# Collaborative Virtual Reality for Laparoscopic Liver Surgery Training and Planning

**DISSERTATION**

*zur Erlangung des akademischen Grades*

**Doktoringenieur (Dr.-Ing.)**

angenommen durch die Fakultät für Informatik
der Otto-von-Guericke-Universität Magdeburg

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# Zusammenfassung

Chirurgische Trainings- und Planungssoftware für die laparoskopische Leberchirurgie ist für die mentale Vorbereitung, die Unterstützung der Entscheidungsfindung sowie die Verbesserung der psychomotorischen Fähigkeiten essentiell. Desktop-basierte Systeme sind leicht zugänglich, bieten jedoch im Vergleich zu Virtual-Reality-Systemen (VR-Systemen) nur eingeschränkte Interaktions- und Visualisierungsmöglichkeiten. Zudem sind ein kollaboratives Training und die Planung mit mehreren Chirurgen nur begrenzt möglich.

Das Ziel dieser Arbeit ist die Erforschung neuartiger immersiver VR-Anwendungen zur Unterstützung von Ärzten bei der Ausbildung, Planung und interprofessionellen Zusammenarbeit in der laparoskopischen Leberchirurgie. Dies kann sowohl in einer gemeinsamen Umgebung als auch räumlich getrennt stattfinden. Zunächst wird eine kollaborative VR-Umgebung für die Ausbildung in der laparoskopischen Leberchirurgie erforscht und entwickelt. Hierfür werden laparoskopische chirurgische Joysticks verwendet und in einen virtuellen Operationssaal integriert. Laparoskopische Verfahren, wie die Simulation von Schnitten in Echtzeit, werden in diesem Zusammenhang anhand von Patientendaten realisiert und ausgewertet. Außerdem wird eine Möglichkeit für das interprofessionelle Teamtraining innerhalb der laparoskopischen Umgebung vorgestellt. Ziel ist es, die intraoperative Kommunikation zwischen Chirurgenteams und Anästhesisten während Eingriffen zu verbessern und zu trainieren. Dazu werden zwei medizinische Trainingsszenarien ausgearbeitet und von Experten bewertet. In einem weiteren Schritt wird eine kollaborative VR-Umgebung für die Planung von Leberoperationen untersucht. Hierbei erfolgt eine Verbesserung der Resektionsplanung durch eine erweiterte virtuelle Resektionstechnik sowie eine Echtzeit-Visualisierung der Risikokarte. Schlussendlich wird eine fortgeschrittene chirurgische Trainingsumgebung entwickelt, welche die vorgestellten Prototypen für das laparoskopische Training, das interprofessionelle Teamtraining und die Planung der Leberchirurgie in einer Umgebung zusammenführt. In diesem Kontext wird eine Technik zur Optimierung der Gruppennavigation in der kollaborativen VR-Umgebung präsentiert.

Jede Umgebung wurde von Fachleuten in einer Nutzerstudie evaluiert. Die Ergebnisse liefern wertvolle Erkenntnisse über potenzielle Vorteile sowie klinische Anwendbarkeit und beinhalten Feedback für weitere Verbesserungen. In dieser Arbeit wird ein neuer Ansatz für die Zusammenarbeit bei der chirurgischen Planung und Ausbildung vorgestellt. Dieser bildet die Grundlage für eine umfassende klinische Bewertung, lässt sich auf andere chirurgische Disziplinen übertragen und eröffnet neue Wege für die künftige chirurgische Ausbildung.

# Ehrenerklärung

Ich versichere hiermit, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe; verwendete fremde und eigene Quellen sind als solche kenntlich gemacht. Insbesondere habe ich nicht die Hilfe eines kommerziellen Promotionsberaters in Anspruch genommen. Dritte haben von mir weder unmittelbar noch mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen.

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Magdeburg, den 31.08.2022

Vuthea CHHEANG

# Collaborative Virtual Reality for Laparoscopic Liver Surgery Training and Planning

**DISSERTATION**

*for the academic degree of*

**Doctor of Engineering (Dr.-Ing.)**

accepted by the Faculty of Computer Science
Otto-von-Guericke University Magdeburg

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# Abstract

Surgical training and planning software in laparoscopic liver surgery is essential in providing mental preparation, supporting decision making, and improving psychomotor skills. Desktop-based systems are easily-accessible. However, they provide limited interaction and visualization possibilities compared to virtual reality (VR) setups. Moreover, collaborative training and planning among surgeons are only viable to a limited extent.

Within this dissertation, the aim is to investigate novel immersive VR to support physicians in laparoscopic liver surgery training, planning, and interprofessional collaboration in a co-located or remote environment. First, a collaborative VR environment for laparoscopic liver surgery training is investigated and developed. Laparoscopic surgical joysticks are used and integrated into a virtual operating room, and laparoscopic procedures, such as real-time cutting simulation on real patient data, are developed and evaluated. Second, an environment for interprofessional team training in the laparoscopic setting is proposed. The aim is to improve and train intraoperative communication between surgical teams and anesthesiologists during laparoscopic procedures. Therefore, two medical training scenarios are proposed and assessed by experts. Third, a collaborative VR environment aimed at liver surgery planning is investigated. This objective is to improve virtual resection planning with an enhanced virtual resection technique and a real-time risk map visualization. The last objective of this dissertation is to develop an advanced surgical training environment, which is an integration of proposed prototypes of laparoscopic training, interprofessional team training, and liver surgery planning, into one environment. Moreover, a group navigation technique is proposed to optimize the navigation processes in the collaborative VR environment.

Each proposed environment was evaluated by domain experts in a user study. The results reveal valuable insights on potential benefits, clinical applicability, and feedback for further improvement. This dissertation presents a new approach for collaboration in surgical planning and training. It builds a basis for extensive clinical evaluation, transfers to other surgical disciplines, and opens new directions for future surgical training.

# Declaration of Authorship

I hereby declare that I have prepared this dissertation without prohibited external assistance and without using any tools other than those indicated. All sources of information, including my own publications, are clearly marked. I did not make use of any commercial consultant concerning graduation. Third parties have not received any monetary benefits from me, either directly or indirectly, for work related to the content of the dissertation.

In particular I have not consciously:

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- plagiarized data or publications,
- misrepresented research results of other researchers in a distorted way.

I am aware of the fact that violations of copyright can lead to injunctive relief and claims for damages of the author as well as a penalty by the law enforcement agency. The work has not been submitted in the same or a similar form as a dissertation, neither in Germany nor abroad, and has not been previously published in full.

Magdeburg, 31.08.2022

Vuthea CHHEANG

# Contents

# List of Publications

## Journal Articles

- **Vuthea Chheang**, Florian Heinrich, Fabian Joeres, Patrick Saalfeld, Bernhard Preim, and Christian Hansen. WiM-Based Group Navigation for Collaborative Virtual Reality **(Under Review)**. *Computers & Graphics*, 2022.
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## Doctoral Symposium

- **Vuthea Chheang**. Collaborative Virtual Reality for Laparoscopic Liver Surgery Training and Planning. *FIN Doctoral Symposium*, Otto-von-Guericke University Magdeburg, Magdeburg, Germany, July 13, 2021.

# Chapter 1

# Introduction

## About this chapter

This chapter gives an overview of the current challenges for laparoscopic liver surgery planning and operating room team training, which are the motivation of this dissertation. The use of virtual reality for medicine is introduced and summarized. Moreover, the main contributions, as well as the dissertation structure, are described.

## 1.1 Introduction

In recent years, liver surgery has been performed more commonly as laparoscopic surgery, also known as minimally invasive surgery [1]. Laparoscopic surgery is performed using small incisions with the support of a laparoscopic camera in the patient's abdomen. This intervention provides many benefits for patients compared to open surgery because it uses smaller incisions that result in less blood loss, less pain, low infection risks, and shorter times for recovery. However, it poses high demands on the surgeons. During the laparoscopic procedure, the surgeons do not have a direct view of the incisions and they rely on the fast imaging modalities from the camera to see and understand the current positions and surrounding organs. Therefore, laparoscopic surgery training is a crucial task for mental preparation and skill training. Current virtual training simulations for these procedures are limited due to the usage of conventional 2D screens with an out-of-context surrounding, which cannot provide a realistic representation of the training environment. Furthermore, those systems do not allow for the use of real patient data, which is crucial for training [2–5].

Immersive virtual reality (VR) has advanced to a point where this technology can be used for various fields, especially medicine [6–9]. Using VR provides a larger field of view (FOV), intuitive 3D interactions, and improved spatial perception compared to desktop-based systems [10]. The exchange of knowledge and collaboration among surgeons are currently conducted by face-to-face meetings, audio/video calls, or even social media [11]. In-person team meeting can reduce the chance of miscommunication. However, this is challenging to achieve during situations that require over-distance collaboration, e.g., during a COVID-19 pandemic [12].

Collaborative VR allows multiple users to join and work together in the same virtual environment, regardless of whether they are co-located or remote [13]. The users can be represented with realistic avatars leading to a highly immersive VR experience [14]. Additionally, collaborative VR shows great potential and can be used to improve communication and team training [15, 16]. Nonetheless, current systems for surgical planning and training provide inadequate interaction possibilities and limited training scenarios during laparoscopic procedures [17–20].

## 1.2 Contributions

This work aims at investigating and providing new approaches to support surgeons and surgical trainees for laparoscopic liver surgery training and planning in the collaborative VR environment. In the following sections, the main contributions of this dissertation are described, including a collaborative VR for laparoscopic liver surgery

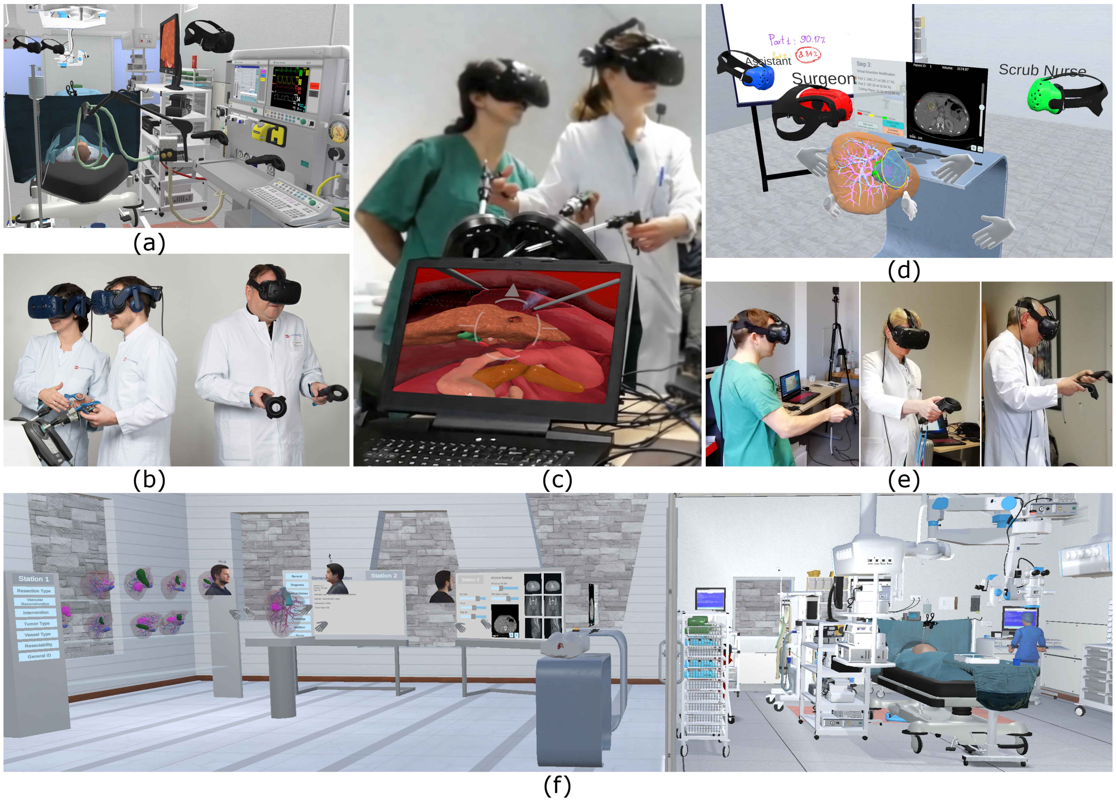


FIGURE 1.1: An overview of the proposed collaborative VR for laparoscopic liver surgery training and planning: (a) collaborative users virtually perform laparoscopic procedures in the virtual operating room, (b) interdisciplinary team (surgeon, assistant, anesthesiologist) performs in the real world, (c) laparoscopic simulation for collaborative training, (d) collaborative environment for liver surgery planning, (e) users in the real world remotely join into the shared virtual environment, and (f) users with photo-realistic avatars perform surgical planning and training in an advanced surgical training environment.

training, interprofessional team training, liver surgery planning with a virtual resection and risk map visualization, and an advanced surgical training environment as well as a proposed group navigation technique (see Figure 1.1).

### 1.2.1 Collaborative VR for Laparoscopic Liver Surgery Training

Training of surgical procedures with numerous training sessions is a prerequisite for surgical trainees. In addition, laparoscopic surgery training is an essential way to improve the psychomotor skills of trainees, i.e., hand-eye coordination and spatial orientation. Using real patient data including liver, tumors, and vascular structures is beneficial for training the surgical trainees. Therefore, the aim is to design and develop a laparoscopic simulation including cutting, bleeding, and clipping features in the collaborative environment. As the focus is on improving communication and teamwork, only a low degree of realism for cutting simulation is necessary. Two modes are developed for laparoscopic surgical procedures: exploration and surgery mode. Moreover, laparoscopic surgical joysticks (Simballs) are used to provide psychomotor skills training and enable surgeons to cooperate as teamwork.

### 1.2.2 Collaborative VR for Interprofessional Team Training

Communication and team-building between surgeons and anesthesiologists during laparoscopic intervention are crucial for a successful surgical outcome. A prototype focusing on operating room training scenarios is developed for an interprofessional team between surgeons, camera assistants, and anesthesiologists. In addition, a layer to interface a standard anesthesia simulation software is proposed. This layer aims to connect and integrate the patient's vital signs into the VR environment. Two training scenarios are presented to tackle critical situations during the intervention, i.e., undetected bleeding and insufficient muscle relaxant medication.

### 1.2.3 Collaborative VR for Liver Surgery Planning

Most of the surgical operations can be performed when the results of virtual resection planning showed a potential resection to remove all the cancer tissues, e.g., a liver tumor. Therefore, preoperative planning is crucial for surgeons in understanding essential information that would help them make accurate decisions and increase their patients' long-term survival rates. Surgical planning software is based on virtual resection and supports surgeons in defining and estimating resection volume and visualizing affected structures. This contribution aims at developing a collaborative VR environment to support surgeons in liver surgery planning procedures. The technique for virtual resection planning is enhanced and adapted into the immersive VR environment. Furthermore, the resection margins, tumor contours, and a risk map visualization are presented to display the distance from tumors to surrounding vessels and resection surface.

### 1.2.4 An Advanced Surgical Training Environment

For comprehensive surgical planning and training, it is essential to provide all related information, including patient history, medical image data, and results of virtual resection planning. In this contribution, an advanced surgical training environment, also referred to as a *virtual teaching hospital*, is proposed to improve team training that ranges from the planning procedure with patient data exploration to laparoscopic training in the operating room. All proposed environments presented in this dissertation are enhanced and integrated into this environment. Moreover, an integration with photo-realistic avatars is presented. Medical data for each patient's case is synchronized across the different rooms, allowing the users to view, analyze, and train on key decision points from diagnosis to surgical incision.

### 1.2.5 A Group Navigation Technique for Collaborative VR

Group navigation is an essential tool to arrange group members in a certain configuration in VR. To provide an effective environment for collaboration, group navigation in the collaborative VR environment is further investigated. A group navigation technique based on *World-in-Miniature*, hereafter referred to as *group WiM*, is proposed. It could allow a leader to control and navigate a team within a miniature replica of the entire virtual environment. A comparative evaluation was conducted to reveal the technique's usability and discomfort, and to provide insights when compared to a state-of-the-art group teleportation technique.

## 1.3 Structure

This dissertation is structured as follows:

- Chapter 2 provides a brief overview of medical and technical background for subsequent chapters. An overview of the human liver, laparoscopic liver surgery, and general anesthesia are described. Furthermore, the technical background of VR and collaborative VR are detailed in this chapter.
- Chapter 3 summarizes related work of VR simulations for laparoscopic surgery training, liver surgery planning, and anesthesia training. This chapter also gives an overview of the related work on co-presence and team training in the immersive VR environment.
- Chapter 4 presents a collaborative VR environment for laparoscopic liver surgery training. The requirements and system architecture as well as the integration of laparoscopic surgical joysticks are described.
- In Chapter 5, an environment for interprofessional team training among surgeons and anesthesiologists is investigated. Two training scenarios were identified and developed related to surgical complications, such as *undetected bleeding* and *insufficient muscle relaxant medication*.
- Chapter 6 describes a collaborative VR environment for liver surgery planning. A virtual resection technique with a deformable resection surface is enhanced into the immersive VR environment. Additionally, a risk map and visualization details, e.g., tumor contours and projection of resection lines, are presented.

- Chapter 7 describes an advanced surgical training environment for liver surgery planning and training, which is a combined prototype of proposed environments reported in this dissertation.
- In Chapter 8, a group navigation technique for collaborative VR environments is proposed and described. The technique aims to allow the group members to navigate together and to arrange and create a group formation based on their roles.
- Finally, Chapter 9 summarizes this dissertation by giving a summary of the proposed collaborative VR environments and the findings. Moreover, limitations and potential research directions for future work are discussed.

# Chapter 2

# Background

## About this chapter

In this chapter, an overview of the medical background of laparoscopic liver surgery, the importance of anesthesia, and surgical phases are described. In addition, the technical background of mixed reality, virtual reality, and the collaborative VR environment are summarized and explained.

## 2.1 Medical Background

In this section, an overview of medical background, which is relevant for subsequent chapters, is described.

### 2.1.1 The Liver

The liver is a large organ in the abdominal anatomy that is located in the right region of the belly. The most well-known functions of the liver are to regulates chemical levels in the blood, filter the blood that comes from the digestive tract, and excrete bile [21]. Moreover, the liver makes important proteins for blood clotting, detoxifies the blood of chemicals and metabolizes drugs, as well as other functions [22]. The terminology of liver anatomy and resections was proposed as a standard for liver segments by the terminology committee of the International Hepato-Pancreato-Biliary Association (IH-PBA) [23]. The segmental liver anatomy was described as the first, second, and third order division.

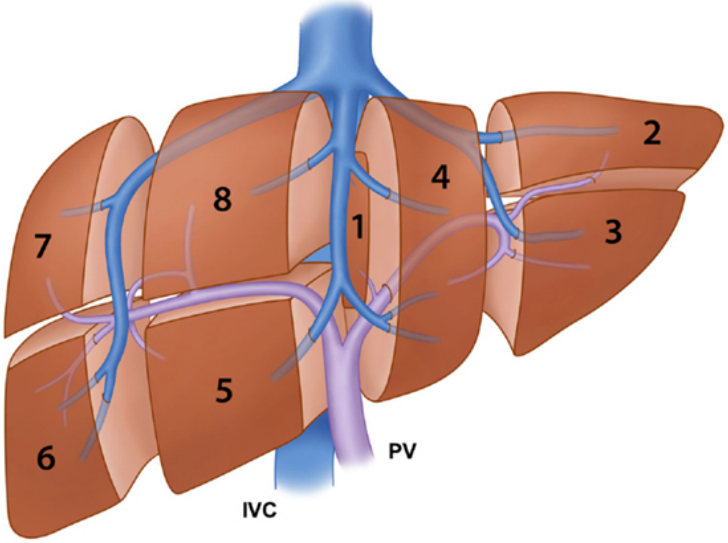


FIGURE 2.1: Segmental anatomy of the liver. *Figure from Orcutt et al. [24] ©2016 Frontiers.*

Figure 2.1 illustrates the classification of the liver anatomy. First, second, and third order branches of the portal tree divide the liver into two parts (left and right liver), four parts (right posterior and anterior section, and left medial and lateral section), and eight individual segments. This division, which is called Couinaud classification, is the most widely accepted definition in the context of hepatectomy [25]. Additionally, the major resections of the liver can be achieved by understanding this definition of segmental anatomy and related major vascular structures [26].

The decision for liver surgery is to decide the amount of parenchyma to be resected. Additionally, blood loss is one of the main factors that influence the outcome of the resection [27]. Hence, it is essential to consider different vascular structures and occlusion techniques to perform liver resection safely and minimize the blood loss [28]. The techniques for liver resection are based on the liver resection type, number of tumors, tumor location and size, pre-operative results for liver function, and importantly the vascular control [29].

### 2.1.2 Laparoscopic Liver Surgery

Laparoscopic intervention, which is referred to as a minimally invasive surgical technique for liver surgery, has been developed and became a wide-adopted standard procedure [30, 31]. The remarkable growth in laparoscopic intervention, including laparoscopic cholecystectomy, is because of improvements in technologies and various laparoscopic instruments to support the intervention [32]. Figure 2.2 illustrates the setup for trocar placement on the patient. The placement of the trocar ports for laparoscopic surgery is dependent on the requirement of the intended procedure. Moreover, the variety of laparoscopic devices can provide the choices for surgeons to help them determine the operative procedures based on their personal experiences and the preferences of the surgical team.

FIGURE 2.2: The setup of laparoscopic trocar placement for laparoscopic liver resection. *Figure from Angelico et al. [33] ©2019 Elsevier.*

The advantages of laparoscopic surgery are to reduce the pain of patients, reduce the size of the surgical incision, decrease blood loss, decrease infection risk, and shorten recovery time for patients [34]. Additionally, results of a study from Fretland et al. [35] indicate that laparoscopic surgery had significantly less postoperative complications and the preparation was more cost-effective compared to open surgery.

The intervention of laparoscopy is supported by a laparoscopic camera (laparoscope). Usually, the view of the laparoscopic camera is projected on a monitor near the patient. Hence, the hand-eye coordination, which is the coordinated control between eye and hand movement, is one of the major challenges for surgeons [36, 37]. This limitation can impede the spatial-awareness and subsequent effect of orientation on motor skills [38]. Furthermore, the haptic feedback from laparoscopic graspers that enables surgeons to perceive tactile information between instrument and tissue is still deficient [39]. Therefore, the laparoscopic intervention requires highly skilled surgeons and has a steep learning and training curve [40].

### 2.1.3 Anesthesia

The aim of general anesthesia is to prevent patients from feeling pain during medical treatment. General anesthesia is also crucial for surgical interventions by preventing any damage [41]. There are not only physical risks that can cause pain for patients after surgery, but there is also the risk of psychological trauma. General anesthesia is usually combined with inhaled gasses called anesthetics and intravenous drugs. When a patient is narcotized by the general anesthesia, there are three main types of narcosis that will effect the nervous system: the reduction of the sensation in feeling pain (analgesia), the reduction of consciousness, and the reduction of muscle movement (muscle relaxation).

#### Vital Signs Monitoring

During the surgery, an anesthesiologist is responsible for monitoring the vital signs of the patient with different medical measurements. The monitoring of vital signs is needed before, during, and after the surgery to guarantee the well-being of the patient. Generally, the vital signs of medical measurements are displayed on a monitor with an attached respirator and inhaled gasses. The anesthesiologist can monitor and adjust the gas according to the situation of the patient. The most important vital signs for monitoring the patient include:

- Pulse (heart rate) measures how often the heart contracts and pumps blood into the body in every minute. It is measured as beats per minute (bpm).
- The arterial blood pressure (ABP) indicates the blood pressure in the arteries. There are two types of ABP: systolic value (the pressure of the blood when the

heard is contracting) and diastolic value (the pressure in the arteries when the heart muscle relaxes between beats).

- Train of Four (TOF), known as a peripheral nerve stimulator, is used to measure the muscle relaxation. Most basically, it assesses the neuromuscular transmission while the neuromuscular blocking agents are given to block movements of the musculoskeletal system.

### 2.1.4 Overview of Surgical Phases

The perioperative period is a term that describes three distinct phases of surgical procedure, such as preoperative phase, intraoperative phase, and postoperative phase. These procedures aim to differentiate the tasks and responsibilities for delivering and maintaining the patient care.

- **Preoperative phase:** The preoperative phase is an initial stage for planning and deciding whether or not to have the surgery. This phase also includes surgical consultation and pre-assessment. It is crucial to evaluate the patient's history, medical image data, and health condition. Moreover, surgical planning is conducted in this period. The majority of surgical operations can be performed when preoperative planning shows the potential resection results needed to remove the cancerous tumors. Hence, surgical planning software is essential to support the surgeons in visualizing the resection volume, affected vessels, and safety margins.
- **Intraoperative phase:** The intraoperative phase refers to the surgery itself. The patient will be prepared and given general anesthesia. Furthermore, the patient's well-being can be monitored by the vital signs, including heart rate, arterial blood pressure, and respiration. There are many roles during this phase. In addition to the role of the surgeon, camera assistant, and anesthesiologist, other members such as scrub nurses will also be involved in the procedure to assist and ensure the safety of the patient.
- **Postoperative phase:** The last phase is known as the postoperative phase. This includes patient care, rehabilitation, and recuperation. Patient care during the postoperative phase is concerned with monitoring physiological health and providing support for a full recovery.

## 2.2 Technical Background

This section is intended to provide an overview of the technical background regarding mixed reality (MR), augmented reality (AR), VR, and the collaborative VR environment.

### 2.2.1 Extended Reality

Extended reality (XR) is a term that includes all immersive technologies, including MR, AR, and VR. MR is an extensive concept that describes the sense between the real and virtual environment [42] (see Figure 2.3). With this reality-virtuality continuum, a real environment refers to the physical world, and AR is described as part of a mixed element between the real and virtual environment. AR is mostly used to view the real environment with mapped virtual objects that are augmented by computer-generated sensory. For augmented virtuality (AV), it describes the virtual environment that maps the real-world objects and allows for interactions within this environment. A virtual environment is commonly referred to as VR that support the computer-generated world.

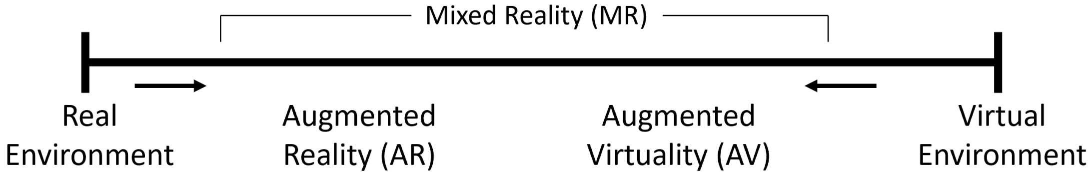


FIGURE 2.3: Reality–virtuality continuum. *Adapted from Milgram et al. [42].*

Table 2.1 provide a conceptual overview of the components necessary for computation and representations in the MR environment [43, 44]. The objects and sensing data in the real world are obtained from the camera and sensing devices. This data is fundamental for recognizing and tracking the region of interest (ROI) and information essential for spatial and event mapper in the virtual environment.

Recognizer refers to the software component for identifying and finding the actions of the captured images and sensing data. Moreover, the recognizer analyzes the signals, e.g., motion, gesture, or interaction from the real world to map with the event mapper in order to process an event in the virtual environment.

Tracker is the software module that is required to process the captured data provided by the sensing devices. It includes color conversion, background removal, and image processing. Furthermore, the tracker mainly refers to the tracking of objects in order to determine the location and identify the ROI.

Spatial mapper aims to support the embedding of the spatial data into the virtual environment. It provides spatial information obtained from the tracker, including position, orientation, and scale. Additionally, it can be used to map the physical objects into the MR scene by applying calibration and supplying mapping information.

Event mapper refers to the process of event mapping between the real world and the virtual world. It creates a relationship between the event functions and events that are recognized by the recognizer. For example, a user may perform a gesture in the

| Dimension | Input | Output |
|---|---|---|
| Sensor / camera | Signal from the real environment | Sensor and capturing data |
| Recognizer | Raw or processed data provided by the sensor / camera and target object recognition | Recognized event or target object |
| Tracker | Processed sensing data recognized by the recognizer | Characteristics of the recognized target signals, e.g., position, orientation, etc. |
| Spatial mapper | Identified sensing data and spatial information | Calibrated spatial information for mapping in a mixed reality scene |
| Event mapper | Identified event and information provided by spatial mapper | Translated event and action information |
| Renderer | Scene data in the mixed reality scene | Rendering outputs |
| Display/UI | Rendering scene data | Display output to the display devices |

TABLE 2.1: Component attributes represent in the mixed reality scene. *Adapted from ISO/IEC 18040:2019 [43].*

real world, and the event mapper triggers an event in the virtual world based on this recognized gesture.

Renderer is a component that integrates the results of spatial and event mappers into the rendering module. It includes the processes for generating data, simulation updates, and rendering outputs to a given display device. The rendering can be varied depending on the hardware and display types, e.g., rendering to a web browser, mobile, PC, and stereoscopic rendering for VR.

Display and user interface (UI) refer to hardware components that are used to process the presentation of the system to the end user. The display includes monitors, head-mounted display (HMD), projectors, and AR glasses. In addition, the specifications of display, e.g., resolution and refresh rate, are required for some systems in order to provide a good experience and quality display. Apart from the display, the UI refers to the component that can be used to capture user interactions. There are many types of UI sensors to modify the state of MR scene such as gesture, voice, and gyro sensing data.

### 2.2.2 Virtual Reality

VR technology has become popular in recent years. With the advent of new HMD devices, they can replace the real world with a completely virtual environment. VR commonly refers to the computer-generated environment that offers a rich sensory experience [45, 46]. It has been utilized for many purposes, such as entertainment, game, education, and training. Unlike the UI that is displayed on a conventional monitor, VR allows the users to step deeply inside an experience of a virtual world that can be similar or completely different from the real world. Levels of immersion in VR can be categorized into three primary simulations: non-immersive, semi-immersive, and fully-immersive environments [47].

- Non-immersive VR (desktop VR) systems provide the least experience of the virtual environment. It is commonly used in everyday life e.g., video games. This type of VR simulation allows the user to keep aware of the physical environment and the inputs rely on keyboards, mice, and controllers. For example, when a user views the virtual environment through one or more monitor screens, the user can interact within that environment, however, it is not deeply immersed into the virtual environment.
- Semi-immersive VR systems provide the user with a partially immersive experience of virtual environment. This kind of simulation can provide immersive perception when the user focuses on the VR environment which is often displayed on a high-resolution display or projectors, however, the VR simulation still allows the user to remain connected to the physical surroundings.
- Fully-immersive VR systems let the user completely immerse in the virtual environment. With the advent of HMD in recent years, it can be used to provide the fully-immersive VR experiences with intuitive interactions in the virtual environment. The display of VR headset splits between the user's eyes and provides a high-resolution VR content with a large field of view.

### Positional Tracking

Positional tracking is essential for VR to track and allow for movement in the immersive environment. Apart from the mobile VR headsets that provide only the rotational tracking with only three degrees of freedom (DoF), recent VR headsets for computer and console VR mostly come with two types of tracking: outside-in and inside-out tracking.

***Outside-In Tracking*** This form of tracking is adapted for most of the VR headsets so that the hardware, such as headset and controllers, is set up inside a VR-room scale tracking by using the lighthouse system. The advantages of using this type of tracking are related to accuracy and latency. Since the lighthouse trackers remain in fixed places, the tracking can provide adequate accuracy. To increase the accuracy, more lighthouse trackers can be added. However, one of the main limitations for the outside-in tracking is an issue regarding occlusion. Thus, it might require more than one tracker in order to provide better tracking. In addition, the tracking area is limited due to the range of sensors.

***Inside-Out Tracking*** With this tracking form, the camera is placed on the headset to track and determine its current position related to the physical environment. Therefore, it is required to track continuously when the headset moves so that the position can be updated in real time. Using inside-out tracking can provide more freedom to the user without a restricted tracking area. Additionally, it does not require a complicated setup with the base station or lighthouse trackers. Nonetheless, issues regarding accuracy and latency might occur with the inside-out tracking [48]. This includes the computer vision's computation that needs to re-coordinate the tracking space continuously. Apart from that, issues for multi-user VR experiences might occur for co-located physical presence. Thus, it means the users can see each other through the video see-through camera. However, the tracked position for user avatars might be different from where they are located.

### 2.2.3 Collaborative Virtual Reality

A collaborative VR environment, also known as multi-user VR, is a networked computer simulation that allows multiple users in shared or remote locations to connect and make interactions within a shared virtual environment (see Figure 2.4). A prior study from Broll et al. [49] indicated that the synchronization of interactive objects in the collaborative environment would not be possible with the current technology at that time. The reason was due to delays caused by network distribution [50]. However, many studies in the following years demonstrated the utilization of the collaborative VR environment for various fields, including medical education, planning, and training [17, 51, 52].

#### Types of Collaborative VR

- Co-located collaborative VR – This refers to the setup where the users are located in the same tracking space and are connected and immersed into the same shared virtual environment.
- Remote collaborative VR – This is a setup where all users are remotely connected and joined into the same shared virtual environment.
- Mixed collaborative VR – This is a mixed setup where some users are located in the same tracking space and some users are remotely joined into the same shared VR environment.

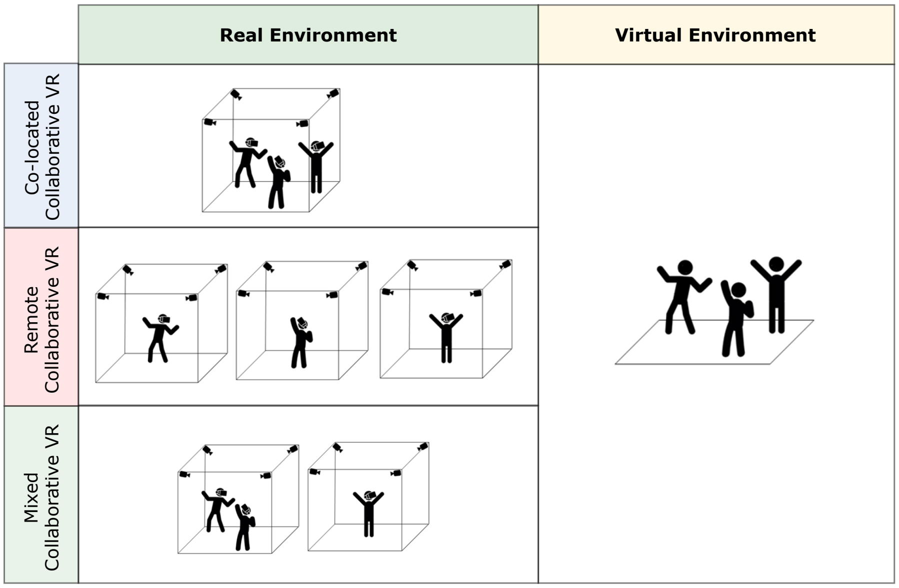


FIGURE 2.4: Types of collaborative VR based on different presences in the real environment. *Adapted from Podkosova [53].*

### Effective Collaboration in VR Environment

Otto et al. [54] discussed the factors that influence the collaboration within the virtual environment (see Figure 2.5). They stated that the cooperative work in VR must be supported by the systems that enable natural communication and interaction. In addition, Paiva et al. [18] discussed the requirements to improve team training in VR environments. Besides providing the immersive experience, the VR systems should consider the tasks for individual and team members in a collaborative manner. The requirements also include the reliability of data transmission and collaborative VR synchronism. While teleconferencing systems attempt to offer support for collaboration, there are difficulties, such as sharing virtual objects and immersive interactions. Different factors that influence effective collaboration in the virtual environment are described as the following:

**Technology factors:** The HMD is used to block the visual stimuli from the physical world and instead replaces it with the virtual environment with a limited FOV. While higher FOV provides better immersion in VR, it requires high resolution with available pixels, high update frames, and low latency. In addition, recent tracking systems for HMD setup enables natural movements and precise tracking which allow a high degree of experience in VR [17, 55]. A UI refers to the hardware and software that allow the interaction between the users and computers. Technically, it includes input and output devices that support the user experiences, e.g., mice, keyboards, tracking systems, and

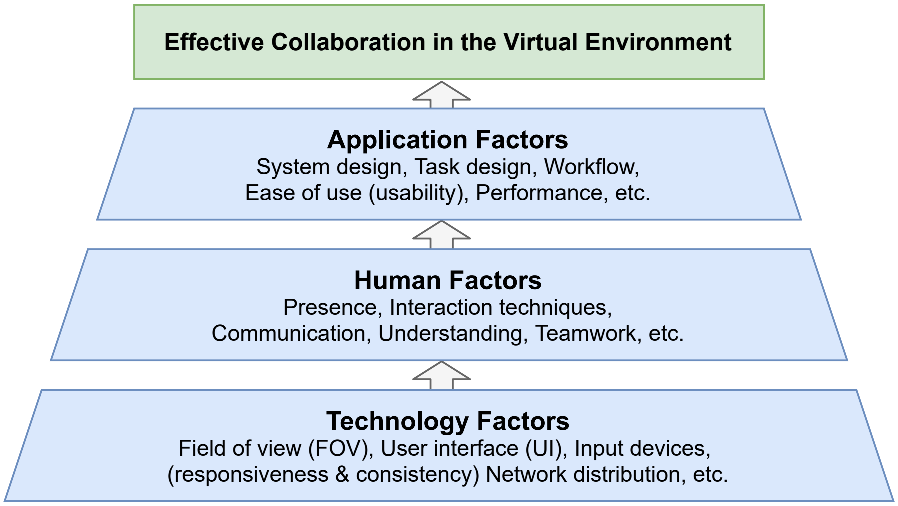


FIGURE 2.5: Different factors influence the collaboration in the virtual environment. *Adapted from Otto et al. [54].*

monitors, as well as software entities. However, the input devices, such as VR controllers, data gloves, VR pens, and 3D joysticks, significantly influence the experience and collaboration in the virtual environment.

To provide collaboration between users, all interactions are required to distribute to other users through a network connection. Moreover, social communication and perception between users in the collaborative VR environment are supported by the virtual avatars which are tracked and handled by the live tracking data. The distribution can be affected by network delays. Traditional desktop-based applications designed to use with mouse and keyboard interactions generate low bandwidths for data synchronization. However, the current setup for collaborative VR generates a large amount of tracking data which are necessary to update and synchronize for other users, e.g., positions and orientations of generated avatars. Aside from the internet speed provided from network hardware, possible solutions can be a reduction of tracking data to fit a level of user perception and reducing redundant updates of tracking data by filtering or prediction [56–58].

Buhr et al. [59] describes the factors for VR latencies, including tracking, transport, simulation, rendering, and display latencies. Wolff et al. [60] presented a study to analyze the event traffic and the characteristics of data stream during a highly collaborative task using both immersive and desktop displays. The results show high event peaks and high input rates through tracking in the immersive displays. Moreover, the motion tracking could cause update events which have a significant impact on the performance of the collaborative VR environment. Thus, understanding of event traffic, including user activity, display interface, and network resources during shared manipulation of virtual objects helps in the design and enhances the distribution for collaborative tasks [61, 62].

**Human factors:** Individual user experience may affect the collaboration in the virtual environment. It is important to consider the factors such as presence and interaction techniques which are essential in providing support for communication, understanding, and teamwork [63, 64]. Communication among users is crucial for teamwork in the collaborative VR environment because it allows users to express their actions, build an understanding of the work process, and achieve the task goals. Four primary elements are required to provide social communication in the collaborative VR environment: verbal, non-verbal, object references, and environment references [54, 65]. Verbal communication supports the linguistic ability, i.e., speech, while non-verbal communication refers to body language, including gesture and posture. Hence, a combination of 3D avatars and the live tracking data to represent the users is essential in providing social communication. These avatars can be improved even more by providing eye-tracking, lip-sync, photo-realistic avatars, unintentional gestures, and posture changes while speaking [66, 67].

Object references refer to surrounding objects or objects of interest that provide the context of understanding for communication. The users may communicate and discuss surrounding objects, but they would also want to manipulate and interact with them [68]. Environment references include the scenes, virtual rooms, or the environments that support collaboration and communication. For example, the users may discuss, navigate, and teleport within the environment [69, 70]. In addition to verbal and non-verbal communication, thus, objects and environment are essential in supporting social communication.

**Application factors:** To provide an effective collaboration in VR, it is not sufficient to focus only on technology and human factors. The most crucial parts for system design such as task design, workflow, usability, and task performance should be evaluated.

Task design is required to incorporate the needs of the users. In addition, a collaborative task, including concurrent object manipulation, requires a design to support user collaboration [13, 71]. For example, providing a user role to perform a specific task. Furthermore, the collaborative task has to support the communication and interaction techniques. Two forms of collaboration should be considered to design a task: synchronous and asynchronous collaboration [72, 73]. In the synchronous collaborative approach, the users perform actions and manipulate the shared objects concurrently. This means the remote users can manipulate and operate the modifications on the same or different properties of virtual objects in real time [74]. For example, the surgeon and camera assistant perform the surgery on the same operative field of the patient. In the asynchronous collaborative approach, users perform actions or manipulate the object properties sequentially. For instance, an anesthesiologist induces the patient into a narcosis state so the surgeon and camera assistant can begin the surgical operation.

### 2.2.4 Usage of Input Devices for VR Applications

In recent years, tracking systems have been developed and provide better accuracy and latency for VR applications [55, 75, 76]. Huber et al. [77] presented a custom setup for VR laparoscopy application by integrating a laparoscopic simulator with their joysticks and VR headset. The results of their testing show that the technical performance in VR showed no significant difference compared to the standard laparoscopic simulator. Additionally, Li et al. [78] evaluated the usability of the laparoscopic setup in the virtual operating room. The results show that the participants were highly engaged to perform the task using laparoscopic input devices while experiencing the immersive environment. In the following, the usage of input devices for VR application, including stylus devices and wearable data gloves, is described.

***Stylus devices*** Stylus devices have been used in VR applications, including haptic devices such as the Geomagic device, and non-haptic devices such as VR Ink, Massless Pen, Wacom VR Pen, zSpace Ink [79–81]. Besides the Geomagic device, which is often used for medical training [82–84], other devices are designed for VR sketching in mid-air [85, 86]. Pham et al. [87] compared pointing devices, including a mouse, VR controllers, and a pen-like device, within an immersive environment. The 3D pen-like device was preferred and significantly outperformed the VR controllers regarding the pointing task.

Fellion et al. [88] demonstrated a prototype with stylus interaction techniques to improve UI navigation and selection. Moreover, Yu et al. [89] introduced an interaction technique with the use of VR Ink that allows the user to perform virtual annotations on the virtual human head. Their results indicate that the technique could perform remotely between VR and AR, and preserve the usability and annotation precision. A hybrid selection technique to simultaneously interact objects in mid-air was proposed by Montano et al. [90]. Their setup allows the user to hold a real tablet and a real pen with the attached VR controllers for haptic feedback. Kern et al. [91] presented a framework using mixed reality input devices for handwriting and sketching in VR. Regarding sketching, Yu et al. [92] presented a VR modeling system that allows freehand sketching in mid-air. With this, they show that mid-air sketching in the immersive environments provides potentials for 3D design processes.

***Wearable data gloves*** Bakker et al. [93] presented a haptic feedback device using *Manus data gloves* and a custom setup. The results show that it could provide natural and intuitive interactions, however, the ergonomics need to be improved. Mizera et al. [94] evaluated the performances of three hand-tracking devices, such as *Leap Motion*, *VRFree gloves*, and *Manus data gloves*, for virtual dexterous manipulation. Their results indicate that using data gloves provides accurate tracking of angles for fingers compared to hand-free tracking. *Manus data gloves* were more robust to changes in configurations; however, their drawback is the lack in precision regarding the thumb position.

The work of Caggianese et al. [95] compared the controllers and a *Leap Motion* in a virtual environment. The study evaluated participants over three tasks. These tasks involved moving a square block from one place to another, stacking up the square blocks to a tower, and sorting square blocks according to the number written on them. Their results suggest that participants were accurate and more comfortable in performing these tasks when using the controllers than a *Leap Motion* controller. These results have been further solidified by another study by Navarro and Sundstedt [96]. They conducted a study with VR controllers and a *Leap Motion* controller using two games. The first game involved throwing balls at a target. The other was to solve a jumbled puzzle involving shapes. Their results indicate that participants using VR controllers were far more accurate in both games. From these studies, it can be observed that the *Leap Motion* controller performed poorly when matched against the controllers. These studies show that the *Leap Motion* controller had difficulties due to its tracking and occlusion problems when the hands were out of sight or in front of each other.

Several studies have been conducted to evaluate the use of input devices, touchless interactions, and haptic feedback for medical applications [97, 98]. However, there is a small number of related work focused on the evaluation in medical immersive VR applications [99–101].

## 2.3 Conclusion

This chapter provides an overview of the medical and technical background, which are related to the research reported in this dissertation. In the medical background, the liver anatomy, surgical techniques for liver surgery, and the overview of surgical phases are described. For technical background, an overview of XR technology and collaborative aspects in VR, as well as the usage of input devices, are summarized. In the next chapter, related work of the research presented in this dissertation is described.

# Chapter 3

# Related Work

## About this chapter

This chapter describes an overview of related work for VR-based laparoscopic surgery simulations, VR systems for liver surgery planning, anesthesia training simulations, and the co-presence in VR. Moreover, related work of collaborative VR for surgical training and planning is described.

FIGURE 3.1: Laparoscopic training setup with an integration of VR headset and laparoscopic simulator in modelled surrounding (left) and 360 degree video-based environment (right). *Figure from Huber et al. [107] ©2017 Springer.*

FIGURE 3.2: The setup of the laparoscopic simulation in the virtual operating room with virtual assistants: replicated operating room surrounding in VR (left) and an external view of a surgical trainee in the physical world (right). *Figure from Li et al. [78] ©2020 IEEE.*

## 3.1 VR Simulations for Laparoscopic Surgery Training

Training of laparoscopic procedures is crucial and requires many training sessions. Various VR-based simulations are proposed and developed to provide psychomotor training and preparation to reduce the risk of intervention [3, 102]. Some simulations are currently used in clinical routine to improve the skills and surgical techniques [103]. Pan et al. [104] presented a desktop-based VR simulation for laparoscopic cholecystectomy. The presented simulation is based on position-based dynamics (PBD) to deform the organs with a hybrid multi-model connection method. Their simulation has been applied to several hospitals for laparoscopic cholecystectomy training. Qian et al. [105] proposed a similar desktop-based VR for laparoscopic surgery training system based on PBD. They integrated a soft tissue deformation with haptic feedback using spherical collision detection and dissection method. Pan et al. [106] introduced a haptic simulation system for laparoscopic rectum surgery with a hybrid model to handle collision detection and deformation of the intestines. While most of the research on surgical simulation focuses on specific topics, e.g., deformation, haptic feedback, and dissection, the training scenarios of the simulation use an abstract graphic design instead of using real patient cases. They also lack collaborative scenarios and use desktop-based rather than the immersive VR environment.

The immersion and perception of training environments can help trainees to gain experience and skills accordingly. Huber et al. [77, 107] conducted preliminary clinical and technical feasibility studies of using immersive VR for surgical training by integrating VR-HMD and a commercial laparoscopic simulator (LapSim, Surgical Science, Gothenburg, Sweden). Their results reveal that the surgical trainees experienced a high level of presence. They also found that rare instances of motion sickness occurred during the testing. Additionally, performance results showed no significant difference compared to the standard training simulation. They further conducted a study comparing surrounding environments with 360 degree video and 3D modelled environment [108] (see Figure 3.1). The environment of 360 degree video was preferred by participants because it provided more realistic surroundings. Nonetheless, video-based surroundings can provide a view from one fixed position and limits possibilities for interactions. Moreover, their presented system is limited due to the availability of advanced training scenarios for patient cases and collaborative training.

Li et al. [78] evaluated the usability and presence of a commercial laparoscopic simulator inside a virtual operating room (see Figure 3.2). The results show that the surgical trainees were highly engaged in completing the training tasks. Moreover, very slight discomfort of VR experience was reported in the study. Another study from this research group was also conducted to determine the effectiveness of VR for procedural training in laparoscopic surgery [109]. The results indicate that using VR with an operating room setup for procedural training has potential and could be a useful tool for training. However, further optimizations of realism and additional disturbance factors in the operating room could result in improvements to the effectiveness.

## 3.2 VR Systems for Liver Surgery Planning

Liver surgery planning is commonly based on 2D image data acquired from computed tomography (CT) or magnetic resonance imaging (MRI). It is challenging because it requires high skills and experience, especially in visual thinking. Planning with 3D visualization generated from these images allows the surgeons to understand complex structures and improve the confidence for planning [110–112] (see Figure 3.3). Hansen et al. [113] presented the methods to determine the risk structures and safety margins for 3D visualization in liver surgery planning (see Figure 3.4). While desktop-based systems show potential for resection planning, several studies indicate that using immersive VR could provide a better environment when compared to the desktop-based

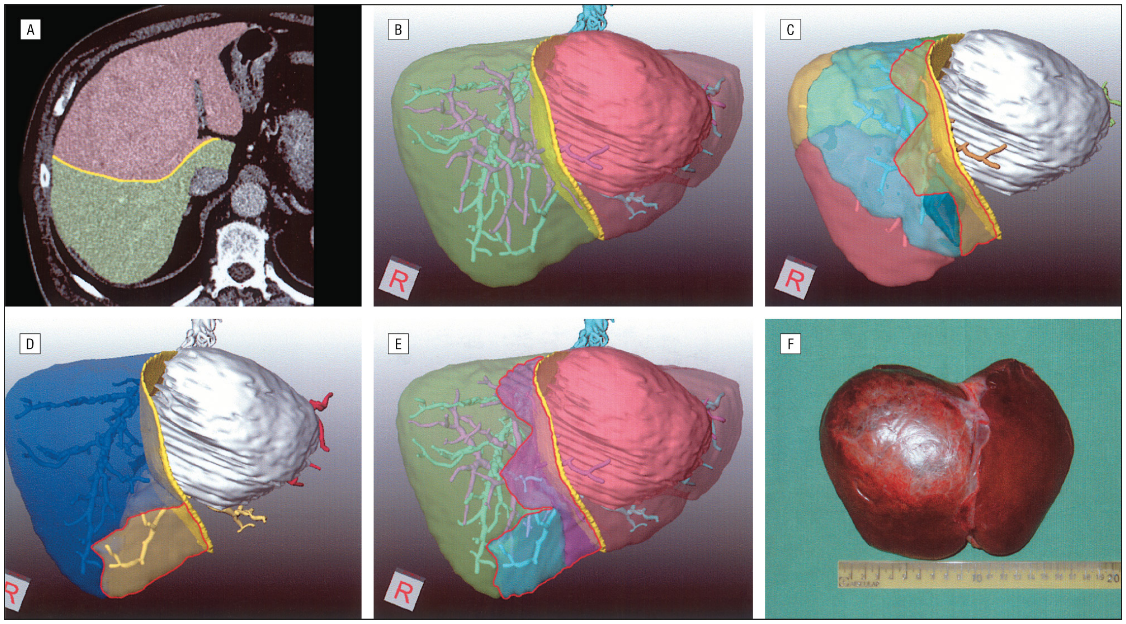


FIGURE 3.3: Computer-assisted risk analysis for liver surgery planning with the computation of volumetric risk. (a) resection planning in 2D computed tomography, a resection plane, yellow; remnant volume, green; and resected parenchyma, red. (b) the resection planning in 3D. (c) Territories of the portal vein within the remnant liver volume and their visualizations according to the definition of liver segmentation. (d) the visualization of territories within the remnant draining (blue) and devascularized area (red bordered). (e) a combination of territories at risk; risk territory for portal vein, magenta; risk for hepatic vein, cyan; remaining functional volume for liver tissue, green. (f) liver resection specimen after extended left hepatectomy in centimeters. *Figure from Lang et al. [110] ©2005 JAMA Surgery.*

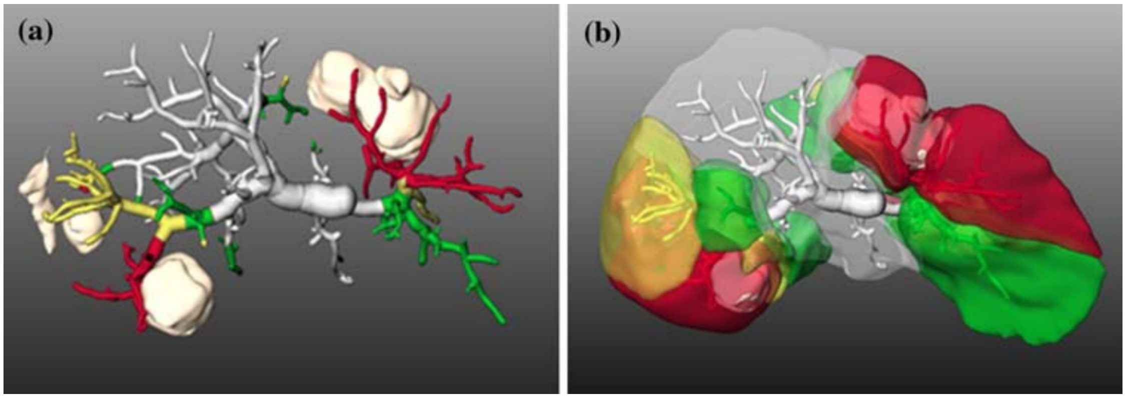


FIGURE 3.4: Risk map analysis for affected vessels in preoperative planning for liver surgery: (a) safety margins of 5 mm to affected vessel branches and (b) analysis of territories at risk. *Figure from Hansen et al. [113] ©2009 Springer.*

approach [114–117].

VR has advanced to a state where it can be used to provide better visualization and interaction that could significantly affect surgical training, planning, and education [8, 119, 120]. The main advantage of VR is to view and interact with virtual objects freely in

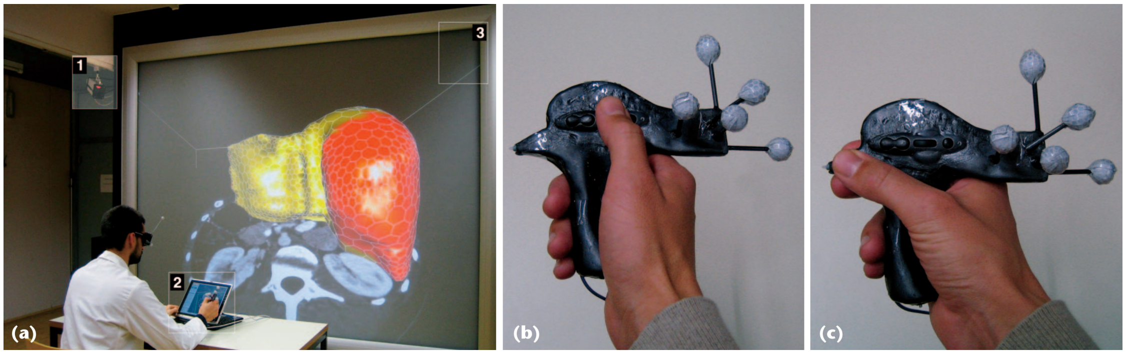


FIGURE 3.5: Liver surgery planning system using hybrid VR setup: (a) the setup with optical tracking system, (b) 3D interaction with power grip, and (c) precision grip for 2D interaction. *Figure from Reitinger et al. [10] ©2006 IEEE.*

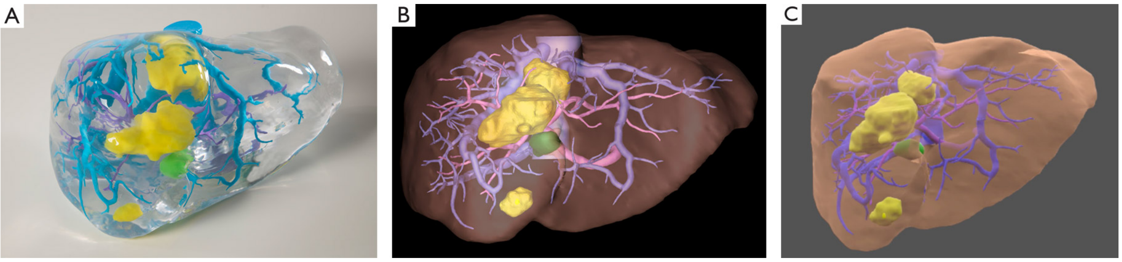


FIGURE 3.6: A comparison of patient's individual liver model visualized as a 3D printed version (a), as a 3D PDF (b), and as a 3D model in VR (c). *Figure from Huettl et al. [118] ©2021 Annals of Translational Medicine.*

the 3D space with a stereoscopic 3D view and depth perception [121]. In the following, the related work of VR systems for liver surgery planning is described.

Reitinger et al. [10, 122] proposed a hybrid VR environment using a tablet PC for liver surgery planning (see Figure 3.5). Their results indicate that using VR with a wide FOV is beneficial for the surgical planning procedure, especially spatial perception. They also presented hybrid input devices for object manipulation that can improve user interactions more intuitively [75]. Saalfeld et al. [76] presented a semi-immersive system to measure and explore patient medical image data for treatment planning. Their setup uses a HMD and a stylus from a zSpace device for user inputs. Besides immersive VR, Kumar et al. [123] demonstrated a MR-based system for surgery planning. Their findings show that MR has a high acceptance for clinical use cases. It provides a better understanding of patient-specific anatomy and improves surgical planning compared to conventional planning systems.

Kenngott et al. [124] presented a cross-professional evaluation to assess the potential of immersive VR environment for liver surgery planning. They found that the highest potential was seen in student training followed by resident training and clinical routine usage. Hattab et al. [125] investigated the utility of VR for spatial understanding in surgical planning compared to the desktop screen. The results show that the learning condition between VR and desktop did not influence the participant's memory and confidence ratings. However, the model type significantly affected the memory regarding internal structures inside the model. Boedecker et al. [126] presented a VR system to load and enable virtual 3D models for preoperative liver surgery planning. The results indicate that using VR was easy to use and may have advantages compared to 3D PDF and 3D print for surgical planning. In addition, Huettl et al. [118] presented a preclinical study to compare between the 3D PDFs, 3D printed models, and 3D VR models for liver surgery planning (see Figure 3.6). They found that the 3D printed models and 3D VR models enable a better and slightly faster anatomical orientation compared to the visualization on 3D PDFs.

## 3.3 Anesthesiology Training Simulations

A full-scale simulator for anesthesia training was introduced by Gaba et al. [127] in the last two decades. This proposed simulator then became a basic standard for scenario-based skills training. A variety of high-fidelity simulators, i.e., Laerdal learning application (LLEAP), are widely used in anesthesiology training program. Moreover, the VR-based simulation on the monitor screen have been developed for years. However, desktop-based simulations are also currently in the stage of early adaptation for anesthesia training [128]. Immersive VR technology has been innovated and shown a great potential for training. Adoption with immersive VR training is also still limited to some clinics and academic institutions. This might be due to the current state of VR simulation development, as well as challenges compared to high-fidelity mannequins.

VR-based simulation training for anesthesia can be used to improve clinical skills such as diagnosing, monitoring, and planning [129, 130]. However, rare events or scenarios for training during laparoscopic surgery procedures are demonstrated [131]. Grottke et al. [132] presented a simulation for anesthesia training with multi-model representations in the virtual environment. Katz et al. [133] introduced a serious game to train anesthesiology management in orthotopic liver transplantation procedure. Moreover, Shewaga et al. [134] proposed a VR-based serious game to train anesthesia-based crisis management. Nonetheless, their presented simulations use the single-person training while Krage et al. [135] claimed that using the single-person training could make the trainees believe the problems can be resolved alone.

## 3.4 Co-presence in the Virtual Environment

The term co-presence refers to the sense of being together and can be understood in two ways: the sense of being together with others in a *shared virtual environment* and the sense of being together with other users in a *remote environment* [136]. Moreover, the sense of being together in the virtual environment, whether a remote or co-located physical space, can be considered an impact that influences the experience of social presence [137]. Co-presence in virtual environment is essential because it provides the perception and immersion of collaborative experiences. Furthermore, the users can communicate and build teamwork as they perform in the real world.

Rios et al. [70] presented an experiment with users' locomotor behavior in collaborative VR when two users share the same virtual environment. The results illustrate the differences in users' preference between the real and VR world. The users awareness of other users' presence in physical space seems to make them pay attention to the movements and velocities. Podkosova et al. [64] conducted a study on the proxemics and co-presence in the shared virtual environment. Their results indicate that the perception of users with co-located and distributed users, as well as proxemics, are different.

Salimian et al. [138] introduced a toolkit for co-presence in mixed reality by augmenting virtual objects in the physical environment. Furthermore, the results of their study with respect to users' preference did not show that it is relevant to other collaborative approaches. In addition, Gugenheimer et al. [139] presented a system with co-located experiences between VR-HMD and no-HMD users. Their results indicated that the shared VR environment increases presence, enjoyment, and social interaction compared to the baseline condition. However, the enjoyment of non-HMD users was higher than VR-HMD users.

Liang et al. [140] evaluated the effects of user's navigation behavior between paired users and a single user in the virtual environment. Their results illustrate the different patterns as well as gender differences in behavior and performance. Female users performed better for the single mode, while male users performed better in the paired users tasks. Christensen et al. [141] presented a study on users' experience between a VR and non-VR multi-player game. Their results illustrated that the user's experience in VR was rated higher than the experience in non-VR game. There is also a study on different strategies used to steer the users from each other in order to reduce collisions in the virtual environment [142]. Thus, understanding of users' behaviors and co-presence in the virtual environment are helpful to define and improve the design and implement of collaborative environment more efficiently.

## 3.5 Collaborative VR for Surgical Training and Planning

In recent years, collaborative VR has shown as an essential research topic for industry, entertainment, education, and medicine. It allows multiple users to join, experience, and manipulate virtual objects within the shared virtual environment. Furthermore, it supports communication, collaboration, and teamwork that leads to significant effects on medical education and training. The team can communicate, discuss, and share information to build a shared mental model and confidence to avoid surgical errors [143]. In the following, the related work of desktop-based and immersive VR for collaboration in medicine is described.

Jung et al. [144] proposed a web-based system for team collaboration with medical visualization and exploration. Their system allows users to explore medical data with their computing devices, e.g., smartphone, tablet, and computer. However, the proposed system did not provide the spatial perception in the immersive environment. Diaz et al. [62] presented a networked virtual surgical simulator for collaborative surgical training. They described the technical requirements of the network, i.e., packet loss, bandwidth, and network delay that have a significant impact on the consistency of collaborative environment. Paiva et al. [18] introduced a desktop-based collaborative VR simulator for surgical education. They also discussed the requirements and networking issues to provide a collaborative simulator for surgical teamwork education and networking issues [145]. The requirements, e.g., individual tasks, collaborative tasks, and simulated surgical procedure, are illustrated and are essential for designing the collaborative prototype.

FIGURE 3.7: Multi-user VR system for orthopedic surgery training. *Figure from Papagiannakis et al. [146] ©2018 ACM.*

Papagiannakis et al. [146] introduced a VR-HMD system for cooperative learning in orthopedic surgery training and education (see Figure 3.7). Their system allows the users to perform different medical scenarios on a knee arthroplasty simulation in the immersive environment. Christensen et al. [147] presented a VR system for team training in robot-assisted minimally-invasive surgery. However, they indicated that the system was not ready to use in actual medical training because it can lead to confusion in real-life feasibility. Additionally, Cecil et al. [148] proposed a networked-based VR simulation for medical residents in orthopedic surgery training. They also compared between a haptic simulator and immersive simulator. The results of their study reveal that the immersive VR simulator was rated higher than the desktop-based with haptic feedback in terms of user's experience. Elvezio et al. [149] introduced a system with low-latency interactions for collaborative VR. Their results show that the collaboration in immersive environment is more effective when network latency is below 15 ms. Moreover, it will be further improved when the latency is about 3-7 ms. Prasolova et al. [150] introduced a VR-based training environment for interprofessional team collaboration and communication with a role of anesthesia. Their results with respect to interprofessional team training conclude that the medical trainees felt more engaged and motivated, and they agreed that using collaborative VR can provide the value of a clear communication and teamwork.

FIGURE 3.8: Collaborative mixed reality environment for team training. *Figure from Cordar et al. [20] ©2017 IEEE.*

Liu et al. [151] presented a collaborative VR system for volumetric data visualization and Kockro et al. [152] proposed a collaborative environment to explore and examine medical imaging data for neurosurgical planning. Their study results confirm that the collaborative environment represents a unique forum for team discussion and enables future teaching methods for relevant domain knowledge. Butnaru et al. [153] proposed a networked cave automatic virtual environment (CAVE) for bone surgery planning. Their work demonstrated that VR technologies are efficient and suitable for surgery planning, e.g., bone fractures. Bashkanov et al. [154] presented a multi-user VR conference room environment for surgery planning. The proposed environment allows users to join with represented 3D model avatars and explore with an enlarged 3D liver model. Fischer et al. [155] proposed a system for volumetric medical image visualization that supports multi-user VR interactions. They claim that their proposed system is capable of real-time performance and high-quality visualization, which can be useful for medical diagnosis.

In addition to the immersive VR, there are some works that provide collaboration in a mixed reality environment. Cordar et al. [20] presented a simulation system that allows anesthesia residents to meet and collaborate with the team in a mixed reality representation on large monitor screens (see Figure 3.8). Additionally, Brunges et al. [156] introduced a similar technology for interdisciplinary teams. The results of their experiment indicated that ineffective team members' communication can lead to serious harm for patients. Brun et al. [157] presented a mixed-reality hologram for heart surgery with the use of the shared view from Microsoft HoloLens for collaborative users. The results from their study indicate that collaboration in the mixed-reality for surgical planning have a high diagnostic value and contributes to understanding of complex morphology.

## 3.6 Conclusion

In this chapter, related work of VR-based systems for surgical training and planning is presented. Many studies indicate that using immersive VR could improve the surgical planning procedure and enable a better anatomical orientation compared to desktop-based systems [10, 124, 126]. Moreover, usability and user experience in VR-based systems could achieve the highest scores without causing significant discomfort symptoms [118]. While most of the systems are designed as single-user VR, collaborative VR could offer greater for team collaboration [18, 155]. However, there is still a limited number of collaborative VR systems for medical specialties in the immersive VR environment, especially for surgical training and planning [17]. In contrast to previously mentioned systems in the related work, this dissertation aims at investigating the use of collaborative VR for liver surgery training, planning, and interprofessional team collaboration. Furthermore, an advanced surgical training environment and a group navigation technique for collaborative VR environments are proposed and described in the following chapters.

# Chapter 4

# Collaborative VR for Laparoscopic Liver Surgery Training

The content of this chapter is based on the following publication:

- **Vuthea Chheang**, Patrick Saalfeld, Tobias Huber, Florentine Huettl, Werner Kneist, Bernhard Preim, and Christian Hansen. Collaborative Virtual Reality for Laparoscopic Liver Surgery Training. In: *IEEE International Conference on Artificial Intelligence and Virtual Reality*, pp. 1–8, 2019.

This work was presented at the IEEE International Conference on Artificial Intelligence and Virtual Reality (IEEE AIVR), San Diego, USA, 2019. The research demonstration [158] was also invited to present along with the full-paper presentation at the conference and has been published in the conference proceedings.

## About this chapter

This chapter is organized as follows: first, an introduction and requirements identified from related work and discussions with the clinical partner are described. This is followed by a detailed explanation of system design and implementation as well as the evaluation and results. Finally, a discussion and a summary of the chapter are described.

## 4.1 Introduction

Current simulations for surgical training are limited due to the usage of conventional monitors with an out-of-context environment, lacking the realism of tasks, using abstract graphic design, interactions, and collaboration [3, 5, 16, 102, 105]. In addition, the integration of video output from the simulator and HMD is limited due to material preparation and difficulties in remote collaboration [107, 108].

In this chapter, a concept, design, and implementation of collaborative VR for laparoscopic liver surgery training are described. Different spatial input devices are integrated, especially laparoscopic surgical joysticks, and natural interaction techniques are implemented that could mimic the surgical instruments more realistically. This could also allow surgical trainees to train, communicate, and improve their psychomotor skills as a team, which are crucial for laparoscopic interventions. The collaborative tasks and data synchronization between the users during the laparoscopic procedures are presented. Two modes are implemented for team training: *exploration* and *surgery* mode. Additionally, the use of real patient cases for manipulation and visualization in VR is introduced, as it is important for training. The contributions are as follows:

- Concept, design, and implementation of a collaborative VR system for laparoscopic liver surgery training.
- Usage of real medical image data for laparoscopic procedures, including cutting and bleeding simulation.
- Insights from system performance, evaluation, and clinical feedback reveal the limitations of the presented system for future investigation.

## 4.2 Requirements

To develop an effective training system, requirements were collected during multiple meetings with our clinical partner. An initial meeting with two liver surgeons (8 and 5 years of working experience) was conducted at the University Medicine of the Johannes Gutenberg-University Mainz, Germany. The meeting served as a basis for collecting information regarding general procedures and the current training environment. Furthermore, valuable insights have been gained from discussions in regards to their previous experiences and studies, e.g., using immersive VR for surgical training [77, 107]. Several meetings, demonstrations, and continuous feedback served to optimize the system and interaction techniques during the system development. Based on these discussions and related work, the following requirements were identified:

**R1** The system has to support multiple users in the virtual environment, whether they are located in a shared or remote physical environment.

**R2** The system should provide features that support collaborative tasks for laparoscopic surgery training and planning procedures. This is essential for surgical trainees to understand the surgical process and improve their skills respectively.

  **R2.1** The users should be able to explore the patient data and conduct the planning before performing laparoscopic training.

  **R2.2** The system should provide features to support the cutting process of laparoscopic intervention with the possibility of bleeding on vascular structures and clipping. A deformable model is not required because the current state of its physical behavior was not sufficiently realistic while performing a cutting simulation.

**R3** Manipulation in laparoscopic surgery is subject to the fulcrum effect. The system should provide motor skill training during the experience in the virtual environment.

**R4** Real-time volumetric cutting might cause a resource-intensive computation. The system performance should provide an adequate frame rate (at least 60 frames per second (fps) [159, 160]) to provide a good user experience in the virtual environment.

**R5** To provide a better collaborative experience between the users in VR, the network latency should be optimized [149, 161]. It is essential, especially for synchronizing the captured view of laparoscopic camera.

## 4.3 Materials and Methods

In the following sections, an overview of system architecture, technical details, and preprocessing steps are described.

### 4.3.1 System Architecture

The system architecture of the proposed environment for laparoscopic surgery training is shown in Figure 4.1. User objects refer to the virtual objects, including 3D models of user avatar and controllers, that initiated after a matchmaking process. Server-owned/client controllable objects are owned by the master user (server), however, these objects can be shared and controlled by other clients. Moreover, user-owned objects refer to virtual objects which are stored and computed on each user's device. The idea is to reduce the network latency and avoid server's bottleneck.

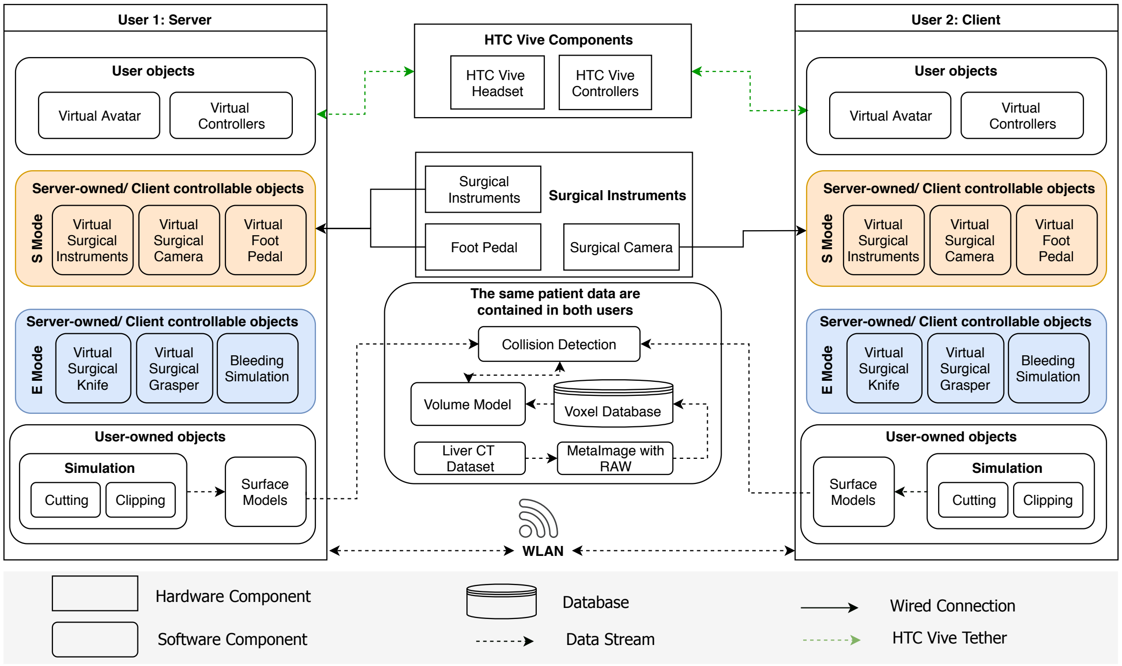


FIGURE 4.1: Overview of system architecture for laparoscopic surgery training using collaborative VR (*E*: exploration mode, *S*: surgery mode). *Figure from Chheang et al. [162] ©2019 IEEE.*

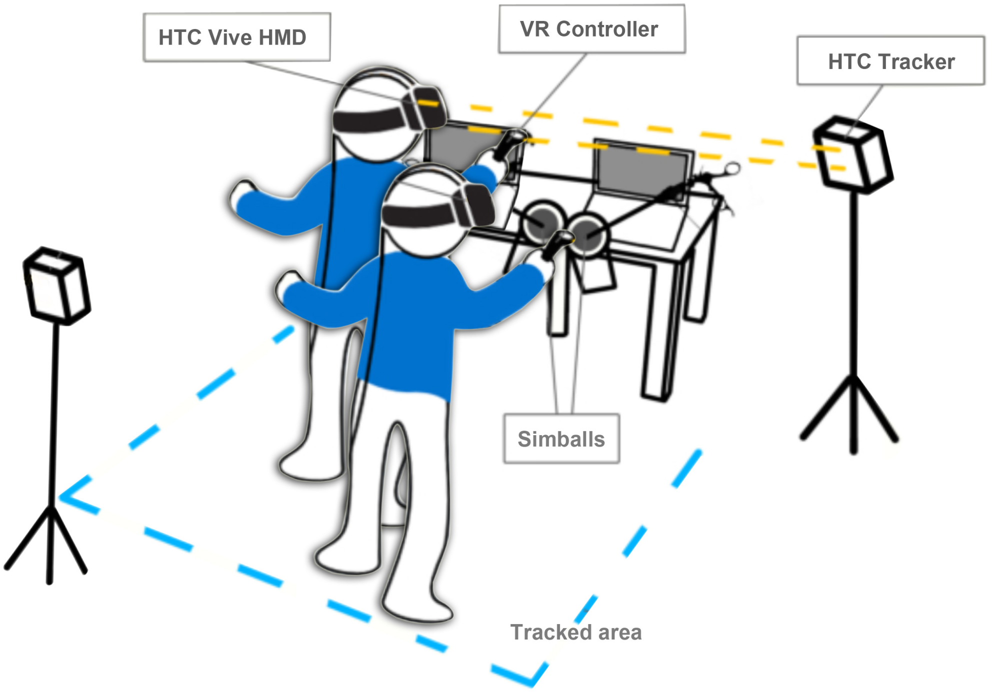


FIGURE 4.2: An overview of system setup. A room-setup is equipped with the HTC Vive headsets, controllers, and their components. *Figure from Chheang et al. [162] ©2019 IEEE.*

To enable users to connect and manipulate objects together in the shared virtual environment, and to provide useful functionalities, different technologies, e.g., Unity, Nvidia FleX, and Cubiquity, are assembled. The Unity platform is used as an environment for system development. The particle-based fluid simulation provided by Nvidia Flex is utilized for basic bleeding simulation. A sculpting function of Cubiquity is used to support the volumetric cutting. Moreover, an asset for fundamental VR interactions, Virtual Reality Toolkit (VRTK) is employed with Unity. The Unity networking (Unet) is used to realize the connection and synchronization between users. HTC Vive headsets, controllers, and their components are used for VR and system setup (see Figure 4.2).

Laparoscopic surgical joysticks with a double foot-switch (Simballs, G-coder System, Sweden) are connected and used to support laparoscopic procedure tasks (see Figure 4.3). The left and right instruments (grasper and cutting tool) and foot pedal are connected to the user 1 (surgeon). The Simball camera instrument is connected to the user 2 (camera assistant). This device is commonly used for laparoscopic training. Using this Simball joystick, it comes with laser-marked ball joints and 3 DoF. Thus, it could allow real-time calculations for the exact 3D angular positions and orientations.

### 4.3.2 Patient Data and Pre-processing

Patient CT image datasets used in the liver surgical routine are utilized in the data preprocessing step. The original image dataset was a series file of digital imaging and communications in medicine (DICOM). To support the pre-processing step, our clinical partner was asked to process the segmentation. The results are divided into different structures, e.g., the liver, tumor, hepatic vein, portal vein, hepatic artery, gallbladder, and inferior vena cava. The original image resolution was 512 × 512 × 1261. After that, the images are cropped to contain only the liver's boundaries. Thus, the resolution for cutting simulation and real-time mesh reconstruction is 242 × 223 × 350. The image data is then imported into MeVisLab software (MeVis, Germany) and smoothed with a *GaussSmoothing* filter. The reason of smoothing and reducing some resolutions is to provide a better performance for real-time cutting simulation. In Unity, the image data is stored in a database (occupancy grid data). This database is used during cutting simulation to process real-time surface reconstruction and preserve the volume density. For initial testing, two different datasets were used. The test relates to the coordination of the volumetric model for real-time cutting within the virtual phantom. Several image resolutions were also tested to analyze their impact on system performance.

### 4.3.3 Cutting, Bleeding, and Clipping Simulation

According to requirements from surgeons, a deformable model was not implemented in this prototype. For cutting simulation, a raycast is attached to the laparoscopic tool.

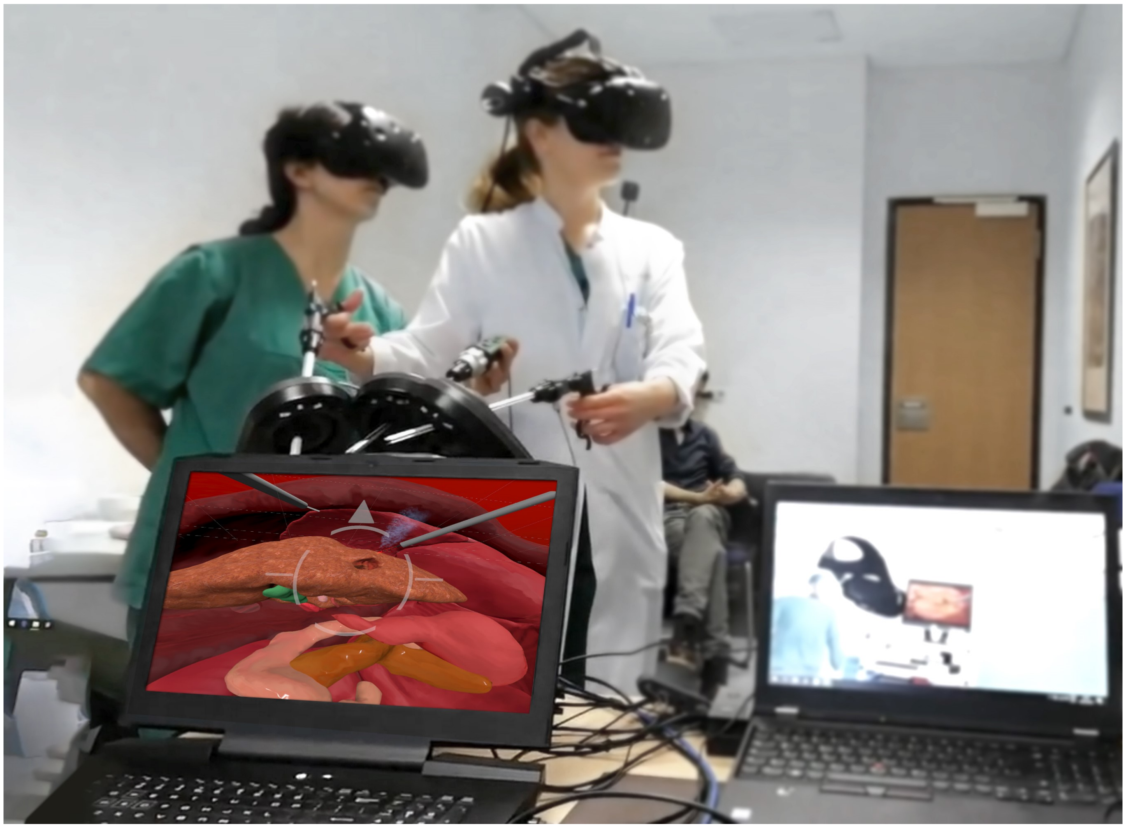


FIGURE 4.3: Laparoscopic surgical joysticks (Simballs) are used and connected to mimic the surgical instruments. Simball grasper, cutting tool, and foot pedal are connected for the surgeon while Simball camera is connected for the camera assistant. The views, positions, and orientations of the instruments are synchronized for both users via network connection.

Hence, the collision with laparoscopic tool is checked, and if there is a collision on the occupancy grid data, the mesh surface is reconstructed and a layered texture is applied to the cutting surface area with a mesh smoothing (see Figure 4.4). Thus, the volumetric model can preserve the volume density that represents the internal structure. This volumetric model is connected with a database and it is checked frequently during the cutting simulation as to whether the mesh representation is synchronized. The Marching cubes algorithm is used to generate the surface mesh. Additionally, the cutting and smoke simulations are applied when the user steps on the foot pedal.

A bleeding with fluid simulation is developed to provide basic understanding for when there is a cut in the vessels. Therefore, vascular structures are used and visualized inside the liver parenchyma model. Furthermore, a possibility to clip the bleeding vessel is provided. The users should be cautious of vascular structures inside the liver during the cutting. Hence, if there is a cut in the vessel, bleeding will occur from the cutting point.

The users can stop the bleeding by using the laparoscopic grasper to place a clip onto

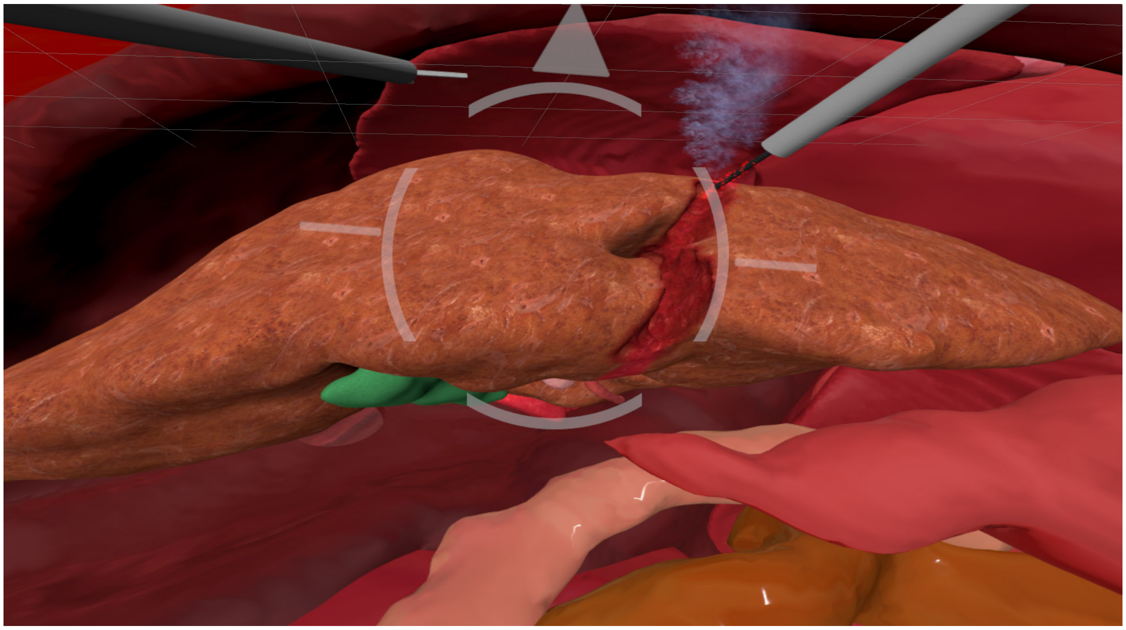


FIGURE 4.4: Cutting simulation for laparoscopic procedures in the surgery mode. *Figure from Chheang et al. [162] ©2019 IEEE.*

the bleeding vessel. While there is a collision on the bleeding vessel, the users can step on the foot pedal to place a clip. As long as the clip is placed on the vessel, the bleeding will stop. This approach could allow the surgical trainees to perform the training in a realistic setup of laparoscopic procedure. The proposed laparoscopic simulation also provides the possibility of training with a semi-transparent model. This feature reveals the inner structures, such as vessels and tumors, to help train and to help provide a mental understanding of hand-eye coordination.

### 4.3.4 Exploration Mode

The aim of exploration mode is to provide a basis for exploration and planning of patient data before performing laparoscopic procedures (see Figure 4.5). Therefore, the collaborative users connect into the virtual room and perform the data exploration. An enlarged 3D organ model including inner-structures and tumors is provided with various options for exploration, e.g., semi-transparent and cutting simulation.

### 4.3.5 Surgery Mode

In a laparoscopic setting, an experienced surgeon generally controls the surgical instruments, while a *camera assistant* controls the laparoscopic camera (see Figure 4.6). To provide training in the laparoscopic setup and improve the motor skills, the laparoscopic joysticks are used in this mode. The virtual operating room was designed and the 3D objects re-positioned according to feedback from the clinical partner. Furthermore, the

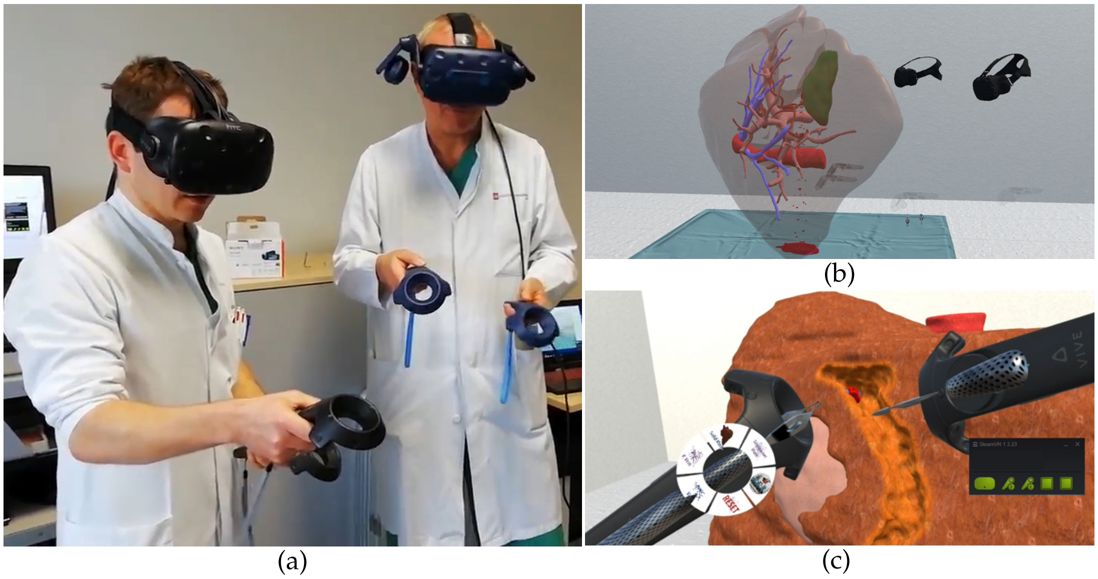


FIGURE 4.5: Two surgeons use exploration mode to explore the patient data before performing laparoscopic procedure: (a) surgeons perform in the real world, (b) the semi-transparent model reveals inner structures, and (c) the cutting simulation is provided with the clipping possibility on the vessels. *Figure from Chheang et al. [158] ©2019 IEEE.*

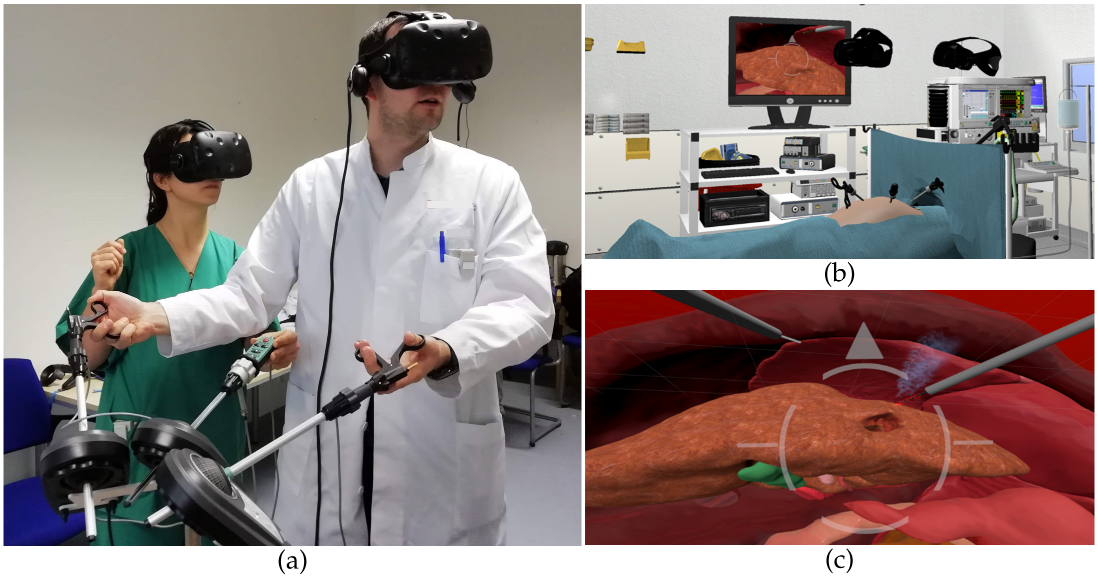


FIGURE 4.6: Two surgeons perform the surgery mode of laparoscopic procedure: (a) surgeons perform in the real world, (b) surgeons virtually collaborate in the virtual operating room, and (c) the cutting simulation. *Figure from Chheang et al. [158] ©2019 IEEE.*

patient organ models are placed inside a virtual phantom in a setup of the operating room. These organs are captured by the laparoscopic camera controlled by the camera assistant. The captured view from the camera is projected to a virtual monitor close to the phantom. Thus, to perform the training, one surgeon holds the Simball's grasper and cutting tool and uses the foot pedal to activate the intervention. Additionally, the other surgeon controls the Simball camera to provide adequate visualization of the view inside the belly. With the development of synchronization over the network, both users are allowed to see the captured view and simulation simultaneously. Hence, this procedure can enable the surgical trainees to communicate, cooperate, and advance their psychomotor skills.

## 4.4 Evaluation

A pilot study was conducted to evaluate the proposed collaborative VR prototype. The aim was to evaluate the usefulness and usability of the exploration and surgery mode as well as collect feedback for further improvement. The system was demonstrated to a group of surgeons from the department of general, visceral and transplant surgery, University Medicine of the Johannes Gutenberg-University Mainz, Germany. Three participants (two male, one female) were general and visceral surgical residents. All participants had previous experiences with desktop-based laparoscopic simulators. An introduction and exploration of the system were conducted before performing the procedure. During the performance, feedback from the participants was recorded. The Think-Aloud protocol was followed and the participants were asked to perform all possible interactions. After the exploration was complete, the participants were prompted to share their overall impression and feedback. Moreover, they were asked to fill a standard questionnaire for quantitative evaluation. The *meCUE* user experience questionnaire (module I) was used [163]. The questionnaire was divided into two sections for each mode. There were six questions for each section with a seven-point rating scale from "strongly disagree" to "strongly agree".

### 4.4.1 Apparatus

Two computers were used for initial testing. The first computer that starts the application acts as the server while the following computer performs as the client. The server (user 1) was equipped with an Intel® Core™i7-8700K CPU @3.70GHz (12 CPUs) processor, an NVIDIA GeForce GTX 1080 (8GB VRAM) graphics card, and 32GB of RAM. The client (user 2) was equipped with an Intel® Core™ i7-7820HQ CPU @ 2.90GHz (8CPUs) processor, an NVIDIA Quadro M2200 (4GB VRAM) graphics card, and 32GB of RAM. The room scale was set up with the HTC Vive trackers. Moreover, a WiFi router (NETGEAR R6120) was used for network connection.

## 4.5 Results

In the following sections, results of the pilot study are described.

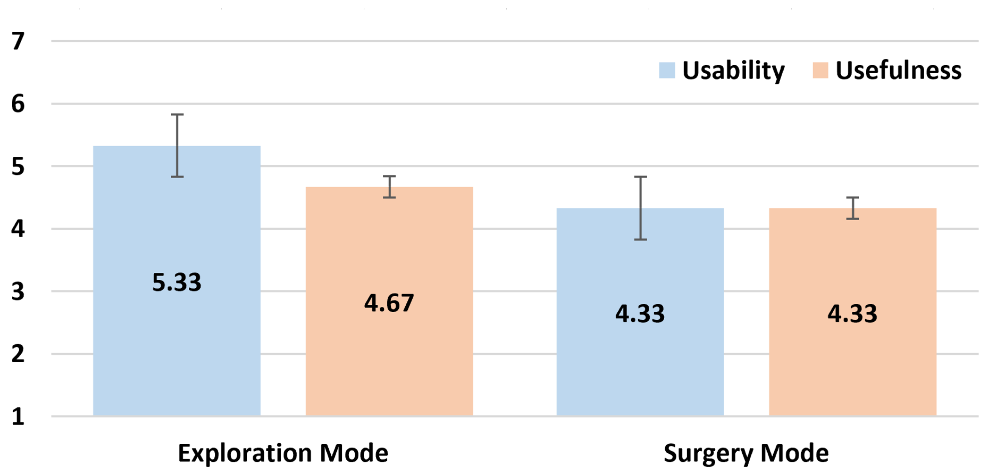


FIGURE 4.7: Results of the user experience questionnaire.

### 4.5.1 Usefulness and Usability

All participants expressed positive feedback with the proposed two modes in the collaborative VR environment. The use of real patient data for training was assessed as an advantage compared to previous training simulators. The proposed collaborative VR provides possibilities for medical exploration, interaction, and training with laparoscopic simulation as a team in the immersive environment. This provides a good basis for operating room team training and further clinical evaluation. For exploration mode, the participants stated that the system helps to visualize and assess the specific medical data for patient case. In particular, it could be a basis for making surgical planning in the laparoscopic procedures, for example, tumor resection planning in the liver. Although the system provides a preliminary to liver surgery planning, the participants emphasized that it would be beneficial to access 2D medical data and estimate resection volumes.

The surgeons assessed the surgery mode as a good foundation for communication and building confidence during the surgery. Handling the laparoscopic instruments caused them to experience the fulcrum effect. Hence, using laparoscopic surgical joysticks for team-based training does not only provide communication skills, but also provides psychomotor skill training such as camera navigation. However, one participant stated that providing hand tracking while holding the instruments would be helpful and can increase the immersion inside the virtual environment.

The results of user experience questionnaire gave an average rating for exploration mode: usability ($M$ = 5.33, $SD$ = 0.33) and usefulness ($M$ = 4.67 , $SD$ = 1.45). The results for surgery mode are: usability ($M$ = 4.33, $SD$ = 1.73) and usefulness ($M$ = 4.33, $SD$ = 1.73) (see Figure 4.7). The usability score in the exploration mode is higher than in the

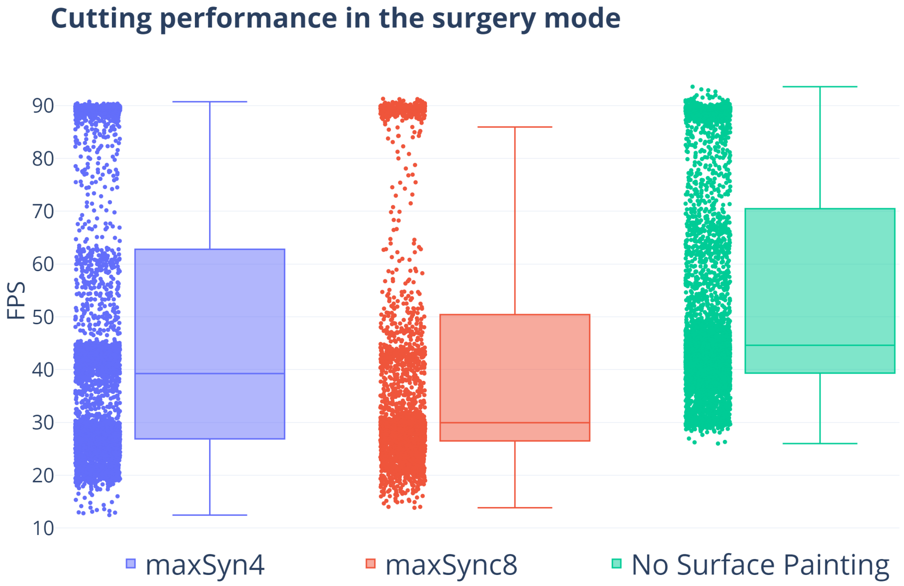


FIGURE 4.8: Results of volumetric cutting performance. *Figure from Chheang et al. [162] ©2019 IEEE.*

surgery mode, since the 3D organ model was easy to explore and visualize, and this was especially true for the visualization of vascular structures inside the liver. In addition, the semi-transparent liver was assessed as useful for the visualization and evaluation of the structures at risks, such as vascular structures and tumors. The implementation of cutting, bleeding, and clipping simulations could simulate the necessary steps of laparoscopic simulation. However, additional training scenarios would encourage team training and provide more benefits.

### 4.5.2 System and Network Performance

Two computers with the specifications described in Section 4.4.1 were used to compare the synchronization factors for real-time volumetric cutting, system performance, and network performance.

The maximum synchronization (maxSync) was determined for synchronized times per update of volumetric cutting. A higher value of maxSync leads the volumetric model to synchronize the collision and regenerate the surface quickly. However, a smaller value can result in a better frame rate for VR users. The cutting performance was assessed with options of 4 times (maxSync 4), 8 times (maxSync 8), and an option without surface painting in the surgery mode. The maxSync 4 and 8 were tested with surface painting, while the option of *no surface painting* was tested with one maxSync (see Figure 4.8). The rendered mesh and collision synchronization are noticeably lagging during the volumetric cutting. Cutting without surface painting can lead to a better frame rate.

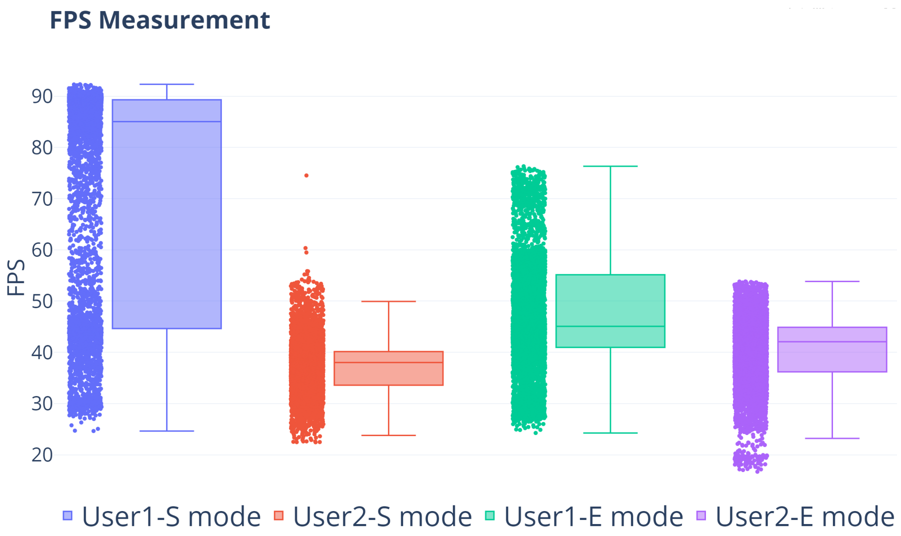


FIGURE 4.9: System performance results in the exploration mode (E) and surgery mode (S). *Figure from Chheang et al. [162] ©2019 IEEE.*

However, the surgeons preferred the cutting simulation with surface painting to determine and remain aware of the cutting area. Therefore, maxSync 4 was considered as a reasonable factor for providing real-time cutting in the virtual environment.

Figure 4.9 shows the preliminary results of system performance for exploration and surgery mode. The cutting simulation was defined with the surface painting during the experiment. The frames per second (FPS) were tracked for both modes. Since the specification of one computer (user 1) was better, the results varied. The results showed that the cause of lower frame rate is due to computation during volumetric cutting. Moreover, the image resolution can affect the results in a noticeable computation of the voxel occupancy, such as the collision synchronization and rendered mesh during the cutting simulation.

Network performance was measured for each mode with a wireless connection speed of 130 Mbps (see Figure 4.10). The average bandwidth for network synchronization of user 1 is: surgery mode (sending: 86.36, receiving: 21.07) and exploration mode (sending: 98.96, receiving: 93.64). For user 2, the average bandwidth is: surgery mode (sending: 25.34, receiving: 82.86) and exploration mode (sending: 98.55, receiving: 93.20). The average network latency of both users is: surgery mode: 34.92 ms (min: 4, max: 51), and exploration mode: 32.06 ms (min: 3, max: 42).

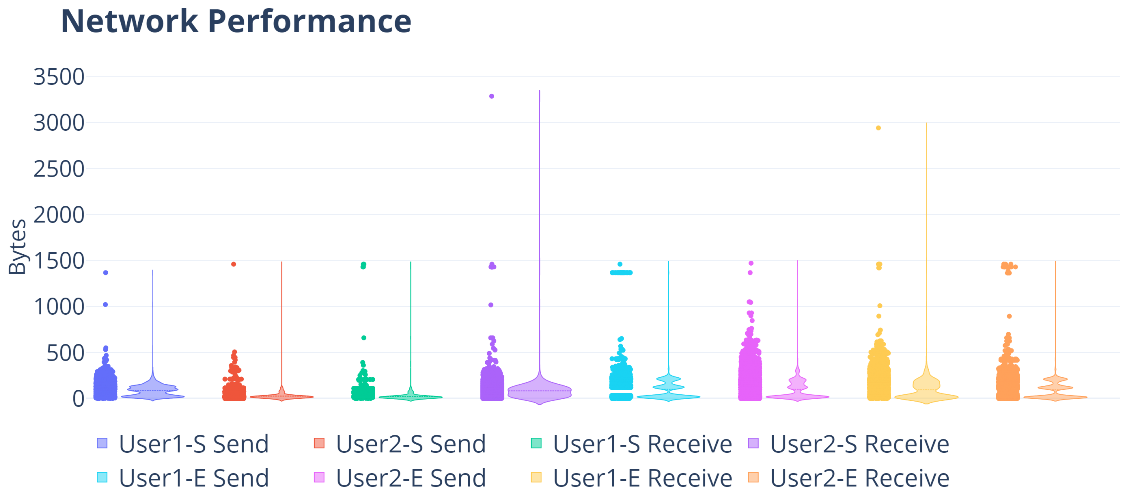


FIGURE 4.10: Network performance results with the sending and receiving bandwidth.

## 4.6 Discussion

The proposed collaborative VR environment was assessed positively with respect to usefulness and usability. The prototype is assessed as a basis and indicates the potential for further development and qualitative assessment. Valuable insights were gained from the evaluation provided by the experts. In contrast to most laparoscopic simulators that use conventional 2D monitors in an out-of-context environment, the proposed VR environment provides the experiences for patient data exploration and laparoscopic training in an immersive surgical environment. In addition, the proposed environment allows collaboration with multiple users, whether shared or remote environment (*R1*). However, long-distance collaboration and assessment is needed for further improvements.

According to *R2* and the feedback from the clinical partner, two modes of surgical procedures were developed for exploration (*R2.1*) and simulation of laparoscopic liver surgery (*R2.2*). Using real patient data and visualization of inner structures inside the liver model were considered as crucial for surgical training. For exploration mode, the participants were able to explore patient data and cut on the liver by using the Vive controllers. The bleeding and clipping simulation were acceptable. However, the blood flow should be investigated for further improvement [164, 165]. Moreover, a comparative model with physical behavior during cutting and clipping should be investigated [166].

In the surgery mode, the system enables collaborative training for laparoscopic simulation with the use of laparoscopic joysticks (*R3*). The development for integrating laparoscopic joysticks and the synchronization of virtual surgical instruments were assessed positively. However, visualizing virtual hands and providing haptic feedback while controlling the instruments may increase spatial awareness and proprioception [167, 168]. The study results from Hagelsteen et al. [169] demonstrates that using haptic feedback in the VR laparoscopic simulator has limited fidelity due to their current design. However, combining them with laparoscopic joysticks may provide better results. The experts stated that this mode provides benefits for improving the motor skills, especially camera navigation. Since the goal was to provide essential practice for surgeons and surgical trainees to collaborate, communicate, and improve their motor skills, providing a team training in the operating room with an anesthesiologist and training scenarios would be advantageous.

The system performance was assessed for each mode (*R4*). The resource-intensive computation happens during the volumetric cutting, and it is the reason that causes low FPS. The user 1's computer, with its specification, provided better frame rates compared to user 2's computer. However, system performance needs to be improved by considering using multi-threading and GPU-based computation. In addition, network performance results were considered as acceptable for network requirement and synchronization (*R5*).

## 4.7 Conclusion

This chapter has presented a collaborative VR prototype for laparoscopic liver surgery training. The system architecture, technical setup, and laparoscopic procedure modes were introduced. The collaboration in the exploration mode with enlarged patient models enables surgeons to explore and organize precise surgical planning. The same patient data used in exploration mode is also utilized for laparoscopic surgical simulation in the virtual operating room. Therefore, surgeons can practice, communicate, and improve their surgical skills as well as motor skills with the use of laparoscopic joysticks. The surgeons were positive about its usability and usefulness. They assessed the developed system as a reasonable basis for training and further evaluation. It enables a new direction for planning and training of surgical procedures. Based on the clinical feedback and evaluation, we identified the elements that could be further improved. In Chapter 5, further research was investigated in depth for surgery mode and additional collaborative training scenarios were supplemented. Chapter 6 investigates in details for exploration mode by implementing virtual resection planning and a risk map visualization. Additionally, evaluation with long-distance collaboration was assessed. With the idea presented in this chapter, Chapter 7 presents an integrated environment with photo-realistic avatars to provide an extensive surgical training environment.

# Chapter 5

# Collaborative VR for Interprofessional Team Training

The content of this chapter is based on the following publication:

- **Vuthea Chheang**, Virve Fischer, Holger Buggenhagen, Tobias Huber, Florentine Huettl, Werner Kneist, Bernhard Preim, Patrick Saalfeld, and Christian Hansen. Toward Interprofessional Team Training for Surgeons and Anesthesiologists using Virtual Reality. *International journal of computer assisted radiology and surgery*, 15(12):2109–2118, 2020.

This work has been published as a journal article at International Journal of Computer Assisted Radiology and Surgery (IJCARS), 2020. It was also presented as a poster [170] at the IEEE Engineering in Medicine & Biology International Student Conference (EMBS ISC), Magdeburg, Germany, 2019. Portions of the work presented in this chapter were conducted as part of the Bachelor's thesis project by Ms. Virve Fischer [171]. Ms. Fischer's Bachelor's thesis project was supervised by the author of this dissertation.

## About this chapter

After the original submission of collaborative VR described in Chapter 4, the surgery mode of the proposed prototype was extended. Based on discussions and feedback from the clinical partner, further research was carried out on team training between the surgeons and anesthesiologists in the virtual operating room. This chapter introduces a VR environment focused on training scenarios for interprofessional team training during laparoscopic procedures.

## 5.1 Introduction

The quality of teamwork and communication between anesthesiologists and surgeons in the operating room is crucial to prevent adverse outcomes [172]. An anesthesiologist is generally responsible for guaranteeing the patients' well-being during the procedure. Additionally, in general narcosis, the patient's welfare needs to be monitored using vital signs [173]. The anesthesiologist aims to allow surgical intervention without irreversibly harming the patient. This includes physical pain and psychological traumas [174]. Therefore, these procedures should be used to create a realistic training environment for different medical fields.

Various training systems have been proposed for surgery training [175, 176]. While the single-user training systems have been developed and proven successful, they have shown impaired teamwork, especially during the laparoscopic intervention. Krage et al. [135] showed that using a single-person training creates a way of thinking which could make the trainees believe that the problems can be solved alone. Complication-free narcosis of patients during laparoscopic surgery is one of the factors for a successful outcome. Therefore, the quality of communication between the anesthesiologist and surgeons is crucial. For team training in laparoscopic surgery, the interprofessional team should consist of at least one surgeon, one camera assistant, and one anesthesiologist because they are the most important roles in the laparoscopic procedure.

The current standard for team training and communication for surgery is based on high-fidelity mannequins [15]. Training with the high fidelity mannequin for team training could provide advantages to control and monitor vital signs, electrocardiogram (ECG), different level of obstruction, and the body's reaction to medication [177]. However, those systems are not flexible concerning the aim of the training and are very costly [178, 179].

Collaborative VR can be used to improve the communication and teamwork during critical situations [15]. However, current VR team training simulations for anesthesia provide inadequate interaction possibilities and limited training scenarios during laparoscopic procedures [19, 20]. In this chapter, a prototype focused on training scenarios for VR-based interprofessional team training between surgeons, camera assistants, and anesthesiologists during laparoscopic procedures is presented. Furthermore, two scenarios, i.e., *undetected bleeding* (Section 5.3.2) and *insufficient muscle relaxant medication* (Section 5.3.2), are introduced. Clinical feedback is also collected to assess the usefulness and current limitations.

## 5.2 Requirements

An initial interview was conducted with two surgeons and an anesthesiologist from the University Medical Center of the Johannes Gutenberg-University Mainz. The interview was structured with many open questions and discussions to collect a broad overview of the topic. Based on the interview and discussion, requirements were identified, which are related to communication in the interprofessional team and tasks for the anesthesiologist during the laparoscopic intervention. The identified requirements are the following:

**R1** **Training scenarios –** communication is one of the most crucial tasks during the intervention. Two possible scenarios were proposed by the experts that could create situations and require communication between the interprofessional team, including surgeons, camera assistants, and anesthesiologists. Therefore, the training scenarios which are described in subsection 5.3.2 should be developed and adapted with the previous laparoscopic simulation proposed in Chapter 4.

**R2** **Anesthesiologist tasks –** This includes the development of VR interactions for anesthesiologists during laparoscopic intervention.

  **R2.1** To monitor the vital signs during narcosis, the anesthesiologist should be able to adjust the respirator's parameters, e.g., respiration frequency, -pressure, and -oxygen concentration ($O_2$).

  **R2.2** The tasks during complication scenarios should be adapted such as refreshing the medication and monitoring the vital signs. Changes on the VR-based respirator should be applied to a standard simulation software stated in (***R3***).

**R3** **Standard anesthesia simulation software –** The experts recommended a standard anesthesia simulation software, which is used for training in their hospital, to be integrated with the virtual anesthesia respirator. Hence, the changes of vital signs on the simulation software should be synchronized and used to monitor different complication scenarios and narcosis.

## 5.3 Materials and Methods

In the following sections, system architecture and training scenarios are described, followed by the explanation of interactions for medication as well as the implementation for changes of vital signs.

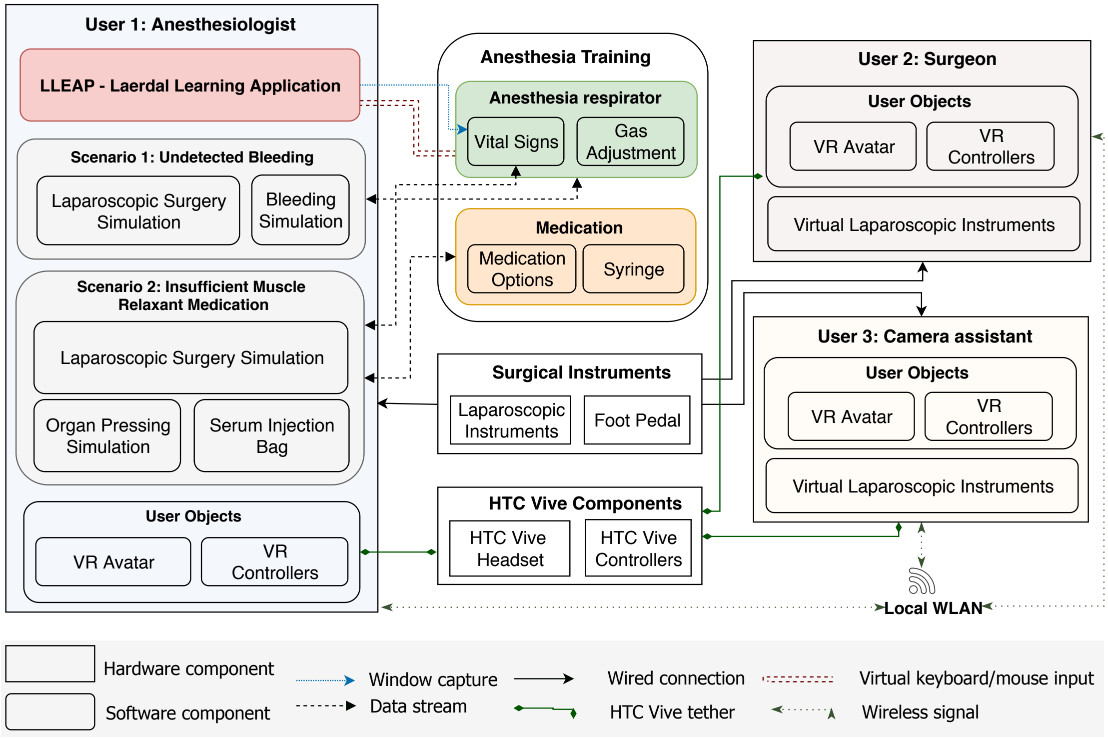


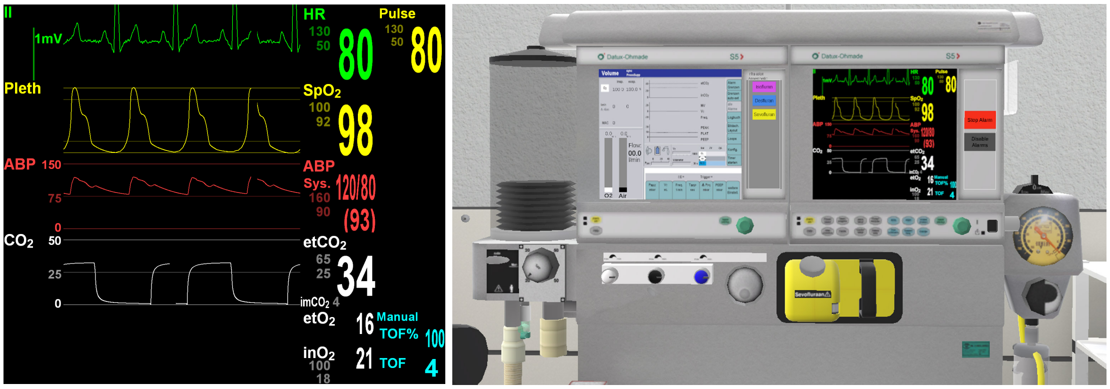
FIGURE 5.1: Technical setup for interprofessional team training. *Figure from Chheang et al. [180] ©2020 Springer.*

### 5.3.1 System Architecture

Figure 5.1 illustrates the system architecture. The HTC Vive headsets and its components are used for the VR setup. Three computers equipped with the VR headsets and their components are connected to a network and represent the user-roles of a surgeon, a camera assistant, and an anesthesiologist, accordingly. A client-server configuration is used so the computer that runs the application first acts as a server and the others as clients. The game engine Unity is used for development and Unity networking (Unet) is utilized for multi-user functionality. Laparoscopic instruments (Simball joysticks) and a foot pedal are used and connected for the surgeon and camera assistant.

#### Anesthesia Simulation Software

The anesthesia simulation software LLEAP (Laerdal Medical, Norway) is used as a component for vital signs monitoring. LLEAP provides functions for developed scenarios such as vital signs for heart rate (pulse), ABP, TOF which is a measurement of muscle relaxation, and the measures of inhaled gases. Usually, LLEAP is used to control a high-fidelity mannequin. However, in this work, this software is integrated to simulate a virtual patient's vital signs in VR. From the options provided in LLEAP, *SimMan 3G* is chose for vital sign monitoring. LLEAP provides a monitoring screen for vital signs in typical ranges and specific curves, e.g., an electrocardiogram (see Figure 5.2a). These vital signs can be altered and used as the monitoring screen. A virtual respirator is developed to monitor vital signs in VR. The screen of LLEAP is captured and converted to a texture for the virtual screen of the respirator (see Figure 5.2b).



(a) (b)

FIGURE 5.2: Vital signs monitoring of the system. The screen of anesthesia simulation software (a) is captured for the respirator's right monitor (b). *Figure from Chheang et al. [180] ©2020 Springer.*

## 5.3.2 Training Scenarios

The possible training scenarios and system requirements were collected through the interview with the experts (***R1***). Simple tasks for anesthesia are required to provide a basic understanding of controlling and monitoring the vital signs. In addition, two training scenarios are designed concerning surgical complications: undetected bleeding and insufficient muscle relaxant medication.

### Training Scenario 1: Undetected Bleeding

During laparoscopic liver surgery, parts of liver tissue and vascular structures are resected. Bleedings could lead to massive blood loss and endanger the life of the patient. Therefore, placing clips on blood vessels is a common task for surgeons during surgery to avoid bleeding. However, these clips can loosen themselves and fall off. In this situation, the surgeons may be distracted, e.g., by a phone call, and miss the bleeding [181].

This scenario describes a situation where a surgeon misses the bleeding while performing laparoscopic surgery. Hence, the anesthesiologist is the only person responsible for identifying the problem by monitoring and checking the change of vital signs. After that, the anesthesiologist is expected to inform the surgeon and camera assistant regarding the issue. Thus, they can detect and stop the bleeding.

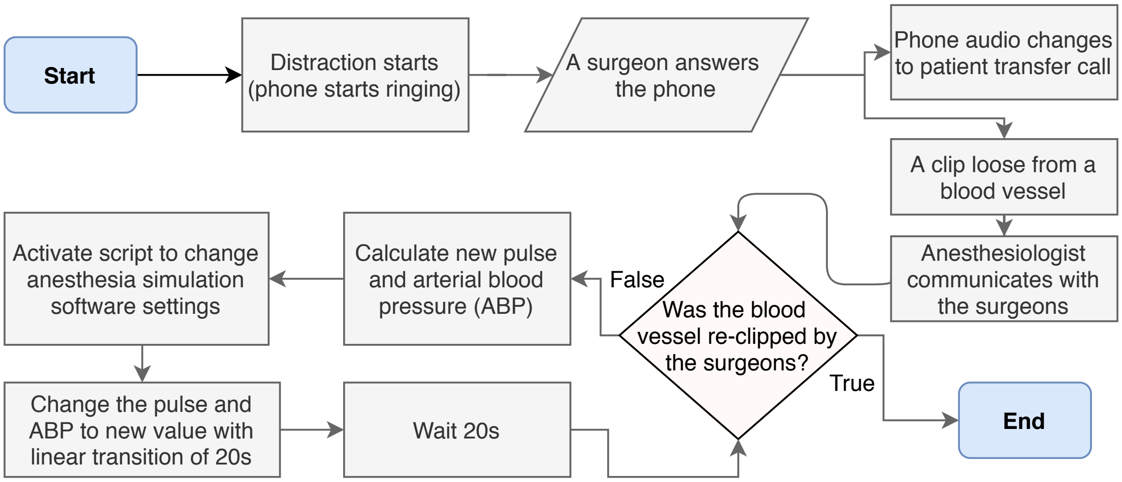


FIGURE 5.3: Flow chart for training scenario 1 (*undetected bleeding*). *Figure from Chheang et al. [180] ©2020 Springer.*

| Situation | Pulse [bpm] | ABP systole [Hg/mm] | ABP diastole [Hg/mm] | TOF |
|---|---|---|---|---|
| Normal [182] | $\sim 80$ | <120 | <80 | 4 |
| Narcosis | $\sim 59$ | $\sim 108$ | $\sim 64$ | $\leq 2$ |
| Bleeding | rises | falls | falls | no change |
| Low muscle relaxant | no change | no change | no change | rises |

TABLE 5.1: The implemented vital signs' typical values and changes during specific situations (ABP: arterial blood pressure, TOF: Train of Four). *Table from Chheang et al. [180] ©2020 Springer.*

Figure 5.3 illustrates the workflow of the scenario. When the surgeons answer the phone, one of the clips previously placed on the blood vessels will slip off. During the bleeding, the ABP will drop and the pulse will rise as shown in Table 5.1. The anesthesiologist monitors these values and suspects a bleeding. Subsequently, the surgeons are notified to find and stop the bleeding accordingly. If the blood vessel gets clipped again, the bleeding will stop, and the vital signs will be stabilized.

### Training Scenario 2: Insufficient Muscle Relaxant Medication

The anesthesiologist monitors muscle relaxation by evaluating the TOF. This value can vary significantly because it is dependent on the placement of the measurement-electrodes. In some cases, the anesthesiologists could not recognize low muscle relaxation. This scenario aims to engage the surgeons to detect the patient's low muscle relaxation and inform the anesthesiologist to refresh the medication. The scenario starts with the *pressing* of the patient's abdominal muscles. If a patient starts pressing, the surgeons should notice the pressing and tell the anesthesiologist about the issue so that the anesthesiologist can administer a refreshment dose of the muscle relaxant.

Usually, the anesthesiologist monitors muscle relaxation by evaluating the TOF. This value can vary significantly because it is dependent on the placement of the electrodes. Thus, it is possible that the anesthesiologist will not recognize the low muscle relaxation themself and need a hint from the surgeons. The scenario starts with the animation for the *pressing* of the patient's organs, parallel with the change in TOF parameters (see Figure 5.4). With the injection of a new dose of muscle relaxant, the animations will stop, but only after the offset of the medication's effect.

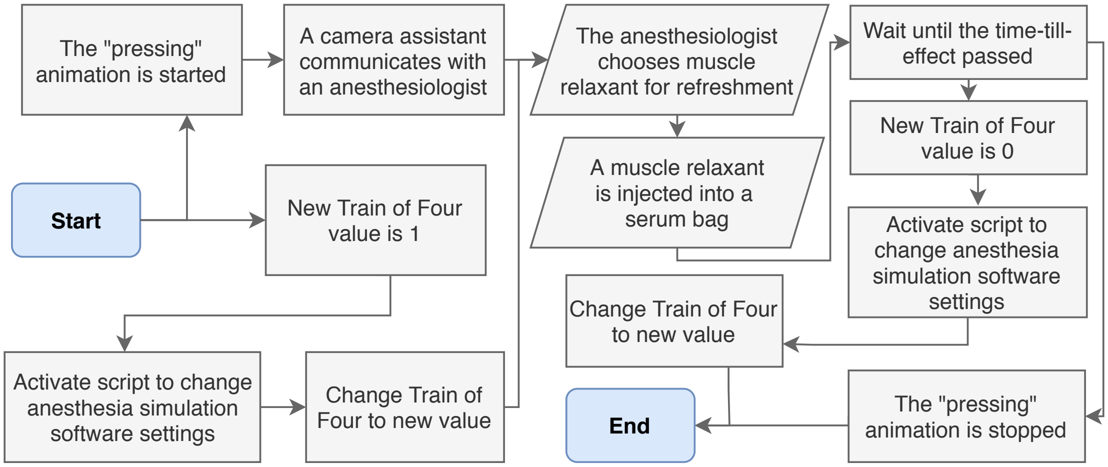


FIGURE 5.4: Flow chart for training scenario 2 (*insufficient muscle relaxant medication*). *Figure from Chheang et al. [180] ©2020 Springer.*

### 5.3.3 Interactions for Medication

The anesthesiologist can operate and monitor the inhalation anesthetics at a virtual respirator (***R2***). There are also possibilities to adjust the gas flow of oxygen, carrier gas, and inhalation anesthetic at the respirator. For muscle relaxant medication, the anesthesiologist can choose from several options displayed on an information panel showing the medication's type and dosage (see Figure 5.5). Table 5.2 shows different muscle relaxant medications presented in this prototype. A syringe is needed to give the medication to the patient. Therefore, after choosing an option of medication from the information panel, the syringe will be released and the anesthesiologist is supposed to inject the medication with a virtual syringe to a serum bag beside the patient (see Figure 5.6).

In this prototype, the inhalation anesthetics can be operated and monitored at a virtual respirator. It is also possible to adjust the gas flow of oxygen, the carrier gas, and inhalation anesthetic with rotatable knobs (***R2.1***). Depending on the current minimal alveolar concentration (MAC) and inhalation anesthetic level, the ABP and pulse will change according to Equation 5.1.

FIGURE 5.5: An example of interactions for choosing different muscle relaxant medications. A user is captured using a chroma keying technique and a green screen to embed in the virtual environment to demonstrate how the user interacts in VR.

The vital medication for our system is the muscle relaxant because it is required as a countermeasure in scenario 2 (see Figure 5.7) (***R*2.2**). Afterward, the anesthesiologist is supposed to inject the medication with a virtual syringe to a serum bag beside the patient.

### 5.3.4 Change of Vital Signs

The vital signs of the anesthesia simulation software need to change realistically depending on the situation for the anesthesiologist to detect symptoms correctly (***R*3**). To replicate how vital signs change in reality, three different ways to affect the vital signs have been implemented (see the following subsections).

#### Changes of vital signs during narcosis

The dosage of the inhalation anesthetic is used to calculate the vital signs during narcosis. The effect of the dosage can be evaluated with MAC which is defined as the alveolar concentration of an anesthetic to prevents muscle movement. However, it could not predict precisely how an individual would react to a specific amount of inhalation anesthetic. Thus, the exact dosage relies on the anesthesiologist's experience. A simple model was formed based on the following assumptions:

| **MR** | **ED95** [mg/kg] | **ID** [mg/kg] | **TTE** [min] | **DUR25$_{ID}$** [min] | **DUR95$_{ID}$** [min] |
|---|---|---|---|---|---|
| Atracurium | 0.23 - 0.25 | 0.3 - 0.4 | 2 - 3 | 40 - 50 | 50 - 70 |
| Cis-Atracurium | 0.05 | 0.15 - 0.2 | 3 - 5 | 45 | |
| Mivacurium | 0.07 - 0.08 | 0.2 - 0.25 | 2.5 - 4 | 20 - 25 | |
| Pancuronium | 0.06 - 0.07 | 0.08 - 0.12 | 2 - 3 | 90 - 100 | 120 - 150 |
| Rocuronium | 0.3 | 0.6 - 1.2 | 1 - 2.5 | 35 | |
| Vecuronium | 0.05 | 0.08 - 0.1 | 2 - 3 | 45 - 60 | 60 - 80 |

TABLE 5.2: Different muscle medications used in this prototype: effective dose (ED95), intubation dose (ID), time till effect (TTE), clinical time of effect after an intubation dose (DUR25$_{ID}$) and total time of effect after an intubation dose (DUR95$_{ID}$) [183].

Each variation of the current inhalation anesthetic concentration $c_{IA}$ can be assigned to a specific value of pulse, systolic and diastolic ABP. These will be called the target vital signs $x'$. They are defined by linear interpolation between the value for the average healthy pulse/blood pressure $x_{norm}$ and pulse/blood pressure during narcosis $x_{narc}$ as found in Table 5.1.

$$x' = x_{norm} + \frac{c_{IA}}{MAC_{IA}} \cdot (x_{narc} - x_{norm}) \tag{5.1}$$

By comparing the current vital sign $x$ with the target vital sign $x'$, the absolute change can be calculated. However, the change of the vital signs will not take place instantly but over time. Therefore, a factor $0 < m < 1$ can be chosen to calculate the absolute change of $\Delta x$:

$$\Delta x = (x' - x) \cdot m \tag{5.2}$$

As a simple assumption, we set $m$ to $\frac{1}{2}$. The next value of the vital sign $x'$ will be calculated by adding the change $\Delta x$ to the current value of the vital sign $x$. The next vital sign $x'$ will be reached after 20 seconds following a linear transition.

### Changes of vital signs during vessel bleeding

The combined change of the pulse and ABP reliably indicates bleeding [184]. If the pulse exceeds the ABP, this is a clear sign for significant blood loss. However, the change of $\Delta x$ should depend on the size of the vessel cut, the duration of the bleeding, and the bleeding speed. The change needs to be estimated as the bleeding factor $b$. It will symbolize the full effect of the parameters on the vital signs and results in a straightforward equation for the next vital signs $x'$.

$$x' = x + b \tag{5.3}$$

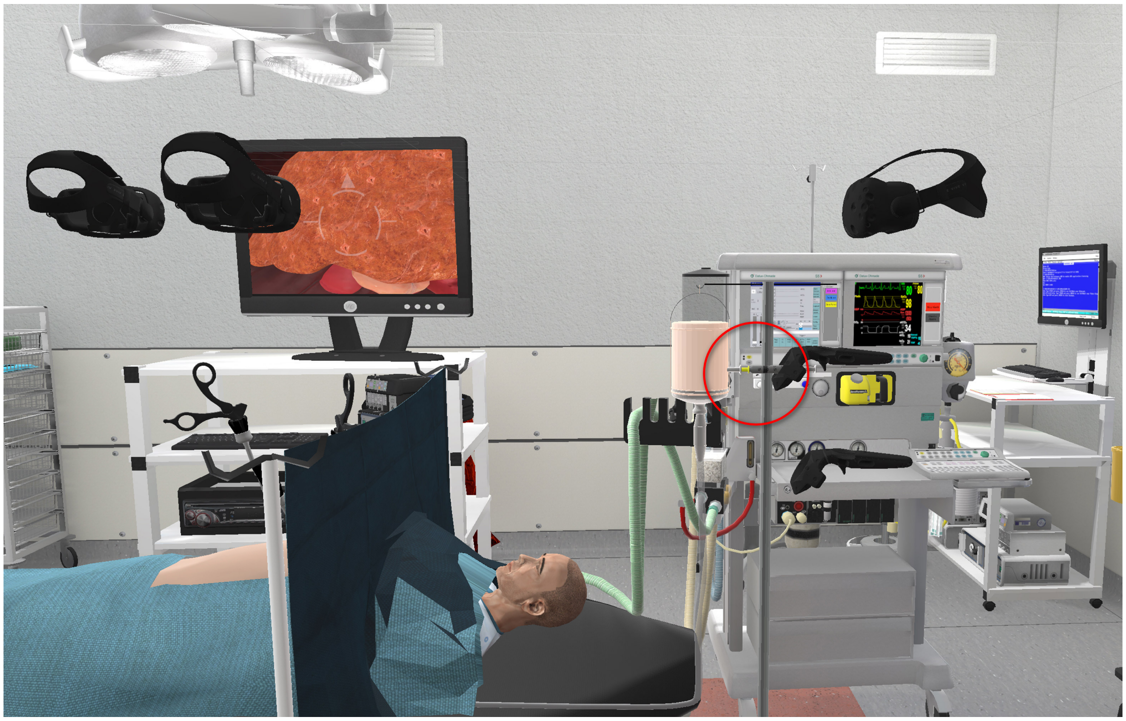


FIGURE 5.6: The anesthesiologist injects the muscle relaxant to a serum bag. The users in the VR environment are represented with 3D models of VR headsets and controllers. *Figure from Chheang et al. [180] ©2020 Springer.*

The factor $b$ is different for each vital sign as they need to change differently to indicate a bleeding:

$$b_{pulse} = 10\,\mathrm{bpm}$$

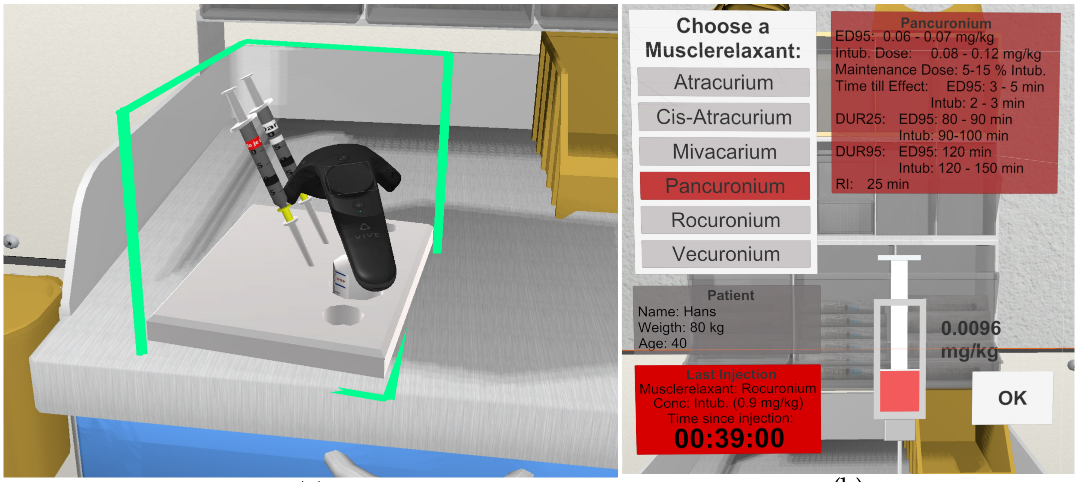
$$b_{ABP,sys} = -8\,\frac{\mathrm{mm}}{\mathrm{Hg}}$$

$$b_{ABP,dia} = -4\,\frac{\mathrm{mm}}{\mathrm{Hg}}$$

The changes are not abrupt and have a linear transition over 20 seconds from one state to the next.

### Changes of vital signs during insufficient muscle relaxant medication

The value of TOF varies between zero and four. Usually, a TOF value of zero implies that the patient's muscles are relaxed enough for a laparoscopy. Therefore, value zero is chose for regular narcosis. To display the muscle relaxant wearing off, the TOF value will change to one to indicate insufficient muscle relaxation. If the muscle relaxant is wearing off due to exceeding the clinically effective duration (DUR25), the TOF value should change to one first, and the pressing will start a certain amount of time later.



Pancuronium
ED95: 0.06 - 0.07 mg/kg
Intub. Dose: 0.08 - 0.12 mg/kg
Maintenance Dose: 5-15 % Intub.
Time till Effect: ED95: 3 - 5 min
Intub: 2 - 3 min
DUR25: ED95: 80 - 90 min
Intub: 90-100 min
DUR95: ED95: 120 min
Intub: 120 - 150 min
RI: 25 min

Patient
Name: Hans
Weigth: 80 kg
Age: 40

Last Injection
Musclerelaxant: Rocuronium
Conc: Intub. (0.9 mg/kg)
Time since injection:
00:39:00

(a) (b)

FIGURE 5.7: Different interactions for refreshing the muscle relaxant medication, (a) interactions with a syringe holder to activate the information panel, (b) interactions for choosing a type of medication. *Figure from Chheang et al. [180] ©2020 Springer.*

## 5.4 Evaluation

A pilot study was performed with an anesthesiologist (27 years of working experience) and two laparoscopic surgeons (8 and 5 years of working experience). The participants were asked to evaluate the simulation using a think-aloud method. The demonstration started with the basic functionalities used for anesthesia. The anesthesiologist was asked to adjust the oxygen, carrier gas, and inhalation anesthetic in a way that he would think of as suitable for narcosis. The underlying procedures were explained. Afterwards, training scenario 1 with the phone call and the vital sign stabilization was demonstrated. Training scenario 2 was shown and the pressing animation, as well as the options for choosing and injecting the muscle relaxant, were demonstrated. Figure 5.8 illustrates how the anesthesiologist and surgeons virtually joined and performed the training in the collaborative VR environment. After the experts completed both scenarios, a detailed interview was conducted with the experts for about one hour. The interview started with the general set up of the virtual operating room, the vital signs and monitoring, and the value of the different medications.

The system was also assessed during development with two surgical residents (5 and 4 years of working experience) and one medical student. The objective was to measure social presence with a cooperative social presence questionnaire [185], as it is essential for VR-based team training. This questionnaire has 25 questions, which are classified as team identification, social action, motivation, and team value. The answers were rated with a five-point Likert scale from “not at all" to “very much". The participants were given equal weights to calculate the average scores. Moreover, participant’s feedback

(a) (b)

FIGURE 5.8: Overview of VR-based interprofessional team training: (a) a surgeon, a camera assistant, and an anesthesiologist virtually collaborate in VR, (b) interprofessional team members perform in the real world. *Figure from Chheang et al. [180] ©2020 Springer.*

with respect to the technical aspects and usefulness was collected to further improve the usability of the prototype.

## 5.5 Results

In the following, the expert's feedback is described.

### 5.5.1 Training Scenarios

For training scenario 1, the condition for virtual patient needs to be identified as critical, so the ABP should fall below 80 (systolic) and 50 (diastolic) $Hg/mm$, and the pulse should rise above at least 100 bpm. The distraction was suggested to insert an animation or add another user role (can be a scrub nurse) to take and hold the virtual telephone. The surgeons usually step back from the patient, let go of the laparoscopic instruments and fold their arms not to compromise sterility. This way, the distraction would ensure that the surgeons do not look at the laparoscopic screen, or the laparoscopic camera does not capture in the right position.

Aside from that, the pulse and ABP should increase slightly during scenario 2. The respiratory parameters usually show the patient's spontaneous breathing and result in an alarm if there is something wrong. Hence, the respiration frequency will become unstable, and the respiration curve will show specific spikes.

In general, the experts were positive and evaluated both scenarios to engage communication between interprofessional teams, and promote the future operating room training.

### 5.5.2 Interactions for Medication

The opioids for analgesia were recommended to be included in the simulation because they are an essential part of the general anesthesia. The experts also stated that additional information screens should be added in the simulation for different inhalation anesthetics similar to the muscle relaxant choice.

The options of the muscle relaxant were helpful to demonstrate the different medications. In addition, the experts commented that the anesthesiologists do not usually fill the syringes during surgery but instead have a broad choice of prepared syringes with different doses of muscle relaxant. However, it could be a basis for the trainees to learn the absolute $mg$ values for the muscle relaxants.

### 5.5.3 Usefulness for Medical Training

The experts confirmed that the scenarios would encourage communication between the anesthesiologists and surgeons. During the interview, the experts were asked how they would use our system as the instructors. They mentioned that they want the students to have a clear goal for the simulation, which should be explained with the patient's history before starting the simulation. Therefore, a patient history is needed and should be shown before starting the simulation. The instructor also needs some approaches to supervision. Additionally, documentation of the simulation session is needed so they can evaluate the students and give them feedback. An assessment to grade and comment on students should also be included. The experts agreed with the idea to induce a specific scenario any time during the simulation with an instructor's control panel.

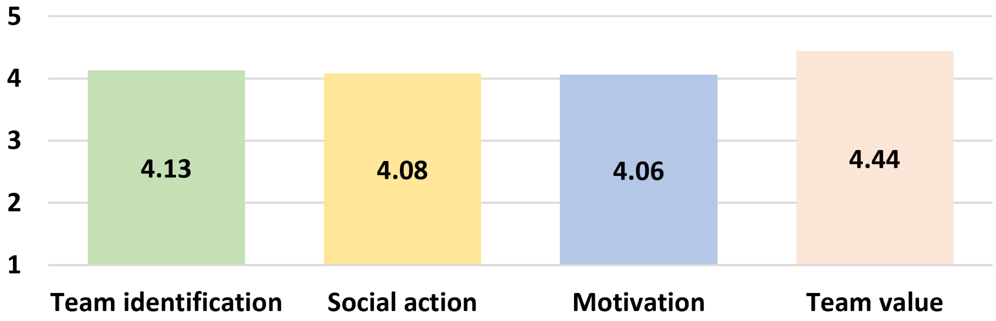


FIGURE 5.9: Average scores of cooperative social presence questionnaire.

### 5.5.4 Cooperative Social Presence

The questionnaire results were divided into four categories (see Figure 5.9).

- *Team identification* ($M$ = 4.13, $SD$ = 0.64) refers to the level of psychological attachment felt by a team member toward the others. Voice chat and representation models were implemented in the VR environment. However, the prototype could be further improved in regard to the flexibility of team setup in the operating room, which allows a user to identify the other user roles in the surgical procedures (see Table 5.3 No. 10.).

- *Social action* ($M$ = 4.08, = 0.83) involves communication and contribution between interprofessional team members. All participants agreed that they had a mutual understanding.
- *Motivation* ($M$ = 4.06, $SD$ = 1.06) describes the action and responsibility to motivate the team. The participants were positive about the proposed scenarios that engaged and induced the communication and responsibilities between the interdisciplinary team.
- Finally, *team value* ($M$ = 4.44, $SD$ = 0.70) refers to the behavior, encouragement, and performance of the team during the training. The average score of team value was higher than other categories obtained in the questionnaire. This could demonstrate the value and benefits of interprofessional team training.

Two questions, “my actions were determined by the objectives of the team" and “I felt my team shared a common overall aim", were rated with the highest scores from all participants. The results reveal that social presence positively impacts the training experience. Moreover, the presence of other members in VR environment influences cognition and behavior of the trainees.

Apart from the questionnaire results, the participants provided valuable insights, which are relevant to support defining the limitations and possible solutions described in Table 5.3. There was no inconsistency between the medical student and experts because the feedback was mostly focused on technical aspects. The participants agreed that VR-based team training could engage and motivate the learning procedures, particularly in a complex situation that requires efficient communication.

## 5.6 Discussion

Valuable insights were gained during the demonstration using the think-aloud protocol and the interview. The feedback from the experts, including anesthesiologist and surgeons, was overall positive, and they appreciated the broad range of functionalities.

The essential features of the scenarios were implemented. The exhilaration experience was evaluated as the key to increase the attractiveness and motivation in the immersive VR training. A summary of the current technical limitations and possible solutions is shown in Table 5.3, with the ratings of clinical importance for anesthesia, surgery, and

| No | Current limitation | Possible solution | An. | Su. | T.v. |
|---|---|---|---|---|---|
| 1 | Movement of pressing animation is not sufficiently realistic | Animation of patient's pressing should be slower and right directed | 2 | 1 | 2 |
| 2 | Synchronization of vital sign monitor to all users | Captured image should be compressed and decompressed over network | 3 | 2 | 1 |
| 3 | Alternation of vital signs during bleeding is not sufficiently realistic | Amount of change in the vital signs for pulse and ABP should be depending on the amount of blood loss | 1 | 1 | 2 |
| 4 | No opioid medication | Implement in the same way as muscle relaxant medication | 1 | 3 | 3 |
| 5 | No patient history information | Adding patient information panel including prior diagnose and treatments | 1 | 2 | 3 |
| 6 | Supervisor menu is needed for assessment during the session | Monitoring menu with possibilities to trigger the complication scenarios anytime during the simulation and documenting the information for evaluation | 1 | 1 | 1 |
| 7 | Collaboration in local network connection is unstable | Optimize network latency and data synchronization for remote collaboration | 1 | 1 | 1 |
| 8 | Only effective doses can be given for muscle relaxant | Enable underdosing/ overdosing of muscle relaxant | 1 | 2 | 3 |
| 9 | Missing haptic feedback from anesthesia objects (syringe, respirator, serum bag . . . ) | Using appropriate haptic device e.g. data glove | 2 | 3 | 1 |
| 10 | Change team setup in the operating room according to surgical procedure e.g. supine split-leg position (French position) . . . | Enable pre-installed standard operating room settings | 3 | 1 | 2 |

TABLE 5.3: Overview of current limitations and possible solutions for future research, including clinical importance and technical viability (Ane.: Anesthesia, Sur.: Surgery, T.v.: Technical viability). Range of clinical importance rating: 1: high importance, 2: importance, 3: low importance. Range of technical viability: 1: difficult, 2: normal, 3: feasible. *Table from Chheang et al. [180] ©2020 Springer.*

technical viability. The scores were determined by one anesthesiologist and two liver surgeons, who took part in the interview.

One of the possible challenges of this training environment is that the system could give students an unspecified impression of how the vital signs change. While the change of vital signs is developed based on typical values extracted from the literature, not every patient reacts in the same way towards medication or bleeding. Thus, the patient's history and medical records should be added for the training. Moreover, the realism of the pressing animation, doses adjustment, opioid medication, and flexible team setup in the virtual operating room could be further improved for training effectiveness. Nonetheless, optimization of network latency for remote collaboration, the realism of vital signs during bleeding, and a user interface for assessment are of high importance for both anesthesia and surgery.

The proposed system was evaluated with a small number of participants and results are subjective. The potential objective measurements for future studies could be task completion time, error rate, and task performance [70, 140]. For instance, the anesthesiologist's role could be evaluated by the amount adjustment and type of medication, time from selection to applying the medication, and response time after the clip loss. The camera assistant's role could be evaluated by identifying aspects of camera navigation such as camera centering and steadiness of camera movement, and response time while the depth of anesthesia is flattened [186]. The surgeon's role could be evaluated in regards to the time needed to apply the clips on bleeding vessels, the amount of blood loss, and the distance to risk structures or their damage [104].

The immersive VR environment is a useful tool for medical training. However, the devices are still expensive, and development is time-consuming, while the anesthesiologist's tasks, such as monitoring vital signs, could be utilized in a simple 2D display. Nevertheless, the proposed system could be useful for team training, refreshing skills, and developing better teamwork in the future.

## 5.7 Conclusion

This chapter has presented a collaborative VR setup for interprofessional team training in the virtual operating room. This system provides potential benefits for training, such as real-time collaboration and communication, to enhance teamwork between the anesthesiologist and surgeons. Two training scenarios were introduced to induce and engage the trainees to communicate during critical surgical complications. Valuable insights gained from an interview with experts of anesthesia and surgery reveal the usefulness for medical training and limitations for future investigation. Overall, the proposed system opens new directions for medical training and provides a basis for future extensive clinical evaluation.

# Chapter 6

# Collaborative VR for Liver Surgery Planning

The content of this chapter is based on the following publication:

- **Vuthea Chheang**, Patrick Saalfeld, Fabian Joeres, Christian Boedecker, Tobias Huber, Florentine Huettl, Hauke Lang, Bernhard Preim, and Christian Hansen. A Collaborative Virtual Reality Environment for Liver Surgery Planning. *Computers & Graphics*, 99(10) : 234–246, 2021.

This work has been published as a journal paper at Computers & Graphics under the special section on *Visual Computing for Biology and Medicine*, and it was invited to present at the annual *Eurographics Workshop on Visual Computing for Biology and Medicine (EG VCBM)*, Paris, France, 2021. A research demonstration based on this proposed environment [187] was presented at the IEEE VR conference, Lisbon, Portugal, 2021. Furthermore, the proposed environment was used in a comparative study of input devices for common interaction tasks in VR-based surgical planning and training [188, 189].

## About this chapter

With the concept of patient data exploration described in Chapter 4, further investigation of a collaborative VR environment for liver resection planning was conducted. In this chapter, the VR environment for shared or remote collaboration, as well as an enhanced technique for virtual resection planning and a real-time risk map visualization are presented.

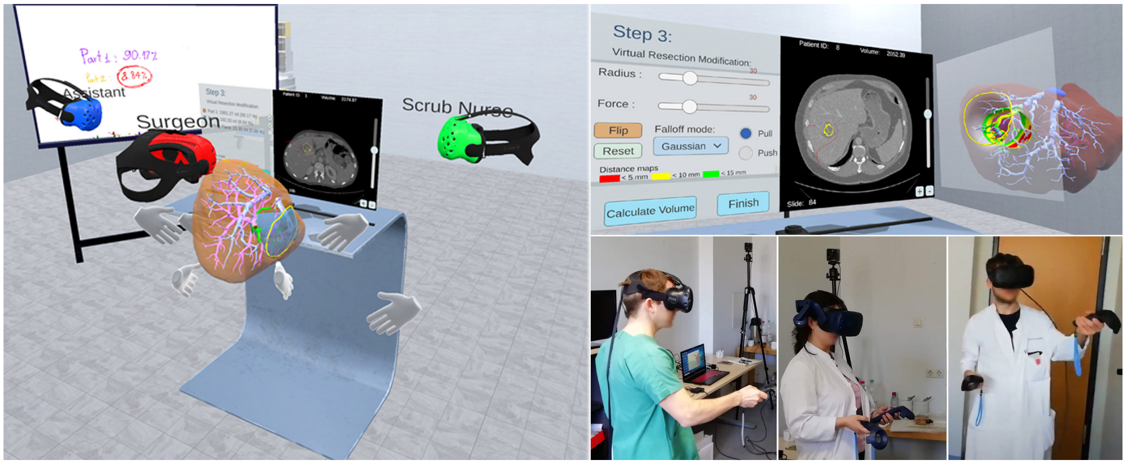


FIGURE 6.1: An overview of collaborative VR environment for shared or remote collaboration among surgeons in tumor surgery planning on the example of liver surgery. *Figure from Chheang et al. [190] ©2021 Elsevier.*

## 6.1 Introduction

Tumor surgery in abdominal organs, for example a liver resection, involves the complete removal of all tumors and a surrounding safety margin [26]. Virtual resection planning aims at defining the resection and the remaining volume, with consideration of the affected vessels and other structures at risk [191, 192]. It is commonly based on medical volume data, e.g., medical image datasets acquired by a computerized tomography (CT) scanner. Thus, surgeons inspect those image slices and extract information of the region of interest.

Surgery planning software is essential to compute and evaluate an estimated resection volume and to increase the potential remnant volume [193]. 3D visualizations in the surgical planning software make it possible to improve the understanding of spatially complex internal structures in the organ [110, 194]. Moreover, surgical planning systems may improve tumor localization, the precision of planning, and the confidence during the intervention procedures [195–197]. However, desktop-based 3D systems offer limited visualizations and interaction opportunities compared to VR setup [198, 199].

A crucial aspect for a successful outcome of surgical intervention is a mutual understanding and collaboration between the team members, including experienced surgeons and novice surgeons [200]. Sullivan et al. [201] describe the critical aspects of collaborative practice among surgeons, including cooperation, coordination, shared decision-making, and partnerships. Currently, the exchange of information between surgeons is mostly performed by face-to-face team meetings, teleconference, and video/phone calls [11]. Face-to-face meetings provide advantages compared to online meetings, including a lower possibility of miscommunication. However, it is challenging for a long-distance collaboration, i.e., during the Covid-19 pandemic.

In this chapter, a collaborative VR environment to support the surgeons in liver surgery planning is proposed (see Figure 6.1). A technique for specification and modifications of virtual resections with a deformable resection surface is adapted into an immersive VR environment [202]. Furthermore, resection margins, tumor contours, a real-time risk map visualization, and synchronizations for collaborative users are presented.

The risk map is used to determine the exact distance from the tumors to the surrounding blood vessels, and the resection surface. It allows surgeons to precisely evaluate the structures at risk and preserve the resection volume. Continuous feedback from our clinical collaborators comprises an essential part of the system development. Additionally, an evaluation from experts provides valuable insights, including potential benefits, clinical applicability, and limitations. The proposed collaborative VR environment builds a basis for future medical planning and opens a new direction for long-distance collaboration.

The main contributions of this chapter are the following:

- An immersive VR environment for co-located or remote collaboration between surgeons in liver surgery planning.
- Adaptation and enhancement of a virtual resection technique with a deformable resection surface [202] and VR interactions. Moreover, a development of the virtual resection with automatic deformation and visualization details, e.g., tumor contours and projection of resection surface onto 2D slices, are presented.
- A risk map visualization that projects the safety margins around tumors onto vascular structures and the resection surface in real time. Furthermore, appropriate methods for resection volume estimation and surface reconstruction are presented.

## 6.2 Related work

Virtual resection is defined to support surgeons in visualization of resection volume, affected vascular structures, and resection margins [122, 203, 204]. Therefore, surgical planning systems should provide the flexibility to specify and modify the virtual resection. The most common techniques proposed to define the virtual resection are summarized in the Table 6.1.

- Drawing traces on 2D slices (DTS) [205]: This approach allows the user to draw the traces on the 2D slices of patient image data. Based on these drawing traces,

| **Aspects** | **DTS [205]** | **DCP [202]** | **Bézier [206]** |
|---|---|---|---|
| Underlying Representation | Bi-quadratic polynomial | Discrete grid | Bi-cubic polynomial |
| Resection margin | ✗ | ✗ | ✓ |
| Data visualization | 2D Slices/3D models | 3D models | 2D Slices/3D models |
| Risk map on resection surface | ✗ | ✗ | ✓ |
| Risk map to vessels | ✗ | ✗ | ✗ |
| Interactions | - Drawing on 2D slices<br>- Using mouse as input | - Traces on surface<br>- Local deformation<br>- Using mouse as input | - Slicing plane<br>- Bezier deformation<br>- Using mouse as input |
| Display | Conventional monitor | Conventional monitor | Conventional monitor |
| Remote collaboration | ✗ | ✗ | ✗ |

TABLE 6.1: Implementation aspects for virtual resections determination in the liver surgery planning systems. *DTS:* Drawing traces on individual 2D slices, *DCP:* Deformable cutting plane, *Bézier:* Deformable Bezier surface.

a linear interpolation is applied between each slice and the virtual resection is specified. In addition, the virtual resection can be modified by redrawing of traces. The volume estimation depends on the multi-resolution triangulation of the B-spline surface.

- Deformable cutting plane (DCP) [202, 207]: The DCP approach uses a discrete grid, so the underlying representation of virtual resection is distinct from the approaches of DTS and Bézier. This technique allows the user to draw lines to specify the resection area on the liver model's surface. The virtual resection is initialized based on these drawn lines, and a deformable surface is constructed.
- Deformable Bézier surfaces (Bézier) [206]: This technique use cubic Bézier curves as a representation of the virtual resection. The representation surface can be deformed by a grid of $4 \times 4$ control points. The initialization of the Bézier surface specified by using a plane to slice through the 3D liver model.

  After specification, it generates the contour representation on the liver model and these contours are used to determine the virtual resection. Regarding modification of a virtual resection, the user can drag any of the control points which influence the resection surface locally. The influence is at a maximum at the corresponding point of the resection surface and decreases to zero in a specific influence zone around that point.

Other approaches are also proposed, such as a virtual resection planning by erasing to remove the tissue [208]. However, this method's evaluation revealed that it was too difficult to specify resections precisely when using this technique. Moreover, the technique was challenging to control for such a fine-grained specification.

A sphere-based virtual resection method proposed by Yang et al. [209] can be used to divide the liver into left and right lobes. This division is performed in the axial view of the overlaid image slices, so a circle is generated by the section of the sphere over the slice. Their proposed method, however, formed the cutting plane based on the large cutting sphere and is explicitly designed for graft resections in living donor liver transplantation.

For the virtual resection technique presented in this work, an enhanced version of the DCP technique is introduced and adapted for a collaborative VR setting using VR controllers. Additionally, a high resolution of the resection surface is given as default to generate a smooth surface for modification. The resection margins, modification of virtual resection on individual 2D slices, and risk map visualization are also presented for this enhanced version.

## 6.3 Requirements

The requirements for system development were identified from related work and discussions with three surgical residents (2 to 14 years of working experience). The following requirements were identified:

**R1** Specification of a virtual resection has to be intuitive and precise. The users may want to decide which anatomic structure should be removed and specify the virtual resection by drawing lines on the organ parenchyma surface.

**R2** The possibility of modifying the virtual resection plane is crucial, e.g., avoiding affected blood vessels, and preserving the desired safety resection margin. Thus, the modification is needed for the resection surface on both 3D and 2D slices.

**R3** Resection volume estimation and surface model reconstruction are essential after the modification. This estimation is essential for surgeons to build confidence for planning.

**R4** The computation must provide a sufficient frame rate in order to provide a better user experience in VR (at least 60 fps [159, 160]). This is a challenging task because the medical volume data is large. Thus, the frame rate should not drop significantly, even during resource-intensive calculations.

## 6.4 Materials and Methods

In the following sections, system overview and surgical planning procedure, as well as virtual resection results of the proposed collaborative VR environment are described.

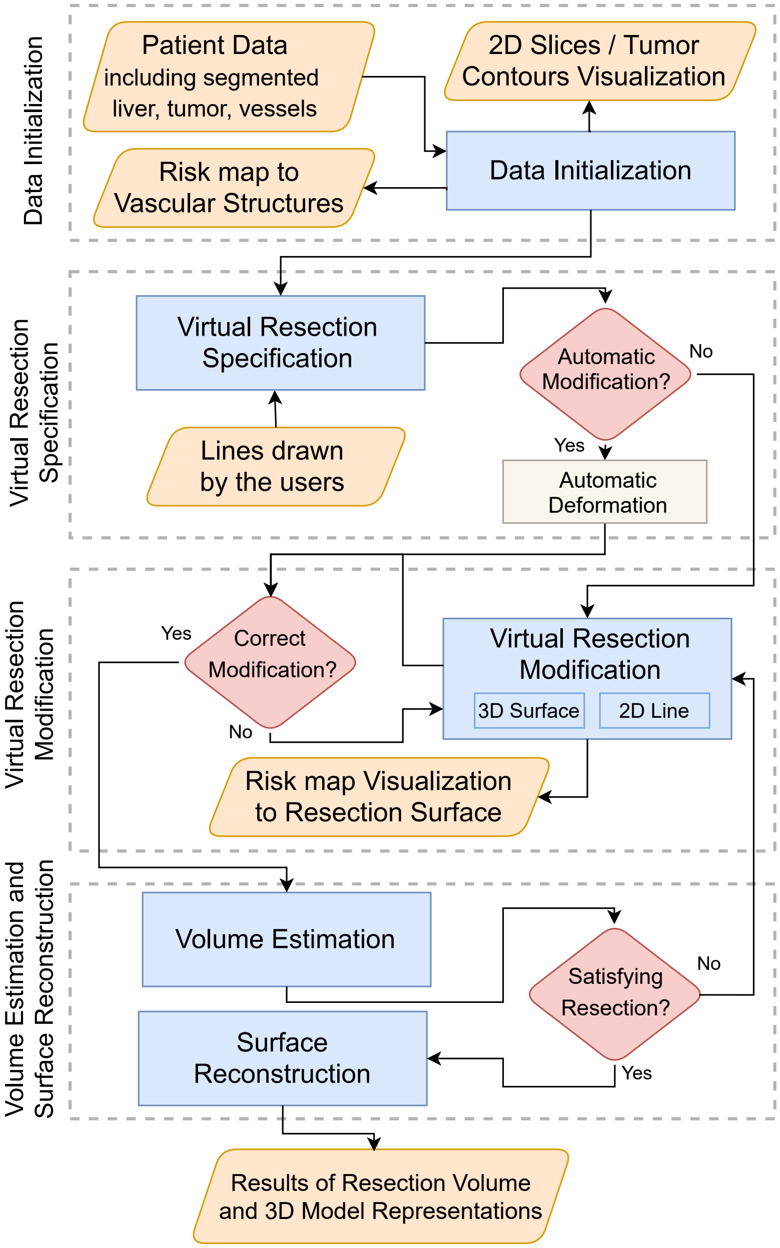


FIGURE 6.2: The procedure of the virtual resection for liver surgery planning contains four steps: data initialization, virtual resection specification, virtual resection modification, and volume estimation and surface reconstruction. *Figure from Chheang et al. [190] ©2021 Elsevier.*

### 6.4.1 System Overview

The proposed collaborative VR environment provides surgery planning via four main stages: data initialization, virtual resection specification, virtual resection modification, and volume estimation and surface reconstruction (see Figure 6.2).

- At the initial stage, the users can choose one of the patient cases, which are displayed on a viewer. Afterwards, they can explore and assess the structures at risk with a real-time risk map visualization.
- Virtual resection specification *(R1)* requires the users to draw lines on the organ parenchyma surface. Based on these lines, a resection surface is initialized, and the generated risk map of the tumors will be mapped.
- Virtual resection modification *(R2)* can be performed using two approaches: deforming with the resection surface and 2D lines representation on 2D slices. The users have the possibility to estimate the resection volume.
- The system will then reconstruct the resection volume results as 3D model representations with different colors to indicate each part and its volume *(R3)*. The users can further explore the individual resection parts, add an additional resection surface, and write issues to discuss on the virtual whiteboard.

#### Development Environment

The Unity game engine (version 2019.4.2) and the VRTK asset (version 3.3.0) are used for fundamental VR interactions. An MS Windows server is set up to handle networking communication and synchronization with the load balancing service provided by Photon (Exit Games GmbH, Hamburg, Germany). HTC Vive headsets and trackers are used for VR setup. The selection of libraries used for the system development was based on the discussion with experts in the field, online forums, and related work. The use of related libraries is described in the following.

The software tool for image analysis *SimpleITK* is integrated and used within Unity to compute and process patient image data. MeVisLab (MeVis Medical Solutions AG, Germany) [210] is also used during the development to test and verify the output images, e.g., voxelized and segmented images from Unity. The mesh reconstruction is based on the Marching Cubes algorithm with the support of the *geometry3Sharp* (Gradientspace, Canada) library. Furthermore, mesh smoothing is performed (*EdgeLengthMultiplier = 2.5, SmoothSpeed = 1.0*, and number of iterations = 20) with the remesh tool provided by this asset. The *SmoothSpeed* refers to the smoothing factor that the value is ranged from 0 to 1. This *SmoothSpeed* controls how quickly the smoothing happens, and it represents the weight for smoothing calculation. More passes mean more smoothing, and the model will shrink accordingly. The *EdgeLengthMultiplier* sets the goal of average edge length. In each pass, it iterates over the edges of the mesh and applies operations such as split and collapse. The split function replaces two triangles with four new ones by adding a vertex, while a collapse function is used to remove an edge.

To ensure a sufficiently high performance of VR system *(R4)*, top computational components realized by the CPU and by the GPU are considered. During development, Performance Profiler provided by Unity was used to track and analyze the resource usages, and we attempted to optimize them accordingly. Moreover, the *Level of Detail* (LOD) technique was employed for mesh rendering, e.g., the meshes representing the virtual room. The meshes can be created with different LODs and groups using a 3D modeling application, e.g., Maya. In this work, 3 LODs were imported to use with Unity's LOD system. The Unity function called LOD group was used to handle the meshes, it will switch between the lower and higher details of the mesh based on the distance to the camera. To support parallel computation, the asset *Thread Ninja* (Ciela Spike, Japan) was used. Using multi-threading is to support the large computation in the background so that the main thread can maintain the VR simulation logic.

In addition to the system performance concerns, the synchronization for collaboration should be considered. In the following section, the collaborative aspects and data synchronization of the proposed system are described.

### Collaborative VR Environment

Figure 6.3 provides an overview of system architecture for the proposed collaborative VR environment. The environment facilitates surgical planning with different user roles, e.g., surgeon, assistant, nurse, anesthesiologist, and observing students, that are essential entities in the surgical planning and training process. While the main focus is on VR users, the non-VR users can also join and collaborate within the environment using conventional input devices.

There are two collaborative modes in the proposed VR environment: asynchronous (sequential) and synchronous (simultaneous) collaboration. In the *asynchronous mode*, users perform the actions sequentially. For instance, the user with the role of a surgeon draws the incision lines so that all users can start the discussion and perform other possibilities, such as initializing the virtual resection. For *synchronous mode*, the remote users perform and modify properties on the same virtual objects. For example, during the virtual resection modification, the users with different roles can discuss and refine the resection surface on the same shared liver model.

A multicast protocol is used for network communication where the source transmits the data to a group of receivers. For instance, a client sends an update to a corresponding server, and the server multicasts all the updates to other clients. This form of architecture provides a stable and secure solution that avoids common connection problems as seen in peer-to-peer architectures [211]. This includes network address translation

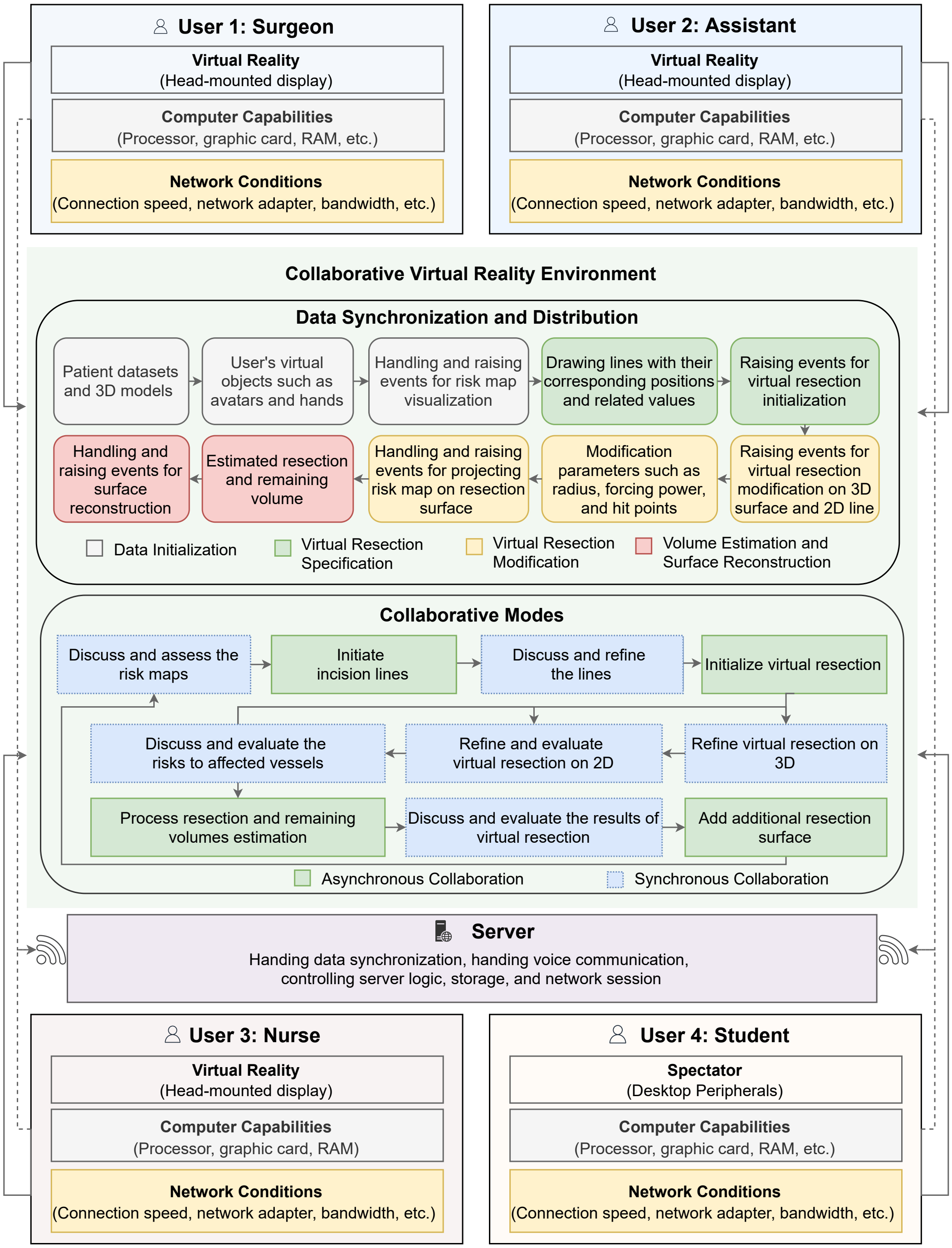


FIGURE 6.3: Overview of the system architecture for our collaborative VR environment. A client-server architecture is used for voice and data synchronization. Two modes of collaboration are supported. Synchronous collaboration allows the users to control and operate the modifications on the same virtual objects in real-time. For asynchronous collaboration, the actions occur sequentially and the virtual objects can be controlled and manipulated by one user at a time, e.g., the surgeon initiates the incision lines so that the assistant and scrub nurse can start the discussion and refinement. *Adapted from Chheang et al. [190] ©2021 Elsevier.*

(NAT) and security concerns. Moreover, it allows clients who join late or need to reconnect to the virtual environment to load synchronized states. This is beneficial for a stable connection of the collaborative environment. When a master client gets disconnected, a new master client is automatically assigned. The master client performs the application logic and sends the results and current states to all other clients, guaranteeing that all users are in sync. As a default, the surgeon's role is assigned as the master client. However, there is also a possibility to request and assign the master client for other clients during runtime.

#### Data Synchronization and Distribution

A real-time socket server is set up to provide the load-balancing services for handling data synchronization, voice communication, and shared network session between the clients (see also Figure 6.3). For remote collaboration, the user's machine capabilities and network conditions can affect the collaborative performance and the user experience. Factors such as delay, bandwidth, jitter and packet loss should be considered [62].

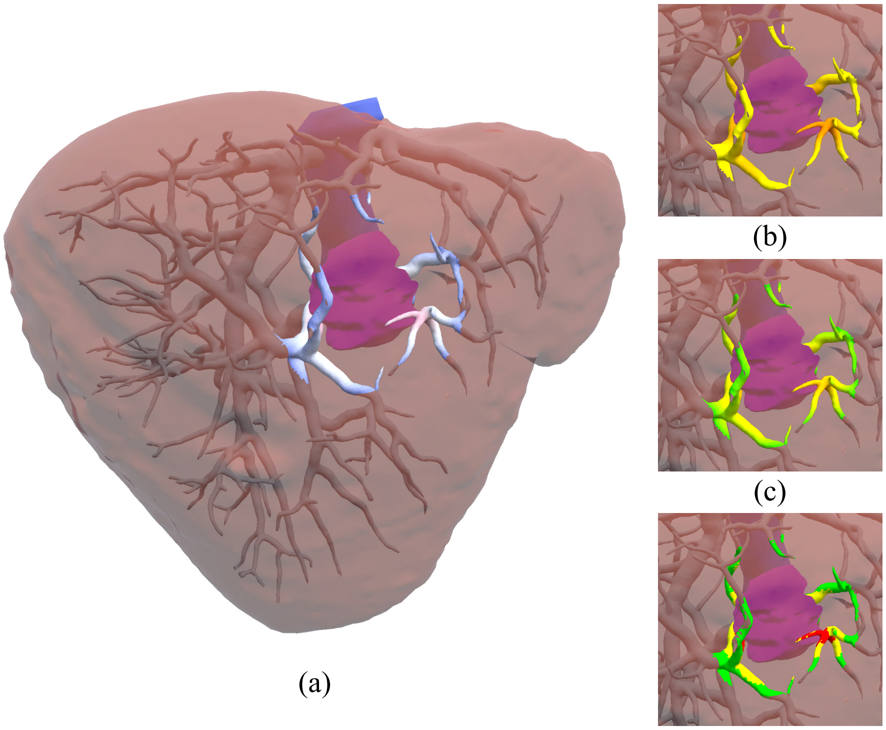
In addition, the synchronization approach suggested by Singhal et al. [212] was followed for system development to compensate for the lack of synchronization between virtual objects. Thus, clients are responsible for sending periodic data, such as avatar position, rotation, and animation during the active replication states. This approach stores their current states locally and sends updates to other clients. The virtual object's position, orientation, and scale should be synchronized during an interaction, such as during grabbing or scaling. To provide stability to the connection and to prevent the server's bottleneck, the clients are responsible for rendering individual graphics. The server manages and handles the primitive values. The communication mechanism *Remote Procedure Calls* (RPC) was used to send requests and distribute the data between the clients. Additionally, sending a large amount of data and unnecessary data for every update frame is avoided.

### 6.4.2 Surgical Planning Procedure

In the following, the procedure of virtual resection planning is explained in detail.

#### Data Initialization

After the user has chosen a patient case, the system initially generates a risk map, contours of tumors and individual 2D slices (axial view) from the selected dataset. The user is provided with a 3D model representation of the liver, tumors, and related vascular structures.



(a)

(b)

(c)

(d)

FIGURE 6.4: Different risk map visualizations of vascular structures: (a) temperature color map, (b) yellow-red color map, (c) green-yellow-red color map, and (d) color map with a discrete distance of 15, 10 and 5 mm. *Figure from Chheang et al. [190] ©2021 Elsevier.*

To support surgeons in accessing the risk structures, different color maps extracted from literature for risk map visualization are provided. The color maps encode the risk based on the distance between vascular structures and tumors. The color maps are as follows: a temperature color map proposed by Moreland et al. [213], a yellow-red color map [206], a general scale of green-yellow-red color, and a discrete distance (15, 10, and 5 mm around the tumors) suggested by Preim et al. [214] (see Figure 6.4).

As a default, the risk map visualization is employed with the discrete distance color map. Below 5 mm margins are indicated with red color, which means this part of the vessel is to be resected. The margin between 5 to 10 mm is visualized in yellow, and between 10 to 15 mm is indicated in green. It is possible to adjust the distance values interactively.

The risk map is generated by calculating the Euclidean distance transform of the tumor image with the assistance of the *SignedMaurerDistanceMapImageFilter* from SimpleITK [215]. The obtained image is transformed into a 3D texture to make it usable in Unity. This 3D texture is displayed with a custom shader to project the visualization to the resection surface and affected vascular structures. Additionally, the texture coordinates of the projected surface is computed so that the texture can be mapped (see Algorithm 1).

**Algorithm 1** Risk map visualization for surface texture coordinates.

**Precondition:** **R** being the root transformation of organ models, **S** represents the surface for projecting risk map, $\vec{w}$ indicates the vector of risk map's size, and $\vec{p}$ represents vector of **R**'s scale.

```
function CALCULATEUVW($\mathbf{R}, \mathbf{S}, \vec{w}, \vec{p}$)
    $M_{world} \leftarrow$ World Matrix transformation of $\mathbf{S}$
    $M_{local} \leftarrow$ Local Matrix transformation of $\mathbf{R}$
    $V \leftarrow$ Initialize list of $\mathbf{S}$ vertices
    $\vec{P_s} \leftarrow 1/\vec{w} \times \vec{p}$
    for $i \leftarrow 1$ to $VerticesLength(S)$ do
        $\vec{n} \leftarrow (M_{local} \times (M_{world} \times V_i) \times \vec{P_s}) \times \vec{p}$ append $\vec{n}$ to $V$
    end for
    return $V$
end function
```

**Algorithm 2** Resection surface initialization

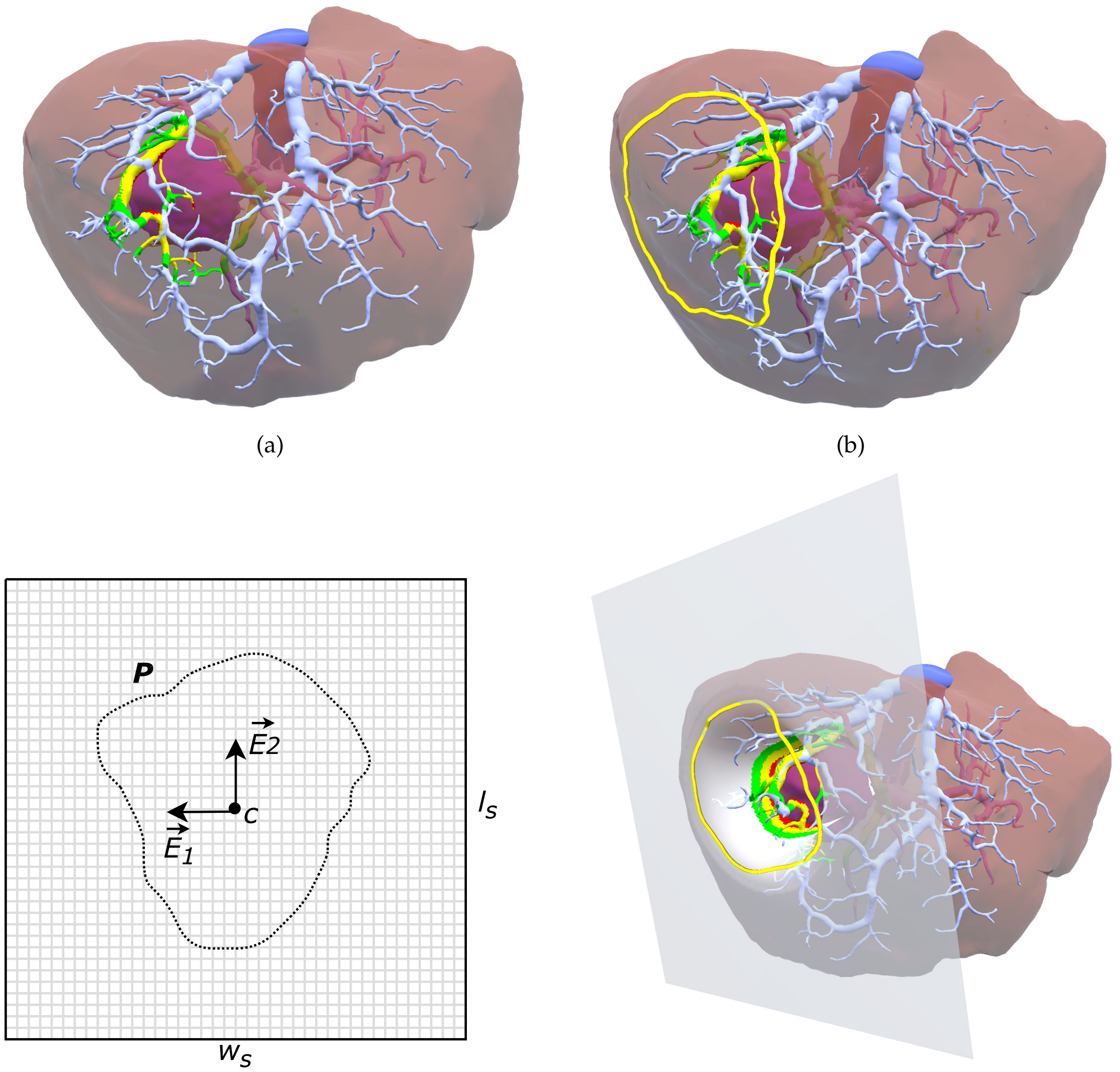
**Precondition:** P being the pointset of the lines drawn by the users with the grid resolution $w_s \times l_s$, and $w \times h$ representing the size of the liver's width and height.

```
function INITIALIZATION($P, w, h, w_s, l_s$)
    $[\vec{E}_1, \vec{E}_2] \leftarrow PCA(P)$
    $c \leftarrow \frac{1}{N}\sum_{i=1}^{N} p_i$                                ▷ $p_i \in P$
    $i \leftarrow 0$
    for $y \leftarrow 0$ to $l_s + 1$ do
        for $x \leftarrow 0$ to $w_s + 1$ do
            $\vec{V_i} \leftarrow (x(\frac{w}{w_s}) - \frac{w}{2}\vec{E}_1 + c, y(\frac{h}{l_s}) - \frac{h}{2}\vec{E}_2 + c)$
            $u\vec{v}_i \leftarrow (x\frac{1}{w_s}, y\frac{1}{l_s})$
            $S_{x,y} \leftarrow \vec{V_i}u\vec{v}_i$
            $i \leftarrow i + 1$
        end for
    end for
    return $S$
end function
```

### Virtual Resection Specification

The specification of a virtual resection is based on the lines drawn on the liver parenchyma (see Figure 6.5). These lines are used to initialize the virtual resection. For this purpose, the line drawn on the surface is transformed into a plane through the organ. The DCP approach of Konrad et al. [202] is adapted and its major steps are recapped in the following.

1. *Determine the oriented bounding box from the incision lines.* This is achieved by using a PCA from the lines drawn by the user. Let $P = \{p_0, p_1, p_2, ..., p_n\} \subseteq \mathbb{R}^3$ be the



(a) (b)

(c) (d)

FIGURE 6.5: Virtual resection specification: (a) projection of risk map visualization to the vascular structure, (b) lines drawn by the users to specify the pose to initialize the resection surface, (c) the centroid and direction of the resection surface is computed based on principle component analysis (PCA) from the drawn lines, and (d) initialization of resection surface with an automatic modification and projection of the risk map on its surface. *Figure from Chheang et al. [190] ©2021 Elsevier.*

point set from the lines and $c$ be the center of the plane (origin). This center $c$ is computed based on the centroid of point set $P$ (see Equation 6.1).

$$c = \frac{1}{N}\sum_{i=1}^{N} p_i \quad , \quad p_i \in P \tag{6.1}$$

2. *Determine the orientation and extent of the plane.* The orientation of the resection

plane is given by two corresponding eigenvectors $\vec{E}_1$ and $\vec{E}_2$ computed by the PCA.

3. A grid with quadrilateral cells is generated based on the defined plane (hereafter resection surface). The resolution of the initial resection surface is adjustable and the grid size is represented by $(w_s, l_s)$. This way, we can specify the grid control points and the resection surface initialization (see Algorithm 2).

4. *Calculate displacements & smoothing.* Following the initialization of the resection surface, the users can choose between automatic and manual deformation. Resection volumes often have a cone-like shape. The automatic deformation aims to support users by initially generating a deformation of the resection surface from the drawing lines to the target tumor (see Figure 6.5d). However, the users can deform the resection surface manually from a flat-surface shape.

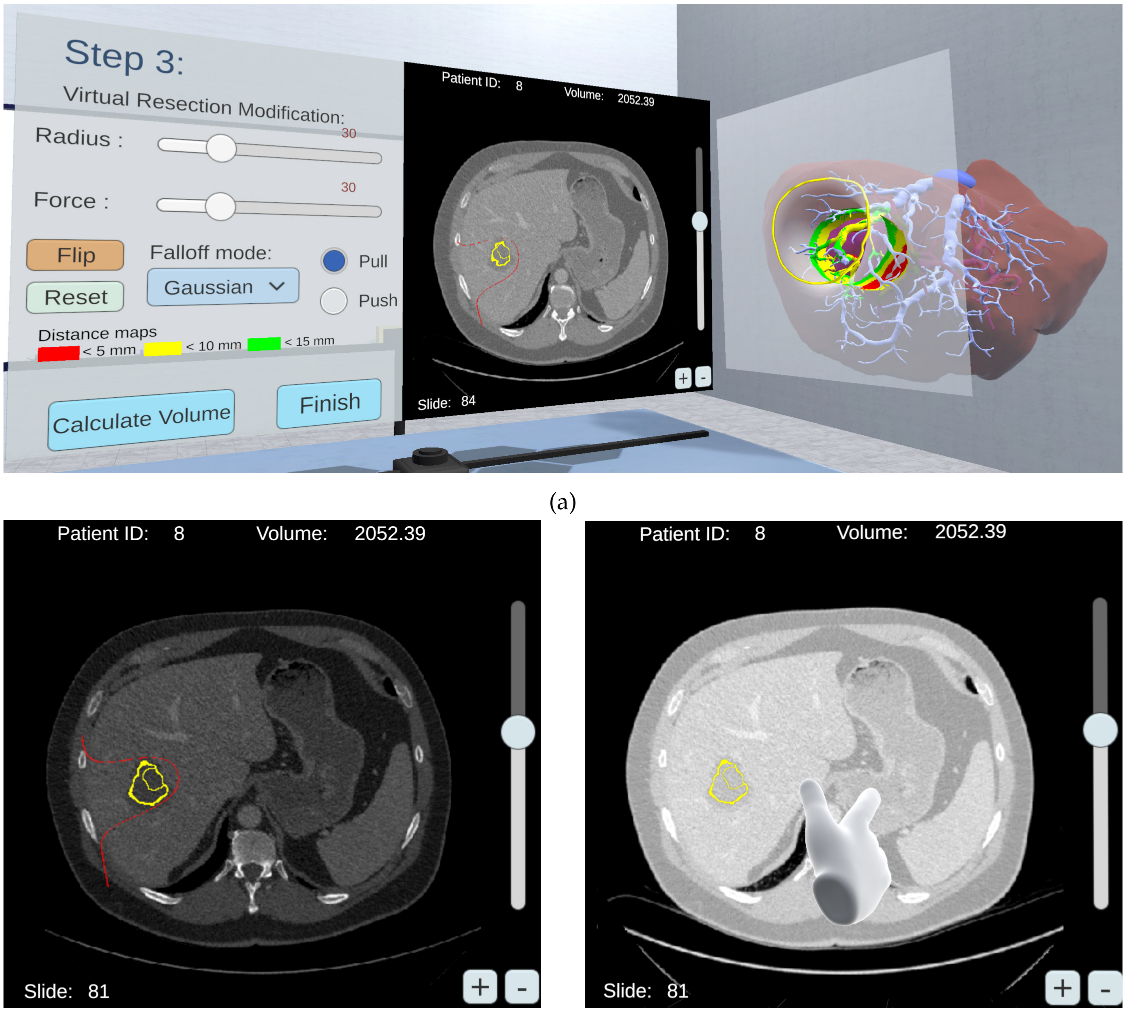
   For automatic deformation, the radius $r$ is determined by the distance between minimum and maximum points of the drawn lines. The displacement $d$ is determined from the distance between the centroid $c$ to the z-component of the target tumor's position. After the distance and radius are determined, the relevant grid points are iteratively smoothed. A Gaussian method is applied so that the distance of the grid point is replaced by the average weight of the distance between neighboring points.

### Virtual Resection Modification

An interaction method where users can use their controllers as VR hands is implemented. The VR hands are animated according to the events from the controller buttons. For example, when a user touches the controller touchpad, the virtual hand is animated as a pointing gesture. Using this approach, a ray pointer is attached to the virtual index finger. With this ray-based interaction, the user can easily interact with the user interface (UI) and resection surface. The ray is enabled when the user presses the controller touchpad.

Two options for modification are provided: on the 3D model in mid-air, and individual 2D slices (see Figure 6.6). Additionally, the UI provides options to adjust the parameters for modification such as radius, forcing power, flip, reset, falloff mode, and "pull" and "push" options. (see Figure 6.6a). The users can directly grab and deform the resection surface with their VR hands. To deform the resection in the 2D view, the users can point to the resection line displayed in red color (see Figure 6.6b).

Because the tumors and vascular systems are essential for resection planning, the system also allows the users to explore the patient data and modify the virtual resection in the 2D view. This is crucial because sometimes not all vascular branches can be segmented



(a)

(b)

(c)

FIGURE 6.6: Modification of virtual resection with the 3D model in mid-air and on individual 2D slices: (a) options for modification, (b) projection of the tumor contours (yellow color) and resection line (red color), and (c) gesture to adjust window/level with the virtual hand model. *Figure from Chheang et al. [190] ©2021 Elsevier.*

and reconstructed as 3D models due to low grey value contrast. Also, the individual structures of the 3D model can occlude each other. Additionally, the contours of the tumor (yellow color) are projected into individual 2D slices (see Figure 6.6b).

The tumor contours are generated based on SimpleITK *BinaryContourImageFilter* and can be projected onto the 2D slices. The users can move their VR hands representation to adjust the window/level settings of the 2D images to view the details and explore the slices using a slider or clicking on the buttons (see Figure 6.6c).

The size of the reconstructed 3D organ model is based on the original size from the segmented image data. The users can move the model freely in VR as well as scale the

3D model by pressing the controller grip buttons on both hands. Thus, they can scale up or down based on the distance between the controllers in a similar way to the pinch gesture used on a smartphone.

***Virtual resection modification on 3D model*** The resection surface can be further refined to avoid the affected vessels and increase the remnant volume as much as possible (see Figure 6.7). This is accomplished by translating the grid points of the resection surface. The radius $r$ and forcing power $p$ can be adjusted by the users. The radius indicates the size around the target point, while the forcing power represents the amount of strain that influences the deformation.

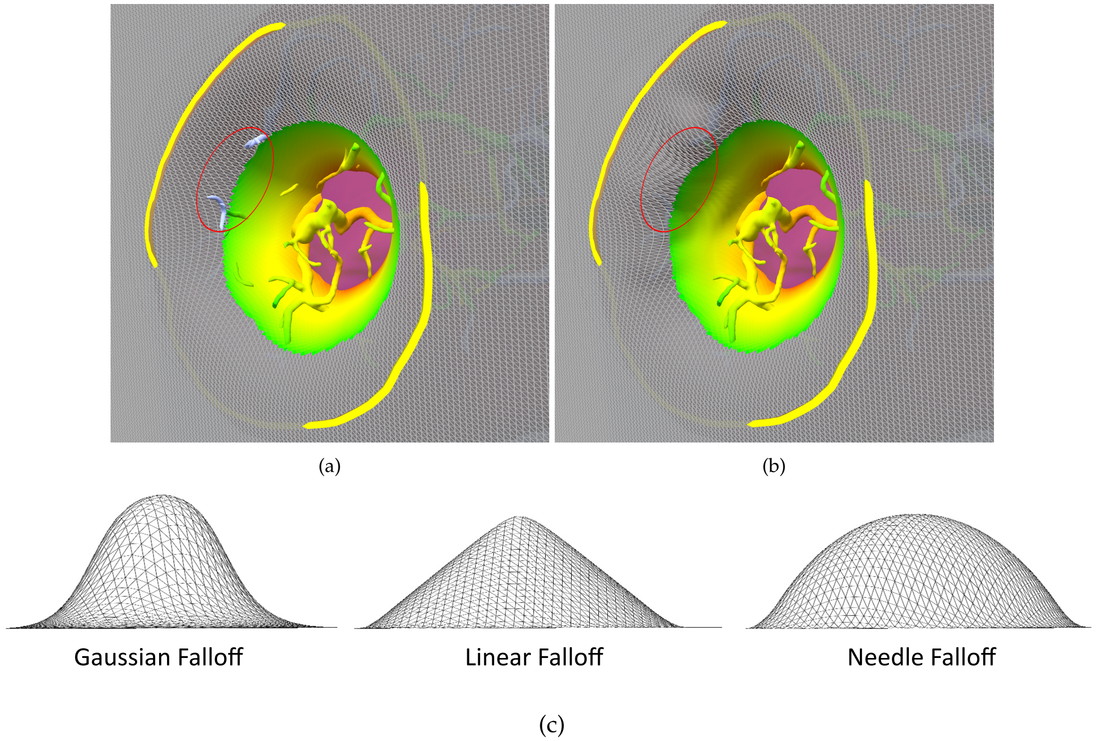
By default, $p$ is set to positive; however, the users can change the direction of the deformation such as inward and outward bending by using “pull" and “push" options. The target point $a$ indicates the hit point of the ray attached to the virtual index finger to the resection surface. This ray pointer is activated when the users press on the touchpad of the VR controller.

Three different falloffs are supported: Gaussian $f = 360^{-(d/r)^{2.5}-0.01}$, linear $f = 1 - d/r$, and *needle* $f = -d^2/r^2 + 1$, where $f$ represents the falloff value which is used to define the relevant point (see Figure 6.7c). As a default, the Gaussian falloff is used, making it possible to combine multiple deformations. For the linear falloff, attenuation of related points is created along with its range, while the *needle* falloff method induces a round attenuation area of influence. Therefore, the grid points $G$ can be modified as $G = a \times f \times p$. This modification is further updated for the resection line which is then projected onto the 2D slices. This line is generated based on the grid points of the resection surface and its orientation.

***Virtual resection modification on 2D slices*** Users can also refine the virtual resection directly onto the projected resection line. The modification on both 2D and 3D modalities are synchronized. This is achieved by assessing the hit point from the ray on the 2D view to the slice index to modify the virtual resection accordingly. Additionally, after deforming the resection surface, those grid points are evaluated in order to define the corresponding texture coordinate and project the risk map on the surface in real time.

### Volume Estimation and Surface Reconstruction

After the users refine the resection surface, they can estimate the resection volume which is essential to understand the potential resection. The steps for determining the resection surface to image-based segmentation, volume calculation, and mesh reconstruction are described in the following:


(a) (b)

(c)

FIGURE 6.7: The initial virtual resection can be refined by the users: the vessel branch (a) is excluded from the resection (b) (see the encircled regions), and (c) falloff options for modification. *Figure from Chheang et al. [190] ©2021 Elsevier.*

***Resection surface voxelization*** To provide a precise calculation of the resection and remnant volume, the resection surface is transformed into the image domain which allows us to manipulate it with image processing methods. In the following, voxelization techniques compared during the system development are summarized.

- The first technique is a *Signed Distance Field* (SDF). The voxelization based on this SDF is similar to Baerentzen et al. [216]. The voxel size ($v$) for the computation is set to the same cell size as the original image.
- For the second technique, the voxelization based on point-containment queries (CPQ) is used. The results of voxelization with this technique are based on the ray-tracing accelerated from *Bounding Volume Hierarchy* to classify the mesh triangles.
- The third technique is a hierarchical evaluation using the fast mesh winding number (MWN) presented by Barill et al. [217]. The MWN is used to determine whether a point is in or outside of the triangle's mesh. It also represents the number of times that the planar curve travels around the point. The MWN is zero when the point is outside and one when it is inside of the component. The MWN results in an integer when the mesh is entirely closed; however, a threshold ($w$) is

| Methods | Parameters | Time (ms) | Volume (ml) |
|---|---|---|---|
| *MT* | $v = 1$ | 468 | 148.74 |
| SDF | $v = 1$ | 1659 | 141.85 |
| CPQ | $v = 1$ | 36337 | 144.16 |
| MWN | $v = 1, w = 0.025$ | 53649 | 149.20 |

TABLE 6.2: A comparison of the results from voxelization techniques of the resection surfaces. Parameters: $v$ voxel size, and $w$ winding number threshold. *SDF:* Signed distance field, *CPQ:* Point-containment queries based on bounding volume hierarchy, *MWN:* Mesh winding number, and *MT:* GPU-based Möller–Trumbore ray-triangle intersection. *Table from Chheang et al. [190] ©2021 Elsevier.*

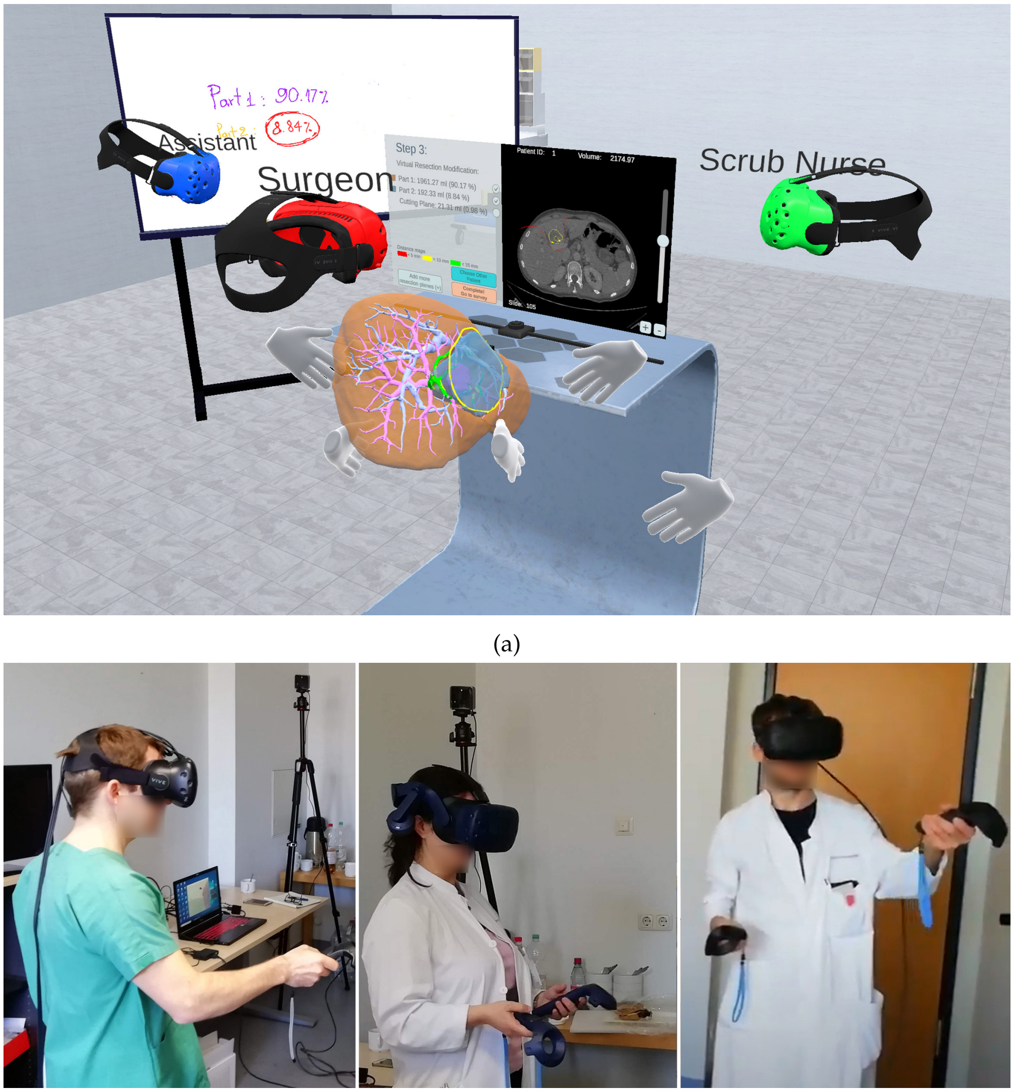
used to determine the range of the MWN values considered inside of the resection surface.

- The last technique is the GPU-based Möller–Trumbore (MT) intersection algorithm [218], which is used to determine a ray intersecting with the triangle mesh.

The techniques were evaluated with nine resection surfaces from patient cases (see Section 6.5.1). The average values of the resection surface are: dimensions 218 × 204 × 62, vertices 61250, and faces 121104. The test was computed on a computer with an Intel® Core™i7-8700K CPU @3.70 GHz (12 CPUs) processor, an NVIDIA GeForce GTX 1080 (8GB VRAM) graphics card, and RAM 32GB. The results are illustrated in Table 6.2.

The SDF, CPQ and MWN were computed effectively with a closed mesh. The plane mesh provided by Unity has only a single sided face, which is also referred to as a *normal* vector. If the resection surface is deformed, the concave areas are filled, resulting in larger volume. Therefore, the implementation of an opposite side for the resection surface should be considered. Using MWN can handle for self-intersection and overlapping components. However, the computation is very slow. Of all three techniques, we decided to choose the ray-triangle intersection based on GPU (MT) since it provides acceptable results regarding dimension, volume, and especially computation times, which is essential for VR.

***Segmentation and surface reconstruction*** The connected component analysis is applied to label the volume data. It provides a simple approach to cluster the voxels and results with different labels. It can be used to label the resection and remaining volume after determining the image-based resection surface. Based on these labels, the volume estimation can be calculated. The resection parts generated from the segmentation are used for surface reconstruction. The reconstructed surfaces are highlighted with different colors allowing users to better understand resection extents and associated volume measures.



(a)

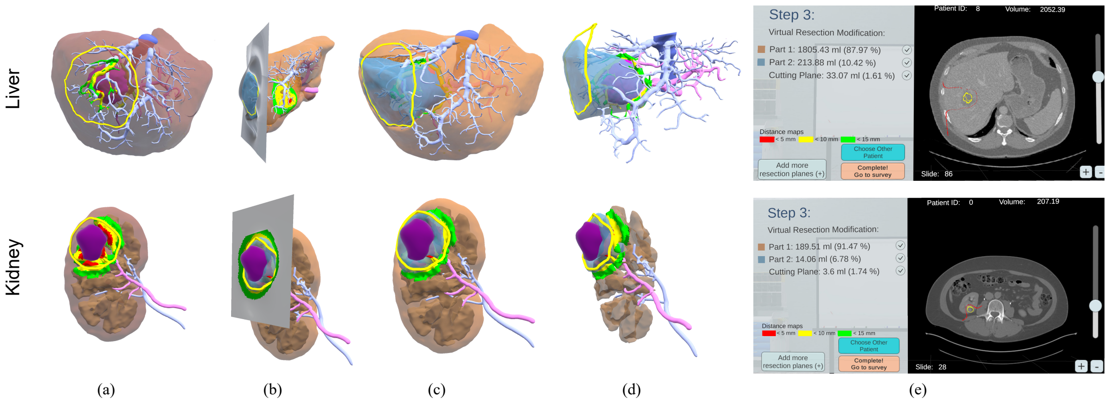
(b)

FIGURE 6.8: Multiple users performing surgical planning: (a) the users as seen in the immersive environment (surgeon: red color, assistant: blue color, and scrub nurse: green color) and (b) users in the real world. *Figure from Chheang et al. [190] ©2021 Elsevier.*

### 6.4.3 Results of Virtual Resection

The proposed VR environment allows for multiple users via join by remote or shared environment. Figure 6.8 illustrates the users joining the virtual room and performing the surgical planning. Various interaction possibilities have been developed to support the planning process, including a virtual screen and a virtual whiteboard.

The users can choose a patient dataset from various cases. After selecting a case, the system generates the 2D image data and a 3D organ model. They can begin interacting, exploring and assessing the risk structures. Furthermore, they can evaluate the details of 2D slices and contours of the tumors. Following the exploration, they can start the planning procedure by drawing incision lines on the 3D liver model with the help of the risk map visualization. Users may choose between automatic and manual deformation. The resection surface can be further refined to avoid affecting vessel branches and risk structures. The users can estimate the resection volume and return to modification. If they are satisfied with the modification, the system generates the surface reconstruction for resection parts with indicated colors and amount (see Figure 6.9). In addition, the collaborative users can discuss the results, write on the virtual whiteboard, define other resection surfaces (in case of multiple tumors), or select other patient cases.



Step 3:
Virtual Resection Modification:
Part 1: 1805.43 ml (87.97 %)
Part 2: 213.88 ml (10.42 %)
Cutting Plane: 33.07 ml (1.61 %)
Patient ID: 8
Volume: 2052.39
Slide: 86

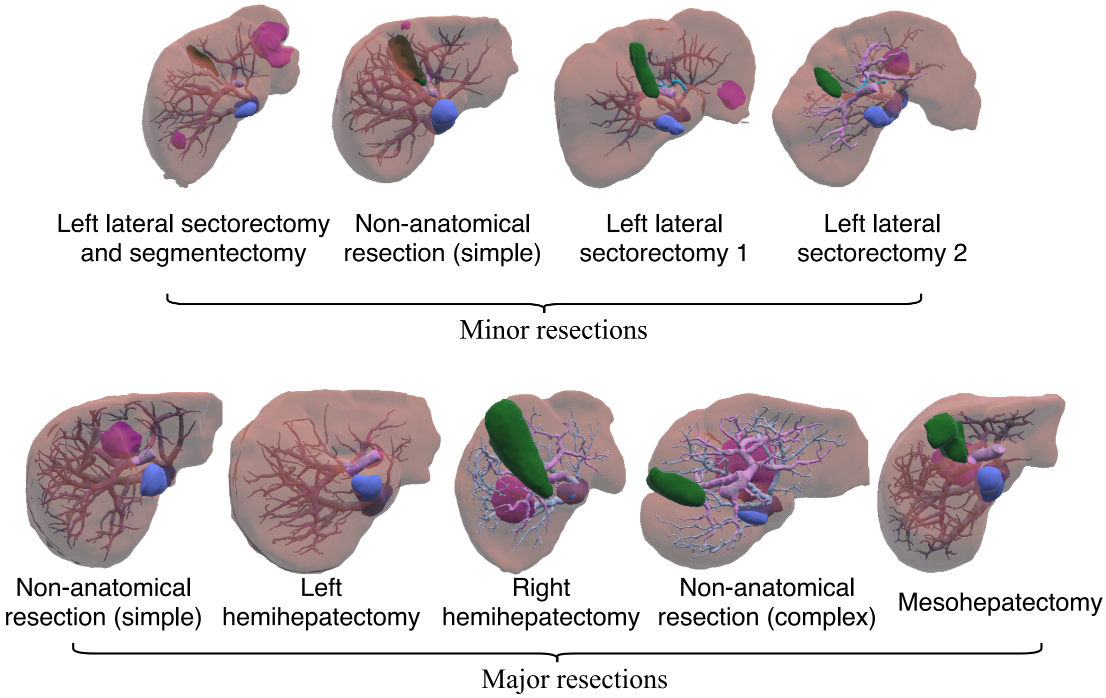
Step 3:
Virtual Resection Modification:
Part 1: 189.51 ml (91.47 %)
Part 2: 14.06 ml (6.78 %)
Cutting Plane: 3.6 ml (1.74 %)
Patient ID: 0
Volume: 207.19
Slide: 28

(a) (b) (c) (d) (e)

FIGURE 6.9: Resection volume and surface reconstruction: (a) organ models with the risk map visualization and the drawn lines from the users (tumors are indicated with dark-red color and lines are represented with yellow color), (b) reconstructed surfaces after the virtual resection modification (resection volumes are indicated with blue color while remaining volumes are indicated with dark orange color), (c) and (d) options to explore the results of resection parts, and (e) the UI for volume estimation and 2D image data. Besides the liver (top), the example of the kidney (bottom) is shown as a potential extension to other abdominal organs. *Figure from Chheang et al. [190] ©2021 Elsevier.*

## 6.5 Evaluation

For an initial user evaluation, exploratory and qualitative interviews were conducted with three surgeons. These interviews aimed to achieve two research objectives: firstly, they aimed to elicit the surgeons' informed opinion about potential benefits, applicability and limitations of a collaborative VR planning tool like ours. Secondly, we wanted to obtain specific feedback to further improve the usability of the tested prototype.


Left lateral sectorectomy and segmentectomy

Non-anatomical resection (simple)

Left lateral sectorectomy 1

Left lateral sectorectomy 2

Minor resections

Non-anatomical resection (simple)

Left hemihepatectomy

Right hemihepatectomy

Non-anatomical resection (complex)

Mesohepatectomy

Major resections

FIGURE 6.10: Overview of different patient cases with varying complexities and characteristics for resection planning. *Figure from Chheang et al. [190] ©2021 Elsevier.*

### 6.5.1 Patient Data and Pre-processing

The models used in our collaborative environment are based on segmented CT datasets. Patient data selection is based on potential resections, types of resections, and the availability of a preoperative high-quality CT scan. With the cooperation of our clinical partner, multiple cases were chosen and integrated. The selected datasets exhibit different complexities and characteristics of the resections (see Figure 6.10).

A left lateral sectorectomy and segmentectomy case was recommended for this study. The left lateral sectorectomy and segmentectomy are the clinical division term for surgical resection. The volumetry is crucial for major and multiple resections. In this patient's case, two resections are planned. Thus, it can show the possibilities of the tool for multiple resections. Besides the volumetry, the surgeons can perform the surgery planning on anatomical and non-anatomical resections, which are necessary in this case. Moreover, the case is not too complex (e.g., with vascular reconstruction), thus, it could provide an average level for planning and a first evaluation of the prototype.

### 6.5.2 Apparatus

A real-time socket server was set up to provide services, including *Photon networking*, for a shared session and data synchronization between connected users. This server was equipped with a Windows Server 2019 operating system, an Intel Xeon Processor @2.49 GHz, and 16 GB RAM.

The VR-ready computer equipped with Intel Core i7-6700 CPU @2.60 GHz processor, an NVIDIA GeForce GTX 1070 graphics card, and RAM 16GB was used for participants during this study. This computer was connected to the VR headset from HTC Vive and its components.

### 6.5.3 Methods

Three surgical residents were recruited to conduct a guided exploration of the proposed VR environment.

#### Study Sample

The three participants (one female, two male) were general and visceral surgical residents. The participants (*P1*, *P2*, *P3*) were aged 35, 30 and 28 years, with 6.5, 2, and 2.5 years of surgical experience. *P1* reported to have performed 12 resections and assisted in approximately 80, *P2* reported having assisted in five liver resections, and *P3* reported having performed one and assisted in 35. All participants had prior experience with VR from similar user studies for other VR tools.

### 6.5.4 Study Design and Procedure

The guided exploration and interviews were conducted remotely due to the safety measures mandated by the Covid-19 pandemic. One clinical team member was present with the participants in order to assist with the VR hardware and interview infrastructure. A second researcher remotely shared the virtual environment with the participants. A third researcher conducted the associated interviews during and after the exploration (hereafter referred to as the interviewer).

After the participants had been informed about the study and their oral consent had been collected, the demographic data and relevant experience were collected. The prototype workflow was split into four phases for the interview:

1. Case selection and 3D model exploration,
2. 3D virtual resection specification and modification,
3. 2D virtual resection inspection and modification,
4. Planning result visualization.

After each phase, the exploration was paused for a brief interview section. The participants remained in the virtual environment for this. During each interview break and after the last exploration phase, the questions included three main interview prompts:

- What is your overall impression?
- What was your approach for the given task?
- Could we make this task easier for you?

After the exploration was complete, participants were again prompted to share their overall impression of the tool. They were then asked to share their views on the benefits, applicability and limitations of such a planning tool for clinical planning and training. Finally, the participants were asked to complete the system usability and presence questionnaire.

### 6.5.5 Data Recording and Analysis

The interviewer took notes of all relevant participant comments during the interview. The comments were collated in a common database and redundancies were removed. The comments were then clustered and categorized. Subsequently, information was extracted from these clusters that were relevant to either of the research objectives. The analysis was conducted by one researcher (the interviewer).

## 6.6 Results

Three interviews were completed, resulting in 70 unique participant comments. These comments were assigned to seven categories: limitations, anticipated benefits, concrete usability issues, expectations, general feedback, training and education, and user approach. The following subsections provide a synopsis of the respective relevant comment categories.

The general feedback was consistently positive for all three participants. The participants commented that the system was helpful for spatial understanding and manipulation. One participant stated that the handling was very intuitive and another participant stated that they were satisfied with the planning result.

### 6.6.1 Applicability and Potential Benefits

Findings in this subsection are based on the comment categories: *anticipated benefits* and *limitations*, *user approach*, and *training and education*. The participants stated that the system might help to visualize and assess the spatial relationship between major vessels and the resection volume and, thereby, help to identify safety-critical areas. However, the participants emphasized that the tool would be primarily beneficial in cases that are challenging for a surgeon, i.e., either surgically complex cases or cases in which the surgeon has limited experience. *P1* and *P2* stated that it might provide experienced surgeons with a means to assess their trainees' understanding of a given case before letting the trainee conduct the operation.

The limitations that participants foresaw included acceptability for senior surgeons, clinical model validity, and logistical requirements: *P3* stated that experienced surgeons may not be willing to spend additional planning time by using the tool. The same participant expressed that the tool's applicability depends on the resection plane model's validity and the conclusions that it allows about blood vessels in the resection volume. Lastly, *P1* stated that patient data privacy requirements would have to be considered in remote collaboration sessions.

Finally, all participants expressed positive feedback about the combination between synchronized 2D and 3D image data representations. One participant stated that it might be case-dependent which of the representations could be more helpful. Another participant stated that they would likely use the 2D representation for initial plane modeling and the 3D representation for resection plane review and further improvements.

### 6.6.2 Usability Issues

The issues that were either observed by the researcher during the study or reported by the participants occurred during the workflow. This section is structured according to the workflow steps during which the issues arose.

*P2* experienced minor difficulties while drawing the initial lines. They had some issues pointing at the correct distance from the liver model. They also experienced some issues with drawing the intended line trajectory at the top and bottom of the model (from their perspective) as the drawing ray becomes more and more parallel to the model surface. *P3* mentioned that they would prefer an option to delete only parts of the incision line rather than deleting the entire line.

After drawing incision lines, *P2* struggled initially to understand the automatically generated surface cone because it reached farther and deeper into the liver model than necessary and expected. The other two participants experienced some confusion at first use with the “pull" and “push" functions. One of them mentioned that they would prefer to “hold on to" one point on the plane so that the changes made to the deformation direction correlates to the direction of the cutting plane. This could make the interaction more intuitive.

Some participant comments referred to the model visualization during the resection surface manipulation. *P1* stated that they would prefer the plane outside the model to be hidden so that the resulting incision line could be made visible. The same participant proposed highlighting blood vessels that cross the planned resection plane and, if possible, those vessels' perfusion areas. The other two participants experienced some confusion concerning the risk map visualization. *P3* stated that the color meaning was not intuitive with the legend. In contrast, *P2* interpreted the risk map such that the entire highlighted volume needed to be resected. The same participant expressed confusion with the risk map highlighted in the 3D model while deforming the resection line on the 2D slices. Therefore, the risk map visualization should be extended to the 2D view as well.

Participants mentioned some minor issues with the 2D image interaction. *P3* experienced minor difficulties with the gesture control for the DICOM windowing function. *P1* proposed adding the 2D control instructions to the instruction board. Regarding the resection plane visualization in the 2D representation, *P1* stated that it should be limited to the area of interest, i.e., to the liver itself, rather than a visualization of the entire dataset volume. *P3* proposed adding a scale or some other visualization to convey information about the absolute distance between the resection surface and structures of interest.

Finally, two participants proposed improvements for the planning result visualization. *P1* suggested hiding the tumor so that only the remaining tissue would be visible. *P3* stated it might be helpful to have an option to hide the blood vessels as well, but emphasized that there is a clear benefit in seeing them.

### 6.6.3 Questionnaire Results

To evaluate the system usability and presence in the virtual environment for the current prototype, we asked the participants to complete a standardized questionnaires after their exploration. For system usability, the system usability scale (SUS) [219] was used. The questionnaire consists of ten questions with a five-point Likert-scale from *strongly disagree* to *strongly agree*. The evaluation using this scale is converted to a range of 0–100% that represents the subjectively perceived usability (0–50%: not acceptable, 51–67%: poor, 68%: okay, 69–80%: good, 81–100%: excellent) [220]. The SUS's results from all participants conveyed an average score of 84.17% (*SD* 6.29), which classifies the proposed prototype as relatively easy to use (see Table 6.3).

The sense of presence in the immersive environment was evaluated by the Igroup Presence Questionnaire (IPQ) [221]. This questionnaire consists of 14 questions with a 7-point Likert-scale. IPQ has three subscales: spatial presence (IPQ: SP), involvement (IPQ: INV), experienced realism (IPQ: REAL), and an additional item, general presence (IPQ: GP).

| Ps | SUS | IPQ: GP | IPQ: SP | IPQ: INV | IPQ: REAL |
|---|---|---|---|---|---|
| P1 | 77.5 | 5 | 4.8 | 4.75 | 3.75 |
| P2 | 90 | 6 | 6 | 5.5 | 4.75 |
| P3 | 85 | 5 | 4.6 | 2.25 | 2.75 |
| Mean | 84.17 | 5.33 | 5.13 | 4.17 | 3.75 |

TABLE 6.3: SUS and IPQ scores for each participant. *Ps*: participants, *SUS*: system usability scale, *IPQ*: igroup presence questionnaire, *GP*: general presence, *SP*: spatial presence, *INV*: involvement, and *REAL*: experienced realism. *Table from Chheang et al. [190] ©2021 Elsevier.*

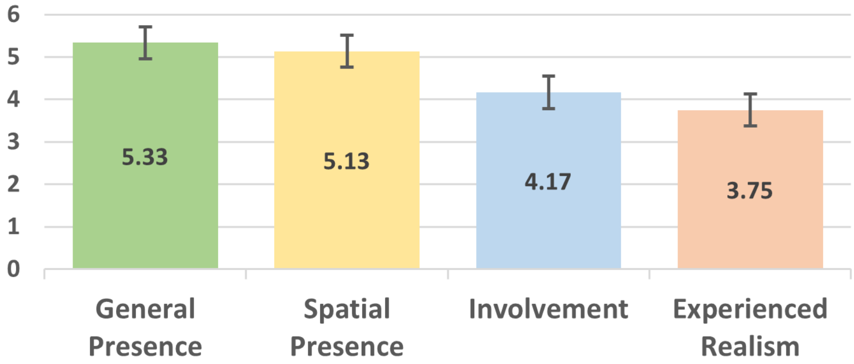


FIGURE 6.11: Results of the subscales of the presence questionnaire (IPQ).

Spatial presence describes the sense of being immersed in the VR, i.e., perceiving the pictures and sense of being present. The involvement measures the experience and attention devoted to the virtual world, and this factor is affected by the virtual realism but not by the environment itself. The experienced realism describes the subjective experience of realism while performing in the virtual environment. It is a comparison between the virtual and the real world. Finally, general presence refers to the general sense and it is a significant main effect of the virtual realism [222].

Figure 6.11 shows the questionnaire results. The general presence was rated highest (*M* 5.33, *SD* 0.58), while the average scores of spatial presence (*M* 5.13, *SD* 0.76) and involvement (*M* 4.17, *SD* 1.70) revealed the proposed VR environment to be rather acceptable for providing sense of presence. However, the average score of experienced realism (*M* 3.75 *SD* 1.00), which included the questions regarding the comparison with the real world, was rated lowest. It received low values because the design of the virtual room has low realism due to its abstract representation. Hence, the design of the virtual room should be further improved.

### 6.6.4 System Performance

Round-trip time (RTT) is the duration it takes for a data packet to be sent plus the time it takes to acknowledge that it is received. The RTT was tracked during the whole evaluation. The internet connection speed was measured at the end of the evaluation with 28.26 Mbps (download) and 34.96 Mbps (upload). The average RTT over all participants in the user datagram protocol (UDP) is 49.38 ms, and the average frame rate is 84.97 fps. Additionally, the researcher who shared the virtual environment with the participants was connected with a wireless connection speed of 93.72 Mbps (download) and 122.89 Mbps (upload). The average RTT is 33.4 ms, and the frame rate is 88.98 fps.

| Ps | Time: Spec *(s)* | Time: Mod *(s)* | Vol. *(ml)* | *(%)* |
|---|---|---|---|---|
| P1 | 50.23 | 989.64 | 2058.88 | 90.98 |
| P2 | 307.13 | 930.29 | 1944.68 | 85.93 |
| P3 | 321.64 | 1297.88 | 2072.16 | 91.56 |

TABLE 6.4: Times and results of remnant volume for each participant. *Ps*: participants, *Time: Spec*: Time required for virtual resection specification, *Time: Mod*: Time required for modification including 2D and 3D, *Vol.*: Remnant volume. *Table from Chheang et al. [190] ©2021 Elsevier.*

### 6.6.5 Planning Results

The planning results from the participants were recorded for the case of the left lateral sectorectomy and segmentectomy. As shown in Table 6.4, the times were recorded for virtual resection specification and modification. The specification time includes drawing lines on the liver model. The modification time includes the interactions on 3D and 2D slices to refine the resection surface. Moreover, the remnant volume results are shown in milliliter (*ml*) and its percentage (%).

Preoperative assessment, including the liver remnant volume, is crucial. The postoperative liver remnant has to be about 1/3 of the healthy liver volume and depends on the patient's general condition and liver disease [223]. For the selected case, the results of the remnant volume are enough and the variations between the participants are 3%. The time differences between the participants (15–30 minutes) are reasonable for resection planning.

## 6.7 Discussion

The proposed VR environment was evaluated by experts and valuable insights were gained during the interview. The general feedback was positive, and comments were collected about advantages, limitations and clinical applicability. The experts emphasized that the system would be beneficial for planning, especially for complex cases, and it could be useful for training. However, data privacy requirements should be considered during remote collaboration.

Clinical feedback was collected to further improve the usability of the prototype. For specification *(R1)*, the drawing lines can be improved by providing an *undo* function to delete only parts of the incision line. Moreover, the distance from the drawing ray and model surface can be considered for visual feedback.

The modification *(R2)* can be advanced by providing more information, e.g., the meaning of colors and the visualization of the risk map on the 2D view. Moreover, the resection surface outside the model surface should be hidden; so that the surgeons can easily see the resulting incision line and manipulation. Additionally, providing the option to hide the tumor and blood vessels on the resection area *(R3)* would be beneficial. We tracked the network latency and frame rate during the evaluation *(R4)*. The results indicate that the system performance is acceptable.

The planning results, including times and remnant volume, were recorded for each participant. As shown in Table 6.4, the time required to specify the resection surface from *P1* was around six times faster than the times from the other two participants. The reason could be that the participant might already be familiar with the features. Because this participant experienced technical connectivity problems at the beginning (after drawing incision lines) and we had to restart the procedure. The results of remnant volumes, however, are quite similar across all participants.

We intend to conduct an evaluation of clinical applicability on real planning cases and multiple resection types, and compare the results after surgical resections. Thus, additional measurements for evaluation can be collected. Examples for this are the complexity of patient cases, preservation of resection margin, and reproducibility of results. The complexity of patient cases can be determined by the number of tasks to accomplish, e.g., the specification and shaping of resection surface, localization, and identification of the type of structures at risk. The preservation of the resection margin correlates with the accuracy of the safety margin after the virtual resection modification. Additionally, the results of resection volume can be measured by how accurately the trainees can reach the same results by virtual resection. Planning time could be considered as a measurement for training. In the actual resection planning, however, time is not a primary factor. Thorough planning requires a higher priority to avoid errors. The surgeons should take time to plan and avoid unexpected errors. An evaluation with more participants, and especially senior surgeons who have less experience with VR, could be beneficial and provide insight regarding applicability and usefulness [118, 126].

The proposed method could be useful for a wide range of surgical interventions, i.e., tumor surgery in the lungs and the abdominal region (kidney and pancreatic cancer).

As shown in Figure 6.9, tumor surgery planning in the kidney (bottom) was tested. Additionally, the virtual resection is mainly conducted after the patient image analysis procedures have resulted in the segmentation of organs, vascular structures and tumors. Thus, segmentation is required for the respective organs. Furthermore, the visualization of risk map to the vascular structures is generated based on the tumor image's distance. Nonetheless, it can be improved to provide all necessary information to affected vessels, e.g., based on the hierarchical vessel structures [192].

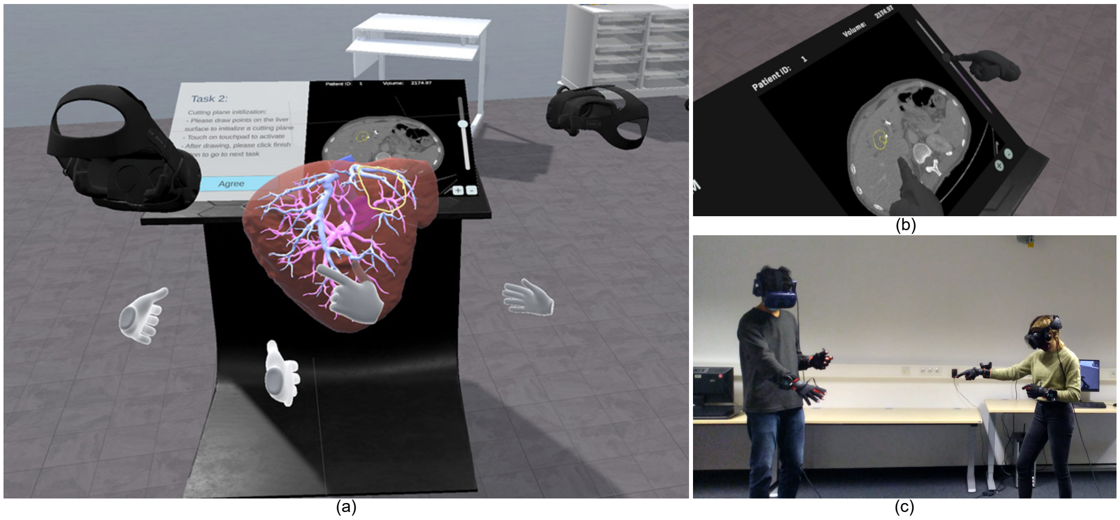
As discussed in [202], the process of specifying virtual resection, e.g., drawing, rotating, and deforming is limited due to using a mouse as input and the conventional screen. Users are more effective with both hands in coordinated movements. Thus, using an immersive VR environment could improve the planning process. The replication of users' avatars and hands in VR could provide advantages for immersion and co-presence in the collaborative VR environment. Providing real hand tracking might be challenging due to tracking and precise interaction issues, e.g., drawing incision lines.

Controllers are the commonly used input device in VR. However, they might not be effective or suitable for all scenarios, especially in medical planning and training. Thus, it would be advantageous to provide a precise interaction and compare various input modalities, e.g., wearable data gloves, VR Ink, and hybrid input devices (see Figure 6.12). The proposed system is based on the 3D rendering of the models extracted from CT medical image data. An alternative option can be achieved with the approach of GPUs direct volume rendering in VR [155].

Aside from VR, using mixed reality [123] can also be an alternative to provide 3D information and visualization for planning. In addition, the requirements for network low-latency and reliability described in [161] should be considered to provide a high quality remote collaboration. For network architecture, peer-to-peer allows for a computation and synchronization of the simulation on the individual client machine, providing lower responses times and network latencies. However, it is challenging to guarantee that the shared states of the objects are consistent with other clients. In addition, it is challenging to realize remote collaboration. Using a client-server architecture to centralize and transmit the results for all clients could guarantee the shared states. Nevertheless, the setup is costly and increases the response time and latency of actions between the clients.

## 6.8 Conclusion

This chapter has presented a collaborative VR environment for liver surgery planning with the virtual resection and risk map visualization. The concept was extended from the exploration mode described in Chapter 4. In this environment, a virtual resection



Cutting plane initilization:
- Please draw points on the liver surface to initialize a cutting plane
- Touch on touchpad to activate
- After drawing, please click finish
ton to go to next task

(a) (b) (c)

FIGURE 6.12: Overview of the use of input devices in the VR environment: (a) two users virtually collaborate in the virtual environment, (b) the exploration of patient data, and (c) the users use wearable data gloves. *Figure from Chheang et al. [187] ©2021 IEEE.*

technique based on DCP is enhanced and adapted into VR environment. Furthermore, a risk map visualization and resection margins are presented.

The virtual resection procedure was described, including virtual resection specification, modification, and volume estimation and surface reconstruction. During the initial stage, the risk map is visualized on the vascular structures, and the tumor's contours are projected on 2D slices. The resection surface can be defined on the organ parenchyma surface. After initialization, the virtual resection can be modified in both 2D and 3D with the real-time risk map visualization. Changes on both modalities are synchronized, and finally, the surgeons can estimate the resection volume and explore the resection parts. An evaluation performed by the experts provides information on potential benefits, applicability, and limitations of further improvement.

This chapter provides a new and objective basis for surgical planning, training, and exchanging knowledge between surgeons, whether in a shared or remote environment. Future work aims to perform a full clinical evaluation and supplement with additional patient cases. In addition, the system and techniques presented in this chapter are enhanced and integrated into an advanced surgical training environment that will be described in the following chapter.

# Chapter 7

# A Virtual Teaching Hospital for Advanced Surgical Training

The content of this chapter is based on the following publication:

- **Vuthea Chheang**, Danny Schott, Patrick Saalfeld, Lukas Vradelis, Tobias Huber, Florentine Huettl, Hauke Lang, Bernhard Preim, and Christian Hansen. Towards Virtual Hospitals for Advanced Surgical Training. In: *IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, Christchurch, New Zealand, pp. 410–414, 2022.

This work was presented at the IEEE VR workshop: *XR for Healthcare and Wellbeing*, Christchurch, New Zealand, 2022.

## About this chapter

This chapter introduces an advanced surgical training environment, which is a combination of the proposed prototypes described in Chapter 4 – 6. Additionally, new features, including photo-realistic avatars and planning stations, were developed and integrated into this environment. The aim is to provide an environment that supports the communication, planning, and training procedures ranging from the planning phase to the operating room training.

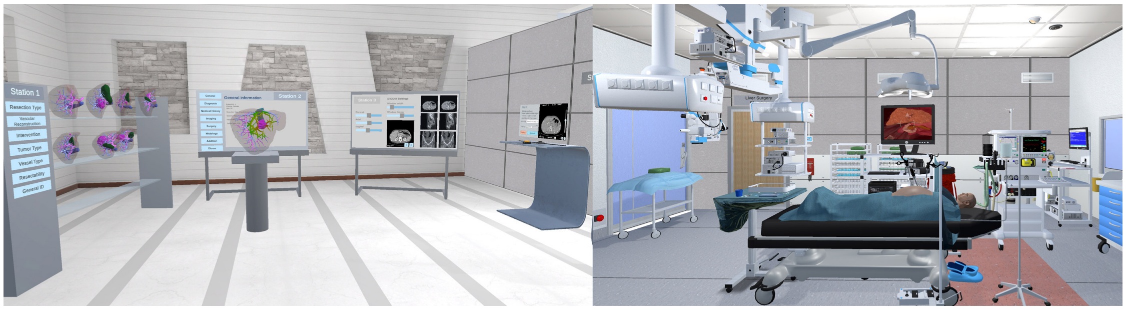


FIGURE 7.1: An advanced surgical training environment for liver surgery planning and training. Left: a room for liver surgery planning that contains four stations, including liver library, information board, *DICOM* board, and virtual resection planning. Right: virtual operating room for laparoscopic liver surgery training. *Figure from Chheang et al. [224] ©2022 IEEE.*

## 7.1 Introduction

Surgical planning and training could improve accessibility and flexibility through interactions with segmented 3D models. However, it is essential to provide all related information, including patient history, medical diagnosis, medical image data, and virtual resection planning [123, 124]. Therefore, a combination of providing all related information of surgical planning in a virtual training environment, could enable more advanced surgical training. In addition, existing VR training environments in medicine usually focus only on the training of a specific medical skill and are conducted in a single virtual room. Nonetheless, medical challenges are often in the context of the surgical planning procedure and operating room intervention.

In this chapter, an advanced surgical training environment, hereafter referred to as *virtual teaching hospital*, is introduced to improve several aspects of team training ranging from planning to training procedures (see Figure 7.1). It also supports photo-realistic avatars, where users can generate their representation models from 2D photos.

For surgical planning, a virtual room that supports various aspects for medical data exploration and planning is developed. It includes an enhanced version of liver anatomy education proposed by Schott et al. [225] and a VR-based technique for virtual resection planning described in Chapter 6. The environment was developed in an iterative process with our clinical partner. The training procedure in their department often starts by choosing patient cases that include the exploration of 3D models, investigating medical background information, and inspecting the medical image data. After evaluating the cases, the procedure will start with virtual resection planning and resection volume estimation. Therefore, four surgical planning stations are proposed: liver library, information board, *DICOM* board, and virtual resection planning stations.

The virtual operating room is a combination of the works described in Chapter 4 and

FIGURE 7.2: Overview of the environment, including a lobby (1), a room for liver surgery planning (2), and a virtual operating room for laparoscopic liver surgery training (3). *Figure from Chheang et al. [224] ©2022 IEEE.*

Chapter 5. A laparoscopic simulation with spatial input devices and training scenarios for interprofessional team training are integrated into the virtual operating room. This allows the users to perform the training with different user roles, including surgeons, camera assistants, and anesthesiologists. Thus, they can train for critical and distracting events, where communication between each professional is necessary.

## 7.2 Materials and Methods

In the following, the proposed collaborative VR environment that can serve as an exploration, planning, and training environment for advanced surgical training is described. There are three main rooms in this environment: a lobby, a surgical planning room, and a virtual operating room (see Figure 7.2).

### 7.2.1 Lobby

After each group members has chosen their roles in the user management system, the leader can press the start button to join the collaborative VR environment. The roles include surgeon, assistant, anesthesiologist, and student. Thereafter, they will connect and form as a group in the lobby (see Figure 7.3). In this room, they can introduce themselves, have a discussion, and explore the overview of the environment as well as interaction techniques, e.g., navigation technique.

FIGURE 7.3: A lobby where the users gather and initiate the training after joining the environment. In this room, they can discuss, assign user roles, form as a group, and explore the interaction techniques.

### 7.2.2 Surgical Planning Room

For the surgical planning room, the aims are not only focused on resection planning but also provide an entry-level surgical education of liver surgery planning through a problem-based learning approach. A high degree of realism for organ models and their complex internal structures was considered to make it easier to memorize anatomical objects [226] Therefore, anatomy education in the collaborative VR environment could also provide great potential benefits for education and teaching. It could also enable collaborative learning by allowing students to participate and acquire knowledge more effectively compared to the single-user systems.

**Patient Cases** Within this room, users are allowed to choose, explore, and conduct virtual resection planning. A curated set of nine patient cases received from the clinical partner is presented in this environment. These patient cases represent the most frequently occurring tumors in the liver and a wide range of different complexities and characteristics for resection planning. Each patient case includes 3D models, 2D medical image slices, as well as medical and treatment information.

**Four Surgical Planning Stations** There are four stations in the planning room, including virtual organ library (station 1), information board (station 2), DICOM board (station 3), and virtual resection planning (station 4).

S1 **Virtual organ library** – The organ models of patient cases are arranged on the virtual compartments similar to the shelves in a library (see Figure 7.4). Hence, an overview of all available cases for exploration and selection could be provided. In

FIGURE 7.4: Patient datasets are presented on a virtual organ library (station 1) and can be interactively sorted according to their meta information, e.g., resection, tumor, and vessel type. The users can interactively investigate the individual case and they can use virtual whiteboard to write and have a discussion. *Figure from Chheang et al. [224] ©2022 IEEE.*

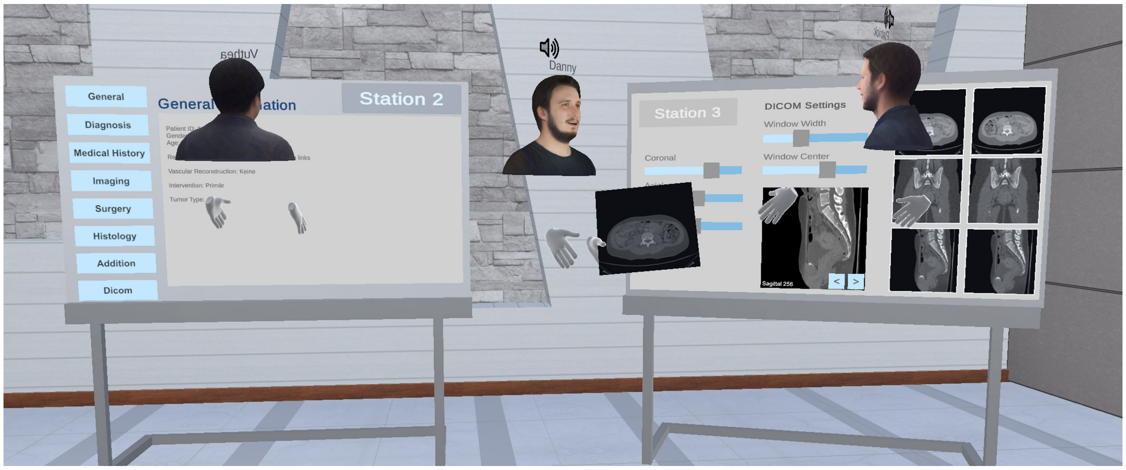


FIGURE 7.5: The users inspect the patient information, e.g., general information, diagnosis, and medical history (station 2) and explore medical image data (station 3). *Figure from Chheang et al. [224] ©2022 IEEE.*

this station, the patient cases can be sorted according to different types of resection and their properties, e.g., tumor and vessel types. The users can select one of the cases from the virtual shelf to inspect further information and perform the planning. Additionally, there is a virtual whiteboard near the station, which can be useful for illustrations and discussion.

S2 **Information board** – After the users choose a case, they can inspect detailed information of the patient data on the information board (see Figure 7.5). The information of the patient case is clustered into seven categories, including general information, diagnosis, medical history, imaging, surgery, histology, and additional

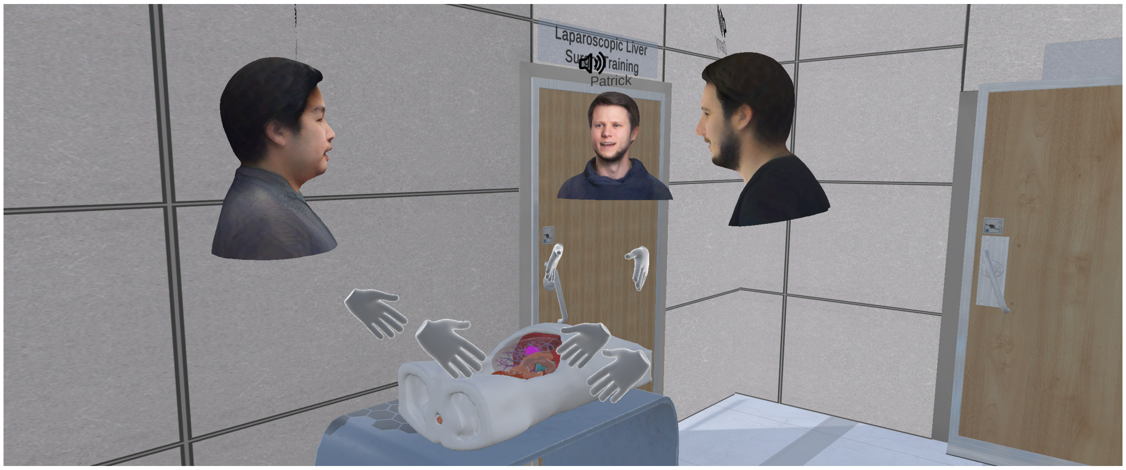


FIGURE 7.6: A virtual mannequin is used for assessing the patient data in the abdominal area for laparoscopic setup, e.g., tumor localization. The center of liver models is calculated for placing inside the standard torso.

information. With this station, the users can load additional medical image data to further explore on the DICOM board at the station 3 as well.

S3 **DICOM board** – A DICOM board allows the users to inspect the medical image data in detail (see also Figure 7.5). Thus, they can use the basic slicing tools to change the image slices in different axes, e.g., coronal (back and front), sagittal (left and right), and axial (head and tail) planes. Furthermore, the adjustments of DICOM images are also provided to change the intensity and gray values of image data. It is also possible to select one image slice and hand it over to the other users for further inspection and discussion.

S4 **Virtual resection planning** – After the users choose a patient case, inspect medical information, and explore the image data, they can further perform the virtual resection planning at station 4. First, they can place the liver model in a virtual mannequin to assess the position and orientation of the liver in the patient's abdomen (see Figure 7.6). This is essential for planning, especially in laparoscopic surgery, because it provides further information about the liver and tumor localization and illustration for laparoscopic instruments' placement. Thereafter, the users can perform the virtual resection planning with the risk map visualization. Thus, they can draw the incision lines, deform the resection surface, and estimate the resection volume (see Figure 7.7).

### 7.2.3 Virtual Operating Room

The virtual operating room was designed according to the feedback from the clinical partner and the environments described in Chapter 4 and Chapter 5. Therefore, most of

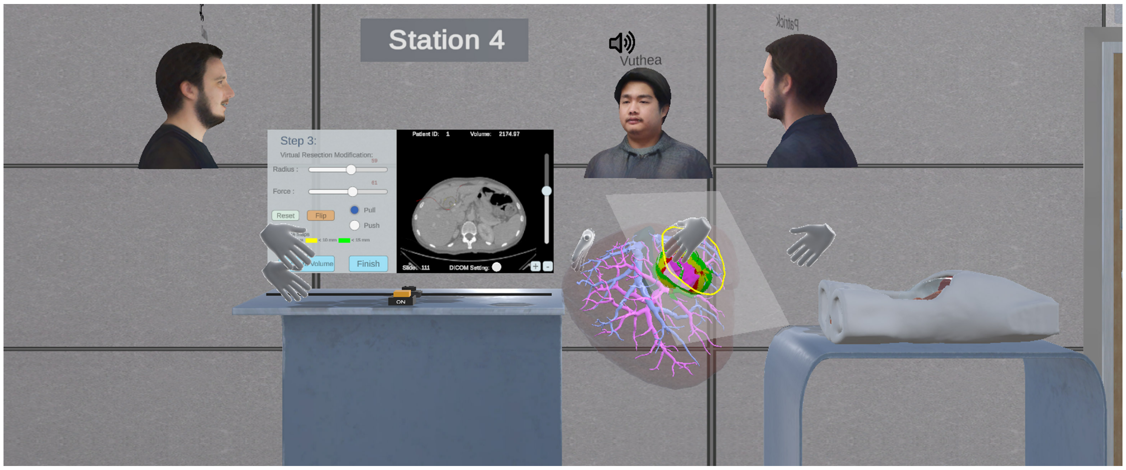


FIGURE 7.7: Surgical planning with virtual resection and risk map visualization (station 4). *Figure from Chheang et al. [224] ©2022 IEEE.*

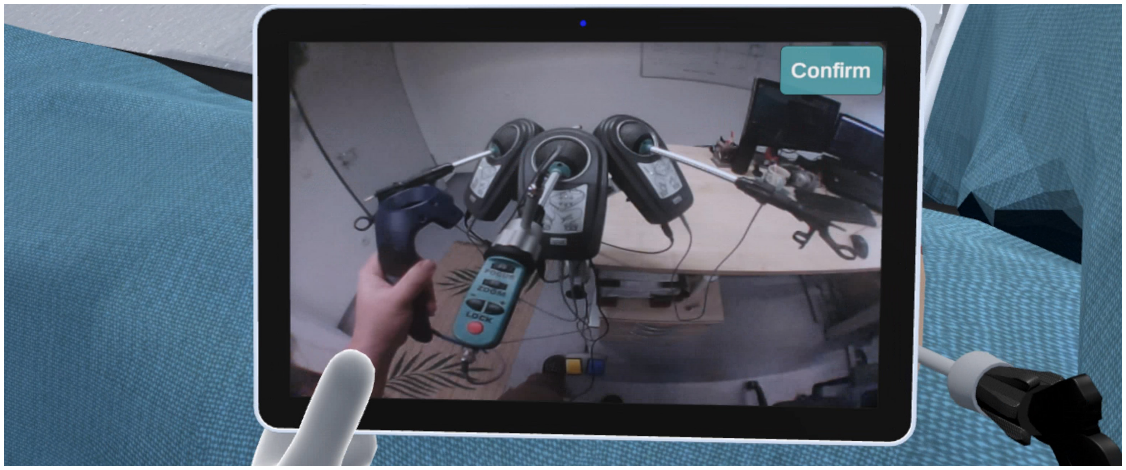


FIGURE 7.8: An option to use a front camera of VR headset to recognize and calibrate the objects in the physical world, e.g., laparoscopic Simballs.

the components and features are enhanced and adapted to the new system architecture.

**Laparoscopic Surgery Training** The main goal for the virtual operating room is to improve communication, train psychomotor skills, and provide an as engaging training environment as possible. The laparoscopic instruments (Simballs) are integrated to enable the training of these two roles: the surgeon performs the cutting and grasping and the assistant controls the laparoscopic camera (see Figure 7.8). The interactions of both users are synchronized in real time. During the laparoscopic cutting, critical events can occur, such as a bleeding vessel that needs to be clipped. Additionally, camera navigation and communication skills between the surgeon and camera assistant during these critical events in laparoscopic procedures can be trained.

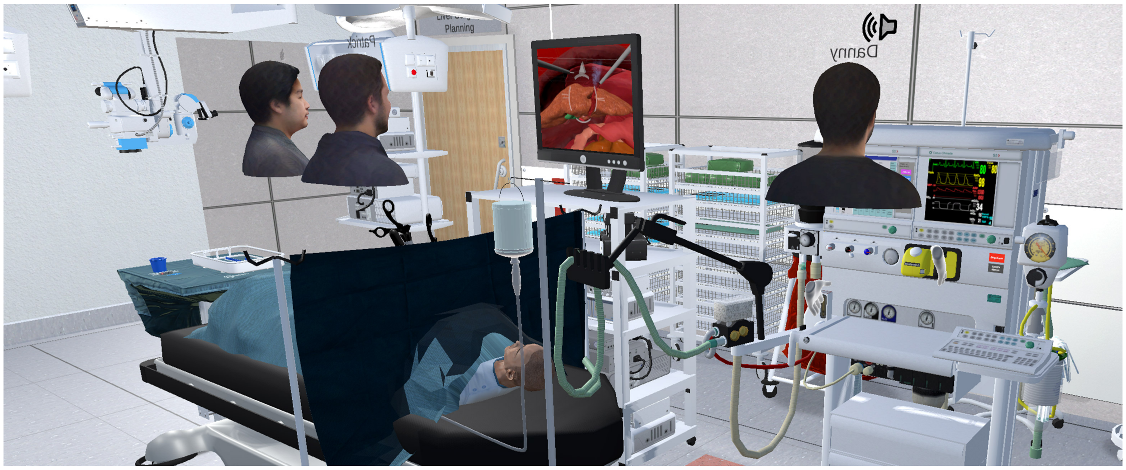


FIGURE 7.9: Laparoscopic liver surgery training in the virtual operating room. *Figure from Chheang et al. [224] ©2022 IEEE.*

**Interprofessional Team Training** Teamwork and communication between surgeons and other professions during laparoscopic procedures are crucial for a successful surgical outcome. Two training scenarios for interprofessional team training described in Chapter 5 are enhanced and integrated (see Figure 7.9). These two training scenarios contain critical events, which are realized to engage communication between the surgeon, the camera assistant, and the anesthesiologist, e.g., during undetected bleeding and insufficient muscle relaxant medication.

A *Pulse Physiology Engine* (Kitware, Inc., New York, USA) [227] is used to achieve a realistic replication of the patient's vital signs. This could provide a better adaptation and flexibility for training scenarios, including surgical procedures and the administration of anesthetic medicine.

### 7.2.4 System Architecture

A *Photon* networking (Exit Games GmbH, Hamburg, Germany) is used to handle the network session and data synchronization. Figure 7.10 provides an overview of the system architecture. A corresponding server is set up to provide the load-balancing services to handle voice communication, network sessions, and data synchronization between the clients. Network conditions and client's machine capabilities could influence and affect the collaborative performance. The major factors, including delay, bandwidth, jitter, and packet loss are considered and optimized accordingly to provide good user experiences [62].

Although the proposed environment focuses on VR-users, it can be used with non-VR users using desktop-based PCs and conventional input devices. The non-VR users are

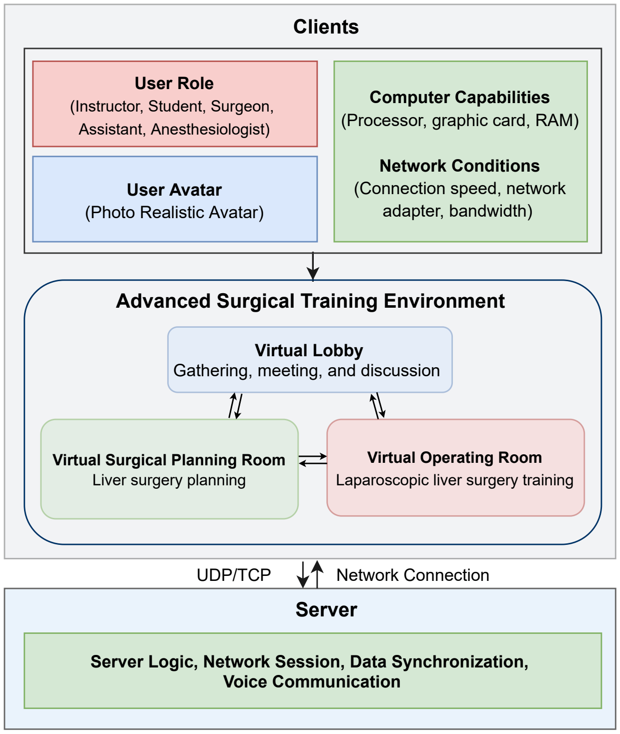


FIGURE 7.10: Overview of the system architecture for the advanced surgical training environment. A corresponding server was set up for providing load-balancing services and a client-server architecture was followed for handling data synchronization.

connected as the spectators. Therefore, they can use mouse and keyboard to navigate in the environment.

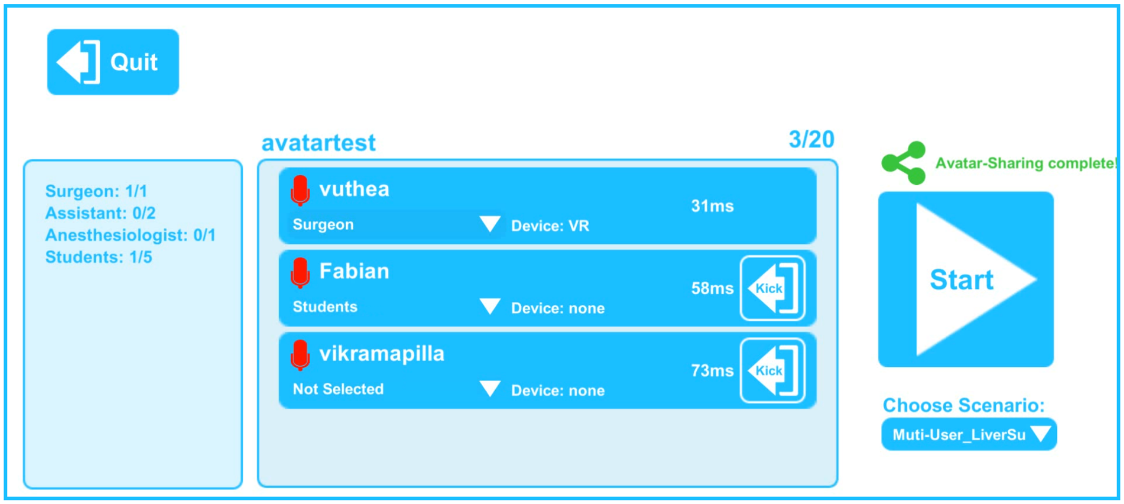


FIGURE 7.11: A user management system that allows the users to create user accounts, upload their avatars, and create/join the matchmaking room.

### 7.2.5 User Management System and Photo-realistic Avatars

A small user management system is introduced to allow the users to create their user accounts, upload their photos for generating the photo-realistic avatars, and create the matchmaking room. The matchmaking refers to the process of connecting users together into a specific session (room). Moreover, the system allows the user to choose their roles and scenarios before forming in the shared virtual environment (see Figure 7.11).

Photo-realistic avatars are supported, thus the user can upload a single 2D photo and generate the avatar that can be stored and used in the collaborative VR environment. With the support of *Avatar SDK* (itSeez3D, California, USA), the uploaded photo is generated to define the feature points of the 3D mesh and its corresponding texture (see Figure 7.12).

FIGURE 7.12: Generated photo-realistic avatar. The users can use their own photos to generate photo-realistic avatars to represent themselves in the collaborative VR environment.

## 7.3 Evaluation

The proposed environment was evaluated with domain experts. Six participants (two females) participated in the pilot study. Five of them were general and visceral surgical residents with 8, 5, 3, 4, and 6 years of working experience, and one participant was a medical student. All of them had previous VR experiences and were right-hand dominant. A think-aloud protocol was followed to collect general feedback. Furthermore, a semi-structured interview and a session for open questions were conducted after the experience of the prototype.

## 7.4 Results and Discussion

In the following, results of the participant's feedback are summarized into its relevant categories.

### 7.4.1 Lobby

P3 and P5 stated that the lobby could be useful to allow the users to find each other after joining the environment and to explore the navigation technique. P3 commented that using the virtual tablet was helpful in changing the configuration, e.g., navigation techniques between the teleportation and steering techniques. However, they had some difficulties keeping the virtual tablet active. Thus, they would prefer to press the controller's trigger button once to activate and press it again to deactivate, rather than press and hold it.

### 7.4.2 Usefulness for Surgical Planning and Training

All participants were positive about the experience and confirmed the potential benefits of this proposed environment. For the surgical planning room, four stations were well integrated. It was essential to provide the planning and training that ranges from case selection to operating room training. P1 stated that the current training for laparoscopic procedure in their department often uses the commercial laparoscopic simulator with the standard 3D model. Thus, it could be advantageous for planning and training with the real patient cases. Moreover, they expressed that linking between the selected patient case from the planning room to be used for training in the operating room is beneficial to train and understand the surgical procedures. P2 stated that the proposed environment could be extremely useful for planning complex patient cases and training surgical planning procedures for laparoscopic liver surgery. They found that the virtual mannequin at station 4 was advantageous to provide the planning for laparoscopic surgery compared to the previous planning software. In addition, P2 commented that the proposed environment could be applied for their surgical training routine, especially for junior surgeons. Regarding the training for medical students, P4 stated that allowing the students to join the environment as spectators without using VR headsets was a useful function. Therefore, in some cases, medical experts can use this system to conduct the surgical planning so medical students can also join as spectators to learn and understand the procedures.

### 7.4.3 Photo-realistic Avatars

P1 expressed that this feature was a good addition to the proposed VR environment. They stated that allowing the users to have their own avatars generated from their photos could be advantageous to provide an engaging collaborative environment. They could use the user management system to create user accounts and generate avatars. The blinking animation of the generated avatar was randomized and the lip movement was animated according to the voice communication. More realistic avatars could be provided if the system could detect the eye and lip movements of the users by using additional sensors. Nonetheless, they commented that it was adequate for this current state because they could notify with an additional chat icon appearing on top of the avatar if one user engages the voice communication.

Overall, the proposed advanced surgical training environment was evaluated as an essential tool for planning and training laparoscopic procedures. The results of the pilot study was followed by the think-aloud protocol and a semi-structured interview. The participants confirmed its potential benefits and clinical applicability. In the surgical planning room, they found that the stations were well integrated. In addition to the virtual resection planning, the virtual mannequin was assessed as an important tool to evaluate the resection planning for laparoscopic setup. Besides the planning stations, P5 and P6 commented that the interactions with the virtual whiteboard were intuitive to draw for further team discussion. In the operating room, the connection of the patient case that was selected in planning room was assessed as beneficial.

## 7.5 Conclusion

This chapter has introduced an advanced surgical training environment to improve different aspects of liver surgery planning and training. In the surgical planning room, four planning stations were integrated ranging from patient case selection to virtual resection planning. For the virtual operating room, a training setup with laparoscopic procedure was presented, which can simulate different laparoscopic liver surgery procedures for connected users in different roles. The integration of the work with interprofessional team training in laparoscopic surgery was also presented, which allows the surgeons and anesthesiologists to practice their communication and teamwork during different critical events. Hence, they can practice, communicate, and improve surgical skills accordingly. Furthermore, the development of photo-realistic avatars was introduced to provide an engaging training environment.

The evaluation results indicate that the proposed environment could support surgical planning, and training, and it was assessed as useful and promotes team communication. Apart from the evaluation presented in this chapter, the evaluation of each component that integrated into the proposed environment throughout Chapter 4 – 6 showed already the perceived advantages, potential benefits, and its applicability. The next step is to investigate a group navigation technique for providing an effective environment for collaborative VR, which will be described in Chapter 8.

# Chapter 8

# A Group Navigation Technique for Collaborative VR

The content of this chapter is based on the following publications:

- **Vuthea Chheang**, Florian Heinrich, Fabian Joeres, Patrick Saalfeld, Bernhard Preim, and Christian Hansen. Group WiM: A Group Navigation Technique for Collaborative Virtual Reality Environments. In: *IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, Christchurch, New Zealand, pp. 556–557, 2022.
- **Vuthea Chheang**, Florian Heinrich, Fabian Joeres, Patrick Saalfeld, Bernhard Preim, and Christian Hansen. WiM-Based Group Navigation for Collaborative Virtual Reality **(Under Review)**. *Computers & Graphics*, 2022.

This work was presented as a poster at the IEEE conference on virtual reality and 3D user interfaces (IEEE VR), Christchurch, New Zealand, 2022. Moreover, a full-paper submission with extended user study for both user roles of the guide and group members was submitted to *Computers & Graphics* journal.

## About this chapter

This chapter describes an overview of group navigation techniques and a proposed group *World-in-Miniature (WiM)* technique, which is an essential tool to form and arrange group members effectively in collaborative VR environments. The proposed advanced surgical training environment described in Chapter 7 was used to evaluate the usability and comprehensibility of the developed technique.

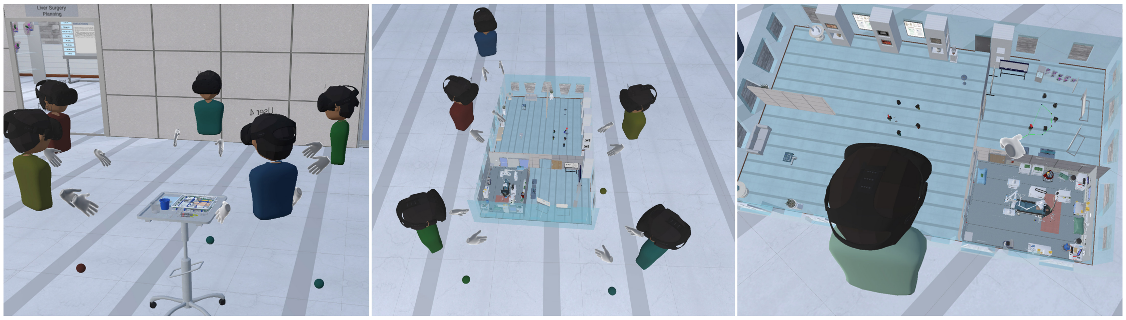


FIGURE 8.1: Overview of the group WiM navigation. *Left:* Five users discuss with each other. *Center:* The group explores the environment and is ready for navigation. *Right:* The group navigates using the group WiM navigation technique. *Figure from Chheang et al. [228] ©2022 IEEE.*

## 8.1 Introduction

In reality, an instructor or a guide often informs a group or leads group members to different locations or rooms, in the same way a guide in a museum might ask the group members to stand in a configuration that is suitable for communication and interaction. Inspired by such situations, group navigation is also discussed for VR. Group navigation allows users to create a spatial arrangement, explore, and navigate together at the same time [69, 229]. While many navigation techniques have been investigated for single-user VR, there is a limited number of techniques concerned with navigation as a group in the collaborative VR environment [230–232]. The most common approach for navigation in collaborative VR environments is to allow each user to navigate individually using single-user techniques. A strong advantage of group navigation is group formation, which supports collaboration and team building and, in particular, helps establish and assign user roles for team training [233, 234].

In this chapter, a group navigation technique based on a *World-in-Miniature*, hereafter referred to as *group WiM*, is proposed (see Figure 8.1). The environment presented in Chapter 7 was used to assess the usability and comprehensibility of the proposed technique. The main contributions are the following:

- Development of a novel group WiM navigation technique for collaborative VR.
- Results of a user study ($n$ = 21), which indicate the usability, discomfort, and insights based on user performance of the group WiM technique compared to a state-of-the-art group teleportation technique.
- Exploratory analysis of qualitative feedback to identify the perceived advantages, disadvantages, and potential research directions for group navigation.

## 8.2 Related Work

Navigation is one of the most common forms of interaction and is an essential element for providing an immersive experience in a virtual environment [235]. A navigation technique is a combination of two components: a motoric component *(motion)* and a cognitive component *(wayfinding)* that allow the users to control and change their movements and viewpoints [236, 237]. Various navigation techniques have been investigated to allow users to navigate and increase their sense of presence in the virtual environments, including redirected walking and virtual travel [230, 238]. In the following, an overview of navigation techniques is described in two categories: individual and group navigation.

### 8.2.1 Individual Navigation Techniques

Most recently developed VR headsets are equipped with two types of positional tracking: outside-in and inside-out tracking. The outside-in tracking uses the lighthouse system to detect the coordinates of the moving headset and controllers inside the VR-room scale's tracking space. For inside-out tracking, the camera is equipped on the headset to determine its current position related to the physical environment [48]. Both tracking systems allow users to navigate by physically walking within a tracking area. Navigation based on the physical movement of the user's body is beneficial for enabling a high degree of presence [239–241].

Redirected walking is widely used to navigate within the limited tracking space [242, 243]. This navigation technique manipulates the physical path of the user's movements by introducing imperceptible rotations to the virtual environment. Hence, the users can travel through the virtual environment, which is larger than the tracking space. Azmandian et al. [142] presented an evaluation of two-user redirected walking and collision avoidance in a shared physical space. Their results indicate that the effects of sharing physical space are modulated by the size and shape of the tracking space. In the large tracking spaces, interruptions approaching the boundaries or collisions are lower compared to small tracking spaces. Lee et al. [244] proposed a predictive algorithm for multi-user redirected walking based on reinforcement learning. Their algorithm also works with untrained physical spaces and can process up to 32 users in real time. In addition to the collision prediction strategies, Dong et al. [245] proposed a multi-user redirected walking using dynamic artificial potential fields, which create repulsion to help users avoid walls and other users. Furthermore, a density-based redirected walking technique was introduced. This technique is based on computing density differences for adjusting the user distribution [246].

Virtual travel techniques usually require less physical space and are adapted for travel over long distances in the virtual environment [247]. There are two common types of virtual travel techniques: target-based (widely known as teleportation) and steering-based approaches. Target-based virtual travel techniques allow the user to specify the target and instantaneously teleport the user to the specified target [248, 249]. The transition between the current location to the target location can be instant, smoothly animated, or multi-stepped interpolation [250–252]. However, it can be inconvenient for exploration and spatial awareness in long-distance teleportation due to missing information along the route [253]. Steering-based travel techniques refer to continuous motion that requires the specification of direction and movement speed continuously [237]. They usually follow metaphors, e.g., driving and flying, where the input can be produced by the controllers or by tracking the user's body posture, hand, or gaze [254, 255]. Various studies showed that target-based virtual travel reduces motion sickness dramatically and is faster for traversal times when compared to steering-based travel [256–258].

A WiM is a duplicate of the entire virtual environment in a scaled-down size [259, 260]. It can be used to support travel. Navigation based on this miniature provides a third-person viewpoint in addition to the user's viewpoint within the virtual environment [261–263]. Thus, the user can interact, scale, and rotate the WiM to spectate the environment from any angle. Furthermore, it allows users to quickly navigate to any points in the virtual environment without any restrictions concerning line of sight or availability of physical space [261]. Changes on the WiM will be simultaneously applied to the original environment [264]. For example, users can move objects in the full-scale environment using the WiM. Berger et al. [265] compared three locomotion techniques, including continuous motion, teleportation, and WiM. Their results indicate that single-user navigation with WiM outperforms the other techniques regarding navigational time for longer distances. Moreover, it provides a good overview while causing the least motion sickness. Chen et al. [266] presented a deformation approach with a non-planar, view-dependent surface for navigation in large virtual environments. In addition, Elvezio et al. [267] demonstrated an interaction technique that allows the user to point at WiM and perform the navigation with a pre-orienting avatar. They also highlighted the benefits of using WiM and pre-orientation of the avatar to reduce effort and task completion time.

Other approaches, such as manipulation-based, portal, and mini-map techniques, enable users to travel by object manipulation, marked point, virtual scene interaction, or direct manipulation of the user's viewpoint [268–272]. While many works suggest the strength of a stand-alone navigation technique, there are also advantages of technique combination, e.g., teleportation and WiM [273, 274]. However, group navigation techniques have received little attention [69, 275]. In the following, related work in group navigation is described.

### 8.2.2 Group Navigation Techniques

Users collaborating in VR often have common interests. However, individual navigation in the collaborative VR can lead to difficulties, such as unnecessary allocation for navigation by each member and a risk of losing each other [69]. Buck et al. [276] investigated the navigation as dyads in a shared virtual environment. Their results indicate that the navigating dyads outperform individuals in the acquisition of survey knowledge. Other studies [277, 278] also reported difficulties with individual navigation regarding finding one another, staying together, understanding spatial references, and sharing experiences. Liu et al. [234] compared social VR platforms using a guided group walk-through method. This method leads to overlapping avatars in spatial navigation with individuals when navigating in proximity to others. Kolesnichenko et al. [279] presented design approaches to characterize avatars and allow the users to form groups using commercial social VR platforms. Navigation in co-located physical space often leads to spatial desynchronization [280]. For example, the voice of co-located users in the real world comes from different directions, while other users expect it to be based on the virtual position of the avatars. Moreover, the voice synchronization between the real world and virtual environment can be delayed, and collisions between users can occur. Group navigation techniques should be assessed as to how co-located or remote users can travel as a single entity in a similar way to the virtual vehicle [278].

Group navigation aims to allow the group to stay together while only one user, potentially a leader, is responsible for the creation, formation, and control of travel. As discussed in previous work [281, 282], group development involves four stages: forming, norming, performing, and adjourning. At the initial stage, users connect in the virtual environment to prepare for subsequent group navigation. The forming stage comprises the creation and forming mechanisms of the group. Norming refers to the navigational responsibilities for the group. Performing describes the process of navigating and travelling together. Finally, the adjourning stage relates to the situation when the group navigation is finished and team members are split up again. Weissker and Froehlich [233] proposed a group navigation technique based on teleportation for guided tours. Four main requirements were described for the group navigation technique: comprehensibility, obstacle avoidance, view optimization, and formation adjustments. Their proposed technique also allows users to choose the pre-defined formations for navigation.

## 8.3 Requirements

The requirements for a group navigation technique were identified based upon prior work on individual, co-located, and group navigation techniques. In addition to general requirements, including comprehensibility and spatial awareness, the new technique should have the following properties:

R1 The technique should provide an overview and full control for the guide to specify the target and group arrangement. It is essential to save navigation time and provide an understanding of the expected destination in a long-distance and complex virtual environment.

R2 The technique should be comprehensible to provide the support for adjusting the group arrangement, including spatial extent and orientation.

R3 The view directions of each member are adjusted according to the selected group formation. The view directions are relevant after the group arrives at the destination, thus, they can observe and perform a group discussion effectively. For this reason, the technique should provide additional visualization to identify and support the spatial understanding of the expected arrangement and reduce the navigation discomfort.

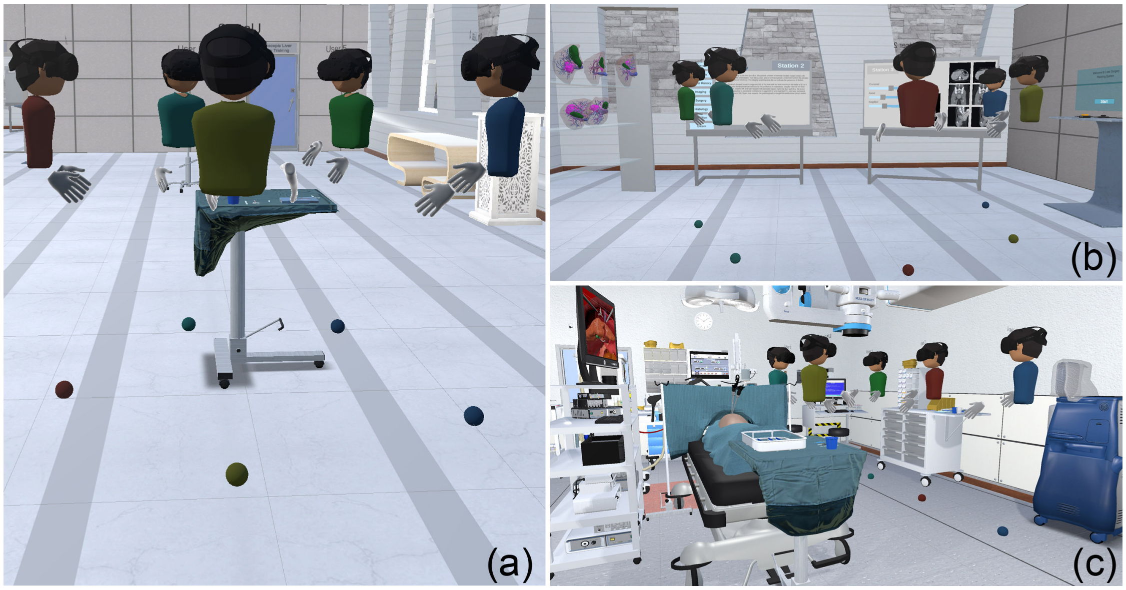


FIGURE 8.2: Five users form a group and discuss with each other in the lobby (a). The group travels to the liver surgery planning room (b). The group explores and discusses in the operating room of laparoscopic liver surgery (c). *Figure from Chheang et al. [228] ©2022 IEEE.*

## 8.4 Materials and Methods

The WiM represents the entire environment, including objects and mimicked avatar representations, that perform as a proxy to the original environment. WiM-based navigation supports spatial understanding and induces less motion sickness compared to steering and teleportation techniques [265]. Moreover, in spite of allowing users to navigate with a single-user navigation technique, we believe that group navigation is beneficial to assign the users and form a group for effective collaboration in the virtual environment. In this section, a group WiM navigation technique using the use case of advanced surgical training environment presented in Chapter 7 is described (see Figure 8.2).

### 8.4.1 Group Representation and Preview Avatars

Each user is represented by an avatar with a virtual head, virtual body with randomized color, and virtual hands. Each avatar is equipped with a virtual head-mounted display emphasizing the viewing direction of the users (see Figure 8.3). A small sphere with the same color as the user's shirt is attached below the avatar's body to represent the current position onto the floor. Moreover, a name tag is highlighted and a chat icon appears over the virtual head when the user engages in voice communication. It is essential to recognize the speaker and their name during the discussion. During the navigation procedure, the preview avatars of the group are highlighted with semi-transparent colors of their shirts. A convex-hull line is also displayed according to the positions of the users and group formations. In addition to the name tag, the user can identify their preview avatar during the travel operation with a location icon that appears on top of the virtual head.

### 8.4.2 Group Navigation

In the initial stage, the group gathers in the virtual environment. A leader has the role of a guide, and other users are assigned as group members. The guide can enable the WiM and explore an overview of the entire environment with the members (*R1*). This can be performed by pressing the menu button on the controller. Once the WiM is enabled, the guide can interact with this miniature by, for instance, grabbing and scaling using the controllers' grip buttons. The navigation procedure starts with the target and group arrangement specification, spatial extent adjustment, and group travel. Figure 8.4 provides an overview of the group navigation procedure. The workflow is described in the following.

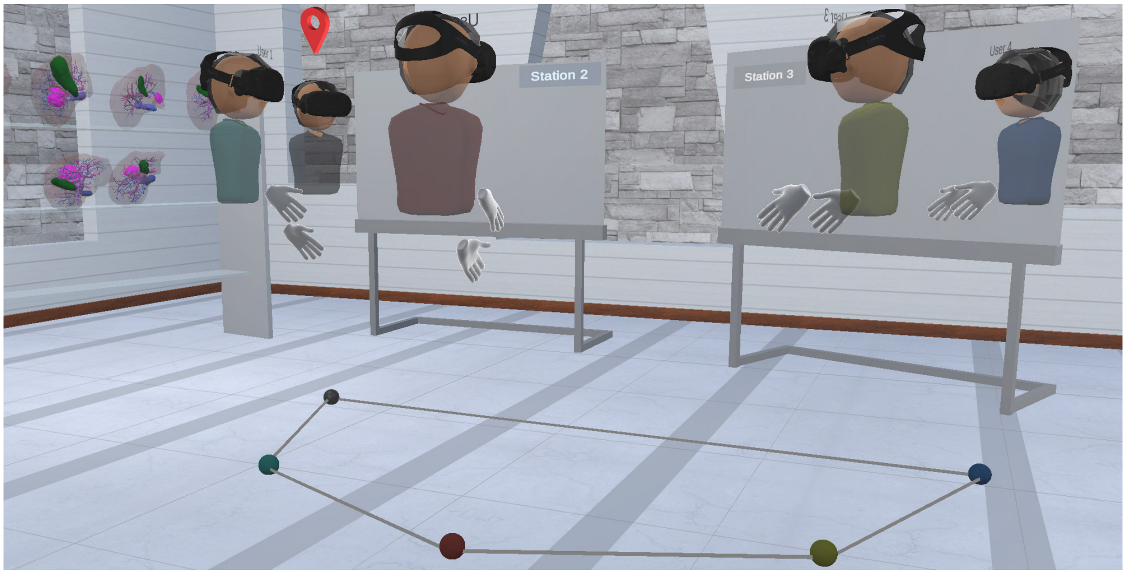


FIGURE 8.3: Group representation with preview avatars and convex-hull line representation during the navigational technique operation.

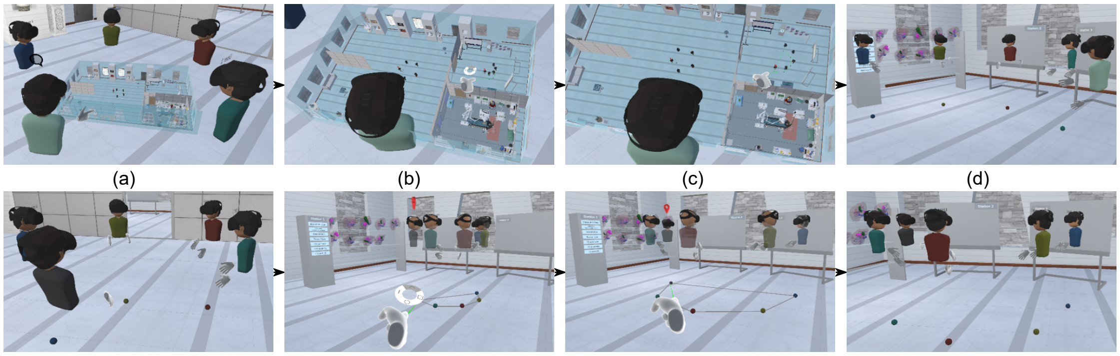
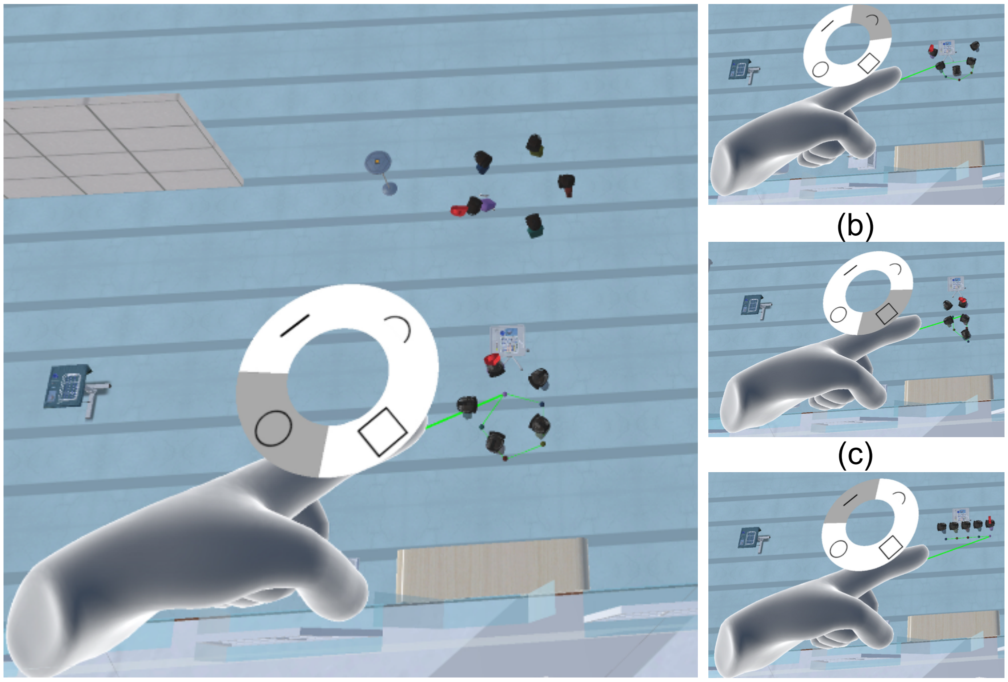


FIGURE 8.4: Group navigation technique based on WiM (top) and teleportation (bottom). (a) The users discuss with each other. (b) The guide uses the controller's touchpad to choose a group formation with the support of preview avatars and convex-hull line representation, and to specify the destination. (c) After pressing the touchpad, a group formation is chosen, e.g., a half-circle formation. The guide can adjust the spatial extent of group arrangement by radial swipes on the touchpad. Using the roll angle of the controller allows the guide to rotate the group arrangement. (d) The navigation is executed by pressing the trigger button, and the group will be transported to the destination.

### Target and Group Arrangement Specification

To specify the target destination, the guide touches the controller's touchpad. Ray casting is used to determine the target destination on the WiM from the virtual hand's index finger. Furthermore, while touching the controller's touchpad, a radial menu appears on the touchpad to show the options for group arrangement. There are four pre-defined formations, developed in a similar way to Weissker and Froehlich [233], i.e., circle, half-circle, grid, and line (queue) formations (see Figure 8.5). The guide can choose one of



(a) (b) (c) (d)

FIGURE 8.5: Group arrangement with four pre-defined formations can be chosen during target specification: (a) circle, (b) half-circle, (c) grid, and (d) line formations.

them by pressing down on the touchpad. In addition to the avatars that represent the users in the WiM, there are also preview avatars and a convex-hull line representation that represent the group when the guide chooses a group formation.

### Group Arrangement Adjustment

When a formation is chosen, the guide can further adjust the spatial extent and rotation of the group arrangement (*R2*) (see Figure 8.4c). Spatial extent adjustment is performed with radial swipes on the controller's touchpad [283]. The preview avatars and convex-hull line are scaled up and down based on swipes with a clockwise and counter clockwise direction. The guide can rotate the group by rotating their controller in the roll angle's direction.

To fulfill *R3*, the view directions of preview avatars are refined as such that they are looking into the centroid. This could be beneficial, especially for discussion after arriving to the destination, so that users don't need to rotate and find the other users. However, view directions of preview avatars was changed for the line formation so that users are standing in a queue, as proposed by Weissker and Froehlich [233].

**Obstacle Avoidance** A simple approach was implemented to perform collision detection between the preview convex-hull line and the mesh geometries in the virtual environment. As shown in Figure 8.6a, if the guide moves the group such that it collides with the wall, the convex-hull line will be highlighted in red color and the travel will be prevented.

**Notifications** In addition to the WiM representation, the group members will be notified via a controller's vibration once the guide chooses a group formation. Furthermore, the group members can use a mini-map on a virtual tablet if they press the controller's trigger button (see Figure 8.6b). The idea of using a mini-map would further support the understanding of navigational procedure and spatial arrangement (*R3*). In this case, a virtual camera is placed above the WiM to generate a render texture for the mini-map.


(a) (b)

FIGURE 8.6: Obstacle avoidance and additional mini-map for group members. (a) During the navigation procedure, if the preview convex-hull line collides with obstacles, it is highlighted in red color and prevents the travel. (b) A group member can enable a mini-map on a virtual tablet for an overview of the environment and the target destination. To generate this mini-map, a virtual camera is placed above the WiM to generate a real-time texture.

### Group Travel

During the procedure, the guide can release the thumb on the controller's touchpad. This allows for the exploration of the preview group arrangement in detail and adjustments to be made if needed. If the guide is satisfied with the current arrangement, the travel can be executed by pressing the controller's trigger button. This can also be applied when the guide is touching the touchpad, in case they want to travel instantly.

However, if the guide is not satisfied with the current arrangement, this can be aborted without travel by pressing one of the controller's grip buttons.

## 8.5 Evaluation

A user study was conducted to evaluate the proposed technique in a comparison with a reference group teleportation technique (see also Figure 8.4). The implementation of group teleportation was based on Weissker and Froehlich [233]. In this study, the goal was to investigate the guide's tasks. Thus, additional simulated users were added to provide more realistic group size for five users. The key research questions are the following:

RQ1 Is the group WiM technique comprehensible compared to group teleportation technique in an advanced collaborative VR environment?

RQ2 Do the navigation techniques induce different degrees of discomfort for the group guide?

RQ3 What are the perceived advantages and disadvantages of each group navigation technique?

### 8.5.1 Study Setup

A collaborative VR environment was developed with six navigational destinations and different formation patterns (see Figure 8.7). In order to avoid bias because of the learning effect, parameters such as the starting location, the size of formation patterns, and the order of group navigation were randomized. The navigational directions also alternated between clockwise and counter clockwise directions. Once the first technique is initiated using a single navigational direction, the second technique begins in the reverse. For example, if the participant started with the clockwise direction in the group WiM, the group teleportation will be in the counter clockwise direction. Additionally, a small table with a yellow button to start and stop the task was randomized around the guide's target position, which is indicated with dark-red color (see Figure 8.9).

A corresponding server was set up to provide services, including load-balancing and *Photon networking*, for a shared network session and data synchronization. The server was equipped with a *Windows Server 2019*, processor Intel Xeon @2.49 GHz, and RAM 16 GB. The experiment was arranged in a VR lab with 3 × 3 meter tracking area. *HTC Vive Pro* headsets (1440 × 1600 pixels per eye, refresh rate 90Hz, field of view 110 degrees), lighthouses, and their corresponding controllers were used. Moreover, a computer equipped with Intel Core i7-8700K CPU @3.70 GHz processor, an NVIDIA

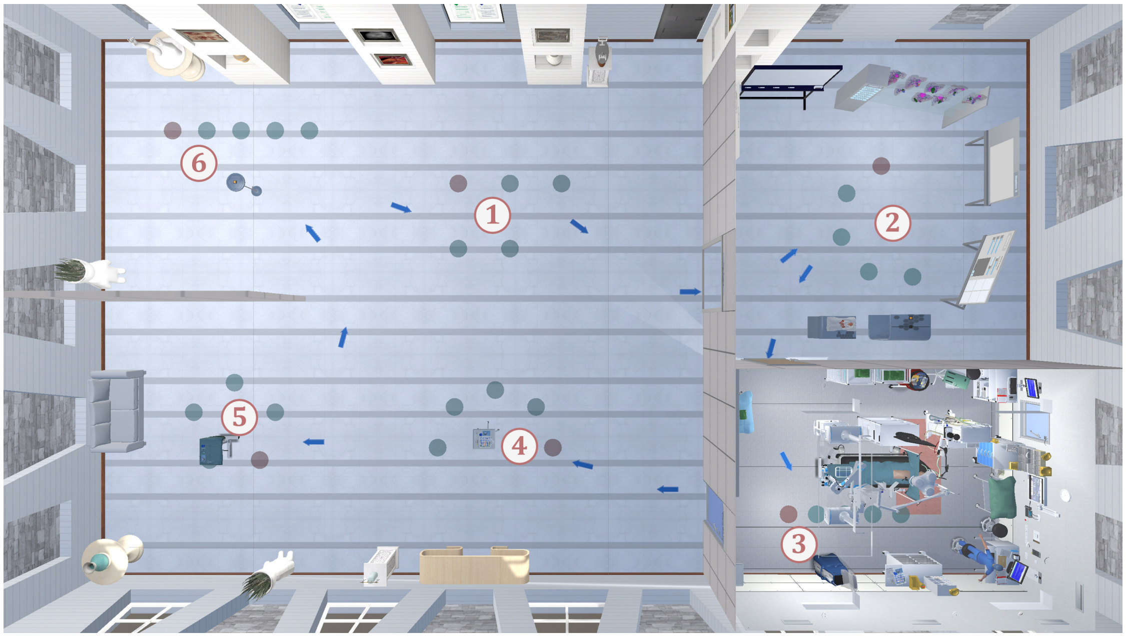


FIGURE 8.7: Top view of a complex collaborative virtual environment used in the user study, in this case for medical training and planning. The starting locations, navigational directions, start/stop buttons, and size of formation patterns are randomized.

GeForce GTX 1080 (8 GB VRAM) graphics card, and RAM 32GB was used for the participants.

### Independent Variables

The study was planned as a within-subject design with a two-factor test. The two factors were defined by independent variables: *group navigation technique* and *difficulty*. The variable *group navigation technique* consisted of two techniques: group WiM and group teleportation. The *difficulty* refers to the levels of difficulty of navigational path for reaching the target destinations. The easy level refers to the navigational path of the target destination that appears in front of user's line of sight, e.g., the path from the fourth to the fifth destination (see also Figure 8.7). The medium level refers to the path that has an obstacle and the user can take a detour, e.g., the path from the fifth to the sixth destination. The hard level indicates the path that has a blocked obstacle, i.e., a closed-door in between, and requires user interactions, e.g., the path from the third to the fourth destination.

### Dependent Variables

During each navigational task, we measured data which were defined as dependent variables, including *task completion time* and *placement error*. The *task completion time* indicates the time taken to complete a navigational task. It was recorded when users

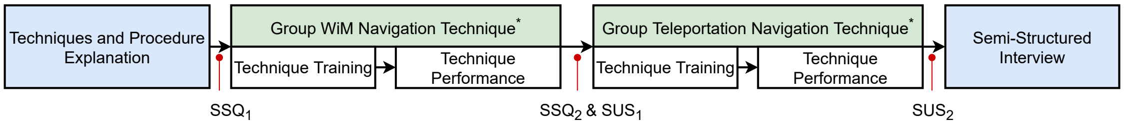


FIGURE 8.8: Procedure of the user study. The order of the group navigation techniques (marked with *) was counterbalanced. Discomfort was evaluated with the simulator sickness questionnaire (SSQ), and usability was assessed with the system usability scale questionnaire (SUS).

pressed down the button to start at their current location until arrival at the destination, where they pressed down the nearby button to stop the task. The navigational task was also designed to place the group as close to the targets' center as possible. Based on this placement, the *placement error* is calculated (see also Figure 8.9). In addition to the variables for statistical analysis, we recorded *number of jumps* that we analyzed descriptively. The number of jumps describes how many times that the user navigates the group to the target destination until it meets their satisfaction after which they press down the stop button.

Apart from the performance data, two additional dependent variables were measured from the questionnaires: *usability* and *discomfort scores*. We used the SUS questionnaire to evaluate the usability [284]. The questionnaire consists of ten questions with a five-point Likert-scale ranged from *strongly disagree* to *strongly agree*. The evaluation for this usability scale was converted to a range between 0–100% (0–50%: not acceptable, 51–67%: poor, 68%: okay, 69–80%: good, 81–100%: excellent) [220]. To evaluate the discomfort, we used a standardized simulator sickness questionnaire (SSQ) [285]. This questionnaire has 16 items with a four-point scale. Each item represents a possible symptom from none to severe condition. Because the order of the techniques was counterbalanced, and the possible symptoms could be influenced by the first technique, the SSQ was used only before and after using the first technique.

### 8.5.2 Study Procedure

Figure 8.8 shows an overview of the study procedure. First, the study objective, group navigation techniques, and study procedure were introduced. The participant gave their consent by signing a form. They were also asked to answer the demographic and discomfort questionnaires. Afterwards, the participants were introduced to the first navigation technique. The order of the techniques was counterbalanced. The procedure started with the technique training in a different virtual environment. In this technique training, simulated users were introduced and the participants were asked to perform all the features, interactions, and navigation possibilities. The interactions included the group navigation procedure described in subsection 8.4.2 and interactions with the start/stop buttons.

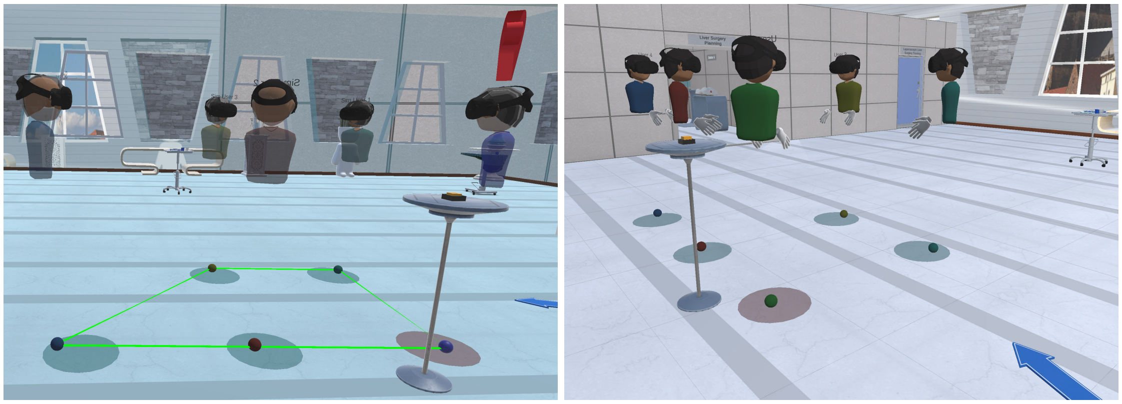

(a) (b)

FIGURE 8.9: Participants in the user study were asked to perform as the guide. The task includes group placement in specific formation patterns and spatial arrangements: (a) during the navigation process and (b) after arriving at the destination. The positions of the guide and members are projected with the spheres shown on the floor, which were used to calculate placement error.

### Tasks

After the training, the participants were connected into the collaborative VR environment, as shown in Figure 8.7. There were six navigational tasks. Once the start button was pressed down, the formation pattern and navigational arrows appeared. The participants were asked to perform as the guide. Thus, the task was to create a group formation and assign the group to each target destination according to its formation pattern and spatial arrangement. As shown in Figure 8.9, a circle with dark-red color was the position for the guide and other circles with dark-cyan colors were the positions for group members. The spheres on the floor showed the projected positions and were used to calculate the placement error. After placing the group into the formation pattern and traveling to the destination, the users' task was to find and press down the yellow button on the small table nearby. This would stop the current task. Once they pressed down the same button, the task for the next target destination could be initiated. After participants completed all navigational tasks, they were asked to take the VR headset off and answer the mid-questionnaires, including discomfort and usability questionnaires. Afterwards, the second group navigation technique was introduced. This followed the same procedure with the technique training and actual performance, and following the last technique phase, users were asked to answer only the usability questionnaire.

### Semi-structured Interview

A semi-structured interview was conducted after the exploration and performance of the two group navigation techniques. The interviewer made notes of all relevant comments from the participants. The following questions were asked during the interview:

- What is your overall impression?
- What are the perceived advantages/disadvantages for group WiM and group teleportation navigation techniques?
- Do you have any questions or comments?

### Data Analysis

The analysis was performed using an analysis of variance (ANOVA) for two dependent variables: *task completion time* and *placement error*, paired t-tests for *usability*, and descriptive analysis for the additional variables, including *number of jumps* and *discomfort scores*. Discomfort symptoms were evaluated and calculated the differences between the pre- and post-SSQ questionnaire results for all scales, as suggested by Bimberg et al. [286]. For qualitative participant's feedback, the comments were collated into a common database and removed the redundancies. The information was then clustered into its relevant categories.

## 8.6 Results

The total average time of the study was 50.29 min ($SD$ = 6.84), while the technique training of the first technique lasted 12.87 min ($SD$ = 4.65) and 6.32 min ($SD$ = 2.38) for the second technique. In the following section, the characteristics of the participants and results measured in the user study are described, including user performance and questionnaire data, as well as the qualitative participant's feedback.

### 8.6.1 Participants

21 participants (12 male, 7 female, and 2 non-binary) participated in the user study (see Table 8.1). They were aged between 23 to 33 years old (median = 26 years old). 16 of them had a background in computer science and 5 had a medical engineering background. They all had previous experience with VR which ranged from little (they had used VR a few times before), much (several times), and expert (regularly). 11 participants were reported as having little; 2 having much VR experience; and 8 were experts. Moreover, two of them were left hand dominant.

**Data Exclusion** During the data analysis, an oversight in the study setup was recognized and noted to have compromised the trial order permutation for the difficulty factor. This led to a repetition of the first navigation always being of an easy difficulty level and the last navigation always being of a medium difficulty level. A first sighting of the data suggested that this may have led to significant order effects. The sample was thereafter reduced by analysing only the second trial that each participant conducted

| Characteristics | Value | Mean |
|---|---|---|
| Age [years, mean (range)] | [23-33] | 26.67 |
| Gender | | |
| Male | 12 | (57.14%) |
| Female | 7 | (33.33%) |
| Non-binary | 2 | (9.53%) |
| Background | | |
| Computer Science | 16 | (76.19%) |
| Medical Engineering | 5 | (23.81%) |
| VR experience | | |
| Little | 11 | (52.38%) |
| Much | 2 | (9.52%) |
| Expert | 8 | (38.10%) |
| Handedness | | |
| Left | 2 | (9.52%) |
| Right | 19 | (90.48%) |

TABLE 8.1: Characteristics of participants ($n = 21$).

| Variable | Task Completion Time (s) | Placement Error (m) | Number of Jumps |
|---|---|---|---|
| Group Teleportation | 43.10 (28.70) [4.43] | 0.13 (0.07) [0.01] | 2.19 (1.09) [0.16] |
| Easy | 33.54 (22.76 [4.96] | 0.15 (0.09) [0.02] | 1.38 (0.59) [0.12] |
| Hard | 52.67 (31.30) [6.83] | 0.12 (0.03) [0.008] | 3.00 (0.83) [0.18] |
| Group WiM | 29.00 (9.36) [1.44] | 0.11 (0.04) [0.007] | 1.00 (0.00) [0.00] |
| Easy | 29.66 (9.53) [2.08] | 0.12 (0.04) [0.01] | 1.00 (0.00) [0.00] |
| Hard | 28.43 (9.38) [2.04] | 0.11 (0.04) [0.01] | 1.00 (0.00) [0.00] |

TABLE 8.2: Summary of descriptive results for all dependent variables of user performance. All entities are in the format: mean value (standard deviation) [standard error].

under the “easy" and “hard" condition, with each technique. Thus, four out of six tasks per participant and technique were excluded. The remaining data are reported below. These data provide a valid insight into the effects of the technique and the effects of the “easy" vs the “hard" difficulty setting. The ANOVA was accordingly changed to a 2x2 design.

### 8.6.2 Statistical Results (*RQ1*)

The summary of descriptive results for dependent variables of user performance is listed in Table 8.2 (see also Figure 8.10). The results of statistical analysis with ANOVA are listed in Table 8.3. Statistically significant effects were found regarding the task completion time for variables *group navigation technique*, *difficulty*, and their interaction effect. The results indicate that the group WiM technique was performed significantly faster than the group teleportation. In the easy condition, the difference regarding task

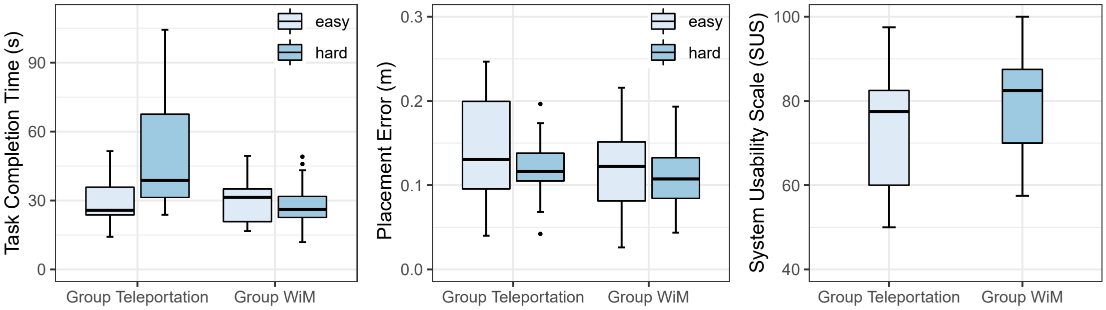


FIGURE 8.10: Statistical results for dependent variables: task completion time (left), placement error (middle), and usability (right).

| Variable | df | F | p | Sig | $\eta^2$ |
|---|---|---|---|---|---|
| Task Completion Time | | | | | |
| Technique | 1 | 9.660 | <0.005 | * | 0.110 |
| Difficulty | 1 | 7.828 | <0.011 | * | 0.047 |
| Technique * Difficulty | 1 | 9.686 | <0.005 | * | 0.060 |
| Placement Error | | | | | |
| Technique | 1 | 3.390 | 8.047 | | 0.029 |
| Difficulty | 1 | 2.514 | 1.285 | | 0.027 |
| Technique * Difficulty | 1 | 2.029 | 1.696 | | 0.017 |

TABLE 8.3: Summary of the statistical results with ANOVA for dependent variables of user performance data ($p < .05$).

completion time between both techniques was small. However, the group teleportation required more time for the hard level of navigational difficulty. The results of the interaction effect also indicate that the impact for task completion time of the technique depends on the level of difficulty. No significant differences were found for the *placement error*. Trends in the descriptive results suggest the benefits of the group WiM, however, the results show a small difference between both techniques.

For *usability*, the SUS questionnaire results from all participants show an average score of 72.30 ($SD$ = 14.40) for group teleportation and 78.80 ($SD$ = 14.80) for group WiM. We further analyzed the usability results with t-tests and found significant differences between the techniques ($t$ = -2.14, df = 20, $p$ = 0.044). The group WiM was rated higher than the reference technique, which could indicate the potential benefits of its usability.

### 8.6.3 Discomfort Scores (*RQ2*)

The descriptive results of discomfort symptoms with the pre- and post-SSQ questionnaires, as well as their differences, are listed in Table 8.4. The results of the comparison between pre- and post-SSQ questionnaires show discomfort symptoms for group teleportation: nausea ($M$ = 11.40, $SD$ = 14.80), oculomotor ($M$ = 11.40, $SD$ = 15.30), disorientation ($M$ = 8.35, $SD$ = 16.30), and total score ($M$ = 12.30, $SD$ = 16.30) and the group WiM: nausea ($M$ = 6.07, $SD$ = 13.00), oculomotor ($M$ = 2.76, $SD$ = 7.78), disorientation ($M$ = 7.59, $SD$ = 11.40), and total score ($M$ = 5.78, $SD$ = 10.40). The results indicate that all the increased discomfort symptoms of the group WiM navigation technique were lower than the group teleportation (see Figure 8.11). Furthermore, they could show that the automatic change of users' view direction was better in group WiM.

| Variable | Group Teleportation | Group WiM |
|---|---|---|
| Pre-SSQ | | |
| Nausea | 1.91 (4.02) [0.00] | 1.74 (5.75) [0.00] |
| Oculomotor | 5.31 (10.10) [0.00] | 4.14 (9.20) [0.00] |
| Disorientation | 6.96 (13.50) [0.00] | 2.53 (5.63) [0.00] |
| Total score | 5.24 (9.85) [0.00] | 3.40 (7.75) [0.00] |
| Post-SSQ | | |
| Nausea | 13.40 (17.50) [9.54] | 7.80 (10.30) [0.00] |
| Oculomotor | 16.70 (23.10) [7.58] | 6.89 (7.92) [7.58] |
| Disorientation | 15.30 (25.80) [0.00] | 10.10 (12.60) [0.00] |
| Total score | 17.60 (24.10) [7.48] | 9.18 (10.20) [3.74] |
| Difference (SSQ) | | |
| Nausea | 11.40 (14.80) [9.54] | 6.07 (13.00) [0.00] |
| Oculomotor | 11.40 (15.30) [7.58] | 2.76 (7.78) [0.00] |
| Disorientation | 8.35 (16.30) [0.00] | 7.59 (11.40) [0.00] |
| Total score | 12.30 (16.30) [3.74] | 5.78 (10.40) [3.74] |

TABLE 8.4: Summary of questionnaire results for discomfort scores with the pre- and post-SSQ questionnaires as well as their differences. All entities are in the format: mean value (standard deviation) [median].

### 8.6.4 Qualitative Participant Feedback (*RQ3*)

A total of 270 individual statements from the participants was collected. In the following, the qualitative feedback is summarized into its relevant categories.

**Group Navigation Techniques** The participants agreed that using the group navigation is useful and beneficial for navigating the users together, especially for training and educational purposes. They stated that both techniques were understandable with preview avatars and pre-defined formations. Furthermore, they stated that, in the collaborative VR environment, it is essential to have someone guide the group. This could save time and navigational accords for way-finding.

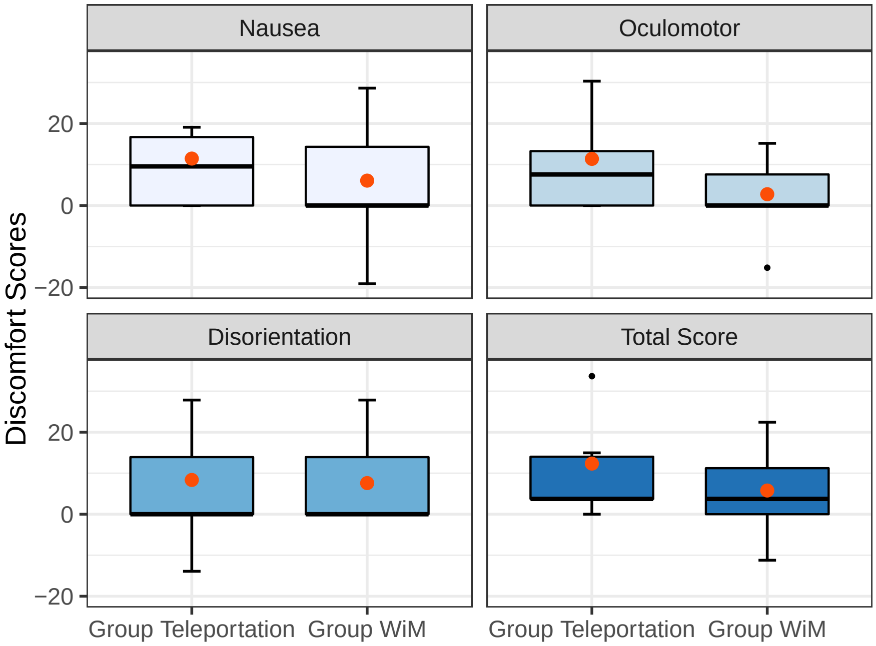


FIGURE 8.11: Results of discomfort scores. Positive values indicate an increase of a symptom comparing between the pre- and post-SSQ questionnaires (*red dots are the mean values*).

**Group Teleportation Technique** 16 participants stated that the navigation technique, with group teleportation, could provide presence and spatial understanding of the environment. This is because it was more direct and provides an impression of navigational paths during travel. The placement of the group could provide a good understanding of the target destination with preview avatars and could be performed directly.

Five participants stated that the group teleportation technique requires multiple steps if the target is a great distance away or is blocked by obstacles. Moreover, seven participants criticized the adjustment of the group arrangement as challenging, as was placing the group into the correct formation pattern and rotation. This was particularly true to them when it was significantly far from, or too close to, the target destination. One participant walked and collided with the physical wall while using this technique.

Three participants suggested that they would prefer to have an option to teleport the guide individually, and without changing the view direction automatically. Hence, it could be helpful for users to adjust their position without moving in the physical world, especially when it comes to the path that requires door interaction.

**Group WiM Technique** 20 participants stated that the group WiM technique provides an overview and impression of the environment. It could be beneficial for training and educational purposes because a trainer can inspect everything, including current avatar representations that are mimicked by the entire environment.

Twelve participants stated that navigation with this technique was intuitive and flexible, and that they could adjust the group arrangement easily. Additionally, this could provide the understanding of their current locations in the environment. Navigation was also faster in the complex navigational path. Eleven participants stated that using the WiM requires more interactions, for example, interactions that enable more exploration of the environment. There were also difficulties when users wanted to place the group in the precise formation pattern and needed to scale the WiM up.

Five participants commented that the WiM might provide less understanding and realism of the spatial environment, as most of the time was spent on the WiM. Despite this, they mentioned that they were able to build a mental map of the environment.

Two participants, the experts, suggested a scaling limitation for the WiM. It was noted that it might be confusing if the WiM is scaled up to such a degree that it reaches the same size as the original environment. Nonetheless, all participants agreed that this technique is essential in guiding and navigating users in the complex VR environment.

**View Directions and Group Formations** Twelve participants stated that the automatic change of their view direction was acceptable. 17 participants, however, criticized that it was initially confusing with the group teleportation, even though there were preview avatars and an indicator that represents them as the guide. They agreed with the usefulness of an automatic change to keep the group in focus. Thus, the automatic change can be considered useful for group discussion. For group teleportation, however, two participants stated that it might not be necessary to make a change for the guide, or rather, that there should be additional indicators to visualize the view direction while performing the technique.

Three participants suggested including a blinking transition with an amount of time upon arriving at the destination. Nine participants stated that the four pre-defined group formations were sufficient and helpful in creating the group arrangement. One participant strongly expressed that the circle and half-circle formations could be extremely useful in most training scenarios. Two participants said that they would prefer to have an option to draw the line themselves, especially on the WiM. Based on this drawing line, the group arrangement can be initialized. One participant stated that the option to point and assign the arrangement manually, or to drag-drop the preview avatars for the users, would be useful as well. Five participants proposed having the option for line formation to change the users' view directions to the left or right side. Thus, this might be considered helpful in some cases.

**General Feedback** The participants were positive regarding the use of group navigation. They had difficulties and some confusion at the initial stage in the training environment, causing the training time of the first technique to take longer than the second technique. After several instances of navigation, however, users stated that they could adapt to the concept and interactions. They stated that it was difficult to place the group precisely inside the strict formation pattern with pre-defined circles, while in a real use-case, it actually might be not necessary.

Regarding the interaction for group placement, eight participants suggested having a two-step interaction between the adjustment of group extent and its rotation. The participants stated that both techniques have advantages and disadvantages, for instance, teleportation could provide a better spatial understanding of the navigation path while the WiM could provide an overview and arrange the group faster.

Five participants commented that a combination of both of them would be highly beneficial in providing a full option for the guide to control and navigate the group more effectively.

## 8.7 Discussion

The evaluation results indicate the advantages of the group WiM navigation technique in terms of lower task completion time for group navigation in obstructed target locations. It also reveals usability advantages of the proposed technique compared to the reference technique (*RQ1*). However, we did not find a statistically significant effect on the placement error between the techniques. The placement error for the group WiM was lower than the reference technique according to the descriptive results. Nonetheless, the differences were small between both techniques and the difficulty level. In group teleportation, the placement error was higher in the easy level than the hard level and the easy level also required less jumps. This could indicate that the users navigated closer to the target destination and placed the group more precisely.

The results of the differences between pre- and post-SSQ questionnaires show that both techniques induce some discomfort symptoms (*RQ2*). However, the increased symptoms for group WiM technique were lower than the group teleportation technique. The results also highlight the benefits of the group WiM for the automatic change of users' view directions according to the group arrangement specification.

The qualitative feedback shows the potential benefits and limitation of both group navigation techniques (*RQ3*). Preview avatars and the convex-hull line representation were helpful in indicating the group arrangement at the target destination. The group WiM technique could thus provide full control and overview of the environment, which would be beneficial for the guide and navigation in complex virtual environments and over longer distances. The group teleportation would then provide a good understanding of the spatial environment and navigational path. As suggested by Berger et al. [265], choosing the right VR navigation technique should depend on the scenario and use case. A combination of both techniques shows the additional potential for effective group navigation [273].

**Limitations** The user study was conducted with the guide's role. Because most of the group navigational interactions are operated by the guide, simulated users were used as group members in this experiment. The evaluation results provide a valid insight and meaningful into the effect of the techniques. However, the medium difficulty level was not evaluated and it should be included in the future experiment. Future studies should also investigate the group navigational procedure in detail. It could be essential to study both user roles with the group scalability and real use cases. For group WiM technique, we developed the group arrangement specification in a similar approach to that proposed by Weissker and Froehlich [233]. Nonetheless, the specifications can be achieved by other approaches, e.g., manipulation-based approaches to arrange the group.

## 8.8 Conclusion

This chapter has presented a group WiM navigation technique to support group arrangement and navigation in collaborative VR. A comparative evaluation was conducted to investigate user performance, usability, and discomfort of the technique compared to a reference group teleportation technique in a user study.

The evaluation results reveal the benefits of the group WiM technique that seems superior in regards to the task completion time and usability. No significant differences were found in the placement error for both techniques. Additionally, the results of discomfort scores indicate that the group WiM induces less discomfort than the reference technique. Qualitative feedback was collected to identify the advantages and disadvantages for both techniques, as well as the feedback regarding further improvements to their usability. The group WiM is an effective navigation tool for group navigation in collaborative VR, especially for the complex virtual environments.

# Chapter 9

# Conclusion

## About this chapter

This chapter summarizes the research contributions reported in this dissertation. It recapitulates the objectives and the results that were identified throughout Chapter 4 – 8. General research perspectives for VR and collaborative VR in laparoscopic liver surgery planning and training are described. Furthermore, current challenges and potential solutions for future work are discussed.

## 9.1 Contributions

This dissertation has presented novel collaborative VR environments to support and improve the planning and training in laparoscopic liver surgery. With this purpose in mind, a variety of research was conducted, including establishing specific requirements and developments, as well as evaluating prototypes and interaction techniques.

First, the research focused on collaborative VR for laparoscopic liver surgery training, which was introduced in Chapter 4. An integration of laparoscopic surgical joysticks and a training simulation were developed. Two modes were also implemented for training procedures: exploration and surgery mode. The exploration mode allows the users to explore patient data while the surgery mode enables the users to train their psychomotor skills inside the virtual operating room. In addition, two surgical roles were adapted in the surgery training simulation: surgeon and camera assistant roles. This setup allows for team training in a realistic setup and for improvement to the psychomotor skills necessary for each role. The prototype was evaluated in a pilot study by the general and visceral surgical residents. The results reveal the usefulness and usability of the proposed prototype as well as valuable insights gained from their feedback and the discussion.

Second, an investigation for collaboration between the interdisciplinary team in the operating room was presented in Chapter 5. Two training scenarios, including unexpected bleeding and insufficient muscle relaxant medication, were identified and developed in relation to surgical complication and communication skills for team-based training. The proposed prototype was assessed as a useful tool and provides potential benefits, such as real-time collaboration and communication, which are essential for operating room training.

Third, a collaborative VR environment for liver surgery planning was investigated and described in Chapter 6. A virtual resection technique and a risk map visualization was introduced to assess the planning procedures, e.g., keeping the safety margins and resection volume estimation. The evaluation was conducted remotely with experts using the proposed collaborative VR environment. The study results highlight the clinical applicability, potential benefits, and system performance.

In addition, an advanced surgical training environment was presented in Chapter 7, which is an integrated and enhanced prototype of all proposed VR environments presented in this dissertation. A user management system and photo-realistic avatars were introduced so the users can create their accounts and customize their avatar representations. Four stations were proposed in the surgical planning room. The collection of patient cases can support surgeons during the decision process. Thus, they can sort and evaluate the cases, e.g., tumor and vessel types. After selecting one case for planning, they can explore the 3D models and 2D image data as well as patient-related information. The planning procedure is further supported by virtual resection planning with the risk map visualization around the tumor. Therefore, the resection and remaining volumes can be evaluated. Besides the planning with the model in mid-air, they can also assess the position and identify the tumor localization of the patient case inside a virtual mannequin. The planning case is also synchronized and used in the virtual operating room to train with the laparoscopic simulation. Additionally, training scenarios and team collaboration with the anesthesiologists can be performed to support the operating room training. This proposed environment was evaluated in a pilot study with domain experts. Qualitative feedback with respect to the usefulness of surgical planning and training, as well as system features, was summarized.

Finally, a group navigation technique based on *World-in-Miniature* was reported in Chapter 8 to improve team navigation in collaborative VR environments. The proposed advanced surgical training environment described in Chapter 7 was used to evaluate this technique. A comparative evaluation of the proposed technique compared to the *state-of-the-art* group navigation technique was performed in a user study ($n = 21$). The evaluation results reveal usability, discomfort, and insights based on user performance. In addition, the results indicate that the proposed technique induces less symptoms of discomfort for the guide and seems superior in regards to the usability and task completion time. Therefore, it could be an essential tool to form, arrange, and navigate group members effectively in collaborative VR environments, especially in complex environments.

## 9.2 Outlook

While the evaluation for each environment revealed the usefulness, usability, and potential benefits, the limitations and potential strategies for further improvement are discussed as follows.

One challenge, among others, is related to the laparoscopic simulation. Since the aim of this work focuses on collaboration and team communication in the immersive VR environment, a low degree of cutting realism for laparoscopic simulation was realized. Using commercial simulators, e.g., *LapSim* and *LapMentor VR*, could provide a better cutting realism and training assessment. However, they are not flexible concerning the usage of the patient case and training scenarios. The cutting simulation can be further improved with realistic haptic feedback and recent techniques of physics-based simulations, e.g., finite element method (FEM) [287–289] and PBD [104, 290, 291]. The FEM has been used in soft-tissue modeling and interactions with high precision and deformation flexibility [292, 293]. One of the well-known frameworks for FEM calculation is provided by *SOFA* [294]. Moreover, there is an extension for VR development in Unity called *SofaUnity* (InfinyTech3D, Nice, France). For PBD approach, it is an alternative solution for soft-tissue deformation [295]. *Nvidia FleX* is a well-known framework for this approach. For medical simulation, Pan et al. [104] presented a real-time simulation based on parallel PBD in GPU. They also proposed an electrocautery procedure for laparoscopic cholecystectomy training [296]. Nevertheless, real-time soft-tissue cutting is still a challenging topic, especially the performance for immersive VR. Furthermore, proper synchronization of soft-tissue deformation requires more investigations in the collaborative VR environment.

The proposed approach for liver surgery planning could be useful for a wide range of other surgical resection planning, i.e., tumor surgery in kidney and pancreatic cancer. It is relevant for future work to investigate how this solution can be applied and properly evaluated for those areas. The risk map visualization can be further improved by providing necessary information to all affected vessels and its hierarchical structures [192]. Artificial Intelligence (AI) has been investigated and utilized for predictive risk stratification and clinical decision support. Future work should investigate the use of this technology in the VR environment to learn, recognize, and provide useful information for surgical planning and training [297]. Bari et al. [298] provided a review of existing research focused on applying AI in the preoperative phase of surgical planning. The results show that many studies have concentrated on evaluating the technical feasibility of using AI techniques. Nonetheless, future research is needed to assess the clinical impact of the techniques.

The proposed VR environment provides potential benefits for surgical training and planning. While it was evaluated as useful, the training assessment is needed to evaluate the performance of surgical trainees. Therefore, additional measurements for evaluation should be collected. The measurements should include the complexity of planning cases, task completion time, preservation of resection margins, and virtual resection results. Additionally, it could be beneficial to include an intelligent virtual agent (IVA) to assist inside the virtual environment [299–301]. Lee et al. [302] presented a study to explore on how humans interact with the IVA. Their results show that the IVA, including AI-agents or chatbots, was highly preferred to accompany in the virtual environment. This could indicate that co-presence alongside with IVA seems to provide a comfortable feeling and provide an engaging environment for training [303]. In addition, research on the use of eye-tracking could be beneficial to provide useful information for understanding and improving the training environment. Marin et al. [304] presented a study to evaluate the use of eye-tracking in laparoscopic surgery. They mentioned that eye-tracking could improve the learning of complex surgical techniques and could indicate important anatomical structures. Beside using the eye-tracking tool for obtaining didactic videos, it can be useful to analyze the tracking data to design the training scenarios and to build an assessment tool with AI, including machine learning techniques, to evaluate training performance in VR.

The evaluation of each environment presented in this dissertation was conducted with the domain experts. However, this work is limited by the small number of participants. Taba et al. [305] presented a study to analyze the effects of using VR simulations on the development of laparoscopic skills. The results of the systematic review show that many studies use a sample size between 18 to 30 participants. However, they suggested that it may not have been enough to provide an adequate population representation. Hence, evaluation with more participants and different levels of experience, including senior surgeons, could be beneficial to reveal the usability and usefulness. Moreover, evaluation should follow Kirkpatrick's four levels to assess the training effectiveness [102, 306]. The four levels of evaluation are as follows: *evaluation of reaction* measures the satisfaction and how the trainees react to the VR environment; *evaluation of learning* assess the skills acquired from the performance; *evaluation of behavior* measures the transfer of learning to the real situation; and *evaluation of results* measures the impact of results, e.g., clinical results and effects on patient outcome [307–309].

Saito et al. [310] presented a clinical report that reveals the potential of intraoperative mixed reality in liver surgery. Using intraoperative MR techniques is feasible and might be a new research direction for intraoperative supports [121, 311–313]. Therefore, it might be interesting and beneficial to further investigate the use of collaborative MR and the virtual resection technique presented in this dissertation for intraoperative support. In particular, the planning results, including resection volumes, affected vessels, and risk structures, in the preoperative phase can be used and visualized to support during the surgery.

With respect to group navigation in collaborative VR, future work should study the effectiveness of collaboration and team training in different rooms, and the use of group navigation techniques and avatar representations [69, 314, 315]. Future research is also needed to investigate the group scalability and real use cases with both user roles, including a guide and group members. In addition, further investigation on networking issues could be beneficial for team collaboration [145, 316]. Elbamby et al. [161] described the networking requirements and challenges for collaborative VR, including bandwidth, latency, and reliability constraints. The networking issues for collaborative VR can be categorized as three types: *client-side* includes the hardware capabilities and network conditions of each client, *application-side* refers to the design and protocol for data synchronization of the collaborative VR environment, and *server-side* refers to the corresponding server, which is set up to handle the synchronization. Using AI techniques to predict and optimize the data synchronization could be essential for collaborative VR [59, 61, 317].

To sum up, the research presented in this dissertation opens new directions for medical planning and training in laparoscopic liver surgery. It provides a basis for extensive clinical evaluation, transfer to other surgical disciplines, and exchange of knowledge between surgeons, whether in a remote or shared environment. Furthermore, it may contribute the scientific research by providing an outlook for future research directions.

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# List of Abbreviations

| | |
|---|---|
| **VR** | virtual reality |
| **FOV** | field of view |
| **ECG** | electrocardiogram |
| **HMD** | head-mounted display |
| **ABP** | arterial blood pressure |
| **bpm** | beats per minute |
| **UI** | user interface |
| **PBD** | position-based dynamics |
| **CT** | computed tomography |
| **LLEAP** | Laerdal learning application |
| **TOF** | Train of Four |
| **Unet** | Unity networking |
| **fps** | frames per second |
| **PCA** | principle component analysis |
| **MRI** | magnetic resonance imaging |
| **DoF** | degrees of freedom |
| **FPS** | frames per second |
| **CAVE** | cave automatic virtual environment |
| **MR** | mixed reality |
| **XR** | Extended reality |
| **AR** | augmented reality |
| **AV** | augmented virtuality |
| **ROI** | region of interest |
| **VRTK** | Virtual Reality Toolkit |
| **DICOM** | digital imaging and communications in medicine |
| **maxSync** | maximum synchronization |
| **MAC** | minimal alveolar concentration |
| **SUS** | system usability scale |
| **DTS** | Drawing traces on 2D slices |
| **DCP** | Deformable cutting plane |
| **WiM** | World-in-Miniature |
| **FEM** | finite element method |
| **AI** | Artificial Intelligence |
| **IVA** | intelligent virtual agent |

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# Appendix A

# Appendix to Chapter 5

In the following sections, interview questions and results of the cooperative social presence questionnaire are described as part of the evaluation described in Chapter 5.

## A.1 Interview Questions

### Topic: Realism

*Training scenario 1: Undetected Bleeding*

- Do the vital signs and animations used precisely depict the scenario “Undetected Bleeding"?
- What was missing, or how could the illustration be improved further?

*Training scenario 2: Insufficient Muscle Relaxant Medication*

- Do the vital signs used precisely illustrate the scenario “Insufficient Muscle Relaxant Medication"?
- Was the usage of muscle relaxant depicted well enough?
- What was missing, or how could the illustration be improved further?

*Functionalities*

- Please rate the realism of the possibilities and amount of change of the following vital signs and parameters:
  - Pulse/ Heart Frequency
  - Arterial Blood Pressure
  - Train of Four
  - $O_2$ flow

  - $N_2O$ flow
  - Inhalation Anaesthetic
  - Muscle Relaxant
- Were there enough functionalities? What did you miss?

*Interactions*

- Were the following interaction possibilities intuitive or difficult to learn?
  - Teleportation
  - Controller-Interactions with objects
  - Laser-Interactions with menus
  - Laser-Interaction with objects
- In which aspect did you find the interactions challenging? If so, what changes would you suggest to improve interaction?

**Topic: Communication**

*Training scenario 1: Undetected Bleeding*

- Do you think the scenario "Undetected Bleeding" will encourage communication?
- What could be improved to encourage communication?

*Training scenario 2: Insufficient Muscle Relaxant Medication*

- Do you think the scenario "Insufficient Muscle Relaxant Medication" will encourage communication?
- What could be improved to encourage communication?

**Topic: Teaching**

- Can you imagine yourself using an application like this for teaching in the future?
- What should be included so you would utilize that?
- Which options of supervision would you like to have as a teacher/ instructor?
- Which options of control would you like to have as a teacher/ instructor?
- What were the positive features of the application?
- What were the negative features of the application?
- Do you have any recommendations to improve the application?

## A.2 Results of Cooperative Social Presence

TABLE A.1: The average rate on five-point Likert scale and related items from cooperative social presence questionnaire [185].

| | **Mean (SD)** |
|---|---|
| **Team Identification** | **4.13 (0.64)** |
| Q1. I acted with my teammates in mind | 3.67 (0.58) |
| Q2. I considered my teammates' possible plans/thoughts | 4.00 (1.00) |
| Q19. I felt a social connection to my teammates (camaraderie) | 4.00 (0.00) |
| Q21. I felt like I was part of a team | 4.33 (0.58) |
| Q23. I was aware of my team | 4.67 (0.58) |
| **Social Action** | **4.08 (0.83)** |
| Q6. I felt my teammates were looking out for me | 3.00 (1.00) |
| Q7. I felt I contributed to the team | 4.67 (0.58) |
| Q8. I felt my actions made a difference to my teammates | 4.67 (0.58) |
| Q11. The actions of my teammates affected my thoughts and actions | 4.67 (0.58) |
| Q13. My team communicated well | 3.33 (0.58) |
| Q14. The team had a mutual understanding | 4.00 (0.00) |
| Q16. My teammates played a significant role in my experience of the simulation | 4.33 (0.58) |
| Q25. I felt the team helped me | 4.00 (1.00) |
| **Motivation** | **4.06 (1.06)** |
| Q5. I did not want my team to think I had let them down | 3.33 (1.53) |
| Q9. My actions were determined by the objectives of the team | 5.00 (0.00) |
| Q12. Being part of a team motivated me | 4.00 (0.00) |
| Q15. I put the performance of the team over my personal performance | 4.00 (1.73) |
| Q17. I wanted my team to value me | 3.67 (1.15) |
| Q18. I felt responsible for achieving the objectives of the team | 4.33 (0.58) |
| **Team Value** | **4.44 (0.70)** |
| Q3. It was as much about the team as about my own game | 4.00 (1.00) |
| Q4. I felt my team shared a common overall aim | 5.00 (0.00) |
| Q10. I felt my team was committed to working together | 4.67 (0.58) |
| Q20. I made an effort to work with my teammates | 4.33 (0.58) |
| Q22. I felt my team shared common short term goals | 4.67 (0.58) |
| Q24. My teammates were useful | 4.00 (1.00) |