Otto-von-Guericke University Magdeburg
Faculty of Electrical Engineering and Information Technology

Bachelor Thesis

Interprofessional Multi User Virtual Reality Training for Anesthesia in a Laparoscopic Setting

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Abstract

Even though anesthesia is rather prominent in medical simulation, it seems to be relatively scarcely respresented in virtual reality simulations. In addition to that, the importance of team training and good communication skills within surgery teams have been stressed multiple times as well as the advantages virtual reality has for building such team trainings. As such it is thought to be suitable, to implement an interprofessional team training which includes anesthetists.

The aim of this Thesis is to build a prototype of a laparoscopy simulator for anesthetists and surgeons. The main objective is to improve problem-based medical communication during the surgery. The main focus will lie on the duties of the anesthetist during a laparoscopy.

It was decided to include two complication scenarios, which should spark a medical problem-based conversation: "A: Undetected Bleeding" and "B: Insufficient Muscle Relaxant Medication". In both scenarios one party will notice the symptoms while the other party will have to treat them, after they have been notified. The simulator includes symptoms of the scenarios like vital sign changes for pulse, arterial blood pressure and Train of Four as well as inhalation anesthetics and muscle relaxants as medications.

The simulator was implemented using virtual reality head mounted displays and controllers (HTC Vive) together with the game engine Unity. The implementation is built upon the work of Heinrich et al. [1]. For the simulation and monitoring of the vital signs the software LLEAP for controlling Laerdal' medical mannequins was included.

Lastly, an evaluation interview with an anesthetist was held. The feedback was overall positive and the anesthetist stated that he would use the implemented simulator for teaching in a more developed version.

OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG
EIT
FACULTY OF ELECTRICAL ENGINEERING AND INFORMATION TECHNOLOGY

Bachelor Thesis

for Virve Tuulia Fischer
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Interprofessional Multi User Virtual Reality Training for Anesthesia in a Laparoscopic Setting

Task of the Thesis:

In this bachelor thesis a virtual reality team training for anesthetists and surgeons should be implemented. To gain a better overview on the topic a research of literature is to be developed on the use of virtual reality team training for medical simulation.
The training simulation is to be evolved from the laparoscopy virtual reality simulator for surgeons, which already exists in the research group for Computer Assisted Surgery of this University[1]. The focus is the need for communication between anesthetist and surgeons. For this reason complication-scenarios which need interprofessional communication during a surgery should be implemented. To ensure realism of the clinical parameters and the possibility of future development with haptic feedback via the additional use of a mannequin and an anesthesia simulation software is to be included.

Magdeburg, 12th August 2019

Day of Assignment:	21st June 2019
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[1]F Heinrich, S Rohde, T Huber, M Paschold, W Kneist, H Lang, B Preim, and C Hansen. VR-basierte Interaktion mit 3D-Organmodellen zur Planung und Simulation laparoskopischer Eingriffe Problemstellung Material und Methoden. Curac, pages 57–62, 2018.

Declaration by the candidate

I hereby declare that this Thesis is my own work and effort and that it has not been submitted anywhere for any award. Where other sources of information have been used, they have been marked.

The work has not been presented in the same or a similar form to any other testing authority and has not been made public.

Magdeburg, August 23, 2019

Contents

List of Acronyms

3D three dimensional

ABP arterial blood pressure

API application programming interface

AR augmented reality

bpm beats per minute

CO_2 carbon dioxyde

CPR cardiopulmonary resuscitation

DUR25 effective duration until 25% of the neurons recover

DUR95 effective duration until 95% of the neurons recover

ED effective dose

ECG electrocardiogram

HMD head-mounted-display

LAVRS Laparoscopic Anaesthesia Virtual Reality Simulator

LLEAP Laerdal Learning Application

MAC minimal alveolar concentration

N_2O nitrous oxide

NPC non-player character

O_2 oxygen

TTE time till effect

VR virtual reality

1 Introduction

With the current rise of virtual reality in education, medical disciplines also started to built virtual reality teaching tools. Virtual reality is deemed especially useful for producing real experiences in a virtual environment and as such support the Constructivist's learning theory ("learning by doing") [2]. This quality can be used to create realistic learning simulations for different medical fields. Right now a big portion is supplied by surgery training for camera-monitored surgeries like laparoscopy [3, 4]. While these single-user trainers have been developed and proven successful, they have also shown to impair team work because they strengthen the idea of being able to solve problems alone [5]. As such it has been stressed by multiple health organizations, that more interdisciplinary team training should be provided to improve physicians' soft skills and team work [5,6]. Because virtual reality has also been claimed to be especially useful for team training [7], this Thesis will make an approach on building an interprofessional team training application prototype for a laparoscopic surgery.

The interprofessional team should consist of two surgeons and one anesthetist as these are the key physicians in a laparoscopic surgery. While virtual reality surgery simulations have been a hot topic and although anesthesia is a medical field which is prominent in simulation, until now virtual reality has not been used for anesthesia simulation much. This makes virtual reality for anesthesia simulation a new and interesting field to study, so the simulation for the anesthetist or anesthesia residents will be the main focus of this Thesis.

To build the anesthesia simulator first an overview on the medical field of anesthesia and its duties during a laparoscopy must be achieved. A short outline of virtual reality and its abilities should also be made. These topics will be explained in the Chapter 2. Secondly, some information on the related work in virtual reality education and medical teaching will be presented, to gain an overview on the state of the art and similar scientific projects. These will be covered in Chapter 3. As a third step, the concept of the simulator will be proposed in Chapter 4, starting with the definition of the objective, followed by a requirement analysis and the discussion of the main functionalities of the simulator and how they could be achieved. Fourth, the Chapter 5 will elaborate how exactly the functionalities were implemented and present impressions of the final prototype. Afterwards the Chapter 6 will depict the evaluation interview of the prototype simulator, which was held with an anesthetist. Finally, the performance of the simulator will be critically questioned in Chapter 7 by recapitulating the evaluation interview, defining future steps and possible problems of the simulator and lastly giving an outlook on additional use cases for the finished simulator.

2 Background

To outline the basic knowledge on which the simulator is build the following sections will cover the medical background needed as well as the essential characteristics of VR.

2.1 Medical Background: Anesthesia and its Tasks

The Medical Background section will present the medical area of anesthesia. Most of the information for this section was taken from Larsen et al.'s book on anesthesia [8].

2.1.1 Anesthesia

The medical area of general anesthesia has the aim to allow surgical interventions without dealing irreversible harm to the patient. Harm in this matter does not only involve the physical pain but also psychological traumas. As such a patient will be narcotised. A narcosis consists of three main branches which target different parts of the nervous system: the reduction of the sensation of pain (Analgesia), the reduction of the consciousness and the reduction of muscle movement. It can either be used locally or as a general narcosis (full-body). For the simulator only the general narcosis is used and as such the monitoring as well as the medications needed for this will be elaborated.

2.1.2 Monitoring of Vital Signs

The anesthetist is in charge of guaranteeing a patients well-being before, after and during the surgery. Since the patients can not express themselves due to the narcosis, this can only be monitored by checking the patient's vital signs using different medical measurements. Usually the measurements are summed up on a single screen as shown in Figure 2.1, so that the anesthetist can gain a quick overview. The most important vital signs for the simulator will be explained here. There is also an overview table (Table 2.1) showing the typical values of the vital signs in different scenarios.

Pulse

The pulse or heart rate measures how often the heart pumps blood through the body every minute. A healthy pulse would be around 80 ± 20 beats per minute (bpm) [1].

[1] Havard Health Publishing: https://www.health.harvard.edu/heart-health/hows-your-heart-rate-and-why-it-matters, Date: 26.04.2019

Figure 2.1: A vital sign monitor, which shows a typical set up of curves and values needed to evaluate the patient's well-being.[2]

During narcosis the pulse will go down because the patient is very calm similar to sleeping. Whenever the body is being stressed the pulse will rise as to deliver more oxygen to the vital organs. The pulse will also rise if for example blood loss results in a too low supply of oxygen with the normal heart frequency [9].

Arterial Blood Pressure

The arterial blood pressure (ABP) is the pressure which can be measured in the arteries. It is built by two values: the systolic value (highest pressure when the heart muscle contracts and blood is pumped out) and the diastolic value (lowest pressure when the heart muscle relaxes and the cardiac chambers refill with blood), which are normally below 120 mm/Hg for systole and 80 mm/Hg for diastole[3]. The ABP will also sink during narcosis as the mean value of the measurements in Hermann's Thesis imply [10], but opposed to the pulse

[2] Picture Source: https://img.medicalexpo.de/images_me/photo-g/70721-7490741.jpg, Date: 08.08.2019

[3] Havard Health Publishing: https://www.health.harvard.edu/heart-health/reading-the-new-blood-pressure-guidelines, Date: 26.4.2019

it will fall during blood loss as well [9] because less blood in the system will lower the overall pressure.

Train of Four

The Train of Four is a measurement of muscle relaxation. It will usually be measured on the ulnar nerve. If a more proximal nerve connected to a more distal nerve is stimulated, the connected distal nerve will contract. When the muscles are relaxed the electrical signal from the proximal nerve will not reach the distal nerve, since the ability to transfer the signal is blocked. This block is not absolute, so a part of the signal will still be transmitted. The degree of the block can be determined with the Train of Four. On a proximal nerve there will be given four electric impulses in 1 Hz intervals. After that the amount of impulses that reach the distal nerve as well as their amplitude is measured. The amplitude of the first and last impulse will be evaluated against one another (amplitude last/amplitude first) as the relative Train of Four. The Train of Four should usually be four for the amount of impulses that reach (all impulses) and the relative Train of Four around 100%. During narcosis the patient should have a Train of Four below or equal to two (thus the relative Train of Four would be 0%).

Situation	Pulse[bpm]	ABP sys[Hg/mm]	ABP dia[Hg/mm]	Train of Four
normal	$\sim$ 80 [1]	<120 [3]	<80 [3]	4 [8]
narcosis	$\sim$ 59 [10]	$\sim$ 108 [10]	$\sim$ 64 [10]	$\leq$ 2 [8]
bleeding	rises [9]	falls [9]	falls [9]	no change
low muscle relaxant	no change	no change	no change	rises [8]

Table 2.1: Vital Signs and their typical values and changes during specific situations.

2.1.3 Medication for Anesthesia

Basically all three branches of narcosis could be medicated with just one anesthetic, but due to the side-effects, which occur when using such high dose of anesthetic, each of the branches will be medicated with a specific medication, in order to keep the side-effects to a minimum.

Consciousness

The medication for reducing the consciousness is called anesthetic because it could also be used to medicate the other two branches. Anesthetics can either be given intravenously (directly into the blood) with an infusion or via inhalation uptake (breathed in). The latter will be used for the simulator. Inhalation anesthetics will be mixed with other gases like oxygen (O_2) and a carrier gas, which can either be air or nitrous oxide (N_2O), and given to the patient with the use of a respirator. They are characterized by their minimal alveolar concentration (MAC). This is the concentration of anesthetic in percent, which needs to be in the alveolars for the medication to be effective on 50% of the patients. It is used to compare the effective dose of different inhalation anesthetic and also to judge whether the current level of medication is enough or not. The MAC will change depending on the carrier gas used: with air the MAC is constant, but using nitrous oxide will lower the MAC, because nitrous oxide itself has a low narcotic effect, which will amplify the effect of the inhalation anesthetic used. By using nitrous oxide as carrier gas with a concentration of 70% of the total gas mixture the MAC will be approximately halved.

Muscle Relaxation

For relaxing the muscles so called muscle relaxants are used. They are always given intravenously either by consecutive injections or an infusion. If given by injection the muscle relaxant will be specified by its effective dose (ED given together with the percentage of patients this dose was effective for, usually 95%), the intubation dose (dose needed for intubation is around twice the ED), time till effect (TTE) and two types of duration of the effect: the clinical duration of effectiveness (DUR25: duration until 25% of the neurons have recovered) and the entire duration of effectiveness (DUR95: duration until 95% of the neurons have recovered).

Pain

The medication for reducing the felling of pain is called opioid. Opioids are given analogously to muscle relaxants. The standardization of the effective dose of an opioid is not possible, because the effective dose does not only vary inter-individually but also intra-individually. Additionally the amount of medication needed varies in dependence of the intensity of the operative stimuli given, so the anesthetist must estimate the dosage for each situation anew using their experience and the patient's background information. Opioids for narcosis are compared among themselves using the equianalgesic chart, which defines a relative value of the effectivity of the opioids listed for analgesia. Apart from that each opioid has certain time periods, which define its effective duration after an injection: the duration after which the maximum effect starts, the minimum duration of its effectivity and its relative effective duration.

2.2 Virtual Reality

The thesis will construct a VR simulator, so this section will cover the basics to understand what exactly that means. First the question "What is VR?" will be answered and afterwards explained together with its characteristics: hardware, immersion, multi-sensory output and typical problems. This section will mostly cover Dörner et al.'s book on Virtual and Augmented Reality [11].

2.2.1 What is Virtual Reality?

VR has become a popular technology within the past few years. Especially since the hardware for visualization made a huge leap and VR devices began to become affordable for entertainment purposes, it is being steadily improved. But what exactly is VR? Already in 1965 Sutherland described his vision of the ultimate display of virtual reality:

> "The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked." [12]

Right now we are still far from that vision Sutherland described. But his words picture the aim the technology of VR is targeting to get close to. Up until now there is no common definition for VR, but there are certain concepts which are commonly understood to be mandatory for a VR device:

- viewer-centered 3D displays and intuitive interaction devices,
- real-time computer generated environment,
- multi-sensory output, and
- use these components to create "immersion"

2.2.2 Hardware

Part of the reason why it is difficult to find a universal definition for VR is because the underlying hardware evolves fast. Computer graphics improve each year and as such the depictions that can be created by a VR device become more realistic. But how does a VR device nowadays look like?

The most well known output devices would be the head-mounted-displays (HMDs). These are displays positioned directly in front of both eyes and usually worn with a construction directly on the head. Another way to display a VR is by a cave automatic virtual environment (CAVE). A CAVE projects images onto three to six walls of a cubic room in which the users stand while wearing shutter glasses to achieve a 3D view of their surroundings. In both cases the user needs to be tracked so that the projection on the displays can change in dependence of the users position. Figure 2.2a shows examples of

hardware used for two popular HMD-based VR systems and Figure 2.2b an example of hardware for a CAVE. Since a HMD is used to build the simulator, the CAVE will not be discussed any further.
For input devices there is a variety of controllers available as well as data gloves and many others. Most need to be tracked in the room as well, to make sure that the user's interaction will take place in the expected positions. As the 3D world is well known by humans the interactions can be made more intuitive by using typical gestures and actions with the gloves and controllers. This is also the reason why VR is seen as a new form of human-machine-interface with huge potential [13].

(a) Hardware needed for HMD-based VR systems (HMD, Tracking Devices, Controllers) shown in two popular variants: the HTC Vive (top) and the Oculus Rift (bottom). [4]

(b) Hardware needed for a CAVE showing the room with projections, shutter glasses and a controller as it is used at Compiègne University of Technology. [5]

Figure 2.2: Two different hardware options for setting up VR.

2.2.3 Immersion

Immersion is another abstract concept which has no universal definition up to now. There are two approaches on defining it:
In a psychological manner immersion is the feeling of "really being there". So it is about the degree that the user feels like the world is behaving in an intuitive way for them to understand and interact. This however is a very subjective parameter and as such difficult to measure or assure.
In a physical understanding immersion can be achieved when the user of a VR device receives as many sensory stimuli by the VR system as possible and the system blocks stimuli of the real world as good as possible. So the other characteristics stated above are required to fulfill this definition of immersion. A physically immersive system would also

[4] Picture Source: https://roadtovrlive-5ea0.kxcdn.com/wp-content/uploads/2016/02/htc-vive-and-oculus-rift-total-system.jpg, Date: 09.08.2019

[5] Picture Source: https://d3hjf51r9j54j7.cloudfront.net/wp-content/uploads/sites/9/2018/04/Antycip-Simulation-Brings-Modular-VR-CAVE-to-Heudiasyc-Laboratory-2.jpg, Date: 09.08.2019

need to give stimuli which are as realistic as possible and make the virtual world feel alive, which once again makes this a quality that is difficult to measure.

2.2.4 Multi-Sensory Output

Usually the visual and auditory senses will be targeted most by VR devices. A HMD covers the eyes so only the virtual world can be seen and has inbuilt speakers to play sounds of the virtual environment. The HMD is also being tracked so that the position and orientation of the head will change the position of the camera in the virtual world and thus the user can virtually look around by turning their head.
A special depth cue that is conveyed by HMDs is binocular disparity. This stereoscopic effect is created by mimicking the two different pictures the eyes usually capture of the world: by using two displays, which are separated in a way that light from one display can only reach one eye, both eyes can be stimulated separately, too. With this the eyes can get images from slightly different perspectives like they would in reality and as such an artificial feeling of depth perception is generated.
It has been shown, that an accurate user-tracking in all six degrees of freedom, stereoscopic visuals and an as wide as possible field of view have the most effect on the feeling of presence (psychological immersion) in a meta-analysis of by Cummings et al. [14]. Other features of immersive systems have been found to be less important. Overall they state, that technical immersion has but a medium-sized effect on the feeling of immersion.
To make the user feel present in VR, they will not only need the sensations to make them believe that they are standing in the virtual world, but they will also need to be able to interact with it. For interaction in VR tracked controllers or something similar are typically used. With the help of these the user has a means of interacting with the virtual world and there is also the ability to give minor haptic feedback by using e.g. vibrations to simulate the touch of an object.

2.2.5 Drawbacks of VR

Using VR also comes with drawbacks. For example the space in reality where the VR equipment will be tracked correctly is limited, while the VR might show the user that they stand in a wide open field. How can the user move within the virtual world without touching the limits of the real one? Usually limitations are shown at the edges of the trackable area, so that the user will not go any further than that, but it is unclear, how they should move from there. Up until now there is no universal solution on how to fix this problem about the locomotion. Many VR applications allow a form of teleportation to make movement possible. A downside to this is that the user might feel confused and disoriented. Another possibility to move the virtual character can be achieved by using a joystick on the VR-controller, but this can also bring another problem: simulation sickness.

People will start feeling sick if their senses are in discord. For example the visual sense tells them, that they are moving, but their sense of balance says, that they are standing still. As such the reason for simulator sickness is the same as motion sickness. This can also happen if the VR system is too slow and does not display changes of the head position in real time.
There is another sense which will usually be mislead by VR systems: the visual sense to estimate sizes. Lin et al. showed in their review that most objects will be assumed to be smaller than they should be and distances seem shorter than they actually are. The precise reason for these phenomenon is not clear yet [15].

3 Related Work

This chapter will give an overview on some important work in the subjects medical simulation and Learning in VR. First background information on VR as a learning platform is given. Afterwards current works in medical simulation and its background will be given. Lastly a connection between these two topics will be made by introducing VR's benefits in medical education and stating some examples of VR simulators for medicine.

3.1 Teaching and Learning in VR

As technology evolves so does the usage of it and thus teaching and learning is bound to develop using VR as well. VR allows the user to experience new scenarios with relatively small effort. That is why it is predicted to give learners the possibility to simulate special situations that will help them comprehend the subjects of learning better. In this section some general information on the effects of VR learning will be explored.

> "If there are limits on the human ability to respond to learning environments, we are so far away from the limit as to make them presently inconsequential. Throughout human history to date, it has been the environments, not the human beings, that have run up against limitations." [16]

With this George B. Leonard described learning environments fifty years ago, way before VR was developed. So can VR bring us to those limits today? In the 90s many researchers started to see VR as the education tool of the future. Bricken et al. [17] wrote in 1990 that VR has special characteristics which align with those of good teaching: It is able to generate direct experience, display a personal view and gives an ability to naturally interact with the virtual environment. So basically every learning method used in classical teaching like words, pictures or field trips can be provided in VR too. Some things are even easier to grasp in VR, because there is no need for an explanation of the context, because oneself would be standing in the midst of the situation. In another paper Bricken et al. [18] stated that VR was developed to enable an easier understanding and interaction with information itself. So VR became not only another Human-Computer-Interface, but a fundamentally different way of communication between human and computers, which is able to reduce the cognitive load of the user for interaction and understanding [19]. Studies have shown that interaction is a crucial factor, which affects learning outcomes [2], and as such VR has been and has to be studied further for its effects on learning.

The presumed effectiveness of learning in VR is built on the learning theory of Constructivism: Learning by constructing knowledge from experience [1]. As aforementioned VR generates a direct experience, which makes it well suited for the Constructivist's learning strategies like situated learning, role-playing, cooperation, problem-based and creative learning [2]. In learning and teaching Schroeder et al. see the strength of VR especially as a tool which is able to simulate the impossible, difficult or dangerous without causing harm rather than reproducing typical real world experience [20]. As such there are different approaches on how to use VR in education, typically these are either as a game, a simulator or open virtual worlds. Merchant et al. have deemed all three learning environments as effective, with games showing the best learning outcomes but at the same time stating an antiproportional relationship between the learning outcome and the number of training sessions [21]. For virtual worlds the same antiproportional relationship was shown but it was less distinctive and in simulators the effects were even less pronounced.

Due to the multi-sensoric nature of VR it seems it is effective as a learning tool independent of learning styles as Lee et al. showed in their study [22]. Similarly Getso et al. stated that computers generally have the ability to be compatible with every type of learning, but this ability seems to be used very little apart from VR [23]. VR is also able to provide affective learning [18] probably due to its immersiveness. As such it was used to teach empathy with disabled peolple by Reese et al. [24] or as a means to educate psychiatrist and psychologists to better understand the mental illnesses of their patients by simulating them like Tichon et al. tried [25]. Another type of empathic learning was tested by Nojavanasghari et al. who taught social-skills to children with autism using a virtual teacher [26].

Next to the special way of interaction, immersion is another key feature of VR. Both, interactivity and immersion, have been shown to improve the long term memory [3], which is beneficial for learning. Dede et al. assume that immersion alone is able to enhance learning by allowing the user of the immersive technology to see different perspectives, simulate situated learning and making the transfer of information easier [27]. In 1995 Psotka et al. already described the feeling of immersion taking place even though the quality of the graphics of the HMDs was low, there was a lag between the movement of the head and the visualization of it and the maximum field of view was 90° [19]. A study by Buttussi et al. found out that the immersiveness of the display had no effect on the learning outcome, but on the motivation of the participants, where more immersive displays were perceived as more engaging and creating a higher feeling of presence [28].

It has been shown that motivation and engagement strongly impact the effect of learning [2, 29] and that a student needs to be sufficiently engaged for learning to occur [30]. Especially in topics, which have been proven to be difficult to teach using traditional methods, an enhancing and stimulating medium has been shown to be more suited for

[1] Wikipedia on Constructivism: https://en.wikipedia.org/wiki/Constructivism_(philosophy_of_education), Date: 20.06.2019

teaching [31]. As such VR can be used to increase the engagement in learning by its novelty, immersion, interactivity, imagination and ability for cooperation [2, 19]. Getso et al. discovered that the enjoyment of VR crossed gender and race boundaries for the most part [23] and Huang et al. state that it has been generally agreed on that VR would impact the motivation of students greatly [2].

Even though it is called *virtual* reality not everything in VR is virtual as there can be real people cooperating with one another. Research in collaborative learning has proved its educational value multiple times [32, 33]. Discussion and collaboration have been shown to not only increase the interests of learners but also promote critical thinking and the development of social skills [2]. As such VR might also provide the benefit of easy and locally independent collaboration.

All in all VR has shown great potential for learning as it has been proven to be easy to use and to reduce the cognitive load for understanding the information. At the same time its immersiveness and interactivity provide engagement, which will benefit the learning outcomes. Even emotional or affective learning can be done using VR which widens its usability to teach social skills too. As such there is much interest in the evolution of VR education applications.

3.1.1 Examples of Successful VR Education Applications

Especially in the early stages VR was tested a lot for military training. For example there was a spatial skill training held by Regian Jr. et al. in 1993, which had proven to help the soldiers navigate an object through a real room after training in virtual test rooms using a console [34]. Another example of early successful VR training would be the SIMNET tank simulator which was used for multi-user training of tank-team-members. Even though the HMDs used were cumbersome and the environment shown was unrealistic Psotka et al. described the training as providing a “sweaty believability”, since the team members were participating earnestly and the communication between the commander and members was realistic [19]. VR military training seems to be so successful, that the Norwegian army already uses it for training their soldiers [23].

Despite this there is still no universally agreed scale to value a VR learning application. Abadia et al. have made a meta-analysis on papers on VR learning applications and found that the criteria for measurement differed for most studies. They state that the most commonly used parameter to grade a VR learning application was presence, which is linked to other evaluation-factors (embodiment, empathy), and empathized the idea to always keep technical factors (usability, embodiment, immersion) and human-factors (presence, empathy, perception, elicit emotion, engagement) in mind when evaluating and designing VR applications as well as always evaluating some kind of measure for the learning-progress [30]. Lastly, it needs to be stressed that technology itself does not improve education by itself and a thoughtful integration of VR into curricula is needed to achieve a progress in education [18, 19].

3.2 Medical Learning

The medical knowledge was stated to double every 3.5 years in 2010 and it is assumed that it will keep growing exponentially [35]. This together with its essential role for the life of humans itself are factors, that lead to a dire need of good teaching and learning methods. Estai et al. state that system-based and multi-modal learning are more effective than the classical curricula used [36] so there should be an interest in upgrading the curricula to make use of multi-modal technologies. Thus this section will discuss the use of classical simulators and VR simulation for medical learning.

3.2.1 Medical Learning with Simulators

> "No industry in which human lives depend on the skilled performance of responsible operators has waited for the unequivocal proof of the benefit of simulation before embracing it." [37]

This is what Gaba et al. stated 1992 on the scepsis on whether simulation should be used in medical education or not [37]. Medical simulation has since then often been compared to flight simulation and became an important part in medical education especially in anesthesia. In some countries like the USA, Denmark and Israel simulations are mandatory for a resident to become a certified anesthetist [38]. Many state that simulators should be part of the curricula for medical students [6, 39, 40] due to their vast benefits:

- It has been shown that simulation does help with technical as well as non-technical skill acquisition alike and can be used for routine and emergency training [41].
- Many fundamental techniques of medicine are time-critical and need to be done quickly and correctly to not harm the patient, as such simulation with medical mannequin can help to train this before the student is to treat a real patient [42].
- Simulation has improved self-reported confidence and clinical performance, though no study was able to link simulations with better patient outcome yet [41].
- While simulators seem expensive at first sight, Al-Elq et al. claimed that they will be cost-effective, if they are used correctly, because the costs associated with medical errors will be reduced [39].
- CPR-skills have been shown to decline over time, if the physicians do not get a refreshment of knowledge or use it regularly [43]. Similar behavior can be assumed for

other scarcely used clinical skills and regular simulation-training could help against this skill-regression.

- Knowledge gained from simulations has been shown to last longer than knowledge gained from traditional teaching methods [41].

For the simulation to have a learning effect, a proper feedback or debriefing is needed [5,41]. As such the debriefing after a simulation should take a major role for educational simulations. Liaw et al. stated that simulation was more effective, if the debriefing was made personally [6]. Still a lot of simulators strive to have a built in feedback-system, which will evaluate the user's skills objectively. These built-in systems seem to coincide with the opinion of professionals for the most part [42] and as such should not be labeled as useless tools. However the evaluation of cognitive and behavioral skills is difficult to measure in any kind of simulation or debriefing [42].
Simulation is mostly used for training different clinical practical skills (technical skills, diagnose, monitoring, recognition, prioritization, decision making and planing), scarce events or crisis management as well as for training follow-up-treatment-talks and teamwork between the physicians [42]. Especially team-training simulation has been a hot topic: It has been known for over 30 years, that human factors have a big influence on patient safety [5]. At the same time studies have shown, that the usually used single-person-training seems to create an isolated way of thinking, which will make the trainees believe that every problem can be solved alone [5]. Thus it should not be surprising, that the World Health Organization (WHO), the Institute of Healthcare and the Helsinki Patient Safety Declaration all recommend for medical personnel to have team-training at least twice a year [5, 6], so obviously team-training should also become part of the medical personnel's curricula.
The current gold standard for communication- and team-training are high-fidelity mannequins [6]. These are medical mannequins which can produce an electrocardiogram (ECG) and other vital signs, different levels of lung-obstructions and even simulate a bodies reactions to medication, which is also why they are called "full scale simulations" [41] (see Figure 3.1). High-fidelity simulation has shown to be especially effective in improving patient safety, if used in-situ (in the real surroundings the simulation would take place) and if the skills needed are clearly defined [42]. While it has been shown, that high-fidelity simulators usually have a better learning outcome than ones with lower fidelity, high-fidelity simulators are not automatically better at teaching a certain topic than low-fidelity ones because this has been shown to be dependent on the aim of the learning [41]. A study from Chinnugounder et al. showed that in radiology training centers the most often mentioned reasons for not using high-fidelity simulators were in 41% of the cases bad availability and in 33% the high costs of the simulators [44]. These are usual problems of high-fidelity

simulators followed by other planning difficulties such as time-constraints of the physicians themselves [6].

Figure 3.1: A high fidelity mannequin by CAE Healthcare as it is used during a simulation session. One can see that different measurement devices (ECG's electrodes and blood pressure cuff) have been set up and the mannequin is getting cardiopulmonary resuscitation (CPR) as well as an artificial respiration. [2]

3.2.2 Medical Learning with Virtual Reality

The motivation for learning medicine in VR is the same as in other educational fields: VR has shown to raise the interest and motivation in medical trainees and to effectively support skill-transfer and skill acquisition by learning-by-doing [45]. Especially for spatially complex topics like anatomy VR was promised to have high-potential [46, 47], which has also been utilized in several anatomy-learning applications [3, 48–54]. The most commonly stated advantage of VR and simulation in comparison to the traditional learning is that it is risk-free learning [4, 46]. The residents can get clinical experience before treating a real patient. Aside from that VR provides many more advantages over the traditional learning, like lower costs (compared to real patients or dead bodies for dissection), being reusable and making adjustments to the learning environment relatively easy [43]. As aforementioned VR can also be used for simulation-based training and as such will be compared to high-fidelity simulators in the following part.

The effectiveness of VR simulation training has been shown to be directly influenced by the feeling of presence during the simulation [55]. Dong et al. studied the feeling of

[2] Picture Source: https://caehealthcare.com/patient-simulation/hps/, Date: 18.08.2019

presence during a high-fidelity simulation, a VR simulation and a first-person video of the simulation and found that high-fidelity simulators would generate the highest feeling of presence (followed by VR, then video) [56]. As such it is unsurprising, that high-fidelity simulators have shown to have a better learning outcome than their VR counterparts; but VR simulators still improved the learning outcome considerably, so that upon the choice a cost-benefit-ratio should be considered [41, 57]. Still Lok et al. found, that the students themselves did not care about the level of realism as long as the simulation was good enough to learn from [55]. It has been shown, that interval training is more effective than a short period of extensive training [57] and so VR, which is more easily available, has an advantage. A big contraindication for VR would be the lack of haptic feedback, as it is up to now difficult to provide it realistically and motoric skills can not be learned as good as on a mannequin [7].
Another big advantage of VR is its team-training ability: McGrath et al. stated that team-training in VR had the same learning efficiency as traditional simulations [7]. This in addition to its lower costs and higher availability make VR the superior choice for team-training. The ability of VR to connect people over the internet helps against other logistical problems, too, but will also cause new problems like bad connectivity or confusion of identities [6]. Mc Grath et al. and Krage et al. both see VR to be especially usefull for interprofessional team training and hope that VR will lead to a better understanding among the different medical specialists [5, 7].

actions and bio mechanics of the human body which would be difficult to show in reality and this way even broaden the possibilities of teaching [54]. In the University of Madrid the curriculum for “Higher Technician in Pathological Anatomy and Cytodiagnosis” was used to perform a comparative study of the learning effects of VR versus the traditional master course by Jiménez et al. They showed that there was a statistically significant difference in the pre- and post-tests that implies that the VR group’s learning was more effective. Using a survey they also demonstrated that the motivation of the students of the VR group could be raised [48]. In the Bond University in Australia the Anatomy and Biomedical Sciences Physiology curriculum already include VR as well as augmented reality (AR). Moro et al. write about the effectiveness of this new curriculum and already give best practices as to how to implement VR and AR into the curricula of other Universities, too [49].

3.2.3 Examples of Medical Virtual Reality Simulations

VR simulation is being used in different types surgeries, emergency training, training for psychologists/psychiatrists and also for virtual patients. The types of surgeries mostly consist of those, which can not be monitored directly, but only through a camera (like tele-surgery, robot-assisted-surgery, minimally invasive surgeries (MIS) like endoscopy and laparoscopy, catheter-, stent- or needle-guidance). In the following paragraph a few examples for VR simulations will be named.

As aforementioned there are many types of MIS-trainers (MIST). In 1999 Chaudhry et al. could already prove, that their MIST-VR could not only simulate a MIS, but also assess the errors of the participants automatically and as such be used as an objective assessment of the user's skills [58]. Grantcharov et al. presented in 2003 another MIST-VR which has proven to be more effective for learning than no training [59] and also showed, that the automated evaluation they created matched the skill-level of actual surgeons [60]. Another laparoscopic VR trainer implemented by Sherman et al. could also demonstrate its automated feedback to be legitimate and had a positive learning curve for all participants [61]. Similarly the Vascular Intervention System Trainer for stent placement by Patel et al. could prove their participants to improve their skills in the simulation [62].
Huber et al. describe a relatively new approach on highly immersive laparoscopy training by combining a 360° video with a LapSim simulator [63]. This highly immersive VR and an artificial operating theatre VR setup were both implemented and optimized with consecutive clinical feedback. Lastly, preliminary testing showed that the highly immersive VR setup resulted in the individuals experiencing "a high degree of exhilaration and presence" , while the technical performance in both setups remained similar, which provides a proof of concept for the technical feasibility of the highly immersive VR approach for surgical training.
Other recent simulators are for example the robot-assisted-surgery simulator by Christensen et al., which is a prototype for team-training of a robot-assisted-surgey-team, that includes the surgeons and nurses, and states to be a promising teaching tool if further developed (the virtual environment, which was used in the evaluation, is shown in Figure 3.2) [64]. Yet another type of surgery simulator would be the emergency endodontic surgery simulator prototype by Sararit et al., which allows a teacher to observe and review the simulation and also to induce emergency situations anytime during the surgery and is stated to be promising for educational use [65].
Semeraro et al. introduced a VR simulator which is coupled with a medical mannequin for haptic feedback: the VR-enhanced Mannequin for CPR training [66]. For this a Mannequin was embedded into a VR scenario which would lead to the need for a CPR (the virtual environment and real mannequin are shown in Figure 3.3). Both instructors and testers (voluntary medical personnel) liked the simulator and would use it for education. But the feedback is only on the Kirkpatrick level 1 and needs further evaluation.

Figure 3.2: Pictures of the virtual operation room showing the positioning of the surgical robot and patient as it was displayed during the evaluation of the simulator [64].

Figure 3.3: Pictures of the real mannequin and the virtual patient, which is overlain, during the evaluation of the VR-enhanced mannequin [66].

4 Concept

The concept will firstly state the objective of the Thesis and afterwards discuss the requirements and draw a conclusion on the prioritization of those. The following sections will elaborate on the important aspects of these requirements and different ways to implement these. The requirements are grouped by topics: the background of the complication scenarios, the monitoring of the vital signs and the needed anesthesia medication.

4.1 Objective

The objective of this thesis is to implement a prototype of a VR simulator for a laparoscopic interprofessional team training. The team should consist of two surgeons who are needed for the laparoscopy (one controls the instruments for cutting and grabbing, another one operates the laparoscopic camera) and an anesthetist, who will observe the patient's vital signs and provide medication. The proposed simulator is named "Laparoscopic Anesthesia Virtual Reality Simulator" (LAVRS) The surgeons' tasks are implemented by another party expanding on the work of Heinrich et al. [1], which simulates a laparoscopic liver resection. Because of that this Thesis only concentrates on the tasks of the anesthetist during a laparoscopic surgery.
The Thesis should also include the usage of a medical mannequin, which should be synchronizable with the VR scenarios for future development of the simulator. For this purpose the software of the mannequin must be connected to the VR simulator.
Like in most team training applications one of the main reasons for the training is to provide an environment to train communication or non-technical skills. As such the VR simulator should include situations in which interprofessional team work and communication is needed and can be taught.

4.2 Requirement Analysis

The requirement analysis for this Thesis consists of the search for requirements and afterwards the prioritization of these. To find the requirements an interview with physicians from university hospital in Mainz (part of the Johannes Gutenberg-University Mainz) was held and evaluated, which will be described in the first Section. The following Sections will discuss important aspects of the found requirements and how important their role is for the LAVRS. Lastly a conclusion is made which will state the final prioritization and divide the requirements in nice-to-haves and must-haves.

4.2.1 Interviews

For the search of requirements an interview with two laparoscopic surgeons and an anesthetist from the university hospital in Mainz was held. The interview was only roughly structured with many open questions to gain an broad overview on the topic and let the physicians state, what they think is most important and not prejudice them in their standing. With the objective (see Section 4.1) given the main questions were either related to the special situations, which are used to encourage communication in the interprofessional team, the tasks of the anesthetist during laparoscopy or the medical mannequin, which is to be used for the simulator.

Communication

During the interview the importance of communication for this training has been stressed multiple times. As such one of the most important tasks is to create situations in which the anesthetist and surgeons need to talk. But usually a laparoscopy, in which no problems arise, does not necessarily need communication. As such it was stated, that there should be complications during the laparoscopy to spark a typical medical problem-based conversation.
Two scenarios were mentioned, which were deemed suitable for the task by the physicians, because they are easy to identify and create a situation where one party finds the problem and the other must fix it: first the scenario of an undetected bleeding and second the scenario of the patient starting to "press" due to low narcosis medication (both will be explained in more detail in the Section 4.3).

Role of the Anesthetist

It was agreed on by the interviewees, that the tasks of the anesthetist should for now only include actions during the surgery and not e.g. analyzing the patient history and deciding the medication based on this, though this could be added as a functionality in a later stage. The tasks during the surgery would mainly consist of refreshing the medication of the patient and monitoring their vital signs. For the vital signs during narcosis it was stated that especially the respiratory vital signs like respiration-frequency, -pressure and oxygen-concentration (O_2) are of great importance to evaluate the state of general narcosis. Out of the respirator settings the most significant ones were said to be the carbon dioxide (CO_2), O_2 and narcosis gas in-/exhalation curves with CO_2 having the highest priority for the anesthetist. Generally the changes in vital signs should have enough realism for the students to learn typical ranges and evaluate them correctly.

The Medical Mannequin

The learning hospital in Mainz uses the high-fidelity mannequin “Laerdal SimMan 3G” for teaching. A picture of the mannequin can be seen in Figure 4.1. Laerdal’s mannequins all run using the “Laerdal Learning Application” software (LLEAP) to simulate a living patient. Since the prototype is made in cooperation with the hospital in Mainz, the VR simulator should be compatible with this software as to be able to manipulate the mannequin. While during a laparoscopy there is usually no need for neither the surgeons nor the anesthetist to directly touch and interact with the patient, making haptic feedback for VR unnecessary, the mannequin’s software is also able to simulate the vital signs in typical ranges and provides a monitoring screen with typical vital sign curves. As such it was requested to use LLEAP to simulate the change in vital signs during the different complication scenarios and narcosis in the VR simulator and also to use that monitoring screen for the VR monitoring. Details on the software’s features and capabilities will be elaborated on later (Section 4.4.1).

Figure 4.1: The “Laerdal SimMan 3G” as presented on the official Laerdal Website. [1]

[1]Picture Source: https://www.laerdal.com/de/products/simulation-training/emergency-care-trauma/simman-3g/, Date: 18.08.2019

4.2.2 Usability of Virtual Reality for Anesthesia Simulation

The objective states that a VR simulator should be built, but is VR suitable for the wanted anesthesia simulation? As the anesthesia simulation is aimed at residents before their first real operation, it is mostly to be used for learning purposes. As already stated in Section 3.2.2 VR is well suited to be used for medical learning in general and has proven its efficiency as well as a rise in the motivation of the trainees [45]. One objective of the simulation for the anesthesia residents is to learn the change in vital signs during different circumstances, which can be simulated in VR easily (change of vital signs on a monitor). This enables the students to benefit from experiencing the changes in a simulation instead of only reading about them, which has been proven to benefit the long term memory [41]. VR is also said to have its greatest benefit in its team training capacities [5, 7], which is why it is especially suitable for the communication training. A VR simulation of the surgery - like other methods of simulation too - will enable the students to get a feeling of how a typical surgery proceeds, before they are standing in a real one. This might help them grasp the typical work flow in a risk-free environment beforehand as well as make them feel more secure and prepared in their first surgery.
When compared to the possibility of simulating using a high-fidelity mannequin, a striking argument is, that the costs for a VR trainer are significantly lower. VR looks like the superior choice especially because the simulation is to be held as a team training, where VR has been shown to be as effective as training with a high-fidelity mannequin [7] and that VR can reduce logistical problems because it has a better availability [6]. The set up of the simulation in a high-fidelity mannequin would probably not be easier either, since it would need to include a laparoscopy trainer inside the mannequin, with both parts influencing the other. So building a VR simulator is a better choice than using a high-fidelity mannequin.
One might also want to compare the VR simulator to a serious game run on a regular 2D computer monitor. Conventional computers with displays are available everywhere and also easy to connect with one another and as such would make team training very easily accessible. The limiting factors for VR's accessibility are the availability of a computer with a suitable hardware for VR as well as the HMD and controllers, which are more expensive, though the connection of the VR set ups is similarly easy. The time and effort to making serious game for conventional computers or a simulation for VR can be regarded as similar, as both can be programmed on the same game engines (e.g. Unity 3D) only using different toolkits for interactions, so there should be no big difference between them. But since Lok et al. stated that the effectiveness of a simulation is directly related to the feeling of presence during the simulation [55], VR will probably be a more effective learning tool as it is more immersive than a 2D display. A study by Christensen et al. showed that, comparing the same multiuser game in VR and on a conventional display,

the VR game was rated as more enjoyable [67]. Because engagement does also have a positive effect on learning, VR seems like the superior choice in comparison to a serious game on a conventional display too.
Even though VR seems to be quite suitable for an anesthesia simulation, according to the research done for this Thesis it has been scarcely used in anesthesia single user training. VR simulators for medicine mostly consist of camera-based surgeries, which are usually set up as a single-user training for the surgeons. In anesthesia training mannequins play a bigger role for simulations because they are used to learn e.g. how to measure vital signs (where to attach the electrodes for an ECG), where and how to puncture the skin with an injection needle for medication or learning how to intubate a patient for full-scale narcosis. These tasks all require a haptic feedback (either for feeling where medical landmarks are or for learning a technical skill correctly) and as such are still difficult to simulate in VR, making a mannequin better suited for this training. But our specific anesthesia training is not in the need of teaching technical skills, because the medication is given via a catheter, which was placed beforehand, or the respirator. So haptic feedback is not of importance in the required setting.
In team training scenarios VR has already been used, but these simulations are usually emergency trainings. Emergencies are very popular in training simulations, because it is especially important that every move is fast and correct. As mentioned in Section 3.2.1 the training for these emergencies is also recommended by multiple health organizations [5, 6] and as such has received a lot of attention. Since the simulator, which is striven to be implemented in this Thesis, does not handle big emergencies but small and common complications in a normal laparoscopy, it is an uncommon set up, which is not that pronounced in the eye of the public yet. Nonetheless it will hopefully be a useful tool to prepare future residents better for their first surgery.
Concluding one can say that the VR team-training simulation of a laparoscopy with surgeons and anesthetists is a rather novel approach and as such there has not been much research in this area, making it an interesting topic to study. The usability of VR for this task can be assumed to be good, as no haptic feedback is required and VR is very suitable for team-training applications. Using VR is also expected to be more effective in teaching than a serious game on a 2D display due to its realism and engagement. So VR seems to be a good choice for setting up this simulation.

4.2.3 Fidelity of a Simulator: What is important?

The fidelity of a simulation describes how close it is to reality. It has been shown that the effectiveness of a simulation training is dependent on its fidelity with a higher fidelity being associated with better learning outcomes [41, 57]. Yet it has also been shown that a higher fidelity is not always better than a lower fidelity simulation, but instead this has been found to be dependent on the aim of learning [41]. Because it is unknown, whether

the wanted simulation-tasks could also be accurately taught in a lower fidelity simulation, there is a need to discuss how high the fidelity should be for this Thesis.
One way of handling this problem would be to aim as high as possible in every detail of the simulation. Unfortunately this is not possible due to time constraints. A better way might be to prioritize, which parts are important and need to be as accurate as possible. So the next question is: What are the crucial parts of the simulation? Lok et al. found, that students did not care about the realism in the simulation as long as the simulation was good enough to learn from [55]. So the most necessary parts of the simulation should be those directly linked to the learning objectives.
The main learning objective is inter professional communication, as it has been stressed by the interviewees multiple times. So the scenarios, which will stir up a problem-based conversation, should be considered as the most crucial parts of the simulation. To make the scenarios work, they need to be well identifiable, meaning the parts of the simulation showing the typical symptoms of the complications need to be accurate. This would be the change of vital signs for the undetected bleeding scenario and the "pressing" of the patient for the insufficient muscle relaxant medication scenario. Another important part of the scenarios is their treatment: the clipping of blood vessels (by surgeons) for the undetected bleeding scenario and the muscle relaxant medication (given by the anesthetist) for the other scenario should actualize the real tasks. Lastly, the undetected bleeding scenario also needs a reasonable distraction for the surgeons, because otherwise they would detect the bleeding themselves.
Other less crucial points for the simulation could be the change of vital signs, which are not critical for the two complication scenarios the simulation should still picture a patient's typical vital signs during general narcosis. The anesthetist in the interview stated that the patient's respiration is an important factor and usually used to evaluate the state of narcosis of the patient. So this together with the settings of the respirator (inhalation anesthetic medication) could be handled with a second rate priority.

4.2.4 Team Training Simulation

Theoretically, a single user anesthesia simulation would also be a valid option for a training. But because the main objective of this simulator is to learn interprofessional communication, it is necessary to have some kind of human-like counterpart for the conversation. This counterpart could be a virtual character (non-player character, NPC) too, but this would limit the interaction options to certain presets and thus reduce the realism of the simulation. The simulator is also not supposed to only train the anesthetist but also the surgeons in communication and as such making it a single user simulation would require two simulations depending on the role the trainee should take. Additionally it had already been explained in the Section 3.2.1, that interprofessional team training

with a real team is recommended by multiple health organizations, because human factors have a positive effect on patient safety [5,6]. The typical single user training is also known for creating an isolated way of thinking [5], which hinders team work. As such it seems especially important to already hold team training in the students curricula, before their first surgery. So team training seems to be the most suitable way to achieve a good interprofessional team work and also prepare students for their work as physicians.
Even though real team training is only achievable by letting multiple users work together, the requested simulation will need the functionalities of the complication scenarios before it is able to engage team work. So the implementation of the functionality of the scenarios will take a higher priority than the connection of multiple players. It would also be good to evaluate, whether the functionalities are correct and appropriate, before the networking takes place. As such the ability to evaluate the simulator's functionalities with only a single user should be the main focus for now.

4.2.5 Resulting Priority Ranking

After having discussed the different aspects of the simulator, it is important to rank them according to their priority, as to have a clear outline of what needs to be done urgently. Concluding from 4.2.2 the simulator should definitely be made using a VR setup. The insight in the fidelity of the simulator in Section 4.2.3 empathized, that learning would be most effective, when the complication scenarios are implemented as realistic as possible. Section 4.2.4 explained, that the main goal of communication training could best be achieved in team training, but to lead the students to have problem-based conversations the complication scenarios are required, so that the implementation of those takes higher priority than a running multi user environment. The resulting prioritization is shown in Table 4.1.

Priority	**Task**
Prerequisites	• Using VR (HMD + Controllers) as Hardware • Realistic vital sign changes of those, which are important for the complication scenarios • Identifiable symptoms for the complication scenarios • Realistic treatment for the complication scenarios • Distraction for the undetected bleeding scenario
Necessities	• Connecting multiple users with specific roles (anesthetist/surgeon) • Realistic changes of vital signs, which are not directly linked to the complication scenarios • Realistic anesthesia medications for narcosis, which are not directly linked to the complication scenarios

Table 4.1: Required tasks for the implementation of the simulator ranked by their priority in "Prerequisites" for tasks that are critical for the simulator and "Necessities" for tasks that are optional for now.

4.3 Scenarios

This Section will elaborate the different scenarios, which will be implemented for the simulator. In fact these are not only complication scenarios but the basis of the simulation should be a “normal” scenario, depicting a regular laparoscopy in which no complications arise. For the two complication scenarios the following factors are of importance: They need to induce communication between the interprofessional parties e.g. by having one party detect the problem, while the other party is in charge of treating it. Ideally these roles change (in one scenario the surgeons detect the symptoms and the anesthetist must act and vice versa in the other). The symptoms for the complication should also be easily identifiable and displayable in VR, so ideally be diagnosed visually or auditory. As such the scenarios were chosen to be “A: Undetected Bleeding” and “B: Insufficient Muscle Relaxant Medication”. Finally the Table 4.2 sums up the most relevant parts of the scenarios, which are to be implemented in the LAVRS.

4.3.1 A Regular Laparoscopy

Figure 4.2: The picture shows two surgeons during a laparoscopy; the surgeon further back holds the laparoscopic camera with both hands while the other operated the two instruments. The inflation of the belly can also be seen. [2]

A laparoscopy is a MIS used for either diagnose or treatment of diseases in the abdomen. The operation is viewed through a special camera, the laparoscope, which will be inserted into the abdominal or pelvic cavities through a small incision in the skin. The Figure 4.2 shows surgeons during a laparoscopy. Usually the patients abdominal cavity will be filled with CO_2 gas to widen the cavity and give the surgeons a better view and more space to operate. In case of using a laparoscopy for treatment more incision might be made to enable better access to the pathological areas with the laparoscopic instruments. In general two surgeons are needed for a laparoscopic treatment: one, that will steer the camera, and another one, who will operate the instruments (graspers, scissors and clip

[2]Picture Source: http://www.kenleong.com.au/images/LaparoscopicSurgery.png, Date: 11.08.2019

appliers) and as such interact with the patient's tissue. [3]
To prepare patients for a laparoscopy, they are always put under general anesthesia. After the anesthesia medication has been given, the patients need to be intubated to connect them to the respirator and then the first incision for filling the belly with gas will need to be made. Because of these preparation steps there are around 35-45 minutes between the start of the narcosis and the point that the patient's treatment or diagnosis will really start [10]. The LAVRS right now does not include this beginning or preparation for the operation, but will start after everything has already been primed. So for the anesthesia medication and vital signs it should be kept in mind, that the patient is already in narcosis and that the timer as to when the medication needs to be refreshed is at around 30 minutes already from the beginning of the simulation. According to the Massachusetts General Hospital, a laparoscopic liver resection can take between one and seven hours depending on the position of the tumor(s)[4]. So even if there are no complications during the surgery, the anesthetist would need to inject new opioids and muscle relaxants just to keep the patient narcotized until the end of the surgery, because both medications will only be effective enough for the surgery for a time span of around 30 minutes [8].

4.3.2 Scenario A: Undetected Bleeding

The scenario "undetected bleeding" aims to let the surgeons miss a bleeding, because they are distracted, and let the anesthetist identify the bleeding by a change in the vital signs. The anesthetist is then supposed to inform the surgeons so that they can stop the bleeding. This scenario is based on the clips for blood vessels, which are used to prevent a bleeding, coming loose.
During a liver resection usually some blood vessels need to be cut to eliminate the tumor. B the liver is well supplied with blood, this could lead to huge blood loss and would also hinder the surgeons field of view, because the blood can not leave the patient's body easily during an MIS. As such blood vessels will be clipped by the surgeons before they are cut (Figure 4.3 shows a blood vessel which was clipped during an MIS).
Sometimes such clips will loosen themselves and fall off, so that a bleeding will still occur. Normally this will lead to blood filling the cavity and obscuring the surgeons view so they will easily detect the bleeding. But in this complication scenario the surgeons are not to detect the bleeding themselves. To achieve this the surgeons will need to be distracted. The only person, who is able to detect the bleeding, is now the anesthetist. During a bleeding the arterial blood pressure will drop and the pulse will rise as shown in 2.1. So by monitoring these values the anesthetist will be able to identify a bleeding and notify

[3] Wikipedia on Laparoscopy: https://en.wikipedia.org/wiki/Laparoscopy, Date: 22.07.2019
[4] Massachusetts General Hospital on duration of a laparoscopic liver resection: https://www.massgeneral.org/digestive/services/procedure.aspx?id=2316, Date: 22.07.2019

Figure 4.3: Picture showing a clipped blood vessel and the instrument for placing clips in action during a laparoscopic cholecystectomy. [5]

the surgeons to act accordingly.
For the distraction the interviewees suggested to either use a laparoscopic camera failure or a phone call. But they also stated that for the vital signs to change significantly some time will be needed. During a laparoscopic surgery a substitute camera is usually prepared so the change to a new camera after the first one failed would be rather fast. A phone call on the contrary could easily stretch over a few minutes. As such it was decided that a phone call is better suited as a distraction for the surgeons. To make sure the surgeons will really listen to the phone call and not ignore it, the phone call should be of relevance to them. This might be achieved by testing the surgeons on the contents of the phone call after the simulation. To keep the phone call realistic, the users of the simulator should not be required to answer questions or respond otherwise to the call, but instead it should be one-sided and informative. The interviewed surgeons said a typical call like this would be for a patient transfer and agreed to provide a phone call audio track, that would meet these requirements.
Lastly the timing of the clip coming loose is important: both surgeons need to be distracted already, when the clip comes off. So the clip can only come off, after the phone call was started and the surgeons reacted to it. As such it was decided to trigger the clip falling off together with the surgeons answering the phone call.

4.3.3 Scenario B: Insufficient Muscle Relaxant Medication

The scenario “insufficient muscle relaxant concentration” aims to let the surgeons detect that the patient’s muscle relaxation is too low and make them inform the anesthetist, to refresh the medication. This scenario evolves around the patient starting to “press” as their muscles regain their ability to contract.

[5] Picture Source: https://img.medscapestatic.com/pi/meds/ckb/78/25678tn.jpg, Date 11.08.2019

As aforementioned patients are under full narcosis during the laparoscopy. As such their muscles will be hindered from contracting by the muscle relaxant, making them unable to breathe alone. For this reason the patients will get artificially respirated during the surgery. The artificial respiration is provided by the respirator. To connect a patient to the respirator a tube from the machine into the patient's trachea needs to be placed (the process is called endotracheal intubation). After some time the muscle relaxant will wear off, if no refreshment of the medication is given. When the muscle relaxant medication becomes too shallow the patient's muscles can move and spontaneous breathing will start again. Because the tube for the artificial respiration is in the way, the patient will reflexively try to cough it out. When coughing the muscles of the abdomen will contract too, resulting in the patient "pressing ": the inflated belly will lower and then rise again according to the coughs and the inner organs will also move slightly due to the pressure.

Figure 4.4: Correct placement of the electrodes for the measurement of the Train of Four. Additionally to the electromyogram an accelerometer has been placed on the thumb to evaluate the effective contraction as well. [6]

If a patient starts pressing, operating gets more difficult for the surgeons, because they are more likely to harm the patient unintentionally. They will notice the pressing and tell the anesthetist about it, so that the anesthetist can give a refreshment dose of the muscle relaxant medication. As mentioned in 2.1.2 the muscle relaxant medication has a time till effect, so the pressing will not stop immediately after giving the medication but a few minutes later.

[6] Picture Source: https://en.wikipedia.org/wiki/Neuromuscular_monitoring#/media/File:NMT_monitor_for_measuring_neuromuscular_blockade.jpg, Date 11.08.2019

Usually the anesthetist monitors the muscle relaxation by evaluating the Train of Four. This value indicates how well electric signals can still be transferred between a proximal and more distal nerve. For the measurement electrodes need to be placed along a peripheral nerve of the patient e.g. the nervus ulnaris as shown in Figure 4.4. As the measurement is dependent on how well the electrodes are positioned, the Train of Four is a soft value, which can vary greatly. As such it is theoretically possible, that the anesthetists will not realize the low medication themselves, because the electrodes were placed badly. Nonetheless the value could be changed at the start of the scenario, so the surgeons will still realize the changes first and tell the anesthetist about it.

Regular Laparoscopy	
Vital Signs	• start in narcosis • react to medication wearing off and refreshments
Anesthetist	• ability to refresh the medications • ability to monitor the vital signs
Surgeons	• ability to operate typical laparoscopy instruments
A: Undetected Bleeding	
Scenario Extras	• trigger to start the scenario • telephone, which plays different audios (ringing, phone call) • loosening a clip from a blood vessel when phone is answered
Vital Signs	• indicate bleeding upon the clip loosening (ABP falls, pulse rises)
Anesthetist	• ability to speak with surgeons
Surgeons	• ability to clip blood vessels • ability to answer a phone call
B: Insufficient Muscle Relaxant Medication	
Scenario Extras	• trigger to start the scenario • animation of the patient's pressing
Vital Signs	• Train of Four rising when muscle relaxant wears off
Surgeons	• ability to speak to the anesthetist

Table 4.2: Required features for the LAVRS grouped by scenario. All features for the complication scenarios A and B are to be understood as additional to the Regular Laparoscopy scenario.

4.4 The Monitoring of Vital Signs

The monitoring of vital signs is a major part of the anesthetists' duties during the surgery. For the anesthetist to be able to monitor the vital signs, they will need a monitor which shows them the relevant curves and values. These values should be realistic enough for the anesthetist to recognize the symptomatic vital signs for the two scenarios. They also should be shown at a typical position in the operating theatre. This section will discuss how this can be achieved in VR using an anesthesia simulation software and in which ways this could be implemented.

4.4.1 The Anesthesia Simulation Software

As mentioned before the interviewees asked to use a specific software called LLEAP [7] to implement the monitoring of the vital signs. This software is compatible with all of Laerdal's medical mannequins and is primarily used to steer their symptoms from simulating measurable vital signs to producing sweat and typical sounds. For this Thesis however these functions of the mannequin are not of importance, but instead the software itself is. LLEAP provides typical curves and values for the vital signs, which can be altered, and should be used to provide the monitoring screen in VR. This Section will elaborate the functionalities and the possible ways to use them in the LAVRS.

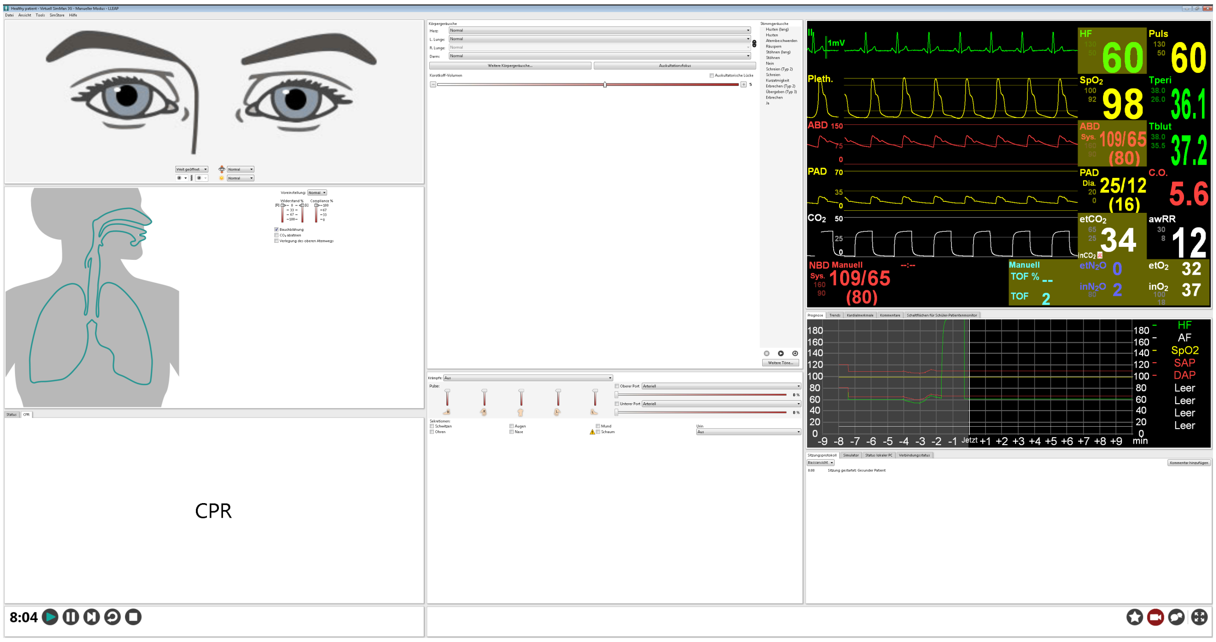
Provided Functionalities

The functionalities of LLEAP are vast, so only the steering of vital signs will be covered here. LLEAP can produce legit and measurable vital signs for ECG, pulse, blood pressure, peripheral oxygen saturation, body temperature, diverse respiration parameters, Train of Four and more. LLEAP is capable of controlling all of Laerdal's medical mannequins, but only the controls for the "SimMan 3G" were used because this is the mannequin, which is present in the university hospital of Mainz. LLEAP also provides special scenarios for the mannequins in which the vital signs would change automatically, but considering that LLEAP should be steered by the LAVRS the manual mode was chosen instead. To adjust the settings for the vital signs in the manual mode, the vital sign is selected with the mouse on the displayed monitoring screen (see Figure 4.5a showing the LLEAP main screen). Another window as shown in Figure 4.5b will pop up and enable different sliders and/or text fields, check-boxes and multiple-choice-boxes to adjust the parameters within a given scale. Within these options not only the absolute change of the vital signs but also the transition to the new state can be controlled by changing the transition time or function. All these changes need a mouse or keyboard input. The Table 4.3 shows the ranges and ways to change the settings of the vital signs, that will be adjusted in the LAVRS.

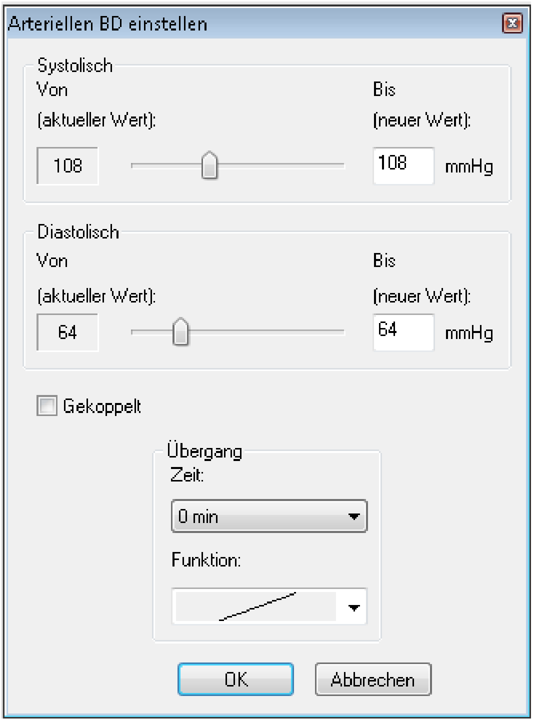
Ways to Export these Functionalities

For the monitoring in VR the anesthetist will need a virtual screen which displays the vital signs' curves and values in a typical setup. The interviewees wanted this screen to be based on the parameters, which the LLEAP software produces, so that the vital signs are realistic. Usually using LLEAP's application programming interface (API) would be the orderly way to connect the LAVRS to LLEAP. To gain access to the API a research proposal was sent to Laerdal requesting exactly that. But since the access to the API might

[7] Laerdal official website to LLEAP: https://www.laerdal.com/de/products/simulation-training/manage-assess-debrief/lleap-laerdal-learning-application/lleap/, Date: 30.04.2019



(a) The complete LLEAP screen in its standard manual control set up. The left side allows manipulation of the eyes of the medical mannequin and simulation of lung obstructions in different areas. The options in the middle can be used to steer different sound and secretions of the mannequin, as well as simulating paroxysms and a pulse in different extremities. The right side shows the vital signs monitor and trends, which were used for the LAVRS. Below these there is another window showing a protocol of the current simulation. At the very bottom there are different options for starting, stopping, fast-forward and repeating the current simulation.



(b) Pop-up window for adjusting the ABP values showing the sliders to adjust the value, a check box on whether to change them ion dependence of one another and the transitional option multiple-choice-boxes.

Figure 4.5: LLEAP's main menu (a) and an exemplary pop-up window (b).

Vital Sign Modification	**Options**	**Way to Change**
Transitional Options		
Transitional Time	0s, 20s, 40s, 1min, 2min, 3min, 4min, 5min, 6min, 8min, 10min	multiple choice box
Transitional Function	Linear, Cosine-shaped (0 to 180°), Exponential, negative Exponential	multiple choice box
Pulse		
Absolute Value	20 - 200 bpm	keyboard input or slider
Transitional Options are available.		
Arterial Blood Pressure		
Systolic Absolute Value	40 - 300 mmHg	keyboard input or slider
Diastolic Absolute Value	2 - 290 mmHg	keyboard input or slider
Coupled Value Change	yes or no	check box
Transitional Options are available.		
Train of Four		
Relative Value	0 - 100%	keyboard input or slider
Number of Impulses	0 - 4	keyboard input or slider
Transitional Options are not available.		
Gas In- and Exhalation		
O_2 Inhalation Percentage	0 - 100 %	keyboard input or slider
O_2 Exhalation Percentage	0 - 94.3 %	keyboard input or slider
Coupled O_2 Value Change	yes or no	check box
N_2O Inhalation Percentage	0 - 100 %	keyboard input or slider
N_2O Exhalation Percentage	0 - 95.1 %	keyboard input or slider
Coupled N_2O Value Change	yes or no	check box
Transitional Options are not available.		

Table 4.3: Available options and ways to adjust the settings of the vital signs, which will be relevant for the LAVRS. Because the transitional options are always the same the table will only state them once and whether they are available for the wanted vital sign.

be granted too late or not at all, the first prototype will need a different way to connect the LLEAP software to the LAVRS. As there has been a lack of clarity concerning the licensing of the software, only one laptop equipped with LLEAP is usable for this Thesis. But this laptop's hardware is not strong enough for VR applications. So additionally to exporting the functionalities from one software to another this would also need to happen from one computer to another.
To decide on the type of networking to use, the exact information, which will be extracted from LLEAP, should be known. So one possible start to look at this would be the required VR monitoring screen. There are multiple ways to produce such a virtual screen. Firstly, one could try to capture the monitoring screen, which LLEAP provides, and use this as the texture of a screen in the LAVRS. The other possibility would be to produce a new monitoring screen as a virtual object in the LAVRS. This screen would plot the curves and parameters for the vital signs completely new only based on parameters gained from the LLEAP software. This however would prove unnecessarily difficult for multiple reasons: The characteristic curvature of the vital sign graphs is not trivial to replicate realistically and the parameters from the LLEAP software to know e.g. the frequency of the curve would still require some kind of screen capturing and automated evaluation of the captured screen. If a screen capture is needed either way, it is easier to just directly capture the screen and use it in the LAVRS.
So to transfer the screen of LLEAP on another computer either a frame grabber/video camera or a screen-sharing-tool could be used. While a frame grabber's setup might be easier, in regards to the next steps it would produce unneeded work once again: the LLEAP software interface will also need to be operated on by the LAVRS using mouse- and keyboard-input. As such it would be useful to directly share the screen as a usable one, so that these operations would only need to be simulated on one computer and not first transferred to another. This makes the screen-sharing-tool the better choice for the transfer.
Lastly, the now shared LLEAP screen would need to be captured and transferred to the LAVRS within one computer and automated mouse and keyboard inputs would need to be simulated. These tasks will be described in detail in the implementation in Section 5.3.

4.4.2 The Change of Vital Signs

As shown in Table 4.3 the anesthesia simulation software used will need an input, on how much to change the different vital signs, and it must also be coordinated, on which occasions to do so. To rebuild the way vital signs change in reality, but still keep the work within a reasonable limit, three different ways to affect the vital signs will be chosen and the choice explained. Finally the change of vital signs during these three events will be explained.

The Choice of Vital Signs and Change Occasions

To select only the most important vital signs as defined in Table 4.1, at first only vital signs with a connection to the scenarios should be regarded. This would include the pulse and ABP for Scenario A as well as the Train of Four for the Scenario B. Of course the occasions on which these change should also be included in the LAVRS, so the change of these vital signs during a bleeding and during shallow muscle relaxant medication needs to be implemented and as such will be illuminated here.
The choice gets more difficult, when more occasions for change are to be included. As the LAVRS does start with the patient in narcosis, the vital signs should also start in typical ranges for narcosis. So another parameter, which has an effect on the depth of narcosis might make a good candidate. While all three medications work together for a general narcosis to take place, in our scenario only one is given continuously: the inhalation anesthetic. Because the interviewees also stressed, that respiration in general was an important sign for the anesthetist to monitor the state of narcosis, it was decided, that the very basic respirator settings should be included in the LAVRS. These would include the choice of inhalation anesthetic medication as well as the carrier gas (air or N_2O) and also the percentages of those and O_2 in the whole gas flow. Because these settings are directly linked with the O_2 and N_2O in- and exhalation, these vital signs are to be changed analogously to the respirator settings.
Finally, three different ways to effect the vital signs were chosen: the change of vital signs during the narcosis in general inflicted by the inhalation anesthetic, the change which occurs during a bleeding and the change in vital signs, which develops due to insufficient muscle relaxant medication.

During Narcosis due to Inhalation Anesthetics

In dependence of the current MAC being reached with the inhalation anesthetic dosage or not one would expect the vital signs to change: When the narcosis is too shallow (current inhalationanesthetic level < MAC) the narcosis should weaken and the pulse and ABP rise and when the narcosis is too deep (current inhalation anesthetic level > MAC) the values for pulse and ABP will lower. While this seems logical at first glance, the human body is very complex and there is no way of telling precisely how a single individual would react to a certain amount of inhalation anesthetic. Anesthetist will usually rely on their experience in combination with the MAC to judge whether the level of inhalation anestetic given is sufficient. This is also the reason why there is no mathematical equation to define the vital signs in dependence of the inhalation anesthetic level. Nonetheless there is a need for the simulator to calculate a specific value for the pulse and ABP to reach in dependence of the current inhalation anesthetic level. Since the simulator is also just "one case" of a specific patient a simple model was formed by making the following assumptions :

Each variation of the current inhalation anesthetic concentration c_{IA} can be assigned to a certain value of pulse p', systolic a'_{sys} and diastolic ABP a'_{dia}.

$$\begin{aligned} c_{IA} &\Longrightarrow p' \\ c_{IA} &\Longrightarrow a'_{sys} \\ c_{IA} &\Longrightarrow a'_{dia} \end{aligned}$$

These will be called the target-pulse/blood pressure x'. They are defined by a linear interpolation between the value for the regular healthy pulse/blood pressure x_{norm} and pulse/blood pressure during narcosis x_{narc} as found in Table 2.1.

$$x' = x_{norm} + \frac{c_{IA}}{MAC_{IA}} \cdot (x_{narc} - x_{norm}) \tag{4.1}$$

The change of the vital signs will not take place instantly but over time. As such it is not realistic to let the vitals signs change directly. Instead by comparing the current pulse p and ABP a_{sys} & a_{dia} with the target pulse p' and ABP a'_{sys} & a'_{dia} that should be reached after some time the absolute change can be calculated. To adjust the realism of not being reached directly a multiplicator $0 < m < 1$ can be chosen to calculate the absolute change Δx:

$$\Delta x = (x' - x) \cdot m \tag{4.2}$$

In the case of this calculation m was set to be $\frac{1}{2}$. Finally the next value of the vital sign x_{next} will be calculated by adding the change Δx to the current value of the vital sign x:

$$x_{next} = x + \Delta x \tag{4.3}$$

During a Bleeding

As already mentioned in section 2.1.2 the change of the pulse and arterial blood pressure have been found as a rather reliable symptom to diagnose a bleeding by the review of Pacagnella et al. in 2013 [9]. Though it must be stressed that the parameters on their own are not entirely reliable enough as the pulse was found as a significant value in only 22 of 24 studies and the arterial systolic blood pressure in 17 of 23 studies. Only the so called “Shock-Index” was found to be significant in ten of ten studies. The Shock Factor is a combined interpretation of the pulse and blood pressure:

$$Shock\ Index = \frac{pulse}{sys.\ blood\ pressure}$$

If the shock index is exactly one it is assumed that a shock is looming a value greater than one would imply a manifested shock and a value smaller than one is the physiologically normal state. So if the pulse is higher than the arterial blood pressure this would count as a safe sign for significant blood loss.
With this information it is clear that the simulator should decrease the blood pressure and increase the pulse when a bleeding takes place. But the amount of change Δx is still unknown. As it would seem to depend on the size of the vessel cut, the duration of the bleeding and the blood's speed it should be parameterizable in three ways: First depending on the diameter of the blood vessel which was cut d_b second the duration of bleeding and third there should be a factor which determines the change of the vital signs in dependence of the blood's speed v_b. The new value x_{next} after a certain duration of bleeding would then be calculated by with n being a factor to translate the effects of those into the correct unit:

$$x_{next} = x + n \cdot d_b \cdot v_b \tag{4.4}$$

20 seconds were chosen to be the duration time for the calculations because this is the minimum amount of time the LLEAP software can produce a transition for. If the bleeding takes longer than 20 seconds the calculation can be repeated and predict the next 20 seconds once again. The blood's speed v_b, vessel diameter d_b and n are to be implemented parameters, which can easily be set (e.g. manually in menu), since the real values are not known and this way the teaching anesthetist could easily adjust them to fit reality.

During insufficient muscle relaxant medication

As the value for the Train of Four will only change between zero and four the change would always seem instant because there is no space for a smooth transition. As such no special calculation was made to illustrate the change of values, instead they are being set as follows:

- Usually a Train of Four of one to two implies that the patient's muscles are relaxed enough. As such the simulator will use a Train of Four of two for regular narcosis.

- To display that the muscle relaxant is wearing off the Train of Four will change to three. In dependence of it being due to the indication of the "pressing" scenario it should start the pressing and change the value to three simultaneously. If the muscle relaxant is wearing off due to exceedance of the clinically effective duration (DUR25) the Train of Four should change to three first and the pressing will start a certain amount of time later.

4.5 Medication

During a surgery another main task of the anesthetist is to keep the patient in narcosis by renewing the medication. Depending on the medication used the anesthetist will need different medical devices and different medicine. Firstly, the choice of areas of medication, which need to be implemented urgently for the complication scenarios will be discussed. Secondly, the choice of the explicit drugs as well as interaction possibilities for the medical devices will be evaluated for the different areas. Finally, the problems and solution arising from the need for movement in the operation theatre will be discussed.

4.5.1 Choice of Medication

Similarly to the choice of vital signs the choice of medications, which are to be included in the LAVRS, should also be linked the priorities defined in Table 4.1. According to the table the most important medication would be the muscle relaxant, since it is needed for the Scenario B as a countermeasure to the complication. In Section 4.4.2 it was also stated, that, due to the interviewees stressing the importance of respiratory parameters and its importance for general anesthesia, Inhalation anesthetics would also be good to include in the simulation. Lastly opioids are the only remaining anesthesia medication. Like it was described in Section 2.1.3 the dosage estimation for opioids is very difficult and would also change during the surgery. As opioids are also not explicitly needed for the scenarios and the full preparation for the laparoscopy is not part of the simulation, it was decided, that the opioids will not be included in the LAVRS yet.

4.5.2 Muscle Relaxant Adjustments

This Section will explain which medical equipment is needed for the muscle relaxant adjustments in reality as well as which muscle relaxants are to be implemented and why. Afterwards it will be discussed, how these equipment and choices can be transferred into VR.

Medical Equipment

In preparation for a laparoscopic surgery a peripheral venous catheter is usually placed on the patient's arm or hand before the surgery starts. It is linked to an infusion and can also be used to give medication during the surgery. For this the catheter has a valve, which allows medications to be injected with a syringe as shown in Figure 4.6. This is also the way muscle relaxant medications would typically be given during a laparoscopic surgery. The typical place to find such a syringe and the anesthesia medications given with it is the anesthesia storage.

Figure 4.6: Picture shows a peripheral venous catheter with a short tube attached to it, which is connected to the valve for giving injections. Here a syringe is placed upon the valve to give an injection. [8]

Another important component is the muscle relaxant medication, which can be chosen from a number of options. In general muscle relaxant medications are grouped in depolarising and non-depolarising medication. Both block receptors for the nervous signal transmission differently, resulting in one blocking the development of a new signal (non-depolarising) and one simulating a continuous signal, which results in the nerves not recovering their potential and being unable to react to new stimuli (depolarising) [8]. While for non-depolarising medications no disqualifying arguments are found, the depolarising medications are seldom used because their reliability in regards to stability of the effective time fades, if they are used continuously for muscle relaxant refreshments. As such the depolarising muscle relaxants are unsuitable for the LAVRS and only typical non-depolarising muscle relaxants are to be included. The Table 4.4 shows the specific muscle relaxants , which will be included in the LAVRS, as well as their characteristics.

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 4.4: Different muscle relaxants (MR) used in the LAVRS and their 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$_{ID}$) [8]

[8] Picture Source: https://www.bd.com/assets/images/our-products/infusion/nexiva-closed-system-catheter_C_MMS_VA_0616-0011.png, Date: 21.08.2019

The Virtual Syringe and Catheter

As indicated above virtual objects for the syringe, the catheter and the anesthesia storage are needed. Apart from that the choice of muscle relaxant must be implemented as well as the choice of dosage. Because both produce a big variety of possibilities, an assortment of prepared syringes to choose from could be confusing. To provide a better overview a graphical user interface (GUI) menu could be better option. Since the LAVRS is a learning application and the medication dose is chosen in dependence of the patient's weight, some small information screens on the characteristics as well as the patient's age and weight could be given. These information could also easily be displayed in the menu and in dependence of the muscle relaxant, which has been chosen. The menu for these changes should be activated at the anesthesia storage and spawn a syringe for injection once the medication and dosage are chosen.

4.5.3 Inhalation Gas Adjustments

This Section will explain how inhalation anesthetic medication is given in reality and which inhalation anesthetics are typically used. Afterwards the virtual way to give the medication will be discussed shortly.

Medical Equipment

As the name suggests inhalation anesthetics are to be inhaled and can only be given using a respirator. The respirator will evaporate the inhalation anesthetic and mix it into a gas flow, where it will be carried along by the carrier gas, which can be either air or N_2O, and O_2. The dosage of the inhalation anesthetic, the amount of gas in the whole flow and portions of the gas mixture can be regulated by using the respirators different settings. These are usually visualized on a screen on the respirator together with other data such as the N_2O and O_2 in- and exhalation as well as the MAC being reached by the current dosage or not. Figure 4.7 shows a respirator and a typical screen for displaying its settings. The choice of inhalation anesthetics for the LAVRS includes all inhalation anesthetics, that are allowed in Germany, as the concept of how inhalation anesthetics actually work in the human body is not yet understood [8] and as such disqualifying criteria are hard to find. The Table 4.5 sums up the MAC of the inhalation anesthetics that are to be implemented, in dependence of the carrier gas chosen.

Figure 4.7: An anesthesia respirator with typical components: a) an additional vital sign monitor, b) a monitor showing respiratory information, next to the flow-display and knobs for gas adjustments, c) containers with inhalation anesthetics connected to a nebulizer, d) connections to the hoses. [9]

IA	**MAC in 100% O_2** [%]	**MAC in 70% N_2O** [%]
Isofluran	1.28	0.56
Sevofluran	2.05	0.8
Desfluran	6	2.83

Table 4.5: Different Inhalation Anesthetics(IA) used in LAVRS and their minimal alveolar concentration in 100% oxygen as well as in 70% nitrous oxide [8].

[9] Picture Source: http://healthprofessions.udmercy.edu/academics/na/agm/Images/Anestar.JPG, Date 21.08.2019

The Virtual Respirator

The virtual respiration device will need the very basic functionalities, which were already described above:

- a way to choose the inhalation anesthetic and the carrier gas,
- a way to regulate the gas flows of O_2, the carrier gas and the inhalation anesthetic (dosage),
- and a display, that shows the current settings and related data (MAC and O_2/N_2O in/exhalation in percent).

These features can be mimicked in VR using a GUI menu like for the muscle relaxant choice, with the difference, that knobs and buttons for interaction can be actual buttons on the virtual respirator to imitate the device more realistically.

4.5.4 Avatar Movement inside the Operating Theatre

In the operating theatre it is not given, that the respirator, the anesthesia storage and the patient are reachable by the anesthetist from the same spot without walking through the room. The space in reality however might be restricted so that really walking there is not possible without crashing into real objects. In VR there are two main approaches on how to handle this space problem, either continuous locomotion induced with a controller or teleportation.

As mentioned in the Section 2.2.5 eluding the drawbacks of VR, both come with negative consequences: Either the risk of feeling motion sickness when using the LAVRS will be higher (continuous locomotion) or the user might feel disoriented (teleportation). Since a typical laparoscopy from the start of the narcosis till its end would usually take multiple hours it is to be expected, that a simulation session which only simulates the cutting would take at the very least half an hour. This is a rather long time span to endure when feeling sick. As such it seems to be the wiser option to choose teleportation as the method of movement in the operation room.

The downside of teleportation is that it might confuse the users and make them feel lost. To reduce the confusion visual hints and feedback can be implemented as to make clear when a teleportation will take place and where it will teleport the user to. An easy way to give such hints would be a marking on the floor, which could also work as a visual feedback as to whether it is selected or not. Teleportation would then be reduced to only certain areas of interest, so that the user is not able to accidentally teleport to unwanted areas too.

It should also be prevented to accidentally teleport, so that there is no confusion due to sudden unwanted changes. Partially this will be achieved by only allowing teleportation to the designated teleportation spots. Another way might be to choose a controller button for teleportation, which has not been used before, or choose a second button for confirmation of the highlighted teleportation spot. But these option are limited because the number of controller buttons is also limited. Additionally there might be more confusion, if e.g. activating a laser-pointer for handling GUIs is a different button than the laser pointer for teleportation. Another problem about the multiple button option is that the user smight need to teleport while they are pressing another button already and adding more buttons to press might be difficult to coordinate. Because of this it was decided, that the teleportation should be simple and realizable with a single hand and a single button.

5 Implementation

This chapter will expound the implementation of the LAVRS. Firstly, the starting point on which the LAVRS was built on will be explained. Secondly, the main toolkit used for implementing VR-interactions will be introduced. Thirdly, there will be a section on the implementation of each of the main functionalities for the anesthetist: the monitoring of the vital signs and the methods for giving medication. Finally, two additional sections to illustrate the two complication scenarios will then finish the implementation chapter. All scripts mentioned in the implementation, can be found on the appended CD, which holds a copy of the entire Unity project of the LAVRS.

5.1 Starting Point

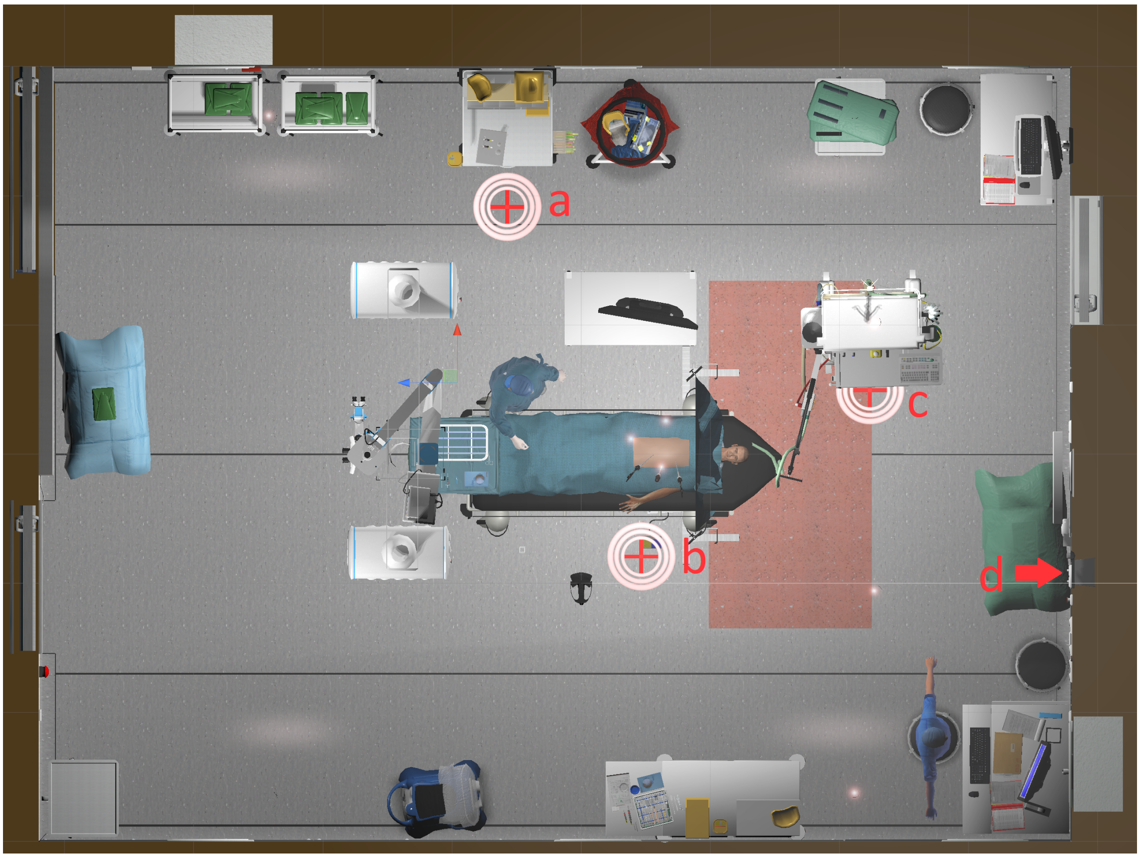
The LAVRS is an addition to an existing VR-laparoscopy-simulator which is the derivative to the prototype introduced by Heinrich et al. [1]. The prototype is built on the game engine Unity, so this is also the software to build the LAVRS on. The hardware used for LAVRS will be the HTC Vive [1].

The laparoscopic-simulator includes two users (surgeons) who are tasked with a liver resection as a tumor treatment. The laparoscopic tools used are the Simball laparoscopic instruments from Surgical Science's TeamSim®[2]. They include two surgery instruments and one laparoscopic camera. With these it is possible for the surgeons to either cut the tissue or clip blood vessels to stop a bleeding.

Another preset due to the laparoscopic-simulator was the surgical environment. The operating theatre was given as a Unity-Prefab and adopted from Huber et al. [63]. A Pictures of the operating theatre are shown in Figure 5.1. A respirator, an anesthesia storage and a telephone were already included in this setup and were used for the implementation of the medication and scenarios.

[1] HTC Vive official website: https://www.vive.com/eu/, Date: 30.04.2019

[2] Surgical Science official website to TeamSim®: https://surgicalscience.com/systems/teamsim/, Date: 30.04.2019



(a) The operating theatre shown from above. The teleportation-spots are marked with encircled red crosses: a) the anesthesia storage, b) the patient's side with the venous catheter and c) the respirator. Label d) shows the position of the telephone for the distraction (it is placed on the wall).

(b) View on the operating theatre's patient bed, laparoscopic instruments and camera screen as well as the respirator respirator. The green beams mark the teleportation spots.

Figure 5.1: Screenshots of the operating theatre from different perspectives.

5.2 The Virtual Reality Toolkit

The Virtual Reality Toolkit (VRTK) [3] is a toolkit for Unity 3D which provides many functionalities to use different VR devices in the usual Unity scenes. In this section the important functionalities used for the LAVRS will be explained.

Interactables

The VRTK implements so called interactable objects ("VRTK_InteractableObject.cs") which is a C# class that gives a game object in Unity the ability to be manipulated using the VR-Controllers. The interactable object will also need a collider to determine whether it is being in contact with a VR-controller or not. The VRTK also provides special interactable objects such as the "VRTK_PhysicalRotator.cs" which is a class which can only be rotated around a certain axis and not moved in other directions.
For a GUI to be interactable using VR-Controllers it needs a special script added to its parent canvas: the "VRTK_UICanvas.cs".

Controller Scripts

Using interactable objects requires special events for being near touch, touching, grabbing and using an object which can be initiated by touching the collider of the interactable object (near touch and touch) or by pushing a button on the controller while touching the collider to trigger an interaction (grabbing and using). These events are defined in scripts associated with the VR-controllers. Each controller has an alias empty game object in the Unity scene which will hold onto the scripts needed for the interactions. The most important scripts are "VRTK_ControllerEvents.cs", "VRTK_InteractTouch.cs", "VRKT_InteractGrab.cs" and "VRTK_InteractUse.cs". In these scripts the controller buttons to be used for the grabbing or using are defined.
The VRTK provides laser pointers which allow interactions with interactable objects that are further away and enables the user to interact with GUI elements. They are also used for choosing the position of teleportation. The scripts for these should also be placed on the controller aliases. Namely the LAVRS includes: "VRTK_Poitner.cs", "VRTK_UIPointer.cs"and "VRTK_StraightPointRenderer.cs". The controller buttons to activate the laser pointers as well as an interaction with the interactable object it is pointed at will be defined in these scripts as well.

Teleporting

As already mentioned the VRTK also enables teleporting. There are different kinds of teleporting, but the LAVRS will only use teleport to certain defined destinations. These

[3] VR-Toolkit official website: https://www.vrtk.io/, Date 03.02.2019

destinations are game objects with the script "VRTK_DestinationPoint.cs" (a derivative class from "VRTK_DestinationMarker.cs" found in an example scene of VRTK).
To be able to teleport, another script needs to be used: "VRTK_BasicTeleport.cs" or any derivative of it. It can be placed anywhere in the scene.

Visual Feedback

To let the user know whether the controller is close enough to the interactable object to touch the collider a visual feedback in form of a colorful halo around the object is used. For this the following scripts need to be attached to the interactable object: "VRTK_InteractObjectHighlighter.cs" and "VRTK_OutlineObjectCopyHighlighter.cs". In the first script the colors which should be used for the highlighting can be chosen, in the second one the Mesh of the objects outline around which the halo should appear. An important thing to know is that not every mesh is usable for highlighting. The objects given in the operating theatre prefab for example are not. As such an invisible primitive 3D unity object (a sphere or cube) was used to highlight the surrounding of these objects.

5.3 Virtual Monitoring

The screen for monitoring the vital signs is placed on the respirator's right monitor. To assure the validity of the displayed vital signs the already discussed LLEAP software was used (more information in Section 4.4.1). But as aforementioned LLEAP is only available on a single laptop in the Computer Assisted Surgery group, so there was a need to connect this laptop to the computer operating the LAVRS on Unity. The data flow between the different hardware is shown in Fig. 5.2.

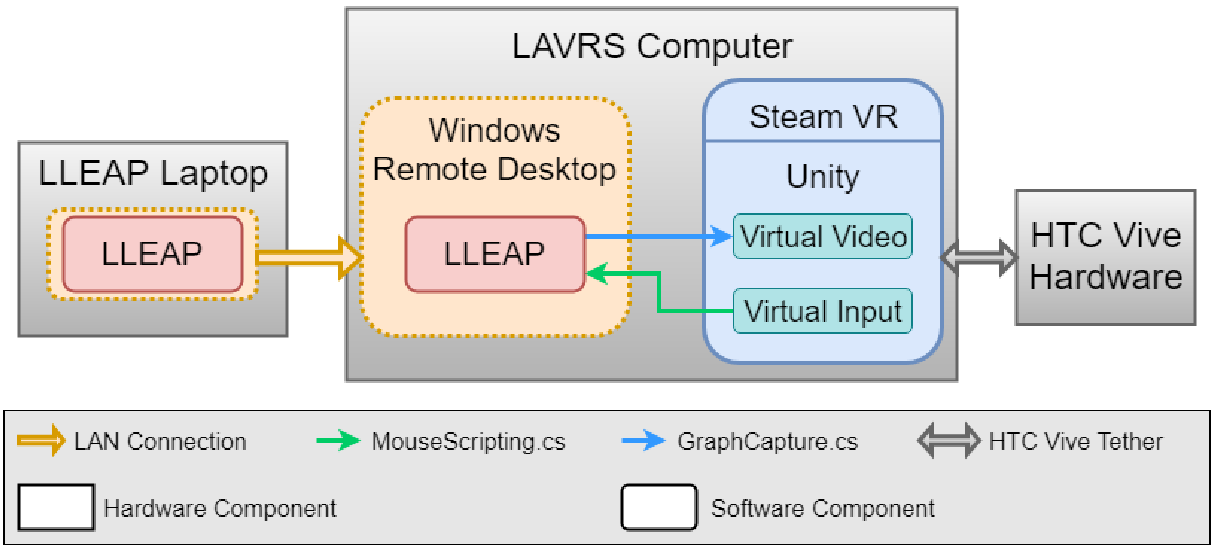


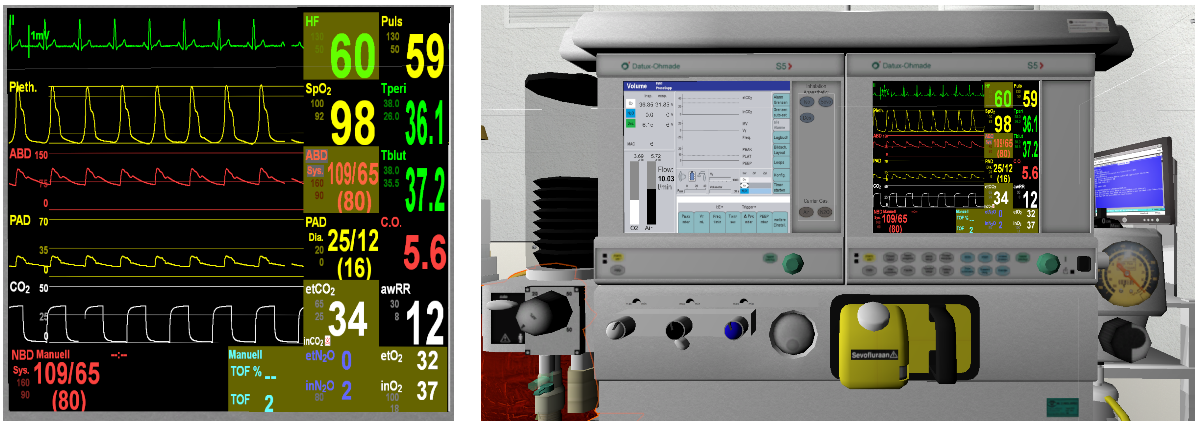
Figure 5.2: Graph showing the connections between the different hardware used.

5.3.1 Connecting the Computers

To connect the LLEAP-laptop to the LAVRS-computer the software Windows Remote Desktop [4] is used. This way the LLEAP-laptop's screen is transferred to the second monitor of the LAVRS-computer and the LAVRS-computer is also able to make changes to the LLEAP-settings by using a mouse or keyboard.

5.3.2 Capturing the Desktop in Unity

To generate the screen for the vital signs in Unity, there is a need to capture the transferred screen of the LLEAP software in a certain region. There is an open-access GitHub project that is able to do this in Unity using C# scripts [5]. With some modifications LLEAP's vital sign monitor can be captured by the script "GraphCapture.cs" and displayed in Unity (see Fig. 5.3). The size of the captured texture in pixels is the same as it was in the resolution of the monitor it was captured from. This results in higher quality textures being obtained by using a higher resolution monitor to show the LLEAP window on the LAVRS-computer. For the LAVRS the deciding monitor had a resolution of 3840 x 2160 pixels resulting in a texture of the size of 1284 x 909 pixels.



(a) The cropped screen showing the vital signs as it is captured by the "GraphCapture.cs" script in the simulator.

(b) The whole respirator with its two monitors and menu buttons. The captured screen is used as a texture for the respirator's right monitor.

Figure 5.3: Screenshots of the vital signs monitor in the simulator.

5.3.3 Flickering Monitor in- VR

The monitor for the vital signs seems to be flickering badly in VR even tough the texture itself seems to be alright judging from the resolution. The problem is especially bad with

[4] Windows official website to Remote Desktop: https://docs.microsoft.com/en-us/windows-server/remote/remote-desktop-services/welcome-to-rds, Date 30.04.2019

[5] Phylliida: https://github.com/Phylliida/UnityWindowsCapture, Date 03.02.2019

the graphs showing the ECG and respiration, as these are very thin lines on the texture. It seems this a problem associated with the limitations of the performance: VR graphic calculations are very costly. As such Unity will automatically render objects that are further away with less quality, to ensure the demand for keeping it a real-time application will be met. It is possible to manually adjust the radius within which the quality is higher, but that reduces the performance too much. As such the flickering of the monitor could not be fixed for positions far from the monitor, but the flickering will be minimized, when the user stands very close to the monitor. In consequence the teleportation-spot for the respirator was chosen very close to the respirator as shown in Figure 5.1a so that the flickering is manageable.

5.3.4 Interactions and Mouse Scripts

There is also a need to adjust the parameters in the LLEAP software to match the scenarios in LAVRS. As the remote controlled LLEAP can only be manipulated using input-devices such as the mouse or keyboard the scripting of input using C# is also needed to be implemented.
Microsoft has a function called “SendInput”[6] included in their “winuser.h” Windows Control header which will send data directly into the input stream and thus can operate mouse clicks at defined positions and keyboard input. With the help of this functionality the automated adjustment of the vital signs could be implemented. The basic structs and functions to use it were implemented in the “MouseScripting.cs” script.
Afterwards the menu of LLEAP shown in Figure 4.5a was measured to find the exact positions, where the mouse clicks should take place. These are hard coded in the “MouseScripting.cs” script, too, so that they will not be changed accidentally. Another functionality of the script is the conversion of the calculated integer numbers for e.g. the pulse into digits that will be typed one after the other for the key board input. Lastly the computer was not able to keep up with the speed of the inputs, resulting in it skipping some of the mouse clicks. To counter this behavior the system is forced to pause for 10 ms after each input action.

5.4 Medication

To implement a way of giving the two different medications the VRTK was used. Building up on the functionalities for controller interactions the mechanics for choosing and adjusting the inhalation anesthetic and muscle relaxant were created.

[6] Windows Documentation to the SendInput function: https://docs.microsoft.com/en-us/windows/desktop/api/winuser/nf-winuser-sendinput, Date: 30.04.2019

5.4.1 Inhalation Anesthetics

All modifications of the gases can be operated and monitored at the respirator. The user has the choice between three different inhalation anesthetics to use: Isofluran, Sevofluran and Desfluran. Their MAC and MAC with 70% N_2O can be read from the table 4.5. The user can also choose between air and nitrous oxide as carrier gases. The choice can be made using GUI buttons in between the two screens of the respirator. These were implemented by using Unity's built-in GUI elements and adding the "VRTK_UICanvas.cs" script to the canvas holding the GUI.
For the adjustment of the gas flow of oxygen, the carrier gas and inhalation anesthetic a rotatable knob was added to the respirator below the left screen for each gas. These knobs are interactable and were implemented using a modification of the "VRTK_PhysicalRotator.cs" script. By grabbing the knob and rotating the controller around the wrist the gas flow can be adjusted. There is a visual feedback for touching the knob with the controller (green halo) as well as for grabbing it (orange halo) implemented with the "VRTK_InteractObjectHighlighter.cs" and "VRTK_OutlineObjectCopyHighlighter.cs". The change in the values and choices can be read from the left screen of the respirator where there are percentages and the overall flow given as numbers and sliders (see Fig. 5.4). The MAC will also be shown. It will be adjusted according to the currently chosen inhalation anesthetic and carrier gas. It is also dependent on the current concentration of nitrous oxide and is interpolated in a linear manner with the value for 70% and 0% of nitrous oxide as a basis. These calculations and the display of the flow will be adjusted by the "SimulationControl.cs" script.
In dependence of the current MAC and inhalation anesthetic level the ABP and pulse will change as described in the Equations 4.1 - 4.3. These changes are also implemented in the "SimulationControl.cs" script.

5.4.2 Muscle Relaxants

Because a syringe is needed to give the muscle relaxant the adjustments to the patient, the choice of amount and muscle relaxant type given will be made at the anesthesia storage, there the activation of a GUI menu (see Fig. 5.6a) can be triggered by "using" the syringe holder with the VR controller. The script "ActivateMRMenue.cs" implements this.
The GUI (see Fig. 5.5) was built the same way the buttons for the choice of inhalation anesthetic were. Buttons allow the user to choose an muscle relaxant out of the six characterized in the Table 4.4 below. Upon the choice of an muscle relaxant the GUI will display important information about the muscle relaxant which is also given in the Table 4.4. An additional windows will give the user more information on the patient which is usually needed for the calculation of the dose like the age and weight, as well as the time since the last injection of muscle relaxant and the dose and muscle relaxant type given

Figure 5.4: Screenshot of the respirator's setting's menu. At the very bottom are three knobs for adjustment of the flow of the different gas types (white: O_2, black: carrier, blue: inhalation anesthetic). The monitor above shows the absolute flow values and concentrations in percent as well as the MAC. Right from the monitor buttons for the choice of inhalation anesthetic and carrier gas can be found.

at that time. Aside from these there is also a slider in form of a syringe which can be dragged to choose a specific dose in mg/kg of the muscle relaxant. This dose will always be a valid maintenance dose which would lie between 5 - 15% of the intubation dose. The specific amount given will still influence the simulation differently because the time until the muscle relaxant needs to be given again and the time till effect will be calculated in dependence of the dose. The higher the given dose the shorter the time till effect and longer the DUR25. These values were also interpolated linearly between the values given in the Table 4.4. For accepting the current choice of muscle relaxant an OK-Button was implemented to close the menu and spawn a syringe when activated. All of these functions are implemented in the script "MusclerelaxantInteractionControl.cs".

The spawned syringe needs to be grabbed and carried to the patient's arm. On the hand of the patient there is a venous catheter. Once the syringe touches the collider of the venous catheter the muscle relaxant will be injected and the syringe will despawn again.

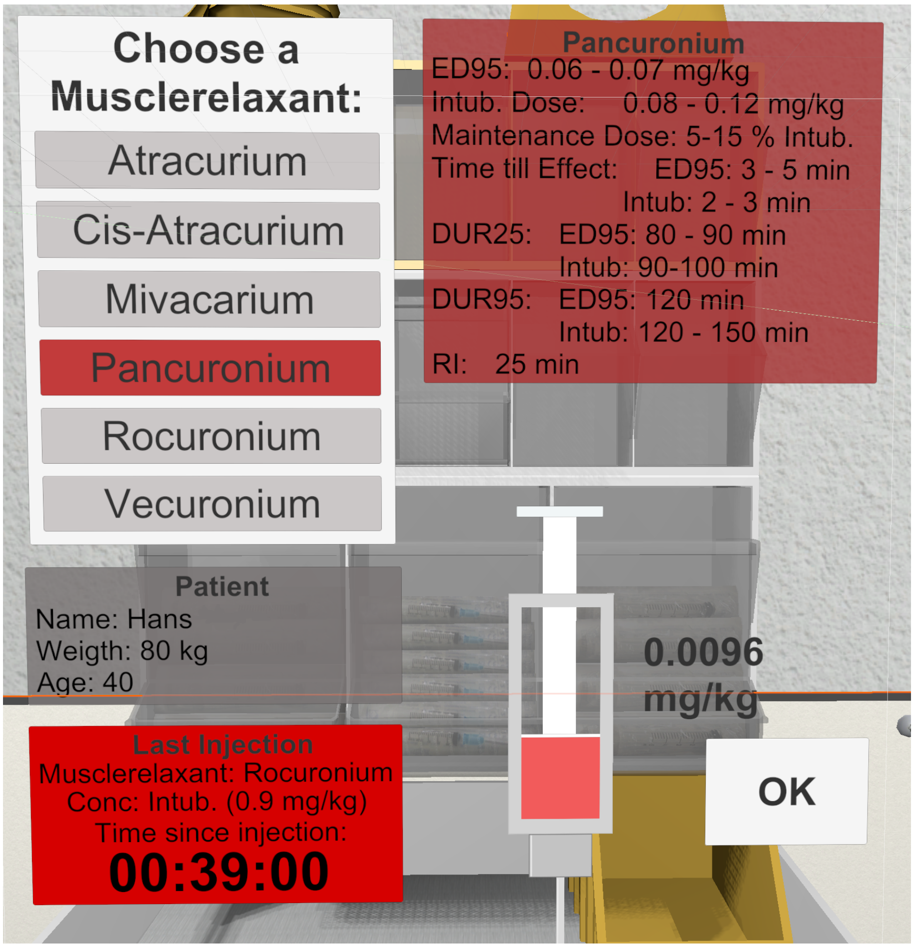
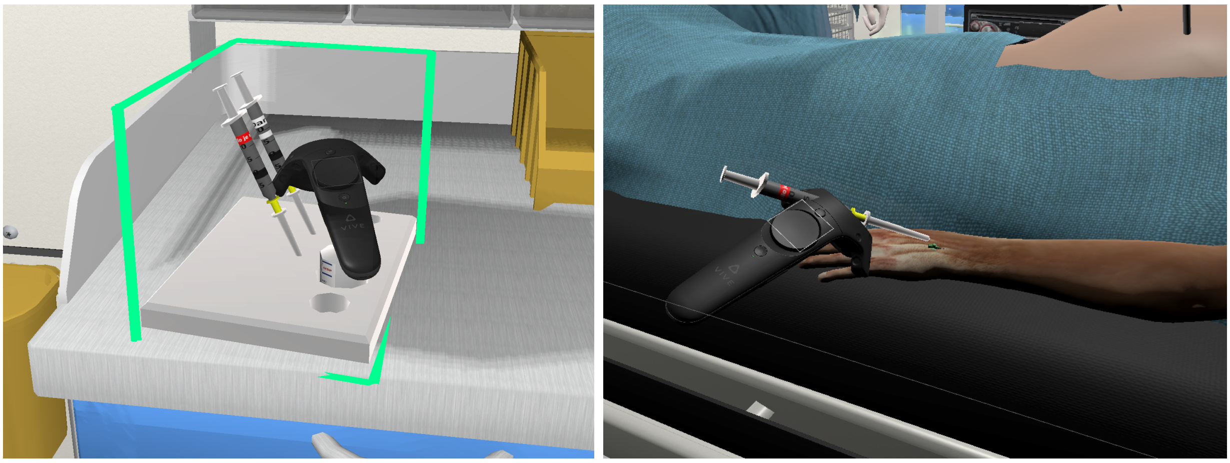


Figure 5.5: Screenshot of the muscle relaxant choice menu. The top left allows the choice of a muscle relaxant with the laser pointer. The right side will then display information on that medication. The bottom left shows different information windows on the last injection and the patient. Lastly, the right bottom shows a syringe, which can be "drawn up" to define the dosage of the medication.

This is handled by the script "VenCathTrigger.cs". Figure 5.6b shows the syringe close to the catheter shortly before despawning.

When the muscle relaxant is injected, a repeating process is invoked which will check the time passed since the last injection and adjust further parameters accordingly. First the timer in the muscle relaxant menu will be reset and the information on the last muscle relaxant injected will be updated. When the TTE is over, the Train of Four will be set to the value of two again. If the DUR25 has passed without a new injection of muscle relaxant, the Train of Four will raise to three again to signal that the medication is wearing off. After that the process will stop repeating. These functionalities are handled by the script "MusclerelaxantInteractionControl.cs" as well.



(a) Screenshot of the activation of the muscle relaxant menue. When the syringe holder is highlighted in green, the controller has entered its collider and the menu can be activated.

(b) Screenshot shortly before giving the injection. The syringe is held with one controller and can be placed close to the venous catheter on the patients hand. The moment the colliders touch, the simulator will give the injection and instantly despawn the syringe.

Figure 5.6: Different interactions needed for refreshing the muscle relaxant medication: a) activating the menu; b) giving the injection.

5.4.3 Teleportation Destinations

As the anesthetist usually stands at the respirator and positions to readjust the muscle relaxant medication are not reachable from there, teleportation is needed as a means of movement. Teleportation in the LAVRS is only allowed to certain destinations: in front of the respirator, in front of the anesthesia storage and in front of the patient as shown in Figure 5.1a. To mark these destination points a plasma beam game object was used. For teleportation the laser pointer of the controller can be pointed on one of the beams and released to activate the teleport. This is implemented by using “VRTK_DestinationPoint.cs” in combination with “VRTK_BasicTeleport.cs”.

5.5 Scenario A: Undetected Bleeding

The complication scenario “A: Undetected Bleeding” requires the implementation of a distraction for the surgeons as well as a connection to the surgeon’s clippings of blood vessels and a trigger to start. The whole sequence of events is shown in Figure 5.7.
The distraction-phone-call was realised using an audio file of around 2 minutes which was provided by the University Hospital of Mainz. This file is the audio of a telephone call in which a physician tells the listener information about the patients she needs to transfer to the listener, because there is an urgent matter and she needs to leave the hospital early. This phone call will be played after a the telephone rang. The ringing of the telephone

and start of the distraction can be triggered by pressing a key on the host-computer. This event is also handled by the “SimulationControl.cs ” script. To stop the ringing of the telephone, the telephone needs to be “answered” by using the laser pointer of the controller. If this is done the script “LaserInteraction.cs” activates the changing of the active sound file and the phone call audio will be played.

When the ringing stops one of the clips placed on the blood vessels by the surgeons will slip off. This event is also triggered by the “SimulationControl.cs”. When a vessel clip slips off, a bleeding animation in form of a particle effect will start. When these particles get activated they will trigger the start for the vital signs to simulate bleeding for at least 20 seconds (“IsItBleeding.cs” as trigger, “SimulationControl.cs” for effects). If the blood vessel gets clipped again, the bleeding will stop and no new changes for the vital signs will follow. The changes of the vital signs due to blood loss will be added to every state of narcosis of the vital signs, so the lost blood will have a lasting effect. The amount of change due to blood loss is calculated in the “SimulationControl.cs” script according to the Equation 4.4. The parameters for blood speed and the factor n were made public so they are easily changeable for testing.

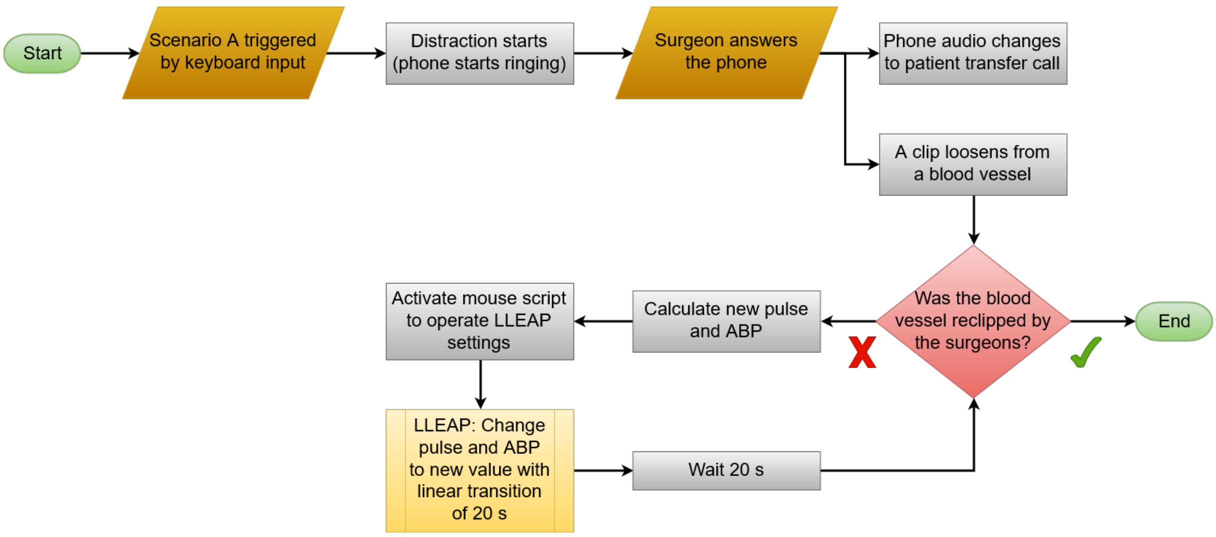


Figure 5.7: Flow chart of the events happening during the scenario “A: Undetected Bleeding”.

5.6 Scenario B: Insufficient Muscle Relaxant Medication

The scenario for “B: Insufficient Muscle Relaxant Medication” will need to start an animation for the “pressing” of the patient as well as a change in the Train of Four parameter when it starts. The muscle relaxant injection given should end these effects later on. Most of this functionality is implemented in the scripts used to give the muscle relaxant already.

The start of the scenario can once again be triggered by pressing a key on the host-computer.

This event will also be captured by the “SimulationControl.cs” script. The script will also start an animation which moves the belly of the patient as described in 4.3.3. The organs of the belly will start moving accordingly as well, to make ignoring it and still operating on the patient difficult.
With the injection of a new dose of muscle relaxant the animations will stop, but only after the TTE (here, the same script as for the other aftereffects of muscle relaxant is used). The whole sequence of events for the scenraio “B: Insufficient Muscle Relaxant Medication” is shown in Figure 5.8.

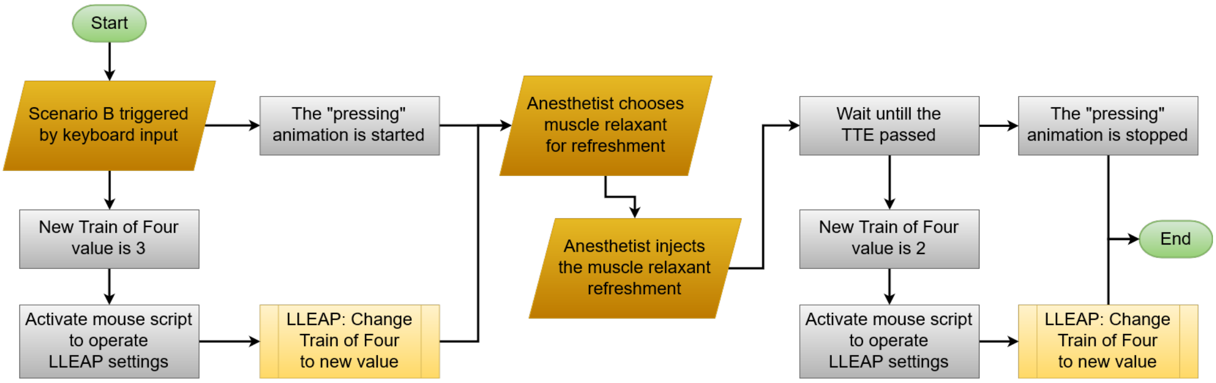


Figure 5.8: Flow chart of the events happening during the scenario “B: Insufficient Muscle Relaxant Medication”.

6 Evaluation

For the evaluation of the LAVRS an expert interview was held with an anesthetist with 27 years of working experience in anesthesiology. In this chapter the procedure of the interview will be explained and afterwards the results from the interview will be illustrated.

6.1 Procedure of the Interview

Before the interview the anesthetist got a demonstration of the LAVRS. This demonstration was made as a single-user demonstration because the multi-user functionalities are yet to be implemented. The actions which would need to be done by the surgeons were mimicked using keys to execute these functions. This way the full range of functionalities could still be displayed and evaluated.
The anesthetist was asked to “think aloud” so that his thoughts on the functionalities could be evaluated. The demonstration started with the basic functionalities of the LAVRS. The anesthetist was tasked to adjust the oxygen, carrier gas and inhalation anesthetic in a way that he would think of as suitable for a narcosis. The underlying processes that would take place were explained, too. Afterwards the scenario “A: Undetected Bleeding” was shown, starting with the phone call and ending with the vital signs slowly changing. Lastly, the scenario of “B: Insufficient Muscle Relaxant Medication” was demonstrated so that the pressing-animation and change in parameters as well as the options for choosing and injecting the muscle relaxant were displayed.
After the single-user demonstration a short trial including two surgeons and the anesthetist was made, to find flaws in the multi-user application. The anesthetists and surgeons joined in VR are shown in Figure 6.1. Lastly, an interview was held with the anesthetist to get an evaluation in more detail. The interview questions can be found in the Annex in their original form (German) B or translated to English C.

6.2 Results

The feedback will start with the general set up of the operating theatre used, lead on to the vital signs and monitoring and then value the different medications. Lastly, the two scenarios will be evaluated and the interaction possibilities as well as the LAVRS as a learning application will discussed.

Figure 6.1: Picture showing the interviewees joined in VR. The two interviewed surgeons are at the right using the SimBall laparoscopic instruments and the anesthetist is on the left, interacting with the VR controllers.

6.2.1 Set Up of the Operating Theatre

The interviewed anesthetist pointed out, that operation rooms are usually spatially separated into a sterile and a not-sterile part. On top of the patient is a curtain which separates the surgically opened and sterile area from the non-sterile area to the head. The anesthetists usually work at this non sterile area only. The non-sterile area around the patient's head typically includes the respirator and also the anesthesia storage, so that the anesthetists have all their tools in one place and do not need to cross the sterile region. The current simulator needs the anesthetist, who is not sterile, to move around a lot, which is not typical.

Similarly the position, where the injection is given in the LAVRS, is untypical: The anesthetists would not give the injection at a sterile area - or if they must then they would at least not give it at the same side as the surgeons are operating since there is no space for that. While the position of the venous catheter is on the hand, there is always a tube attached to it, that is connected to an infusion. The tube would usually follow alongside the head to an infusion. Along the way in the head-area there would be a special attachment where injection can be given. So this should be adjusted in a future version of the LAVRS.

It would also be a good idea to have another monitor for the vital signs for the surgeons, so that they can have an eye on it, too. The monitor for the vital signs was also mentioned to be flickering badly in VR, which was already identified as a potential problem beforehand (see 5.3.3).

It was also mentioned that the brand name of the respirator device should not be shown.

The anesthetist also criticized that there was too little space in reality to move around, so if possible the VR should be tested and used in a more spacious room the next time.

6.2.2 Vital Signs and Monitoring

The anesthetist mentioned that not all of the vital signs shown on the monitor were relevant. Only the respiratory-curves and values, the Train of Four, the ECG, the Pulse, the O_2-saturation and the ABP measured invasively as well as non-invasively should be shown on the vital sign monitor as to not confuse the users with more information than needed.
It was also suggested with special emphasis that the respiratory curves and CO_2 exhalation should be implemented next in the simulator because they propose a very important parameter for the anesthetist. It was also said that the ECG would be accompanied by a beeping sound which is modulated in dependence of the O_2-saturation. With this auditory sign the anesthetist will not need to look at the monitor the whole time, but can hear whether there is an emergency coming up. So the O_2-saturation was also stressed to be another "must-have" for the future of the simulator. Moreover the values for the breathing frequency and respiratory pressure should also be implemented. As the respiratory behavior is not easily grasped the anesthetist said to be available for another talk to explain the respiration in detail for the scenarios of the simulator.
The anesthetist also mentioned that he would like to have alarms for the vital signs. Usually the monitoring devices will sound an alarm if the vital signs exceed or fall beyond a certain value. The values which mark the boundaries of the safe region are implemented into the LLEAP simulator and can be copied from there.

6.2.3 Medication

Even tough the opioids for analgesia were not needed directly for the currently used scenarios, the anesthetist recommended to implement these in a future version too, since they are an important part of the general anesthesia. Apart from this he liked the broad functionalities given with both muscle relaxants and inhalation anesthetics implemented relatively close to reality. Minor changes should still be made in both and will be explained in the following sections separately.

Inhalation Anesthetic Settings

The options for choice and amount of inhalation anesthetic and the other gases are implemented differently than respirators usually do (placement of buttons and knobs). Aside from that each gas used for anesthesia has a certain color, which should also be used in the LAVRS to prevent confusion. N_2O is typically not used anymore and as such the choice of the carrier gas can be left out and the MAC calculations can be simplified.

It was said that the MAC value shown on the respirator is usually different from the real MAC value: the MAC value shown will indicate how close the inhalation anesthetic concentration is to the ideal MAC. As such if the inhalation anesthetic concentration is exactly the MAC the respirator will show the value one. If the concentration is above the ideal MAC the respirator will show a value greater than one and vice versa. The ideal MAC will also be calculated in dependence of the patients weight and age.
The anesthetist also stated that he would like to have information screens to the different inhalation anesthetics similar to those implemented for the muscle relaxant choice.

Muscle Relaxant Settings

The anesthetist liked the information panels shown for the different muscle relaxants. Apart from that he remarked that the anesthetists would usually not fill the syringes during the surgery but instead have a broad choice of prepared syringes with different doses of muscle relaxant, they can choose from. As such the students would need to learn the absolute mg values rather than the mg/kg values for the muscle relaxants. So either the menu to choose the concentration is adapted to giving a choice of preset syringes or the fillable syringe will be kept, but absolute values for the dosage in mg should be shown.

6.2.4 Scenario A: Undetected Bleeding

Regarding the Scenario “Undetected Bleeding” the anesthetist confirmed, that the scenario will encourage communication between surgeons and anesthetists. He also said that the scenario itself is identifiable by the vital signs which are changing, but that this change would need to be much bigger. For the patient’s condition to be identified as critical the ABP would need to fall below 80 (for systolic) and 50 (for diastolic) Hg/mm and the Pulse would need to rise above at least 100 bpm. This change would need to take place before the phone call ends, for the scenario to work. as such the parameters d_b, v_b and n mentioned in Equation 4.4 would need to be changed to produce a higher amount of change.
If the ABP is able to fall that much the anesthetist also stated that the O_2-saturation would drop drastically if a systolic ABP smaller than 60 is reached and a systolic ABP smaller than 50 would lead to a saturation of zero.
Aside from that theoretically the central vein pressure and pulmonary ABP would also be affected by a bleeding but because the anesthetist also mentioned, that these parameters should not be shown on the vital sign monitor, this can be regarded as a non-essential detail.
Lastly, the distraction was still rated as being unrealistic. With the telephone using speakers the surgeons could still operate and look at the monitor of the laparoscopy and might notice the patient’s bleeding themselves. As such it was suggested to insert an

animation or another player for a nurse to take and hold the telephone for one of the surgeons. For this a surgeons would usually step back from the patient, let go of the laparoscopic instruments and fold their arms to not get any dirt into the sterile area of the incision. This way the distraction would ensure that the surgeons do not look at the laparoscopic screen or that the laparoscopic camera is not looking at the right position.

6.2.5 Scenario B: Insufficient Muscle Relaxant Medication

This scenario was also evaluated to engage communication between surgeons and anesthetists. The scenario itself is already identifiable as an insufficient muscle relaxant medication. Still the animation used is too extreme: usually the belly as well as the organs would move much less and slower. The movement of the organs would be in anterior and posterior direction, not superior and inferior.
Aside from that, the pulse and ABP would increase slightly during the scenario too. The anesthetist also mentioned that the respiratory parameters would show that the patient's spontaneous breathing would start again and this would result in an alarm of the respirator. The respiration frequency would become unstable and the respiration curve would show specific spikes.
The anesthetist also criticized that the scenario would be rather unusual: for the medication to wear off so much that the patient would start "pressing" is very unlikely, as the medication wearing off is usually noticed earlier. So maybe this scenario would need some readjustments on the way it is shown.

6.2.6 Interaction Possibilities

The anesthetist rated the used interactions as easy to learn and did not have any difficulties using them.

6.2.7 LAVRS as a Learning Application

Since the LAVRS is intended to become a learning application, the anesthetist was asked to answer questions on what he would need to use it as an instructor.
The anesthetist mentioned that he would want the students to have a clear goal for the simulation which should be explained together with the virtual patient's history before starting the simulation. So a patient history would need to be developed and maybe shown before starting the simulation. He would also like to stress to the students that the LAVRS has the goal of training communication in the surgery team and as such communication is possible and wanted.
For the sake of the distraction being truly distracting, it was also said that it would be a good idea to include the distraction-phone-call in a test after the simulation. This way one could be sure that the students will concentrate on the call and not ignore it and keep

operating when they should not. This would probably need to be told to the students beforehand or they might still ignore the phone call. The phone call should also have a typical structure for a patient transfer dialogue so that it is of pedagogical value.
The instructor would also need some method of supervision, so the current status of the simulator (vital signs, proceedings with the operation's currently active scenarios) should be shown as well as the students' view in VR. It would be favoured if the instructors would also have a means of documentation of the simulation session, so that they could evaluate it later. A method to comment and maybe grade the students would also be welcomed.
The anesthetist also liked the idea to induce a certain scenario any time during the simulation with an instructor's control panel. He would prefer that over a pre-scripted scenario which will activate a certain complication after a certain amount of time or event. Considering this the anesthetist confirmed that he could picture himself using the LAVRS in a more developed version as a new tool for teaching students.

7 Discussion

So after all has been said and done the final questions are: Was the LAVRS prototype favorable and where will it go from here? Both question will be answered in the following part by first looking back onto the concept of the Thesis in combination with the interview evaluation and secondly recapitulating what is missing for the LAVRS to become a full-fledged educational tool. Thirdly new problems which might occur, when using the LAVRS will be discussed. The Thesis will be concluded with a short outlook on which further uses the LAVRS might have in its finished version.

Looking Back

The feedback from the anesthetist was overall positive and he especially appreciated the broad range of functionalities, which were already realized. This leads to the conclusion, that the overall prioritization was on point and the most important features were implemented. Still the anesthetist mentioned, that the symptoms of the two complication scenarios in particular were slightly inaccurate. While they did mimic the symptoms, both did not do so in a realistic manner (the vital sign changes for the bleeding were too small, while the animation for the "pressing" was too extreme). As these effects are difficult to judge with an amateur's view, including more clinical feedback for the fine tuning of the symptoms would be a good course of action. The choice of medication was well liked for being broad and portraying the real way of giving the medication mostly well, but once again the research alone was not enough to replicate the reality perfectly and more consultation with experts will help getting a clearer picture of how exactly these things should be displayed. Finally, the interviewed anesthetist stated that he would like to use the LAVRS for teaching in a future version, so this can be regarded as the prototype showing potential and as such fulfilling its purpose.

Next Steps

Firstly, the already existing functionalities should be adjusted to meet the newly found expectations. This would include:

- Changing the symptoms of both complication scenarios to be more realistic as stated in the Sections 6.2.4 and 6.2.5,

- Reducing the amount of vital signs shown to the relevant only as stated in 6.2.2,
- Repositioning the furniture in the operating theatre as stated in 6.2.1,
- Adding an information panel for the inhalation anesthetic choice,
- Adjusting the muscle relaxant menu to show the medication dosage in absolute weight [mg],
- Finalizing the multi user implementation.

The interview evaluation also provided information on which features should be added in addition to the existing features. These include:

- Adding the change of the respiratory vital signs, this requires another interview with an anesthetist to determine the changes in different situations,
- Adding the change of the O_2 saturation together with its characteristic sound,
- Adding opioids as a medication, this too will need an expert interview to define the needed dosages,
- Adding alarms for the respirator and vital signs monitor, which sound when a certain threshold is reached,
- Adding missing visualizations (tube of the infusion with valve for injections, animate the injection, add a nurse to hold the telephone during the distraction),
- Adding a supervisor menu for triggering the complications and evaluating the students,
- Adding a realistic patient history to be displayed before the simulation.

Potential Problems

By now only one anesthetist has evaluated the prototype in an interview. As such some things might have been missed, which might cause future problems of the LAVRS. One possible challenge might be, that the LAVRS could give students a wrong impression on how the vital signs change. While the change of vital signs in the simulator is based upon how vital sings usually change in reality, not every patient reacts the same way towards medication or a bleeding as it was already stated in Section 4.4.2. So it is important to make clear, that the simulation is but “one specific patient” right now and can not display the behavior of every patient. To reduce this problem the simulator could strive to include multiple patients in the future, where each will react differently to the medication and complications and require a different laparoscopic treatment. The natural fluctuation of

the vital signs should also be mimicked by a minor random change in the vital signs. This will make symptomatic changes in the vital signs more difficult to spot as well as it will make the simulation more realistic and prepare the residents better for their first surgery. Another potential wrong impression of the surgery itself might occur, because the LAVRS currently only simulates the part of the surgery, where the patient is surgically opened. As such the preparation and end of the surgery are missing, which might lead to uncertainty in these phases. So including these phases into the simulation might be an option. Since the LAVRS is built to enable the connection to a medical mannequin, this might be a good opportunity to use it because e.g. the preparation for the surgery will need haptic feedback (e.g. for intubation or placement of the measurement instruments).
Finally, the small amount of complications might also give the students a wrong impression of typical complications. Additionally the complications in the current LAVRS are minor and not yet penalized in any way, which might let the students underestimate the situations in reality. Both problems could be tackled by adding different and maybe more severe complications in future version of the LAVRS, which have effects on the virtual patient's well being.

Outlook

The LAVRS was constructed for teaching residents before their first surgery. But there can be additional uses for the LAVRS, if it is developed further. For example the evaluation of the students might become automatized as it is in a lot of VR simulators already. Apart from that it might also be used for teaching surgeons by demonstrating when to use the different laparoscopic tools and how to make decisions depending on the anatomy of the patient. VR provides the ability to do this without a real patient and with ideal views for the students because nobody can block the way in a virtual room.
Additionally to its teaching capabilities the LAVRS might also be used for training and refreshing the skills of surgeons and anesthetists, who have not worked in a laparoscopy lately. As a team training application it might also help for the laparoscopic team members to train together and as such develop a better team work.

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A Software

Unity 3D: from https://unity3d.com/de as game engine

Visual Studio 2017: from https://visualstudio.microsoft.com/de/ as programming tool

Steam VR: from https://steamcommunity.com/steamvr as a connection tool for the HTC Vive

Laerdal Learning Application LLEAP: from https://www.laerdal.com/de/products/simulation-training/manage-assess-debrief/lleap-laerdal-learning-application/lleap/ as simulation tool for vital signs

Windows Remote Desktop: preinstalled on Windows Professional as transfer tool for data from LLEAP

Overleaf: from https://www.overleaf.com/ as LaTex Editor for writing the Thesis

Mendeley: from https://www.mendeley.com/ for the bibliography

B Interview Questions (original in German)

B.1 Bereich: Realismus

Szenario A: Unentdeckte Blutung

- Bilden die verwendeten Vitalparameter das Szenario „Unentdecke Blutung“ erkennbar ab?
- Was hat gefehlt bzw. wie lässt sich die Darstellung weiter verbessern?

Szenario B: Unausreichende Muskelrelaxanzien Medikation

- Bilden die verwendeten Vitalparameter und Animationen das Szenario „Unausreichende Muskelrelaxanzien Medikation“ erkennbar ab?
- Ist die Verwendung des Muskelrelaxans ausreichend gut abgebildet?
- Was hat gefehlt bzw. wie lässt sich die Darstellung weiter verbessern?

Existierende Funtionalitäten

- Bitte bewerten Sie den Realismus der Möglichkeit und Größe der Änderung der gegebenen Vitalparameter/Medikamente :
  - Puls/ Herzfrequenz
  - Arterieller Blutdruck
  - Train of Four
  - O_2 Gas-Fluss
  - N_2O Gas-Fluss
  - Inhalationsanästhetikum
  - Muskelrelaxanz
- Gab es genügend Auswahlmöglichkeiten? Was haben Sie vermisst?

Interaktionsmöglichkeiten

- Fanden Sie die Interaktionsmöglichkeiten intuitiv oder waren sie schwer zu erlernen?
  - Teleportation
  - Kontroller-Interaktionen mit Objekten
  - Laser-Interaktionen mit Menüs
  - Laser-Interaktionen mit Objekten
- Was hat Sie gestört oder hätten Sie sich anders gewünscht?

B.2 Bereich: Kommunikation

Szenario A: Unentdeckte Blutung

- Glauben Sie, dass durch das Szenario „Unentdeckte Blutung" die Beteiligten zur Kommunikation angeregt werden?
- Was könnte man verbessern?

Szenario B: Unausreichende Muskelrelaxanzien Medikation

- Glauben Sie, dass durch das Szenario „Unausreichende Muskelrelaxanzien Medikation" die Beteiligten zur Kommunikation angeregt werden?
- Was könnte man verbessern?

B.3 Bereich: Lehre

- Können Sie sich vorstellen eine Anwendung dieser Art in Zukunft zur Lehre zu nutzen?
- Falls nein: Was fehlt bzw. wieso nicht?
- Was würden Sie sich an Überwachungsmöglichkeiten für die Lehre wünschen?
- Was würden Sie sich dafür an Einstellmöglichkeiten wünschen?

B.4 Bereich: Allgemein

- Was hat Ihnen an der Simulation besonders gefallen?
- Was hat Sie an der Simulation gestört?
- Haben Sie weitere Verbesserungsvorschläge?

C Interview Questions (translated to English)

C.1 Topic: Realism

Scenario A: Undetected Bleeding

- Do the vital signs used illustrate the Scenario "Undetected Bleeding" identifiably?
- What was missing or how could the illustration be improved further?

Scenario B: Insufficient Muscle Relaxant Medication

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

Existing 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
- Which functionalities did You miss? Were there enough choices for the given options?

Interaction Possibilities

- Were the following interaction possibilities intuitive or difficult to learn?
  - Teleportation

- Controller-Interactions with objects
- Laser-Interactions with menus
- Laser-Interaction with objects

- Was there something that bothered You or You would have liked better?

C.2 Topic: Communication

Scenario A: Undetected Bleeding

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

Scenario B: Insufficient Muscle Relaxant Medication

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

C.3 Topic: Teaching

- Can You imagine Yourself to use an application like this for teaching in the future?
- What should be included so You would do 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?

C.4 Topic: General

- What did You like about the application?
- What bothered You in the application?
- Do You have any recommendations to improve the application?