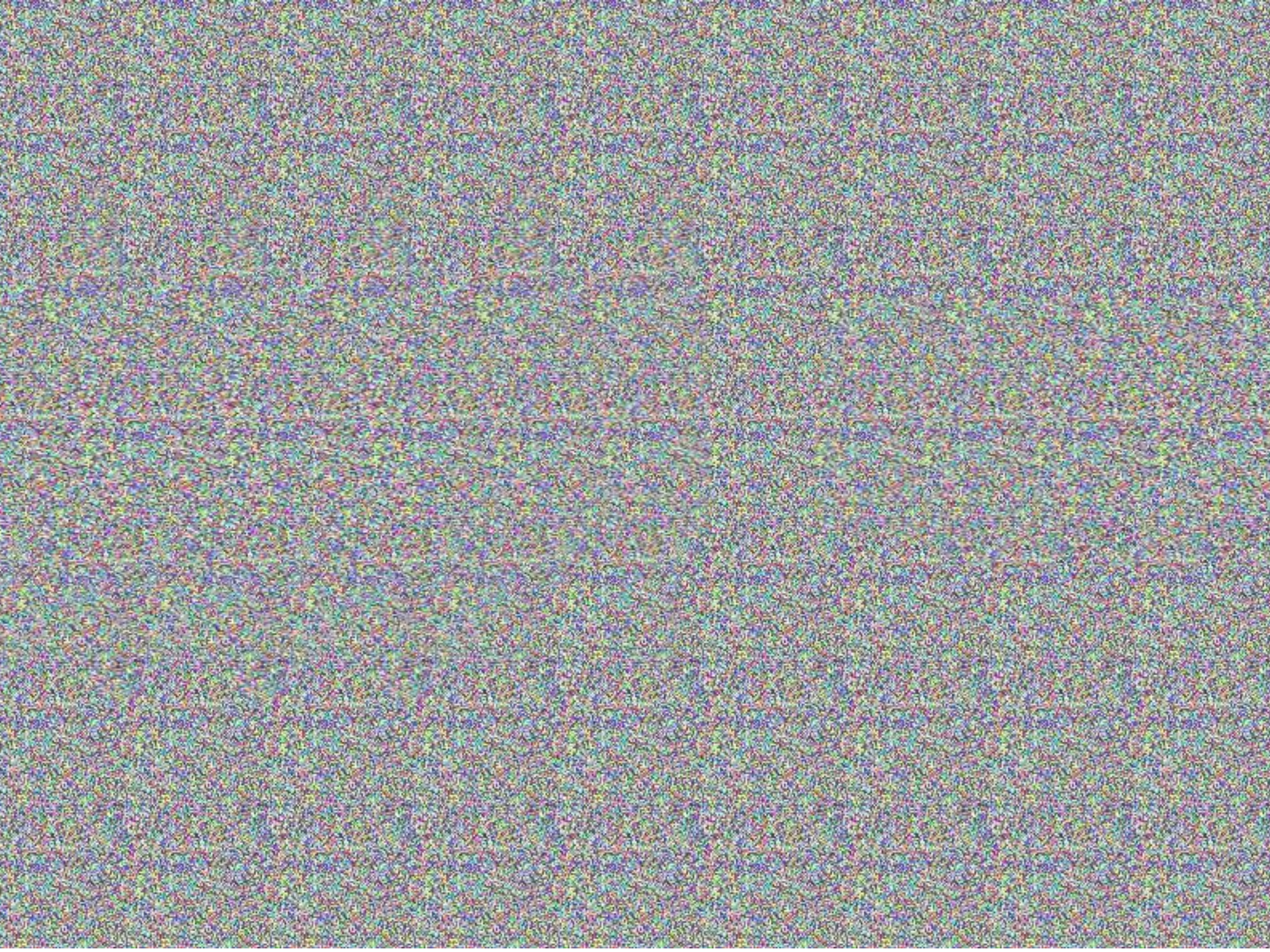

THE EVALUATION OF STEREOPSIS ON THE PREOPERATIVE SURGICAL PLANNING FOR COLORECTAL LIVER METASTASES SURGERY

LAURENT COOPMANS

Wondering what to see, I recommend you to read the Preface.

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The Evaluation of Stereopsis on the Preoperative Surgical Planning for Colorectal Liver Metastases Surgery

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Preface

For those wondering if the correct image on the title page has disappeared, I must inform you that it was intentional. Feel free to call it not beautiful or even ugly; tastes differ. Despite the possibility that you might prefer not to look at it anymore, I still challenge you to take another glance. But this time, in a slightly different way.

Looking at something in a different way, that has also been central in the past 6.5 years of my study in Technical Medicine. Looking at medicine, looking at technology, looking at their combination. Sometimes, looking at the combination of medicine and technology seems far-fetched, even within my study. However, ultimately, this link between them often appears to be closer than initially thought. Searching for a link between two worlds is also something from which the medical world can still learn. Within, but also outside of my studies, I have learned that there are significant challenges in healthcare. We all strive to continue improving the quality of medicine, but the reality tells us that our new duty lies in not allowing it to become worse.

That will also mean that we need to look at healthcare differently. Curing becomes caring: cure that we offer today as a matter of course could suddenly become unnecessary tomorrow. Not taking action is also an option, as long as the patient is informed about it. Helping a patient with its diet can sometimes mean more than performing a complex surgery.

These insights that I have gained during my studies are owed to many people. Firstly, to the teachers and mentors who inspired me to continue in this field. Do not underestimate it, but some people can mean a lot in determining where your future lies. Additionally, my family and friends who always wanted to provide me with advice, whether asked for or not.

Lastly, specifically during the writing of this master thesis, my PhD supervisors Tom and Martijn, thank you for always being ready to help, provide feedback, and guide. You together with all students and PhD's from the GreenLight Leiden make graduating a lot easier and more enjoyable. Thanks to Alexander and Jouke for the weekly meetings, your patience, and advice. Thanks to Bas Boekesteijn for extensively assisting in evaluating the radiological images. Thanks to all liver and transplant surgeons who were stalked during my graduation to participate in my research, but ultimately almost all participated. And many thanks to Victorien, Sven and Alexander, for collaborating, critically questioning, but above all, inspiring enthusiasm for research in the medical world.

Returning to the cover page of my thesis, at first glance, one looks at the image as if it were a random pattern of colours without structure. However, when one looks differently, and thus does not focus on the picture but beyond it – read the introduction to know more about how stereopsis works -, new discoveries suddenly appear. With this thought, I conclude this chapter and eagerly look forward to a future in the medical world with great joy and pleasure.

And for those who really don't know what to look for, the answer lies in the title of this thesis. Enjoy reading!

Laurent Coopmans

Leiden, March 2024

Abstract

Background
The surgical management of Hepato-Pancreato-Biliary (HPB) cancer poses significant challenges, primarily due to the complexity of patients. However, the role of stereopsis (depth perception) in visualizing three-dimensional (3D) anatomical models remains relatively underexplored. Integrating stereoscopic technologies with 3D anatomical modelling holds promise for enhancing surgical planning and navigation, thereby addressing the inherent complexities of HPB surgeries.

Aim
This study aims to evaluate the effect of stereopsis on the preoperative surgical planning of colorectal liver metastases surgery.

Methods
A retrospective study was conducted with participants from the Department of Surgery, Leiden University Medical Centre (LUMC), to investigate the occurrence and severity of symptoms resulting from the use of a stereoscopic display. Subsequently, liver and transplant surgeons from the same department participated in another retrospective study comparing surgical plans for colorectal liver metastases performed stereoscopically with those performed monoscopically, within the same surgeon.

Results
14 out of 18 participants experienced (slight) symptoms from the use of a stereoscopic display, yet no one discontinued the study due to symptoms. In the subsequent study on the effect of stereopsis on preoperative surgical planning for colorectal liver metastases, 13 liver and transplant surgeons participated. Relative to a gold standard, there appears to be no significant difference between surgical plans executed monoscopically or stereoscopically. There is also no significant difference in the time taken to create these surgical plans ($p=0.401$). Despite the absence of significant difference between the plans, surgeons do express a (strong) preference for stereopsis in locating the tumor (61%), determining the surgical plan (61%), and assessing vascular involvement (69%).

Conclusion
It is evident that surgeons have a preference for stereopsis in visualizing 3D models, although our study found no discernible differences in outcomes between monoscopic and stereoscopic preoperative planning for colorectal liver metastases surgery. Future research is recommended to compare surgical plannings based on conventional two-dimensional imaging alone with conventional two-dimensional imaging supplemented by additional stereoscopic 3D models. This comparative analysis could offer further insights into the potential advantages of integrating stereoscopic technology into preoperative planning practices.

Table of Contents

List of Abbreviations

CT	Computed Tomography
MRI	Magnetic Resonance Imaging
US	UltraSound
2D	Two-dimensional
3D	Three-dimensional
AI	Artificial Intelligence
HMD	Head-Mounted Display
XR	Extended Reality
VR	Virtual Reality
AR	Augmented Reality
MR	Mixed Reality
LUMC	Leiden University Medical Centre
HPB	Hepato-Pancreato-Biliary
IKNL	The Netherlands Comprehensive Cancer Organisation
PhD	Doctor of Philosophy
N	Number
RGB	Red Green Blue

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1. General background

1.1. Rationale

In oncology, surgery remains a cornerstone for curative treatment. However, the landscape of how cancer patients present is changing due to aging populations. Patients now often present with multiple comorbidities alongside cancer, complicating treatment decisions. Moreover, advancements in medical treatments have further complicated patient cases. Where patients were previously treated palliatively, there are now more curative treatment options available. To navigate this complexity effectively, a refined diagnostic approach paired with a strategic surgical plan is crucial. Perioperative imaging plays a pivotal role in this process, facilitating a comprehensive understanding of the disease, accurate diagnosis, and tailored surgical strategies. By providing detailed insights into the spatial relationship between tumours and surrounding anatomical structures, perioperative imaging enables surgeons to perform surgeries more effectively with greater precision. The role of imaging in oncology over time is described in the following section.

1.2. Advancements in Medical Imaging

The use of medical imaging has a long history, starting in the 20th century with the German physics professor Wilhelm Röntgen, who made a X-ray of his wife's hand. (1) Over time, the number of imaging modalities has increased, with X-rays, Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and ultrasound (US) as the most commonly used modalities. Additionally, medical imaging have become increasingly advanced. These advancements include the generation of higher resolution images, visualization of cellular and molecular events, integration of modalities, and processing of images from two-dimensional (2D) images into three-dimensional (3D) models. (2, 3)

1.2.1. The Use of Three-Dimensional Models

Particularly, this latter advancement is gaining momentum in oncology due to the increasing interest in artificial intelligence (AI). Medical imaging presents an ideal platform for AI applications, given the enormous amount of data available. One method to apply AI in medical imaging is through supervised learning, a subcategory of machine learning. In this approach, an algorithm is provided with annotated images, wherein structures visible in the images are segmented. By supplying the algorithm with sufficient information on how structures, such as organs and the tumour, appear in imaging (=labelled images), it can ultimately provide predictions on the visibility of structures in new data. In order to make accurate predictions, it is important to provide the algorithm with accurate information. Therefore, it is recommended to validate the labelled images against a gold standard, in this case, the determination by a radiologist. Eventually, the algorithm can automatically delineate the images featuring visible structures. These automatically delineated images serve as the basis for creating a 3D model of the patient's anatomy. In oncological surgery, 3D anatomical models can complement conventional 2D images by offering a more intuitive depiction of the spatial relationship between the tumour and surrounding structures. Such insights are invaluable for surgeons, enabling them to conduct operations with enhanced precision and effectiveness.

1.2.2. Visualisation of Three-Dimensional Models

The use of 3D models alongside the traditional 2D images opens up new opportunities. Enhancing the intuitiveness of the visualisation of these 3D models can be achieved through the use of stereopsis, which enhances depth perception. Before exploring the application of stereopsis in the medical field, it is essential to provide additional background on its definition, underlying mechanisms, potential applications, as well as its advantages and disadvantages.

Stereopsis

Stereopsis, derived from the Ancient Greek words stereós (solid) and ópsis (appearance), refers to the visual perception of 3D structures in the world. It primarily refers to depth perception arising from binocular disparity, where the distinct positions of each eye provide different perspectives. The brain then processes these divergent visual inputs in the visual cortex to construct a unified depth representation (Figure 1, A). (4) This process allows the brain to interpret 2D images as 3D structures by synthesizing multiple perspectives.

There are various 3D technologies available for projecting stereoscopic images. In the following section, different technologies will be discussed, each with its own set of advantages and disadvantages for projecting stereoscopic images.

A relatively simple 3D technology for projecting stereoscopic images is anaglyph. This technique utilizes red and blue images viewed through glasses, where each lens filters out either the red or blue image for each eye (see Figure 1, B). (4) This technique is cost-effective, and easy to implement, requiring only coloured filters or glasses. However, anaglyph has limitations, as it cannot reproduce the full colour spectrum and is often associated with colour distortion and a reduction in image quality.

Another technique that utilizes filters is the polarized 3D system. Similar to anaglyph, glasses are employed to filter out lights with different polarizations. Each eye of the viewer filters out lights with different polarizations, presenting separate images to each eye (see Figure 1, C). (4) Compared to anaglyph, the use of polarized 3D glasses produces a full-colour image, with a more immersive and visually appealing experience. However, a drawback is that polarized 3D glasses significantly increase expenses. This is primarily due to the specialized display panels used, which can polarize light in different directions for each eye. Furthermore, polarized 3D systems have a restricted viewing angle, causing the 3D effect to degrade or disappear when viewed from off-centre angles.

A third technique used is the active shutter 3D system. It functions by alternately presenting images to each eye, synchronized with shutter glasses (Figure 1, D). (5) An advantage of this technique is that the image can be viewed in a full colour spectrum and at full resolution. However, flicker may be noticeable due to the refresh rate of the images. Additionally, the glasses are more expensive since they require batteries to synchronize and alternate between blocking each eye's view.

Another technology are the head-mounted displays (HMDs), which deliver separate images to each eye using integrated miniature display screens (Figure 1, E). (6) They offer an immersive viewing experience by placing screens directly in front of the user’s eyes, while boasting a lightweight and portable design. However, HMDs have limitations, including a restricted field of view, potential motion sickness with extended use, and a relatively heavy weight leading to discomfort.

Lastly, autostereoscopic technology integrates filters directly into the television screen, eliminating the need for glasses. These built-in filters automatically deliver separate images to each eye, enhancing the viewing experience for users (Figure 1, F). (4) A significant advantage of this technology is the elimination of glasses, making it more accessible. However, there are several disadvantages to consider, including the limited viewing zone in which the 3D effect is optimal, reduced image quality, and the complexity and costs associated with implementation.

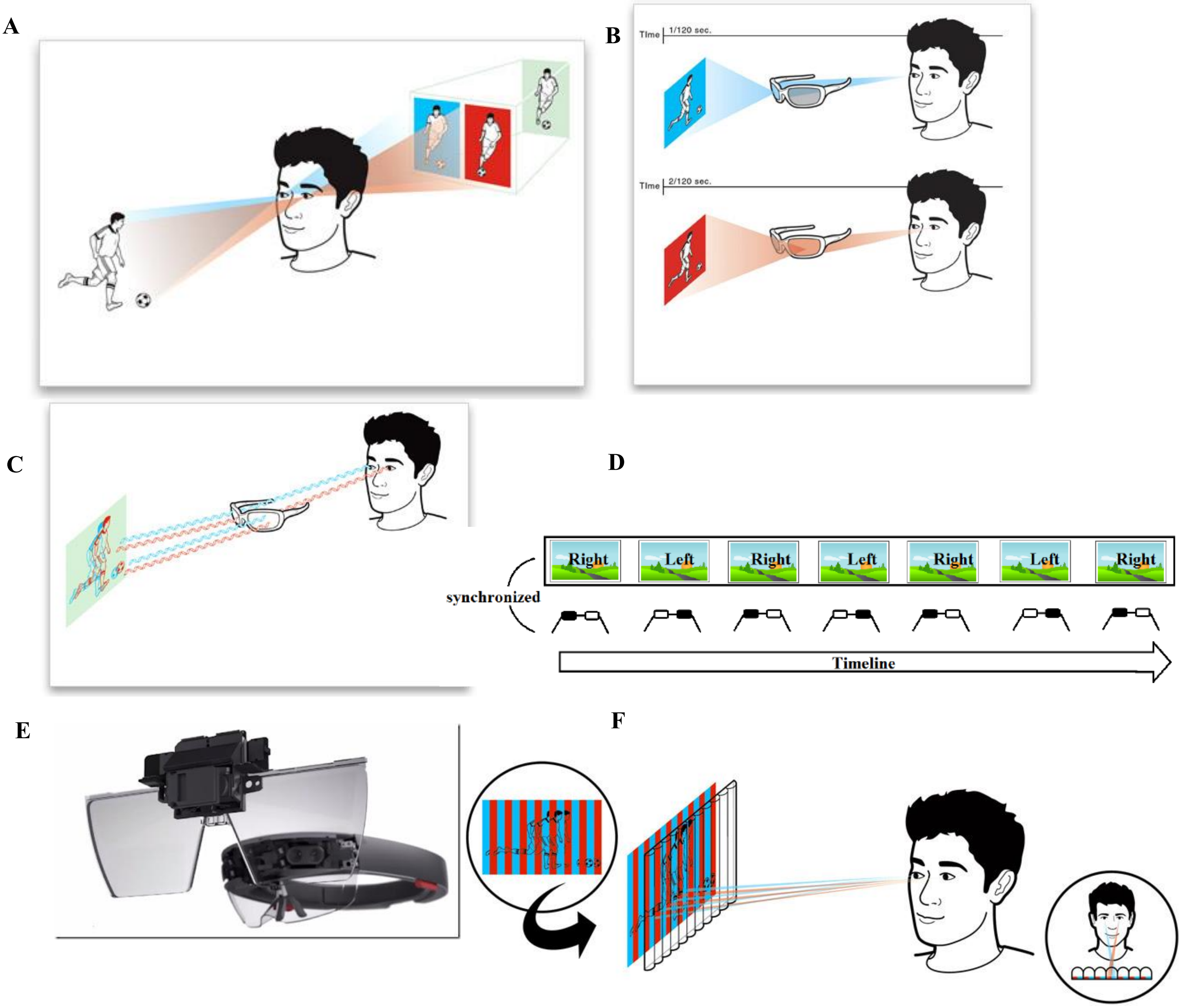

Figure 1.
Visualisation of the principle of

- A. Stereopsis
- B. Anaglyph
- C. Polarization
- D. Active shutter
- E. Head-mounted display, where each glass displays a different perspective
- F. Autostereoscopy

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For now, a common drawback of stereopsis is that users may experience symptoms. This is mainly due to existing techniques presenting separate images to the eyes. This can lead to a parallax - a difference in the position of an object when viewed from different angles - between the different images, causing a conflict between ocular vergence and eye accommodation (Figure 2). (7) As a result, visual discomfort such as fatigue and headaches can occur.

Stereoscopic Devices in the Medical Field

Among stereoscopic techniques, HMDs (Head-Mounted Displays) stand out as particularly popular in the medical field, with growing utilization primarily in educating in anatomy, procedural skills, and clinical decision-making. A variety of devices are available on the market, each offering different forms of extended reality (XR), including virtual reality (VR), augmented reality (AR), and mixed reality (MR). The distinction lies in how these technologies interact with the real world, making AR and MR more suitable for intraoperative use, while VR, providing full immersion in a virtual environment, is better suited for preoperative applications such as decision-making and surgical planning. (8) More information on the use of HMDs in the medical field is given in the introduction.

The Stereoscopic Display of Barco

Before the start of the study, an experimental stereoscopic display from Barco (Kortrijk, Belgium). was available at the Leiden University Medical Centre (LUMC). This display is a 55” polarized 3D system, allowing users to view stereoscopically with the aid of polarized glasses (Figure 3). All studies were performed with the use of this display.

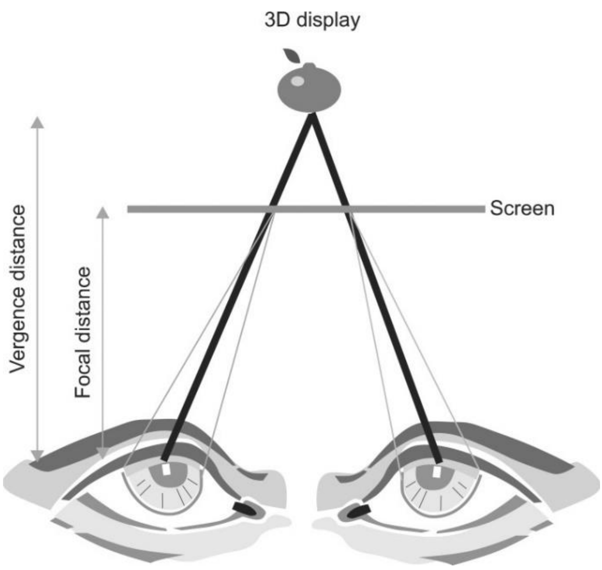

Figure 2. Vergence-accommodation mismatch, from Nam et al.

Figure 3. Images of the stereoscopic display and 3D polarized glasses

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2. Introduction

2.1. Hepato-Pancreato-Biliary Cancer

Hepato-pancreato-biliary (HPB) cancer is a collective name for malignancies arising from the liver, pancreas, and biliary tracts. Over the past few years, the incidence of HPB cancers increases, mainly under influence of factors such as aging, smoking, alcohol consumption, obesity and diabetes. (9) To address malignancies located in this intricate region, the Netherlands Comprehensive Cancer Organisation (IKNL) recommends diagnosis and treatment to be >90% multidisciplinary in a specialized hospital. (10) Despite this recommended multidisciplinary approach and improved strategies for curative-intent treatment, HPB cancer continues to steadily climb the ranks among the deadliest malignancies. (11) This rise is mainly caused by the fact that in the last decades there was marginal improvement in survival rates of HPB cancer – mainly in pancreatic- and biliary cancer -, in contrast to other cancer types. (12)

Nowadays, surgery is the cornerstone in the curative treatment of HPB cancer. (13-17) Nevertheless, complete resection of the tumour may not always be achievable in advanced stages, when the tumour has spread extensively to vital, surrounding tissues. With the fact that in HPB cancer the number of patients diagnosed in an advanced stage remains high, it becomes clear why the survival rates stay low. (10, 18) Unfortunately, advancing the timing of diagnosis – where complete resection is more often achievable - is difficult due to the absence of clinical symptoms and lack of accurate tests for early detection. Enhancing the success of complete resection – with sufficient surgical margins - is therefore crucial for improving the survival rates. However, complete resection of HPB cancer remains challenging. This challenge is primarily attributed to the proximity of numerous organs and critical blood vessels. Additionally, various anatomical variations further contribute to the complexity of these surgical procedures. (19-22)

2.2. The Role of Imaging in Diagnosis and Treatment

Within oncological surgery, there are ongoing developments aimed at supporting these complex surgeries. This support primarily focuses on a better preparation *before* surgery and navigation *during* surgery. Improved preparation and navigation can facilitate the decision-making process, which enhances the safety and effectiveness of (complex) operations – e.g. complete surgical resections with tumor-free surgical margins.

Currently, surgeons' preparation for HPB surgery is predominantly based on 2D CT images and, in some hospitals, additional 2D MRI. Additionally, intraoperative ultrasound (IOUS) is used to rapidly and safely display structures during surgery. Surgeons are trained to translate these 2D images into a 3D reality of the pathophysiological and anatomical situation. However, especially for the complex HPB region, this translation can be a challenging task. (23) The use of additional 3D anatomical models can, therefore, assist in representing the patient's anatomy, including the relationship of tumour(s) to surrounding structures, in a more intuitive manner. It even enables surgeon to practice their surgery virtually. Additionally, this 3D anatomical model can be used for intraoperative navigation by registration of the 3D model on the patient's anatomy.

Advances in automatically generated 3D anatomical models using AI for HPB surgery are creating even greater possibilities for representing patients' anatomy more intuitively, bringing it closer to reality. XR's such as virtual reality VR, augmented reality AR, and MR, or stereoscopic displays can play a role in a more intuitive display of 3D models by adding stereopsis. With software and hardware developments – driven by other industries - these technologies have become more accessible for clinical practice. In education, the introduction of XR has already made an impact by enhancing learning capabilities. (24, 25) The question, however, is whether trained surgeons also benefit from depth perception in preparation and decision-making or that it introduces an additional burden before and during surgery.

2.3. Literature Review

To investigate this possible benefit of stereopsis in displaying 3D anatomical models in preparation and decision-making of HPB surgery, a literature research was conducted on PubMed, Web of Science, Embase and Cochrane (publication date until August 2023) using the PICO framework (Table 1). The complete literature review is added to Appendix A.
The query yielded a total of 579 papers from PubMed, Web of Science, Embase, and Cochrane. After a full-text screening, 18 articles published between 2013 and 2023 were included in this review. XR's – such as MR (9), AR (7) and VR (2) – were used to display the 3D models with stereopsis (Table 2). The applications vary between studies and were subdivided per organ (Table 3).

Liver

In the vast majority of studies, specifically 14 out of 18, sterescopically displayed 3D models were used in liver surgery cases. In 2013, Onda et al. were the first to use stereoscopic 3D models in open liver procedures. (26) In total, six studies described the use of stereoscopic 3D models to determine the tumour localisation, (27-32) eight studies to identify blood vessels (26, 27, 29-34) and another eight studies to determine the resection plane. (26, 27, 29, 30, 32-35) The stereoscopic displayed 3D models were also used to virtually perform preoperative training and to calculate the residual postoperative liver volume (five studies). (29, 31, 33, 34, 36)

Pancreas

The main application of stereoscopic 3D models in pancreatic surgery focused on the identification of anatomically relevant vascular structures. (26, 32, 37-39) Considering the pancreas's complex central and retroperitoneal placement among many vital vascular structures. Simultaneously, surgeons aim to achieve complete tumour resection to hinder the progression of the disease. In the included studies, surgeons used stereoscopic 3D models to gain a comprehensive understanding of the anatomical situation. A more informed assessment enabled surgeons to find the balance between preserving blood vessel relationships and determining the necessary resection for optimal tumour removal. This application underscores the potential role of stereoscopic 3D models in enhancing surgical precision and decision-making in pancreatic surgery.

Table 1. PICO framework

Characteristic	*Description*
Population	Patients with Hepato-Pancreato-Biliary (HPB) cancer undergoing surgical treatment
Intervention	Use of conventional 2-dimensional (2D) imaging with additional a stereoscopic 3-dimensional (3D) model of the patient for surgical purposes
Comparison	Use of conventional 2-dimensional (2D) imaging alone for surgical purposes
Outcomes	Assessment of perioperative and surgical outcomes

Table 2. Characteristics included studies

Characteristic	*Augmented Reality (n=9)*	*Mixed Reality (n=7)*	*Virtual Reality (n=2)*
Study type			
Clinical trials	1	2	0
Proof-of-concept study	8	5	2
Device			
HoloLens (I/II)	0	6	0
HTC Vive v2.0 headset	0	0	2
In-house developed setup	9	1	0

Biliary System
Two studies focused on application of stereoscopic 3D models in the biliary system. Diana et al. used the stereoscopic 3D model based on MRI to visualise and identify the biliary ducts. (40) Tang et al. describe in their case report the utilization of a CT-based stereoscopic 3D model to visualize the biliary ducts and delineate the surgical plane for resection peri-hilar cholangiocarcinoma. (41) The distinction between these studies lies in Tang et al's report, where significant intrahepatic cholangiectasis enhanced the visibility of biliary structures on CT images.

Reported Clinical Outcomes
From the literature research, we learn that this field is still in early phase with a lot of heterogeneity in setups between studies. For example, the devices that were used to display the stereoscopic 3D models differ between studies, with nine studies that use in-house develop setups. Furthermore, 13 out of 18 studies were still in the proof-of-concept phase. As a result, clinical outcomes on the use and effect of stereopsis were limited.

Quantitative outcomes were only described in three studies. Diana et al. showed that the image quality of VR-AR to visualise the cystic duct was significantly lower compared to intraoperative X-ray cholangiography ($p<0.0001$). (40)

The two other studies showed a beneficial effect of stereopsis. Pelanis et al. showed in a study with fictive patients that the median time to determine the location of a liver lesion in one of the segments was significantly lower in HoloLens compared to MRI ($p<0.001$). (28) Furthermore, the accuracy of the diagnosis remained similar ($p=0.74$). It should be noted that participants had a median age of 30, with a median practical medical experience of 6 years, which does reflect a more educational context. Furthermore, the artificially placed lesions were marked as tumours in the 3D models, whereas this information was absent in the MRI images. In essence, an interpretation step what tumour tissue is, was already incorporated in the 3D models. Zhu et al. was the only study that focused on multiple clinical outcomes in the application of stereoscopic 3D models. (31)

Table 3. Applications for stereoscopic 3D-models

Application	*Liver (n =14)*	*Pancreas (n=6)*	*Biliary system (n =2)*
Tumour localisation	6	2	0
Identification of blood vessel(s)	8	5	0
Determination resection plane	8	4	1
Incision positioning	2	1	0
Identification of biliary ducts	0	0	1
Calculation remnant organ volume	5	0	0

They demonstrated that the use of stereoscopic 3D models via the HoloLens, in comparison to conventional 2D-imaging with CT, yielded statistically significant improvements, including: a reduction in operation time (p=0.003), a decrease in portal vein obstruction time (p=0.019), a notable reduction in intraoperative bleeding (p=0.028), faster recovery of ALT- (p=0.014) and ALB- (p=0.032) levels – as markers for the liver function - lower rate of 30-day postoperative complications (p=0.032), and lower rate of hospitalization days (p=0.049). None of the articles researched the impact of stereoscopic 3D-models on survival, recurrences, or other long-term outcomes.

Future Opportunities and Horizon Scanning

Based on the available literature and the lack of clinical studies, it is difficult to answer the question whether surgeons benefit from stereopsis in surgical planning in HPB surgery. Nonetheless, it should be noted that there is an upward trend visible in the use of stereoscopic 3D-models in HPB surgery. Based on the literature research, stereoscopic display of 3D models is beneficial for: the localization of tumour(s), identification of blood vessels and determination of resection planes. The limitation of these findings, however, is that they were often anecdotally reported and therefore subjective. This makes it difficult to compare findings and draw general conclusions for the use of stereoscopic 3D models.

The question that arises is: How do we transition from feasibility studies to prospective clinical trials aimed at assessing the impact of stereoscopic 3D models in HPB surgery on clinical outcomes. In the ideal situation, these studies could primarily focus on evaluating the impact of stereoscopic 3D models on achieving clear tumour margins. Additionally, they would explore follow-up aspects such as survival rates and recurrences. Secondary, the effect of using stereoscopic 3D models on surgical outcomes, such as operation time, complications, hospitalization days, etc. could be investigated. However, currently there exist too many uncertainties concerning the practicability and validity of stereoscopic 3D models for a HPB surgical planning. Therefore, it is recommended to first investigate the potential value of stereopsis in making HPB surgical plans through a retrospective study. This study design enables the possibility to determine the possible the effect of stereopsis on decision outcomes. These decision outcomes can then be linked to existing clinical data and information. By identifying the value and potential applications of stereopsis, it also provides clarity on the design of future prospective clinical studies.

2.4. Conclusion

Given the limited research on the effects of stereopsis in HPB surgery and the availability of a Barco stereoscopic display at the LUMC, this study aims to retrospectively evaluate the impact of stereopsis on preoperative planning for colorectal metastases surgery. Specifically, the study focuses on 3D models of colorectal liver metastases within the HPB context, as these models were readily accessible. By enhancing the intuitive visualization of 3D models, the objective is to improve surgical preparation and execution, ultimately aiming for better outcomes in HPB surgery.

The primary aim of this study was investigated through two consecutive studies (Part I and Part II) involving different participants. Prior to examining the impact of stereopsis on surgical planning among a large cohort of surgeons, non-surgeon participants assessed the feasibility of using the experimental stereoscopic display without encountering severe symptoms or discontinuation of use. As surgeons were not essential for this investigation due to time constraints, the study focused on students, PhD candidates, and researchers. Additionally, a small pilot study assessed whether there was no significant difference between outcomes in the students/PhD candidate/researcher group and the surgeon group. If symptoms were present to such an extent in this first part that the use of stereopsis was not feasible, the study was not continued. If symptoms did not lead to the termination of the experiment, a second part was conducted to investigate the impact of stereopsis on surgical planning within a larger surgeon cohort. An overview of the preformed studies is given in Table 4.

Table 4. An overview of the performed studies in part I and Part II

Chronology		***Name***	***Study population***	***Primary aim***	***Secondary aim***
↓	*Part I*	Study A	Students/PhD candidates/researchers (N=18)	Symptoms occurrence and severity	Effect stereopsis on surgical planning
		Study B	Surgeons (N=5)	Symptoms occurrence and severity	Optimize visualization 3D liver models
	Part II	Study	Surgeons (N=13)	Effect stereopsis on surgical planning	Symptoms occurrence and severity

3

3. Part I

3.1. Aims and Objectives

This study is part of the *Automation, Surgery Support and Intuitive 3D visualisation to optimize workflow in image guided therapy SysTems* (ASSIST) project.

The primary aim of this study was to

- Investigate factors that affect the use of stereopsis in the preoperative surgical planning for colorectal liver metastases surgery

The secondary aim of this study was to

- o Examine the effect of stereopsis on the preoperative surgical planning for colorectal liver metastases surgery

- ❖ Optimize the visualisation of 3D liver models in terms of colours and opacity

Therefore, this study focuses on the following objectives

- Quantify the occurrence and severity of symptoms resulting from the use of stereopsis *(study A and study B)*
- Examine whether symptoms resulting from the use of stereopsis prevent users to use stereopsis again *(study A and study B)*
- Examine whether wearing 3D glasses prevent users to use stereopsis again *(study A and study B)*

- o Compare outcomes between monoscopically and stereoscopically performed cases, such as certainty in the given answer, time per case and preference to perform the task *(study A)*

- ❖ Examine and test the colour and opacity settings of structures visible in the 3D liver models, including the liver, tumour(s), vena cava, vena hepaticae, venae portae, gallbladder and the arteriae hepaticae. *(study B)*

3.2. Materials and Methods

In the following paragraphs, the Materials and Methods section of study A is described.

3.2.1. Study A

The study design is summarized in Figure 4.

Study Population

Students, PhD candidates and researchers from the Department of Surgery in the LUMC were invited to participate in the study's primary aim, which focused on investigating factors influencing the use of stereopsis on the preoperative surgical planning for colorectal liver metastases surgery. Individuals using stereoscopic displays may experience symptoms (such as headache, dizziness and nausea). If applicable, this could hinder the future implementation of stereoscopic displays in the clinical practice. Due to their availability for scheduling experiments compared to surgeons, this group was primarily selected to investigate the first aim of this study. The recruitment of participants stopped once the number of new participants reached saturation.

Study Design & Materials

A retrospective study was conducted at the LUMC, in the summer of 2023. Participation in the experiments was voluntary. Before the experiment started, participants were alternately allocated to group A or B. The experiment started with adjusting the convergence distance - the distance from the eyes to the 3D model – according to the participant's preference. Participants were provided with practice time in the software for viewing 3D models to minimize differences in outcomes between the first and second cases caused by the learning curve of manipulating the 3D models. Finally, all tasks were reviewed in a practice case to prevent participants from misunderstanding the instructions while performing the case.

During the experiments, six 3D models of livers with tumour(s) were presented to participants in an individual session with one researcher (Figure 5). The 3D models were used from the study of Bijlstra et al. and were already available before the start of this study. (42) The selection of six cases was made based on the completeness of the segmented structures, and the complexity of the case. The included patient cases all underwent minimally-invasive surgery for colorectal liver metastases using a robot-assisted approach in a single academic university hospital (Amsterdam UMC, Amsterdam, The Netherlands). All patients were operated using the Intuitive da Vinci Xi (Sunnyvale, California, United States) robotic surgical system.. Software was used to semi-automatically segment the liver, the arterial, hepatic venous and portal venous structures from CT scans. All tumours were manually segmented by an expert. Colours of the 3D models were adopted from the study by Bijlstra et al. More information on patient's characteristics or 3D model creation/validation is given in the paper of Bijlstra et al.

All cases were presented on an experimental stereoscopic display from Barco. The 3D models could be viewed in both monoscopic and stereoscopic modes using their in-house developed software, Mercury3D (Barco, Kortrijk, Belgium) (Figure 6). The primary distinction between the setup of monoscopic and stereoscopic cases was the inclusion of stereopsis, introduced by enabling the 3D settings in the software and wearing polarized 3D glasses. This allowed for a comparison of tasks between monoscopic and stereoscopic views.

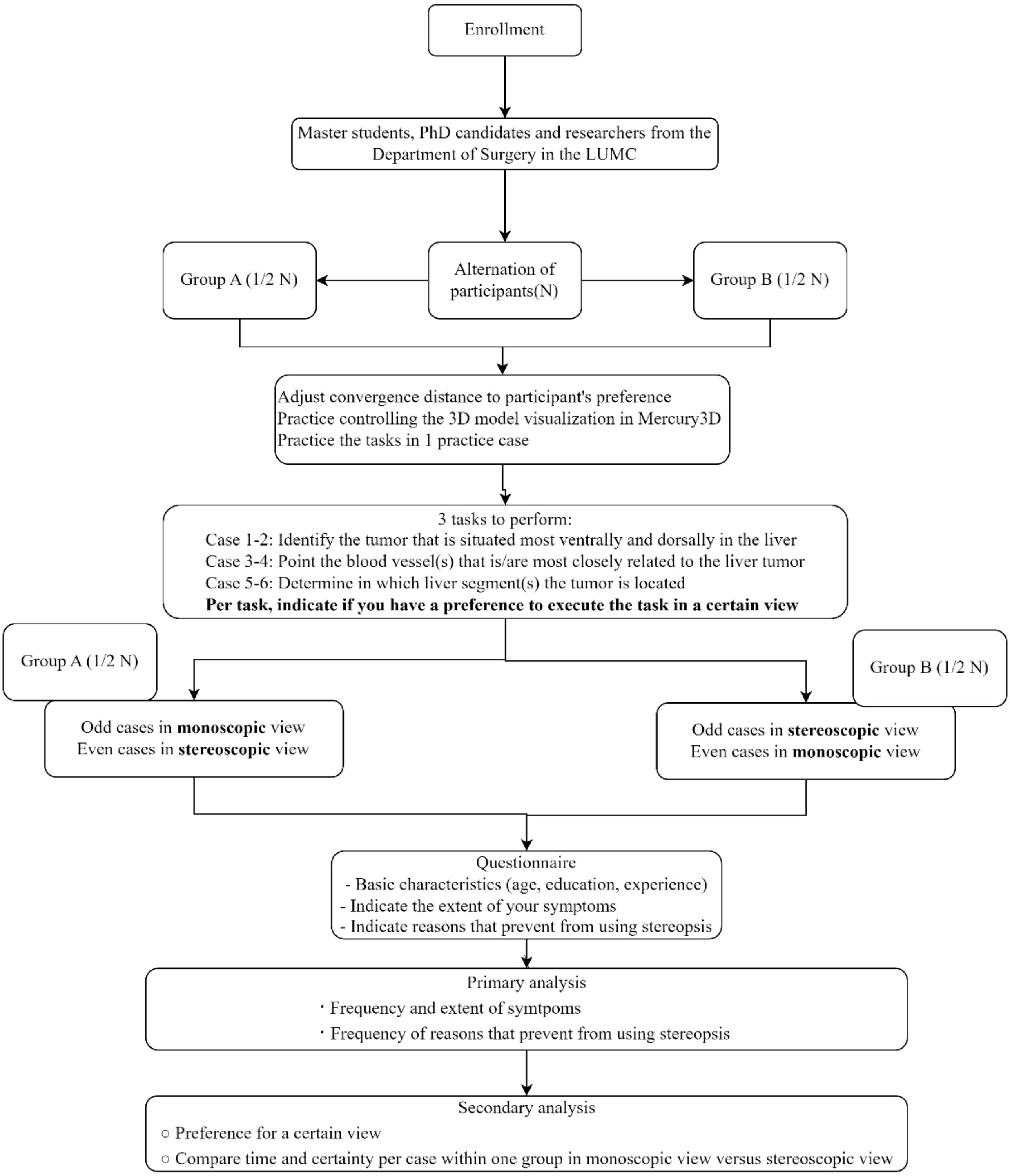

Figure 4. Flow chart of the study design

PhD, Doctor of Philosophy; LUMC, Leiden University Medical Center; N, number of participants

Figure 5. Example of study setup with the stereoscopic display of Barco

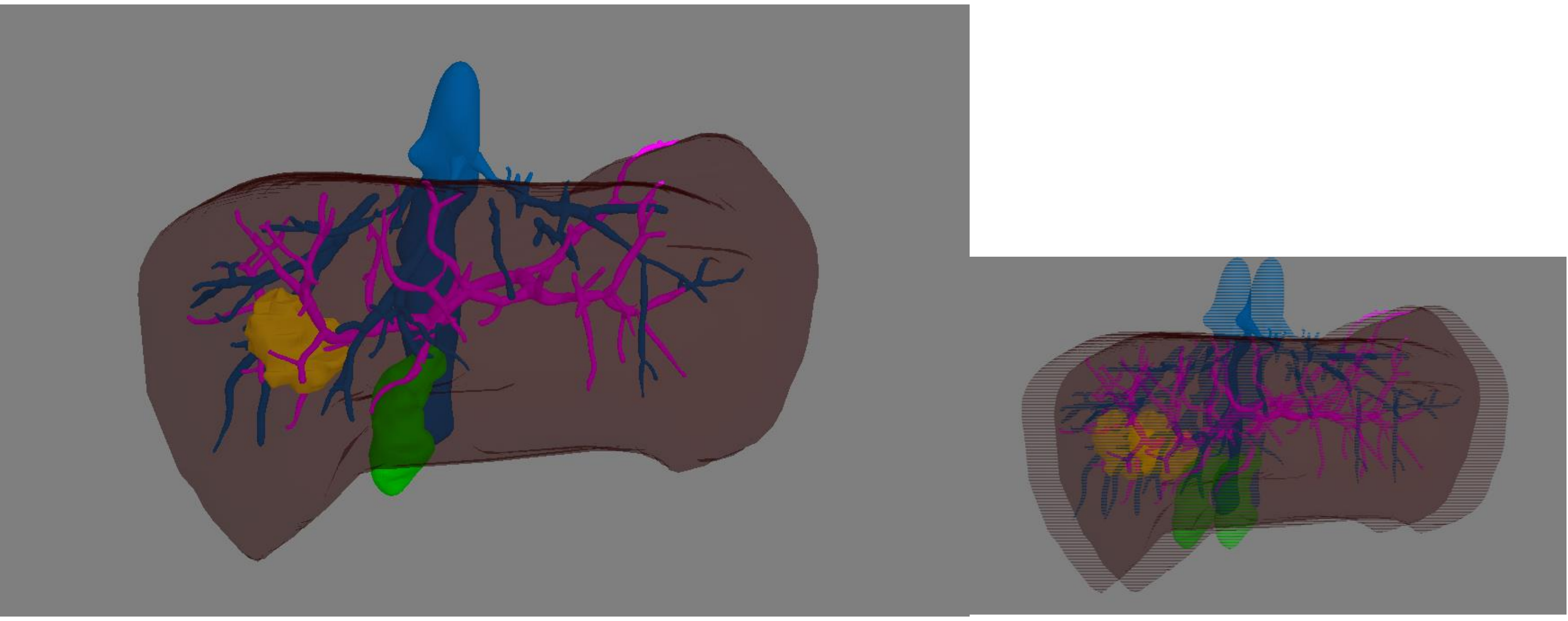

Figure 6. Example of a case with a colorectal liver metastasis, both in monoscopic view (left) and stereo-scopic view (right, visible with stereopsis in Mercury3D software on the Barco display)
The following structures were visible in the 3D model:
Liver (transparent in brown), tumour (yellow), gallbladder (green), vena cava, hepatic veins (blue) and the portal vein (purple)

To investigate the study's primary aim in a representative manner, participants were tasked with a realistic assignment focusing on spatial understanding for surgical planning. The six 3D liver models were grouped into three sets, each comprising two cases. Participants were assigned a specific task for each set of cases, where one case was performed monoscopically (in regular view) and the other stereoscopically. Since participants were not expected to possess medical knowledge about the cases, the tasks were kept simple yet relevant for surgical planning. Additionally, for all tasks, participants received an image illustrating the anatomy of the liver. The following tasks were assigned to participants:

- Identify the tumour that is situated most ventrally and dorsally in the liver -> cases with multiple tumours were shown
- Point the blood vessel(s) that is the most closely related to the liver tumour
- Determine in which liver segment(s) the tumour is located

The participants in Group A performed the initial cases monoscopically per set, whereas those in Group B executed the initial cases stereoscopically per set. This approach prevented any improvement in execution time from the second case from being associated with a specific viewing. Additionally, as mentioned earlier, the tasks were discussed beforehand to ensure clarity of instructions.

Each case was timed from the moment the participant opened the case until the participant indicated giving a final answer. Furthermore, participants were asked both in monoscopic and stereoscopic view to score their confidence of their answers using a the Likert scale, from (very) uncertain, neutral, to (very) certain. Only confidence in the answer was considered – not the content of answers - since it was assumed that participants had no prior knowledge of 3D liver models with tumours. Finally, after the completion of each task, participants were asked about their preference using a Likert scale, ranging from (strong) preference for monoscopic view, no preference, to (strong) preference for stereoscopic view.

After performing all tasks, participants were required to fill out a questionnaire (Appendix B) covering basic demographic characteristics, such as age, education, and experience with 3D visualisations. Participants were also asked if they had any eye conditions that could affect depth perception. Furthermore, participants were questioned whether they experienced symptoms such as general discomfort, headache, dizziness, eye strain, and others – based on the Simulator Sickness Questionnaire (SSQ). (43) The symptoms were scored none, slightly, moderate, or severe based on their presence. Moreover, participants were asked if these symptoms made them stop the research while using the stereoscopic display. Finally, participants were asked if wearing the 3D glasses hindered their use of the stereoscopic display.

Analysis

• *Primary Outcome*

The study's primary aim was to quantify the occurrence and severity of symptoms that may result from the use of the stereoscopic display. It was also recorded whether participants considered stopping the task. Finally, it was noted whether the 3D glasses prevent participants to use the stereoscopic display again. The results were recorded and presented in a figure indicating their frequency.

○ *Secondary Outcomes*

One of the secondary outcomes examined was the time required to complete tasks. The recorded times were rounded to the nearest integer. For each task, a Wilcoxon rank-sum test was conducted to compare completion times between monoscopic and stereoscopic views. Additionally, participants' confidence in their responses was evaluated using the same test. Furthermore, the participants' preference for performing tasks in either monoscopic or stereoscopic view was illustrated.

All statistical analyses were performed using SPSS software Version 29.0 (IBM, New York, NY, USA). Statistical outcomes were considered significant when the p-value was lower than 0.05. Tables and figures were generated with Microsoft Excel Version 2021 (Microsoft 365, Remond, WA, United States)

Study B was conducted when in the first study symptoms did not lead to termination of the experiments. In the following paragraphs, the Materials and Methods section of study 2 is described.

3.2.2. Study B

The study design is summarized in Figure 7.

Study Population

Liver and transplant surgeons from the Department of Surgery in the LUMC with experience in oncological liver surgery were invited to participate in the study's primary aim, which focused on investigating factors influencing the use of stereopsis for visualising 3D models.

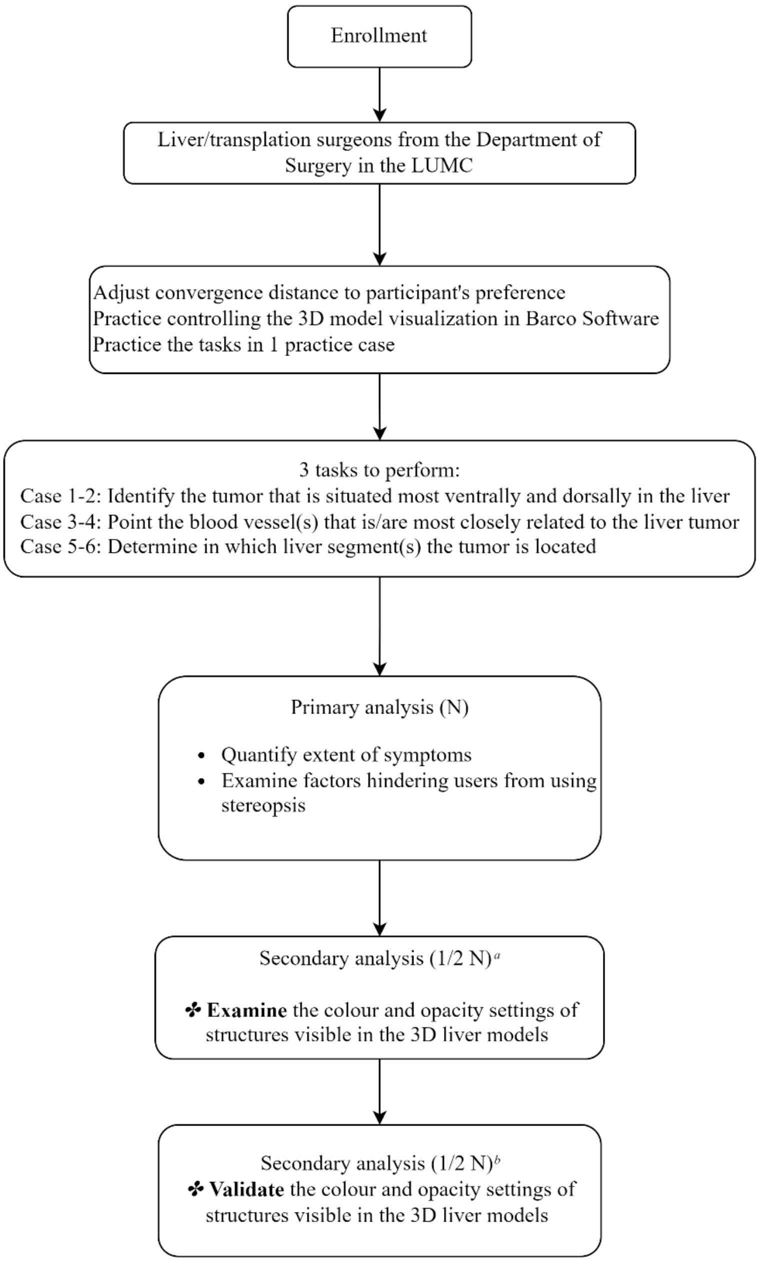

Figure 7. Flow chart of the study design

[a]The colour and opacity settings of structures were examined with the first half of participants

[b]The averaged colours and opacity per structure were validated with the second half of participants

Study Design & Materials

A retrospective study was conducted at the Leiden University Medical Centre (LUMC), in the summer of 2023. The setup of the study with surgeons was designed identically to the study with students, PhD candidates, and researchers. Therefore, for the execution, reference is made to the study design in the first study.

The difference in this study compared to the previous study involving students, PhD candidates and researchers was that participants were not divided in groups, basic characteristics were not queried, and secondary outcomes such as time per case, confidence per answers or preference for performing tasks were not examined. However, in this study group representing the future users, after the experiments another secondary aim was explored: optimizing the visualisation of 3D liver models in terms of colour and opacity. To optimize the visualisation of 3D liver models, participants were asked to indicate the ideal colour and opacity for each structure. The colours and opacity of structures were adjusted via the Blender software Version 4.0.2 (Blender Institute, Amsterdam, AMS, The Netherlands) and presented to surgeons in the Mercury3D software. Since it takes time to adjust these colours and opacities, the modified 3D models could not be visualized and validated immediately. Therefore, the responses of the first half of participants were averaged for each structure to determine an ideal colour and opacity. The second half of the participants were then asked to provide feedback on the chosen colours. This resulted in optimized visualisation of the 3D liver models. The questionnaire and a step-by-step guide for adjusting the colours of the 3D models are both included in Appendix C and D, respectively.

Analysis

• *Primary Outcome*

The primary outcome measure of this part of the study was identical to the primary outcome in the previous study: to quantify the occurrence and severity of symptoms that may result from the use of the stereoscopic display. Again, reasons that prevent users from using stereopsis to visualize 3D livers models were examined. The results were recorded and presented in a figure indicating their frequency.

✤ *Secondary Outcome*

The surgeon's preference for colour were reported per structure. An average colour code per structure was chosen and transformed in a Red Green Blue (RGB) colour code - to specify a colour. The adjusted 3D models were presented to the second half of the participants for validation of the selected colours.

All statistical analyses were performed using SPSS software Version 29.0 (IBM, New York, NY, USA). Statistical outcomes were considered significant when the p-value was lower than 0.05. Tables and figures were generated with Microsoft Excel Version 2021 (Microsoft 365, Remond, WA, United States)

3.3. Results

In the following paragraphs, the Results section of study A is described.

3.3.1. Study A

12 PhD candidates, four master students and two researchers participated in the first part of the study, making a total of 18 participants. In both group A and B, two-thirds of the participants had experience with 3D visualizations. The basic characteristics of the participants are summarized in Table 6.

• Primary Outcome

14 out of 18 participants reported experiencing one or more symptoms during/after making a preoperative surgical planning for colorectal liver metastases surgery. These symptoms varied among participants. Figure 8 illustrates which symptoms were present in participants, in what frequency, and to what extent. 'General discomfort' and 'eye strain' were the most common reported symptoms, each by 8 (44%) participants. All present symptoms in the different categories were reported as 'slightly', except for one participant who indicated 'moderate' symptoms in the category of 'eye strain'. Under the section 'other symptoms', where participants were free to provide additional information, no additional symptoms were reported. Furthermore, the questionnaire revealed that none of the participants considered stopping the study due to the symptoms caused by the stereoscopic display. The same applied to wearing the glasses; no one indicated finding them bothersome during the study.

○ Secondary Outcome

For the secondary outcomes, a comparison was made between cases performed in monoscopic view and stereoscopic view regarding 1) the preference for performing the task, 2) the certainty in the given answer, 3) the time per case.

Table 6. Characteristics of the participants

Characteristics	*Group A (N=9)*	*Group B (N=9)*	*All participants (N=18)*
Mean age, STD (years)	28.1 ± 2.9	30.6 ± 13.1	29.4 ± 9.0
Function			
Researcher (N)	1	1	2
PhD candidate (N)	7	5	12
Student (N)	1	3	4
Experience with 3D view (N)	6	6	12

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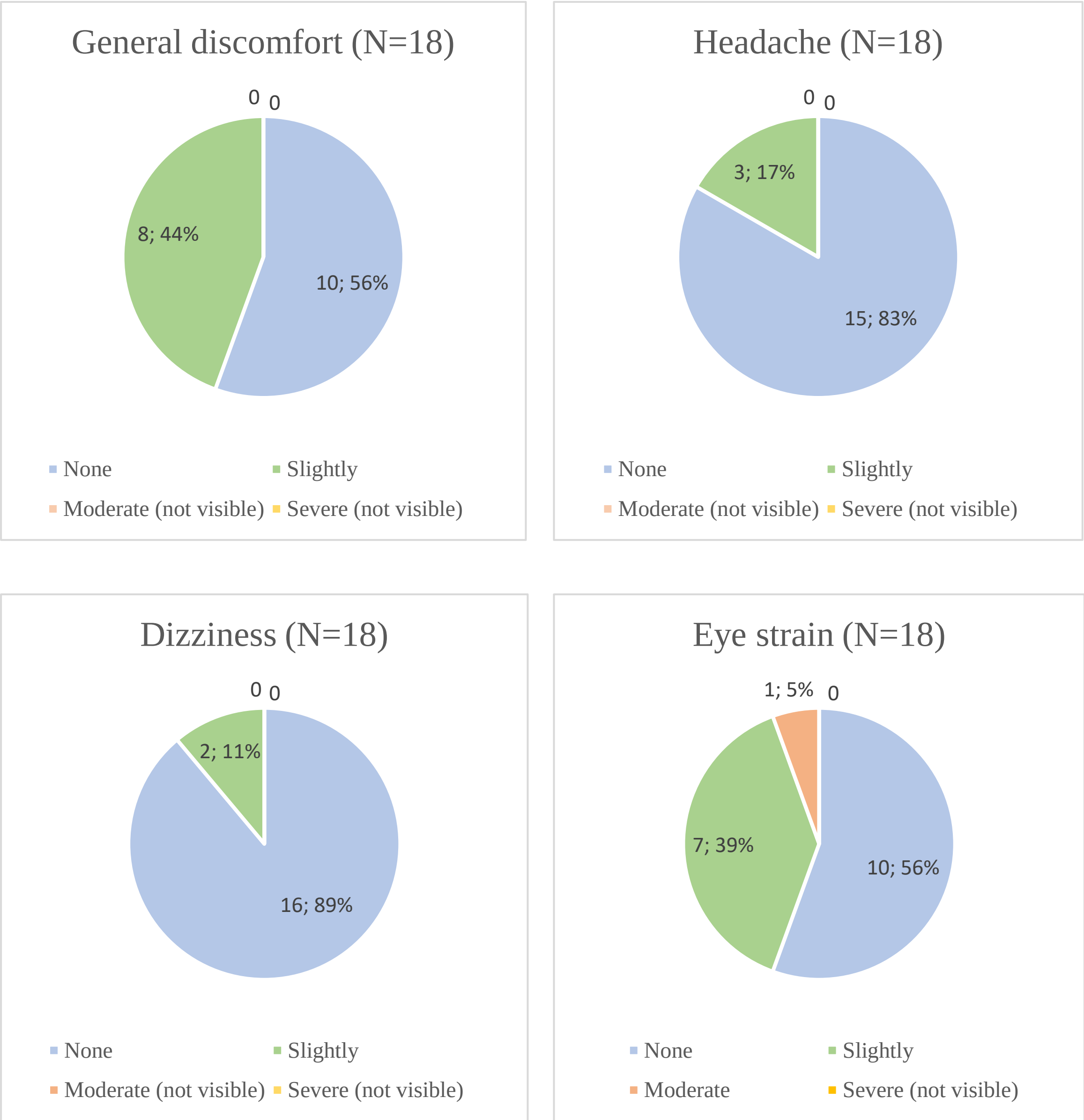


Figure 8. Occurrence and severity of symptoms resulting from the use of the stereoscopic display

The participants' preferences for the view to perform the tasks varied depending on the task. When determining the most ventrally/dorsally situated tumour, 14 (78%) participants preferred executing the task in stereoscopic view, with four (22%) expressing a strong preference. For assessing blood vessel involvement, 10 (56%) participants preferred the stereoscopic view, with three (17%) having a strong preference. In contrast, seven (39%) participants had no specific preference. Regarding identifying the tumour segment, responses were more diverse: seven (38%) participants preferred the monoscopic view, three (17%) had no preference, and eight (45%) favoured the stereoscopic view. For certainty, the cases were compared monoscopically and stereoscopically per task. This way, it was visualized within a group between cases what the certainty was in the answer and between groups within a case. Mainly for determining which tumor is most ventral/dorsal, we see that in case 2 monoscopic presents lower certainties. Conversely, for vessel determination, in case 3 monoscopically, we observe a higher frequency of "very certain" responses. The reported preferences and certainties are visualized per task in Figure 9.

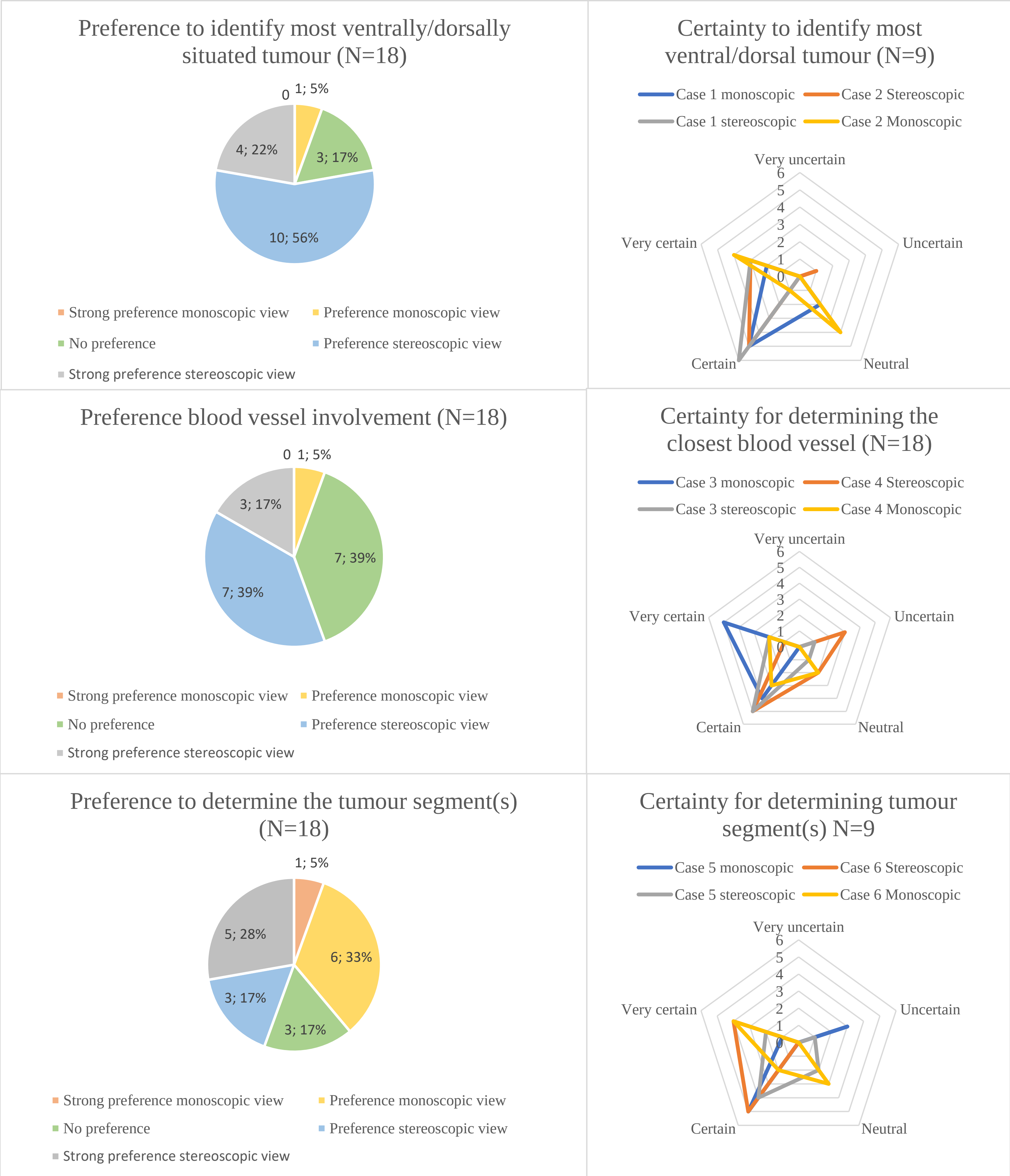


Figure 9. Preferences and certainty for view to perform the task

The blue and orange lines were performed by participants from group A and the grey and yellow lines were performed by participants from group B

The median times in seconds per case within group A and B (monoscopic view versus stereoscopic view), and in total is summarized in Table 7. Within group A, the times to determine in which segment(s) the tumour is situated was significantly shorter (p=0.011) in monoscopic view compared to stereoscopic view. In the total group, we do not observe a significant difference (p=0.138) to perform this task. For all other tasks, there were no significant differences in times between the views. Irrespective of the viewing mode used, cases 2, 3, and 5 were completed faster than cases 1, 4 and 6, respectively.

Table 7. Median times to perform the task in monoscopic view and in stereoscopic view, within group A, group B and in the total group

	Group A			*Group B*			*Total*		
Task	***Monoscopic view***	***Stereoscopic view***	***P-value***	***Monoscopic view***	***Stereoscopic view***	***P-value***	***Monoscopic view***	***Stereoscopic view***	***P-value***
Ventral/dorsal	***Case 1***	***Case 2***		***Case 2***	***Case 1***				
Median time (s), IQR	34.0 [29.0, 40.0]	28.0 [24.0, 39.0]	0.812	41.0 [30.0, 49.0]	46.0 [30.0, 74.0]	0.678	33.5 [29.0, 44.0]	34.0 [26.0, 68.0]	0.632
Closest blood vessel(s)	***Case 3***	***Case 4***		***Case 4***	***Case 3***				
Median time (s), IQR	32.0 [28.0, 34.0]	39.0 [33.0, 52.0]	0.123	35.0 [30.0, 55.0]	29.0 [27.0, 45.0]	0.171	32.5 [28.0, 46.0]	37.0 [28.0, 47.0]	0.760
Tumour segment(s)	***Case 5***	***Case 6***		***Case 6***	***Case 5***				
Median time (s), IQR	13.0 [12.0, 17.0]	26.0 [19.0, 44.0]	0.011	26.0 [21.0, 35.0]	20.0 [17.0, 36.0]	0.514	17.5 [13.0, 35.0]	21.5 [17.0, 38.0]	0.138

S = seconds

IQR = Interquartile Range; 25% - 75%

In odd-numbered data, the IQR 25% - 75% were calculated according to the inclusive method due to the small sample size (44)

In the following paragraphs, the Results section of study 2 is described.

3.3.2. Study B

• *Primary Outcome*

The main objective of study B was to compare the findings of study A with those of surgeons, who have distinct baseline characteristics. To accomplish this, a sample of five surgeons was selected for study B, including two specialists in colorectal liver metastases surgeries and three transplant surgeons, in order to compare their findings with those of study A. Three participants reported experiencing no symptoms. Two participants reported symptoms, one experiencing slight dizziness and the other slight general discomfort. None of the surgeons indicated that these symptoms would prevent them from using the stereoscopic display again. The same applied to wearing 3D glasses. A summary of the questionnaires per surgeon is described in Table 8.

✤ *Secondary Outcome*

The colour preferences per surgeon are described in Table 9. Figure 10 shows how the colours have been adjusted compared to the colour settings of Bijlstra et al. Finally, in Table 10, the RGB values of the adjusted colours for each structure are shown. These colours have been maintained throughout the experiments.

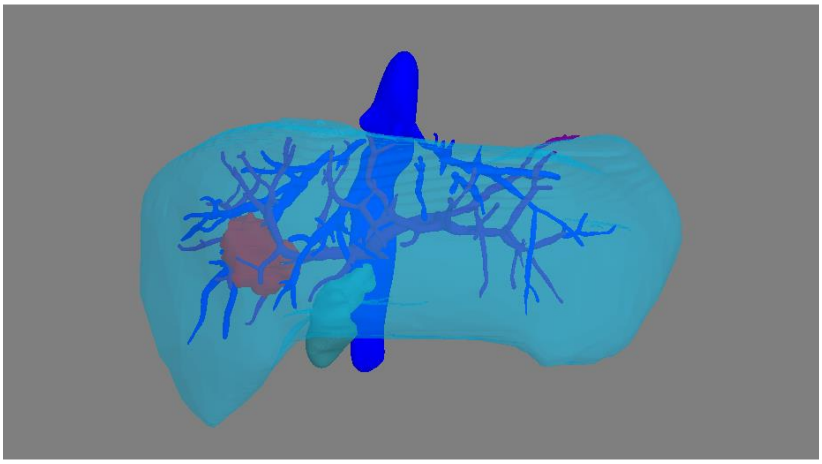
Table 8. Summary of the questionnaire per participant

Participant	*Symptom(s)*	*Severity*	*Would symptoms prevent you from use?*	*Problems 3D glasses?*
Surgeon 1	None	-	No	No
Surgeon 2	Diziness	Slightly	No	No
Surgeon 3	General discomfort	Slightly	No	No
Surgeon 4	None	-	No	No
Surgeon 5	None	-	No	No

Table 9. Summary of the visualization questionnaire per participant

	Colour per structure					
Participant	***Liver***	***Tumour***	***Arterial veins***	***Vena Cava/hepatic veins***	***Portal veins***	***Gallbladder***
Surgeon 1	Red/brown	Yellow	Red	Blue/light blue	Light purple	Green
Surgeon 2	Red/brown	Yellow	Red	Blue	Purple	Green
Validation						
Surgeon 3	✓	✓	✓	✓	✓	✓
Surgeon 4	✓	✓	✓	✓	Lighter purple	✓
Surgeon 5	✓	✓	✓	✓	✓	✓

The first two surgeons were asked to indicate the preferred colours per structure, the last three surgeons were asked to validate (✓) these colours



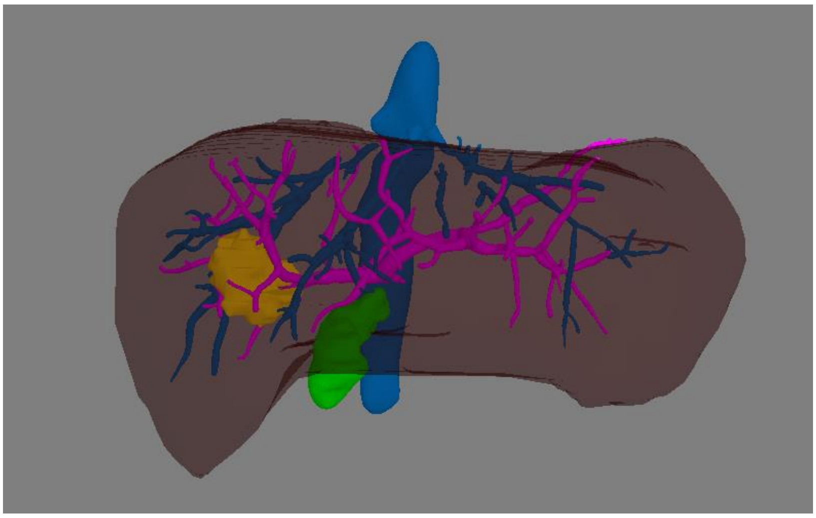


Figure 10. 3D model of case with colours adopted from the study of Bijlstra et al. (top image) 3D model of adjusted colours according to the surgeons' preferences (bottom image)

Table 10. RGB values per structure

Liver structure	***Red***	***Green***	***Blue***	***Opacity***
Lever	0.458	0.067	0.012	0.5
Tumour	1.000	0.916	0.274	1
Vena Cava/Venae Hepaticae	0.089	0.627	0.8	1
Venae Portae	1.000	0.001	1.000	1
Gallbladder	0.006	0.869	0.000	1
Arteriae Hepaticae	0.800	0.003	0.003	1

Red, Green, Blue values are normalized intensities from values between 0 and 255 to values between 0 and 1

3.4. Discussion

The primary aim of the first part of the study was to investigate the occurrence and severity of symptoms induced by stereopsis and to examine whether symptoms or wearing the 3D glasses prevent uses to use stereopsis for visualisation of 3D liver models again. In study A with students, PhD candidates and researchers, the results confirm that the stereoscopic display caused symptoms in 14/18 participants. These symptoms, except for one participant, were described as 'slightly'. However, nobody considered stopping the experiment due to the symptoms.
In study B with surgeons, the frequency and severity of the reported symptoms matched those of the first study. Again, although symptoms were reported during these sessions, none of the participants considered discontinuing the sessions due to symptoms or wearing the 3D glasses.

Based on our findings, we can conclude that within this research setting, there are no factors present that affect the use of stereopsis in making a preoperative surgical planning for colorectal liver metastases.

The described symptoms cannot be compared with other studies using extended realities in HPB surgical planning, as they are not mentioned in other studies. This underreporting may be because other studies did not provide information on technical specifications and user-friendliness of the head-mounted displays used. Additionally, the studies that has been described in the literature review used a variety of head-mounted displays. Onda et al. was the only study that used a stereoscopic display similar to ours. (26) However, they did not report on the presence or absence of symptoms.

When our findings are compared to areas beyond HPB surgical planning, even outside the medical field, discussion arise regarding the primary factors causing symptoms, as described in the literature as simulator sickness. (45) The study of Moss et al. aimed to examine the effects of several display characteristics, including display delay and reduced field of view, on simulator sickness. They recommended to provide the user with a degree of peripheral vision to reduce symptoms. (45) With our setup with a stereoscopic display, this is present, whereas with head-mounted displays, this is not always the case. Another factor that is associated with simulator sickness is age, as demonstrated by Kawano et al. (46). Despite the significant age difference between the student/PhD candidate/researcher group and surgeons, our study did not observe any noticeable variations in the symptoms reported. The difference between their study and our study may be attributed to the use of a different device - a driving simulator - with another degree of peripheral vision compared to the use of a stereoscopic display.

Translating these findings into understanding how the implementation of a stereoscopic display would affect clinical practice remains a challenging task. Firstly, due to the limited sample size of surgeons studied, we cannot definitively determine whether symptoms would hinder implementation in a larger group of surgeons with varying baseline characteristics compared to students, PhD candidates, or researchers. Secondly, the clinical practice may differ from these research conditions (alternating between monoscopic and stereoscopic views over a period of approximately 30 minutes) leading to different outcomes.

A limitation of this study was its design which involved comparing six cases under monoscopic and stereoscopic conditions. This setup posed challenges in comparing secondary outcomes such as time and preference for viewing. One approach to compare monoscopic versus stereoscopic for a specific task was to observe within one participant within different cases; however, regardless of the viewing mode, some cases were consistently executed slower, as described in the results. From this, it can be concluded that the time per case was influenced by the difficulty of the case. Furthermore, it seems evident that the viewing mode in which difficult cases were performed automatically receives less preference when participants are asked to indicate their preferred viewing mode. To minimize the impact of case difficulty, monoscopic versus stereoscopic could be examined within one case. However, this method involved comparing secondary outcomes between different participants, leading to variations in baseline characteristics such as age and experience with performing these tasks. These differences could lead to faster and more confident responses.

This limitation underscores the necessity for future studies to adopt a study design that compares surgical planning between monoscopic and stereoscopic views within the same participant and case. Such an approach ensures that participant characteristics and case complexity do not skew the outcomes between monoscopic and stereoscopic cases. Additionally, within this study, the effect of stereopsis on the visualization of 3D liver models in surgical planning remains uncertain for surgeons. Therefore, future research should evaluate the influence of stereopsis on the development of liver surgical plans by liver/transplant surgeons. Since the validation of 3D models – determining accuracy by radiologists - is typically time-consuming, a retrospective study design is better suited for this aim.

3.5. Conclusion

In conclusion, this study aimed to assess the occurrence and severity of symptoms induced by stereopsis among students, PhD candidates, researchers and surgeons. The results indicated that the stereoscopic display induced symptoms in 14 out of 18 participants, with no one discontinuing the sessions despite reported symptoms. While translating these findings into clinical practice remains challenging, our study suggests that these symptoms would not hinder the implementation of stereoscopic display in clinical practice. However, further validation in a larger study population is warranted, preferably among surgeons as they are the intended users. Additionally, it is recommended to investigate the added value of stereopsis in colorectal liver metastases surgery through retrospective studies, given the current lack of standard validation for 3D models in clinical practice. Conducting comparisons between monoscopic and stereoscopic views within one participant and one case will help eliminate biases and provide valuable insights into the implementation of stereoscopic displays in surgical planning.

To address this recommendations, the second part of this research will focus on retrospectively evaluating the effect of stereopsis in the visualisation of 3D liver models in making a surgical plan.

4

4. Part II

4.1. Aims and Objectives

This study is part of the *Automation, Surgery Support and Intuitive 3D visualisation to optimize work-flow in image guided therapy SysTems* (ASSIST) project.

The primary aim of this study is to

- Evaluate the effect of stereopsis on the preoperative surgical planning for colorectal liver metastases surgery

The secondary aim of this study is to

- ○ Investigate factors that affect the use of stereopsis on making a preoperative surgical planning for colorectal liver metastases surgery

Therefore, this study focuses on the following objectives

- Compare outcomes between monoscopically and stereoscopically performed cases, including
  - I. Accuracy of the preoperative surgical planning
  - II. Time to complete the preoperative surgical planning
  - III. Preference for viewing during the preoperative surgical planning

- ○ Quantify the occurrence and severity of symptoms resulting from the use of stereopsis when making a preoperative surgical planning for colorectal liver metastases surgery

4.2. Materials and Methods

Study Population

Liver and transplant surgeons from the Department of Surgery in the LUMC were invited to participate in the study's primary aim, which focused on evaluating the effect of stereopsis on the preoperative surgical planning for colorectal liver metastases surgery. All surgeons that had experience in making a preoperative planning for oncological surgery were asked to participate. The recruitment of participants stopped once there were no available surgeons left.

Study Design & Materials

A retrospective study was conducted at the LUMC, in the winter of 2023-2024 (Figure 11). Participation in the experiments was voluntary. Before the experiment started, participants were alternately allocated to group A or B. Furthermore, participants were asked if they had experience with manipulating 3D models for visualisation.

During the experiments, eight 3D models of livers with (a) colorectal liver metastasis/metastases were presented to participants in an individual session with one researcher. The 3D models were used from the study of Bijlstra et al. and were already available before the start of this study. The preferred colours and from part I of the study were retained to visualize the 3D models. Primarily, the selection of eight cases was made based on the completeness of the segmented structures. Secondarily, the selection of cases was made based on variation between the cases (such as number and location of tumours), aiming for representation of the variation in clinical practice of treatment of colorectal liver metastases. The eight included patient cases all underwent minimally-invasive surgery for colorectal liver metastases using a robot-assisted approach in a single academic university hospital (Amsterdam UMC, Amsterdam, The Netherlands). All patients were operated using the Intuitive da Vinci Xi (Sunnyvale, California, United States) robotic surgical system. The segmentations were scored for the quality of each structure based on their completeness. More information on how the 3D models were created and validated is given in the paper of Bijlstra et al. (42) The case characteristics, including the 3D model characteristics are summarized in Table 11.

To investigate the study's primary aim, in a representative manner, realistic tasks regarding the surgical planning were assigned to the participants. These tasks were based on the literature review regarding the use of stereoscopic 3D models in HPB surgery. From this literature review, the most reported arguments for the use of stereoscopic 3D models were: tumour localisation, blood vessel identification, and resection plane determination. Based on these arguments, per case surgeons were asked to answer the following questions regarding the surgical planning:

I. In which segment(s) is the tumour located?
II. Is the tumour resectable and if so, what will the surgical strategy be?
III. Is there vessel involvement with the tumour? If so, which one(s) would you resect?

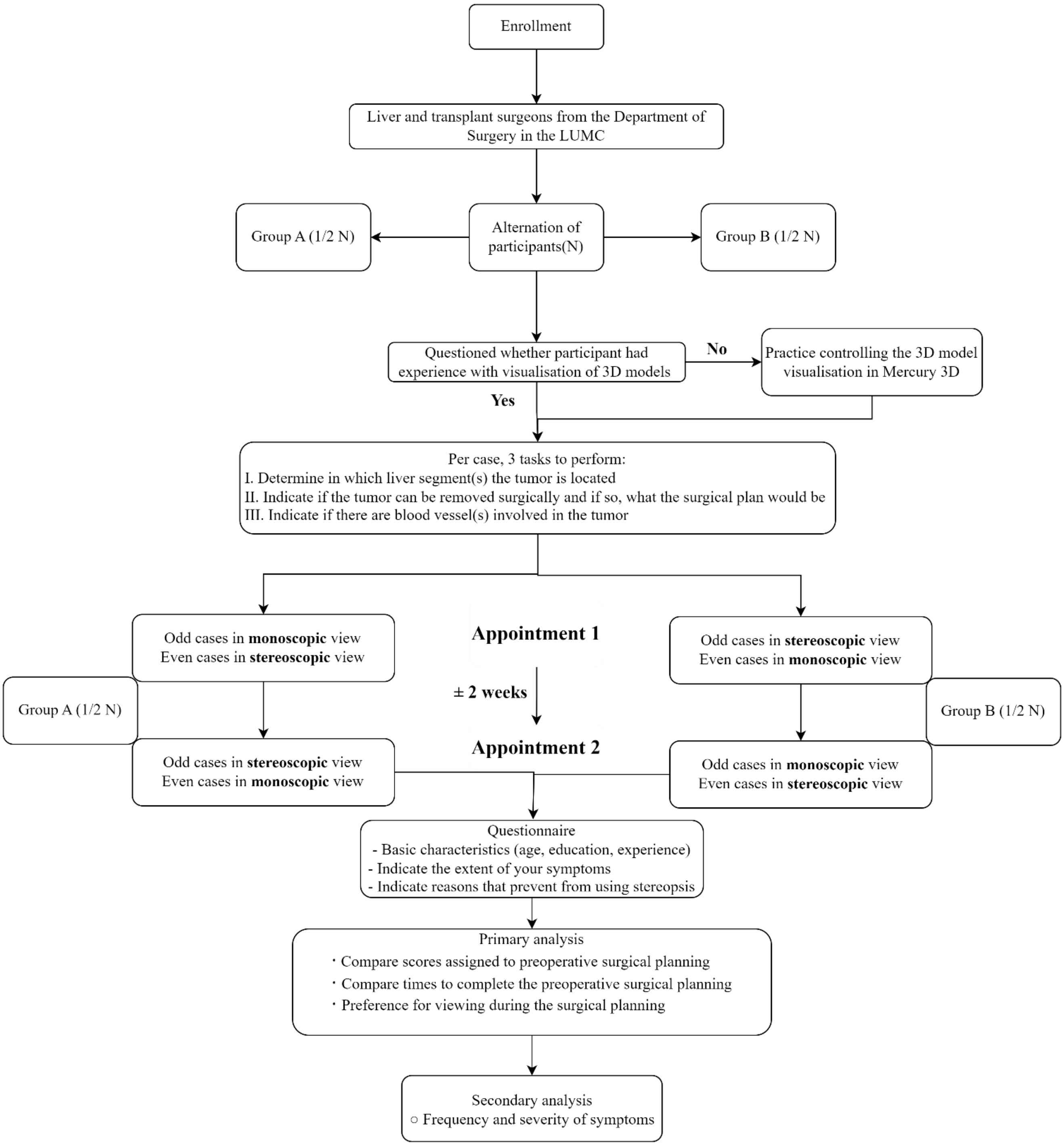


Figure 11. Flow chart of the study design

Table 11. Characteristics of the patient cases

Patient case	***Liver***	***Vena Cava***	***Vena Hepatica***	***Vena porta***	***Gall-bladder***	***Number of tu-mours***	***Tumour segment(s)***	***Preoperative surgical planning***	***Performed surgery***	***Blood vessel(s) involvement***
1	+	+	+	+	+	1	S5/8	Hemi-hepatectomy (right)	Hemi-hepatectomy right	Contact right anterior portal vein > 270°, contact right posterior portal vein 90-180°
2	+	+	+	+	+	1	S5	Sectionectomy (S5/6)	Irresectabel due to multifocal intrahepatic metastatic iCCA	No contact
3	+	+	+	+	+	1	S6	Segmentectomy (S6)	Segmentectomy (S6)	Contact right anterior portal vein (S6) = 180°
4	+	+	+/-	+/-	+	1	S7	Segmentectomy (S7)	Segmentectomy (S7)	No contact
5	+	+	+	+/-	+	1	S7/border 8	Hemi-hepatectomy (right)	Hemi-hepatectomy (right)	Contact right hepatic vein peripheral (S7) <90°, contact right posterior portal vein (S7) >90°
6	+	+	+/-	+	+	1	S1	Segmentectomy (S1)	Segmentectomy (S1)	Contact vena cava <90°
7	+	+	+	+	+	1	S5-8	Sectionectomy (S6/7)	Sectionectomy (S6/7)	Contact right hepatic vein peripheral (S6) <90°
8	+	+	+	+	-	8	S5	Two-stage 1) wedge resection (S2 and S3), 2) hemi-hepatectomy (right)	Two-stage, 1) wedge resection (S2 and S3) 2) hemi-hepatectomy (right)	Contact right hepatic vein peripheral, contact posterior portal vein (S6), <90°

The segmentations were evaluated using the following scoring system: "+", indicating complete segmentation of the structure; "+/-" signifying incomplete segmentation; and "-", indicating the absence of any segmentation.

S = segment

PVE = Portal Vein Embolization

** The steps between surgery grades are defined across wedge resection/segmentectomy -, sectionectomy, - hemi-hepatectomy - extended hemi-hepatectomy – irresectable*

The eight 3D liver models were presented twice to the surgeons in separate sessions, each conducted individually by a surgeon with one researcher present. During these session, the surgeon had to answer the predefined questions for each case, with the researcher recording the responses. This setup allowed the surgeon to focus on manipulating the 3D model. Furthermore, the case was timed from the moment the participant opened the case until the participant indicated giving the final answers. The 3D liver models were displayed on an experimental stereoscopic display from Barco (Kortrijk, Belgium), using the in-house developed software Mercury3D (Barco, Kortrijk, Belgium).
In the first session, the eight 3D liver models were alternately displayed in monoscopic and stereoscopic view, with four models in each.
For the second session, the same eight 3D liver models were presented again, but the viewing mode for each case was switched compared to the first session. To account for potential improvements in answers due to case recognition in the second sessions, surgeons were divided into two groups. Group A received the odd-numbered cases monoscopically in the first session and the even-numbered cases stereoscopically, while group B had the opposite arrangement. Additionally, the order of cases was reversed in the second session. At last, to minimize case recognition, there was a minimum interval of 1 week between the two sessions, preferably with a 2-week gap.

After performing the experiment, participants had to complete a questionnaire with questions regarding basic characteristics, such as age, surgical experience (after training) and number of liver surgeries per year. Additionally, participants were asked to score their preference to perform the case within a specific view, using the Likert scale. Finally, participants were questioned whether they experienced symptoms during or after the experiment and if these symptoms would prevent them from using the stereoscopic display. The complete questionnaire is added to Appendix E.

Analysis

• *Primary Outcome*

The primary aim was to evaluate the effect of stereopsis on preoperative surgical planning for colorectal liver metastases surgery. This evaluation involved comparing outcomes between monoscopic and stereoscopic views, including the accuracy of preoperative surgical plannings, task execution times and task preference.

I. Comparing Scores assigned to the Preoperative Surgical Plannings

Initially, the scoring system was established, wherein the accuracy of responses was evaluated based on their concordance with the gold standard. Each response began with a score of 4, with points deducted (-1) for increasing deviation from the gold standard. This method resulted in categories ranging from 1-4, reflecting the degree of concordance with the gold standard. Both the determination of the gold standard as the scoring was performed in collaboration of an oncological liver surgeon. Detailed explanations and justifications for determining the gold standard and scoring the question are provided in subsequent sections. An overview of the scoring system is provided in Table 12. An example of the scoring per question is added to Appendix F.

Tumour localisation

For the tumour localisation, surgeons had to answer in which segment(s) the tumour was situated, based on the Couinaud classification. (47) The scoring is based on how closely the location provided matches what was stated in the radiological report. The radiological report was validated by a HPB-dedicated radiologist of the LUMC, based on the preoperative CT scans. In case the radiologist from the LUMC deviated from the radiological report, the segment determined by the radiologist was followed. If the answer did not match, penalty points were assigned. Answers were penalized more severely if 1) the correct segment was not mentioned or 2) if a segment was mentioned that does not border the correct answer. An explanation on how the segments border each other has been added to Appendix G.

Furthermore, in the event that multiple segments are provided as an answer, and only one segment is provided in the gold standard, one point will be deducted for each additional incorrect segment. Conversely, if only one segment is provided as an answer, and the gold standard provides multiple segments, one negative point will be given for each missing segment. In this way, categories were formed indicating how close the given location(s) were to the gold standard, extracted from the radiological report.
To further elaborate on the content of the responses, the number of segments deviating from the radiological report was recorded (plus or minus). This way, not only the presence of a potential effect of stereopsis could be determined but also its nature and extent.

Surgical planning
For surgical planning, the focus was on whether the operation was accurately estimated, underestimated, or overestimated. Therefore, there was no assessment regarding whether the operation accurately represented the correct segments, as this is evaluated in a separate task. The provided surgical planning was compared with what was planned to be executed, according to the surgical report. Since both preoperative surgical plannings were based on the same preoperative CT and/or MRI scans, an unbiased assessment of the concordance between the plans can be made.
For scoring the surgical plan, different types of liver resections were identified and divided in categories, based on the Brisbane 2000 Terminology meeting. (48) These categories reflect the size of the resected portion of the liver. Therefore, if participants deviate from the performed category, it indicates either an overestimation or underestimation of the surgery. The surgical plans were divided in the following categories, ascending in the impact for the patient: wedge/segment resection, sectionectomy, hemi-hepatectomy, extended hemi-hepatectomy, and unresectable. The wedge/segment resection is subdivided into one category instead of two because it is difficult in practice to determine whether an operation involves a wedge or an entire segment. The scoring is based on the deviation from the categories. For each step by which the surgical planning deviates, a penalty of -1 is given. Again, categories between 1-4 were formed indicating how closely the surgical planning made with 3D models was to the preoperative surgical planning described in the surgical report.

Vascular involvement
For vascular involvement, the following aspects of an answer were examined: did the participants indicate involvement of one or more blood vessels, if so, which blood vessel(s) and from where (main vessel or more peripheral). In the 3D models, only the portal vein and hepatic vein were visible, so only these vessels were scored for involvement. The portal vein is divided into segments, from the main vessel to peripheral: the portal vein -> the right portal vein and the left portal vein -> the anterior/posterior portal vein. The hepatic vein is also divided into segments from the main vessel to peripheral: the vena cava -> right/middle/left hepatic vein -> right/middle/left hepatic vein peripheral. For each blood vessel that deviates from the gold standard, penalty points were assigned. The closer the deviating blood vessel is to the main branch, the more impact is has on the surgery and thus the more penalty points were given. The gold standard in the vascular involvement was determined by a HPB-dedicated radiologist from the LUMC, based on the preoperative CT scans, since it was not reported in the radiological or surgical report.

The scores assigned to cases performed in monoscopic view were compared with those performed in stereoscopic view within each individual using the Wilcoxon rank-sum test, a paired test appropriated for analysing ordinal data. Furthermore, the height of the score was described as 'concordance with the gold standard' and compared between answers provided in both monoscopic and stereoscopic views. Scores were converted from numbers into descriptive categories (1 = no concordance, 2 = partial concordance, 3 = high concordance, 4 = complete concordance). Deviations in responses between the second and first sessions were also analysed.

Table 12. Scoring table for answers compared to the gold standard

Segment scoring	
Score	*Description*
4	Complete concordance with the gold standard
-1	Per non-matching segment that is adjacent
-2	No matching segment but is adjacent
-3	Per non-matching segment that is not adjacent
Surgical planning	
Score	*Description*
4	Complete concordance with the gold standard
-1	Per step between surgery grade*
Blood vessel involvement	
Score	*Description*
4	Complete concordance with the gold standard
-1	When involvement is/ is not indicated peripheral[†] that is not/ is present
-2	When involvement is/ is not indicated in a side branch[‡] that is not/is present
-3	When involvement is/ is not indicated in a main branch[⁋] that is not/is present

** The steps between surgery grades are defined across wedge resection/segmentectomy, sectionectomy, hemi-hepatectomy, extended hemi-hepatectomy, unresectable*

† Peripheral branches were defined as the portal vein anterior/posterior and the hepatic vein peripheral

‡ Side branches were defined as the portal vein right/left and the hepatic vein right/middle/left

⁋ Main branches were defined as the vena cava and portal vein

II. Comparing Times to complete the Preoperative Surgical Plannings

For the outcome of time, a histogram is generated to illustrate the distribution of times recorded for both monoscopic and stereoscopic views. Based on the distribution, a paired test is selected to compare the execution time per case between monoscopic and stereoscopic views within each individual.

III. Preference for viewing during the Preoperative Surgical Planning

The frequency of preference for a specific view to perform the preoperative surgical planning was recorded for each specific task assigned to the participants.

○ *Secondary Outcomes*

The study's secondary aim was to quantify the occurrence of symptoms that may result from the use of the stereoscopic display. It was also recorded whether participants considered stopping the task. Finally, it was noted whether the 3D glasses prevent participants to use the stereoscopic display again. The results were recorded and presented in a figure indicating their frequency.

All statistical analyses were performed using SPSS software Version 29.0 (IBM, New York, NY, USA). Statistical outcomes were considered significant when the p-value was lower than 0.05. Tables and figures were generated with Microsoft Excel Version 2021 (Microsoft 365, Remond, WA, United States)

4.3. Results

13 surgeons from the Department of Surgery in the LUMC participated in the study. 12 surgeons had more than five years of experience in performing oncological liver surgery. The number of liver surgeries per year varied through all categories. The characteristics of the participants are summarized in Table 13.

• ***Primary Outcome***
The scores and times in cases performed in monoscopic view were compared with the scores and times in cases performed in stereoscopic view. The results are described in Table 14.

All eight cases were evaluated for tumour segment localization and vascular involvement in both monoscopic and stereoscopic views. Surgical planning scores were available for seven cases. In assessing tumour segment localization, monoscopic view received a higher score more frequently (23) than stereoscopic view (13). Similarly, for vascular involvement assessment, monoscopic view achieved a higher score more often (20) compared to stereoscopic view. Regarding surgical planning, both views received equal higher scores (13). Tie scores occurred 3-5 times more often than instances where one view outperformed the other. No significant differences were observed in the scores for any of the tasks.

To gain deeper insights into the responses, deviations in segment count compared to the radiological reports were recorded. In the monoscopic view, the number of segments matched the number reported in the radiological report for 63 cases (60.6%). Similarly, in the stereoscopic view, the number of segments was accurately estimated in 60 cases (57.7%). In both views, the number of segments was more frequently overestimated (48 cases) than underestimated (37 cases). The results are summarized in Table 15.

Table 13. Characteristics participants

Characteristics	*Group A (N=7)*	*Group B (N=6)*	*All participants (N=13)*
Median age, IQR (years)	47 [43, 55]	53.5 [46, 56]	52 [44.5, 55.5]
Years of surgical experience* (N)			
0-5 years	1	0	1
6-15 years	3	2	5
16-25 years	2	4	6
>25 years	1	0	1
Number of liver surgeries per year (N)			
0-5	2	2	4
6-10	1	3	4
11-20	1	1	2
21-50	2	0	2
>50	1	0	1

** Years of surgical experience after surgical training*

Table 14. Characteristics of monoscopic and stereoscopic views

Characteristics	*Higher score monoscopic view[a]*	*Higher score stereoscopic view[b]*	*Ties[c]*	*P-value*
Tumour segment (N=104)				
Score (N)	23	13	68	0.189
Surgical planning (N=91)				
Score (N)	13	13	65	0.968
Blood vessel involvement (N=104)				
Score (N)	19	14	71	0.588
Median time, IQR (seconds)	41.0 [28.5, 58.5]	43.0 [32.0, 60.5]		0.417
Score[d] (N)	51	47	6	

IQR = Interquatile range at 25% and 75%

The IQR 25% - 75% were calculated according to the exclusive method due to the even-numbered data set (44)

[a]In N cases, the score in monoscopic view > score in stereoscopic view

[b]In N cases, the score in stereoscopic view > score in monoscopic view

[c]In N cases, the score in monoscopic view = score in stereoscopic view

[d]Score is the number (N) of cases in a certain view with a faster execution time

The analysis for concordance with the gold standard revealed that the highest percentage of complete concordance is observed within the responses given in monoscopic view for surgical planning (65.9%). In vascular involvement, the largest differences between monoscopic and stereoscopic views are observed, with a complete concordance of 55 (52.9%) vs. 45 (49.5%) and a high concordance of 30 (28.8 %) vs. 44 (48.4%), respectively. The smallest differences between responses given in monoscopic and stereoscopic views are observed in determining the surgical planning. The numbers are summarized in Table 16.

For determining the tumor segment, surgical planning, and blood vessel involvement, respectively, in 46 out of 104 cases, in 26 out of 91 cases, and in 32 out of 104 cases, the response from the second session deviated from the response from the first session.

All cases were timed in both monoscopic and stereoscopic views. The distribution of times did not follow a normal distribution. The median was calculated for both the monoscopic and stereoscopic views. The median time was 41.0 [28.5, 58.5] in the monoscopic view and 43.0 [32.0, 60.5] in the stereoscopic view. The Wilcoxon rank-sum test was employed to compare the times between monoscopic and stereoscopic views within each individual. No significant differences (p=0.417) were observed.

The participants' preferences for the view to perform the tasks varied depending on the task. When determining the segment(s) where the tumour was situated, eight (61%) participants preferred executing the task in stereoscopic view, with two (15%) expressing a strong preference. The other six (39%) participants indicated no preference. For determining the resectability and surgical planning, similar numbers were reported. For indicating vascular involvement, nine (69%) participants preferred the stereoscopic view, with two (15%) having a strong preference. One participant (8%) preferred the monoscopic view to indicate vascular involvement. The reported preferences are described per task in Figure 12.

○ *Secondary Outcomes*

1 out of 13 participants reported experiencing symptoms during and/or after making a preoperative surgical planning for colorectal liver metastases surgery. Furthermore, the questionnaire revealed that none of the participants considered stopping the study due to the symptoms caused by the stereoscopic display. The same applied to wearing the glasses; no one indicated finding them bothersome during the study.

Table 15. Estimation in number of segments relative to the gold standard

	Monoscopic view		*Stereoscopic view*	
N=104	***Frequency***	***%***	***Frequency***	***%[a]***
Underestimation (N)	18	17.3	19	18.3
of 3 segments (N)	*4*	*3.8*	*3*	*2.9*
of 2 segments (N)	*8*	*7.7*	*10*	*9.6*
of 1 segment (N)	*6*	*5.8*	*6*	*5.8*
Correct number of segments (N)	63	60.6	60	57.7
Overestimation (N)	23	22.1	25	24.1
of 1 segment (N)	*20*	*19.2*	*24*	*23.1*
of 2 segments (N)	*3*	*2.9*	*1*	*1.0*
of 3 segments (N)	*0*	*0*	*0*	*0*

[a]The percentage does not add up to 100% due to rounding

Table 16. Concordance per task monoscopic view vs. stereoscopic view

	Monoscopic view		*Stereoscopic view*	
Concordance with gold standard	***Frequency (N)***	%[a]	***Frequency (N)***	%[a]
Tumour segment (N=104)				
No concordance	6	5.8	7	6.7
Partial concordance	24	23.1	25	24.0
High concordance	23	22.1	28	26.9
Complete concordance	51	49.0	44	42.3
Surgical planning (N=91)				
No concordance	2	2.2	1	1.1
Partial concordance	4	4.4	4	4.4
High concordance	25	27.5	27	29.7
Complete concordance	60	65.9	59	64.8
Vascular involvement (N=104)				
No concordance	1	1.0	0	0.0
Partial concordance	18	17.3	15	16.5
High concordance	30	28.8	44	48.4
Complete concordance	55	52.9	45	49.5

[a]The percentage does not add up to 100% due to rounding

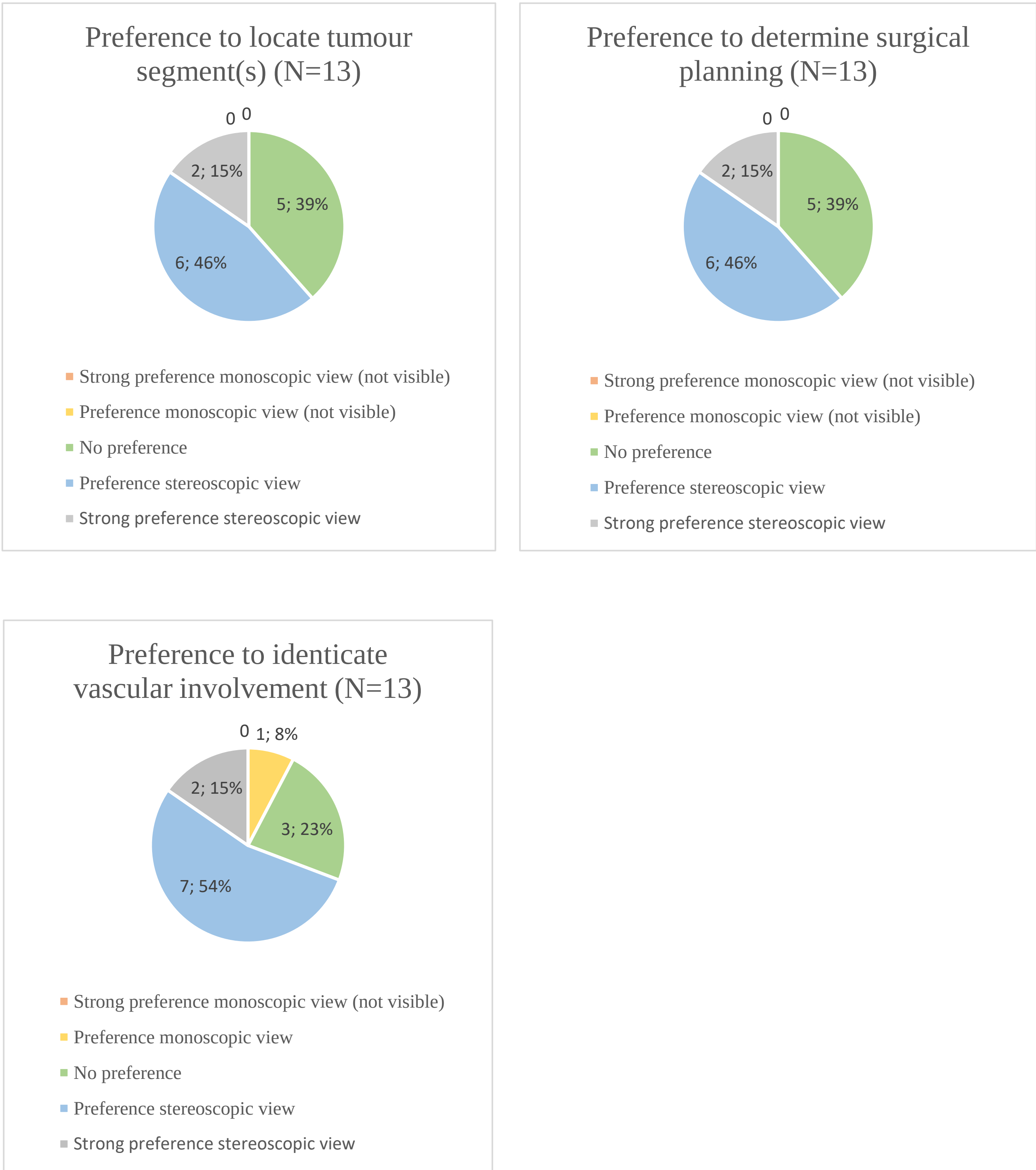


Figure 12. Illustration of the preferences for viewing to execute the task

4.4. Discussion

The primary aim of this study was to evaluate the effect of stereopsis on preoperative surgical planning for colorectal liver metastases surgery. No significant differences were shown between the scores for the surgical plannings, while performed monoscopically versus stereoscopically. It is notable that surgeons (strongly) preferred stereopsis for determination of tumour location (8/13), surgical planning (8/13), and vascular involvement (9/13). Only for determining the vascular involvement, one participant indicated a preference to perform the task monoscopically.

From this, we can infer that stereopsis does not have a direct impact on tasks related to the preoperative surgical planning for colorectal liver metastases surgery. However, surgeons' preferences to perform the tasks stereoscopically suggests that stereopsis has a benefit in visualising 3D liver models. Another plausible explanation is that participants' perceptions are biased due to the hype surrounding stereoscopic devices. This could potentially account for the preference observed, despite the absence of differences in outcomes between monoscopic and stereoscopic view.

Among studies exploring the impact of stereopsis on preoperative surgical planning for HPB surgery, this study stands out as one of the few studies to use a stereoscopic display. Onda et al. was the sole study that used a stereoscopic display for HPB surgeries, although for intraoperative purposes. They did not formally report outcomes regarding the potential impact of using the stereoscopic display. Instead, they provided anecdotal evidence suggesting that it assisted in localizing the tumour, determining the surgical strategy, and indicating the vascular involvement. (26) The anecdotal evidence for stereopsis in their study aligns with the findings regarding surgeons' preferences in our study.

There were other studies using stereopsis in HPB surgery, although they made use of different devices. Six studies specifically investigated the application of stereopsis in the preoperative phase for planning. Two studies focused on VR did not report outcomes regarding use or usability. (32, 35) There were four studies reporting on the preoperative application of stereopsis via AR. Three of them used the HoloLens I/II (28, 36, 49), and one used an in-house developed technology, the Hyper accuracy three-dimensional technology (HA3D™). (29) Each study offered limited information about their setup, making it again challenging to compare potential advantages and disadvantages.

Given the challenge of directly comparing our study's use of a stereoscopic display with the use of extended realities in HPB surgical planning, it becomes necessary to widen our scope. Although not directly investigated in this study, analysing the inherent advantages and disadvantages of different stereoscopic technologies can assist in determining the appropriate device to use, as previously described by Held et al. in 2011. (50)

The stereoscopic display used in this study with the Mercurcy3D software from Barco for visualising 3D models is relatively intuitive to use, especially for users accustomed to viewing 3D models. The software settings are the same for monoscopic and stereoscopic display and similar to most software used for visualising 3D models. Using the same software for both monoscopic and stereoscopic viewing offers an additional benefit: if stereopsis is unnecessary, users can effortlessly switch to monoscopic viewing on a standard screen using the familiar software.

Another benefit of a stereoscopic display over extended realities is that it allows for easier collaborative viewing, particularly of benefit in oncological surgery where complex cases are prevalent and multidisciplinary work is crucial.

A limitation of the specific stereoscopic display from Barco available at the LUMC is that it is large and heavy, making it difficult to move. This is less of an issue with extended realities. Since the use of this display was experimental, there are certainly possibilities for other sizes, but it remains challenging to physically move a display, especially during intraoperative use in the already limited space of the operating room.

Furthermore, the positioning of the viewer during the interpretation of 3D models with a stereoscopic display significantly impacts the perception of depth and spatial relationships. While our experiments did not specifically address this aspect, we did not observe problems in stereoscopic viewing. In fact, although the research design only involved one participant, the potential for multiple viewers to observe the scene from different positions exists. To ensure successful clinical implementation, further exploration of the effects of multiple viewers from varying positions is recommended in future studies.

A strength of this study was that the effect of stereopsis was directly tested. The information provided to participants was the same in both cases, except that stereopsis was added. Clear comparisons could also be made between monoscopic and stereoscopic views. This was possible because comparisons could be made within a participant and a case, eliminating the need for corrections due to case difficulty or participant differences.

What further strengthened the study was its retrospective nature. This allowed surgical plans to be correlated with what was actually performed. Additionally, the retrospective design enables the demonstration of the impact of stereopsis without influencing patient care. Before commencing a prospective study, it is essential to clarify the role of (stereoscopic) 3D models in diagnosis and treatment of colorectal liver metastases surgery. Therefore, it is crucial to confirm that determining your surgical strategies based on conventional imaging with additional (stereoscopic) 3D models is as effective as relying solely on conventional imaging. Surgeons must avoid making surgical plans primarily based on non-valid 3D models – that do not accurately represent the patient's anatomy-, which could lead to incorrect clinical decisions.

There were also limitations to this study. Because cases were presented twice to the surgeons, responses of the first session (1-4 weeks before) can be recalled, especially for two specific cases that were exceptional. To prevent case recognition, an attempt was made to schedule a gap between the first and second sessions. Additionally, correction for the score and time in the second session was achieved by dividing participants into two groups, with group A receiving the opposite view compared to group B. While there is a possibility that this may have impacted the outcomes of the second session, the lack of consistent reflection in the results suggests that surgeons deviate from their initial responses in 104/299 questions from the first session

Another limitation is that it is unknown how accurate the gold standard for determining surgical strategy is. The gold standard was established by examining preoperative surgical planning documented in the surgical report. However, given the retrospective nature of this study, it remains subject to interpretation. An incorrect interpretation may potentially explain the variations in incorrect scores between cases, as it could lead to both underestimation or overestimation of the incorrect answers provided by surgeons.

Basing the surgical plan solely on a 3D model brings further limitations. One could argue whether all structures are accurately segmented. Moreover, some structures may be missing, and there is an interpretation step embedded in the formulation of the 3D models. Specifically, the interpretation of 2D scans involves (semi-) automatic segmentation to distinguish between tumour and healthy tissue. Even though this has been verified by an expert, it is a limitation that the surgeon cannot directly view the raw data.

Moreover, the questionnaire introduces potential bias, as responses given by participants are subjective and can be influenced by the interpretation of the questions. The semi-open responses give a limited depth of information on the surgeon's considerations. Particularly, consistency in interpretating and scoring vascular involvement was challenging due to significant variations among surgeons' responses, which were not always categorizable. Furthermore, case eight was excluded from scoring the surgical strategy because the two-stage strategy made the answers unclassifiable.

All previous described limitations could affect the accuracy of the scores. However, as this study compares monoscopic and stereoscopic views relatively to the gold standard, any discrepancies in the responses in both views will have an impact.

A preference for performing cases stereoscopically by the surgeons was found, despite the minimal potential clinical impact of stereopsis on preoperative planning of colorectal liver metastases surgery. However, our study could not elaborate on the benefit of stereopsis in surgical planning through surgical outcomes. On the other hand, we did not identify possible drawbacks of using stereoscopic displays, such as wearing glasses or experiencing symptoms. In a study by Moll et al. from 1998, although conducted decades ago, we see a similar situation where angiography was compared with a new stereoscopic digital angiography system. (51) In their study, radiologist stated easily perceiving an accurate stereoscopic effect. However, they also noted a lack of definite overall medical interest in this new technique. Similarly, with surgeons that are used to make surgical plannings based on 2D images on normal displays, and with no observable improvement in direct outcomes, our findings mirror this sentiment.

With ongoing advancements in automating and validating 3D models, their integration into clinical practice alongside conventional imaging is becoming more standard. However, comprehending the precise role of 3D models in preoperative planning of colorectal metastases surgery requires further research to pinpoint the specific application(s) where they offer potential benefits. Knowing the potential benefits will also facilitate into whether stereopsis enhances this value.

Furthermore, standardizing follow-up studies and providing comprehensive setup descriptions are essential. This not only allows for the replication of successful setups but also enables comparisons between studies. Standardization efforts should prioritize the reporting of qualitative outcomes, accompanied by detailed explanations of the methodologies employed.

4.5. Conclusion

In conclusion, the incorporation of stereoscopic 3D models into clinical practice holds promise for improving surgical planning. Although our study did not reveal differences in outcomes between monoscopic and stereoscopic preoperative plannings for colorectal liver metastases surgery, it seems clear that surgeons prefer stereopsis for visualising 3D liver models. As advancements in other industries progress, the accessibility and user-friendliness of stereoscopic visualisation of these models will increase. However, to fully understand the value of stereopsis in clinical practice, further research is needed. This future research should include comprehensive reporting on specific applications, setups, and potential advantages and disadvantages.

Furthermore, the implementation of stereopsis in visualising 3D models is dependent on the integration of 3D models in clinical practice. The successful integration of 3D models into surgical planning still requires enhancements in automation and validation of these models. By addressing these aspects, stereoscopic 3D models have the potential to improve the efficiency of complex oncological procedures in the future.

5

5. *Future Research Directions and Opportunities*

The utilization of stereopsis in HPB surgery is on the rise, and this trend is expected to continue due to advancements in other industries that are making devices more user-friendly and valuable. As a result, there is growing interest in adopting these technologies in the medical world, warranting further research investment in this domain. While the use of stereoscopic devices is not essential, it presents opportunities for a more intuitive approach for visualizing patient anatomy, simulating surgeries virtually, and aiding navigation during operations. However, it is crucial to demonstrate through research that for clinical professionals these applications indeed provide added value compared to conventional methods, rather than merely following a trend.

The enhanced user-friendliness of stereoscopic devices is also evident in our findings. None of the participants in this study reported refraining from using the stereoscopic display due to usability obstacles – including symptoms. It is important to note that since this study specifically focuses on the stereoscopic display by Barco, these results regarding user-friendliness may not be directly applicable to other stereoscopic devices. For future studies involving other stereoscopic devices – each with distinct advantages and disadvantages, as described in the general background – it is crucial to reevaluate the product's user-friendliness. This becomes especially pertinent if user-friendliness has not been documented in comparable prior studies with similar applications. The ease of use could profoundly impact the effective integration of stereoscopic devices.

Since the results of this study currently show no difference between planning in monoscopic and stereoscopic displays, the question arises whether surgeons' preference alone justifies further research with this stereoscopic display. It is essential to remember that acquiring this display incurs additional costs, and finding a physical space for implementation is also necessary. In comparison, a monoscopic view can be viewed anywhere with a standard screen. On the other hand, as previously mentioned, stereoscopic devices will only improve, and the current study specifically did not show an added value in planning for colorectal liver metastases. An experimental deployment of stereoscopic devices - which can also involve concurrent studies across multiple fields - at least provides the opportunity to explore possibilities.

Another crucial area for future research, although beyond the stereoscopic focus of this study, yet paramount for implementation, pertains to the exploration of 3D model utilization in HPB surgery. Currently, this practice is not standardized and is confined to research settings. Primarily, this is due to the time-consuming process, attributed to manual interventions in the semi-automatic creation of 3D models. Additionally, validating these models for anatomical accuracy requires manual efforts, further elongating the process and incurring additional costs. However, due to advancements in automatic algorithms, it can be expected that in the future these 3D anatomical models will be automatically generated for each patient. Therefore, it is important to clarify the precise role of 3D models in HPB surgical planning. Future studies should investigate the contrast between plans based solely on conventional imaging and those integrating additional (stereoscopic) 3D models. By clarifying the role of (stereoscopic) 3D models, it becomes easier to determine where to implement them in the process of HPB surgery.

6

6. References

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7

7. Appendices

A. Literature Review

The Role of Stereoscopic 3-Dimensional Models in Hepato-Pancreato-Biliary Cancer: A Comprehensive Review

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Abstract

Background

Surgical resection of hepato-pancreato-biliary (HPB) cancer is inherently complex due to the anatomical abdominal region with proximity of multiple organs, central blood vessels, and the presence of individuals anatomical variations. With advancements in creating and visualizing 3-dimensional (3D) anatomical models, these structures can be visualized with stereopsis (depth perception). Stereoscopic 3D models hold promise as a valuable tool, providing a comprehensive visual representation of the spatial relationships between the region of interest and surgically relevant structures. Therefore, this study aims to provide an overview of the current role of stereoscopic 3D models in HPB surgery.

Methods

A literature review was performed with the databases of PubMed, Web of Science, Embase and Cochrane. These databases were systematically screened for studies regarding the use of stereoscopic 3D models in the treatment of HPB cancer.

Results

18 articles were included, of which nine employed Augmented Reality (AR), six Mixed Reality (MR), and the remaining two utilized Virtual Reality (VR) to visualize the 3D models in stereopsis. These stereoscopic 3D models primarily served for tumor localization, blood vessel identification and resection plane determination. The articles were mainly proof-of-concept studies, focusing on the feasibility of the technique. Quantitative outcomes were reported in 3 articles.

Conclusion

Stereoscopic 3D models show promise in HPB surgery, especially in intraoperative settings with AR and MR. Qualitative evidence indicates benefits in tumor localization, blood vessel identification and resection plane determination, but direct contributions to patient outcomes are limited. Cost, time or workload savings might provide alternative incentives for short-term adoption, though feasibility of the used setups should be critically evaluated.

Keywords Stereopsis ▪ Extended Reality ▪ Imaging, Three-Dimensional ▪ Surgical Planning ▪ Computer-assisted Surgery ▪ Biliary Tract Surgical Procedures* ▪ Liver / Surgery ▪ Pancreas / Surgery

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Introduction

Hepato-pancreato-biliary (HPB) cancer is a collective name for malignancies arising from the liver, pancreas and biliary tracts. Over the past few years, the incidence of HPB cancers has been on the rise. Furthermore, they are steadily climbing the ranks among the deadliest malignancies. (11) Diagnosis and treatment of these malignancies have a strong multidisciplinary character. This approach is pivotal in addressing the diagnosis and treatment plan of these disease.
The shared characteristic of treatment of HPB cancer is that surgery is the cornerstone of a treatment with curative intent, which improves the chances of relatively long-term survival. (13-17) Nevertheless, complete resection may not always be achievable in advanced stages, when the tumor has spread extensively to vital, surrounding tissues. The timing of diagnosis therefore has a strongly impact on the survival rate. (52) Unfortunately, the timing of diagnosis cannot be advanced due to the absence of clinical symptoms and lack of accurate tests for early detection. Enhancing the success of surgery is therefore crucial for improving the clinical outcome.
The success of surgery, obtaining a complete resection with sufficient surgical margins, is largely dependent on detailed knowledge of tumor anatomy and its interactions with surrounding tissues. Planning surgery requires mentally translating 2-dimensional (2D) preoperative images - acquired from computed tomography (CT) and/or magnetic resonance imaging (MRI) - into the real 3-dimensional (3D) world. (23) Additionally, intraoperative ultrasound (US) can be used to identify and assess structures in real-time. HPB surgery however is a challenging region for surgical planning and for intraoperatively identifying and assessing structures, because of the proximity of multiple organs and blood vessels. Furthermore, this anatomical region is known for numerous anatomical variations, adding even more complexity. (19-22, 53)

Providing a 3D model can facilitate these tasks and makes it easier for the surgeon to translate the individuals anatomical situation to a surgical plan and a 3D reality. By utilizing 3D models, the suspect tumor(s) can be visualized with precision in relation to anatomical structures, offering a clear depiction of their spatial relationship.
Moreover, the increased use of extended realities (XR) - e.g. virtual reality (VR), mixed reality (MR) and augmented reality (AR)- and stereoscopic displays can enhance this 3D visualization, by adding stereopsis (depth perception) making it even more intuitive and closer to reality. The difference between these technologies in how they interact with the real world makes AR and MR more suitable for intraoperative use. VR - where users are fully immersed in a virtual world – on the other hand is better suited for preoperative applications, such as decision-making and surgical planning. (15)

Up to this point, the use of 3D visualization alongside XR technology has been mainly focused on educational purposes. In contrast to clinical use, educational 3D models can be used multiple times as anatomical examples, saving time and effort in preparation. Moreover, educational 3D models have fewer standards and requirements – in terms of accuracy and usability - compared to their use in clinical context. However, problems hampering the use of 3D models with XR technology in daily, clinical practice are being addressed through recent research advancements. Within the field of creating 3D models, developments in (semi-) automatic segmentation techniques, particularly the use of deep learning algorithms, have revolutionized the field. These new developments have made segmentation of structures more efficient, accurate and less time-consuming. (54) This makes the use of 3D models more accessible for clinical practice. Additionally, the progress in XR technologies – driven by other industries - enhances overall usability. The improved user's experience makes the use more accessible, including its application in clinical practice of HPB surgery. (8)

As 3D models together with XR advancements continue to emerge, the importance to address the clinical usability in HPB surgery grows. To date, the role of stereoscopic 3D models in HPB surgery seems not clearly defined yet.

This comprehensive review describes the role of stereoscopic 3D models in HPB surgery. A graphical summary of the role of stereoscopic 3D models divided in different phases of HPB surgery is given in Figure 1. To provide a clear overview, this review is divided in several sections. Firstly, the included studies are characterized to contextualize the topics. Secondly, applications for stereoscopic 3D models are discussed (fig. 1, B,E). Thirdly, different concepts of the use of stereoscopic 3D models in different phases and disciplines are described (fig. 1, A, C-D). Furthermore, outcomes on the use of stereoscopic 3D models are reported (fig. 1, F). Finally, factors hampering the use of stereoscopic 3D models in HPB surgery are discussed together with recommendations for future research (fig 1. 1-3).

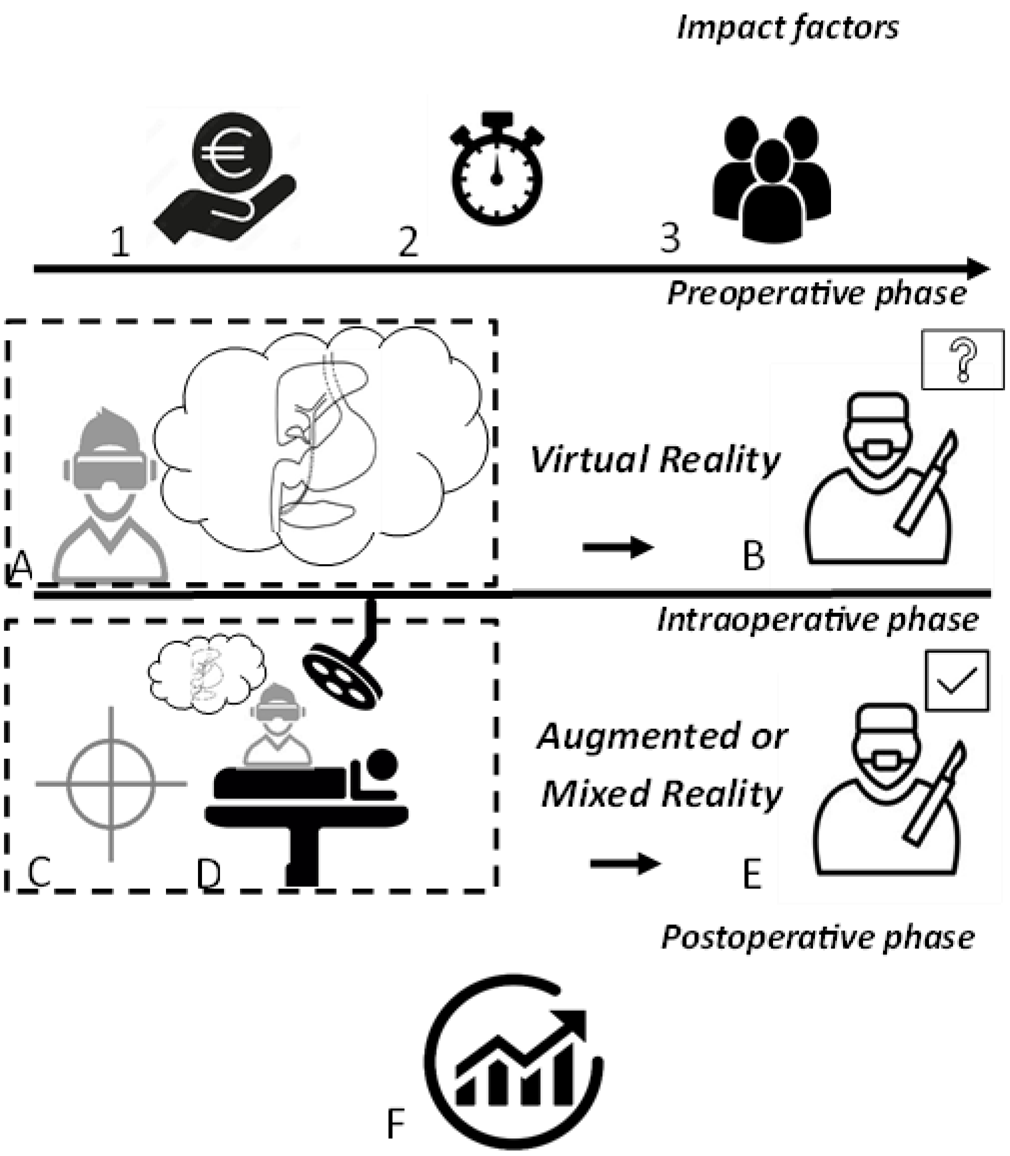

Fig. 1 *Summary of the use of stereoscopic 3D-models in the clinical process*

Impact factors: ***1)*** *Costs,* ***2)*** *Time,* ***3)*** *Workload;*
Preoperative phase: ***A)*** *Virtual Reality,* ***B)*** *Surgical Planning;*
Intraoperative phase: ***C)*** *Registration,* ***D)*** *Use of Augmented Reality or Mixed Reality,* ***E)*** *Executed surgery with surgical characteristics;*
Postoperative phase: ***F)*** *Postoperative outcomes.*

Study Selection and Characterization

To describe the role of stereoscopic 3D models in HPB surgery, a literature search on PubMed, Web of Science, Embase and Cochrane searches was conducted (publication date until August 2023) using the PICO framework (table 1). (55)
The search strategy per database is added to Appendix A. The query yielded a total of 579 papers from PubMed, Web of Science, Embase, and Cochrane. After screening, 32 articles underwent full-text assessment. 18 articles published between 2013 and 2023 were included for this review. All studies used XR's – MR (9), AR (7) and VR (2) - to display the stereoscopic 3D models. Notably, 15 out of the 18 studies were characterized as proof-of-concept investigations with relatively small patient sample sizes. (26-31, 33, 34, 36-41, 49, 56) Of the 18 studies on stereoscopic models in HPB surgery, in 14 studies it was applied to liver surgeries (26-36, 49, 56), in 6 studies to pancreatic surgeries (26, 32, 37-39, 49) and in 2 studies to surgeries of the biliary system (40, 41). Various devices were employed for presenting stereoscopic models, including the HoloLens (I or II) (Microsoft Corp., Redmond, WA, USA) – a head-mounted display - for MR, the HTC Vive v2.0 headset (HTC Corp., Taoyuan, Taiwan) for VR, and customized setups for AR or MR that varied among different hospitals. The screening process is visually represented in figure 2, while table 2 provides a summary of the characteristics of the included studies.

Table 1 *PICO Framework*

Population	*Patients with Hepato-Pancreato-Biliary (HPB) cancer undergoing surgical treatment*
Intervention	*Use of conventional 2-dimensional (2D) imaging with additional a stereoscopic 3-dimensional (3D) model of the patient for surgical purposes*
Comparison	*Use of conventional 2-dimensional imaging alone for surgical purposes*
Outcomes	*Assessment of perioperative and surgical outcomes*

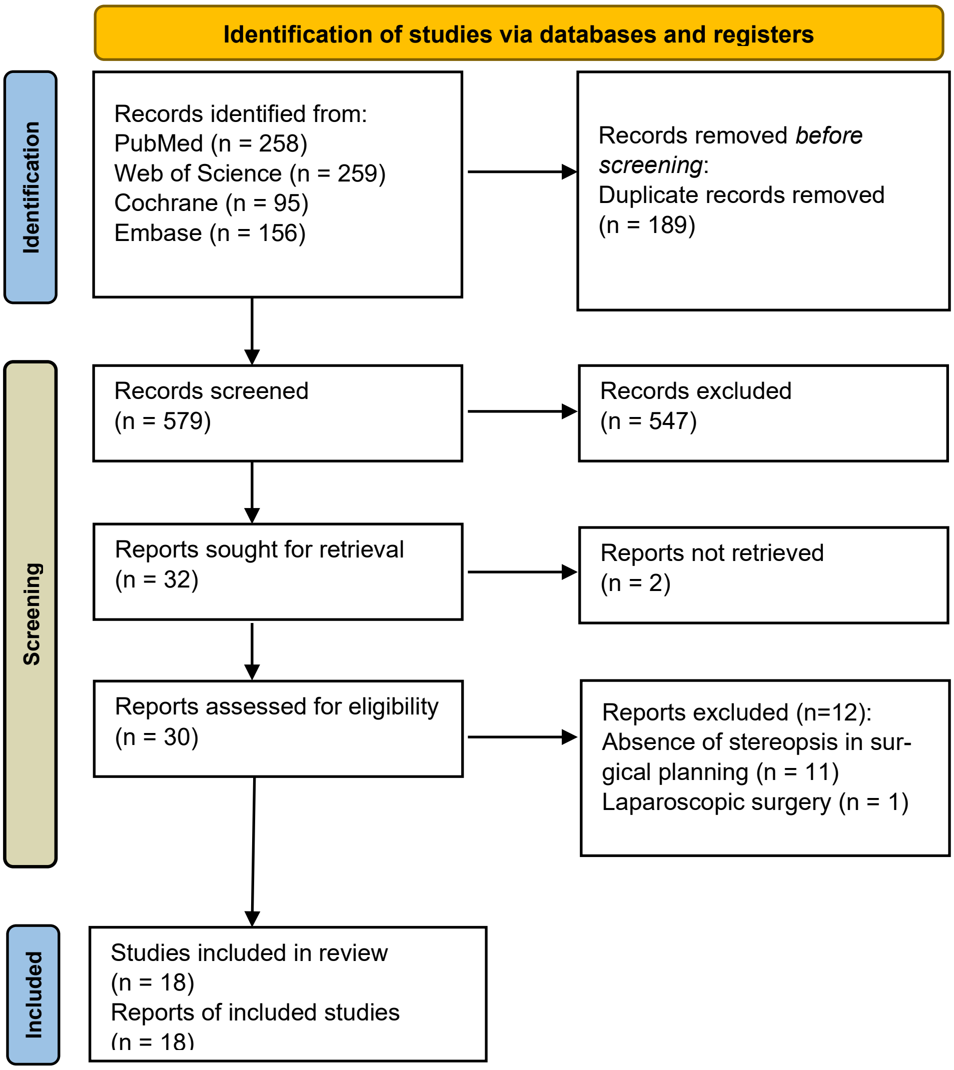

***Fig. 2** Flowchart of study selection*

Table 2 *Study characteristics, divided in study type, organ for which the stereoscopic 3D model is used and device that is used to display*

Variables	Augmented Reality (n=9)	Mixed Reality (n=7)	Virtual Reality (n=2)
Study type			
Clinical trials	1	2	0
Proof-of-concept study	8	5	2
Organ			
Liver	5	7	2
Pancreas	4	1	1
Biliary system	2	0	0
Device			
HoloLens (I/II)	0	6	0
HTC Vive v2.0 headset	0	0	2
In-house developed setup	9	1	0

Applications for stereoscopic 3D-models

In the included articles, various applications were identified in which the utilization of stereoscopic 3D models were considered an enhancement to conventional imaging, (Table 3). The applications are subdivided per organ.

Liver

Stereoscopic 3D models were in 14 of the 18 studies applied in liver cases. In 2013, Onda et al. were the first to use stereoscopic 3D models in open liver procedures for tumor localisation, blood vessel identification and resection determination. (26) Subsequently, Pessaux et al. (2015) used stereoscopic 3D models in two robotic segmentectomies to virtually plan the resection line based on the future remnant liver volume (FRLV). (34) The preoperative assessment of the FRLV helps the surgeon in decision-making, to ensure that the remaining liver is sufficient for normal liver function. Furthermore, by practicing the surgery virtually, decisions that are typically made intraoperatively may be adjusted preoperatively in a more controlled environment. After the study of Pessaux et al., four other studies described the use of stereoscopic 3D models for performing a virtual liver surgery. (29, 31, 33, 36)

Another application of stereoscopic 3D models, described by Pessaux et al., was to determine where the robotic port should be placed on the patient. By displaying the 3D model on the patient with a beamer, the incisions were set.

Over the years, applications for stereoscopic 3D models in liver surgery did not really change. The spatial relation between tumor and critical structures (6 studies) (27-32), the identification of blood vessels (8 studies) (26, 27, 29-34) together with resection plane determination (8 studies) (26, 27, 29, 30, 32-35) were still the main reasons to use the models. However, Cremades Pérez et al. added a new element in their study by using stereoscopic 3D models to share the procedure with a consultant in another place. The use of AR glasses together with the stereoscopic 3D models made it much easier to explain the surgical problem as well to understand the response of the consultant surgeon. (49)

Table 3 Applications for stereoscopic 3D-models

Application	Liver (n =14)	Pancreas (n=6)	Biliary system (n =2)
Tumor localisation	6	2	0
Identification of blood vessel(s)	8	5	0
Determination resection plane	8	4	1
Incision positioning	2	1	0
Identification of biliary ducts	0	0	1
Calculation remnant organ volume	5	0	0
Share surgical procedure with consultant	1	1	0

Pancreas

The predominant application of stereoscopic 3D models in pancreatic surgery focused on the identification of blood vessels. (26, 32, 37-39) Given the intricate positioning of the pancreas among numerous critical blood vessels, preserving these vessels is a priority. Simultaneously, surgeons aim to achieve complete tumor resection to hinder the progression of the disease. In the studies included, surgeons used stereoscopic 3D models to gain a comprehensive understanding of the scenario. A more informed assessment enabled surgeons to find the balance between preserving blood vessel relationships and determining the necessary resection for optimal tumor removal. This application underscores the potential role of stereoscopic 3D models in enhancing surgical precision and decision-making in pancreatic surgery.

Biliary system

Two studies focused on application of stereoscopic 3D models in the biliary system. Diana et al. used the stereoscopic 3D model based on MRI to visualize and identify the biliary ducts. (40) On the other hand, Tang et al. used a stereoscopic 3D model based on CT to visualize the biliary ducts and determine where to resect the hilar cholangiocarcinoma. (41) The difference between these studies was that in the case report of Tang et al., the intrahepatic cholangiectasis was significant, making the biliary structures clearly visible on CT images.

Setups of stereoscopic 3D models in different surgical phases

Considerable variations exist among studies in the configurations employed for stereoscopic 3D models. This heterogeneity is partly caused by the surgical phase in which the extended reality is applied. Furthermore, most studies are still in the proof-of-concept phase, where setups are tested and optimized. The following section will describe the different concepts – with its advantages and disadvantages - that are categorized based on the surgical phase (preoperative or intraoperative) in which they are applied.

Preoperative phase (fig. 1, A-B): The role of Virtual Reality and Augmented or Mixed Reality

In the preoperative phase, the surgeon makes a surgical planning with patient's consent based on the patient's medical history, diagnosis, preoperative imaging, and surgical goals. Additional to the conventional 2D-images, the 3D-model can be showed for an improved spatial understanding of the anatomy in relation to the tumor(s). (**A**, fig 2.) The role of virtual reality (VR) is entirely focused on this preoperative phase. VR is an environment in which the user is completely immersed, detached from the real world. In the medical domain, it is therefore ideally suited for preparing surgeons for real-life situations during operations. However, the clinical use of stereoscopic 3D models in VR for HPB surgery is limited. Only two studies published findings on the use of stereoscopic 3D models in VR. Pfeiffer et al. primarily concentrated on developing an open-source framework where 3D models can be easily controlled and manipulated. This environment has the potential for various clinical applications on the condition that provided patient data can be presented and integrated correctly from hospital information systems. The aim of their study, however, was more on the theory of a framework for 3D models in VR instead of implementation. (35)
Lyuksemburg et al. went a step further and described in their article from 2023 the use of VR in a retrospective and prospective study. Similar to Pfeiffer et al., they used the HTC Vive headset to display 3D models. In their study, they emphasized the importance of a proper workflow - comprising content acquisition, segmentation, quality control, content optimization, and clinical impact - for displaying 3D models. However, the usability of their VR setup for rendering 3D models was not reported, making it challenging to critically evaluate. (32)

In the field of AR and MR, preoperative applications have also been described. While these realities are ideal for intraoperative use, as they allow the viewing of the real world with an overlay, they can also play a role in the preoperative phase. Pelanis et al. together with Balci et al. and Cremades et al. used the HoloLens I/II to display the generated 3D models preoperatively. (28, 36, 49) Ruzenette et al. used their Hyper accuracy three-dimensional (HA3D™) technology to reconstruct 3D models. (29) In all four studies, details on the setups were not provided, which makes it again difficult to critically evaluate the usability with its advantages or disadvantages.
What is noteworthy in general is that there were more AR/MR studies that did describe the preoperative use of 3D models to prepare surgeries. However, these 3D models were preoperatively not displayed through XR but on a monoscopic screen. Since this application is beyond the scope of this review - stereoscopic 3D models for surgical planning – these setups will not be further elaborated upon.

Intraoperative phase (fig. 1, C-E): The role of Augmented Reality and Mixed Reality

The intraoperative phase, is the phase of the surgical workflow where the actual surgical procedure is conducted in the operating room. During this phase, surgeons identify lesions and critical anatomical structures and orient the structures relative to each other and other surrounding organs. They also iterate preoperative surgical plans based on intraoperative findings.
AR or MR can play a pivotal role in bridging the preoperative plan to the surgical field. The most common setup that is used was with the HoloLens I/II (6 studies) (28, 30, 31, 33, 36, 49). In the study of Balci et al. and Saito et al., they displayed the stereoscopic 3D model with the HoloLens II above the patient as intraoperative aid for the surgeon. In these studies, the stereoscopic 3D model was not used for navigation but for 'last-minute' simulation.
Four other studies that displayed stereoscopic 3D models with the HoloLens aimed to overlay the virtual model on the real world patient's anatomy. This was achieved by performing image registration to align the stereoscopic 3D-model with the surgical field. This alignment aims for a one-to-one correspondence between the virtual model and the patient's anatomy (**C**, fig. 2), which can serve as a guidance for the surgeon. In case of the studies that used the HoloLens, this registration was performed

manually. Manual registration involves a human intervention during surgery. It therefore requires a human operator – often a technician – who visually aligns the 3D model with the surgical field. The operator manually adjusts the alignment of the data by manipulating transformation parameters (e.g., translation, rotation) until they are satisfied with the alignment. This can all be performed real-time to be able to adapt to specific surgical situation. Disadvantages of manual alignment is that it is a subjective task, making the results prone to high interobserver variations affected by the level of the individual expertise of the human operator.

Nine studies used other setups than with the HoloLens. At first, Marzano et al. used an exoscopic camera to obtain intraoperative images to display the 3D model on. (37) Okamoto et al. made a similar setup, though used a camera hung from the ceiling. The camera's location was followed with an optical location sensor, in order to enable the operator to navigate with the operation field images taken from various viewpoints. (27) Subsequently, Onda et al. improved this design by making a short rigid scope to capture real-time operative field images. In this way, the setup of Okamoto was replaced by only a simple scope. (26) The setup of all these studies have in common that the reconstructed images of the patient's anatomy were superimposed on the real-time operative field via a 2D monitor display. Marzano et al. did the registration with manual registration. This was done by a computer scientist that manually merged the 3D-model on the patient's anatomy with a video mixer. Okamoto et al. and Onda et al. were the first to use a mathematical registration method: paired-point registration.

The paired-point registration method is an automatic, mathematical registration method where the objective registration errors are measured. The aim of this method is to align two sets of various points into the same coordinate system or space by finding the optimal transformation (e.g., translation, rotation, scaling) Compared to manual registration, scaling is added to the transformation matrix. This enables the model to deform non-rigidly enabling more accurate alignment of the model and the surgical field which can be deformed due to the surgical procedure. However, it should be noted that it can still be difficult to align the 3D model with the intraoperative field, since these transformations does not include all possible organ shifts or deformations.

In both studies by Onda et al. (2013 and 2014) and in the study of Okamoto (2013), although they used paired-point registration, they still experienced problems with accurately registering the model with the intraoperative field. Okamato et al. reported a fiducial registration error (FRE) – which is the root mean square between corresponding fiducial points -of 5 mm in 1/3 of the cases. They did not measure an error in 2/3 of the cases. (27) Onda et al. (2013) reported a FRE of 6.49 mm-10.59 mm. (26) Subsequently, in their study from 2014, they reported a FRE of 6.20 mm in successful cases. Furthermore, in their study of 2014 they improved their setup by exchanging their monoscopic display by a stereoscopic display for better depth perception. Only FRE's were reported, since the main aim of the study was more focused on the feasibility and safety of their setup. (38)

In 2015, Pessaux et al. introduced a new setup using an external beamer to display the 3D model on the patient to guide the port positioning. During the surgery, the virtual model was displayed on the patient's anatomy via the robot. Again, rigid patient's models were used, making corrections impossible. Another disadvantage of this setup was that the beamer light could be obstructed by someone, causing the 3D model to disappear. (34)

In 2017, Diana et al. used a similar setup with manual registration to display a 3D model of the biliary ducts on the patient's anatomy. (40)

Also in 2017, Tang et al. created an alternative setup where the organ of interest was scanned with an iPad, displaying the 3D model. Registration was based on 4 anatomical landmarks and could manually be adjusted in orientation. (41) In 2021, this setup was changed by using QR codes at the calibration position, which could be scanned with a smart phone. The in-house developed app, X-Liver software, automatically recognized the QR code and displayed the images according to the pre-set effect. In this study, Tang et al. reported a FRE of 2-8 mm. In both studies images could only be registered rigidly. (39)

Ruzenette used their in-house developed intraoperative cognitive navigation system (ICON) to intraoperatively display 3D-models. However, details of the setup were not described. (29)
At last, Golse et al. was the only study that tried to non-rigidly correct for deformations. (56) In theory, non-rigid registration can correct for deformed or shifted organs, often the case in the HPB region. In their feasibility study, they developed a non-rigid registration system by real-time using an efficient finite element method to fit the 3D model on the deformed intraoperative field. A RGB-camera was used to capture a point cloud of the organ of interest, which then was aligned with the meshes of the created 3D-model. With the finite element method, required deformations were computed to align the meshes with the acquired point cloud. The reported FRE was between 8.4-13.6 mm, in a similar range of Okamato et al. and Onda et al.. A limitation of their setup was that it could only be applied in open surgeries, not in laparoscopy.
All described registration methods with reported registration errors are summarized in table 5.

Reported outcomes (fig. 1, F)

Since most studies were still in the proof-of-concept phase, clinical outcomes are still missing. Diana et al. performed a study on the visualization of cystic ducts with preoperative 3D-VR and intraoperative AR navigation during robotic cholecystectomy. A comparison of the quality of images was made with other imaging modalities, such as x-ray intraoperative cholangiography (IOC) and near-infrared cholangiography (NIR-C). A questionnaire was administered to the operating team and two independent evaluators. They concluded that the image quality of VR-AR was significantly lower ($p<0.0001$) compared to X-ray IOC for visualization of the cystic ducts. VR-AR, on the other hand, was significantly better than NIR-C ($p<0.01$). (40)
Pelanis et al. showed in a study with fictive patients that the median time to determine the location of a liver lesion in one of the segments was significantly lower in HoloLens compared to MRI ($p<0.001$). Furthermore, the accuracy of the diagnosis remained similar ($p=0.74$). It should be noted that participants had a median age of 30, with a median practical medical experience of 6 years. Furthermore, the artificially placed lesions were marked as tumors in the 3D models, whereas this information was absent in the MRI images. In essence, an interpretation step what tumor tissue is was already incorporated in the 3D models. (28)
Zhu et al. was the only study that focused on multiple clinical outcomes in the application of stereoscopic 3D models. They demonstrated that the utilization of stereoscopic 3D models via the HoloLens, in comparison to conventional 2D-imaging with CT, yielded statistically significant improvements, including: a reduction in operation time ($p=0.003$), a decrease in portal vein obstruction time ($p=0.019$), a notable reduction in intraoperative bleeding ($p=0.028$), faster recovery of ALT- ($p=0.014$) and ALB- ($p=0.032$) levels – as markers for the liver function - lower rate of 30-day postoperative complications ($p=0.032$), and lower rate of hospitalization days ($p=0.049$). (31) None of the articles researched the impact of stereoscopic 3D-models on survival, recurrences, or other long-term outcomes.
All reported outcomes are summarized in table 4.

Table 4 *Summary of clinical trials*

	Number of patients	Year(s)	Significant outcomes	Limitations
Augmented Reality				
Diana et al., 2017 (40)	58	2013-2016	The *image quality* to *visualize the cystic duct* with *VR-AR* is significantly **lower** compared to *X-ray intraoperative cholangiography* (IOC)($p<0.0001$)	Exclusion of cholecystitis, where an enhanced guidance is more relevant, rigid 3D models for cystic duct visualization
Mixed Reality				
Pelanis et al., 2020 (28)	28	2018	*Median time to diagnosis* with *HoloLens* is significantly **lower (**$p<0.001$) compared to *MRI*, while *accuracy* is **similar** ($p=0.74$)	Fictive patients, limited number of participants, time stress during tasks, tumor is not segmented in MRI images
Zhu et al. 2022 (31)	95	2018-2020	*HoloLens* group has significant **shorter** *operation time (p=0.003),* **lower** *intraoperative bleeding (p=0.028),* **shorter** *obstructive time of portal vein (p=0.019),* **faster** recovery *of ALT (p=0.014) and ALB (p=0.032) levels*, **lower** *rate of 30d postoperative complications (p=0.032)* and *hospitalization days (p=0.049)*	Retrospective study, single center, choice of MR-assistance was the surgeon's preference, rigid 3D holograms difficult to fuse on liver due to deformations

Impact Factors (fig. 1, 1-3) influencing Clinical Implementation of Stereoscopic 3D-models

In this review, several factors that impact the clinical implementation were identified, such as time, costs, and workload. These impact factors are reported in 3 included articles as parameters. Onda et al. reported in their article from 2013 that preoperative tasks – such as segmentation and operative planning – in HPB surgery could take 5-10 extra hours. Furthermore, they noted that the preparation for setting up the operating room took 1 hour the day before. (26)

Other studies only reported the time to registrate their 3D models with the intraoperative field. For most studies, registration was achieved under 10 minutes, see table 5. However, Tang et al. reported extra registration times of 20-40 minutes. (39)

None of the studies reported on the costs of their self-developed systems. For studies that used the HoloLens I/II, it is know that the HoloLens II costs approximately between 3000-5000 euros, depending on the additional services and accessories purchased. (57)

Table 5 Summary of registration methods with reported errors and registration time

AR/MR articles (n=16)	Registration method	Registration error	Extra intraoperative time
Cremades Pérez et al., 2023 (49)	Manual registration	-	-
Diana et al., 2017 (40)	Manual registration of VR model	-	For search relevant images: Mean (191.9 190.06 seconds)
Golse et al. 2021 (56)	RGB-camera registration	8.4-13.6mm	Registration <10 minutes
Marzano et al., 2013 (37)	Manual registration with video mixer	-	Superimposition and registration 6 minutes
Okamoto et al., 2013 (27)	Paired-point registration	1/3 cases 5mm error, 2/3 cases 'no error'	-
Onda et al. 2013 (26)	Paired-point registration	6.49-10.59mm	1-2 min registration
Onda et al. 2014 (38)	Paired-point registration	6.20mm	Similar to conventional(p=0.934), total 6-minutes
Pessaux et al., 2015 (34)	Manual registration with video mixer	-	6-10 minutes to achieve AR
Tang et al., 2017 (41)	Manual registration with 3D-printed model saved with QR code	-	-
Tang et al. 2021 (39)	QR code registration with overlay relative to QR code	2-8mm	Registration 20-40 minutes

Future opportunities and horizon scanning

This review aimed to present the role of stereoscopic 3D models in HPB surgery. Firstly, it should be noted that there is an upward trend visible in the use of stereoscopic 3D-models in HPB surgery. Between 2013-2019, eight articles were published, while in the last three years (2020-2023), ten articles were published on this topic.

Furthermore, most articles reported an added value of the use of stereoscopic 3D models. This added value of stereoscopic 3D models was mainly described in qualitative outcomes. Most reported applications where stereoscopic 3D models were described as benefit were: the localization of tumor(s), identification of blood vessels and determination of resection planes. The limitation of these qualitative findings, however, is that they were often subjective. This makes it difficult to compare findings and draw general conclusions for the use of stereoscopic 3D models.

There were three studies that reported on quantitative findings. Among the quantitative findings, Zhu et al. were the only that demonstrated that an additional stereoscopic 3D model of the liver displayed in the HoloLens leaded to significant shorter operation time (p=0.003), lower intraoperative volume bleeding (p=0.028), lower obstructive time of portal vein (p=0.019), lower 30d postoperative complications (p=0.032) and hospitalization days (p=0.0490). The limitation of this study, however, was that it was the surgeon's choice to use the HoloLens for his/her surgical planning. Reasons from the surgeon to choose for the HoloLens were not given. (31)

Pelanis et al. also demonstrated an improved quantitative outcome, in a study with fictive patients where the HoloLens significantly reduced the time to diagnosis compared to MRI, while maintaining similar accuracy.

The main limitation of this study was that is was in fictive patients. A prospective study with real patient cases is thus needed. (28) At last, Diana et al. showed that the image quality of VR-AR to visualize the cystic duct was significantly lower compared to X-ray IOC, making VR-AR less feasible for their described application. (40)

The lack of quantitative outcomes can be mainly explained by the early-phase in which this research field currently exists. In this phase, searching for a setup and demonstrating feasibility has the main focus. The strength of these studies lie in the direct practical testing of a concept, serving as a foundation for further development. However, they do not yet constitute a comprehensive basis for the practical application of the concept in daily healthcare. This search for an optimal setup is also reflected in the heterogeneity in setups that are used.
The HoloLens device was the most frequently used device in six studies, while HTC Vive v2.0 headset was the sole device used for virtual reality. The other ten studies that focused on AR or MR employed diverse configurations for presenting the stereoscopic 3D models.
Again, this heterogeneity is made visible in the diverse methods of registration during surgery. Registration was not consistently employed in AR or MR. Among studies employing registration, there was considerable variability in its application, ranging from manual to automatic, mathematical methods. The duration required for registration exhibited minimal variance across studies and between manual and automated approaches with most studies under 10 minutes. Only Tang et al reported registration times of 20-40 minutes. This extra time can be explained by there unique method of QR code placement, as well as time-consuming software to recreate the models. (39) Registration errors were only documented in studies utilizing a mathematical method, ranging from 5-13 millimetres. Most studies used a rigid registration method for the 3D model. However, this registration created errors in the surgical field, especially in the deformable HPB region. This issue was frequently acknowledged in multiple articles; however, the impact on feasibility was frequently unaddressed. Golse et al. were the only to apply a non-rigid method for registration, though could not achieve smaller registration errors than rigid registration methods. (56)
It remains difficult to interpretate the reported numbers on registration error and registration times, since there is lack of clinical validation that the quality of resection could benefit from registration with XR technologies. In a report of Dilley et al., it is even stated that perfect registration could lead to imperfect performance in a simulated laparoscopic cholecystectomy. (58) The balance between perfect intraoperative registration in relation to extra intraoperative registration time is thus difficult to determine. Future studies in the field of AR/MR registration should therefore focus on the interpretation of registration errors and what consequences they can have in clinical decision-making. In this way, the consideration for extra intraoperative time to achieve better intraoperative registrations can better be made. If then needed, non-rigid methods – which better allow the correction of deformations in the HPB region - could further be researched to decrease registration errors.

What also becomes clear from this review, it that it is difficult to compare the different setups that are used. This is mainly caused by the lack of detailed technical specifications about the devices used, making it challenging to assess and compare their capabilities. In a comparison with the included articles of Palumbo et al.'s review, there is a under reporting of limitations in the use of the HoloLens 2 for AR/MR. The main limitations that were addressed in their review were the limited field of view in which overlays can be displayed and the limited battery life. Furthermore, the total weight of the headset play was described as a crucial factor in facilitating acceptance of the AR device. (59) However, none of the included articles in this review mentioned these limitations. It is therefore recommended to further investigate and report on the workability of the techniques used.
Furthermore, in order to make a comparison between studies, it is recommended for future studies to report in a standardized manner on the method used to visualize stereoscopic 3D models. This standardization should also include reporting on how the 3D models were created and validated. Although this topic is beyond the scope of this review, it is crucial for the implementation of 3D models. Specifically, if 3D models deviate significantly from actual anatomy, while having a well-designed setup, it is still challenging to successfully implement. Standardization is also necessary in reporting on the techniques employed, taking into account outcomes influencing clinical implementation such as time to prepare and execute – with information on possible interruptions or significant delays before or during surgery -, costs for the setup and extra workhours, and the possible increased workload.

The question that rises is how do we come from feasibility studies to implementing stereoscopic 3D models in daily healthcare. An ideal assessment of the practical application of stereoscopic 3D models in daily healthcare would involve comprehensive, large-scale patient studies. These studies would involve evaluating the impact of stereoscopic 3D models on achieving clear tumor margins. Additionally for the long-term, these studies would involve a prolonged patient follow-up with a focus on aspects such as survival rates and recurrences. However, currently there exist too many uncertainties concerning the practicability of stereoscopic 3D models in HPB surgery to warrant their investigation in large-scale patient studies. Particularly when these techniques are employed for intraoperative decision-making. In an intraoperative setting, high standards must be met, with a primary focus on accuracy and precise registration of these models with the surgical field.
To widely demonstrate the added value of stereoscopic 3D models in HPB surgery, it should be possible to critically evaluate designed setups. By transparently and comprehensively reporting on the used setup, more research groups could help in developing or optimizing setups – making the use of stereoscopic 3D models feasible. In this way, these techniques could become faster accessible for daily practice. Subsequently, larger-scale clinical studies can be conducted to investigate the impact of stereoscopic 3D models on long-term clinical outcomes. On the short-term, an examination can be made to determine whether stereoscopic 3D models have a positive influence on the costs, time, and workload per procedure.

Conclusion

In conclusion, the role of stereoscopic 3D models in HPB surgery in the literature predominantly pertains to intraoperative settings using AR and MR. Primarily, qualitative evidence is provided for improved tumor localization, blood vessel identification, and resection plane determination. However, there is limited evidence to suggest that stereoscopic 3D models directly contribute to enhanced patient outcomes. To substantiate the actual impact of these 3D models on improved outcomes, transparent and detailed reporting on the techniques and its feasibility is essential before embarking on large patient studies to investigate surgical and long-term outcomes. Optimizing the technique of stereoscopic 3D models can eventually offer substantial advantages to surgeons in preparing for and navigating during HPB surgery. Given that larger-scale clinical studies can take a period of time, other considerations, such as cost savings, time efficiency, and workload reduction, might provide alternative incentives for the short-term adoption of stereoscopic 3D models in HPB surgery. This can potentially offer prompt insights into the added value of using stereoscopic 3D models in HPB surgery.

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Appendices

Appendix A. Search terms databases

PubMed

("Digestive System Surgical Procedures"[Majr] OR "Digestive System Surger*"[tiab] OR "Digestive System Surgical*"[tiab] OR "Robotic Surgical Procedures"[Majr] OR "Robotic Surgical*"[tiab] OR "Robot-Enhanced Procedure*"[tiab] OR "Robot-Enhanced Surger*"[tiab] OR "Robot-Assisted Surger*"[tiab] OR Pancreaticojejunostom*[tiab] OR " Pancreatico-jejunostom*"[tiab] OR whipple[tiab] OR pancreaticoduodenectom*[tiab] OR "pancreatico-duodenectom*"[tiab] OR PPPD[tiab] OR pancreatectom*[tiab] OR hepatectom*[tiab] OR cholecystectom*[tiab] OR Cholecystostom*[tiab] OR Choledochoduodenostom*[tiab] OR "Choledocho-duodenostom*"[tiab]) **AND** ("Depth Perception"[Mesh] OR "Depth Perception*"[tiab] OR "Stereoscopic"[tiab] OR "Stereopsis"[tiab] OR "Stereovision"[tiab] OR "Virtual Reality"[Mesh] OR "virtual realit*"[tiab] OR "virtual-realit*"[tiab] OR "VR"[ti] OR "virtualreality"[tiab] OR "Augmented Reality" [Mesh] OR "Augmented Real*"[tiab] OR "Mixed Real*"[tiab] OR "three dimensional"[ti] OR "3 dimensional"[ti] OR "3D model"[ti]) **AND** ("Planning Techniques"[Mesh] OR planning[tiab] OR preoperative[ti] OR "pre-operative"[ti] OR "preoperative period*"[tiab] OR "pre-operative period*"[tiab] OR "multidisciplinary*"[tiab] OR "multidisciplinary team meeting*"[tiab] OR "multidisciplinary meeting*"[tiab] OR "multidisciplinary consult*"[tiab] OR "Perioperative Period"[Mesh] OR "perioperative*" [tiab] OR "peri-operative*" [tiab] OR "Postoperative*" [tiab] OR "Post-operative*" [tiab]) NOT ("laparo*"[tiab] OR "Anxiety"[tiab])

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Cochrane Library

(("Digestive System Surgical Procedures" OR "Digestive System Surgery" OR "Digestive System Surgeries" OR "Digestive System Surgical" OR "Robotic Surgical Procedure" OR "Robotic Surgical Procedures" OR "Robotic Surgical" OR "Robot-Enhanced Procedure" OR "Robot-Enhanced Procedures" OR "Robot-Enhanced Surgery" OR "Robot-Enhanced Surgeries" OR "Robot-Assisted Surgery" OR "Robot-Assisted Surgery" OR Pancreaticojejunostomy OR Pancreatico-jejunostomy OR whipple OR pancreaticoduodenectomy OR "pancreatico-duodenectomy" OR PPPD OR pancreatectom* OR hepatectom* OR cholecystectom* OR Cholecystostom* OR Choledochoduodenostom* OR "Choledocho-duodenostomy"):ti,ab,kw **AND** ("Depth Perception" OR "Depth- Perception" OR "Stereoscopic" OR "Stereopsis" OR "Stereovision" OR "virtual reality" OR "virtual-reality" OR "VR" OR "virtualreality" OR "Augmented Reality" OR "Augmented Realities" OR "Mixed Reality" OR "Mixed Realities" OR "three dimensional" OR "3 dimensional" OR "3D model"):ti,ab,kw **AND** ("Planning Techniques" OR "Planning Technique" OR planning OR preoperative OR "pre-operative" OR "preoperative period" OR "pre-operative period" OR "pre-operative periods" OR "multidisciplinary" OR "multidisciplinary team meeting" OR "multidisciplinary team meetings" OR "multidisciplinary meeting" OR "multidisciplinary meetings" OR "multidisciplinary consult" OR "multidisciplinary consult" OR "Perioperative Period" OR "perioperative" OR "peri-operative" OR "perioperatively" OR "peri-operatively" "Postoperative" OR "Post-operative" OR "Postoperatively" OR "Post-operatively"):ti,ab,kw) NOT (laparoscopy OR laparoscopic OR Anxiety):ti

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Embase
(exp*"Abdominal Surgery"/ OR "Digestive System Surger*".ti,ab. OR "Digestive System Surgical*".ti,ab. OR exp*"Robot Assisted Surgery"/ OR "Robotic Surgical*".ti,ab. OR "Robot-Enhanced Procedure*".ti,ab. OR "Robot-Enhanced Surger*".ti,ab. OR "Robot-Assisted Surger*".ti,ab. OR Pancreaticojejunostom*.ti,ab. OR " Pancreatico-jejunostom*".ti,ab. OR whipple.ti,ab. OR pancreaticoduodenectom*.ti,ab. OR "pancreatico-duodenectom*".ti,ab. OR PPPD.ti,ab. OR pancreatectom*.ti,ab. OR hepatectom*.ti,ab. OR cholecystectom*.ti,ab. OR Cholecystostom*.ti,ab. OR Choledochoduodenostom*.ti,ab. OR "Choledocho-duodenostom*".ti,ab.) **AND** (exp"Depth Perception"/ OR "Depth Perception*".ti,ab. OR "Stereoscopic".ti,ab. OR "Stereopsis".ti,ab. OR "Stereovision".ti,ab. OR exp"Virtual Reality"/ OR "virtual realit*".ti,ab. OR "virtual-realit*".ti,ab. OR "VR".ti. OR "virtualreality".ti,ab. OR exp"Augmented Reality"/ OR "Augmented Real*".ti,ab. OR "Mixed Real*".ti,ab. OR "three dimensional".ti. OR "3 dimensional".ti. OR "3D model".ti.) **AND** ("Planning Techniques".mp. OR planning.ti,ab. OR preoperative.ti. OR "pre-operative".ti. OR "preoperative period*".ti,ab. OR "pre-operative period*".ti,ab. OR "multidisciplinary*".ti,ab. OR "multidisciplinary team meeting*".ti,ab. OR "multidisciplinary meeting*".ti,ab. OR "multidisciplinary consult*".ti,ab. OR exp"Perioperative Period"/ OR "perioperative*" .ti,ab. OR "peri-operative*" .ti,ab. OR "Postoperative*" .ti,ab. OR "Post-operative*" .ti,ab.) NOT ("laparo*".ti,ab. OR "Anxiety".ti,ab.)

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Web of Science
(((AB=(("Digestive System Surgical Procedures" OR "Digestive System Surger*" OR "Digestive System Surgical*" OR "Robotic Surgical Procedures" OR "Robotic Surgical*" OR "Robot-Enhanced Procedure*" OR "Robot-Enhanced Surger*" OR "Robot-Assisted Surger*" OR Pancreaticojejunostom* OR " Pancreatico-jejunostom*" OR whipple OR pancreaticoduodenectom* OR "pancreatico-duodenectom*" OR PPPD OR pancreatectom* OR hepatectom* OR cholecystectom* OR Cholecystostom* OR Choledochoduodenostom* OR "Choledocho-duodenostom*"))) AND AB=(("Depth Perception" OR "Depth Perception*" OR "Stereoscopic" OR "Stereopsis" OR "Stereovision" OR "Virtual Reality" OR "virtual realit*" OR "virtual-realit*" OR "VR" OR "virtualreality" OR "Augmented Reality" OR "Augmented Real*" OR "Mixed Real*" OR "three dimensional" OR "3 dimensional" OR "3D model"))) AND AB=(("Planning Techniques" OR planning OR preoperative OR "pre-operative" OR "preoperative period*" OR "pre-operative period*" OR "multidisciplinary*" OR "multidisciplinary team meeting*" OR "multidisciplinary meeting*" OR "multidisciplinary consult*" OR "Perioperative Period" OR "perioperative*" OR "peri-operative*" OR "Postoperative*" OR "Post-operative*"))) NOT AB=((laparoscopy OR laparoscopic OR laparoscopically OR Anxiety))

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B. Questionnaire and Protocol Part I, Study 1

Questionnaire monoscopic versus stereoscopic display A								
General								
What is your age?	------------------							
Did you have anatomy lessons?	Yes No							
What is your function?	--							
Since when?	--							
Do you currently have any eye problems or conditions?	--							
Can you see depth?	--							
Do you have experience with 3D?	Yes No							
If applicable, can you describe your experience?	--							
Cases on monoscopic and stereoscopic display	*Indicate your level of certainty*							
Which tumor lies most ventral? Which most dorsal?	2D	Uncertain	0	0	0	0	0	Certain
	3D	Uncertain	0	0	0	0	0	Certain
		Indicate the display you prefer to execute the task						
		Monoscopic display	0	0	0	0	0	Stereoscopic display
Which bloodvessel lies closest to the tumor?	3D	Uncertain	0	0	0	0	0	Certain
	2D	Uncertain	0	0	0	0	0	Certain
		Monoscopic display	0	0	0	0	0	Stereoscopic display
Define segmental tumor locations	2D	Uncertain	0	0	0	0	0	Certain
	3D	Uncertain	0	0	0	0	0	Certain
		Monoscopic display	0	0	0	0	0	Stereoscopic display
SSQ	*Circle how much each symptom below is affecting you right now*							
General discomfort	None	Slightly	Moderate	Severe				
Headache	None	Slightly	Moderate	Severe				
Dizziness	None	Slightly	Moderate	Severe				
Eye strain	None	Slightly	Moderate	Severe				
Other	None	Slightly	Moderate	Severe				
If applicable, did you consider to stop executing the task?	--							
If applicable, would it prevent you from using the stereoscopic display?	--							
Do you think the stereoscopic display is useful for other purposes? If applicable, could you describe where and how?	--							
Do the glasses prevent you from using the stereoscopic display? If applicable, can you describe why?	--							

C. Questionnaire and Protocol Part I, Study 2

Questionnaire monoscopic versus stereoscopic display			Opmerkingen
Doel onderzoek uitleggen	Toegevoegde waarde van 3D-scherm tijdens het weergeven van 3D-modellen		
	- Modellen ontwikkeld met een specifieke vraag dus niet altijd compleet/kunnen beter gemaakt worden		
Aanwijzingen onderzoek	Meteen aangeven als je oncomfortabel wordt van stereotactisch kijken		
Introductie onderzoek	LC: - 3D model lever laten zien (casus 19) + instructies kleuren + instructies besturing Mercury 3D + muis settings		
	Stereotactisch + optimale afstand uit scherm + oefenen casusopdrachten		
Cases on monoscopic and stereoscopic display			
Welk segment ligt de tumor? Wat zou uw chirurgische strategie zijn?	2D		**Casus 008:**
	3D		**Casus 011:**
Overige opmerkingen			
Welk segment ligt de tumor? Wat zou uw chirurgische strategie zijn?	3D		**Casus 012:**
	2D		**Casus 018:**
Overige opmerkingen			
Voorkeur om chirugische strategie te bedenken?	2D kijken 0 0 0 0 0 3D kijken		
Extra vragen			
Voegt 3D-kijken iets toe?			
Zijn alle relevante structuren accuraat (met de juiste kleur) en volledig gesegmenteerd voor een preoperatieve planning? Zo niet, wat mist?			
Op welk moment in de behandeling zou u het 3D-scherm inzetten?			
Zijn er nog andere toepassingen voor deze 3D-modellen? (anders dan chirurgische strategie)			
Ziet u het zitten om dit 3D-scherm inclusief bril te gebruiken?			
Symptomen			

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D. *Step-by-step Guide for loading Stereoscopic 3D-Models in Mercury3D (Barco Software)*

- Save each object (such as liver, tumor, etc.) via the "Save Data" option in ParaView.
- Import this object into Blender.
- Choose a color for the object via material properties -> use nodes -> base color -> RGB.
- Export it as a single object.
- Open the MTL file to adjust the D (opacity).
- Drag both the MTL file and OBJ file into Mercury3D simultaneously.

Liver	R = 0.458 G = 0.067 B = 0.012 D = 0.5
Tumour	R = 1 G = 0.916 B = 0.274 D = 1
Hepatic veins	R = 0.089 G = 0.627 B = 0.8 D = 1
Vena Cava	R = 0.089 G = 0.627 B = 0.8 D = 1
Portal veins	R = 1.000 G = 0.001 B = 1.000 D = 1
Gallbladder	R = 0.006 G = 0.869 B = 0.000
Artery	R=0.800 G=0.003 B=0.003

E. Questionnaire and Protocol Part II

Per case (in total 8 cases per session), the surgeon had to answer the following questions. The responses and total execution times were by the researcher.

Questionnaire monoscopic versus stereoscopic display		
Case number		Time per case
In which segment(s) is the tumor located?		
Is there a surgical option to remove the tumor? If applicable, what would it be?		
If applicable, which main branch is directly involved and would you resect it?		

Preference				No preference			
Tumor segment	Monoscopic display	0	0	0	0	0	Stereoscopic display
Surgical strategy	Monoscopic display	0	0	0	0	0	Stereoscopic display
Main branch involvement	Monoscopic display	0	0	0	0	0	Stereoscopic display
Symptoms							
Did you experience symptoms? If applicable, what kind of symptoms?							
If applicable, do your symptoms prevent you from using the stereoscopic display?							
Do the glasses prevent you from using the stereoscopic display?							
Age							
Years of surgical experience							
Number of liver surgeries per year (now)							

F. Example of scoring the responses

Case 1

Segment bepaling	***Monoscopisch***	***Stereoscopisch***	***Gold standard***
Answer	S5/6/7	S6/7	S5/8
Score	1	0	
Surgical planning	***Monoscopisch***	***Stereoscopisch***	***Gold standard***
Answer	Wedge resec-tion	Sectionectomy	Hemi Right
Score	2	3	
Blood vessel involvement	***Monoscopisch***	***Stereoscopisch***	***Gold standard***
Answer	No	Right Portal Vein Anterior	Right Portal Vein Anterior and Poste-rior
Score	2	3	

For segment determination, the number of correctly and incorrectly identified segments is considered. In the monoscopic response, one segment (segment 5) is correct, so all incorrect segments result in only 1 penalty point each. Segments 6 and 7 are incorrect, resulting in two penalty points each. Segment 8 is missing, resulting in an additional penalty point. The final score is then calculated as 4 - 1 - 2 * 1 = 1.

In the stereoscopic response, no segment is correct, so one of the incorrect segments results in a 2 points penalty. Furthermore, two segments are missing, with gives additional 2 times 1 point penalty. The final score is then calculated as 4 – 2- 1 -1 -1 = lower than 1, thus the lowest score.

For the surgical planning, the difference in surgical degrees was considered. In this case, a wedge is 2 degrees off from a right hemi, and a sectionectomy is only 1 degree off. Monoscopically, the response thus receives 2 penalty points, while stereoscopically it receives 1.

G. Explanation Segment Scoring

Lastly, for blood vessel determination, two peripheral vessels (last degree in vessels) are provided in the gold standard. In the stereoscopic view, one peripheral vessel is missing, hence one penalty point is assigned, resulting in a total score of 3. In the monoscopic view, two peripheral vessels are missing, so two penalty points are assigned, making it 2. In this case, the answer "portal right" is considered entirely correct because with a slight interpretation, the right portal vein anterior and posterior together form the right portal vein.

- Segment 1 borders with: 4A, 2, and 8; it also diagonally borders with 4B and 5; 6, 7, and 3 are not adjacent.
- Segment 2 borders with: 3, 4A, and 1; it also diagonally borders with 4B; 5, 6, 7, and 8 are not adjacent.
- Segment 3 borders with: 2 and 4B; it also diagonally borders with 4A; 5, 6, 7, and 8 are not adjacent.
- Segment 4A borders with: segments 1, 2, 4B, and 8; it also diagonally borders with 3 and 5; 6 and 7 are not adjacent.
- Segment 4B borders with: 4A, 3, and 5, and diagonally with 8, 2, and 1; 6 and 7 are not adjacent.
- Segment 5 borders with: 8, 4B, and 6, and diagonally with 7, 1, and 4A; 2 and 3 are not adjacent.
- Segment 6 borders with: 7 and 5, and diagonally with 8; 1, 4A, 4B, 2, and 3 are not adjacent.
- Segment 7 borders with: 6 and 8, diagonally with 5; 1, 4A, 4B, 2, and 3 are not adjacent.
- Segment 8 borders with: 5, 7, 1, and 4A, and diagonally with 6 and 4B; 2 and 3 are not adjacent.