HIDDEN TUMOR VISUALIZATION IN AUGMENTED MONOCULAR LIVER LAPAROSCOPY

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ABSTRACT

We address the hidden tumor visualization problem in augmented monocular liver laparoscopy. Conveying a hidden tumor's depth correctly to the surgeon in augmented monocular laparoscopy is extremely difficult and still forms an unsolved problem. The depth conveyance can be splitted into two subsequent problems. First, designing a visualization that convinces the user to see the tumor inside the organ. Second, enhancing this visualization so that it also provides metric depth perception. We focus on the first problem where existing methods mostly fail. The most promising visualization methods rely on a preoperative CT organ model with the tumor to be registered to an intraoperative laparoscopic image. Such a registration allows the organ's intraoperative shape mesh to be overlaid on top of the augmented tumor. The overlaid organ mesh guarantees a partial occlusion on the augmented tumor. This provides a powerful depth cue for the surgeon's perception. However, this type of registration, especially in liver laparoscopy, is usually not real-time and sometimes not possible. This is because of the liver deformation and lack of matchable features between the multimodal images. Subsequently, the tumor augmentation cannot be carried out continuously to guide the surgeon. We propose MoT (Mesh-over-Tumor) visualization to address these limitations. MoT replaces the deformable preoperative to intraoperative liver registration with a rigid tumor registration via laparoscopic ultrasound (LUS) imaging. MoT handles surgical tool occlusions, runs faster than existing methods, and outperforms the state of the art in terms of depth perception, as shown in the provided user study.

KEYWORDS

Augmented Reality, Laparoscopic Surgery, Tumor Visualization

1. INTRODUCTION

Mini-invasive surgery (MIS) offers significant advantages over open surgery, including reduced complications, shorter hospital stays, and lower costs. However, MIS brings two challenges. First, it prevents the surgeon from palpating organs directly, making it harder to locate tumors inside the organs. Second, while laparoscopic ultrasound (LUS) is a valuable intraoperative tool for real-time visualization of in-organ tumors during MIS, it requires significant expertise to operate effectively. As a result, accurately localizing tumors inside the organ remains a challenging task, even when using LUS.

Augmented reality (AR) guidance can make using LUS easier and help surgeons by giving clear and intuitive visual feedback. AR-guided surgery involves two critical steps. First is registration, where preoperative CT scans are aligned with intraoperative laparoscopic images. Second is visualization, where the registered tumor is overlaid on the laparoscopic images to show its location. Most of the literature on AR-guided surgery focuses on the registration step and ignores the second yet important visualization step. We address the visualization step in laparoscopic liver surgery. This corresponds to the well-known difficult occluded object visualization problem in AR (*i.e.*, the occluded object is perceived to float over its occluding surface rather than behind it). This problem does not exist at all in the context of 3D cameras, but is nonetheless highly relevant in monocular liver laparoscopy which uses a standard 2D camera. Specifically, in AR-guided liver surgery, hidden tumor visualization can be splitted into two subsequent problems. First, designing a visualization that convinces the user to see the tumor inside the liver. Second, enhancing this visualization so that it also provides metric depth perception. We focus on the first problem, where existing methods mostly fail.

Most promising visualization methods rely on a preoperative CT liver model with the tumor to be registered to an intraoperative laparoscopic image. Such a registration allows the liver's intraoperative shape mesh to be overlaid on top of the augmented tumor. The overlaid liver mesh guarantees a partial occlusion of the augmented tumor. This provides a powerful depth cue for the surgeon's perception. An example of this type of visualization can be seen in figure 1 retrieved from (Le Roy et al. 2019). The visualization in the right-most image in figure 1 convinces the surgeon to see the tumor inside the liver and not floating over the liver. This is because of three powerful perceptual reasonings. First, the registered liver mesh overlaps the liver surface. Second, the registered liver mesh partially occludes the augmented volumetric tumor. The augmented volumetric tumor is thus perceived behind the registered liver mesh. Third, since the registered liver mesh tightly envelopes the liver surface, the augmented volumetric tumor cannot be between the mesh and the liver surface. Consequently, the augmented volumetric tumor is perceived behind the liver surface.

Figure 1. The left image shows a raw laparoscopic liver image. The middle image shows Transparent Overlay visualization of the registered hidden structures such as the tumors (yellow) and veins (blue). The right image shows the overlaid registered liver mesh on top of the augmented hidden structures. Images are taken from (Le Roy et al. 2019).

However, preoperative to intraoperative laparoscopic liver registration is usually neither real-time nor possible for every laparoscopic image. This is because of two reasons. First, the registration has to handle the liver's intraoperative deformation. This is computationally very demanding. Second, preoperative to intraoperative laparoscopic liver registration requires that the liver is visible as much as possible in the laparoscopic image so that the registration succeeds, see figure 1. However, the liver is usually very partially visible in the laparoscopic images. This substantially reduces matchable features between the preoperative liver model and the intraoperative laparoscopic image. Subsequently, the tumor's registration and thus its augmentation cannot be carried out continuously to guide the surgeon.

We propose MoT, a visualization method, to address the above limitations. MoT stands for "Mesh-over-Tumor". MoT has two important contributions:

1. MoT eliminates the deformable preoperative to intraoperative liver registration. Instead, it suggests a rigid tumor registration between three multimodalities: preoperative CT tumor model, intraoperative laparoscopic image, and intraoperative LUS image. This makes it significantly faster and possible even with a very partially visible liver.
2. MoT handles surgical tool occlusions. This often occurs during the suggested rigid tumor registration process through the use of an LUS probe.

The rest of the paper is organized as follows. Section 2 reviews the related work. Section 3 explains MoT. Section 4 presents the user study and results. Section 5 concludes the paper and outlines future work.

2. RELATED WORK

We review prior methods in surgical AR visualization. Each has its distinct strengths and limitations.

Transparent Overlay visualization. In (Van Gestel et al. 2023; Solbiati et al. 2022; Evans et al. 2025), tumor models are semi-transparently overlaid onto the liver surface, offering positional cues. However, this visualization misrepresents spatial depth relationships. This is because the augmented tumor appears to protrude outside the organ surface and is thus perceived as floating above the organ rather than underneath.

Inverse Realism visualization. In (Lerotic et al. 2007), the method addresses hidden structures visualization in MIS. This method renders the organ's surface textures onto a structure's 3D model using edge features. This creates an 'inverse realism' effect where a hidden structure remains visible with the occluding organ's surface texture. However, when the organ's occluding surface lacks texture, the effect breaks down, and the visualized hidden structure appears floating above the organ.

Visualization via preoperative to intraoperative organ registration. (Collins et al. 2020) performs rigid organ registration for the uterus tumor localization. Although it produces tumor visualizations with the right spatial depth relationships, its rigid organ registration would not yield correct tumor localization for the liver. This is because the liver is highly deformable compared to the uterus. (Le Roy et al. 2019) performs deformable registration for the liver. It produces tumor visualizations with the right spatial depth relationships. However, the deformable liver registration is not real-time and cannot be sustained for all laparoscopic images as discussed in the introduction.

3. METHODOLOGY

MoT visualization method's pipeline is presented in figure 2. Its inputs are the current intraoperative laparoscopic and LUS images, and the preoperative 3D tumor model.

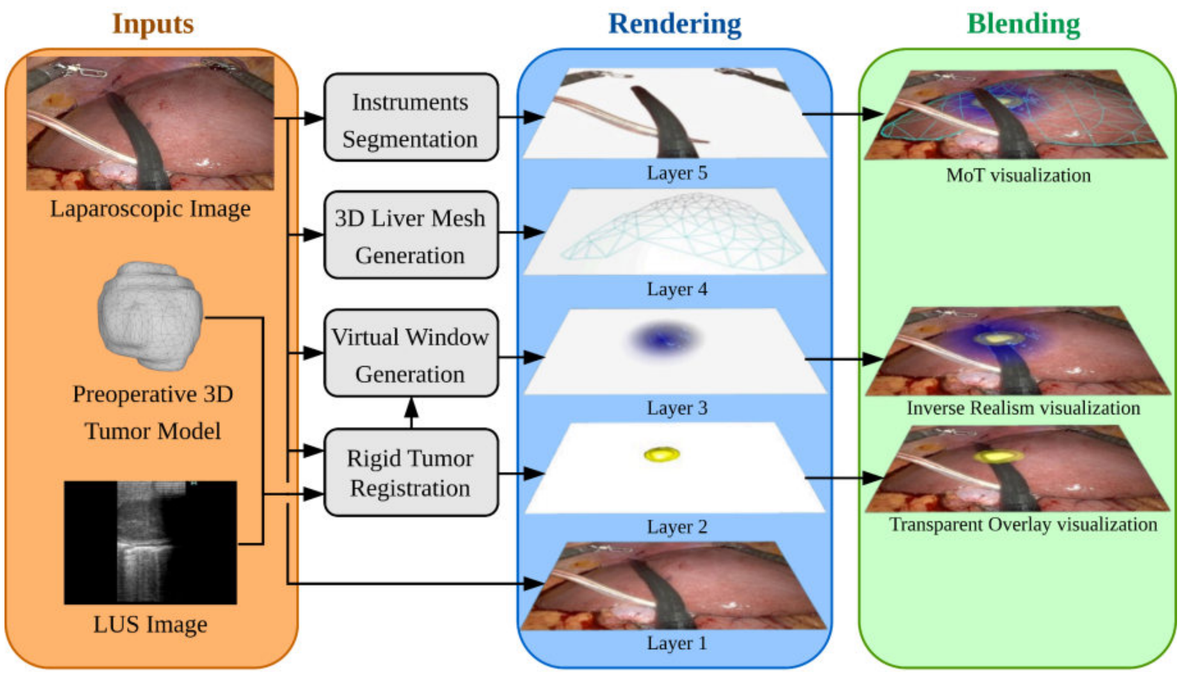

Figure 2: MoT visualization method's pipeline.

These inputs undergo several processing steps: (*i*) rigid tumor registration, (*ii*) virtual window generation, (*iii*) 3D liver mesh generation, and (*iv*) instrument segmentation. The processed inputs through these steps are then rendered and blended to produce MoT visualization. MoT pipeline requires less than 4 seconds on average (3 seconds for rigid tumor registration, 10 milliseconds for virtual window generation, 100 milliseconds for mesh generation, 20 milliseconds for instrument segmentation, 100 milliseconds for rendering and blending of layers). This is a lot faster compared to the methods requiring deformable registration between a preoperative 3D liver model and an intraoperative laparoscopic image. For instance, in (Koo et al. 2017), a visualization solution with deformable registration requires 2 to 3 minutes on average. We next explain each step below.

Rigid tumor registration. This step registers a rigid preoperative 3D tumor model to a 2D laparoscopic image using an intraoperative LUS image. The 3D tumor model is created from the segmented preoperative CT. This step involves solving two substeps. First, registration of the rigid preoperative 3D tumor model to the LUS image, *e.g.*, similar to (Ramalhinho et al. 2021). Second, LUS imaging plane's pose computation in the laparoscope's coordinate frame, *e.g.*, similar to (Kalantari et al. 2024).

Virtual window generation. This step generates a virtual window centered on the rendered tumor's center of mass pixel position. Its size is about 1.5 times of the tumor's rendered size. It also includes the edge features computed from the liver's surface in the laparoscopic image.

3D mesh generation. This step generates the 3D mesh of the visible liver as shown in figure 3. First, it segments the liver in the laparoscopic image using MedSAM by (Saha and Pol 2024), a foundation model fine-tuned for laparoscopic imagery. Second, it computes the depth map of the segmented liver using the Depth Anything model by (Li et al. 2024). The depth map is then used to generate the visible liver's 3D mesh. Although this 3D mesh is not very accurate, its rendering perfectly aligns with the segmented liver in the laparoscopic image. Subsequently, this replaces the difficult deformable registration between the preoperative 3D liver model and the intraoperative 2D laparoscopic image, which was providing the full liver shape mesh.

Figure 3. From left to right: raw laparoscopic liver image, segmented liver, depth map estimation, and the mesh generated from the depth map overlaid on the laparoscopic image.

Instruments segmentation. We know that the visible parts of the surgical instruments occlude everything behind them. Therefore, the instruments' pixels must not be altered. We find these pixels using SurgicalDeSAM by (Sheng et al. 2024). SurgicalDeSAM is a foundation model adapted from Segment Anything and trained on surgical scenes to segment instruments in laparoscopic images.

Rendering. This step renders five layers: (*i*) input image, (*ii*) tumor, (*iii*) virtual window, (*iv*) visible liver's mesh, and (*v*) instruments. The input image layer is rendered as the original input image. The tumor layer is rendered from the registered tumor. The virtual window layer is rendered from the generated virtual window. The visible liver's mesh layer is rendered from the generated 3D mesh. The instruments layer is rendered from the segmented instruments image.

Blending. This step blends the rendered layers to form three visualizations: (*i*) transparent overlay visualization, (*ii*) inverse realism visualization, and (*iii*) the proposed MoT visualization. The transparent overlay visualization is blended from the input image and tumor layers using depth-aware transparency. The inverse realism visualization is blended from the input image, tumor and virtual window layers, similar to (Lerotic et al. 2007), which has been shown to improve the hidden structures perception. The virtual window in this visualization gradually transitions from semi-transparent at the center to fully transparent at the boundary. The proposed MoT visualization is blended using all the layers, namely the input image, tumor, virtual window, visible liver's mesh, and instruments. The visible liver's mesh is blended using depth-aware brightness, enhancing the liver's shape perception.

MoT's limitations. We list the most important limitations of MoT. Rigid tumor registration requires detection and segmentation of a tumor in an LUS image. This can be hindered for two reasons. First, LUS images are usually very noisy. Second, the tumor might be isoechoic. Afterward, 3D mesh generation requires an accurate liver segmentation. This can be hindered if the laparoscopic image is underexposed.

4. USER STUDY AND RESULT

We conducted a user study to compare MoT against the Transparent Overlay visualization method, (Van Gestel et al. 2023; Solbiati et al. 2022; Evans et al. 2025) and the Inverse Realism visualization method, (Lerotic et al. 2007).

Visualization cases. We used 10 laparoscopic liver images. Each image was retrieved from a different liver resection surgery. This helps evaluate the visualization methods across 10 diverse cases. These cases are shown in figures 4, 5 and 6. Each column in each figure shows one visualization method. Each row in each figure shows one case with different visualizations. The first column in each figure shows Transparent Overlay visualization. The second column in each figure shows Inverse Realism visualization. The third column in each figure shows MoT visualization.

User study. We removed the methods' names. Instead, we used "Visualization 1" for Transparent Overlay, "Visualization 2" for Inverse Realism and "Visualization 3" for MoT. Participants read the following: "*We propose 3 different hidden tumor visualizations for cases from 10 different surgeries. The best visualization is the one that convinces you the most to see the tumor inside the liver. Please vote for the best visualization".* Participants then voted.

Participants. Twenty people participated in the study. Three participants were laparoscopic liver surgeons. Most participants had never seen a liver and a tumor before. Participants were only told to vote for the visualization that convinced them most to see the tumor inside the liver.

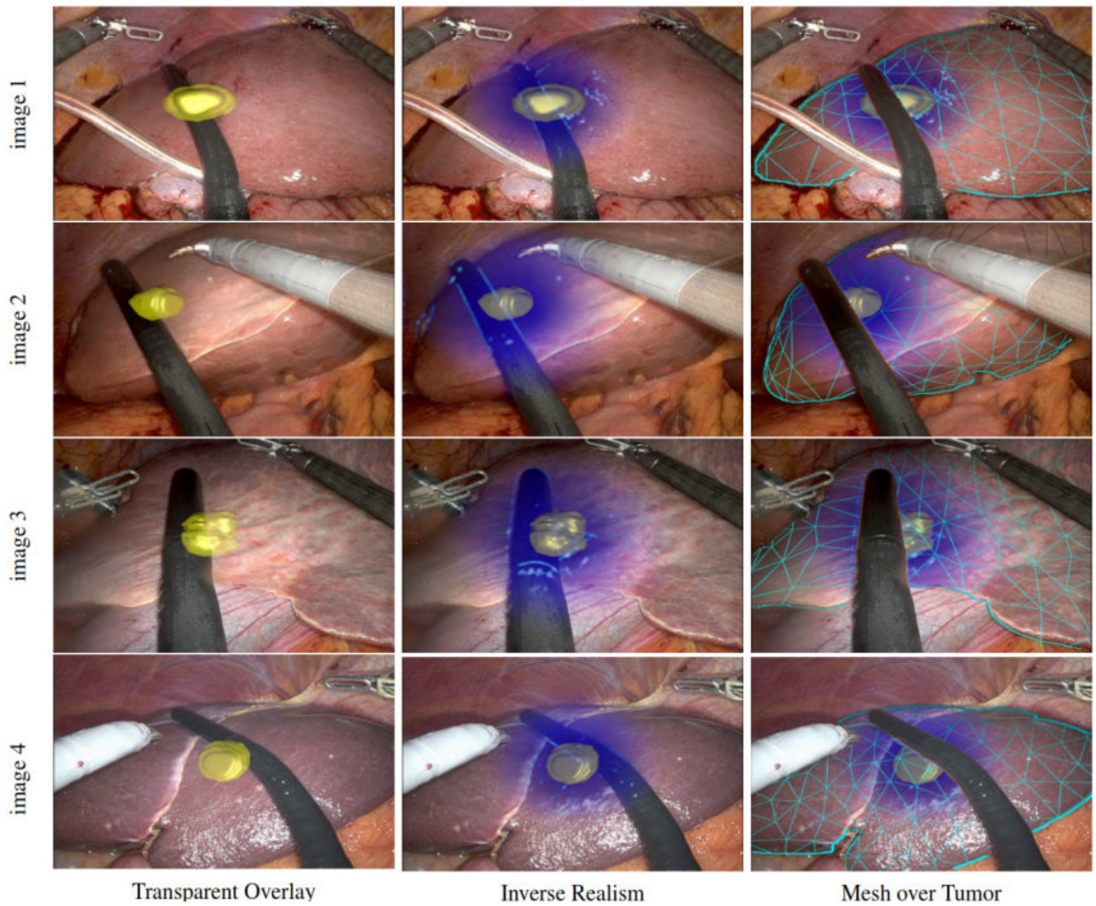

Figure 4. Visualizations for tumors occluded by a surgical instrument.

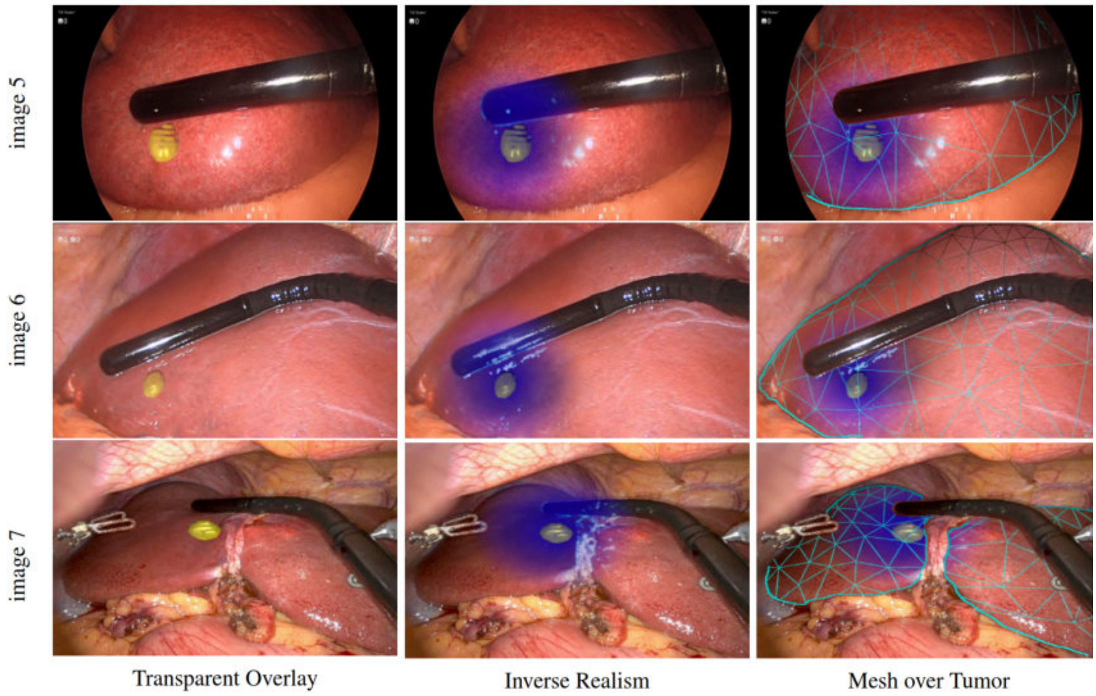

Figure 5. Visualizations for tumors not occluded by a surgical instrument.

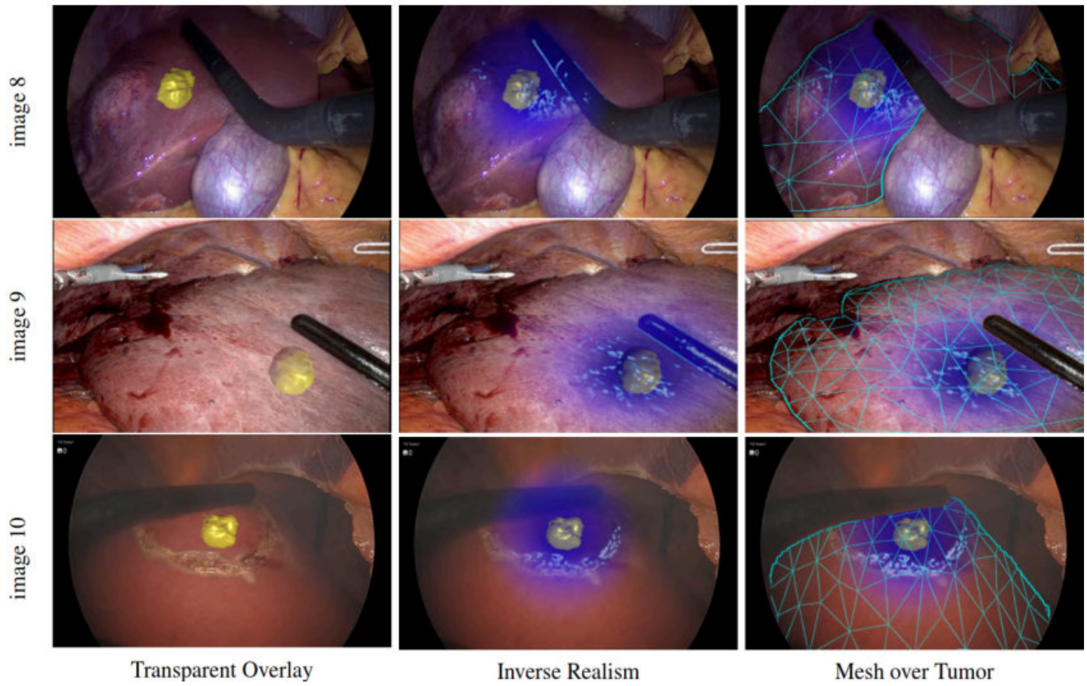

Figure 6. Visualizations for tumors with imperfect liver segmentation.

Results on all cases. The user study in figure 7 reveals that MoT outperforms the other methods in all cases. Transparent Overlay visualization outperforms Inverse Realism visualization. This shows that participants also prefer less cluttered visualization.

Results on cases where tumors were occluded by an instrument. The user study in figure 7 reveals that for cases shown in figure 4, MoT substantially outperforms the other methods.

Results on cases where tumors were not occluded by an instrument. The user study in figure 7 reveals that in the three cases shown in figure 5, MoT outperforms the other methods even when the tumor is not occluded by an instrument.

Results on cases where the liver's segmentation was imperfect. The user study in figure 7 reveals that in the three cases shown in figure 6, MoT performs similarly to the Transparent Overlay visualization method. In these cases, the images were underexposed or cluttered by blood, which degraded liver segmentation.

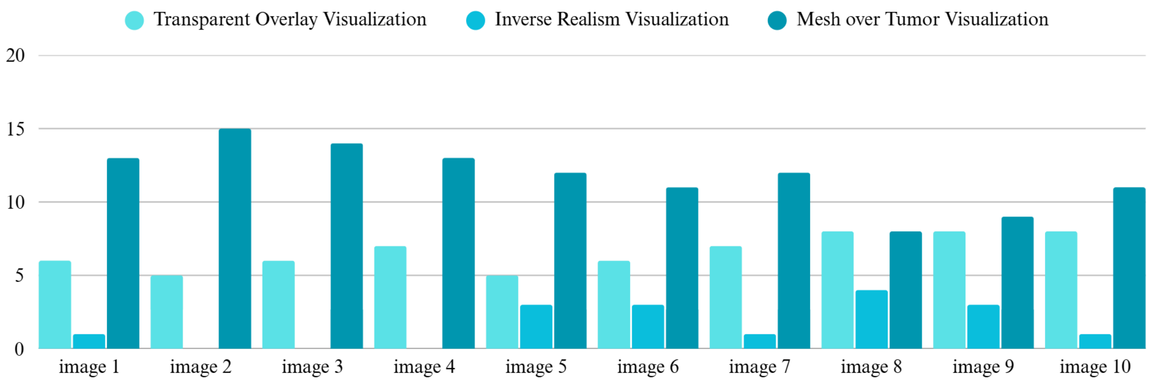

Figure 7. User study results.

5. CONCLUSION

We have proposed MoT, an organ Mesh-over-Tumor visualization method for hidden tumors in liver laparoscopy. As opposed to existing methods requiring deformable registration to account for the complete parenchyma, we only require registration of the tumor, which can be expressed rigidly owing to its higher stiffness, resulting in a simpler problem with stabler outcomes. This makes MoT more applicable. MoT can be seamlessly applied to multiple subsurface structures, including multiple tumors and the vascularisation; for simplicity however, we discussed and experimented with the single tumor case only. User study reveals that MoT improves perception of the hidden tumor's spatial depth relationship in various surgical scenes compared to state-of-the-art tumor visualizations. Future work shall study (*i*) segmentation of gall-bladder, falciform ligament, and blood pixels to improve the liver's outlines in the visualization, (*ii*) tracking of the liver's mesh across successive images to prevent flickering in the visualizations, (*iii*) real-time implementability, and (*iv*) extension to other organs.

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