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ORIGINAL ARTICLE

Use of mixed reality for improved spatial understanding of liver anatomy

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ABSTRACT

Introduction: In liver surgery, medical images from pre-operative computed tomography and magnetic resonance imaging are the basis for the decision-making process. These images are used in surgery planning and guidance, especially for parenchyma-sparing hepatectomies. Though medical images are commonly visualized in two dimensions (2D), surgeons need to mentally reconstruct this information in three dimensions (3D) for a spatial understanding of the anatomy. The aim of this work is to investigate whether the use of a 3D model visualized in mixed reality with Microsoft HoloLens increases the spatial understanding of the liver, compared to the conventional way of using 2D images.

Material and methods: In this study, clinicians had to identify liver segments associated to lesions.

Results: Twenty-eight clinicians with varying medical experience were recruited for the study. From a total of 150 lesions, 89 were correctly assigned without significant difference between the modalities. The median time for correct identification was 23.5 [4–138] s using the magnetic resonance imaging images and 6.00 [1–35] s using HoloLens ($p < 0.001$).

Conclusions: The use of 3D liver models in mixed reality significantly decreases the time for tasks requiring a spatial understanding of the organ. This may significantly decrease operating time and improve use of resources.

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Liver surgery; parenchyma sparing; segmentation; 3D model; mixed reality

Introduction

Colorectal cancer is the third most common type of cancer and approximately 23% of the patients have metastasization at the time of diagnosis [1,2]. The liver is the most common location for metastases with 70% of the cases [3]. Liver resection is considered to be the only potentially curative treatment for resectable colorectal liver metastases. Liver resection can be performed as open or laparoscopic surgery, which changes the surgeon's perspective of the organ by directing it through a camera inside the abdomen. This camera view is used by the surgeon to establish understanding of the working area and safely manoeuvre the tools. The treatment strategy is gradually moving from anatomical resections to parenchyma-sparing liver resections.

Parenchyma-sparing liver resection is as safe as and efficient as traditional anatomical resection [4]. The parenchyma-sparing approach allows radical resection preserving more of the healthy liver parenchyma, thereby decreasing the risk of postoperative liver complications and liver failure and facilitating repeated resections in the case of recurrence [5]. A recently published article, based on a randomized control trial, supports that in patients undergoing parenchyma-sparing liver resection for colorectal metastases, laparoscopic surgery is associated with significantly less postoperative complications, shorter hospital stay and more cost-effective compared to open surgery [6].

Currently, surgeons rely on pre-operative images such as contrast-enhanced computed tomography (CT) and/or magnetic resonance imaging (MRI), which are used for clinical decision-making, as well as

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for surgery planning and guidance. These volumetric images are visualized in two dimensions (2D) and mentally reconstructed in three dimensions (3D) for a spatial understanding of the lesion and the vessels.

As a step prior to liver surgery planning, the surgeons need to understand the location of tumors by identifying the liver segment containing the tumor. These liver segments are traditionally based on the Couinaud classification of the liver, which is well-known and taught in the medical schools [7]. The task of determining the segment is accomplished by going through the different slices of the image and looking for liver vessels, as guidelines for the division of the liver into different segments. This requires a high level of spatial understanding of the lesion and surrounding anatomical structures and, in many cases, can be time-consuming, especially if it is a borderline case or atypical liver anatomy.

Medical image segmentation is an image-processing technique where different anatomical structures are marked separately for analysis and posterior reconstruction into 3D models. The process of segmentation requires specialized software tools that take volumetric data as input. The process can be either manual (high degree of user interaction), semi-automatic (reduced degree of user interaction) or fully automatic (no user interaction). Liver analysis application is one such tool available through Siemens syngo.via platform (Siemens Healthcare, Erlangen, Germany) [8]. These segmentations are exported to the PACS systems as an image sequence where the movement is limited by predetermined viewing angles or rotation paths. This limitation can be a disadvantage if the requested viewing angle is not available. However, a 3D model can be moved, rotated and shown from different perspectives and give the user full freedom. The easiest and probably the most common way to interact with these models is by using a computer with a 2D display, a mouse and a keyboard. A possible improvement to the visualization is to use a 3D display, with polarized glasses, which would provide a perception of depth to the image.

A more advanced way of visualizing and interacting with the liver models is to use head-mounted displays in either virtual or mixed reality.

In virtual reality, the user is placed in a fully computer-generated environment. This allows the user to view 3D models with understanding of depth although being completely detached from reality. The implementation of virtual reality in the clinical environment has already been tested for a variety of clinical tasks and training [9–11]. However, the use of virtual reality for surgical training on simulators is being criticized for lack of skill transfer from training to clinical setting [12].

Augmented reality brings virtual reality closer to reality by superimposing computer-generated images on a user's view of the real world. A group of augmented reality devices, which integrate virtual objects into the real world and make them respond to it, are called mixed reality devices. In mixed reality, virtual objects have their position in the reality, and thus physical objects may hinder the view of and interaction with the virtual object, as if they were mixed into user's environment.

The use of a head-mounted mixed reality device in surgery is discussed and shows a high potential for this technology, although it still is in a development phase [13,14]. An example of a mixed reality device is Microsoft HoloLens (Microsoft, Redmont, WA, USA) (hereafter Hololens), which is a head-mounted all-in-one computer with a transparent display. Hololens allows the visualization of 3D models as holograms embedded in the physical world. Transparent display is a key feature for mixed reality to be used during normal surgical routine. In addition, Hololens allows the user to interact with the 3D model without disappearing completely into the virtual world, which is beneficial for intraoperative use as well as the benefit provided by the possibility to share the model with multiple users in a room or at different locations.

The aim of our work is to show the advantage in spatial understanding of the liver, by comparing 3D models using a head-mounted display, Hololens, to the conventional way of using MRI images.

Material and methods

We planned to conduct a simple task to compare the spatial understanding of liver anatomy using conventional 2D image visualization with 3D models in mixed reality. A protocol was written with the primary outcome set to be the time to correct location of a liver lesion. For the study, the MRI images were obtained from a healthy volunteer at Oslo University Hospital.

Liver parenchyma was segmented using available tools in ITK-Snap [15]. Liver vessels were segmented using 3D Slicer and a segmentation method previously developed at our department [16–18]. The vessel segmentation starts with pre-processing of images to reduce the image noise and limit the intensity range of the image to the blood vessel intensity range. This is followed by multiscale vessel

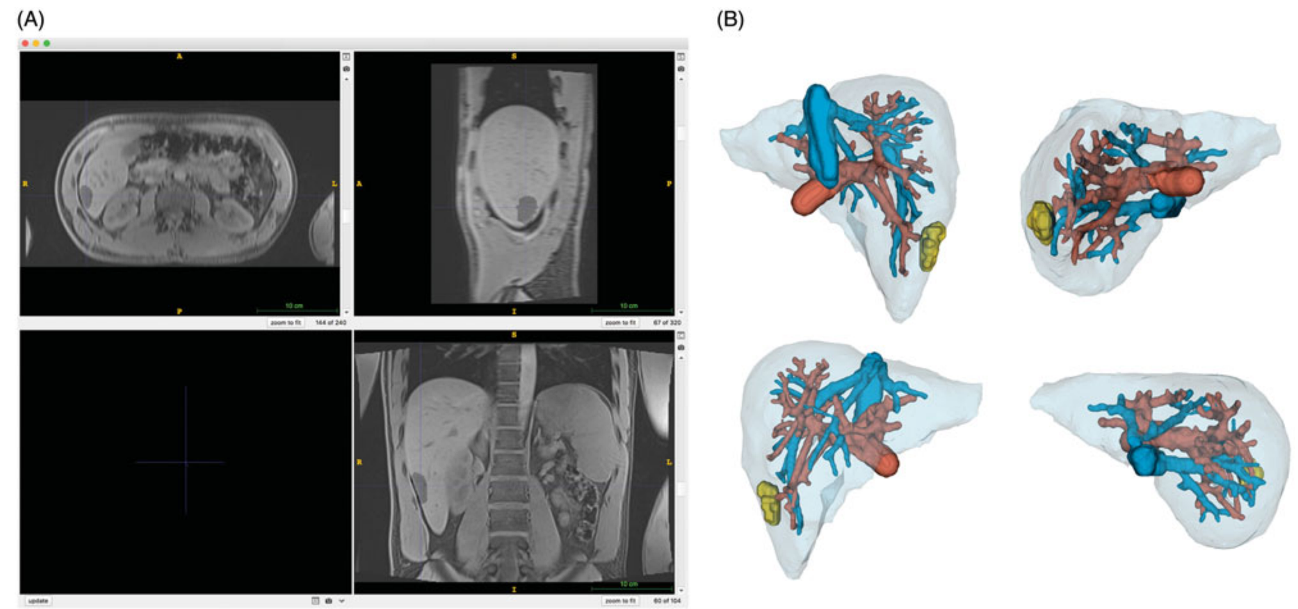

Figure 1 MRI image with a superimposed lesion. (A) 3 D model of a liver with parenchyma, portal and hepatic veins as well as a lesion. (B).

enhancement filter for final vessel enhancement, which allows the vessels to be segmented by just thresholding as a final step.

Artificially constructed lesions were superimposed into healthy volunteer MRI within the borders for each liver segment referring to Couinaud's classification [7]. These lesions were used to alter according to the original MRI image to create a lesion-like appearance as seen in Figure 1(A). Using this method, a set of nine different MRI images was created, each containing one liver lesion in a different liver segment.

The segmented lesions were paired together with the segmentation of the parenchyma as well as vessels from the healthy volunteer MRI to create an equivalent set of nine liver segmentations. These segmentations were transformed into 3D models using a previously developed method at the department [19]. The applied method uses Poisson surface reconstruction to obtain 3D models of the segmented liver and marching cubes for segmented blood vessels and tumor [20,21]. The resulting 3D model is shown in Figure 1(B).

At the Intervention Centre, Oslo University Hospital, a visualization application is being developed for Hololens. The application has the ability to show 3D models in a mixed-reality environment and gives the user the ability to interact with them using hand gestures. For the study, the application was used to load the models and the use was limited to visualization only to avoid time-consuming training for gestural manipulations of the models. This required participants to move around the model to be able to view it from different angles.

Some post-processing techniques are often available on the image viewers for greater spatial visualization (e.g. multiplanar reconstruction (MPR) [22]. A simplified radiology workstation was deployed running ITK-Snap, showing MRI images in MPR, where the same image was shown in an axial, sagittal and coronal plane at the same time. In this way a detected lesion could easily be centred on with one click and shown in all three different planes.

To refresh knowledge of the liver segments, an information sheet was provided. This shows different liver segments on CT images as well as illustrations in both 2D and 3D.

Forms were prepared, for both modalities, with a short description of the participant and case name, guess on lesion location and time taken to complete the task. For the 3D models, additional questions were added regarding the use of Hololens. The questions were designed to evaluate the screen, the comfort and the usefulness of this particular head-mounted device.

The study was conducted during the 6th national congress of Young Surgeons of the Hungarian Surgical Association (FISESZ) from March 24th to March 25th in 2018. All participants were invited from the conference. They were randomly assigned to start from a different modality. The participants viewed three different cases per modality. The cases were switched at fixed intervals to show all nine cases. At no point, the same case was given on MRI and HoloLens at the same time to the same participant. This was to avoid accumulative experience with a specific case.

A brief introduction was given for both modalities before the start of the task. For MRI images a short instruction was given on how to use ITK-SNAP. For the mixed reality, a demo was given on Hololens showing an educational model of the liver.

Participants were timed from the presentation of the case until a final answer was given orally and the answers together with the time used were noted on to the answer form.

Statistical method and statistics were chosen and completed in collaboration with statisticians at Oslo Centre for Biostatistics and Epidemiology. The proportion of correctly completed task is shown as a percentage for each modality. The time taken to response with a correct location is shown as a median (range). When applicable Chi-Square test with Fisher's exact test were used to compare categorical variables. Results were confirmed using mixed models in R by the consulting statistician. For non-normally distributed continuous data significance was calculated using Spearman's rank-order correlation and Wilcoxon signed-rank test. SPSS software (IBM Corp. Released 2017. IBM SPSS Statistics for Windows, version 25.0, Armonk, NY, USA: IBM corp) was used for statistical analysis.

Results

The study included 28 participants, with a median age of 30, the youngest being 26 and the oldest 54 years of age. Counting from the graduation of the university, the median practical medical experience was 6 years. Out of 28 participants two were females.

The median time to correct diagnosis was 23.5 [4–138] s using the MRI images and 6.00 [1–35] s using Hololens ($p < 0.001$). Age and clinical experience had no significant effect on time to correct diagnosis. Time for individual segments is shown in Table 1.

From the total of 150 attempts divided equally for each modality, MRI had an accuracy rate of 61.3% and Hololens of 57.3% ($p = 0.74$). Mixed model analysis confirms this insignificance and shows that variation from subjects and segments are controlled for by inclusion of the random effects. However, comparing the individual segments, there was some variation between the modalities. For segment 7 the difference was significant ($p = 0.041$) in favor of Hololens with 87.5% against 25% using MRI images. Clinical experience had no significant effect on accuracy. Otherwise, there were no significant differences in accuracy between MRI and Hololens for specific segments.

In total, 89 of 150 lesion locations were assigned correctly – 46 using the MRI images and 43 using the HoloLens.

We found a decrease of the average time to successful task completion with increasing number of attempts for both modalities. Between the first and the third attempts, on average, there was a 62% improvement ($n = 8$) on MRI images and 15% improvement ($n = 9$) for the use of HoloLens.

After the completed assignment using HoloLens, participants filled in a questionnaire with selecting answers on a 6-point Likert scale. The field of view, the area where holograms appear, was rated median 4 (2–6) and comfort using Hololens median 5 (3–6). 92% of the participant rated 5 or higher for the recommendation of the Hololens to others in their field.

Discussion

For determining the location of the lesion in segments, the use of segmented 3D models was overall equally good compared to the use of the original MRI images visualized in 2D, with exception of segment 7, which had a significant advantage in accuracy using the HoloLens. A possible explanation could be an easier determination of the border between segments 7 and 8 in a 3D model with depth compared to a mental fusion of coronal and axial planes on an MRI image. This indicates that there is no loss of tumor

Table 1. Median time and range to correct diagnosis for different modalities and segments.

	MRI count (n)	MRI time (s, range)	HoloLens count (n)	HoloLens time (s, range)	Sig.
Overall	46	23.5 (4–138)	43	6.00 (1–35)	$p < 0.001$
Segment 1	6	17 (12–37)	3	18 (6–29)	NS
Segment 2	5	22 (4–138)	8	5 (2–15)	NS
Segment 3	4	20 (7–46)	3	11 (8–14)	NS
Segment 4A	4	25 (17–29)	2	10 (1–18)	NS
Segment 4B	8	20 (5–26)	6	7 (4–10)	NS
Segment 5	5	22 (12–28)	1	15	NS
Segment 6	6	26 (9–54)	8	5 (2–9)	NS
Segment 7	2	36 (34–37)	7	11 (2–35)	NS
Segment 8	6	26 (21–35)	5	5 (3–6)	NS

localization accuracy when converting standard images to 3D models. Images viewed in MPR are shown from several directions, although there is lack of depth information compared to the Hololens, which expands the understanding of the relationship between different structures of the liver. This also explains the drastically reduced correct task completion time using Hololens.

This limited data suggests a much steeper learning curve for MRI images compared to the 3D models and may indicate the ease of use of the segmented 3D models.

The significant difference in time for correct localization between the modalities for this relatively simple task may be transferred into a clinical scenario. The spatial localization of vessels and lesions within the liver are calculated continuously from 2D images, such as MRI or CT, to render a mental 3D understanding of the volume of interest. In this study, we have shown that the time for this 2D-into-3D transformation together with clinical assessment can be decreased almost four times using 3D models from segmented liver images in combination with head-mounted display. The time saved outside and inside the operating room may lead to a significant decrease of operating time, which would result in improved use of resources and an economic benefit.

Segmentation and model creation time, which is around 1 h per case at our department, was not included. Currently, we are working towards automatic segmentation and model implantation in HoloLens that almost eliminate this time.

Previous research has shown potential benefits and a perceived increase in safety and confidence of the surgeon while using 3D models with resection planes for liver resections, though visualized in 2D [23,24]. Spatial understanding of the patient-specific liver anatomy might have an important role for an accurate and safe surgery planning.

Use of a patient-specific 3D liver model during the resection of a single lesion could possibly save time although the biggest gain might be during resections of lesions at multiple locations in the liver. A retrospective historical cohort study shows that multiple simultaneous laparoscopic parenchyma-sparing liver resections are feasible and may be preferred over single major resection in a substantial portion of patients [25]. To find these multiple lesions laparoscopically with conventional imaging techniques might be challenging and/or time-consuming. For that reason, the use of 3D models, for multiple tumor localizations intraoperatively, might have a significant effect on the operating time. This needs to be tested clinically to determine the effect and significance.

Another study comparing the use 2D CT/MRI images to 3D reconstructions for liver resection planning shows an increase in accuracy and a decrease of time while using segmented images [26]. This is in line with our results although our study shows a greater advantage in the time saved. The Yeo CT et al. study also emphasizes the possible decrease in cognitive load, which may relieve the surgeons focus for other tasks.

One of the limitations of our study is a relatively low number of participants, which were not paired nor matched. For that reason, it was not possible to conduct a statistical analysis applicable to cross-over studies. Another possible weakness is that some of the participants acted under stress while completing the task in both modalities, presumably because they knew that they were timed. This may explain the lower than anticipated rate of correctly completed tasks in an attempt to reduce the time.

The participants rated the HoloLens to be quite comfortable and would recommend it to others in their field. This indicates that the use of HoloLens in clinical practice is wished upon and could be used comfortably during procedures. For parenchyma-sparing resections this may shorten surgeon's learning curve for understanding of lesion location and resection plane. More data is needed to evaluate comfort levels during longer continuous use. In previous reports, the field of view of HoloLens was defined as limited [13]. In our study the field of view was rated to be above average (Likert scale 4), which shows this not to be a limitation.

This study highlights potential benefits of segmented 3D models for laparoscopic liver surgery, especially using additional methods of visualization such as HoloLens. Our research group actively works in this specific research area to create planning and navigation tools for laparoscopic liver resections. We are developing a system with tracked laparoscopic tools shown in patient-specific 3D biomechanical liver model from pre- and intraoperative images, that will help the surgeon during the procedure. The system could be used in mixed reality to alleviate the need for additional screens and provide understanding of depth. Our goal is to improve clinical workflow, patient safety and decrease the surgeon's workload.

In conclusion, the use of three-dimensional liver models in mixed reality significantly decreases the time, and in some localization increases the accuracy, of a task requiring a spatial understanding of the organ. Further validation studies will be performed in the future for better evaluation of clinical benefits.

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Declaration of interest

The authors declare that they have no conflict of interest.

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