Augmented Reality Navigation Surgery Facilitates Laparoscopic Rescue of Failed Portal Vein Embolization

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BACKGROUND

Despite the complexity of minimally invasive surgery (MIS) of the liver, no system in clinical practice today enhances the digitalized laparoscopic view to facilitate the surgery.[1] In addition, all robotic surgery currently in use facilitates MIS by providing "tele-manipulation" (the surgeons performs the surgery remotely from the patient), without creation of an automatically enhanced interface (augmented reality, AR) between the patient and the operating surgeon.[2] Augmented reality, however, could help to overcome the difficulties of laparoscopic surgery in general and advanced laparoscopic liver surgery specifically: loss of depth perception, decreased spatial understanding and tactile feedback in the 3-dimensional (3D) space of the liver, and complicated 3D anatomy without significant outward landmarks.[3,4]

Nevertheless, providing AR for advanced laparoscopic liver surgery (different from other organs such as the brain, which is fixed in the skull) requires continuous compensation and realignment of the preoperative 3D reconstruction with the moving laparoscopic image of the mobile liver (displacement).[5] These positional changes currently require manual alignment of the AR by an external operator. This manual alignment leads to a subjective evaluation of the overlay accuracy and is ultimately dependent on the operator.

Disclosure Information: Dr Peterhans is an employee and board member of CAScination AG. All other authors have nothing to disclose.

Disclosures outside the scope of this work: Dr Gayet is a consultant for Olympus, receives royalties from Microfrance for bipolar forceps, and is paid for developing educational presentations by Fujifilm.

Support: This study was supported by grants from the Swiss Commission for Innovation and Technology and the Eurostars programme.

Received December 15, 2015; Revised May 19, 2016; Accepted June 22, 2016.

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To overcome manual updating of the alignment between the 3D reconstruction and the laparoscopic imaging, we developed an image-guided surgery system, and we report, for the first time, use of this new AR system in humans. This system provides a continuously automated update between the liver and the AR, even during displacement. This automatic alignment and tracking of the position of the laparoscopic instruments eliminates the need for an external operator, allowing AR technologies to be used without a significant increase in workflow complexity. Additionally, due to the constant tracking of the laparoscopic view, the overlay accuracy remains consistent (video). This AR system was evaluated during the first reported case of laparoscopic rescue of failed portal vein embolization (PVE), considered to be one of the most challenging cases in laparoscopic liver surgery.

PATIENT AND STUDY DESIGN

The patient was a 54-year-old (94 kg) man being considered for curative laparoscopic liver resection of 5 bilobar colorectal liver metastases after 2 failed attempts at PVE via percutaneous and laparoscopic-assisted ileocolic vein access.[6] The patient had undergone 13 cycles of FOLFOX (folinic acid, fluorouracil, oxaliplatin) chemotherapy. His future liver remnant was only 13% (290 of 2,222 mL). Salvaging PVE failure was planned using a total laparoscopic 2-stage rescue surgery with a hypertrophy-inducing total liver split followed by curative resection after an adequate future liver remnant had grown to 490 mL. The surgical challenge, which AR helped to overcome, was a narrow dissection plane during the liver split and the need for metastectomy of a lesion close to the portal pedicle of the future liver remnant (video).

The bases for AR creation were preoperatively obtained and manually segmented liver images from 1.25-mm slice CT (Discovery CT750-HD, GE). From this, a precise 3D reconstruction of the liver, specific to the patient, was performed using MEVIS software. This provided tumor volumes and location, portal and hepatic vein vasculature and territories, and a proposed resection plane (Fig. 1A and video).

http://dx.doi.org/10.1016/j.jamcollsurg.2016.06.392
ISSN 1072-7515/16

Abbreviations and Acronyms

3D = 3-dimensional
AR = augmented reality
MIS = minimally invasive surgery
PVE = portal vein embolization

Intraoperatively, AR was achieved by coupling an image-guided surgery system for open liver surgery (CAScination) with the real-time laparoscopic imaging and instrument tracking. Instrument localization was accomplished by triangulating the position of infrared retro-reflective spheres attached to the laparoscope and instruments, detected by the image-guided surgery stereo-infrared tracking system. To overlay the preoperative 3D reconstruction with the laparoscopic view, 2 phases aimed at aligning the 2 scenes, compensating for the laparoscope motion and tracking liver displacement, were performed (video).

Alignment between the 3D reconstruction and the liver was achieved by defining 4 anatomic landmarks on the 3D reconstruction, and by subsequently digitalizing their equivalent position with a tracked instrument, obviating the need for placing fiducials for AR tracking. The digitalized landmarks were placed at the insertion of predefined anatomic structures (video). The alignment resulted in mapping from the preoperative 3D reconstruction to the laparoscopic scene expressed as a 3D geometrical relationship. The aligned 3D reconstruction was displayed together with the position of the tracked instruments on a secondary sterile touch-screen monitor (Fig. 1B, bottom right) for intraoperative use by the surgeon.

Automatic compensation of the laparoscope motion was accomplished by detecting in real time the location of the laparoscope and by updating the mapping between the 3D reconstruction and the new laparoscopic scene. Through this constant laparoscope localization following the preoperative calibration, the laparoscopic perspective was continuously recovered and directly transferred to the virtual camera, depicting the 3D model. This allowed mimicking the pose and optical properties of the laparoscopic view. This, in turn, allowed the 3D reconstruction to be rendered at the same perspective as the laparoscopic view. The 2 views were subsequently merged in a single enhanced view, in which the newly rendered 3D reconstruction was overlaid onto the laparoscopic view (video).

RESULTS

The subsequently merged AR view displayed a semi-transparent 3D reconstruction of the underlying vital structures onto the laparoscopic image (Fig. 1B, top, bottom left, bottom center). Accuracy of the enhanced view was qualitatively evaluated by validating the correct overlay of surface tumors with their respective 3D models. The 3D visualizations of portal and hepatic veins, their territories, tumor location, and the resection plane were selectively enabled by the surgeon, allowing for successful anticipation of instrument position and underlying anatomy.

The alignment procedure at beginning of the operation required 1 minute, resulting in an accurate overlay at first attempt. Moreover, continuous alignment was performed automatically through the tracked camera movements by the operating surgeon, and due to its automatized update, the need for manual updating by an external operator was eliminated.

Limitations of the technology were mainly accuracy to a range of 3 mm and lack of AR transparency under control of the surgeon. Although the accuracy achieved was relatively high (within the range of 5 mm), greater accuracy is needed for optimal clinical application due to the closeness of critical structures in the porta, tumor margins for colorectal liver metastasis that are within the range of the accuracy (5 mm), and planned anatomic resection planes that aim at exposing structures that are easily damaged if an accuracy range of 5 mm is applied (eg left hepatic vein). A limitation discovered during the clinical application was the lack of AR transparency under the surgeon's control. Although little transparency was required when targeting surface tumors, adjustable transparency was needed during dissection of portal structures. Transparency under the control of the surgeon avoids the AR obstructing the laparoscopic view. Further, although there was some minor time delay of the AR realignment during liver displacement in the performed case (in the range of milliseconds), this tended to not be a limitation because the surgeon rarely engaged in dissection while the liver was being displaced. Additional limitations of this technology are expense, providing AR within a 3D laparoscopic image, and AR that is continuously adapting to liver deformity and displacement.[7]

CONCLUSIONS

Augmented reality is an area of active research, and important contributions have been made for its use in open, laparoscopic, and robotic surgery.[5,7] Surgeon-controlled AR, similar to heads-up displays in military aircrafts, has the potential to overcome challenges intrinsic to advanced laparoscopy. Our newly developed AR system provides an automated real-time update between the 3D reconstruction and the laparoscopic image under the control of the surgeon. This fused image adjusts to