2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) | 979-8-3503-2838-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/ISMAR59233.2023.00114

LiVRSono - Virtual Reality Training with Haptics for Intraoperative Ultrasound

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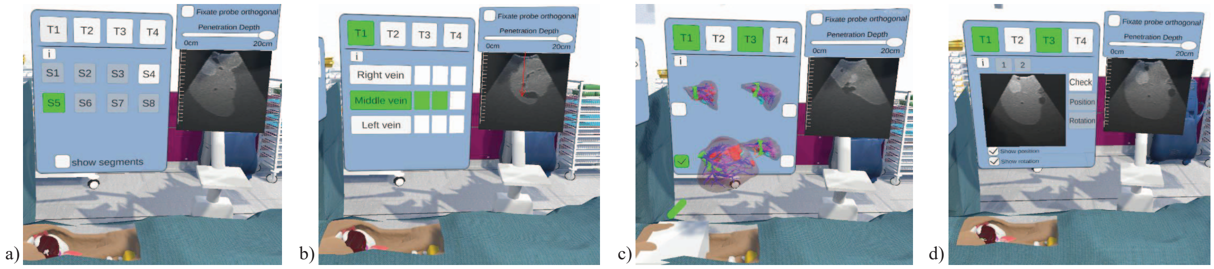

Figure 1: Immersive virtual reality training environment for intraoperative liver ultrasound. Training scenarios include (a) identification of liver segments, (b) scanning veins, (c) transfer of ultrasound to 3D model, (d) and probe handling.

ABSTRACT

One of the biggest challenges in using ultrasound (US) is learning to create a spatial mental model of the interior of the scanned object based on the US image and the probe position. As intraoperative ultrasound (IOUS) cannot be easily trained on patients, we present *LiVRSono*, an immersive VR application to train this skill. The immersive environment, including an US simulation with patient-specific data as well as haptics to support hand-eye coordination, provides a realistic setting. Four clinically relevant training scenarios were identified based on the described learning goal and the workflow of IOUS for liver. The realism of the setting and the training scenarios were evaluated with eleven physicians, of which six participants are experts in IOUS for liver and five participants are potential users of the training system. The setting, handling of the US probe, and US image were considered realistic enough for the learning goal. Regarding the haptic feedback, a limitation is the restricted workspace of the input device. Three of the four training scenarios were rated as meaningful and effective. A pilot study regarding learning outcome shows positive results, especially with respect to confidence and perceived competence. Besides the drawbacks of the input device, our training system provides a realistic learning environment with meaningful scenarios to train the creation of a mental 3D model when performing IOUS. We also identified important improvements to the training scenarios to further enhance the training experience.

Index Terms: Applied computing—Life and medical science—Health informatics; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Interaction devices—Haptic devices;

1 INTRODUCTION

Intraoperative ultrasound (IOUS) provides real-time information without ionizing radiation. It is used to locate and characterize lesions, evaluate the vasculature, assess the planned surgical margin, and guide operative procedures [26]. The ultrasound (US) probe is directly placed on the organ surface so that no overlying structures influence the image. Surgeries are carefully planned preoperatively; however, the intraoperative situation differs due to significant deformations of the organ. IOUS is also superior to preoperative data in terms of detecting small lesions.

The most common limitation of US is its operator dependence [13, 49]. The main challenge during the procedure is to build a mental model of the organ based on the US image and the position of the probe on the organ [13, 33], which is illustrated in Figure 2. Thus, the surgeon needs two skills. First, they need good hand-eye coordination. Second, they have to understand where on the US screen an anatomic structure is represented and link it to its respective location in the organ using a spatial mental model [13]. This hand-eye coordination and visuospatial skill can only be trained hands-on and the lack of proper training and education is often mentioned as a limitation of IOUS [13, 49, 50]. IOUS is used for example during surgery in the liver, kidney, pancreas, and during brain surgery [26, 31].

US training systems in general can either be physical, e.g. using 3D printed models [36], or virtual [35]. A physical phantom has the benefit of haptics and the US image can either be obtained by using an US-capable model and a real US probe, or a simulated US image using patient data such as computed tomography data. Because printing a 3D liver is expensive, it would be unfeasible to print many patient-specific livers. If only one non-patient-specific liver is used, there is either no variation or the US image does not fit to the physical model, leading to confusion when moving the probe on the liver surface. These restrictions do not exist for virtual systems, and haptics can be included by a haptic device. Using desktop-based systems, the trainee sees the virtual patient and probe representation on an additional monitor. This does not represent the real situation w.r.t. to the patient's position in relation to the user position and, thus, the hand-eye coordination. In an immersive virtual reality

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DOI 10.1109/ISMAR59233.2023.00114

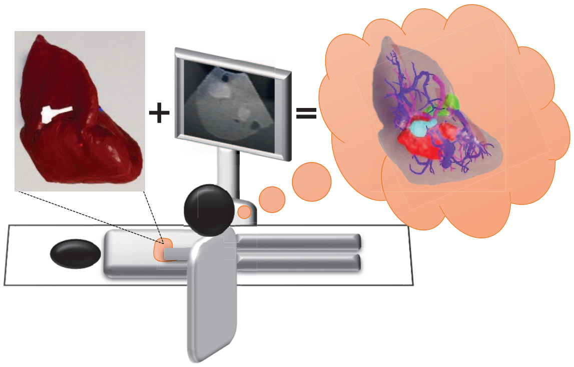

Figure 2: Illustration of the challenge to create a spatial mental model based on the US probe position and US image.

(VR) environment, this situation and hand-eye coordination can be simulated in a more realistic way. Furthermore, immersive VR and its realistic setting can improve the learning experience [16, 25, 28, 39] and can evoke realistic physical responses, as well as behavioral changes due to different environmental conditions [15].

To advance hand-eye coordination and manual skills, haptics play a crucial role. As the physician moves the US probe directly on the organ and is looking at the US image, the physician depends on the haptic feedback. This is particularly important because the surgeon has to apply light pressure to avoid air between the probe and the organ. Thereby, the hand position should be similar to the real hand position [3]. Consequently, we use the haptic device *Geomagic Touch* (3D Systems, United States).

We propose *LiVRSono* (**Li**ver **V**irtual **R**eality **Sono**graphy), an immersive VR training system for IOUS for the liver. IOUS is the gold standard for navigation during liver resection [19]. The creation of a patient-specific mental model of the liver anatomy is especially difficult due to the complex vasculature and interpersonal variations [46].

The main goal of training should be to increase performance and the transfer to the real situation. Before the training outcome can be evaluated, it is important to examine whether the training application itself emulates the real setting or at least the most important aspects that are relevant for the learning goal. Thus, face and content validity are investigated [8].

To provide a plausible and appropriate IOUS simulation for this use case, we contribute the following:

- We analyzed the learning goal *anatomical and 3D understanding and orientation* and workflow in detail with liver surgeons. The focus is on visuospatial skills and hand-eye coordination but not directly on probe manipulation such as learning an appropriate sequence of movements.

- We defined and implemented four training scenarios based on the intraoperative workflow and mental task.

- We evaluated *LiVRSono* with physicians with varying expertise regarding IOUS. The main part of the evaluation is a study focusing on the realism and the meaningfulness of the training scenarios. An additional pilot study serves to get first impressions of the learning outcome.

2 RELATED WORK

This section is divided into papers focusing on the US simulation itself and papers presenting training systems for US.

2.1 Ultrasound Simulation

To simulate US, there are *interpolative* and *generative* approaches. Interpolative simulations use prerecorded 3D US volumes that are resliced. In these approaches, differences between the actual US probe position and the position from where the image was acquired lead to an incorrect depiction of typical direction-dependent US artifacts, such as shadows [9, 12]. On the other hand, direction-independent features, such as tissue texture, are very realistic.

Generative approaches are based on other image modalities such as computed tomography or magnetic resonance data, or on mesh models. The methods vary significantly regarding accuracy and costs. Accurate and most realistic methods solve wave equations such as the Green's functions or Westervelt equation [20]. These methods require several hours to simulate the image. Less accurate but faster methods first create a slice and then simulate the US using for example texture synthesis with radial blur [29, 40, 51], convolution [10] or ray-tracing [24, 47]. There are also approaches combining different methods such as convolution and ray-tracing [6, 43], aiming to combine the advantages of both methods. Starkov et al. [45] combined the interpolative approach with ray-tracing for transvaginal US. In this case, the generated US image of the target structure is fused with a background US volume acquired in vivo.

Another approach uses ray-tracing with deep learning. Vitale et al. [48] use generative adversarial neural networks (GANs) that synthesize a new image based on an input image to simulate abdominal US. As input, they use CT data and a voxel-wise segmentation of the organs. Based on these, a ray-tracing approach is used to get a synthetic US image. The more realistic US image is then retrieved using a CycleGAN.

Methods using convolution or texture synthesis are the most performant ones. Ray-tracing approaches can be interacted with in real-time, however, a frame rate of about $15-30 fps$ [6, 45] might be sufficient for desktop applications but not for immersive VR.

The choice of an appropriate approach is highly dependent on application-specific requirements. For example, the training of the diagnosis of non-obvious lesions, or the understanding and perception of minor differences in US images require realistic simulations. Our focus is on gaining an overall orientation, anatomical understanding, and interpretation of the US image. Therefore, we decided to use a fast, texture-based approach suitable for real-time interaction in a VR application. However, we made sure that the US simulation is plausible enough to enable proper training by continuously including expert feedback in the development process.

2.2 Virtual Ultrasound Training

Besides intraoperative liver US, there are also other areas like obstetrics and gynecology [37], where US training via virtual simulations is beneficial. Multiple studies [2, 27] ascertained that after training with the Scantrainer (Medaphor^{TM}, Cardiff, UK), the performance of transvaginal US examination was increased. This is a desktop-based simulator with two monitors and an US probe. One monitor displays the US image and the other monitor shows a virtual patient and the probe position on the abdomen.

US-based needle interventions also require careful training. Mastmeyer et al. [29] focus on simulating a realistic US for US-guided needle insertion including breath and deformations. By investigating the use case of US-guided biopsy, Ni et al. [32] use the haptic device *Phantom Omni* as the US probe and a *Phantom Premium* for the needle in combination with a PC desktop environment. A similar haptic device, the *Geomagic Touch*, was also used by Barnouin et al. [4] in their simulation for needle insertion. They also concentrated on simulating realistic US using textures and ray-tracing and included tissue deformations by using displacement functions.

Orr et al. [35] investigated the impact of integrating transabdominal US simulators in the curriculum. Their performance assessment included general skills, such as the use of equipment, hygiene, and ergonomics, as well as US techniques. For liver US, the skills were among others scanning the whole volume, acquiring images in different planes to maximize visualization, and identifying the portal vein with color Doppler. The group using the simulation shows significantly higher confidence regarding obtaining diagnostic images of the liver and identifying pathologies than the control group.

In contrast to the desktop-based approaches, Bublak et al. [5] present an immersive VR training in combination with phantoms. They focus on combined training of cardiopulmonary resuscitation and US imaging. Physically separated users, each with their own phantom, are brought together in one virtual environment, working together on the same virtual patient. Thus, the training focuses on communication skills. For the US simulation, the hardware from *Schallware* (Schallware GmbH, Berlin, Germany) is used. A semi-immersive VR US-guided liver biopsy simulator using a semi-transparent mirror was presented by Johnson et al. [18]. They focus on task analysis and appropriate performance metrics. Jacobsen et al. [17] presented an immersive VR system including a test for core competencies in contrast-enhanced US.

In summary, most existing work regarding US training is in gynecology and US-guided interventions. Furthermore, most works focus on either the US simulation itself or on the performance and learning outcome when integrating it to the curriculum. The latter evaluates the general handling based on tasks that are directly transferred from the clinical routine such as scanning the volume or identifying the portal vein. However, only a few approaches focus on US training directly addressing visuospatial skills. Simon et al. [44] identified the lack of training focusing on hand-eye coordination in the case of US-guided needle intervention for anesthesia. To manipulate the US probe and needle, they used two *Geomagic Touch* devices. They evaluated the face and content validity using non-validated questionnaires, revealing moderate to positive results for face validity and positive results for content validity. Their training simulates the medical workflow; however, there are no specific tasks that the user has to solve. Thus, no feedback and guidance are provided. Law et al. [23] also recognized this gap and focused on including a didactic system to an US simulator. Besides the US simulation, their desktop application comprises 3D anatomical models, haptic feedback (*Phantom Omni*), and an annotation system for didactics. The annotations provide labels for all anatomical structures that are currently visible in the US image. An US training game that only focuses on the visual-spatial relations without any medical context is presented by Mayer et al. [30]. Using a standard PC desktop and mouse and keyboard input, they introduce four minigames:

- Identify the correct scene with 3D models using US.
- Identify the correct US image without seeing the scene.
- Identify the correct US probe position and rotation that creates the given US image.
- Identify the probe movement to recreate a given US image.

With these tasks, they want to improve the understanding of the correlation of the US probe and the resulting image, the transfer of the 2D image and 3D anatomy, as well as the understanding of the probe movements and the resulting changes in the US image. As *LiVRSono* has a similar learning goal, our training scenarios were partially derived from their tasks and were adapted to the specific medical use case. A similar work is presented by Byl et al. [7]; however, their game is VR-based. A more abstract desktop-based game is presented by Olgers et al. [34]. Here, the players have to collect hidden coins in an underwater world.

These three games support learning the basic understanding behind US. Nevertheless, this should be followed by a specialized training using complex anatomical structures to become familiar with the application-specific workflow and landmarks.

Similar to these four approaches, we aim at targeting the challenge of creating the spatial mental correlation of the US image and the 3D model. In contrast to Byl et al.'s [7] immersive VR training and Mayer et al.'s [30] and Olgers et al.'s [34] desktop-based learning games, our system and training scenarios emulate the real situation including probe handling and, thus, hand-eye coordination as well as visuospatial skills in an immersive surgical setting. In the proposed prototype, we focused on the clinically relevant application IOUS in liver surgery.

3 DESIGN AND DEVELOPMENT OF AN ULTRASOUND-BASED TRAINING

In the following, we describe requirements, the US simulation, and the whole training system including the different training scenarios.

3.1 Requirements

The requirements for *LiVRSono* were established based on intensive discussions with our clinical development team with different levels of experience in IOUS. Thereby, different implementations of haptic feedback and important aspects of the US image were considered. For a better understanding, we were also allowed to watch a real IOUS procedure.

The requirements can be classified into two categories: plausibility and training.

Plausibility This refers to the US simulation, the handling, and the setting. The most important part of any training is that it includes the relevant aspects in a plausible way. In our case, the US image should exhibit the main artifacts and should have a similar appearance, but aspects such as the exact gray values are less important for spatial understanding. Furthermore, the handling of the US probe should be similar to the real one. This includes haptics to perceive the curvature of the surface as well as a real hand position. Finally, the setting should be similar to a real surgery, meaning that the user should stand next to the patient's abdomen with the US monitor on the other side of the patient. Thus, the following requirements arose:

R1 The US simulation should be plausible, including a proper image section, the most relevant artifacts, and the main functionalities such as depth regulation.

R2 The user should be able to move the US probe in a realistic manner and there should be haptic feedback when touching the liver surface.

R3 The whole setting in the VR environment should be similar to a real setting.

Training This requires appropriate training scenarios and the assessment of the user's performance. Consequently, there is an additional requirement:

R4 The training should include training scenarios that vary in regards to their anatomical focus or mental transfer, but they should all require the building of a mental model and spatial orientation.

3.2 Ultrasound Simulation

In consultation with our team of medical experts, we decided on using rigid models to reduce complexity. Otherwise, realistic deformation and interaction with the deformable liver would be necessary. Furthermore, the US simulation also has to automatically adapt to the current shape of the model leading to a much higher computational effort. This would be more relevant for a realistic handling of the liver and surgical procedure than for our learning goal.

Our real-time US simulation uses 3D surface models that are also displayed in the virtual environment. The whole procedure is summarized in Figure 3.

3.2.1 Generation of 3D render texture

To simulate US during runtime, a 3D render texture is required. This texture is created using the anatomical 3D models. The texture is aligned with the bounding box of the liver and each voxel is assigned a corresponding tissue type. This is done by casting a ray starting from the voxel. The first object it hits from the inside is the object or tissue it belongs to. The gray values are approximated using real US images as a template leading to the allocation of RGB values shown in Figure 3b. This preprocessing step has to be done once for each patient that is included.

3.2.2 Slice shader

The render texture is used to simulate the US image via shaders. First, a slice representing the current US image has to be created. This is done based on the current US probe position and orientation. The position is mapped to the bounding box and is scaled to the range of $[0,1]$. Then the field of view is adapted to match a common US image. A texel T_{ij} lies within the field of view if it meets the following two conditions:

$$(-v1_i * (T_j - S1_j) + v1_j * (T_i - S1_i)) < 0 \tag{1}$$

$$(-v2_i * (T_j - S2_j) + v2_j * (T_i - S2_i)) > 0 \tag{2}$$

If both conditions are fulfilled, the texel T_{ij} lies between the two vectors $v1$ and $v2$ defining the trapezoid together with the two upper corners $S1$ and $S2$. The trapezoid depends on the probe size s and the angle α. (refer to Figure 3c).

3.2.3 Attenuation

If the conditions 1 and 2 are met, attenuation is included based on the exponential function:

$$I^k_\alpha = I^k_i e^{-\beta d f} \tag{3}$$

where I^k_i is the intensity of the incoming beam and I^k_α of the output beam. β is the absorption coefficient of the material, d the distance traveled in the material and f the frequency of the wave. Because we do not use material-specific parameters, we use a general absorption coefficient, the length to the current texel ST_{ij} and the penetration depth p, which is inversely proportional to the frequency, to simulate the attenuation. The resulting slice is shown in Figure 3c.

3.2.4 Reflections

Reflections occur at boundaries of tissues of different acoustic impedances. The larger the difference, the more reflection occurs. The reflection also depends on the angle of incidence. A wave hitting the interface perpendicularly results in the highest reflection. If the angle is smaller, the wave is deflected away from the probe. We neglected tissue information and therefore our reflection shader calculates the absolute difference between the current texel and the texel above. The texel above T_{above} is not $T_{i,j+1}$ but the texel lying on the vector between the current texel T_{ij} and the US probe S_{ij}: $T_{above} = T_{ij} + (S_{ij} - T_{ij}) * TexelSize.j$. The output (see Figure 3d) is then added to the image.

3.2.5 Noise shader

In the next step, noise is added to the US image. US images exhibit a so-called speckle noise. Because of the inhomogeneity of tissues, waves are scattered, leading to interferences that create the speckle pattern. Consequently, different soft tissues and diseases cause different speckle patterns [11]. Since we disregarded tissue information, a general noise was added. Inspired by Mastmeier et al. [29], Perlin noise [38] was used. [1] Using the same origin and axes as for the slice shader, a single noise slice is created and the corresponding texels of the main texture and noise texture are multiplied (see Figure 3d).

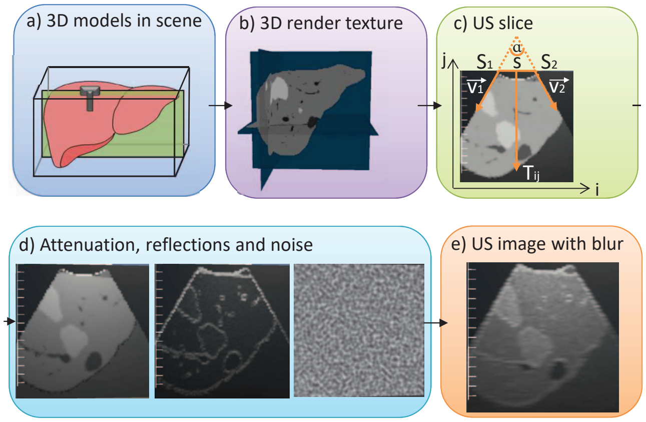

Figure 3: Simulation of real-time US based on 3D models.

3.2.6 Blur shader

The lower the frequency, the larger the penetration depth and the more blurry the image is. Thereby, the blur is also increasing with distance to the probe. In our medical case, $5MHz$ is usually used [22]. To simulate this, a 1D horizontal blur that scales with the texel distance to the probe and the current penetration depth was added.

The last part of creating a realistic US is to zoom the image so that only the part within the current depth is visible. The scale also has to be adapted to show the size of one centimeter.

Shadows are also a typical component of US images. However, as they appear behind bones or air and, thus, are not crucial in intraoperative liver US, they were neglected after consultation with liver surgeons. The final US image can be seen in Figure 3e. With the described slice shader, attenuation including depth regulation, and the other artifacts, we meet *R1*.

3.2.7 Ultrasound Probe

To address *R2*, the user can move an US probe using the *Geomagic Touch*, on the liver of a patient approximated by a torso [21]. The *Geomagic Touch* has six degrees of freedom (DoF) of movement, three DoF for force feedback, and a workspace of approximately $160W x 120H x 70D\ mm$; thus, a restricted workspace compared to a real US probe. As the input device is pen-like and the US probe is not held like a pen, we printed an attachment to enable a more realistic hand position (see Figure 4). Instead of using a haptic device we also considered a printed liver. We discarded this idea during the development of the current prototype because one has to either print many livers or use one liver; in this case, however, there is a mismatch between the haptic feedback and visual feedback when using different virtual liver models.

For the haptic feedback we used the *Haptics Direct for Unity V1* from *3D Systems* and assigned a haptic material with a stiffness of 0.073 to the liver surface. This value was determined with the clinical development team. The device has a nominal position resolution of $> 450dpi$ and a refresh rate of $1kHz$.

We did not include virtual hands because only the position of the US probe is relevant and studies revealed that visualizing hands is not necessary when performing motor tasks in VR [41].

3.3 Learning Environment

In *LiVRSono*, the user is situated in a virtual operating room adapted from Huber et al. [16]. To fulfill *R3*, an US monitor was modeled

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[1] K. Takahashi, Perlin Noise for Unity (2015): https://github.com/keijiro/PerlinNoise

Figure 4: *Geomagic Touch* Device with a 3D printed attachment mimicking the US probe.

and placed according to a real scenario. In summary, the learning environment addresses the following aspects:

- Building a spatial mental 3D model
- Understanding and interpreting (with respect to anatomical understanding, not diagnosis) the US
- Orientating within the liver using US
- Hand-eye-coordination.

Direct interactions with the liver, such as slightly lifting it, and feeling different health states would require very realistic deformations and haptics and is not addressed by our training system.

We identified four scenarios based on the learning goal and the tasks proposed by Mayer et al. [30]. The scenarios and their suitability for liver surgeons were discussed with medical experts of varying levels of experience. *Scenario 1* and *scenario 2* are based on the IOUS workflow which consists of the three steps (1) identification of hepatic veins, (2) identification of portal veins and their branches, and (3) the systematic scanning of the whole liver parenchyma [1,13], whereas *scenario 3* and *scenario 4* focus on the spatial mental model. All scenarios can be seen in Figure 1 and the supplementary material. The order of the scenarios was chosen based on their level of difficulty after consultation with the experts and not according to the IOUS workflow. Consequently, the first scenario refers to the third step of the workflow and the second scenario to the first two steps.

Scenario 1 This scenario focuses on the systematic scanning of the whole liver parenchyma. In order to train procedural skill and hand-eye coordination, the user has to scan and identify all segments (see Figure 1a).

Scenario 2 Finding and following important anatomical structures trains the anatomical understanding and deduction of 3D anatomical structures from 2D US images, as well as the orientation within the liver. Although for *scenario 1*, one also has to find the vessels for identifying the segments, *scenario 2* was rated as more difficult because of tracing the vessels. Therefore, it was placed as the second scenario and not as the first scenario which would be in accordance with the IOUS workflow (see Figure 1b).

Scenario 3 The deduction of 3D models from 2D US images is also trained with the third scenario. Based on Mayer et al.'s [30] learning tasks, the user has to scan an invisible liver and has to determine which 3D liver model corresponds to the US images. In order to prevent the user from determining the correct liver based on the liver surface and outer appearance, a white cube occludes the liver in the abdomen (see Figure 1c).

Scenario 4 With the last scenario, users can train interpreting an US image, as well as the relation between probe position and orientation and the US image. This scenario is a combination of learning games two, three, and four of Mayer et al. [30]. In our scenario, one US image is given; the user has to interpret the image and create a mental model to place the US probe in the immersive VR environment in the same position and orientation to reproduce the image (see Figure 1d).

4 EVALUATION

During the development, the US simulation was assessed by a resident several times to adjust the different artifacts, such as the amount of noise and blur. Despite this, the focus of this evaluation is to investigate whether *LiVRSono* would be useful as additional training. Before the learning outcome and training effect can be evaluated, the application has to be assessed regarding its general suitability. We concentrated on two aspects that were also relevant regarding the requirements: plausibility and training.

An expert study was conducted with eleven medical experts with varying experience regarding IOUS. Consequently, we gained feedback from six experts of IOUS that can rate the plausibility, and from five persons belonging to the target group of the training system. The experiences and demographics are summarized in Table 1. The limited number of participants is caused by the specific use case that requires more knowledge and practical experience with surgical liver resection than a medical student has. Complex liver surgery is very demanding. Thus, only a subset of experienced surgeons performs this type of surgery. Because of the limited number of participants and to get in-depth feedback, we decided to include a qualitative analysis.

Additionally, we conducted a short pilot study to get an impression of the training effect using *LiVRSono*.

4.1 Apparatus

For the implementation and the study, the HTC Vive Pro Eye (HTC Corporation, Taiwan) was used. The studies were conducted with a laptop with the following properties: NVIDIA GeForce RTX 2080 Super with Max-Q graphics card, Intel Core i7-10850H 2.70GHz CPU, and 32GB RAM. Once the 3D render texture is precalculated, scanning the liver with the *Geomagic Touch* and using described US simulation is possible with about 90fps.

4.2 Setup and Procedure

4.2.1 Expert Study

Each expert first became familiar with the VR environment, haptic device, and interactions. Keeping the learning goal in mind, they had to rate the plausibility of the virtual environment, handling of the US probe, haptic feedback, and US image using a 5-point Likert scale. The exact questions and procedure are provided in the supplementary material. They were also encouraged to think aloud and to mention problems, as well as positive aspects. In the second part, they had to go through the four scenarios to state whether they are helpful for the learning goal using a 5-point Likert scale. Thereby, they were again encouraged to mention improvements.

4.2.2 Pilot Study - Learning outcome

For the additional pilot study regarding learning outcome, we had six non-medical participants. This limited number was because we want to reserve the target group, which is difficult to recruit, for a large study assessing the learning outcome and comparing it to the current learning method. Before such a study is possible, appropriate cases, difficulties, and feedback from this evaluation have to be included. Because of this, we only used the third task, which was also rated the best and which does not require anatomy knowledge.

Table 1: Characteristics of experts ($n = 11$).

Characteristics	Value	Mean
Age [years, mean (range)]	[28-59]	42
25-34	3	(27%)
35-44	4	(36%)
45-54	2	(18%)
55-64	2	(18%)
Gender		
Male	6	(55%)
Female	5	(45%)
Medical Experience		
Resident	3	(27%)
Specialist	3	(27%)
Attending	4	(36%)
Chief physician	1	(10%)
IOUS Experience		
None	2	(18%)
5-20 times	3	(27%)
More than 200 times	2	(18%)
More than 1000 times	4	(36%)
Experience with VR		
None	2	(18%)
Less than 15 times	6	(55%)
More than 15 times	3	(27%)

The six participants had a pre-test, three training sessions with four tasks each plus repetition of the previous sessions on following days, and a post-test. Due to technical problems during the first test, we had to conduct a similar test before starting the second training session, which we will refer to as ’pre-test’. The procedure can be seen in the supplementary material. During the tests, errors and time per task were recorded and they had to answer questions based on the competence item of the standardized intrinsic motivation inventory [42] plus two additional questions with a 5-point Likert scale (refer to the supplementary material). Before each test, the participants were told that both error and time are measured, but also that it was more important to be right than to be fast.

4.3 Results

4.3.1 Expert Study

Plausibility In general, the setting as well as the US were rated as realistic, which can be seen in Figure 5. Regarding the general setting, some participants mentioned that it would be better and easier if the US monitor was more to the left or directly in the viewing direction. However, the current setup is similar to the intraoperative setting. It was also mentioned that the monitor position could be a way to include various levels of difficulty. Regarding the virtual patient, the abdomen should be opened further to reveal the whole liver. In Figure 1, it can be seen that the liver was partially covered.

The 3D printed attachment simulating an US probe was sometimes mentioned positively, but experts also emphasized that they used a different one and that the real probe was more cumbersome to handle. One problem regarding the US probe was that the device juddered when there was an indentation on the liver surface. However, the main problem was the restricted workspace. Because of this, experts in particular were not able to scan the liver in the same way they would during surgery. Another aspect concerning the input device was the height. To enable a proper height of the device, it should have been placed on a height-adjustable surface.

The haptic feedback was the least realistic aspect; however, many participants who rated it as not realistic mentioned that it is still supportive and better than without haptic feedback. Only one participant would prefer to have no haptic feedback.

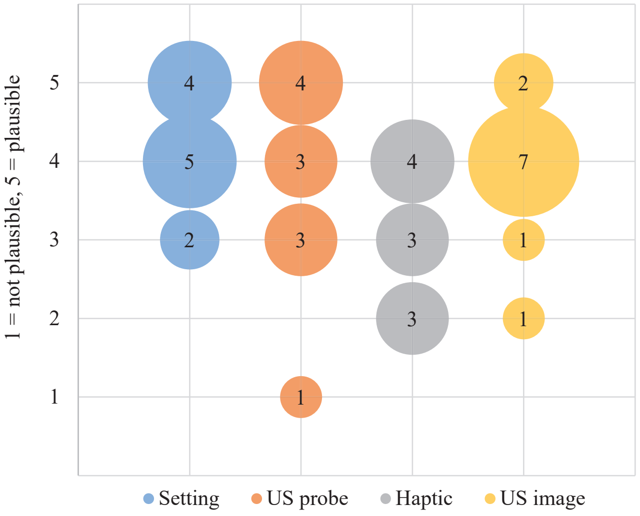

Figure 5: Rating of the plausibility of different aspects.

Feedback regarding the US image was very positive. Some experts mentioned that it should be less noisy and edges should be a bit sharper. Two aspects should be improved to increase realism. First, the US image should only be visible if there is contact with the liver surface. Second, it is possible to rotate the probe around its longitudinal axis. This is not possible to such an extent in real life, and the behavior of the simulation was not correct. This was recognized by some of the experts.

Training Scenarios The detailed rating of the scenarios is summarized in Figure 6. Nearly all participants appreciated the first scenario. To further improve the learning experience, some participants suggested the possibility of seeing all liver segments. This could also be included in an additional training room where the liver could be inspected using transparent colors and grabbing interactions. For more clinical relevance, one participant suggested modifying the scenario so that the user has to indicate in which segments metastases are located.

In general, the second scenario was rated as effective. However, there are two important aspects that have to be changed to enable proper training. It was very difficult to place the segments of the vein in the middle of the US image. Instead, it was suggested to point and click on the corresponding vessels using the controller. As mentioned before, the workspace of the input device is limited. Due to this, experts in particular were not able to trace the veins using the method they use during surgery.

The third scenario was the most preferred one. Comments show that the white cube occluding the liver model is not relevant, especially when using more similar cases. Various difficulties could be included if cases with different amounts of metastases are used or if cases with different courses of vessels are used. Furthermore, the liver models in the menu should be rotated because during surgery the liver is seen from ventral and not dorsal perspective.

The last scenario was mostly rated as inappropriate. The reason given for this was that there was no benefit in simulating a given US image. Sometimes it is also possible to create a very similar image or an image showing the same relevant structures without having the probe at the same position. Alternatively, a scenario to count metastases or to show a given structure would be more effective and clinically relevant. In this context, some participants mentioned including CT data, because surgeons usually have a mental model of the liver based on the preoperative data. Accordingly, a scenario could also be to find metastases that are not visible in the CT data.

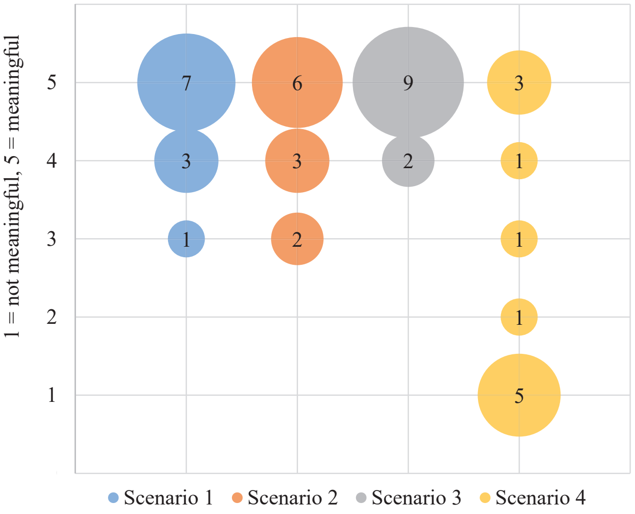

Figure 6: Rating of meaningfulness and efficacy of scenarios.

Table 2: Errors (E), the average time (t) per liver scan in seconds of the pre- and post-test, and the competence difference (Comp_{diff}).

	E_{pre}	E_{post}	t_{pre}	t_{post}	t_{post} - t_{pre}	Comp_{diff}
P1	3	1	26	24	-2	0.875
P2	4	1	41	72	31	1.375
P3	0	0	29	24	-5	0.125
P4	0	0	80	40	-40	0.625
P5	2	0	58	41	-17	1.375
P6	0	0	32	29	-3	0.75

4.3.2 Pilot Study - Learning outcome

In the pilot study, three participants had no errors in the pre-test as well as in the post-test, which consisted of 12 tasks each. Three participants reduced their errors: from three to one, from four to one, and from two to zero. Additionally to reduced or constant errors, five participants were also faster in the post-test by $13.4s$ on average per liver scan. One participant needed $30s$ more on average per liver scan. However, this participant reduced their errors from four to one, which is more important than being fast. The detailed results are summarized in Table 2. Using the eight questions q_n, the competence difference between the pre- and post-test is calculated by:

$$Comp_{diff} = \frac{\sum_{n=1}^{8} q_{n,post} - q_{n,pre}}{8} \tag{4}$$

All participants had an increased competence (see Table 2). All participants answered the question regarding perceived improvements of their US skills with a 5. For the question regarding applying their skills, three participants gave a 4 and three gave a 5.

Three participants used the comment field to emphasize that repetitions were very helpful in producing a learning effect, that they recognized their perceived learning effect and had an increased confidence in performing the US, and that they developed strategies on their own. They also stated that especially small differences in lesion positions such as the height within the liver were much easier to identify after the training sessions.

4.4 Discussion

4.4.1 Ultrasound Simulation

As emphasized in Section 2, our simulated US image is not complex and does not include, among other things, deformations. Nevertheless, the image was rated as realistic enough for our learning goal, showing that a fast simulation can be used for training. The US simulation can be further improved by requiring contact with the liver, less noise in the image, and restricting the probe rotation along the longitudinal axis. Although most participants appreciated the US image and its quality, some mentioned that the image, especially the edges, is blurred too much. Because of this varying subjective feedback, directly comparing the US image with a real image might be helpful in giving a more objective result.

Similarly to Simon et al. [44], our evaluation revealed that the haptic feedback is the main limitation of face validation. Although the haptic feedback does not realistically simulate touch sensations from a real liver, nearly all participants stated that the haptic feedback is supportive. The mentioned jiggling and limited workspace are distracting and also limit the user's performance. For an appropriate training, it is crucial to solve these drawbacks. This can be done by either setting the initial device position such that the whole liver can be reached, or, alternatively, scaling the movement. However, this is only possible to a certain degree while still preserving realism and an appropriate level of difficulty. If this is not possible, another input device or haptic feedback simulation might be more useful, and alternative products such as the *Emerge Wave-1* (Emerge Now, Inc., California) should be considered in the future. Furthermore, a direct comparison of having haptic feedback versus no haptic feedback should be considered. The drawbacks of using a 3D-printed liver were already discussed in the introduction. However, one could investigate the impact of the mentioned mismatch of the printed and virtual models and compare the two input modalities. Using no haptic feedback might work with the current state. However, when considering the requirement that the probe has to have contact with the liver surface to create an US image, it will probably be very difficult and exhausting to scan the liver.

Most participants rated their position in relation to the patient and to the US monitor positively. The height of the input device was sometimes not appropriate. This can be solved by using a height-adjustable surface, as the operating table is also adjusted to the surgeon's height. Some participants also mentioned that they would prefer to have the monitor in their field of view, which would differ from the real setting. Including different monitor positions might be a way to include varying difficulties. Having the monitor not in the field of view is much more difficult due to hand-eye coordination. This is a great benefit of VR: the three components – patient, user, and monitor – can be arranged in the correct way. Using a normal desktop, such as in Law et al. [23], cannot provide this. Only Byl et al. [7] provide an immersive VR environment; however, here the user did not have to handle an US probe.

4.4.2 Training Scenarios

Three of four scenarios were rated as helpful with minor improvements As there is no clinical benefit to the last scenario, and the handling of the US probe can also be learned with other scenarios, it is recommended to remove or replace this scenario. In a simpler setting such as in Mayer et al. [30], this scenario might work, but in a liver with many vessels and metastases, different probe positions and rotations might also lead to similar images. Some participants mentioned that they would prefer a scenario where the user has to find either all metastases or a specific one. For this scenario, the user has to scan the whole liver. Thus, they need a good orientation and understanding to differentiate whether a metastasis is a new one or one they have already scanned but seen from another perspective. This would also have a high clinical relevance because there are metastases that are not visible in the CT data and therefore have to be found with US. Alternatively, this could be included in the first scenario. Instead of simply stating which segment they are scanning, the user could also have to count the metastases in the current segment.

Another aspect of a meaningful training are the included medical cases. Although *LiVRSono* includes four cases, only one case was used for the evaluation due to time restrictions. This case is difficult for the first scenario because the gallbladder was already removed. In everyday clinical practice, the gallbladder is used for orientation within the liver, since it attaches to segment five of the liver. The four liver cases are very different in regards to their diseases (such as the number of metastases leading to a relatively easy third scenario). It was not part of the evaluation to include appropriate training cases regarding anatomy and difficulty, but this might be considered for further studies assessing, for example, the learning outcome.

4.4.3 Evaluation

Regarding the expert evaluation, we stuck to questions directly referring to the application instead of using standard questionnaires like questionnaires concerning usability or task load. The reason for this was the very limited time of surgeons. It was not possible to include more questionnaires and, thus, we preferred the direct questions over the more general ones. Furthermore, we assume that if the usability as well as technical aspects would not be sufficient, the participants would mention this as we used the think-aloud method and their task was to assess the quality of the training application. Questions referring to the mental and physical load would also only be beneficial in comparison to the real IOUS, otherwise, a high load could indicate that the application is too difficult or it could reflect the real situation. However, in a large user study comparing the training to a control group, these standardized questionnaires are recommended. It is also necessary to emphasize that this study only assesses face and content validity and that the questionnaires used are not validated. Further studies must be conducted to evaluate other types of validity such as construct validity, or content validity. Aside from validity, the fidelity of the simulation could also be assessed [14].

In the pilot study we did not include difficult tasks where the exact position of a lesion (in relation to the vessels) has to be determined because of the missing medical background of the participants. Due to the reduced difficulty, the ceiling effect could be observed as three participants had no error in the first test (and also the second test). However, the reduced time, errors, and the questionnaire in particular showed positive results regarding the increased confidence and competence. Comments emphasize the learning effect regarding spatial orientation and exact lesion positions in particular. The study reveals that something new can be learned after training with the system. Since the tasks require visuospatial skills, it can be hypothesized that these are trained. However, further studies are necessary to confirm whether this target skill can be learned and to investigate whether it can be transferred to the real procedure using statistical analyses. This will be described in future work.

4.4.4 Generalization

As described in the introduction, IOUS is also used for other applications than the liver. Although our application is specialized on the liver, some aspects might be generalizable to other applications. In other organs such as the pancreas or kidney, IOUS is also used to identify tumors, metastases, or other anatomical structures like the duct. Consequently, the third training scenario with its possible variations that we discussed previously is applicable. The first two scenarios are specialized on the liver and might be removed or adapted for other organs.

4.4.5 Future Work

In Table 3, we summarize the main aspects that should be improved to enable a proper training environment.

Table 3: Summary of the main future work.

	Improvements
US image	Sharpen edges, reduce noise
Haptic	Smooth the surface, workspace
Probe	Add more and different US attachments
Setting	Adjust the height of input device
Scenario 1	Show segments for learning
Scenario 2	Remove arrow
Scenario 3	Change liver orientation
Scenario 4	Remove or replace

Furthermore, a training system requires different levels of difficulty. These can be included by incorporating:

- different sizes, locations, and amount of metastases,
- different levels of the information shown to, or asked of, the users. For example, whether the users have to differentiate the livers in the third scenario based on the amount of metastases, their location or simply based on the vessels. In the second scenario, the precision of tracing the veins could be varied.
- further scenarios, such as measuring the size of a metastasis or showing its relation to vessels, and
- including cases with common anatomical variations and cases with rare anatomy.

After including varying difficulties, future studies should assess the learning outcome with the target group when using *LiVRSono* over a longer period. By comparing a group regularly using *LiVRSono* to a control group with no additional training, one could measure whether the aspects described in Section 3 could be the result of learning from the system. Furthermore, it should be investigated whether the learned skills can be transferred to real IOUS. This follow-up study requires a large organizational effort because regular training sessions have to be included in the clinic routine and proper pre- and post-tests have to be set up. For assessing the transfer of what was learned, one probably has to create a physical dummy as real patients should not be used due to the anatomical variations and, thus, varying difficulties and the missing ground truth.

As emphasized in the introduction, *LiVRSono* focuses on IOUS for liver but addresses the general need to train visuospatial skills for US and the lack of training possibilities for IOUS. In the future, our training system can be adapted to other applications, such as IOUS for the kidneys or pancreas. The adaptation would include adjusting the grey values of tissues (if necessary) and replacing workflow-related training scenarios.

5 CONCLUSION

With *LiVRSono*, we address the need for training systems to train the mental skills that are necessary for IOUS. The proposed immersive VR system for liver surgeons benefits from a real-time US simulation, a modified haptic input device, as well as a virtual operating room, which improve the learning experience by providing a setting similar to the real situation. Furthermore, training scenarios were identified based on the application-specific workflow and the transfer between the US image and 3D anatomy. Using this system, we identified drawbacks of the chosen input device, as well as important improvements of the training scenarios to enhance the training without harming real patients.

ACKNOWLEDGMENTS

This work is partly funded by the BMBF within the Forschungscampus *STIMULATE* (grant no. 13GW0473A) and partly by the federal ministry of education and research (16SV8057 ’AVATAR’).

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