Ph.D. Dissertation

Investigation of the adjustable three-dimensional simulator for surgical planning

February 2023

Graduate School of Engineering

Seoul National University

Electrical and Computer Engineering

Wang Zihuan

Investigation of the adjustable three-dimensional simulator for surgical planning

수술 계획을 위한 가변형 3 차원 모의수술장치 연구

지도교수 서종모

이 논문을 공학박사 학위논문으로 제출함

2023 년 2 월

서울대학교 대학원

전기정보공학부

왕재환

왕재환의 공학박사 학위 논문을 인준함

Chair	조남익
Vice Chair	서종모
Examiner	원태빈
Examiner	박재형
Examiner	이종호

Abstract

In the past three decades, simulation has become a key tool for training doctors and maintaining patient safety. Simulation provides an immersive, realistic way to learn technical skills. Recently, the training programs of many surgical specialties have changed, coupled with other pressures (such as reducing operation time), which means that surgery has changed from a traditional apprenticeship model to a competency-based model. Simulation can be a standardized and safe method of training and evaluating surgeons. With the development of laparoscopic technology, the use of simulation for training has become important, and there is evidence that virtual reality simulators have been used to allow experts to plan complex surgeries and assess perioperative risks. In this article, we have shown how to use real patient data and use virtual reality technology to develop a system that allows users to plan surgery. Not only that, but with this system, doctors can more easily explain the situation to patients or their family members, thereby enhancing the trust between them.

Keywords : surgical planning, surgical training, Surgical education, VR, 3D printing, surgical simulation

Student Number : 2016-39052

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1. History of surgical simulation

Surgical simulations are growing in popularity due to their efficacy and efficiency in training surgeons in various fields. New surgeons need ongoing practice, and surgical simulations provide a safe way to gain experience. One of the earliest known uses of surgical simulations was for nasal reconstruction in India around 600 BC [1] [2]. Early surgical training also involved using wooden models, live animals, and human corpses [3]. Ambrois Paré, considered a father of surgery, used anti-corrosive bodies to practice new techniques [4]. Through simulations and practice with lifeless models, surgeons have developed innovative techniques while avoiding putting patients at risk.

The next big advancement in medical simulation occurred in the 1980s with the use of human models for anesthesia training. The first successful commercial human model, the Comprehensive Anesthesia Simulation Environment (CASE), was created to train and evaluate physician abilities in anesthesia and critical care. These early manikins utilized microprocessors and computer software to imitate vital signs that react to interventions, emergencies, and other relevant factors. The success of the CASE series resulted in the creation of the Boston Anesthesia Simulation Center, the first center dedicated to medical simulation using human models [5]. Since then, human models have utilized wireless technology, and high-fidelity portraits and computer images have been developed to achieve outstanding realism in training a variety of surgical procedures [6].

The field of innovative surgical simulations with the greatest potential for expansion is the VR simulation first introduced in the 1990s. VR simulation is a computer-based system that allows practicing surgical techniques on a computer. Surgical interns use tools to manipulate a series of computer images for surgery in a virtual environment including the first VR simulator of virtual Achilles tendon repair, cholecystectomy, wound debridement and suture [6-8]. Unlike previous simulation models, VR simulators are safe, ethical and repeatable. Over time, the integration of extensive clinical research simulators and new technologies related to VR has led to the development of increasingly effective, universal models. For example, minimally invasive surgical trainer virtual reality (MIST-VR) and other VR tools have demonstrated improved performance in the operating room for laparoscopic surgery [9, 10]. Today, VR simulators combine computerized operating room images with actual surgical tools, and these "hybrid simulators" mimic fine details and high-fidelity of the entire operation well [11]. The latest development in surgical simulation involves creating a simulation program for robots, the Da Vinci assisted surgery system. For example, the Robotic Surgery Simulator (RoSS) is a stand-alone device that teaches novice surgeons the skills required to perform Robotic Assisted Surgery (RAS) [12]. In addition, the simulation software can be loaded directly onto Da Vinci [6]. As RAS gains prominence, we expect to see more Da Vinci training simulators shortly.

1.2. Surgical simulators

1.2.1. Live animals

Surgery on live animals is an effective form of surgical simulation because animals have many of the same functions as those of humans. Successful operation of anesthetized animals requires proper control of the hemostatic system, which is also required for human surgery [11]. The advantage of using live animal simulation is that the surgeon can have hands-on experience in every element of the operation, not only with the skills involved in the operation, but also with mitigation plans for possible complications and contingency plans if they were to occur. In addition, since operating on live animals is very close to the actual operating environment, using these simulators allows resident physicians to enhance their communication skills and teamwork necessary in the operating room [11, 13].

Figure 1. An anesthetized pig used for training a surgeon [96]

Due to many benefits of dealing with live animals, pig and dog models have been widely used for endoscopy, laparoscopy, and other forms of training, including endoscopic submucosal dissection, cholecystectomy, and coronary bypass surgery [11, 14] . There have been many studies on the effectiveness of these forms of training, and most studies have verified that they can effectively improve technical skills and self-confidence [14-16]. Ex vivo animal tissue is also sometimes used in surgical training, but provides lower fidelity than live animals. Usually, animal tissue is combined with a desktop synthetic model to create a high-fidelity simulator [17]. Of course, there are also disadvantages to using animals in surgery. First, there are structural differences between human and animal anatomy. Moreover, some ethical issues arise when using animals as surgical simulators. In fact, the UK bans the use of live animals for surgical simulation [11]. Finally, the use of live animals for surgical simulations is very expensive and requires a concerted effort of associated staff to monitor changes in hemostasis.

1.2.2. Cadavers

Fresh cadaver tissue is a gold standard for surgical simulation due to its resemblance to live tissue [18]. Cadaver tissue offers a more accurate simulation of actual operating room anatomy compared to animal models. Although using dead tissue differs from live tissue in terms of physiological conditions, autopsy procedures that involve blood perfusion create high-fidelity models for vascular, microvascular, and trauma surgery. [18-21].

Figure2. The Anatomy Lesson of Dr. Nicolaes Tulp by Rembrandt shows an anatomy lesson-taking place in Amsterdam in 1632 [97]

In addition, corpses have been used to train flap coverage techniques and various endoscopic and laparoscopic procedures [22, 23]. However, the anti-corrosive corpse has poor tissue compliance, which makes some operations difficult [24]. Human corpses are also expensive, and their limited availability limits their widespread distribution and use [25]. In addition, corpses require regular maintenance and special facilities, and are actually found not suitable for use in certain procedures. Therefore, it is important to determine the environment in which cadaver training is superior to other simulation methods to ensure proper allocation of resources. For example, surgeons in orthopedic residency programs and joint replacement courses can gain confidence working with cadavers [26, 27].

1.2.3. Bench-top and laparoscopic box simulators

With advancements in technology, tabletop simulators have emerged as synthetic self-contained models for practicing and evaluating surgical skills. Low-fidelity benchtop simulators offer training in techniques such as knotting and stitching, while high-fidelity desktop simulators, combining synthetic and animal parts, have been developed to simulate complete procedures like fracture fixation, joint replacement, and aneurysm repair[17, 28]. Due to their simplicity and effectiveness, educators to quickly train novice surgeons and assess their proficiency frequently use tabletop simulators.

Figure 3. Lap VR (CAE, Montreal, Canada). [98]

Minimally invasive surgery simulators have also been developed to train surgeons in a closed environment that includes a camera to observe their movements. One of the most popular laparoscopic simulators is the McGill Lifeless Laparoscopy Skill Training and Evaluation System (MISTELS) which includes basic laparoscopic skills tasks like peg transfer, cutting, ligature ligation, and suture [29]. High-fidelity laparoscopic simulators, utilizing 3D printing technology, can recreate complex procedures under realistic conditions, such as laparoscopic pyeloplasty and thoracoscopic esophageal atresia repair [30, 31]. These simulators offer a more accurate representation of minimally invasive procedures.

Recently, 3D printing has been used to create patient-specific models for preoperative planning of complex procedures [32]. The efficacy of benchtop and laparoscopic box simulators in improving surgical skills has been proven in multiple studies [25], [33-36]. Observed benefits using these simulators include the development of hand-eye coordination and flexibility in performing surgical tasks. Scott et al created a standardized curriculum for cost-effective knot-tying and suturing skills. It has been found that surgical techniques can be transferred in a cost-effective manner in the training of surgical residents using this simulation technique [35, 36]. In addition, the advantages of MISTES in laparoscopic training are widely known, making them useful in many surgical training programs [29].

The disadvantage of these simulators is that although high-fidelity models can replicate complete operations, they are expensive and not easily available, whereas the low-fidelity simulator teaches only the rudimentary surgical skills. Furthermore, both low-fidelity and high-fidelity benchtop / laparoscopic box simulators combine synthetic materials, which limits the degree of reality they can achieve compared to cadaver and animal simulators.

1.2.4. VR simulators

Virtual Reality (VR) surgical simulators enhance the development of surgical skills with simulated tools that interact with virtual environments. The advancement in computer processing power and graphics capabilities has enabled modern VR simulators to create realistic environments that accurately depict fine anatomical details [37]. These simulators offer reusable, high fidelity, anatomically correct simulations, and the convenience of performing multiple simulations on one computer-based unit. One example is the NeuroTouch VR neurosurgery simulator, which offers simulations of procedures such as microdissection, tumor aspiration, reduction, and hemostasis [38].

Figure 4. 3D Systems Leverages Virtual Reality to Advance Surgical Training [99]

One of the most attractive features of VR simulation is that these systems are able to provide users with real-time haptic feedback about their performance in the simulation. They provide objective and quantitative assessment of the trainee, and common indicators produced by VR simulators include time to complete tasks, economics of surgery and surgeon motion [39]. Therefore, VR simulators provide direct advantages over other simulators by allowing trainees to practice repeatedly without supervision while receiving direct feedback from the simulator itself. In addition, tactile indicators generated by VR simulators enable educators to assess and monitor the proficiency of novice surgeons and their improvement over time [40]. Most VR simulators are designed to teach laparoscopy and endoscopy procedures [29], as their dependence on video surveillance makes them natural for VR platforms.

Low-fidelity simulators ("task trainers") that teach basic surgical procedures and high-fidelity models of complete surgery are commonly used in VR as well. For example, the MIST-VR system is a low-fidelity system designed to teach basic laparoscopic techniques, stitching, and knotting [41]. High-fidelity VR systems include LapSim, Lap Mentor, and NeuroTouch. Leadership is a particularly inclusive system that includes more than 65 cases of surgery, gynecology, urology, and bariatric surgery in the general field.

There is substantial evidence to support the use of VR simulators in surgical training [9, 10]. VR simulations have been found to reduce surgery time and improve the performance of prospective surgeons [10]. In addition, performance indicators generated by VR simulators have been shown to be closely related to the operating

room performance [42, 43]. The disadvantages of VR simulation include high cost, lack of force feedback, and limited authenticity of some simulation models [44]. However, with the development of VR technology, simulators have become more cost-effective and better able to replicate human anatomy. Due to the versatility of VR systems and evidence of their efficacy in improving surgical performance, it is recommended that these simulators be formally incorporated in surgery courses [45], [11].

1.2.5. RAS simulators

Robot-assisted laparoscopic surgery (RAS) simulators were introduced relatively recently in the field of surgical simulation. The DaVinci Surgical System was first introduced in the United States in 1999. It involves a surgeon who uses a foot pedal, dual-handed control and a controllable 3D camera to guide robots for surgery [46]. The DaVinci system is designed to fit naturally into VR simulation; by using the simulator, surgeons can view virtual endoscopic videos in real time rather than through the user interface.

There are four main RAS simulators used in the DaVinci system: SEP-Robot, RoSS, dV-Trainer, and DaVinci Skill Simulator. The DaVinci Skill Simulator is a hardware package that integrates a VR simulator with a real DaVinci device, while RoSS and dV-Trainer are standalone devices with controls similar to the DaVinci system. These low-fidelity simulators are used to train hand-eye coordination, tissue manipulation, stitching, and knotting. The DaVinci simulator generates performance metrics based on completion time, error metrics, and motion analysis, making it a widely used tool for training novice surgeons in RAS. Studies have shown that using RAS simulators can accelerate initial console training for surgeons [46-48].

Figure 5. Da Vinci ® Surgical Skills Simulator™ [100]

Some studies have shown that the Da Vinci Skill Simulator may be a valuable tool for assessing RAS technical skills and RAS surgeon certification [47]. However, the available DaVinci simulators have been criticized for their high cost and lack of high-fidelity surgical simulations [46]. Development of the RAS simulator is still in its infancy, so cheaper and more complex systems are expected in the future. In addition, more research is still needed to confirm the transferability of the acquired skills from RAS simulator to Da Vinci [49].

1.3. Innovations in surgical simulation and simulators of the future

Traditional surgical simulations have involved practicing common procedures and tasks that are likely to be encountered in the operating room. Simulators that train simple hand-eye coordination skills, knot-tying, and suturing have wide utility because these operations are frequently performed. However, modern advances in technology have enabled development of surgical simulators that replicate complex surgeries unique to the anatomical variations and disease states of actual patients [54]. These patient-specific surgical simulators achieve the highest level of fidelity by allowing surgeons to practice the specific case they will perform on models that accurately represent their patients. Additionally, augmented reality combined with wireless technologies is making telesurgery a legitimate tool for expert surgeons to guide novice surgeons in complex operations. Therefore, recent innovations in the surgical simulation are focused on improving surgical outcomes, either by increasing the operating expertise of the surgeon (rapid prototyping and patient-specific VR) or increasing access to expert surgeons (telesurgery).

1.3.1 Patient-specific VR simulator

VR surgical simulations using patient imaging data is another effective way to practice a procedure preoperatively. While many surgeons simulate procedures mentally before entering the operating room, the mental simulation does not allow information sharing among team members and might unintentionally forget important details. Anatomically accurate VR simulations with patient-specific anatomy eliminate the risk of human error and allow visual communication of surgery plans not only within the team, but also with the patients themselves [59].

Recently, patient-specific simulators have been utilized in a variety of surgeries, including keratectomies, hepatectomies, renal surgery, and hand surgery [59-61]. One such simulator, used in renal surgery, captures patient CT data and reproduces it on a 3D virtual simulator, allowing surgeons to practice laparoscopic procedures preoperatively with accurate renditions of the patient's anatomy [61]. With up to 100% accuracy in capturing structures such as tumors, ureters, and renal vessels, the simulator's overall accuracy is high [61]. Generating these simulations is also relatively quick, taking around two and a half hours for certain procedures [59]. These technologies can be valuable tools for preoperative planning of complex surgeries and are readily reusable, unlike 3D printers, making them economically efficient. However, patient-specific VR simulation is a new technology and requires further validation.

1.3.2 Virtual interactive presence and augmented reality (VIPAR)

With higher camera resolutions, faster internet connectivity, and the emergence of augmented reality, new technologies now allow surgeons to collaborate remotely. One such system for remote surgical cooperation is Virtual Information Processing Agent Research (VIPAR) [62]. Through this system, the visual field of a surgeon is converted into a simulated field of vision projected to the surgeon from the device. As a result, the operating surgeon can be apprenticed in real time by a more experienced surgeon. The VIPAR system utilizes augmented reality technology to enable audiovisual collaboration over the internet with just a 760 *ms* of delay [63]. As a result, participants at different locations are able to collaborate to identify anatomical structures, guide surgical maneuvers, and discuss the overall surgical approach.

The clinical use of VIPAR has been validated in numerous studies. For example, VIPAR has been used in orthopedic surgery for training residents with an attending surgeon immediately available in an adjoining room. The surgeons utilizing the VIPAR system [64] rated this practice, known as telemetering, positively. Additionally, VIPAR is feasible for long-distance tele collaboration in neurosurgical studies on cadavers [64]. Finally, the system is highly affordable, which costs $15,000 for one year of use [65]. Because of its low cost and clinical applicability, VIPAR presents one potential way to improve collaboration and facilitate training.

1.4. 3D printing in surgical simulation

In recent years, 3D printing technology has been applied to medical imaging (including CT and MRI) to create patient-specific 3D models to assist doctors in making surgical plans. Currently, multiple technologies are being used to build comprehensive models of patient-specific organs and vasculature. These technologies include fuse deposition, stereolithographic, scintigraphy, and 3D printing [50]. Some newly developed multi-material 3D printers can generate models with multiple different tissue types. As a result, some models made by rapid prototyping can realistically replicate the anatomy of real patients [32], [50-53]. However, due to the limitation of printing speed and the urgent situation of emergency surgery, a 3D printing surgery site is not an optimal choice.

Some of the most pioneering work in rapid prototyping is performed in the field of neurosurgical simulation, where 3D printers are used to create reliable models of patient-specific cerebrovascular pathology based on information provided by CT angiograms. When printed with these models, they can surround the bone structure, allowing surgeons to plan the trajectory of the aneurysm and test different aneurysm clips to obtain the appropriate size and shape [50, 51]. In addition, rapid prototypes have been used in cardiac surgery, where 3D printed heart models drawn from patients' cross sectional images were used to simulate and train staff for postoperative intensive care [52]. Many studies have agreed with the benefits of using 3D printing before surgery, noting high correlation between 3D printed models and the anatomy of actual patients [53]. Besides, studies have shown that surgeons consider these models easier and better to use than the traditional imaging simulation [50], [54]. With enough evidence to support the benefits and accuracy of rapid

prototyping, it is possible to routinely print 3D models to plan procedures and improve patient prognosis.

1.4.1 3D rapid prototyping

3D rapid prototyping involves using medical imaging, including CT and MRI, to create patient-specific 3D models than enable the planning of various operations. Multiple technologies are currently being used to build synthetic models of patient-specific organs and vasculature. These technologies include fused filament deposit, stereolithography, scintigraphy and 3D printers [54]. Some newly developed multimaterial 3D printers can produce models with multiple tissue types. As a result, some of the models produced by rapid prototyping are able to replicate actual patients' anatomical structures with remarkable realism [37, 54-57].

Some of the most pioneering work in rapid prototyping is occurring in the field of neurosurgical simulation, where 3D printers are used to create reliable models of patientspecific cerebrovascular pathology from information provided by CT angiograms. When printed with the surrounding bony structures, these models allow the surgeon to plan the trajectory of approach to aneurysms and to test different aneurysm clips for the appropriate size and shape [54, 55]. Additionally, rapid prototyping has been used in cardiac surgery, where 3D-printed heart models rendered from cross-sectional patient images have been used in simulations to train staff on postoperative critical care [56].

Many studies have shown the benefit of using 3D printing preoperatively. One study found a strong correlation between 3D-printed models and the actual patients' anatomy [57]. Additionally, studies have shown that surgeons using these models find them easy to use and superior to the use of traditional imaging alone [54, 58]. With further evidence supporting the benefits and accuracy of rapid prototyping, it

is possible that 3D models will one day be routinely printed to plan procedures and improve patient outcomes.

1.5. Computer graphics and visualization

Visualization and 3D rendering technologies are probably the most developed of all the components that make up a neurosurgery simulator. The need to visualize the complex spatial relationships between structures displayed in image data from several modalities in 3D has driven research efforts on patient data display before surgery.

Volume rendering was used to depict the gyro anatomy of the brain fused with positron emission tomographic image data to facilitate preoperative planning as early as the late 1980s [43]. When using volume image data, as opposed to surface rendering, direct volume rendering can often reproduce the basic geometric structure more reliably despite its higher computational cost [1]. However, with the enhancement of the capabilities of modern graphics processing units, the latest technology is capable of rendering multi-modal images in real time and with high quality [13]. In a simulation environment, volume data is often used in conjunction with polygonal representations of surgical instruments and other segmented structures. A rendering technique must be designed to accommodate these two representations [44].

If the purpose of the simulation is primarily to teach the understanding and manipulation of visual space, then an illustrative rendering of anatomy and pathology is sufficient. In fact, for this purpose, visualizations that selectively convey the most surgically relevant information are often better than physically realistic renderings [45]. However, if the purpose is surgical training or rehearsal in an immersive virtual environment, the goal of visualization may be to look as close as possible to what the surgeon actually sees in the surgical field of view. Correctly

synthesizing such images is equivalent to simulating the transmission process [46] when light is reflected from a surface or scattered through a tissue, which is a computationally expensive problem. Although this physically-based rendering of volume data is difficult to achieve at an interactive rate (typically a 15 Hz visual update rate is required to maintain the performance of psychomotor tasks) [47], recent research has shown that modern graphics processing units can calculate complex lighting models at an acceptable rate [48].

In terms of graphic display hardware, the topic worth discussing is stereo rendering, which provides one of the main depth clues needed to understand the complex spatial relationships in 3D [49]. Although stereo computer displays have been around for decades[50], their high cost and limited quality have hindered the development of virtual reality simulations. However, it currently appears that stereo rendering is recovering, which is mainly driven by trends in the entertainment industry[51]. Although immersive virtual environments previously cost thousands of dollars in display technology, high-resolution 3D displays are now available for business desktops and laptops and can be assembled for less than $ 1,000. This technology is good news for designers because it makes it easy to widely deploy immersive simulation software on personal or portable computers used by surgical interns or doctors.

1.6. Purpose of Research

In this thesis, the following three problems were investigated and improved.

1. Sense of reality and user calibration.

Since each individual has a different perception of 3D vision, the model used in the existing method is a specially customized model. The user knows that the model used in the exercise is different from the actual patient, so the existing method focuses on the user's subjective feelings and observation distance, to adjust the depth value according to the user's comfort.

This thesis uses real patient data. Compared with the comfort of the user, it focuses more on the accuracy of the restoration model. Therefore, in this article, based on the user's pupillary distance and observation distance, additional consideration given to the size and resolution of the display to calculate the optimized depth value.

2. Use real patient data to build a 3D model through automatic segmentation of HU values.

Existing surgical simulators use special examples. Models and blood vessels are manually segmented and more accurate than automatic segmented case relatively. However, in clinical applications, the current method is obviously flawed in that it cannot be applied to the real data of every patient, because manual segmentation will consume a lot of work and time. At this time, an automatic segmentation method has to be considered. In this article, a method of using HU value automatic segmentation has been used and to some extent realize automatic segmentation of bones, skin, muscles, and blood vessels.

3. A way to explain the condition to patients or their family members and strengthen their trust in doctors.

The traditional general method is to use CT images to explain the condition of the patient and his family. For some special conditions, some hospitals will prepare physical models.

The traditional method has two disadvantages. First, most patients and their families do not have the professional knowledge to fully understand CT images. When using CT images for explanation, doctors can accurately point out the problem, but patients and their families without professional knowledge, cannot get accurate information. Second, the traditional physical model cannot reflect the real situation of each patient. In this thesis, with the solution of problem 2, we propose a method to explain the condition to the patient, which can solve the above two problems.

4. A simpler method, using the existing equipment in the hospital as much as possible, can construct a three-dimensional environment and reproduce the operation process.

Considering the factors of cost and convenience, here we use the traditional 3D vision method, sacrificing some accuracy, but focusing on the practical aspect, and propose a device design that can help doctors perform 3D surgical reconstruction.

The general idea is shown in Figure 19. The impact of the operation will be transmitted to a view box through the commonly used devices at present, and the observer can experience the three-dimensional image through this View box.

Chapter 2. Related Research

2.1. Binocular disparity

The visual cortex receives information from numerous neurons, each of which responds selectively to a specific feature in the visual scene. For example, edges and their orientation in space carry an enormous amount of information about the visual environment and each neuron responds only to a narrow range of edge orientations: horizontal edges activate some neurons, vertical edges activate other neurons and still other neurons respond to different orientations in between. The visual cortex gathers all the incoming information and, depending on which neurons are activated, reconstitutes visual representations of the surrounding environment.

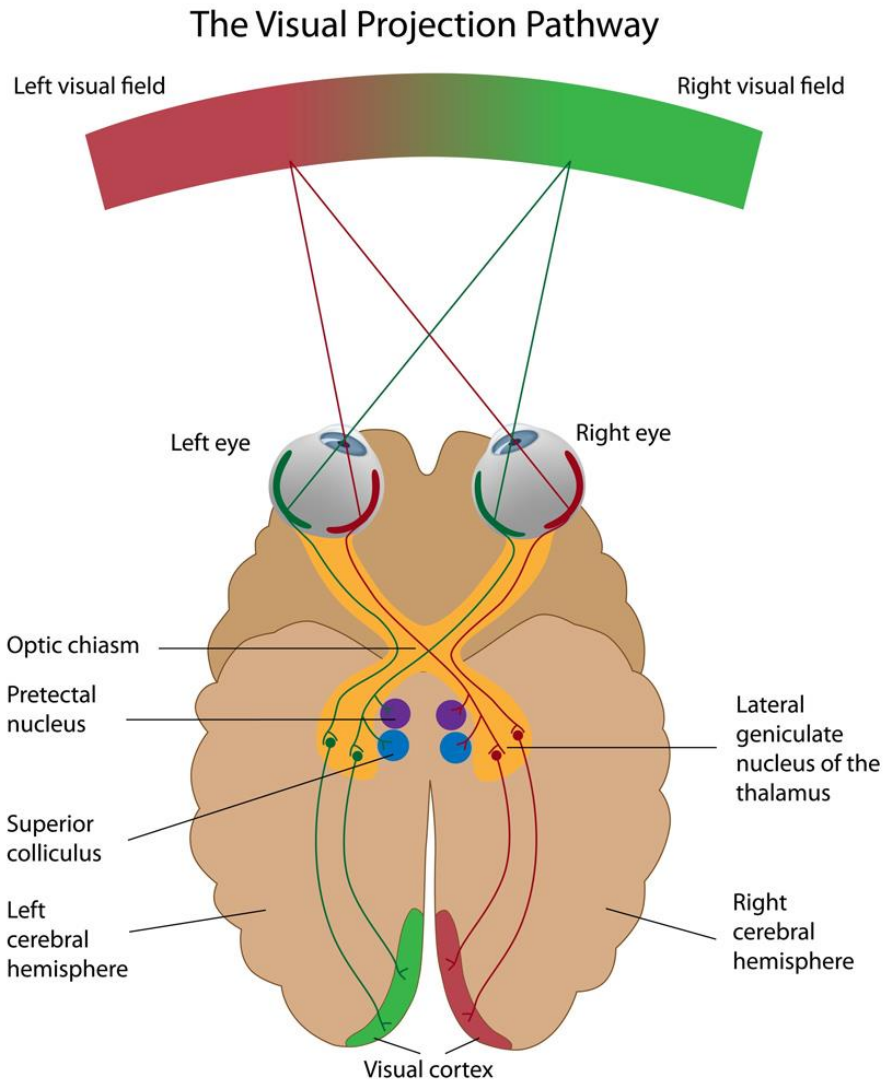


Figure 6. Principle of binocular vison [101]

2.1.1 Binocular disparity

Although the input of the visual system (the image projected onto each retina) has only two spatial dimensions, we can perceive the world from three angles. It is well known that the visual system can recognize three dimensions from various visual cues in retinal images. One such cue is binocular parallax, the positional difference between two retinal projections at a given point in space (Figure 6). It is also referred to as binocular disparity, and it is the basis for stereoscopic vision and depth perception. This positional difference is due to the two eyes being spaced apart on the side. The two eyes mostly provide similar optical images projected on the human retina, but the world is seen from two slightly different vantage points. Therefore, the two monocular images perceived from each of the two eyes construct information highly critical for vision processing, not available if an image was projected single-handedly.

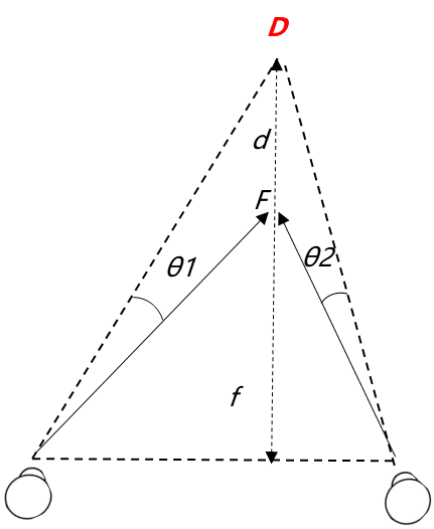


Figure 7. Binocular parallax

The fixation point is projected to two corresponding foci (fs), and parallax is zero by definition. It can be seen from Figure 7 that all zero parallax points on the plane fall on a circle passing through the fixed point and the two eyes (or more precisely, the nodes of the two lens systems). All other points are not projected to corresponding locations on the two retinas and have a non-zero parallax. The magnitude of parallax is usually expressed in terms of viewing angle in relation to the line of sight from the fixation point.

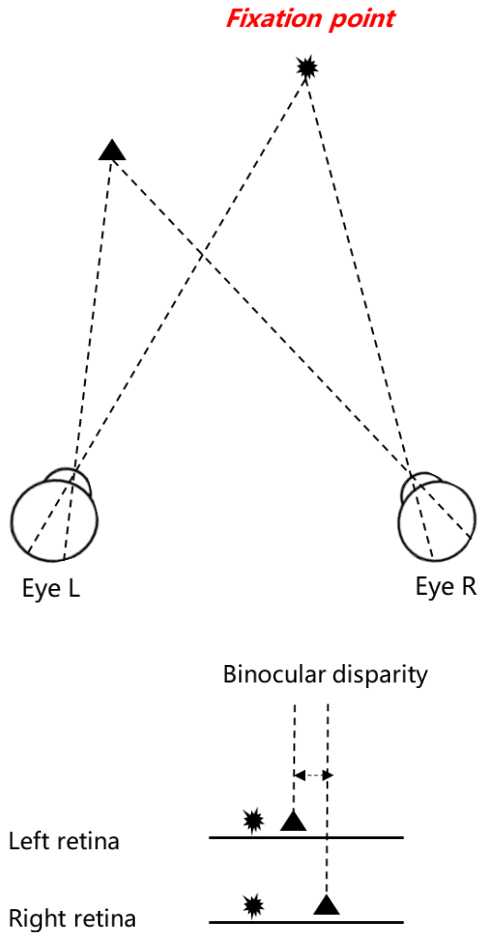


Figure 8. The Geometry of Binocular Projection (Top) and the Definition of Binocular Disparity (Bottom)

2.1.2 The correspondence problem

In order to measure binocular parallax, the vision system must solve the problem of correspondence: it must determine which part of the two retinal images come from an object. Historically, it has been proposed that the visual system solves this problem by matching image features between the two retinas. In the case of a random point stereogram, the correspondence problem is usually stated as identifying which point in the left image matches which point in the right image. Since all points in the two images have the same shape, it is often argued that any two points can be matched, and the visual system faces a very difficult problem, which is to separate the true matches from a large number of mismatches. This argument is the starting point of a complete set of stereo algorithms [22, 33, 35, 23]. However, this is not physiologically correct because the left and right receptive fields of a typical binocular cell may be much larger than the points in the stereogram. Monkey striate cortex, which represents the fovea, maximum visual acuity and minimum receiving area, has a size of about 0.1 degrees. When viewed from a distance greater than 35 cm, this size is more than twice as large as the points in the stereogram in Figure 6. A closely related fact is that most cells are widely tuned for difference recognition. Even the most tuned unit has a tuning width of about 0.1-0.2 degrees [11, 31]. Therefore, it is difficult to imagine how a cell matches a particular pair of points while ignoring many other points in its acceptance domain. It seems more reasonable to assume that binocular cells are trying to match two image patches covered by their receptive fields, each of which may contain two or more points, rather than operating on fine image features such as a single point. Since each image patch may contain a unique point distribution, it is best to match only one (corresponding) patch in another image. Therefore, for algorithms that avoid operating at the level of a single

point, the mismatch problem does not actually exist. The Stereo model demonstrated that complex cells in the eyes, as described by Ohzawa et al. (1990), have suitable physiological characteristics, which can match the image plaque in its receptive field. After careful mathematical analysis of the complex cells of the model, it is found that their calculation form is equivalent to the sum of the two correlated cross products of the left and right image blocks after band pass filtering. This operation is related to cross-correlation, but it overcomes some of the main problems of standard cross-correlators.

2.2. 3D visualization

2.2.1 Depth perception in electronic stereoscopic images

[62] proved that by showing a separate 2D image to each eye, a sense of stereo depth can be recreated. From a slightly different perspective, the views from left and right should be 2D flat images of the same scene; differences in viewpoints can cause parallax in the image. When subsequently viewing the image, the observer perceives the depth in the scene, because image differences produce retinal differences that are similar but not the same as those seen when looking directly at a natural scene.

Wheatstone proved this effect by making the first stereo mirror, a myriad of devices for stereo image rendering, each device with its own optical configuration. Reviews of these devices and the history of stereo imaging can be found in multiple sources [23, 55, 41, 33, 30]. To help characterize and compare the performance of different electronic 3D display designs, we consider the depth perception in flat stereo image pairs and how it differs from the depth stereo perception in the natural world. The key physiological difference is that although the eyes need to turn out from the stereo image plane to fix the depth point, their adaptation state must always keep the image plane itself in focus. This requires the observer to be able to change the normal connection between divergence and adaptation, which is one of the reasons why it is difficult to observe images with a larger perceived depth. This indicates the necessity to limit the perceived depth range in a stereo image pair to ensure that the observer is able to find a stereo image pair that is comfortable to look at. Although several studies were conducted on the comfortable range of perceived depth on electronic 3D displays [67, 17, 66], it is difficult to ignore other factors related to display performance. In addition to stereo image alignment and crosstalk, display variables

include absolute values of brightness and contrast, as well as changes between channels. All of these components affect the comfort range of perceived depth on a particular display. For example, displays with high-crosstalk often do not support dark images properly because as screen parallax increases, the ghosting effect interferes more with the observer.

Assuming the display has an ideal performance, analyzing the geometry of the perceived depth helps identify geometric variables that affect the perceived depth independently of the display used. Helmholtz [23] and Valgus [55] studied geometric models of perceived depth, and have recently studied them in [24, 66, 8, 27]. A simplified model in Figure 7 is presented for discussion, which helps to highlight the key geometric variables that affect the. Perception of stereo images. Figure 8 shows the geometry of the perceived depth of a flat stereo display. For simplicity, we only consider the geometry along the centerline of the display. More general expressions can be used [23, 66]. The viewer's eyes, L and R, are separated by an intraocular distance e, and the viewing distance from the display plane is z. The screen disparity d between corresponding points in the left and right images is a physical distance caused by the image parallax, and the physical distance is a logical value measured in pixels. For a given stereo pair, the image parallax is constant, but the screen parallax varies depending on the characteristics of the physical display. The screen parallax in a pair of aligned stereo images is just the difference in the physical x coordinates of the corresponding points on the right xr and left xl images::

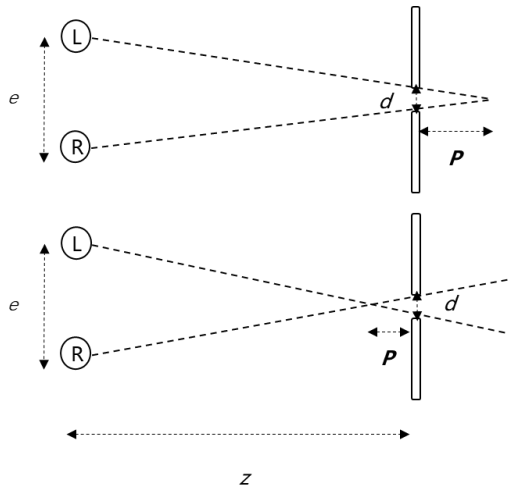


Figure 9: Perceived depth behind (up) and in front (bottom) of the display plane.

$$d = \mathrm{x_r} - x_l \tag{1}$$

Two key expression relating screen disparity to perceived depth can be derived from the similar triangles in figure 9. Perceived depth behind the screen plane, i.e. positive values of d, is given by:

$$p = \frac{z}{\left(\frac{e}{|d|}\right) - 1} \tag{2}$$

Perceived depth in front of the screen plane, i.e. negative values of d, is given by:

$$p = \frac{z}{\left(\frac{e}{|d|}\right) + 1} \tag{3}$$

Equations (2) and (3) provide several insights into the geometric factors affecting perceived depth:

• *z*, the viewing distance to the display. Perceived depth is directly proportional to the viewing distance, z. Therefore, a viewer looking at the same stereoscopic image from different distances perceives different depth. How important this is, is

application dependent, but applications such as CAD, medical imaging and scientific imaging may critically depend on accurate and consistent depth judgements.

• *d*, the screen disparity. Perceived depth is also directly proportional to screen disparity, d. The screen disparity for any given stereoscopic image varies if the image is displayed at different sizes, either in different size windows on the same screen or on different size screens. Again, this is important to note in applications where depth judgement is a critical factor. It means stereoscopic images are display dependent and an image displayed on a larger display than originally intended could exceed comfortable perceived depth limits or give a false impression of depth.

• *e*, individual eye separation. Perceived depth is inversely proportional to individual eye separation which varies over a range of approximately 55mm to 75mm with an average value often taken as 65mm. Children can have smaller values of eye separation and therefore see significantly more perceived depth in a stereoscopic image than the average adult. It may be particularly important to control perceived depth in systems intended for use by children, as they will reach the limits of their vengeance/accommodation capabilities sooner than most adults.

For display design controlling these variables so that the viewer sees a consistent representation of depth ideally requires tracking head position, identifying eye separation and controlling screen disparity. These are challenging goals in addition to designing a display with as good imaging performance as a 2D display.

The calculations for this table assume an observer eye separation of 65mm.

Table 1. Comparing characteristics of the generic displays and the eye.

Characteristic	**Twin-LCD** **Twin View**	**Single-LCD** **Twin View**	**Single-LCD** **Multi (9) View**
Total resolution	2*1280(h)*1024(v)	1280(h)*1024(v)	1280(h)*1024(v)
View resolution	1280(h)*1024(v)	640(h)*1024(v)	426(h)*341(v)
View pixel width	0.3mm	0.6mm	0.9mm
View distance	750mm	750mm	750mm
Voxel depth: 0 pixels disparity	7mm	14mm	21mm
Stereo resolution (in +/-100 mm)	60 voxels	31 voxels	20 voxels

2.3. AR, VR for surgical planning

Preoperative planning is essential for the success and safety of surgery. This planning should be based on individual image data and is necessary for modern surgical care. CT and MRI are the typical methods used for preoperative imaging in otolaryngology. Image manipulation and measurements are usually performed using PACS tools and volume renderings, which limit the view to 2D cross-sections and screens and lack stereoscopy and dimensional control. Despite advancements in preoperative imaging, images are still viewed in 2D, making it difficult for surgeons to understand complex 3D relationships, even for experienced surgeons in complex cases. To overcome these restrictions, recent advancements in VR technologies have led to numerous VR applications for surgical planning [1]. These VR tools offer promising options for both surgical training and preoperative planning [2-4].

The first medical VR applications were introduced in the 1990s. They mainly focused on visualization of complex anatomy, preoperative planning, surgery training and telemedicine [5]. In recent years, the availability of consumer grade VR technology has brought back the interest for its medical use. The VR is a stereoscopic three-dimensional (3D) computer-generated environment, which provides an interactive stereoscopic 3D view of objects. The development of head-mounted displays and hand-held controllers with motion tracking sensors provide users with versatility and a possibility to approach the multidimensional anatomy of the patient at any possible angle. Users can freely control magnification, windowing of image parameters and mark or paint objects in the image view. State-of-the-art VR systems already reproduce 3D anatomy to a high level of immersion and authenticity not

achievable with conventional cross-sectional 2D images and thus may contribute to a better understanding of the anatomy in question [6]. The VR environment allows users to perceive critical anatomical landmarks and their relationship in the same virtual space, which adds to better memory recall compared to traditional 2D screen interface [7]. However, nausea, vertigo and headache have been reported with VR in 30–80% of the users, depending on the software [8, 9].

VR surgical planning is gaining increasing attention since it has been shown to augment operative accuracy, efficiency and outcomes [10–12]. However, there are only very few independent studies, which investigate the validity and accuracy of VR in authentic settings [13]. Best practice requires that new medical applications such as the VR surgical planning software be tested for subjective and objective validity [14]. Subjective validity is commonly evaluated with the face and content validity via different acceptance surveys by experts in the field. The face validation demonstrates the degree of resemblance between a method under investigation and real activity. The content validity is established by demonstrating that the system or the method measures what it is intended to measure in terms of e.g. surgery or planning [15–17]. Temporal bone (TB) and skull base anatomy are considered among the most complex anatomical regions in humans and their accurate evaluation and understanding is challenging even for experienced otologic and skull base surgeons. The aim of this study was to examine the accuracy of VR compared to cross-sectional viewing and to establish its feasibility in a simulated preoperative planning setting. Our hypothesis is that the accuracy of the VR environment is comparable to cross-sectional PACS viewing. However, it can be helpful if more

accessible information on the topographical anatomy in TBs is provided with better subjective validity compared to cross-sectional viewing.

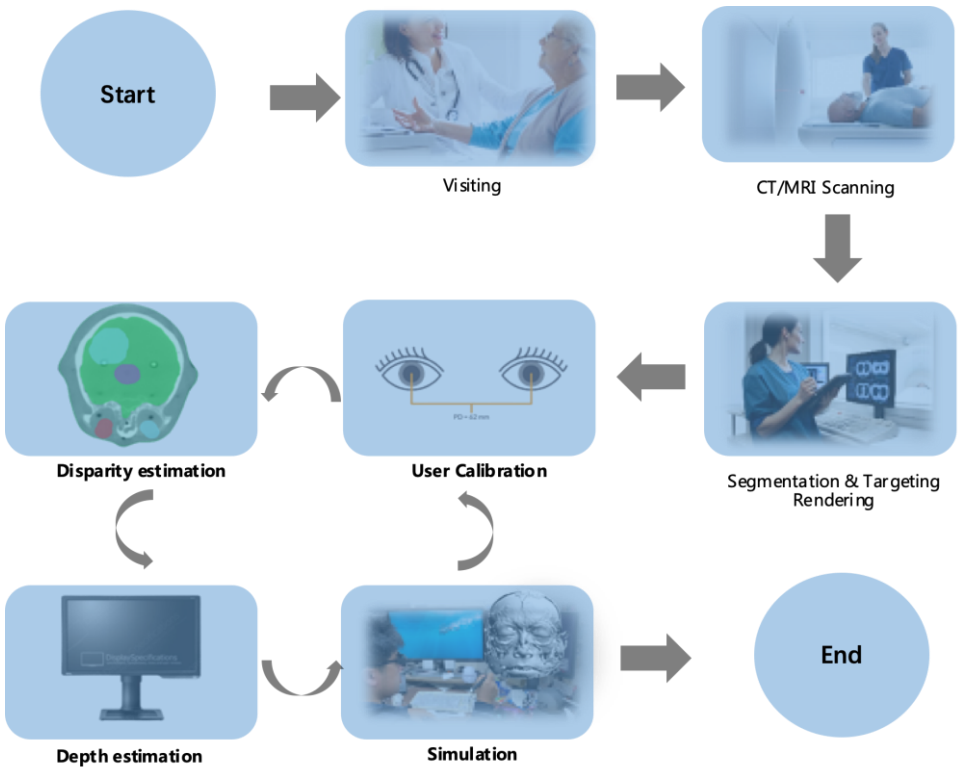


Figure 10. Consultation and surgery planning process

In the process of using AR, VR technology for surgical practice and planning, it is important to improve the accuracy of the model. This issue can be viewed in two ways: one is how we use the original medical data for 3D modeling, and the other is how we can use the 3D model in the virtual environment to present to our simulator users while reproducing the real situation as much as possible. Before addressing this issue, it is necessary to investigate what happens between the patient's visit and the surgeon's surgical planning rehearsal using the surgical simulator:

1. The patient feels unwell and goes to the hospital.
2. The patient goes to the radiology department for a CT/MRI as recommended by the surgeon.
3. The location of the lesion is manually or automatically segmented, and 3D modelling.
4. Calibration (pupil distance, lesion position, observation position) for the simulator user.
5. Calculate the disparity according to the settings of Step 4.
6. Calculate the depth value according to the size and resolution of the monitor used and the observation position set in Step 4.
7. The surgeon performs the exercise using the simulator

Here, the points where there is a possibility of error in the determination of the lesion location are.

- CT/MRI equipment: the accuracy of the equipment can lead to errors
- Segmentation of lesion location: physician's experience, or automatic segmentation algorithms can lead to errors.

- Different methods of 3D modeling may lead to errors.

In the past, there were many studies focused on the simulation of force feedback. In the field of visual simulation there are also some studies focused on simulation of 3D modeling, dedicated to improving its accuracy. It is worth noting that within the scope of the surgical simulation, i.e., from step 4 to step 7, there is also the possibility of errors. The most important of these is the calculation of the depth value, which depends on the pupil distance, the distance between the lesion and the observation, and the size and resolution of the monitor. In step 7, the physician uses the simulator to perform a walkthrough in which the following values are changed in real time, considering the actual situation:

- Position of the lesion: the position of the virtual image of the lesion from the screen changes as the model moves, zooms in or out.
- Observation position: the position of the user's eyes from the screen.

These two points cause the depth value to change in real time. In other words, it is important to calculate the depth value in real time. This will be analyzed in detail in the following sections

2.4 Virtual Reality in Sinus Surgery

In surgical treatment of chronic sinusitis, endoscopic sinus surgery (ESS) has established its own standard treatment method, and its scope is expanding day by day in the surgical treatment of benign and malignant sinus and chronic sinusitis.

However, the sinuses are close to important structures, and fine bones separate each important structure and the sinuses with a thickness of only 0.5mm to 1 mm [13]. Therefore, beginners who are not familiar with endoscopic surgery are afraid of performing ESS. In addition, for the safety of patients, it is desirable to perform actual patient surgery after surgeons are fully familiar and confident with ESS. As mentioned in the introduction, while it is difficult to continue with the existing methods of training major doctors by practicing under the supervision of actual patients, there is still concern about how to effectively educate major doctors. In addition, it is reported that even if the actual patient or corpse is not used, if the surgeon is educated on the surgical method through multimedia before the operation, it can also reduce the complications during the operation [14]. The simulator for ESS training using VR technology is the Endoscopic Sinus Surgery Simulator (ES3), which was developed by the US military and Lockheed Martin (Lockheed Martin, Akron, Ohio, USA). It was jointly developed in 1998 and several research papers using it have been published [15, 16]. Especially in 2010, [17] compared the surgical techniques of 12 experienced ES3 emulator main doctors with 13 inexperienced ES3 emulator doctors. However, the above-mentioned equipment is only a prototype stage model, which is very expensive and it has not been widely used. The simulator released after ES3 is the McGill simulator (MSESS) of ESS. In 2014, [18] reported the results of the study using this simulator. MSESS uses CT images of real patients

to reproduce a virtual sinus cavity and adds a sense of realism by virtually adding a layer that feels like a real mucosa on the surface of each space. In addition, a 4mm virtual endoscope with tactile feedback function was added, and when the end of the endoscope gets in contact with the mucosa, the field of view becomes blurred to increase the sense of realism, and a virtual micro debridement running at 5000 rpm is also installed in the device.

The model includes the following:

1. Pass the endoscope from the nasal vestibule to the nasopharynx with minimal damage to the nasal mucosa;
2. Pass the endoscope and use minimal debridement to contact the maxillary mouth, sphenoid sinus mouth and nasopharynx;
3. Complete the anterior ethmoidectomy,
4. 5 pre-programmed exercises, including a complete posterior ethmoidectomy
5. Wide sphenoid sinus incision (quantification, comparison, report of performance of each step)

2.5 Virtual Reality in Facial Plastic and Reconstructive Surgery

The application of VR in the field of facial plastic surgery and reconstructive surgery can be roughly divided into three areas: surgical planning, surgical navigation and surgical education [77].

Figure 11. Most used haptic devices, Touch 3D systems [102]

In the field of facial plastic surgery, VR uses tactile devices, as shown in Figure 9, and AR instead of HMD, and sometimes 360° cameras are used for surgical education. The 360° camera used for surgical teaching requires higher resolution than the ordinary 360° camera, and is installed under the shadeless lamp with Jimmy Jib crane. Before performing facial fracture surgery, tactile devices can be used to move each bone fragment to make a surgical plan [78], and it can also be used to predict the degree of mandibular incision before performing facial contours [79]. In the navigation of facial plastic and reconstructive surgery, the AR method is mainly used, and the virtual image of the bone or target organ is matched with the actual patient's face and displayed. Through the displayed virtual images, it is possible to visually check the exact location to perform osteotomy, screw insertion or

implantation, prior to actually performing each procedure [80]. In addition, like sinus surgery, facial plastic surgery involves most of the neighboring bones, so anatomy and surgery education through VR image construction is helpful. [81] and [82] introduced a method for Lefort 1 osteotomy using immersive virtual reality teaching equipment, and drilled real patients while performing bone cutting and plate fixation through tactile devices. It allows the user to experience the forced feedback simultaneously. Due to the nature of facial plastic surgery and reconstructive surgery, a variety of procedures are used, and the method of performing the same procedure is slightly different, so it is difficult to know exactly how the operation is performed before directly experiencing and participating in the operation. By using a high-resolution 360°VR camera to record the operation, many aspects of the surgery can be captured in a single image, such as how the surgeon performs the operation, how to use the instrument, the posture of the patient, and the breath of the surgeon and assistants. When observing, the HMD wearer can experience immersion into the virtual world, just like entering the actual operating room and observing the operation directly from above. Through this process, medical students and doctors who are not familiar with a certain surgical procedure can be provided with more direct information about plastic surgery, which is very useful for teaching surgical assistant skills to nurses in the operating room.

2.6. Preoperative surgical planning

The surgeons only have a short period of time during the operation to carry out complex technical tasks. Hence, it could be vital to know beforehand what exactly has to be done, for two reasons: operation time would be decreased the risks could be reduced.However, to date doctors have not received enough training and methods to face these problems. [84]

It has been demonstrated in different studies that surgeons who are trained with physical models or surgical planning prototypes, known as phantoms (simulated biological bodies[85], had better skills in comparison with those who did not have the same opportunity[86]. One of the skills improved is application of the correct amount of force, since surgical simulation revealed that more than 50% of errors are attributable to excessive force[87]. In general, novice surgeons apply more force than they should in comparison with experienced surgeons. Considering the data[88], the average force applied is mainly around 0.5 N, although at specific moments, such as gripping tumor tissue, it might reach up to 1.25 N. Phantoms are also used for training prospective doctors in Medical Schools. As it is not always possible to practice with real human bodies, using phantoms can provide an excellent solution.

Regarding preoperative surgical planning, the surgical planning prototypes are manufactured for two reasons:

Visualization: these prototypes are manufactured in order to give the surgeon an idea of what to expect. In addition, these prototypes can be sterilized and introduced in the operation room for last-minute inquiries.

Mimicking live tissues: these prototypes are for preoperative surgical planning, in other words, for preparing the surgery. For that purpose, the materials need to mimic

the corresponding soft living tissue as closely as possible. However, as most of the materials used in this case are hydrogels, there will not be any chance to introduce it in the operating room.

The prototypes that are used just for visualization do not need to achieve a matching of mechanical properties of the soft living tissue and the material. However, if the prototype is introduced into the operation room, it needs to be either sterilized or left far from the sterilized surgery area.

Generally, surgical planning prototypes are additively manufactured using PA12 printed by SLS; filaments extruded by FFF and silicones extruded by DIW; resin-based polymers printed by SLA; and finally, liquid photopolymers drop printed by material jetting, and then cured by UV light;

Both steam sterilization by autoclave (121 °C) and ethylene oxide are used for prototypes done in SLS. Also, according to [89], Steam Formaldehyde at 60-80 °C can also be used for prototypes manufactured by SLS. This sterilization technique can also be applied to material jetting [89]. On the other hand, filaments are deformed if they are exposed to high temperature (more than 60 °C) and, therefore, ethylene oxide (EtO) or gamma radiation are the best options[90],[91]. Then, regarding the silicones extruded by DIW, their properties change if they are subjected to conventional high temperatures. Therefore, EtO would be the most effective sterilization method [92]. Finally, regarding SLA, hydrostatic pressure (HHP) showed more potential to be used in SLA than autoclave for SLA printed materials[93].

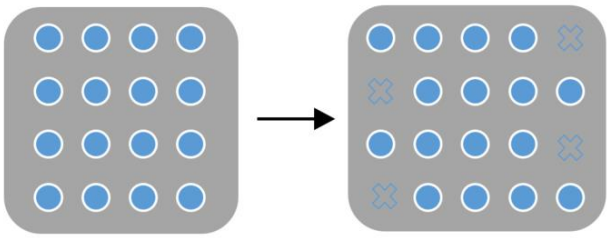
Chapter 3. Experiments and Results

3.1. Binocular depth optimization

3.1.1 Method for depth optimization

Binocular parallax is a property that can be extrapolated to formulate an input for 3D perception to be used in surgical simulations. In order to mimic 3D experience within a given 2D image plane, image interlacing technique is used. A general method to interlace an image is to separate odd and even rows of an image and dislocate its pixels with an offset of *n* pixels in either odd or even rows, as illustrated in detail in Figure 10. Clearly, we can find that even rows of pixels are shifted one bit to the right. Inevitably, the size of the image changes with the number of displacements. Generally, we fill these spaces with white color or colors like the background of the image.

One thing to notice is that determining *n* is the key for a good performance. Theoretically, the position of observation point determines the value of *n*. The disparity between two monocular images becomes more dramatic if an object is (more closely situated / further away), and the value of *n* needs to vary depending on the distance of the perceived object since disparity needs to be optimized at each depth level. Through experiments, we found an appropriate value for *n*. However, we cannot judge whether it is the optimal solution, which will be introduced in detail in the next section.



(a) (b)

Figure 12. (a) Image with 4*4 pixel (b) Interlaced image with 4*5 pixel 42lm5800

In this study, we used DICOM format images to convert them into point clouds a4t first. We use a rendering tool called “plotly” to do the rendering and put it on a web browser. After that, we map the 3D model to a 2D image and use the above method to convert it to an interlaced image so that we can observe it through a 42 inch 3D monitor (LG, 42LM5800).

3.1.2. Experiment results for depth optimization

Data used in this study was obtained from the National Lung Screening Trial chest CT dataset. Using the general method described above, we have different values of *n* and conducted many experiments, and the results are shown in Figure 13.

Figure 13-(a) shows the original image before interlacing. Figures 12(b-e) shows interlaced images with varied values of *n*. The figure from (b) to (e) describes interlacing with pixel offset values *n* = 5, 10, 15, 20, respectively. Obviously, it can be observed that the larger the *n* is, the more blurred and distorted the image becomes. However, the performance from 2D images is quite misleading because these distortions are the key elements required, which represents binocular parallax and depth perception for a 3D vision system. In the actual observation using a 3D monitor, it resulted in the best performance when *n* is 10, which means the even-numbered row is shifted 10 pixels to the right.

When *n* is greater than 15, the observer experiences a sensation of vertigo. As the observer moves away from the object being observed, vertigo diminishes until it disappears. It shows that there is no absolute optimal value for *n*, and the distance between the observer and the observed object determines whether the value of *n* is appropriate.

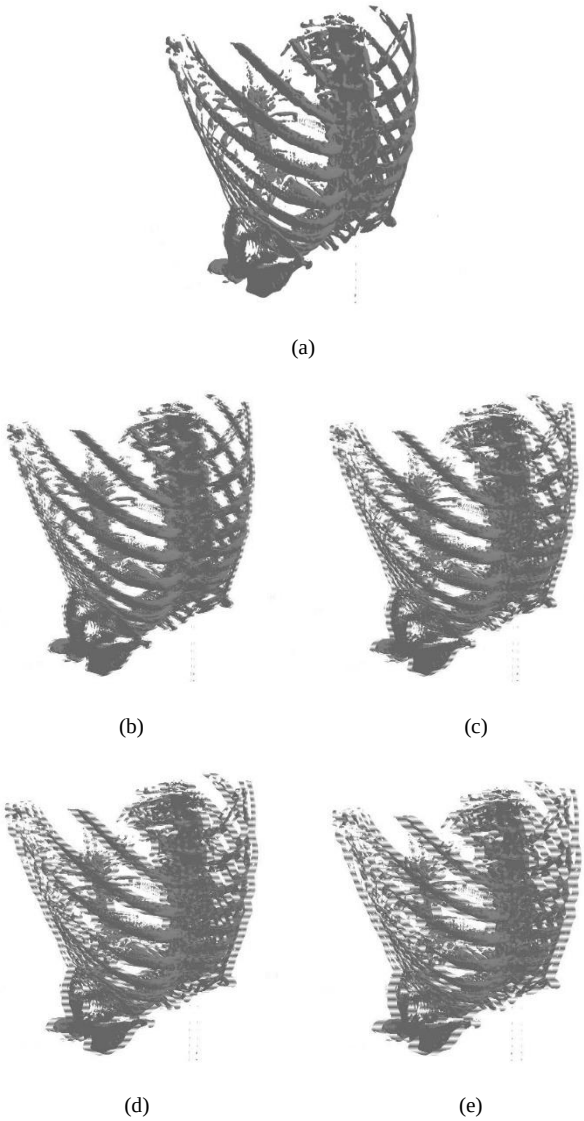


Figure 13. (a) Chest 3D image (b) Interlaced chest image with n = 5 (c) Interlaced chest image with n = 10 (d) Interlaced chest image with n = 15 (e) Interlaced chest image with n = 20

Table 2. Virtual depth generated by binocular disparity

Distance shifted on Monitor		***Virtual depth generated by binocular disparity(mm)***
by pixel	***by mm***	
5	2.42	27.07
10	4.84	56.31
15	7.26	88.02
20	9.69	122.64

3.2 User oriented depth value calibration and evaluation.

3.2.1 Real-time depth value calibration

The metric nature of stereo depth perception remains an important source of depth information for many studies of depth values.

Many studies focus on how to detect the distance more accurately between the observer and the surface of the object, to infer the depth value for 3D modeling. This has a positive impact in many areas, such as autonomous driving, 3D models construction of traditional objects, etc.

However, during the actual operation, the surgeon will focus on the specific location of the lesion. In other words, the distance between the specific location of the lesion and the doctor's observation location needs to be calculated as accurately as possible, so that the depth value can be calculated more accurately for 3D restoration.

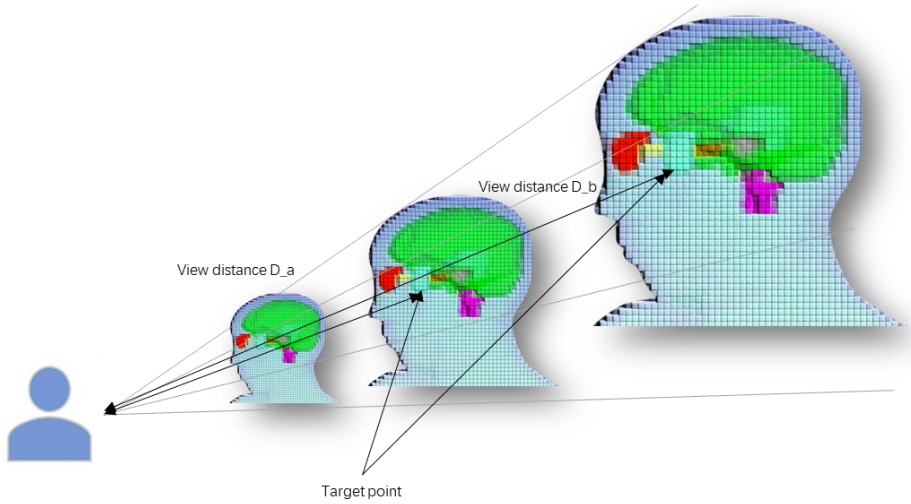


Figure 14. 3D model simulation diagram

In the case of surgery simulation, Figure 14 shows that the observation point of the user (the user of the surgery simulator) changes subtly, and the 3D model is moved, enlarged or reduced in real time. This causes the distance between the focus point and the observer to change in real time.

In this case, a method that can calculate the distance more accurately has become one of the criteria for measuring the accuracy of the surgical simulator.

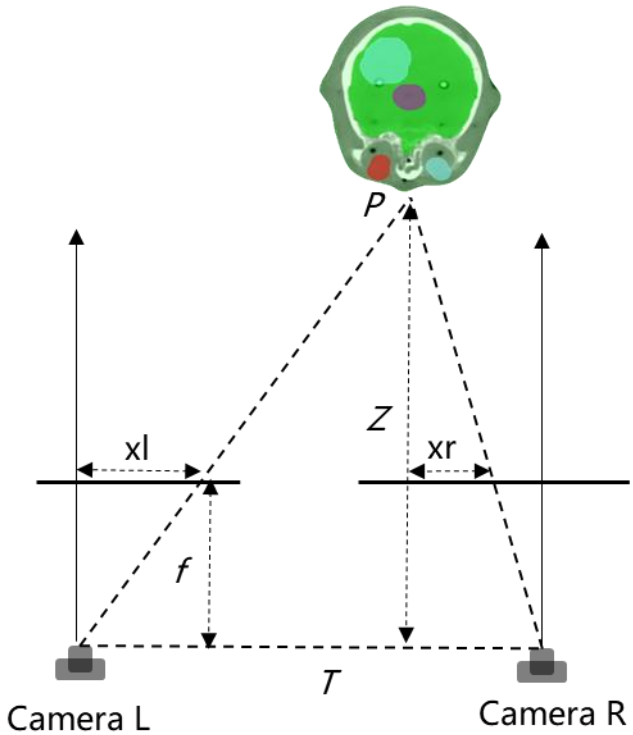


Figure 15. Basic stereo vison

According to the triangle similarity principle:

$$\frac{T-(xl+xr)}{T}=\frac{Z-f}{Z} \tag{4}$$

$$ZT-Z(xl+xr)=ZT-fT \tag{5}$$

Then we can get

$$Z=\frac{fT}{xl+xr} \tag{6}$$

By equation (6), if it is assumed that the pupillary distance is 65*mm*, the depth value can be calculated as 130*mm*.

Table 3. Virtual depth value calculated after user calibration

Pupil distance	Basic Stereo Vison	User Calibration	Depth value discrepancy
74	130	**148**	+18
70	130	140	+10
65	130	**130**	0
60	130	120	-10
54	130	108	-12

However, if the actual situation is considered, the pupillary distance of an adult is roughly 54*mm*~75*mm*. The accurate depth value ranges from 108*mm*~148*mm*. The error range will be at 0*mm*~18*mm*. For a huge object, the 18mm error may not be important. However, in the human body, especially inside the skull, an error of 18 mm is enough to cause major medical accidents. In the field of surgical simulation that imitates the real environment as much as possible, how to reduce this error is extremely important. Therefore, in this case, the pupillary distance of the user of the surgical simulator, is an important parameter to be considered.

In addition to considering the user's pupillary distance, another critical factor must be taken into account. In conventional depth calculation, only the closest distance between the object and the observer is typically considered, such as the distance between the front vehicle and the observer or the distance between the head and the observer. However, in surgical environments, it is crucial for doctors to determine the location of the lesion and the path to reach it, rather than just the closest distance. In this case, based on the BSV (Basic Stereo Vison), we can consider some deformation of BSV to pay more attention to the location of a certain lesion.

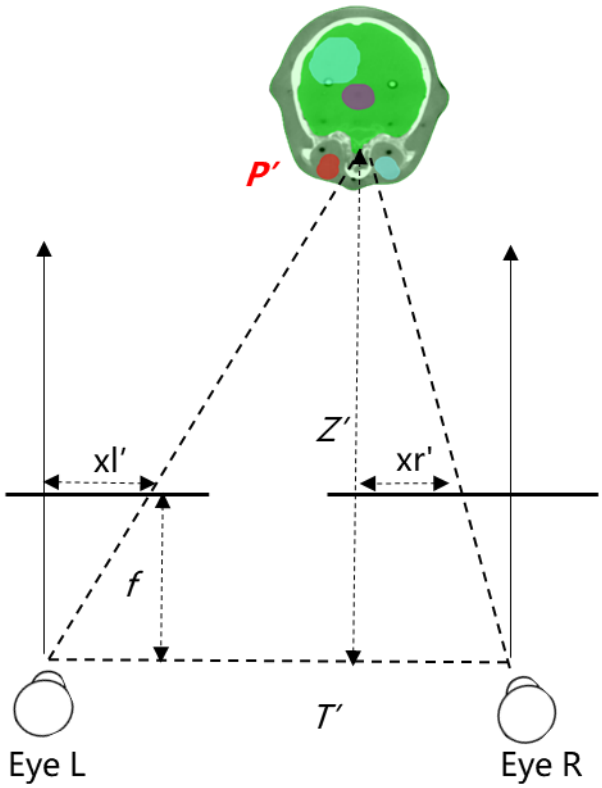


Figure 16. Stereo vison in virtual environment

Figure 16 shows this situation, where P' represents the location of a specific lesion and T' represents the user's pupillary distance.

Here, we consider if the model is zoomed in, zoomed out, moved, or the observer changes the viewing distance. Then the actual distance Z' can be represent as

$$Z' = nZ + \Delta f \tag{7}$$

Considering that the actual user pupillary distance will be slightly different, T' can be represent as:

$$T' = T + \Delta T \tag{8}$$

Substituting Equation (7) and Equation (8) into Equation (6), we can get

$$\frac{T + \Delta T - (xl + xr)}{T + \Delta T} = \frac{nZ + \Delta f - f}{nZ + \Delta f} \tag{9}$$

Here we consider an ideal situation where the observer keeps the watching distance constant, and the 3D model is not enlarged, reduced, or moved in parallel.

So, we can let $\Delta f = 0, n = 1$. Z' can be represent as Equation (10):

$$Z' = \frac{f(T + \Delta T)}{xl + xr} \tag{10}$$

Under the special conditions mentioned above, if the location of the lesion is 5mm above the surface, as shown in Figure 15, we set this 5mm as Δy = 5mm.

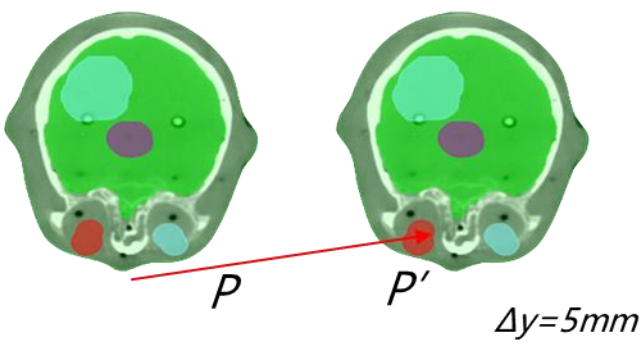


Figure 16. Target point with *Δy=5mm*

We assume that the user's pupillary distance is 54mm, 60mm, 65mm, 70mm and 74mm. According to formula (10), we can calculate the depth value; Table 5 shows the results in detail.

At this time, we can conclude that the error range is 2.1mm~3mm. Compared with the case where only the pupil distance gap is considered, this error has been reduced a little. However, one thing should be noticed is that, the results were obtained when the considered lesion was located only 5 mm from the surface.

Table 4. Virtual depth value calculated after user calibration, *Δy=5mm*

Unit:mm

Pupil distance	Basic Stereo Vison	User Calibration	User Calibration&Target point	Depth value discrepancy
74	130	148	145	-3
70	130	140	137.2	-2.8
65	130	130	127.5	-2.5
60	130	120	117.6	-2.4
54	130	108	105.9	-2.1

Δy=1mm → Error : 0.42mm~0.6mm

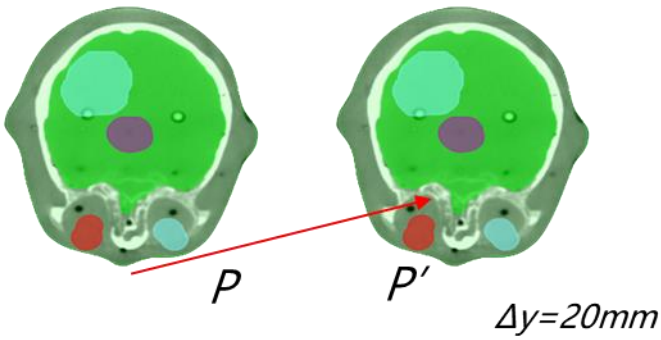


Figure 17. Target point with *Δy=20mm*

If we consider the case where the lesion is 20*mm* from the surface, the result will be as shown in Table 6. The range of error will increase to 8~11*mm*.

Table 5. Virtual depth value calculated after user calibration, *Δy=20mm*

Unit:mm

Pupil distance	Basic Stereo Vison	User Calibration	User Calibration&Target point	Depth value discrepancy
74	130	148	137	-11
70	130	140	129.6	-10.4
65	130	130	120.3	-9.7
60	130	120	111.1	-8.9
54	130	108	100	-8

Δy=1mm → Error : 0.4mm~0.55mm

Combining the above results, we can estimate that every time the lesion is 1*mm* away from the surface, the error will be about 0.42*mm*~0.6*mm*.

In summary, it can be proved that in order to reduce the error, when calculating the depth value, we should not only consider the closest distance from the object to the observer, but need to accurately locate the specific location of the lesion.

Figure 18. Adjustable depth value *f*

In summary, it can be proved that in order to reduce the error, when calculating the depth value, we should not only consider the closest distance from the object to the observer, but need to accurately locate the specific location of the lesion.

In the actual depth value calculation, we take this into account, and Figure11 shows our results.

3.3. Automated segmentation from CT images

3.3.1 Method of segmentation

Table 6. HU value in parts of the body

Substance		HU
Air		−1000
Fat		−120 to −90
Soft tissue on contrast CT		+100 to +300
Bone	Cancellous	+300 to +400
	Cortical	+1800 to +1900
Subdural hematoma	First hours	+75 to +100
	After 3 days	+65 to +85
	After 10–14 days	+35 to +40
Other blood	Unclotted	+13 to +50
	Clotted	+50 to +75
Pleural effusion	Transudate	+2 to +15
	Exudate	+4 to +33
Other fluids	Chyle	−30
	Water	0
	CSF	+15
	Abscess / Pus	0 or +20, to +40 or +45
	Mucus	0 - 130 ("high attenuating" at over 70 HU)
Parenchyma	Lung	−700 to −600
	Kidney	+20 to +45
	Liver	60 ± 6
	Lymph nodes	+10 to +20
	Muscle	+35 to +55

	Thymus	• +20 to +40 in children • +20 to +120 in adolescents
	White matter	+20 to +30
	Grey matter	+37 to +45
Gallstone	Cholesterol stone	+30 to +100
	Bilirubin stone	+90 to +120
Foreign body	Windowpane glass	+500
	Limestone	+2,800
	Copper	+14,000
	Silver	+17,000
	Steel	+20,000
	Gold, steel, and brass	+30,000 (upper measurable limit)
Earwax		<0

3.3.2 Result of segmentation

In surgical simulation, it is also very important to know the position of blood vessels accurately. Although manual segmentation is the most accurate method, based on time considerations, in practical applications, it is impossible to arrange a professional doctor to perform manual segmentation on each patient. Therefore, how to use automatic segmentation while being more accurately obtaining a model of the blood vessel becomes a problem.

Like the previous article, we perform automatic segmentation to obtain the blood vessel model based on the HU value. Figure 19 shows the experimental results. Based on the theoretical and experimental results, 90 is the most suitable cut off value. In the figure, we can see that the blood vessel can be reconstructed when the HU value is selected at 90~180

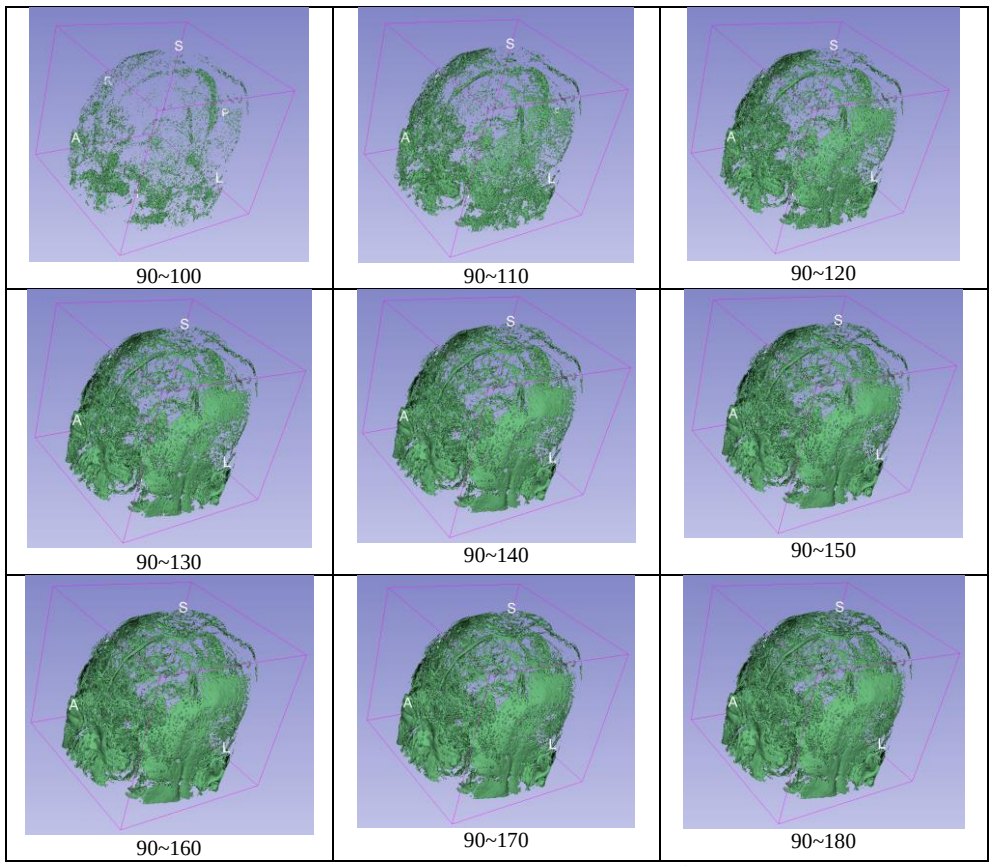


Figure 19. Automated vessel segmentation by Hounsfield units

Figure 20 shows the 3D reconstruction model when the HU value is selected at 90~180. In the figure, we can see that although the blood vessels are successfully reconstructed, the skin tissues that we do not need, here we call them noise, also appear. In order to solve this problem, it is easy to think of a method that, before performing the 3D reconstruction of the blood vessel, we have selected the location to be reconstructed in advance instead of taking the entire CT picture as input.

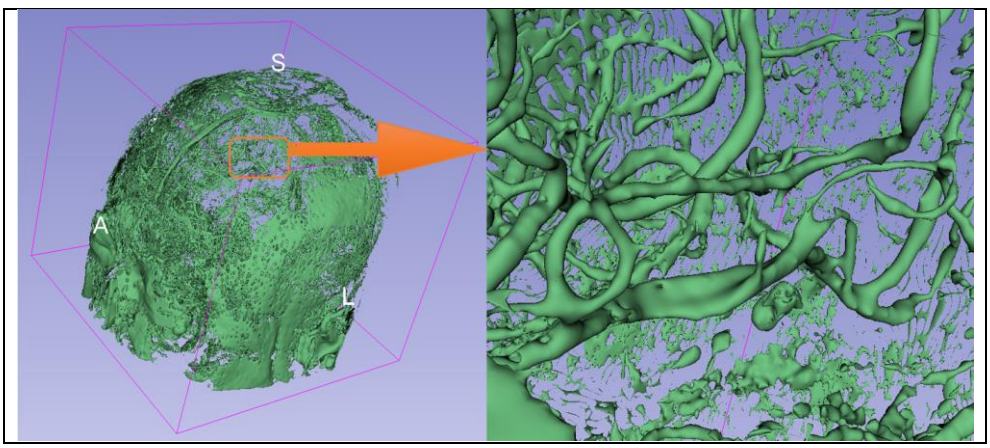


Figure 20. Vessels with noise

As shown in Figure 21, we have selected the areas that need to be reconstructed in three dimensions in advance. Given that the positions of the blood vessels in the human head are roughly the same, we can assume that there is no error here.

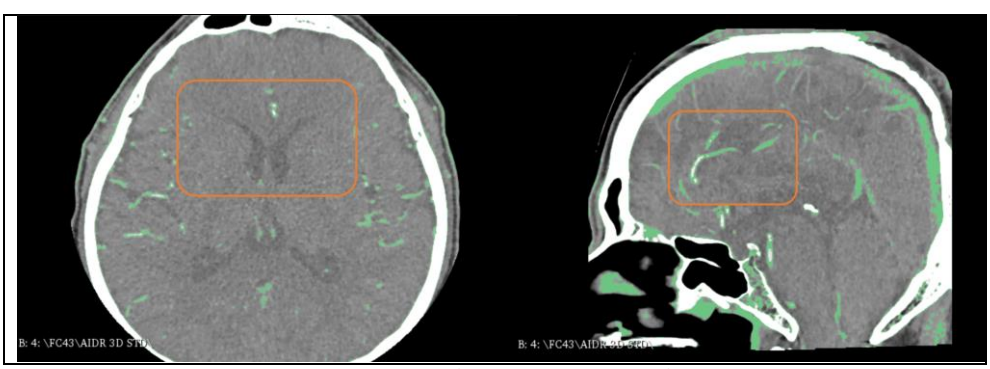


Figure 21. Selected are of segmentation by hounsfield units

.

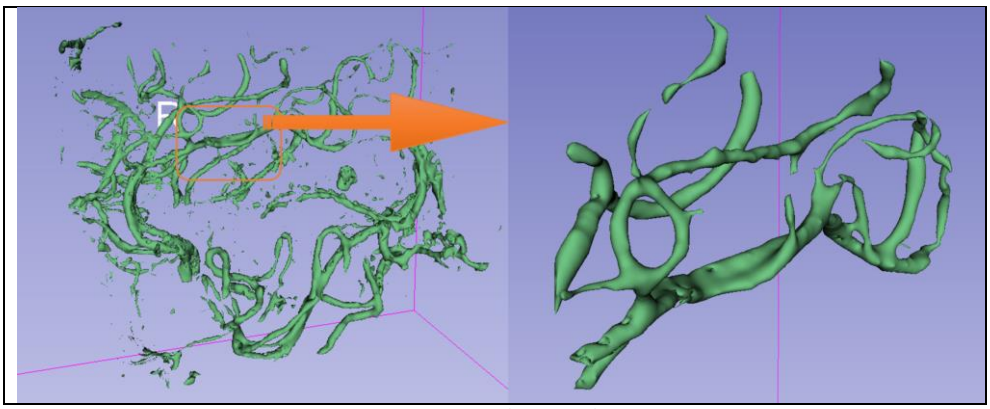


Figure 22. Vessels after noise filtering

In this way, after using the processed CT file for vascular reconstruction, the result is shown in Figure 22. The blood vessels reconstructed by this method may be broken in the middle. Currently, we are still studying how to solve this problem

3.4. VR system for surgical planning

The nose and surrounding sinuses are structures located in the center of the face. Various bones such as the maxilla, nasal bone, frontal bone, ethmoid bone, and lacrimal bone are intricately intertwined amongst cartilage tissues. In addition, the intracranial space is located at the top. The orbits including the eyeballs are located on both sides, and important structures such as the carotid artery and optic nerve are placed close to the back. Therefore, in order to perform a safe operation, it is important to accurately grasp the relationship between the anatomical structure of the operation target and the surrounding vital organs before performing the operation on the nose and sinuses.

Although the surgical techniques of modern medicine have developed rapidly in the past few decades, there have been no major changes made in lecturing surgical techniques. For beginners, it is best to deliver actual practice under the supervision of a senior doctor in charge. Patients and the guardians also visit the operation site to be instructed about the surgery beforehand. It is almost the only way of gaining knowledge about surgical techniques for non-medical staff [73]. However, patient safety issues are emerging on a global scale. In order to protect the rights of professionals and the safety of patients, regulations have been formulated to limit professional training time. In Europe, through the "European Working Hours Directive", recommendations for professional training time limits are put forward. Similarly, in the United States, the Postgraduate Medical Education Certification Board made a recommendation to limit the training time to 80 hours per week [74]. In South Korea, special laws for professions came into effect in December 2017, along with the Labor Standards Law for doctors in March 2018, limiting the training

time for doctors to 80 hours per week.The Labor Standards Law for doctors in March 2018. In addition, due to the increasing responsibility of doctors for patient safety, the number of doctors who need to be trained is increasing, despite reduction of available training time. There are obvious limitations in surgical education through existing apprenticeship training programs. Learning through cadavers rather than actual patients is helpful and is used a lot, but because it requires a large facility and high cost, it is necessary to lower the entrance barrier [75]. In this case, it is obvious that compliance with the existing medical education and surgical education methods will lead to a decline in the quality of education, and a demand for new education methods is emerging.

Virtual reality (VR) refers to the interface between a person and a computer. The interface connects a specific environment or situation in a computer to a person, whose experience is as if the person is interacting with the virtual surrounding situation or environment. Recently, it has become one of the most popular keywords describing the fourth industrial revolution. In the 2000s, the application of VR technology has expanded to the medical field apart from leisure activities such as games and has been applied to various fields such as surgical education, rehabilitation, and mental illness treatment [76].

Considering the recent trends, the role of VR in healthcare is expected to increase, especially in nose and sinus surgery. Surgery with VR requires both sophisticated techniques and anatomical knowledge, which can be reconstructed in three dimensions. Therefore, in this article, VR technology in sinus surgery and

facial reconstruction surgery is briefly introduced, regarding what is currently being used in the field, and what can be used in the future.

Head-mounted wearable Virtual Reality devices are emerging as a new immersive training method in the field of medicine. A benefit of these systems is that it actually simulates the viewpoint of the surgeon as the operation proceeds, but a technical downside fades its advantage all at once. Head-mounted displays (HMD) show the objects through the screen attached to it. While Organic Light Emitting Diodes (OLED) are widely adapted for HMD VR devices due to its higher pixel density (pixels per inch, PPI) than that of Liquid Crystal Display (LCD), only around 1400 ppi of resolution for less than 10cm of distance is still not able to conceal the gaps between each pixel [94].

According to [95], an optimal viewing distance for a 6-inch display can be calculated as 0.256 meters, indicating that the HMD should be mounted at least 25cm away from the eyes to not reveal the pixel gaps of the display. Therefore, the use of HMD for VR simulations is not an ideal method in providing a VR-based environment unless it offers higher pixel densities.

Figure 23. HMD+VR (left) [103] and 3D reconstructed VR on a flat display (right) [104]

3.4.1 Method of VR planning system

We used Voxelsens' VR station product as the main equipment. Figure 15 shows all the components. It is worth mentioning that the device allows users to use their own 3D display. In the previous chapters, we have analyzed the problem of the best observation point. The size, resolution, and distance of the observer from the display determine the effect of 3D imaging. The device uses BENQ XL2411 as the default display, and the optimal pixel separation value is set in advance. If you use other models of 3D displays, you need to contact Voxsense in advance to change the default value.

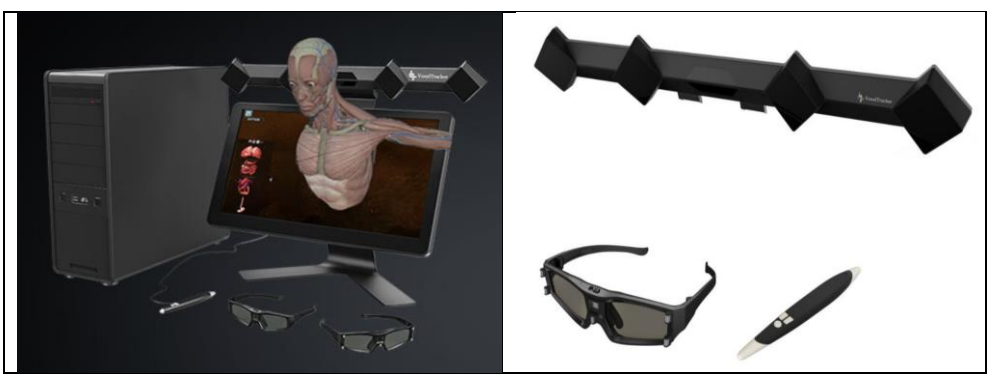


Figure 24. Voxsens VR station

Table 6. Working requiments of VR station

Monitor	*24 inch – 32 inch*
Resolution	1920*1080 or Above
Accuracy	1*mm*, 0.5 °
Work Space	Horizontal 1200*mm*,Vertical 800*mm*,Depth 800*mm*
CPU	intel core i5 quad (i5-6400) or Above
Hard	500GB or Above
Memory	8GB or Above
Graphic Card	GeForce 1050Ti or above
Device size	740*mm* * 60*mm* * 70*mm* (L*W*H)
Operation Temperature	5-40 ° C , humidity： 10 % - 80%
Power	20W
OS	OS win10 64 bit HOME1709 or above

After using the 3D slicer to convert the DICOM file to STL format, we will say that it is equally cut into five parts like Figure 16, and then each part is saved separately and converted into FBX format, and then transferred to the VR station for reading. For the time being, the VR station cannot perform operations such as cutting the model. Any cutting, marking and color modification of the model must be completed in the stage of exporting the 3D model.

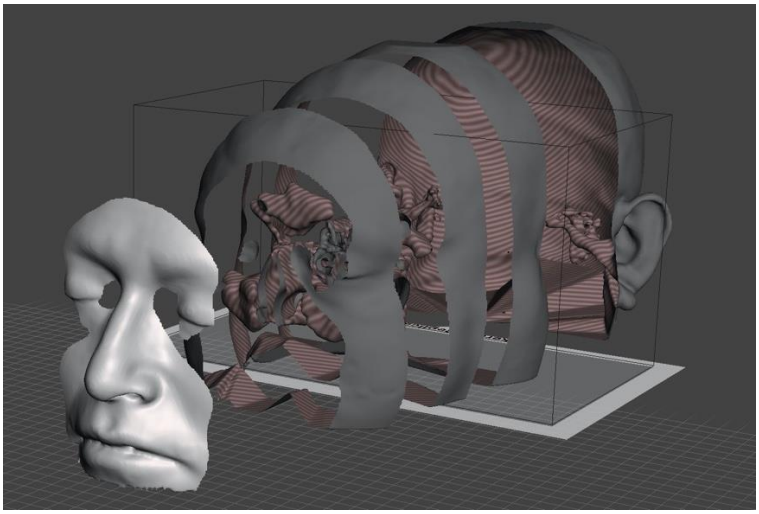


Figure 25. Thick slice voxel image

As mentioned previously, these reconstructed slices of 3D images offer a better understanding regarding how neighboring organs, bones, and structures look like, compared to the images obtained from CT. It would be possible for non-medical professionals to intuitively obtain knowledge even faster, especially for the situations where it is necessary to train younger generations to be placed in the field as fast as possible. Moreover, this technique can also be used for fast surgical planning since it would be easier to understand all possible variables in advance.

3.4.2. Results of VR surgical planning system

Perhaps the composition of internal organs is the same in general, but the exact location, orientation and condition vary among individuals. This is especially important for surgical operations, and the need for preoperative surgical planning is apparent. If the body of the actual patient were used for practicing and planning rather than a cadaver, the surgical procedure would run unimpededly, reducing the chance of encountering all the potential variables beforehand. The VR surgical planning system enables such capability with its 3D modeling and slicing of the reconstructed image created based on the actual patient.

To show the bones and muscles separately, the STL models of muscles and bones should be exported separately and converted into FBX format, then input it to the VR station. As shown in Figure 18, (a) contains the bone and muscle models. The bones can be observed when the interactive pen is moved away from the muscles, as shown in (b).

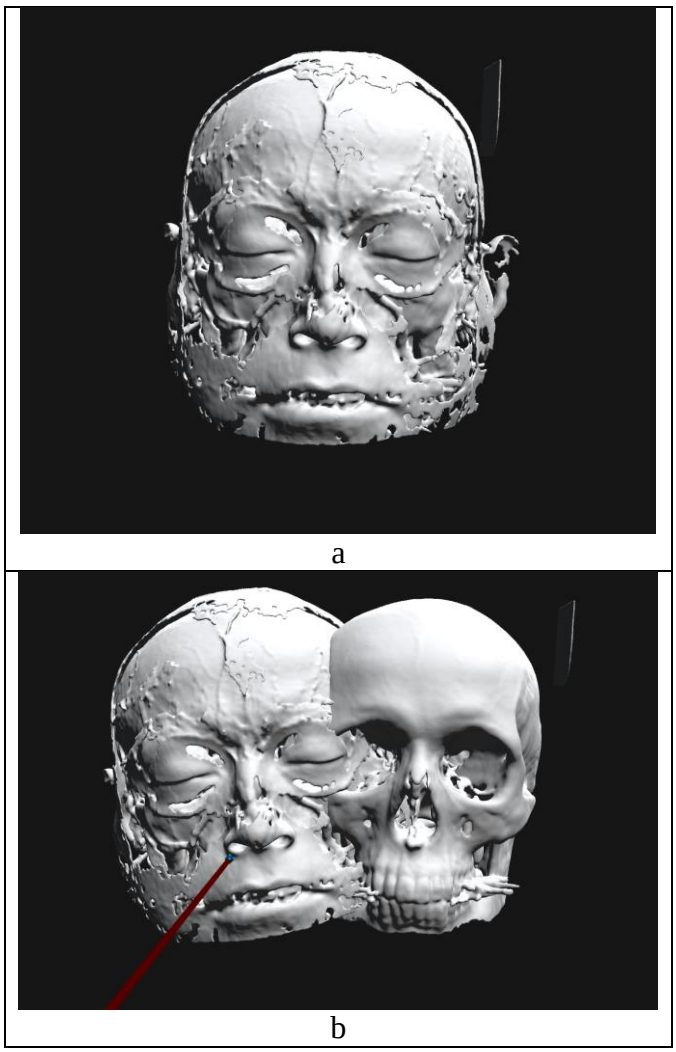
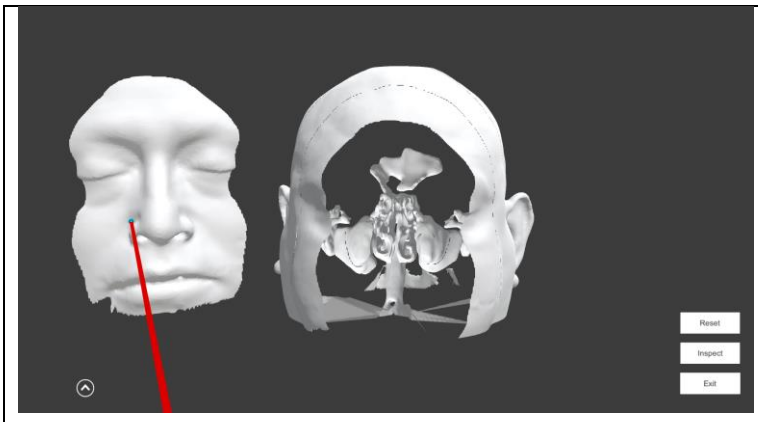
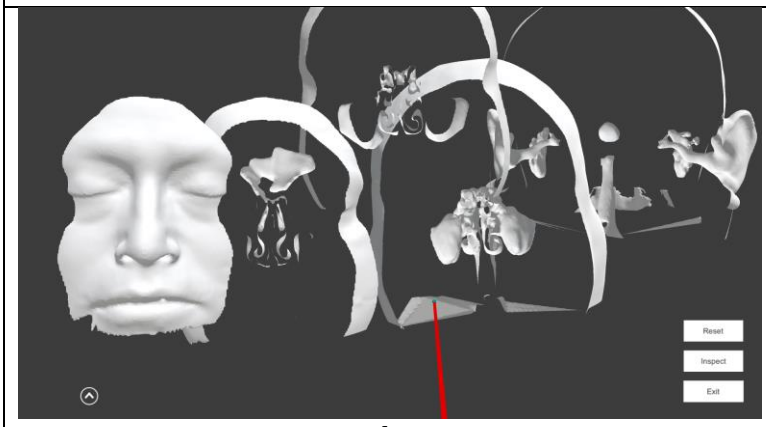


Figure 26. Combination of muscle and bone model. (a) Muscle model with bone model inside
(b) The muscle model is being separated from the bone model

In order to see the inside of the nasal cavity, when making the model, we divided the head vertically into 5 parts equally. After reading the model file, we can clearly observe the internal structure after removing the front face. If you need a local analysis, you can take it out separately for magnification analysis.



a



b

Figure 27. Uniformly modified skin model. (a) nasal cavity view（b）separated nasal cavity view

3.5. Three-dimensional view box for surgical training and planning.

In order to see the inside of the nasal cavity, when making the model, we divided the head vertically into 5 parts equally. After reading the model file, we can clearly observe the internal structure after removing the front face. If you need a local analysis, you can take it out separately for magnification analysis.

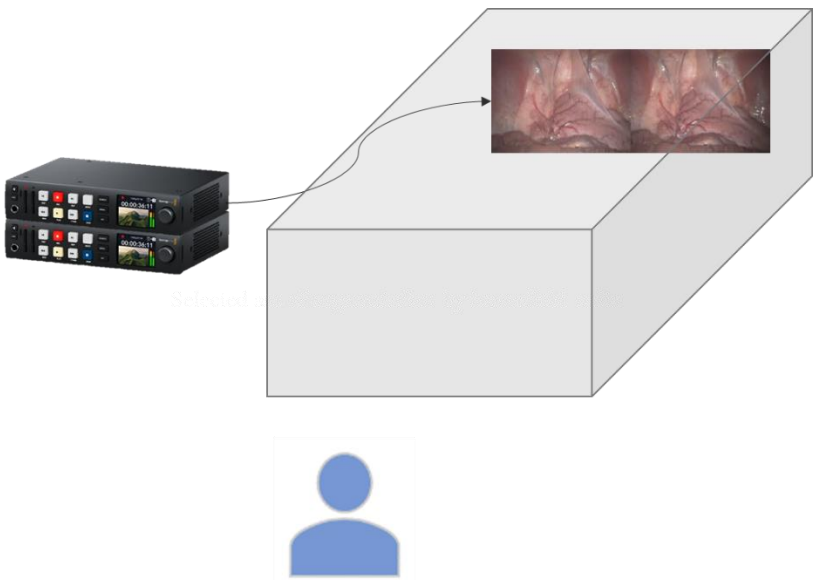


Figure 28. View box structure idea

In the previous chapters, we proposed a depth value calculation method combined with the actual situation and used this method to construct a virtual training environment after 3D modeling with CT original files. Here, we want to explore a simpler method, using the existing equipment in the hospital as much as possible, to construct a three-dimensional environment, to reproduce the operation process, and to help more training doctors to learn through examples.

Considering the factors of cost and convenience, here we use the traditional 3D vision method, sacrificing some accuracy, but focusing on the practical aspect, and propose a device design that can help doctors perform 3D surgical reconstruction.

The general idea is shown in Figure 19. The impact of the operation will be transmitted to a view box through the commonly used devices at present, and the observer can experience the three-dimensional image through this View box.

The general structure that can be easily imagined is shown in Figure 20 and Figure 21.

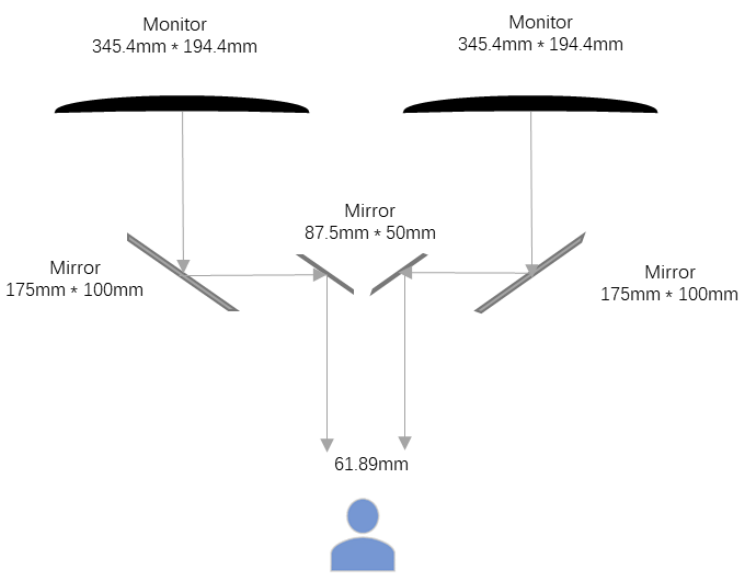


Figure 29. View box structure – double reflect

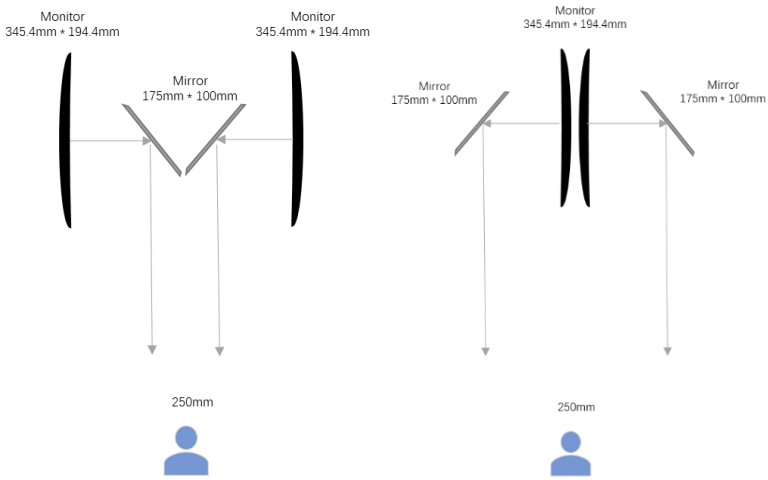


Figure 30. View box structure – single reflect

Here are some important factors to be considered

* The average adult's pupil distance is between **54*mm*~74*mm***

* Optimal viewing distance: **500~600*mm***

* Video reflection times using mirror: 2, 4, 6 …

* Size & Price

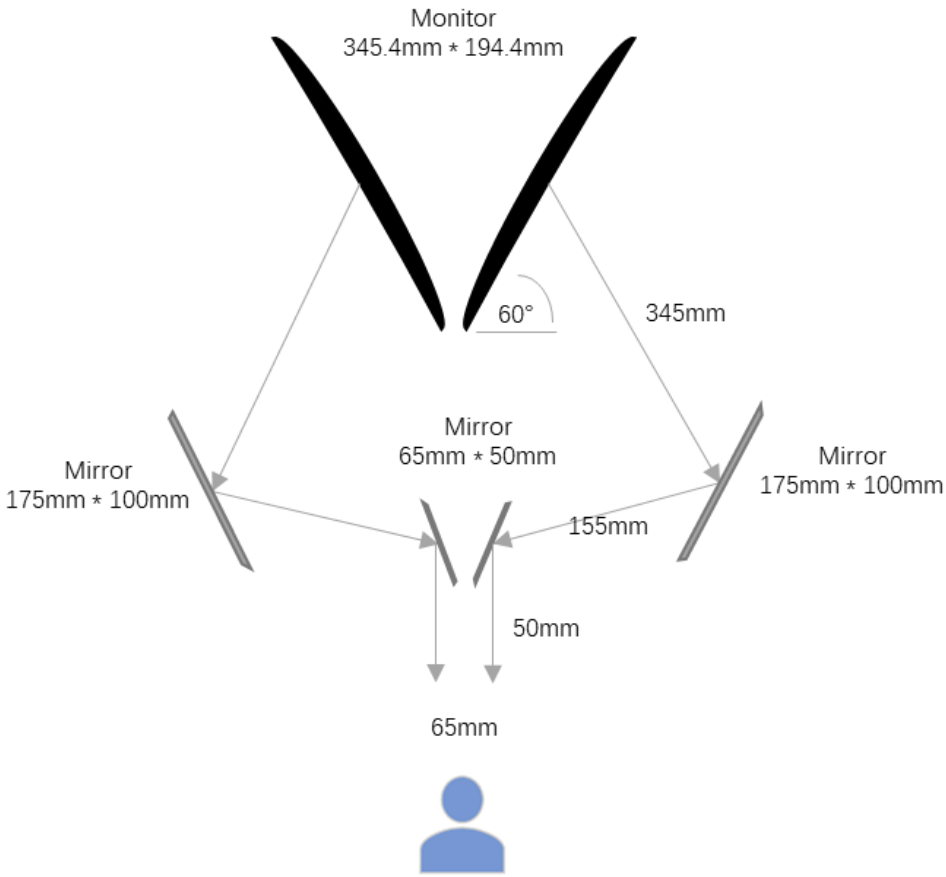


Figure 31. Optimal structure of the view box

Based on the above considerations, we design the structure as shown in Figure 31 This design ensures the observer's interpapillary distance, observation distance, and overall view box size

It is worth noting that here we use a portable flat panel as a display, which supports HDMI interface. In theory, we could use a smaller, higher-resolution display, such as a micro display attached to a camera. Considering the price factor (the unit price is about 1.8 million won), we did not use it here.

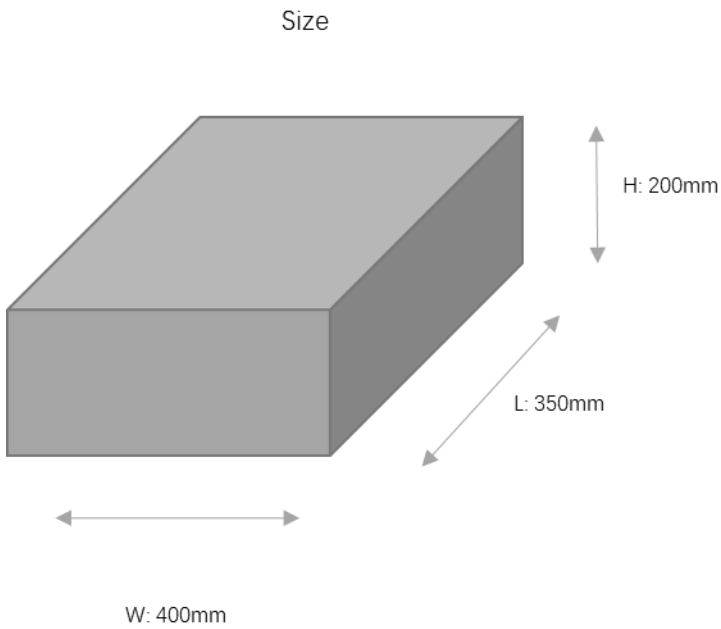


Figure 32. Form factor of the view box

In summary, the size of the View box is W: 400*mm*, L: 350*mm*, H: 200*mm*.

It is roughly the size of a medium-sized desktop computer host, does not take up too much space, and can be used on an ordinary table to meet the needs of portability

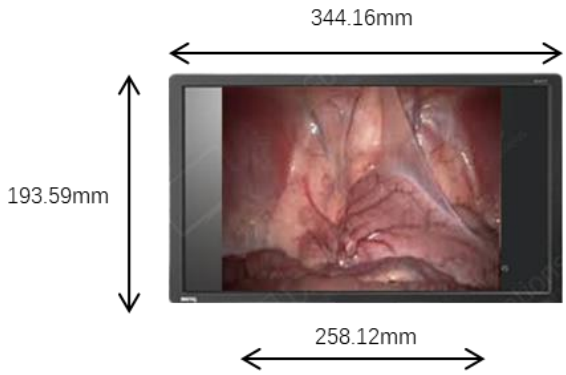


Figure 33. Screen size and video size

It is roughly the size of a medium-sized desktop computer host, does not take up too much space, and can be used on an ordinary table to meet the needs of portability.

As mentioned in the previous section, in order to improve the accuracy of 3D imaging, the distance of the user's pupil needs to be taken into account. Therefore, in the design of View box, we also consider this point.

The existing standard design defaults to the user's pupil distance of 65*mm*, and the optical design is just right for two displays to be projected to the naked eye. We can simply pan the position of the built-in mirror in the middle to ensure that it matches the user's pupil distance. However, if the mirrors are moved parallel to each other, a portion of the video on the screen will be obscured based on the current design.

Here, we first look at Figure 33, where we use a monitor with a display ratio of 16:9 and a display range of 344.16*mm* * 193.59*mm*. The video ratio used is 4:3, with a length of 258.12*mm*, and is positioned in the middle. The maximum distance the mirror can be moved from side to side without affecting the observation is 21.51*mm*. Here we fix the maximum value to 15mm, and if converted to the pupil distance that can be supported, the range is 50~80*mm*. The average adult’s pupil distance range (54*mm*~74*mm*) can be satisfied.

Chapter 4. Conclusion

I would like to compare the five aspects of Visulization, Haptic, Case, Realt time depth, and Patient consultation with some existing simulators, as shown in Figure 34.

		Visualization	Haptic	Case	Real time depth	Patient consultation
Lap VR		2D	O	Standard	X	X
3D Systems Leverages		3D	O	Standard *Real patient	X	X
CardinalSim		3D	O	Standard *Real patient	X	X
Proposed		3D	X	Real patient	O	O

Figure 34. Surgery simulator comparison

Visualization - Most simulators use 3D visualization, which provides a better sense of integration and closer to reality than 2D. Here we also use 3D visualization.

Haptic - Existing simulators focus on haptic simulation and are used to help physicians practice haptics. Our proposed simulator does not yet cover the haptic domain, which is a shortcoming and an area for improvement.

Case - The earliest simulators can only provide a single, customized case. Subsequent simulators will also refer to real patients to create special practice cases. The advantage is that the practice cases are relatively accurate, but the disadvantage is that the cases are relatively single and cannot cover all patients. Here we

completely use real patient data to help the surgeon better understand the patient's situation before surgery as much as possible to go for targeted planning and rehearsal. Real time depth - Unlike the existing simulators, we have conducted an in-depth analysis and application of Real time depth estimation to improve the visual accuracy of the simulator, which will be sumarized in more detail in section 4.1.

Patient consultation - Existing simulators focus on how to help physicians perform simulation exercises. In addition to this, we also considered how to use the simulator to help patients or their families to better understand their condition and deepen their trust in the physician. From a technical point of view, it helps physicians to better explain their conditions to patients and improve the efficiency of their consultations.

4.1. Significance of this system

We propose a method to calculate depth values in real time based on the location of the lesion and the distance of the user's pupil. The method takes into account practical applications. When using the simulator for training. The method we proposed can reduce errors, improve the realism of the simulation and help the surgeon to improve hand-eye calibration. This helps the surgeon to become familiar with the actual surgery beforehand, improves familiarity with the patient, and enhances his or her own surgical confidence in the premise, which in turn improves the success rate of the surgery.

At the same time, we have developed a way to help patients better understand their own conditions. Unlike the traditional explanation of the original CT documents, this method helps patients understand their condition faster and deepens their trust in the doctor. In addition, it can also reduce the time doctors spend explaining their conditions and improve the efficiency of patient visits.

In addition, we propose a method for designing a naked-eye 3D imaging device that can provide naked-eye 3D learning scenarios by taking into account the user's pupil distance and using existing surgical videos of real medical surgical robots.

Different from most simulators, our developed simulator and imaging device can use real patient data and real surgical videos. Starting from the data source, we use real data to improve the realism of the simulation.

4.2. Limitations and future work

The system designed in this paper obtains images from existing patient DICOM information, but a lot of manipulation and modification is needed to turn it into a usable and practical model. However, it is believed that in the near future, with the development of artificial intelligence technology, the 3D reconstruction and segmentation of individual patient images will be faster and more accurate.

The method proposed in this paper takes into account practical application scenarios to improve accuracy and reduce errors from the perspective of 3D imaging. However, how to measure the degree of help to physicians in practical applications is something we need to consider further. At present, there is no guarantee or requirement for surgeons to have a general, standardized response to the location of the lesion and its treatment. It is difficult to define a general method to evaluation criteria to determine how helpful the system is to the surgeon. However, from a subjective point of view, questionnaires can be used to grasp the usefulness and shortcomings of the system, and then to investigate ways to improve it.

VR is a very innovative approach to overcome the spatial and economic limitations of medical education and training. If VR technology becomes widespread, doctors could improve its accessibility and increase the efficiency of education by repeating exercises or working on the necessary components.

In addition, there is the possibility of pre-inputting the skills of experienced surgeons into VR simulators to help beginners follow the movements of experts (phantom mode) for imitation practice. This approach is applicable to standard, special cases and cannot be applied to all patient examples for the time being. If the technical development of automatic image segmentation and automatic surgical planning can

be met with ultra-high precision, application to real patient data will also become a possibility.

How to develop a practical evaluation criterion is also a problem that we need to overcome in the future. At present, the subjective questionnaire way to let doctors judges by themselves is a feasible method at present. However, how to define the efficiency of the simulator with an objective, quantitative evaluation method is an issue worth studying.

Finally, in the design of the naked eye imaging device, we will also try to reduce the production cost as much as possible. For example, avoid using too high-resolution screens while satisfying a specific accuracy. Theoretically, higher resolution will provide higher accuracy, but once the threshold of naked eye resolution reached, higher resolution will prevent cost control.

4.3. Extension of the present system to commercial purpose

Take South Korea as an example. First, the main body of the system uses an external adapter for DC power supply, and the use of an adapter that has passed KC certification can ensure electrical safety compliance. Secondly, the accessories are powered by lithium battery or USB, which are not within the scope of KC's mandatory safety certification. Furthermore, the system does not provide measurement, correction and treatment functions for the human body, even if it is used in the medical field, it is not within the scope of medical equipment. That is, the device only needs to pass EMC tests before it can be used for commercial purposes.

In terms of functions, unfortunately, it is currently not possible to link with the PACAS system to export patient DICOM files in real time. In the next improvement work will strengthen the work of DICOM file is automatically exported and automatic 3D imaging.

Bibliography

[1] Hutter MM, Kellogg KC, Ferguson CM, et al. The impact of the 80-hour resident workweek on surgical residents and attending surgeons. Ann Surg 2006;243:864-7; discussion 871-5.

[2] Valentine R, Padhye V, Wormald PJ. Simulation Training for Vascular Emergencies in Endoscopic Sinus and Skull Base Surgery. Otolaryngol Clin North Am 2016; 49:877-87.

[3] Gallagher AG, Ritter EM, Champion H, et al. Virtual reality simulation for the operating room: proficiencybased training as a paradigm shift in surgical skills training. Ann Surg 2005;241:364-72.

[4] Zevin B, Aggarwal R, Grantcharov TP. Surgical simulation in 2013: why is it still not the standard in surgical training? J Am Coll Surg 2014;218:294-301.

[5] Satava RM. Historical review of surgical simulation--a personal perspective. World J Surg 2008;32:141-8.

[6] Gause CD, Hsiung G, Schwab B, et al. Advances in Pediatric Surgical Education: A Critical Appraisal of Two Consecutive Minimally Invasive Pediatric Surgery Training Courses. J Laparoendosc Adv Surg Tech A 2016;26:663-70.

[7] Rosen JM, Long SA, McGrath DM, et al. Simulation in plastic surgery training and education: the path forward. Plast Reconstr Surg 2009;123:729-38; discussion 739-40.

[8] Limberg AA. The Planning of Local Plastic Operations on the Body Surface: Theory and Practice. Lexington, Mass.: DC Heath and Company; 1984.

[9] Persin J, Evans GR. Soft-Tissue Surgery of the Craniofacial Region. Boca Raton, FL: CRC Press; 2007, 402.

[10] Owen H. Early use of simulation in medical education.Simul Healthc 2012;7:102-16.

[11] Scardino PT, Kelman J. Dr. Peter Scardino's Prostate Book, Revised Edition: The Complete Guide to Overcoming Prostate Cancer, Prostatitis, and BPH. London: Penguin; 2010, 627.

[12] Cooper JB, Taqueti VR. A brief history of the development of mannequin simulators for clinical education and training. Qual Saf Health Care 2004;13 Suppl 1:i11-8.

[13] Delp SL, Loan JP, Hoy MG, et al. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. IEEE Trans Biomed Eng 1990;37:757-67.

[14] Satava RM. Virtual reality surgical simulator. The first steps. Surg Endosc 1993;7:203-5.

[15] Alaker M, Wynn GR, Arulampalam T. Virtual reality training in laparoscopic surgery: A systematic review & meta-analysis. Int J Surg 2016;29:85-94.

[16] Seymour NE. VR to OR: a review of the evidence that virtual reality simulation improves operating room performance. World J Surg 2008;32:182-8.

[17] Tan SS, Sarker SK. Simulation in surgery: a review. Scott Med J 2011;56:104-9.

[18] Rehman S, Raza SJ, Stegemann AP, et al. Simulationbased robot-assisted surgical training: a health economic evaluation. Int J Surg 2013;11:841-6.

[19] Munshi F, Lababidi H, Alyousef S. Low- versus high-fidelity simulations in teaching and assessing clinical skills. Journal of Taibah University Medical Sciences 2015;10:12-5.

[20] Sarker SK, Patel B. Simulation and surgical training. Int J Clin Pract 2007;61:2120-5.

[21] Roberts KE, Bell RL, Duffy AJ. Evolution of surgical skills training. World J Gastroenterol 2006;12:3219-24.

[22] Parra-Blanco A, González N, González R, et al. Animal models for endoscopic training: do we really need them? Endoscopy 2013;45:478-84.

[23] Vázquez-Sequeiros E, de Miquel DB, Olcina JR, et al. Training model for teaching endoscopic submucosal dissection of gastric tumors. Rev Esp Enferm Dig 2009;101:546-52.

[24] Fritscher-Ravens A, Cuming T, Dhar S, et al. Endoscopic ultrasound-guided fine needle aspiration training: evaluation of a new porcine lymphadenopathy model for in vivo hands-on teaching and training, and review of the literature. Endoscopy 2013;45:114-20.

[25] Carey JN, Rommer E, Sheckter C, et al. Simulation of plastic surgery and microvascular procedures using perfused fresh human cadavers. J Plast Reconstr Aesthet Surg 2014;67:e42-8.

[26] Aboud ET, Krisht AF, O'Keeffe T, et al. Novel simulation for training trauma surgeons. J Trauma 2011;71:1484-90.

[27] Garrett HE Jr. A human cadaveric circulation model. J Vasc Surg 2001;33:1128-30.

[28] Aboud E, Al-Mefty O, Ya ş argil MG. New laboratory model for neurosurgical training that simulates live surgery. J Neurosurg 2002;97:1367-72.

[29] Carey JN, Caldwell AM, Coughlin RR, et al. Building Orthopaedic Trauma Capacity: IGOT International SMART Course. J Orthop Trauma 2015;29 Suppl 10:S17-9.

[30] Imakuma ES, Ussami EY, Meyer A. Laparoscopic training model using fresh human cadavers without the establishment of penumoperitoneum. J Minim Access Surg 2016;12:190-3.

[31] Reznick RK, MacRae H. Teaching surgical skills--changes in the wind. N Engl J Med 2006;355:2664-9.

[32] Anastakis DJ, Regehr G, Reznick RK, et al. Assessment of technical skills transfer from the bench training model to the human model. Am J Surg 1999;177:167-70.

[33] Sheckter CC, Kane JT, Minneti M, et al. Incorporation of fresh tissue surgical simulation into plastic surgery education: maximizing extraclinical surgical experience. J Surg Educ 2013;70:466-74.

[34] Chambers S, Deehan D, Gillinder S, et al. Cadaveric surgical training improves surgeon confidence. Bulletin 2015;97:E1-4.

[35] de Montbrun SL, Macrae H. Simulation in surgical education. Clin Colon Rectal Surg 2012;25:156-65.

[36] Cheung CL, Looi T, Lendvay TS, et al. Use of 3-dimensional printing technology and silicone modeling in surgical simulation: development and face validation in pediatric laparoscopic pyeloplasty. J Surg Educ 2014;71:762-7.

[37] Chan HH, Siewerdsen JH, Vescan A, et al. 3D Rapid Prototyping for Otolaryngology-Head and Neck Surgery: Applications in Image-Guidance, Surgical Simulation and Patient-Specific Modeling. PLoS One 2015;10:e0136370.

[38] Scott DJ, Goova MT, Tesfay ST. A cost-effective proficiency-based knot-tying and suturing curriculum for residency programs. J Surg Res 2007;141:7-15.

[39] Goova MT, Hollett LA, Tesfay ST, et al. Implementation, construct validity, and benefit of a proficiency-based knot-tying and suturing curriculum. J Surg Educ 2008;65:309-15.

[40] Scott DJ, Bergen PC, Rege RV, et al. Laparoscopic training on bench models: better and more cost effective than operating room experience? J Am Coll Surg 2000;191:272-83.

[41] Scott DJ, Bergen PC, Euhus DM, et al. Intense laparoscopic skills training improves operative performance of surgery residents. Am Coll Surg Surg Forum 1999;50:670-1.

[42] de Visser H, Watson MO, Salvado O, et al. Progress in virtual reality simulators for surgical training and certification. Med J Aust 2011;194:S38-40.

[43] Delorme S, Laroche D, DiRaddo R, et al. NeuroTouch: a physics-based virtual simulator for cranial microneurosurgery training. Neurosurgery 2012;71:32-42.

[44] Seymour NE, Gallagher AG, Roman SA, et al. Virtual reality training improves operating room performance: results of a randomized, double-blinded study. Ann Surg 2002;236:458-63; discussion 463-4.

[45] Wilson MS, Middlebrook A, Sutton C, et al. MIST VR: a virtual reality trainer for laparoscopic surgery assesses performance. Ann R Coll Surg Engl 1997;79:403-4.

[46] LAP Mentor. Simbionix (Internet). (cited 2016 Jul 19). Available online: http://simbionix.com/simulators/lapmentor/

[47] Kundhal PS, Grantcharov TP. Psychomotor performance measured in a virtual environment correlates with technical skills in the operating room. Surg Endosc 2009;23:645-9.

[48] Hyltander A, Liljegren E, Rhodin PH, et al. The transfer of basic skills learned in a laparoscopic simulator to the operating room. Surg Endosc 2002;16:1324-8.

[49] Palter VN, Grantcharov TP. Simulation in surgical education. CMAJ 2010;182:1191-6.

[50] Liu M, Curet M. A review of training research and virtual reality simulators for the da Vinci surgical system. Teach Learn Med 2015;27:12-26.

[51] Lyons C, Goldfarb D, Jones SL, et al. Which skills really matter? proving face, content, and construct validity for a commercial robotic simulator. Surg Endosc 2013;27:2020-30.

[52] Abboudi H, Khan MS, Aboumarzouk O, et al. Current status of validation for robotic surgery simulators - a systematic review. BJU Int 2013;111:194-205.

[53] Moglia A, Ferrari V, Morelli L, et al. A Systematic Review of Virtual Reality Simulators for Robot-assisted Surgery. Eur Urol 2016;69:1065-80.

[54] Vakharia VN, Vakharia NN, Hill CS. Review of 3-Dimensional Printing on Cranial Neurosurgery Simulation Training. World Neurosurg 2016;88:188-98.

[55] Kimura T, Morita A, Nishimura K, et al. Simulation of and training for cerebral aneurysm clipping with 3-dimensional models. Neurosurgery 2009;65:719-25; discussion 725-6.

[56] Olivieri LJ, Su L, Hynes CF, et al. "Just-In-Time" Simulation Training Using 3-D Printed Cardiac Models After Congenital Cardiac Surgery. World J Pediatr Congenit Heart Surg 2016;7:164-8.

[57] Anderson JR, Thompson WL, Alkattan AK, et al. Three-dimensional printing of anatomically accurate, patient specific intracranial aneurysm models. J Neurointerv Surg 2016;8:517-20.

[58] Khan IS, Kelly PD, Singer RJ. Prototyping of cerebral vasculature physical models. Surg Neurol Int 2014;5:11.

[59] Endo K, Sata N, Ishiguro Y, et al. A patient-specific surgical simulator using preoperative imaging data: an interactive simulator using a three-dimensional tactile mouse. J Comput Surg 2014;1:1-8.

[60] Eschweiler J, Stromps JP, Fischer M, et al. Development of a biomechanical model of the wrist joint for patientspecific model guided surgical therapy planning: Part 1. Proc Inst Mech Eng H 2016;230:310-25.

[61] Makiyama K, Yamanaka H, Ueno D, et al. Validation of a patient-specific simulator for laparoscopic renal surgery. Int J Urol 2015;22:572-6.

[62] Shenai MB, Dillavou M, Shum C, et al. Virtual interactive presence and augmented reality (VIPAR) for remote surgical assistance. Neurosurgery 2011;68:200-7; discussion 207.

[63] Shenai MB, Tubbs RS, Guthrie BL, et al. Virtual interactive presence for real-time, long-distance surgical collaboration during complex microsurgical procedures. J Neurosurg 2014;121:277-84.

[64] Ponce BA, Jennings JK, Clay TB, et al. Telementoring: use of augmented reality in orthopaedic education: AAOS exhibit selection. J Bone Joint Surg Am 2014;96:e84.

[65] Davis MC, Can DD, Pindrik J, et al. Virtual Interactive Presence in Global Surgical Education: International Collaboration Through Augmented Reality. World Neurosurg 2016;86:103-11.

[66] Sutherland LM, Middleton PF, Anthony A, et al. Surgical simulation: a systematic review. Ann Surg 2006;243:291-300.

[67] Gurusamy KS, Aggarwal R, Palanivelu L, et al. Virtual reality training for surgical trainees in laparoscopic surgery. Cochrane Database Syst Rev 2009;(1):CD006575.

[68] Sturm LP, Windsor JA, Cosman PH, et al. A systematic review of skills transfer after surgical simulation training. Ann Surg 2008;248:166-79.

[69] Aggarwal R, Ward J, Balasundaram I, et al. Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. Ann Surg 2007;246:771-9.

[70] Ahlberg G, Enochsson L, Gallagher AG, et al. Proficiencybased virtual reality training significantly reduces the error rate for residents during their first 10 laparoscopic cholecystectomies. Am J Surg 2007;193:797-804.

[71] Grantcharov TP, Kristiansen VB, Bendix J, et al. Randomized clinical trial of virtual reality simulation for laparoscopic skills training. Br J Surg 2004;91:146-50.

[72] Orzech N, Palter VN, Reznick RK, et al. A comparison of 2 ex vivo training curricula for advanced laparoscopic skills: a randomized controlled trial. Ann Surg 2012;255:833-9.

[73] Aïm F, Lonjon G, Hannouche D, Nizard R. Effectiveness of virtual reality training in orthopaedic surgery. Arthroscopy 2016;32(1):224-32.

[74] Philibert I, Friedmann P, Williams WT, ACGME Work Group on Resident Duty Hours. New requirements for resident duty hours. JAMA 2002;288(9):1112-4.

[75] Bakker NH, Fokkens WJ, Grimbergen CA. Investigation of training needs for functional endoscopic sinus surgery (FESS). Rhinology 2005;43(2):104-8.

[76] Li L, Yu F, Shi D, Shi J, Tian Z, Yang J, et al. Application of virtual reality technology in clinical medicine. Am J Transl Res 2017;9(9):3867-80.

[77] Kim Y, Kim H, Kim YO. Virtual reality and augmented reality in plastic surgery: a review. Arch Plast Surg 2017;44(3):179-87.

[78] Olsson P, Nysjö F, Hirsch JM, Carlbom IB. A haptics-assisted craniomaxillofacial surgery planning system for restoring skeletal anatomy in complex trauma cases. Int J Comput Assist Radiol Surg 2013;8(6):887-94.

[79] Wang Q, Chen H, Wu W, Jin HY, Heng PA. Real-time mandibular angle reduction surgical simulation with haptic rendering. IEEE Trans Inf Technol Biomed 2012;16(6):1105-14.

[80] Mischkowski RA, Zinser MJ, Kübler AC, Krug B, Seifert U, Zöller JE. Application of an augmented reality tool for maxillary positioning in orthognathic surgery - a feasibility study. J Craniomaxillofac Surg 2006;34(8):478-83.

[81] Wu F, Chen X, Lin Y, Wang C, Wang X, Shen G, et al. A virtual training system for maxillofacial surgery using advanced haptic feedback and immersive workbench. Int J Med Robot 2014;10(1):78-87.

[82] Lin Y, Wang X, Wu F, Chen X, Wang C, Shen G. Development and validation of a surgical training simulator with haptic feedback for learning bone-sawing skill. J Biomed Inform 2014;48:122-9.

[83] Irvine, S. A., and S. S. Venkatraman. Bioprinting and differentiation of stem cells. Molecules 21:1188, 2016.

[84] Chikwe, J., A. C. de Souza, and J. R. Pepper. No time to train the surgeons. BMJ 328:418–419, 2004.

[85] Ito, K., K. Furuya, Y. Okano, and L. Hamada. Development and characteristics of a biological tissue-equivalent phantom for microwaves. Electron. Commun. Jpn. 84:67–77, 2001.

[86] Sekhar, A., M. R. Sun, and B. Siewert. A tissue phantom model for training residents in ultrasound-guided liver biopsy. Acad. Radiol. 21:902–908, 2014.

[87] Tang, B., G. B. Hanna, and A. Cuschieri. Analysis of errors enacted by surgical trainees during skills training courses. Surgery 138:14–20, 2005.

[88] Sugiyama, T., S. Lama, L. S. Gan, Y. Maddahi, K. Zareinia, and G. R. Sutherland. Forces of tool-tissue interaction to assess surgical skill level. JAMA Surg. 153:234–242, 2018.

[89] Krauel, L., F. Fenollosa, L. Riaza, M. Pérez, X. Tarrado, A. Morales, J. Gomà, and J. Mora. Use of 3D prototypes for complex surgical oncologic cases. World J. Surg. 40:889–894, 2016.

[90] Perez, M. Sterilization of FDM-manufactured parts Mireya 285–296, 2012

[91] Shaheen, E., A. Alhelwani, E. Van De Casteele, C. Politis, and R. Jacobs. Evaluation of dimensional changes of 3D printed models after sterilization: a pilot study. Open Dent. J. 12:72–79, 2018.

[92] Davison, G. C. In reply: behaviour therapy. Br. J. Psychiatry 112:211–212, 1966.

[93] Linares-Alvelais, J. A. R., J. Obedt Figueroa-Cavazos, C. Chuck-Hernandez, H. R. Siller, C. A. Rodríguez, and J. I. Martínez-López. Hydrostatic high-pressure post-processing of specimens fabricated by DLP, SLA, and FDM: an alternative for the sterilization of polymer-based biomedical devices. Materials (Basel) 11:2540, 2018.

[94] Vieri, Carlin, et al. "An 18 megapixel 4.3 ″1443 ppi 120 Hz OLED display for wide field of view high acuity head mounted displays." Journal of the Society for Information Display 26.5 (2018): 314-324.

[95] Unwin, Nigel. "Nicotinic Acetylcholine Receptor at 9 Resolution." Journal of molecular biology 229 (1993): 1101-1101.

[96] Wikipedia contributors. (2022, November 17). Vivisection. Wikipedia. https://en.wikipedia.org/wiki/Vivisection

[97] Wikipedia contributors. (2022b, November 30). Cadaver. Wikipedia. https://en.wikipedia.org/wiki/Cadaver

[98] Mm, M., Th, L., H, D., & Lf, W. (2019, April 4). Development of In-situ Simulation Lab for Training Gynecology Residents in Basic Laparoscopic and Hysteroscopy Operative Skills. Abstract - Europe PMC. https://europepmc.org/article/pmc/6555493

[99] Leverages Virtual Reality to Advance Surgical Training. (2017, February 27). 3D Systems. https://www.3dsystems.com/press-releases/3d-systems-leverages-virtual-reality-advance-surgical-training

[100] Skills Simulator. (n.d.). https://www.davincisurgerycommunity.com/Systems_I_A/Skills_Simulator

[101] Alila Medical Media. (n.d.). Visual Projection Pathway Stock Illustration 78254164. Shutterstock. https://www.shutterstock.com/image-illustration/visual-projection-pathway-78254164

[102] Touch. (2022, December 7). 3D Systems. https://ko.3dsystems.com/haptics-devices/touch

[103] DiGiulio, S. (2017, August 22). 3 Ways Virtual Reality Is Transforming Medical Care. NBC News. https://www.nbcnews.com/mach/science/3-ways-virtual-reality-transforming-medical-care-ncna794871

[104] Virtual Reality helps in surgical planning. (2016, December 21). https://healthcare-in-europe.com/en/news/virtual-reality-helps-in-surgical-planning.html

Abstract

수술 시뮬레이션은 의사 교육과 환자 안전을 위해 매우 유용한 도구이다. 또한 수술 시뮬레이션 기술은 실감나고 사실적인 학습을 가능하게 하기 때문에 최근 많은 외과 전문의 교육 프로그램으로 활용되고 있는 추세이다. 그렇기 때문에 수술 시뮬레이션이 전통적인 학습을 위한 도구에서 역량 향상을 위한 도구로의 역할이 변화되고 있다. 이러한 수술 시뮬레이션은 외과의를 교육하고 평가하는 표준화되고 안전한 방법이 될 수 있는데 복강경 기술의 발전과 함께 훈련을 위한 시뮬레이션의 사용이 중요해지고 있을 뿐만 아니라 전문가가 복잡한 수술을 사전에 계획하고 수술 전후 결과를 평가하는 데에도 유용하기 때문이다.

본 논문에서는 실제 환자 데이터를 사용하여 가상 현실 기술을 이용하여 사용자가 수술을 계획 할 수 있는 시스템을 제안한다. 이러한 수술 시뮬레이션 시스템은 의사가 환자에게 환자의 상태를 보다 쉽게 설명할 수 있어 환자와 의사 간의 신뢰를 높일 수 있게 된다.