C**] Review perfusion of remaining, not to be resected, renal segments with *Firefly*™ fluorescence imaging.

Surgical phase	Challenge	Strategies [S], cues [C], and explicitly expressed information needs [E]
		[**C**] Level of bleeding and visibility of resection plane indicate need for further clamping.
		[**E**] Visualise vessels directly supplying the tumour.
	II.10 Decision: Was the resection oncologically successful?	[**C**] Visual inspection of resection bed and resected volume.
		[**C**] Frozen section analysis.
III Repair of renal defects	**III.1** Apply correct positioning, strength and distance of sutures.	[**C**] "Experience" and, therefrom, "gut feel" as key components.
		[**C**] Push side of the bent needle into the resection bed. The needle sinking into the elastic resection bed helps estimate were the needle will enter and exit the tissue when suturing.
		[**C**] Strength of bleeding (apply deeper stitches in case of stronger bleeding.)
		[**E**] Visualise arteries.
	III.2 Identify, localise and manage collecting system lesions.	[**S**] Continuous suture of lower resection bed closes smaller lesions.
		[**S**] Compressing parenchyma helps prevent leakage.
		[**S**] Mental fusion of kidney position, location and size of lesion, lumen and orientation of collecting system help to prevent blocking of segments of the collecting system with sutures.
		[**C**] CT imagery data and nephrometry scores are preoperative indicators for probability of collecting system lesions.
		[**C**] Visual recognition of collecting system tissue.
		[**C**] Administer dye into collecting system to detect leakage.
	III.3 Identify, localise and manage major vessel lesions.	[**S**] Suture strongest bleeding vessel, then strongest bleeding remaining vessel, etc., until remaining vessels do not require individual treatment (see below).
		[**S**] In case of continued bleeding: Improve previous suture, augment suture, replace suture, coagulate vessel, or clip vessel. [*Note: One participant commented that the use of clips entails postoperative safety risks*.]
		[**C**] Apply early unclamping (i.e. unclamping before full renorrhaphy has been complete) to detect sources of bleeding.
		[**C**] Reduce peritoneal pressure to detect sources of bleeding.
		[**E**] Visualise blood vessels crossing the resection area.
	III.4 Prevent and manage visibility issues due to profuse bleeding.	[**S**] Nephrometry scores indicate probability of major vessels in the resection area.
		[**S**] High quality CT arterial phase helps detect all relevant major vessels to prevent profuse bleeding.
		[**S**] Avoid early unclamping to prevent profuse bleeding.
		[**S**] Remove blood by suction to identify source of bleeding.
		[**S**] Increase peritoneal pressure to reduce bleeding.
		[**S**] Apply compression to reduce bleeding.
		[**E**] Intraoperative visualisation of blood vessels.
		[**E**] Visualise source of bleeding.
	III.5 Distinguish vessels which require individual suturing from those which do not.	[**S**] Suture all visible vessels individually.
		[**S**] Select based on lumen and strength of bleeding.
		[**S**] Suture all arteries individually, select veins based on lumen and strength of bleeding.
		[**C**] Observe experienced surgeons perform the procedure to form standard for which size of vessels require individual suturing.
		[**E**] Visualise arteries.
		[**E**] Quantify and visualise strength of bleeding.
	III.6 Problem: Undetected lesions of collecting system or vasculature.	*No solution reported by participants.*
	III.7 Problem: In deep incision sites, the first suture	[**S**] Replace the previous suture.

Surgical phase	Challenge	Strategies [S], cues [C], and explicitly expressed information needs [E]
	can contract the resection too far to apply further sutures.	
IV Other	**IV.1** *Step 2.1*: Trocar placement is challenging in retroperitoneal approach due to very limited space.	*No solution reported by participants.*
	IV.2 *Step 2.4*: Trocar placement is patient-individual and challenging due to robot arm trajectories and constraints.	[**E**] Algorithm for ideal placement with maximum tumour accessibility and minimum robot arm interference.
	IV.3 *Step 4.2*: Intraparenchymal tumours are difficult to detect intraoperatively, despite use of ultrasound.	*No solution reported by participants.*
	IV.4 *Step 4.6*: The kidney may have to be fully mobilised. In laparoscopic surgery, holding the kidney in position binds one of the available tools (and arms) for the duration of the procedure.	*No solution reported by participants.*

Appendix C

Translated version of the SUS (Chapter 6).

VP: _____ Methode: _____

Bitte geben Sie an, wie sehr Sie die folgenden Aussagen ablehnen, bzw. wie stark Sie den folgenden Aussagen zustimmen.

Bitte beziehen Sie sich dabei auf die gerade durchgeführte Registrierungsmethode.

	Starke Ablehnung 1	2	3	4	Starke Zustimmung 5
1. Ich glaube, ich würde dieses System häufig benutzen.					
2. Ich fand das System unnötig komplex.					
3. Ich fand das System einfach zu benutzen.					
4. Ich glaube, dass ich technische Hilfe bräuchte, um dieses System zu benutzen.					
5. Ich finde, dass die verschiedenen Funktionen des Systems gut integriert sind.					
6. Ich finde, es gibt in dem System zu viel Inkonsistenz.					
7. Ich glaube, die meisten Menschen würden die Benutzung dieses Systems schnell erlernen.					
8. Ich finde das System sehr aufwendig zu benutzen.					
9. Ich habe mich bei der Benutzung sehr sicher gefühlt.					
10. Ich musste viel lernen, bevor ich anfangen konnte, das System zu benutzen.					