Augmented Reality in Open Surgery

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Abstract

Augmented reality (AR) has been successfully providing surgeons an extensive visual information of surgical anatomy to assist them throughout the procedure. AR allows surgeons to view surgical field through the superimposed 3D virtual model of anatomical details. However, open surgery presents new challenges. This study provides a comprehensive overview of the available literature regarding the use of AR in open surgery, both in clinical and simulated settings. In this way we aim to analyze the current trends and solutions to help developers and end/users discuss and understand benefits and shortcomings of these systems in open surgery. We performed a PubMed search of available literature updated to January 2018 using the terms 1) "augmented reality" AND "open surgery", 2) "augmented reality" AND "surgery" NOT "laparoscopic" NOT "laparoscope" NOT "robotic", 3) "mixed reality" AND "open surgery", 4) "mixed reality" AND "surgery" NOT "laparoscopic" NOT "laparoscope" NOT "robotic". The aspects evaluated were the following: real data source, virtual data source, visualization processing modality, tracking modality, registration technique, and AR display type. The initial search yielded 502 studies. After removing the duplicates and by reading abstracts, a total of thirteen relevant studies were chosen. In one out of thirteen studies, in-vitro experiments were performed, while the rest of the studies were carried out in a clinical setting including pancreatic, hepato-biliary, and urogenital surgeries. AR system in open surgery appears as a versatile and reliable tool in the operating room. However, some technological limitations need to be addressed before implementing it into the routine practice.

Keywords Augmented reality, mixed reality, open surgery, image-guided surgery, surgical navigation

Introduction

Over last decade augmented reality (AR) technology has been successfully helping surgeons during surgical procedures in the operating room. In AR-based surgical navigation systems, patient specific 3-D models commonly generated from pre-operative images (e.g., CT, MRI) are superimposed on the real views of the surgical field to provide surgeons with improved visualizations of the anatomical structures and/or to assist them throughout the procedure. AR visualization is indeed capable of providing the surgeon with the ability to access the radiological images and surgical planning contextually to the real patient anatomy. Consequently, in image-guided surgery (IGS) systems, AR technology appears as a significant development, because it aims to profitably integrate surgical navigation with virtual planning contextually to the real patient's anatomy [1,2]. In the last years, AR based IGS systems for maxillofacial surgery, orthopedic surgery, neurosurgery have been increasingly tested, even if mostly at research level [3,4]. However, up to date only few studies have been carried out involving the use of AR in open surgery of soft tissues. The reason for this is that in open surgery, registration of the virtual and real scene remains an open issue. AR registration is affected by problems associated with the deformation of the organs, uncontrolled breathing and continuous contact of surgical instruments with soft tissues. Nonetheless, in open surgery, AR represents a particularly useful asset to improve the surgeon's spatial perception of the surgical field to avoid unnecessary manipulations or inadvertent injuries to inner organs.

We present a literature review aiming to describe and evaluate the advantages and shortcomings of each of the different AR setups tested in-vitro, in-vivo and ex-vivo, to understand the efficacy of AR in aiding open surgical procedures and to define potential future research directions.

Methods

In this systematic review, we present an overview of the available literature regarding the use of AR in open surgery. We performed a review of available literature updated to January 2018 by performing a search using the PubMed database with the following terms:

1. "augmented reality" AND "open surgery"
2. "augmented reality" AND "surgery" NOT "laparoscopic" NOT "laparoscope" NOT "robotic"
3. "mixed reality" AND "open surgery"
4. "mixed reality" AND "surgery" NOT "laparoscopic" NOT "laparoscope" NOT "robotic".

The search included human, animals and in-vitro studies. Eligibility assessment was performed independently in an unblinded standardized manner by two reviewers (BF and FC). Disagreements between reviewers were resolved by consensus. Exclusion criteria were based on; language of publication other than English, field of application other than open surgery (i.e., excluding neurosurgery, orthopedic and maxillofacial surgery), literature review and abstracts (Figure 1).

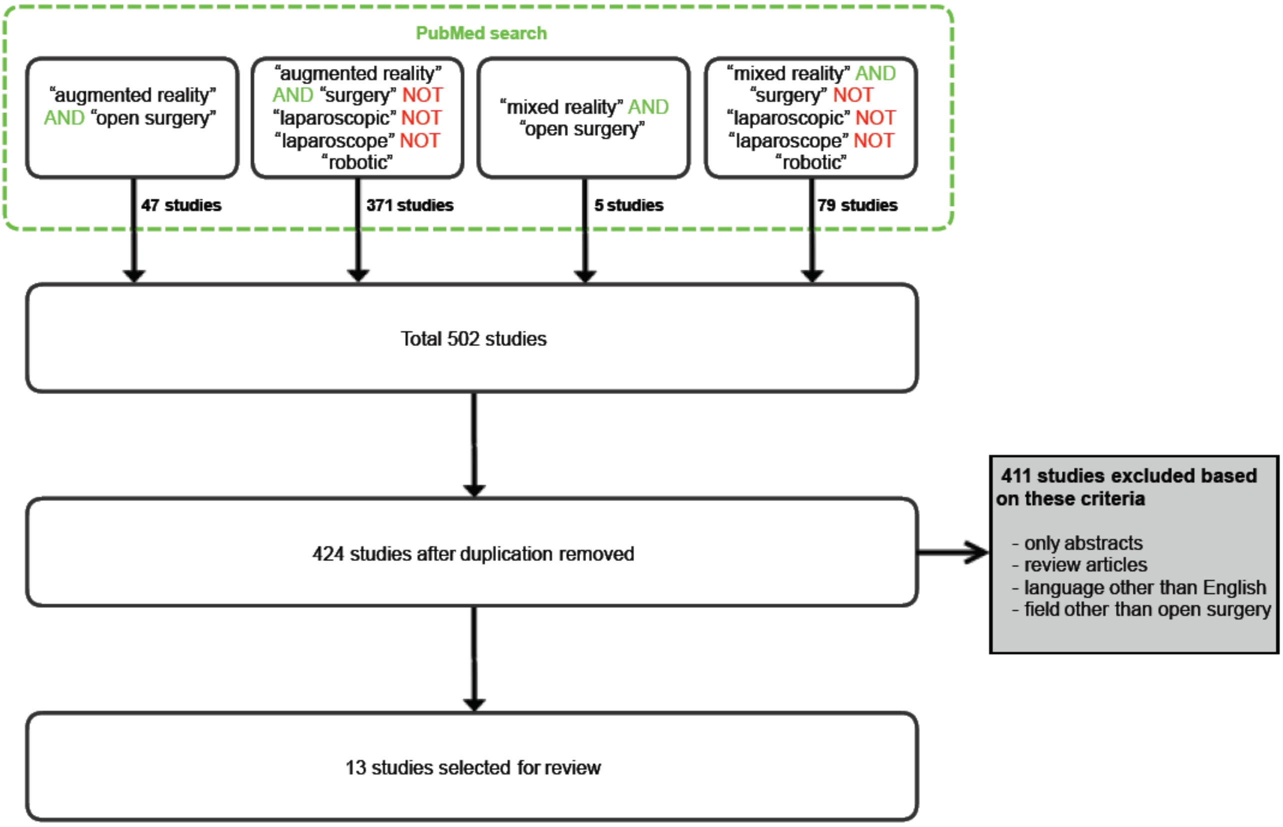

Figure 1. Flowchart of selected literature

After enlisting the feasible articles, we classified the papers according to a taxonomy originally proposed in 2010 by Kersten-Oertel M et al. [5] and then specifically modified by Meola et al. in 2010 [6], so to refer to some features that we intended as relevant. The aspects evaluated were the following: real data source, virtual data source, visualization processing modality, tracking modality, registration technique, AR display type. Unfortunately, qualitative parameters concerning the accuracy of the real-to-virtual image registration and the frame-rate of the AR application could not gathered from all the papers. Finally, due to the nature of the studies (small case series) and the subjective nature of the qualitative assessments, publication bias should be considered. For this reason, no statistical analysis was performed.

Results

The initial search yielded 502 studies. After removing the duplicates and by reading abstracts based on exclusion and inclusion criteria, a total of 13 relevant studies were chosen. In proper terms, to be considered an AR device, the system should comprise the following three components: a computational unit with a rendering module engine, a display unit (e.g., two-dimensional, three-dimensional, wearable, hand-held, etc.), and a tracker unit (embedded or external) [7-10]. Yet, the authors included in the selection also two studies that did not comprise all the key components [11,12] but whose content explicitly referred to an AR surgical navigation system.

In one out of thirteen studies, in-vitro experiments were performed, while the rest of the studies were carried out in a clinical setting including pancreatic, hepato-biliary, and urogenital surgeries.

AR: technical implementation

We have classified the thirteen papers by means of a set of classes and sub-classes derived by the taxonomy proposed by Kersten et al. in 2010 [5]. The results of this classification are reported in Table 1. In this section we will analyze each factor (real data source, virtual data source, AR visualization modality, tracking modality, registration technique, AR display modality and accuracy) and we will describe in more details the solutions proposed in the selected papers.

Real data source

With the term real data source, we refer to the specific means used to acquire real-views of the surgical field. In most of the studies, AR was implemented through video see-through (VST) mechanism, hence an external camera was used as capture tool. In five studies, the real surgical field was captured by means of an exoscope [13,14] or of a stereoscope [15-17]; in [18,19], a fluorescence camera (FC) was used as real data source and the operator could switch between white light or near-infrared light mode. In [20], a simple RGB camera was used. In [21], the camera of a commercial hand-held device (iPad) was used as real data source. In [22], the real world was captured by a pair of stereo cameras rigidly anchored to the head mounted display (HMD) with an anthropometric interaxial distance. Differently from the other VST approaches, this solution allows to reduce the parallax shift between the acquiring camera and the user's own viewpoint.

Finally. in the remaining two studies, an optical see-through (OST) approach was adopted, hence the user's own eyes were the actual real data source [12,23].

Table 1: Studies about augmented reality in open surgery

Author	In-vivo/ In-vitro	Subspeciality	RDS	VDS	VPM	Tracking modality	Tracking body site	Registration techniques	AR Display Type / Submodality	Acc	FR
Ferrari V. et al. 2009	In-vitro	NILL	Stereo cameras	CT	Mesh representation of the anatomical structure	OT of the phantom	Phantom (at least three or more radio opaque markers)	Marker-based automatic registration	HMD / VST	Mean FRE 3.47 mm	25 fps
Gavaghan KA. et al. 2011	In-vivo, Ex-vivo	Liver surgery	User eye	CT	Mesh representation of the anatomical structure	OT of the IOD, which is preoperatively calibrated to estimate its extrinsic parameters in terms of pose in the optical tracker reference system	Image overlay display (4 Passive markers)	Anatomical landmark based rigid registration using CUSA surgical tool	Patient / OST	None	20 Hz
Okamoto T. et al. 2013	In-vivo	Hepatobiliary surgery	RGB camera	CT	Mesh representation of the anatomical structure	OT of the VST system	Video camera (set of optical markers)	Point based registration using a stick-like shape pointer	2D monitor / VST	None	None
Marzano E. et al. 2013	In-vivo	Artery first PD	Exoscope	CT	Mesh representation of the anatomical structure	None	None	Manual registration	2D monitor / VST	None	None
Onda S. et al. 2013	In-vivo	Hepatobiliary surgery and Distal pancreatectomy	Monoscope or stereoscope	CT	Mesh representation of the anatomical structure	OT of the scope	Monoscope or Stereoscope (set of optical markers)	Paired-point based registration through anatomical landmark points of visceral organs using an Optotrak pen-probe with 24 IRED markers	2D or 3D monitor / VST	None	None
Onda S. et al. 2014	In-vivo	Subtotal stomach-preserving PD	Stereoscope	CT	Mesh representation of the anatomical structure	OT of the scope	Stereoscope (set of optical markers)	As in Onda S. et al. 2013	3D monitor / VST	6.2 mm	None
Okamoto T. et al. 2015	In-vivo	Hepatobiliary and pancreatic surgery	Stereoscope	CT	Mesh representation of the anatomical structure	OT of the scope	Stereoscope (set of optical markers)	As in Onda S. et al. 2013	2D monitor / VST	None	None

Table 1 (continued)

Author	In-vivo/ In-vitro	Subspeciality	RDS	VDS	VPM	Tracking modality	Tracking body site	Registration techniques	AR Display type / submodality	Acc	FR
Ntourakis D. et al. 2016	In-vivo, Ex-vivo	Chemo followed by CRLM	Exoscope	MRI, CT	Mesh representation of the anatomical structure	None	None	Manual registration	2D monitor / VST	5.0 mm	None
KleinJan GH. et al. 2016	In-vivo	Urogenital surgery	FC	SPECT / CT	SPECT based target (SN)	OT of the patient, FC	Reference tracker contains three fiducials placed on the patient and FC	Marker-based registration through IR markers anchored to the patient and FC	2D monitor / VST	None	None
Borgmann H. et al. 2017	In-vivo	Urogenital surgery	User eye	CT	CT scan displayed on the upper right corner of the Google glass	None	None	None	HMD / OST	None	None
Sauer IM. et al. 2017	In-vivo	Hepatectomy	User eye	CT	Mesh representation of the anatomical structure	None	None	None	HMD / OST	None	None
Tang R. et al. 2017	In-vivo, In-vitro	Open radial HCAC	RGB camera	CT, MRCP	Mesh representation of the anatomical structure	OT through template marker ("2D code pattern") of the patient	Liver (4 3x3 cm 2D code patterns)	Four 2D code pattern-based registration with manual adjustments based on IOUS 3D scanning	Handheld display / VST	None	None
Van Oosterom MN. et al. 2018	In-vivo, Ex-vivo	Urogenital surgery	FC	SPECT/ CT, fhSPECT	SPECT based target (SN) and 3D numerical value depicting distance from the calibrated probe tip to the middle of the targeted [illegible]	OT of the patient, FC and probe	Patient, FC and probe (3 infrared markers)	Marker based registration through IR markers anchored to the patient, FC and scope	2D monitor / VST	-3D T-T distance acc 2.1 mm - 3D AR registration acc 1.1 mm	None

RDS real data source, *VDS* virtual data source, *VPM* visualization processing modality, *Acc* accuracy, *AR* augmented reality, *FR* frame rate, OT optical tracking, *FC* fluorescence camera, *PD* pancreaticoduodenectomy, *IOUS* intraoperative ultrasound, *HCAC* hilar cholangiocarcinoma, *SN* sentinel lymph node, *OST* optical see-through, *VST* video see-through

Virtual data source

In AR-based IGS systems, the initial step of the workflow is the 3D geometric model of the anatomy, performed by processing the preoperative radiological images. Usually these reconstructions of the anatomy (i.e., the virtual data) are generated by manually or automatically segmenting radiological images of the abdomen. In ten out of thirteen studies [11-17,20,22,23], the virtual data source was preoperative computed tomography (CT) scan.

In two studies, virtual data was elaborated from Single-photon emission computed tomography (SPECT) [18,19], in one study magnetic resonance (MR) images were used as a medical reference and to amend the CT-based reconstruction [21].

In three studies, CT slice thickness of range 0.5 mm to 1 mm were used for the reconstruction of the CT data [16,17,21], whereas rest of the studies didn't mention any CT scan property.

AR visualization processing modality

In AR-based surgical navigation systems, according to the DVV taxonomy [5,24], the output of the visualization processing modality represents the type of virtual content introduced to aid the surgeon throughout the surgical task. Depending on the specific surgical scenario considered, the semantic of the visually processed data may be anatomical, that is dealing with the anatomy or pathology of the patient, operational, that is in relation to the surgical act during different stages of the surgery, or strategic, that is dealing with data primitives associated to the surgical planning (e.g. lines, points, contours, geometric shapes).

In most studies virtual content was presented with an anatomical semantic, as the anatomical structures involved in the surgery: tumors, pancreas, liver, vascular structures [11-18,20-23]. In two of these studies [15,20], a strategic semantic, in the form of a preoperatively estimated resection line, was also displayed as a virtual content. In one study, operational semantic in addition to anatomical semantic was displayed as a numerical value depicting the distance from the calibrated probe tip to the middle of the targeted tissue [19].

Tracking modality

The choice of the tracking modality used in surgical navigation systems is highly application dependent and requires an understanding of the working setup, volume and accuracy. Nine out of the thirteen studies included in this review were based on an optical tracking modality [15-23]. In four studies tracking was not performed [11-14].

As for the studies in which optical tracking was performed, in two of them standard RGB cameras were used [21,22] while in rest of the studies infrared cameras were used [15-20,23]. Frequent advancements and use of infrared technology in the operating room, make it more robust than visible light trackers under uncontrollable lightening conditions in the operating room [25].

Nevertheless, also infrared tracking systems may encounter few problems when FC is used to capture the surgical field. For instance, in two studies [18,19], an infrared tracker of a commercial surgical navigation system (declipseSPECT) was used to track the patient and the FC. Here, when fluorescence imaging was performed in the near-infrared mode of the FC, flickering interference was occurring due to the overlapping of the wavelengths between the near-infrared light emitted from the optical tracking device and the emission spectrum of the ICG (near-infrared fluorescence dye). This flickering could be blocked only by covering the tracking light source, therefore the fluorescence imaging could not be performed while the infrared tracking was on [18]. Thus, registration had to be repeated if the camera was moved.

Moreover, surgical navigation systems based on external infrared trackers have the major drawback of introducing unwanted line-of-sight constraints into the operating room and of adding error-prone technical complexity to the surgical procedure [25,26].

In all the studies involving infrared tracking modalities, an optical reference (composed of infrared markers and/or a reference frame) was attached to the body to be tracked. In [23], a tracking reference composed of four markers was attached to the image overlay device and the projector was calibrated to define the transformation from the projector to the reference frame (i.e., hand-eye calibration approach). In three studies [15-17] optical tracking of the monoscope or stereoscope was carried out through the attached markers. In these works, we believe that a pre-operative hand-eye calibration had to be performed to associate the acquiring camera reference system to the tracker reference system. However, no details are given in the text on this key aspect. In [20], an optical location sensor was installed to measure the position of the video camera; yet, no further information is provided in the study regarding the needed calibration.

Among RGB cameras-based tracking modalities, Tang et al. performed the tracking of four 2D code patterns (3x3 cm size, placed on the patient's liver) by using iPad camera, whereas no tracking was needed for the in-vitro part of the study which involved the use of an integral videography image overlay device [21]. As for the in-vivo part of the study, authors reported that the positioning of 2D code on the liver surface covered some part of the surgical view and that this could limit the effectiveness of the navigation method.

Finally, in [22], stereo tracking was performed based on three colored markers attached on the patient's skin.

Registration technique

The accurate AR visual registration between the computer-generated image and real surgical view is an extremely important aspect in AR-based IGS systems. The simplest method to perform patient-to-image registration is to do that manually. Manual registration can be carried out by aligning virtual and real images based on visible landmarks as reference. This method is very slow, user-dependent, and it requires a continuous interaction between the surgeon and a technician to update the AR scene. The other way to perform manual registration is to preoperatively measure the position of selected landmarks on the surgical region of interest by using a tracked pointer; by knowing the position of the landmarks in both the navigator reference system and the virtual scene reference system we can estimate the registration matrix. This method also counters few problems and it must be repeated whenever organ deformation occurs. In automatic registrations based on artificial fiducials, the set of markers (superficial or bone-implanted) placed on the patient's body can be used to accurately register AR images intraoperatively by determining their position through the external camera. The patient-to-image registration matrix can be computed in real-time if the position of the markers is given (and fixed) in the radiological reference system. For this reason, usually in this method the reference markers must be anchored on the patient's body before undergoing radiological examination, so their position on the medical images can be easily retrieved. However, if markers are not bone-implanted, their positioning over the patient is hardly maintained during surgery, which make automatic marker-based registration techniques prone to uncertainties.

Automatic registrations based on surface reconstruction are ideally more accurate than marker-based registration [27,28], but they are still difficult to implement with respect to the other methods.

In two studies, real and virtual images were registered manually by a computer scientist whose task was to align few anatomical landmarks so that their real and virtual appearance are properly aligned in the augmented image [13,14]. In two studies, the authors described a standard point-based rigid registration based on anatomical landmarks. The surgeon performed the registration manually by means of a surgical pointer [20,23]. During surgery if liver deforms, the acquisition of the landmark position and the registration steps must be repeated. A similar method was adopted by the authors in [15-17], even if by means of a commercially available NDI Optotrak pen-probe by using 24 IRED (infrared emitting diode) markers. In some of the surgeries, blood vessels landmarks were used in place of soft tissue landmarks to improve the registration alignment. During surgery, if the registration error (Fiducial Registration error (FRE)) was high, registration was repeated [16]. In their subsequent studies, an efficient registration tool was developed where FRE of all possible fiducial point combinations was calculated and displayed in the descending order. However, because FRE relies only on the geometric alignment of the fiducial points registered, the overall registration accuracy had to be checked by looking at the augmented images. After, the high rank FRE navigation images were displayed on a quad split monitor display, and the best image in terms of real-to-virtual alignment was then selected by the user [15,17].

In [21], four 3x3 cm 2D code patterns were placed on the surface of the liver for patient-to-image registration using an iPad. Manually refinement of the registration was performed by moving the code patterns. If during surgery, registration become unstable, ultrasonography was performed to visualize the internal hepatic structure for 3D image correction and registration was repeated. A 3D-printed model of the patient's biliary duct and vascularization was also used intraoperatively as a surgical reference, rigid registration between 3D-printed model and reconstructed 3D images was performed by using a pointer. In two studies [18,19], registration was achieved by anchoring the reference tracker containing three infrared markers to the patient bone (pubic or iliac) before undergoing CT. In [22], marker-based registration was performed by placing three radio opaque markers on the patient's skin (abdomen).

In two studies, the 3D virtual model was not registered to the surgical scene. In one study, the CT scan of the patient was displayed on the upper right corner of the surgeon's field of vision to assist during surgery [11], whereas in [12] the 3D model of the patient's liver, was positioned above the surgical site, having no interference with the surgeon's line of sight.

AR Display Type

Augmented reality can be displayed on the wide range of displays, it can be an external monitor, handheld display, HMD or a patient itself (projection). Using the external monitor, the surgeon must divert attention from surgical site to the monitor to gather the augmented information that will be mentally transferred to the surgical field. In the case of direct view of AR on the patient, AR scene can be directly projected on the patient [23] or displayed on the device (tablet) [21] placed in the line of sight between the surgeon and the surgical field. In this review, different modalities have been used including 2D monitors, stereo-display 3D monitors, image projection over patient and HMDs. In one study, virtual content was directly projected over the surgical site by means of an image overlay device [23]. In eight out of thirteen studies, AR data was displayed on the 2D VST display; in [21] the authors used a hand-held display (iPad), Okamoto et al. used a VST display developed at their institute, in [13-16,18,19], the display unit was a standard external monitor. In [17], AR was displayed on 3D monitor.

Among all the studies where HMDs were used to display the AR scene, only in [22] a detail description of the VST HMD has been provided. In that study, the visor was assembled by mounting two internal SXGA LCD monitors and a pair of external USB cameras on a commercial visor for mixed reality. In [12], patients 3D model was displayed on the commercially available MR HMD display (Microsoft HoloLens). In [10], Google Glass was used to display the patients CT scan [11].

Accuracy of the method

Unfortunately, there are no standard criteria mentioned in the literature to calculate the accuracy of the positioning of the virtual scene over the surgical scene. Three studies calculate the registration accuracy over the phantom [19,22,23], five studies calculate it over patients, while rest of the studies did not mention system accuracy. Gavaghan et al. reported an approximate error of 8 mm for the complete navigation system, which is the result of 6.3 mm patient registration accuracy obtained in their previous study [29] and 1.3 mm of a mean surface projection accuracy (on phantom) [23]. Van Oosterom et al. reported a 3D tool-target distance accuracy of 2.1 mm and 3.2 mm for SPECT and fhSPECT, respectively, and 2D AR registration accuracy of 1.1 mm and 2.2 mm, respectively on the Phantom [19]. Okamoto et al. observed the residual error of 5 mm between the simulated and real resection line [20]. Onda et al. reported FRE of 10.59 mm in four patients where fiducial registration points were the soft tissues and 6.49 mm in other four patients where landmarks were the blood vessels [16]. In [17], registration accuracy was calculated with FRE; the root mean square between the corresponding fiducial points. The registration accuracy (in terms of FRE) of six patients was 6.20 mm. Okamoto et al. reported a registration error of approximately 7 mm to 12 mm in first two cases, however for rest of the two patients when they changed the fiducial registration points from the margins of the soft organs to vessels, the error rate improves to less than 5 mm [15]. In [13], authors reported an average accuracy of 1.98 mm when AR navigation system was tested on the animal model, whereas under clinical settings position error of 13.3 mm was observed during inspiration phase and this error was reduced to 5 mm in the expiratory phase. In [22], mean FRE of the registration was 3.47 mm.

Frame rate

Navigation system in the surgery requires sufficient video frame rate to provide a smooth and un intercepted video streaming for a surgical intervention. Gavaghan et al. mentioned the 20 Hz frame rate of the navigation system [23]. Ferrari et al. obtained a localization refresh rate of 25 fps [22]. All the remaining works did not report any data regarding the frame rate provided by the AR display.

AR in open surgery: clinical applications

AR in open surgery has found application in pancreatic, hepato-biliary and in urogenital surgery. The use of AR during pancreatic surgery was reported by some authors, all describing the usefulness of AR for the identification of the lesions, a safe dissection while preserving the adjacent vessels or organs and a right resection line [15,16]. Moreover, for the pancreaticoduodenectomy (PD), different approaches were described and one in particular is the artery-first approach in locally advanced tumors for the evaluation of invasion of the Superior Mesenteric Artery (SMA). Marzano et al. reported a case of successful use of AR for a PD with artery-first approach and during the isolation of the SMA at its origin; here AR based on a virtual transparency of the vascular and parenchymal structures, was particularly useful to safely perform the hanging maneuver allowing the finding of the correct dissection plane along the right margin of the SMA. Moreover, AR ensured the easy identification of the right hepatic artery, a variation in hepatic arterial anatomy, and so it allowed preventing vascular damages [14]. Moreover, in PD, the early ligation of the inferior pancreaticoduodenal artery (IPDA) before efferent veins has been advocated to decrease blood loss by congestion of the pancreatic head to be resected. Onda et al. reported a successful use of the AR for the early identification and ligation of the IPDA in six patients even if there was no significant difference in operating time and intraoperative blood loss compared to the control groups. The authors claim these indexes depend on many other factors, including body mass index, disease, inflammation, experience of surgeon, and so forth [17]. The use of AR has been described also for distal pancreatectomy by Onda et al. in three cases with a successful identification of the exact location, size, and shape of the tumor as well as the location and course of the vessels and of the resection line [16].

AR has been used also in hepatobiliary surgery for the treatment of primary neoplasm of the liver and biliary tract and for metastatic disease. Onda et al. used AR in two cases of hepatectomy showing the planned resection lines of the liver and allowing the successful identification of the exact location, size, and shape of the tumor as well as the location and course of the vessels [16]. Also, Sauer et al. positioned 3-dimensional reconstructions of the anatomical structures above the operating site of the liver allowing the surgeon to anticipate which vascular structures are close to the line of resection and they tested their system for partial hepatectomies for hepatic metastases, hepatocellular carcinoma, and for living donation liver transplantation [12]. For the treatment of metastatic colorectal cancer, a R0 resection of all colorectal cancer liver metastases (CRLM) is crucial. However, because of the shrinkage of the metastases after chemotherapy, it could not be possible the identification of the missing CRLM intraoperatively by palpation or intra-operative ultrasound (IOUS). Moreover, in case of multiple CRLM it could be difficult the identification of all CRLM by palpation or IOUS. Furthermore, the philosophy of "parenchymal-sparing surgery" have gained popularity and recent data demonstrate equal oncologic outcomes compared to standard treatment. In this scenario, AR with the IOUS, can help the surgeon to obtain a R0 resection because AR could be an excellent aid for the identification of all metastases. Ntourakis et al. reported about the use of the AR for the surgical treatment of CRLM in three patients. All metastases, including the missing CRLM, were removed with non-anatomic liver parenchyma sparing resections with the AR image guiding the resection and identifying the hepatic vascular structures [13]. Tang et al. reported about the use of AR technology in open radical hilar cholangiocarcinoma (HCAC) surgery with concomitant hepatic resection in a patient with obstructive HCAC to assist surgical resection of HCAC and concomitant left hemi-hepatectomy [21]. Okamoto reported about a case of benign biliary stricture in which through AR the exact site of the bile duct obstruction and that of each vessel was overlaid on the operating field image seen on the monitors [20].

AR was also used in urogenital surgery. Two authors described the use of AR for sentinel lymph node (SN) biopsy procedures for penile cancer [18,19]. Borgmann et al. described the feasibility and safety of augmented reality-assisted urological surgery using Google glass [11]. Urologists performed 31 procedures with different levels of complexity ranging from simple (vasectomy) to complex (cystectomy) using the AR HMD. Surgeons used the HMD during surgery for different technical applications: taking photographs/recording videos/live broadcasting for learning, teaching and training; taking photographs/recording videos for documentation; connecting with physicians, nurses and surgeons outside the operative field for hands-free teleconsultation during surgery; reviewing patients' medical records (e.g. history, lab results, ...); reviewing patients' images (e.g. CT scan, MRI, ultra- sound, X-ray); searching the internet (e.g. Google) for online health information. Usefulness was rated high for taking/recording photographs and videos for teaching and documentation ahead of reviewing patients' records and performing teleconsultation.

Discussion

From a clinical viewpoint, AR navigation in surgery has enormous potentialities to help the surgeon in identifying tumor locations, delineate dissection planes and resection margins and to reduce the risk of injury to invisible structures or in case of anatomical variations. The main potential areas of use of AR are those surgical operations where a fine dissection is to be performed while avoiding injury to adjacent structure or for those specific procedures where an accurate localization of the tumor is required. For instance, due to the close relationship between pancreas and vascular structures (SMA, portal-mesenteric and celiac axis, comprising vascular variations), the dissection phase during pancreatic surgery can be particularly difficult and dangerous, AR could play an important role in helping surgeons in overcoming these issues.

AR could also gain a widespread use in hepatobiliary surgery for the treatment of primary neoplasm of the liver and biliary tract but also for treating metastatic disease. The main reason is related to the importance of the knowledge of the vascular and biliary tract anatomy (with their multiple variations) and its relations to tumors.

However, while pancreas is a retroperitoneum organ with a relatively insignificant organ shifting or deformity, intraoperative deformity of the liver is a problem that could limit the use of the AR in open abdominal surgery.

The few data about the use of AR in urogenital procedure indicate its usefulness, particularly for the individuation of SN during surgery for penile cancer. This application could be of interest in patients with increased fatty tissue surrounding the SNs since the limited tissue penetration of the fluorescent signal could not be always sufficient to optically identify the SNs via fluorescence guidance.

In general, in the context of open surgery, AR has not yet been explored as much as in the surgical specialties, such as open abdominal and urogenital surgeries. This is mostly due to technical and usability reasons. As for the source of the real view of the surgical field, the main distinction is between (VST and OST) systems that rely on camera-mediated view of the world (VST systems) and those who rely on the augmentation of direct views of the surgical field (OST systems). Due to technological and perceptual limitations, the degree of adoption of the OST HMDs in many applications has slowed down over the years [30,31]. The OST paradigm is particularly suitable for augmenting the reality by means of simple virtual elements (models, icons or text labels) but shortcomings remain both from a technical and a perceptual standpoint, especially in case of virtual contents of greater complexity.

In VST systems, images captured by the cameras usually have viewing perspective different from that of the user, introducing a parallax between the would-be-seen image and the effectively acquired image. However, in VST displays the visual experience of both the real and virtual content can be unambiguously controllable by computer graphics, with everything on focus at the same apparent distance from the user. In VST systems, real scene and virtual information can be synchronized, whereas in OST devices there is an intrinsic lag between the immediate perception of the real scene and the inclusion of the virtual elements.

Depending on the specific surgical scenario considered, the semantic of the visually processed data could be anatomical, operational, or strategic. It is necessary to display only essential virtual details because the overlapped virtual data may hide the actual surgical field. In HMD AR applications, one of the important aspect is to adjust the opacity of the displayed objects, which could allow the surgeon to turn off the augmented content and to remove any possible distraction faced during surgery.

However, when dealing with soft tissues surgeries, deformation of the organs occurs significantly during surgery, which limits the performance of the AR. It is important to address this problem by constantly updating the virtual scene by performing CT, ultrasound or MRI intraoperatively. One should consider the shortcomings of some techniques, such as, when undergoing a CT scan, the patient is exposed to radiation, therefore, it can only be performed in a limited number of times.

Talking about the tracking modality, the choice of the tracking modality used in surgical navigation systems is highly application-dependent and it requires an understanding of the working setup, volume, and accuracy. In the literature, several studies used infrared trackers [15-20,23], which involves the tracking of the patient, camera or surgical scope.

The main advantage of this modality is the clear visibility under different lighting conditions. Infrared tracking systems may encounter few problems, specifically when fluorescence imaging is performed in the near-infrared mode of the FC, flickering interference may occur due to the overlapping of the wavelengths between the near-infrared light emitted from the optical tracking device and the emission spectrum of the ICG. A visible light tracking (RGB camera) carried out by Ferrari et al.[22], involved using radio opaque markers attached to the patient skin. The tracking of these type of markers is very sensitive under uncontrollable lightning conditions in the operating room, yet not explored very much in open surgery. Commercially available tracking systems for AR in open surgeries are mostly relied on the infrared tracking. In the future, it may be possible to track the visible organ in real time without using markers. These approaches are based on the real time estimation of the organ deformation for adjusting the image registration to the organ movement. Other approaches based on the employment of electromagnetic sensors are being investigated in in-vitro tests with hybrid simulators for cholecystectomy [32,33].

The accurate AR visual registration between the computer-generated image and real surgical view is an extremely important aspect in AR-based IGS systems. The patient-to-image registration is usually done manually or by using a set of markers attached to the patient's body and/or camera. However, if markers are not bone-implanted, their placement over the patient is hardly maintained during surgery, which make automatic marker-based registration techniques prone to uncertainties. Additionally, these methods counter few problems and registration must be repeated whenever organ deformation occurs. Another possibility is automatic registration based on surface reconstruction [34-36], but this method is very difficult to implement, specifically in soft tissues surgeries where organ deformation occurs constantly.

Though the use of AR in open surgery has not significantly improved the operation time and blood loss with respect to the conventional procedures, the reported studies proved that it can help the surgeon delineating dissection planes and resection margins with less risk of injury to the organs. The advancement in the technology are likely to improve the clinical outcomes due to the use of AR, also in open abdominal surgery.

Conclusion

AR represents a ground-breaking improvement in the context of IGS. Computer-generated data derived from radiological images and directly superimposed onto the surgical field view can aid the surgeon in performing the procedure. Current literature confirms that as in craniomaxillofacial surgery, neurosurgery, and in orthopedic surgery, also in open surgery AR is starting to spread as a promising tool, although prospective randomized studies have not yet been published.

In this paper, we have discussed the use and importance of AR in open surgery and issues and challenges related to the implementation of each component of AR system. The study finds that AR is an effective, reliable and promising tool under open abdominal surgery. However, further advancement is much needed in improving the AR system performance, making them robust across different surgeries. An intraoperatively constant updating of virtual model is needed to overcome the organ deformation issue, resulted in registration inaccuracies. Use of other imaging techniques such as intraoperative ultrasonography, MRI could provide additional information to the virtual model. Currently, a manual input is given to AR system to perform the patient-to-image registration, an improvement in the registration technique is needed to make AR system fully automated. Displaying frequency of AR system is also of concern because lower frame rate results in lower precession and un comfort visualization.

Compliance with Ethical Requirements: The authors confirm that no animal nor human testing were performed in this study.

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