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Contribution of Augmented Reality to Minimally Invasive Computer-Assisted Cranial Base Surgery

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***Abstract*— Cranial base procedures involve manipulation of small, delicate and complex structures in the fields of otology, rhinology, neurosurgery and maxillofacial surgery. Critical nerves and blood vessels are in close proximity of these structures. Augmented reality is an emerging technology that can revolutionize the cranial base procedures by providing supplementary anatomical and navigational information unified on a single display. However, the awareness and acceptance of possibilities of augmented reality systems in cranial base domain is fairly low. This article aims at evaluating the usefulness of augmented reality systems in cranial base surgeries and highlights the challenges that current technology faces and their potential solutions. A technical perspective about different strategies employed in development of an augmented realty system is also presented. The current trend suggests an increase in interest towards augmented reality systems that may lead to safer and cost-effective procedures. However, several issues need to be addressed before it can be widely integrated into routine practice.**

***Index Terms*— augmented reality, otology, rhinology, cranio-maxillofacial surgery, skull-base surgery, image-guided surgery.**

I. Introduction

DURING the last two decades, augmented reality (AR) has gained immense popularity but its use in the operating room is still under development and investigation. Unlike virtual reality which completely replaces the user's environment with a simulated one, AR is an interactive environment in which physical objects are augmented by computer generated virtual information. These auxiliary cues can be in different forms: visual, audio, haptics, taste and smell. AR systems can be classified into two types, based on the level of the sensation of being inside a particular environment: immersive (direct) and semi-immersive (indirect). Immersive AR refers to the systems in which the user visualizes real environment directly and additional information is projected over the environment. Whereas semi-immersive AR refers to the systems in which the user is partially disconnected from reality and cannot receive the proprioception information directly on his body. In the operating room, AR can theoretically be delivered through goggles, screens, loud-speakers, gloves, joysticks or co-manipulated robots, etc. In this field, the usefulness of the information, its reliability, the user-friendliness, as well as its ergonomic aspects are paramount.

AR was first described in 1960s under the title of *Experience Theater* which involved overlaying a physical room with digitized objects [1]. The early systems targeted entertainment and gaming industries. Other sectors have shown great interest in the technology ever since. New innovations in the field have paved way for the technology to be introduced in the surgical domain. AR allows surgeons to incorporate additional pre or intra operative data into the physical surgical field thus improving localization and approach, treatment, efficiency and safety. Traditional imaging schemes such as conventional X-ray, computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET) and ultrasound (US) or advanced imaging modalities such as functional MRI (fMRI) have allowed surgeons to better visualize and understand the diseases and to preplan their actions in the operating room. New developments have accelerated the image acquisition: the final goal being to operate these systems in real-time. Today, conventional CT-scan, MRI, ultrasound and Cone-Beam CT (CBCT) can be used within the operating room, requiring less than one minute for image acquisition in a small field [2].

Any image-guided surgical system follows three basic principles: localization, orientation and navigation [3]. (a) Localization defines the task that needs to be performed and determines the locus of the target e.g. a tumor, an anatomical structure, an abscess or a foreign body (such as an instrument or an implant). (b) Orientation defines the relationship between the current locations of the patient with respect to the surgical instruments. (c) Navigation refers to the process of guiding the surgical instruments to perform the desired task such as tissue resection, tissue repair, fluid injection or implant positioning. Surgeons have endorsed image-guided interventions as a means to avert perceptual distortions that downplay the impact of traditional imaging schemes such as endoscopy and microscopy. Image-guided interventions have proven to outperform conventional procedures both in terms of better outcomes and reduced complications [4]. Supplementary tools such as haptic feedback devices, tele-manipulated robotic manipulators and enhanced image displays are being developed to further enhance the potential

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of image-guided interventions [3, 5].

The principal interest of AR in surgery is the ability to see through structures and access hidden information without interfering with the surgical process. AR has been employed in surgical planning, intra operative imaging, surgical navigation and target structure localization [4, 6, 7]. It can particularly be useful in highlighting critical structures, pathologies and risk regions in an intuitive manner. AR also has the potential to facilitate minimally invasive procedures by allowing the surgeons to visualize structures without exposing them [8-10]. The main advantage that AR based procedures enjoy over traditional image guidance procedures is the significant improvement in ergonomics of the system. With AR, everything is available on a single view thus eliminating the need for the surgeon to go back and forth between different sensorial systems (Fig. 2).

Most of the articles on AR surgical systems available in literature have targeted applications in orthopedic [11-13], neurologic [14-16], hepatobiliary and pancreatic [17, 18] surgeries. This is mostly due to the fact that these types of surgeries involve very limited organ movement and deformation. (For details on general augmented reality applications in the operating room and other surgical applications, please refer to the following recent studies: [19-20].) Although this holds true for cranial base procedures, due to limitations in workspace, maneuverability and direct access to the anatomy coupled with high precision demands (typically 1-2 mm), AR has not been very successfully applied in this domain.

Some review articles are available in the literature with some degrees of overlap with this article that provide interesting information on applications of AR in otolaryngology, neurosurgery and maxillofacial surgery [22-25]. However, these reviews are focused on applications rather than the technical characteristics of the available systems. All the above-mentioned surgical specialties deal with a large variety of anatomical regions (nose, ear, neck, cranium, vertebral column), a multitude of surgical setups and different navigation requirements. Contrarily, in this review paper, we describe the specific challenges in the field of skull base surgery, the role of computer-assisted navigation and the possibilities offered by AR to enhance navigation in this field.

Cranial base surgery is one of the domains which has most benefited from the progress in the imaging technology [26]. This region separates the brain and the posterior fossa (cerebellum and brainstem) from the mid facial region and the neck. It gives passage to a multitude of cranial nerves and vessels with vital functions (Fig. 1). Several sensory organs such as nasal cavities, ears and eyes are also in the vicinity of the cranial base. Therefore, carefully comprehending the relationship between bony structures and soft tissues is indispensable [27, 28]. Operations in the cranial base region often require reestablishing aesthetics and functional anatomy by implants or by grafting, contouring or displacing skeletal elements [3].

The anterior skull base is frequently approached through the nasal cavities by rigid endoscopes introduced through the nostrils. The surgical view is provided on a screen in front of the surgeon. Navigating in this region requires a fine knowledge of anatomical landmarks, and a significant capacity of 3D orientation based on a 2D image and the endoscope orientation. In many cases, the anatomical landmarks are modified or missing due to previous surgeries, the disease or excessive bleeding [29]. A millimetric precision is required to avoid vital (carotid artery, intracranial space) or major functional structures (orbit). Consequently, surgeons continue to use computer-assisted navigation for the access to the anterior skull base as a reliable tool despite several years of training and experience [30]. A second screen is set to display the preoperative images and the location of the instrument. They confront the information provided by the system to their judgment based on anatomy in real-time in order to validate their decisions [30].

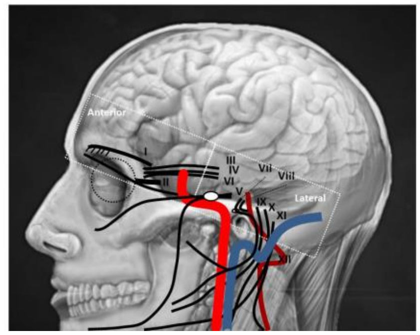

Fig. 1. Schematics of the cranial base region with the projection of cranial nerves (I to XII), and the major vessels: the carotid artery (light red), the sigmoid sinus (blue), the vertebral and basilar arteries (dark red).

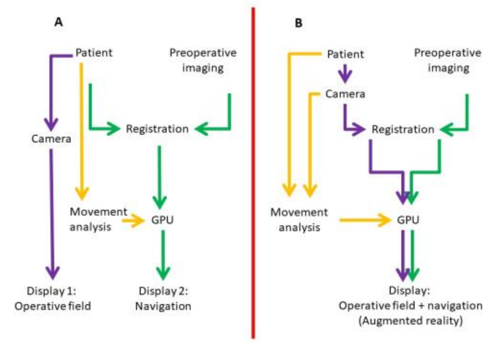

Fig. 2. Comparison between the structures of conventional navigation system (A) and a navigation system integrating augmented reality (B). GPU: Graphic processing unit.

The lateral skull base is frequently approached through the petrous bone which contains the ear and major vessels (carotid artery, sigmoid sinus). This region requires a quite different training, instrumentation and surgical setup. Neurotologists drill the petrous bone under a surgical microscope uncovering, layer by layer, the anatomical structures as they progress towards the cerebellopontine angle and the intracranial space in a pyramidal space [31]. Although the microscope offers a 3D vision of the field, navigation and orientation requires several years of experience and training since there is huge inter-individual variability in the size and the position of anatomical elements in a temporal bone [32]. Similar to the nasal cavities, destruction of the landmarks by disease and the

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management of bleeding, cerebrospinal fluid and bone dust may hamper the progression. In contrast to the anterior skull base approaches, following a navigation screen while operating under microscope raises significant challenges. Both fields have a common positive aspect: they are composed of rigid non-articulated bony structures. This makes the computer-assisted navigation relatively precise in comparison to navigation in soft tissues.

With a more precise diagnosis and preplanning, the approaches to this region have become less invasive. The mortality and the morbidity of the interventions have been significantly reduced [33]. Until the '90s, a conventional approach to the anterior cranial base required a frontal craniotomy associated to one or several bone flaps in the mid facial region [34]. Today, thanks to the imaging-based preplanning, the majority of procedures can be conducted by endonasal endoscopy through nostrils and no visible scars [35]. For the lateral cranial base which mainly involves the temporal bone and the posterior fossa, approaches have become more selective and the use of endoscope combined to a key-hole route has become routine in many diseases [36].

Computer assisted surgical planning has proved highly advantageous when dealing with complex interventions in the cranial base area. In this region, the anatomical landmarks can be absent or disappear with the disease. The exposure of the target and the avoidance of vital structures through a key-hole access solely based on vision can be difficult and dangerous.

However, until today, the preplanning data is often confronted to the surgical view in the surgeon's mind and not on an integrated interface. By augmenting the surgical viewpoint with preoperative imaging information, the surgeon has the opportunity to incorporate his knowledge (target and structures to avoid) with enhanced patient-specific landmarks to develop optimal surgical workflow [5]. A typical AR surgical schematic is shown in Fig. 2.

This review article evaluates different methods that have been reported pertaining to AR-based procedures in a specific anatomical domain (skull base surgery) and discusses different techniques used to address the specific issues in this field. This appeared to us as a more coherent approach than the one based on surgical specialties. To our knowledge, there is no such review available in the literature.

In this systematic review, we will describe the AR contribution to current neuro-navigation systems and its application to the minimally invasive skull base surgery. Then, we will discuss the technical aspects underlying AR. Finally, we will discuss and confront different approaches to AR and touch upon future AR developments before it can be widely accepted in cranial base surgery.

II. Methods

In this study, we performed a systematic review of the available literature dating up to January 2019 in 'Pubmed' using combinations of the following terms: 'augmented reality, image-guided, diagnosis and surgery' with 'cranial base, ear, nose, otology, otolaryngology, rhinology, cranio-maxillofacial, sinus, skull base, nasal, ENT, temporal bone, head and neck, and functional neurosurgery'. The initial search yielded 210 studies. After removing duplicates, reading the abstracts for appropriateness in terms of scope and including 4 additional articles through cross-referencing, a total of 45 studies were included in the review.

III. Neuronavigation

Neuronavigation systems were primarily developed for image-guided tumour resection in neurosurgery. The intricate nature of neuroanatomy required establishing a highly accurate relationship between the patient and different devices and instruments. Current neuronavigation systems display axial, coronal and sagittal views of the patient's preoperative CT or MRI scan on a screen. The location of different instruments relative to the preoperative images are tracked and displayed directly on the anatomical planes [37]. This provides accurate 3D information about different devices to the surgeon.

Neuronavigation is regarded as a standard in cranial base minimally invasive surgery (MIS) where it is increasingly being used to manoeuvre instruments when they are obstructed from view [37-39]. It is well-suited to such applications as the surgical field is mainly comprised of bony structures, making perfect alignment of pre-operative scans operative findings possible. Information from different modalities can also be overlaid on each other intraoperatively for supplemental information [40].

The main drawback of neuronavigation systems is that information is provided on different axes separately and the surgeons have to mentally combine information from different planes to figure out the navigation information. Also, since this information is available on pre-determined axes and not from the direct view-point of the surgeon, difficulties often arise which lead to discomfort and decrease in accuracy [41, 42]. These problems are further amplified by the complicated structural anatomy in the cranial region.

Integration of AR technology into neuronavigation systems can offer immense advantage over traditional neuronavigation, however this technology has not been widely introduced into the surgical setup. A unique methodology that can be used in a range of surgical applications will probably improve general acceptability of AR systems in this field.

Numerous studies have proposed AR-based image-guided navigation systems for endoscopic cranial base surgeries that allowed the surgeons to carry out the procedure with less mental workload. This was achieved by providing virtual boundaries of structures and using an optical tracking system for navigation data [28, 43, 44]. Alternatively, Citardi et al. used an electromagnetic system to provide navigation information on both preoperative CT-scan images and real-time endoscopic video [4]. Critical structures such as optic nerve and carotid artery and pre-planned trajectories were also highlighted for user comfort.

Li et al. and Caversaccio et al. assessed quantitatively the usefulness of AR-based neuronavigation systems in terms of operative time and task load score indexes and concluded the effect to be significantly positive [45, 46]. The impact of AR systems was seen to be much greater in less-experienced

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surgeons. Such systems may also be helpful for teaching and training purposes.

AR has the potential to replace the neuronavigation techniques entirely. Different AR systems are being developed that display navigational information on the primary sources of visualization or directly on the patient/operative view (Table 1) [6, 7, 47, 48]. Robot-based AR systems might also ultimately replace traditional neuronavigation systems [49].

IV. Applications in Minimally Invasive Surgery

Different surgical options are available for cranial base procedures. Open surgery is the most conventional option in which incisions are made in the face and the skull areas to get access to target structures. Despite providing the largest access to the target structures, this strategy causes more tissue damage around the approach, and may entail increased bleeding, infection, pain, complications and longer postoperative stays at hospital [28]. Additionally, the incisions have to be made carefully in order to avoid damaging vital structures present in the region.

Recently, MIS or keyhole surgery has emerged as an alternative to traditional procedures. MIS pertains to the process in which surgical instruments and an endoscope are passed through a small puncture in the skin or skull to access target structures. Although it counters most of the drawbacks cited above, the limited view provided by the endoscope, the lack of haptics and intricate movements introduce new complications: the lack of 3D view may alter the estimation of the target position in relation with vital structures, the lack of haptics may interfere with the assessment of tissue resistance and modify the way the surgeons manipulate them. Moreover, key-hole access may also include injuries along the trajectory since the lateral view in the approach tunnel is nearly absent [50]. These limitations are especially significant in cranial base surgery as it deals with critical vascular and neural edifices within a confined workspace. These factors may influence surgical time and surgeon's comfort and stamina, ultimately leading to a negative effect on the surgical outcome and efficiency [28, 51].

Consequently, tools that improve visualization, location and orientation are highly beneficial particularly when natural anatomy is eclipsed. Surgeons dealing with cranial base diseases use surgical microscope for magnification and focused lighting. The advantage of this tool is the absence of encumbrance in the surgical field, the binocular 3D vision, and the possibility of using both hands for surgery. Although the endoscopes provide a 2D view of a limited field and encumber the route, they can improve other aspects of vision by providing an angled view (30°, 70°) and/or a wide-angle exposure (e.g. Trueview II, Olympus Inc. and Hopkins II, Storz Inc.) [52]. Image-guided navigation can be coupled to both microscope and endoscope: The focal point of the microscope or the tip of the endoscope together with a pointer instrument can be tracked on preoperative images in real-time thanks to infra-red or magnetic tracking of these tools [53, 54]. These developments have enabled MIS procedures to be precise and safe.

AR based MIS procedures have also been found to be effective in improving surgical outcomes and reducing operative time [46]. In otology, AR has been employed for middle ear transtympanic procedures (through the eardrum) and robotic cochleostomy [6, 8, 49]. In rhinology and skull-base surgery, AR has been used to remove cancerous nasal tissues and provide information about critical hidden structures and navigational aids [4, 28, 44, 51, 55, 56]. An example video of an AR based nasal endoscopic system can be found as Supplementary File 1 [51] (under CC BY license). In cranio-maxillofacial procedures, AR has been employed mainly for zygomatic bone reconstruction by providing information about hidden anatomical target structures without needing to expose them [57, 58]. Tables 1 and 2 describe different AR surgical systems for conventional and MIS cranial base procedures respectively and these systems are detailed in the following sections.

In most AR based MIS applications, virtual information from pre-operative data is overlaid onto the real endoscopic camera view. The view outside the endoscope view remains unknown to the surgeon. To counter this, Bong et al. and Li et al. developed image-guided navigation systems for endoscopic sinus and skull base surgery which provided an extended view of the surgical area (Fig. 3) [28, 45]. The endoscope view was displayed in the middle whereas the structures outside the endoscope view were portrayed as virtual reconstruction of pre-operative CT data.

Several teams have reported on the use of AR in real operating room conditions for skull base surgery [43, 46, 48, 56-61]. These encouraging publications indicate that after improvement and training AR can be used more routinely and in a progressively broader variety of surgical scenarios.

V. Techniques

Various technical approaches to AR are available in other domains, but these solutions have to be selected and adapted to the field of skull base surgery respecting the ergonomics, and the need for precision, reliability and security in this particular domain.

In image-guided procedures, it is necessary to define a 3D world coordinate system within the operation room that will be used as reference. This is normally achieved through tracking devices that track the patient, the instruments and other devices [62]. These devices should not hinder the surgical process. The main factors that influence the choice of equipment and algorithms are the registration time and the tracking accuracy. Clinically, 5-10 minutes of registration and 1-2 mm precision are regarded as acceptable ranges in cranial base domain [51].

Conventional image-guided navigation systems do not provide the virtual information directly on the operative view, thus increasing the mental workload of the surgeon who has to relate navigational information with the surgical viewpoint. This potentially leads to an increase in surgical time and error. Majority of commercially available AR systems exhibit accuracies larger than 1-2 mm making them improper for the cranial base procedures. Different systems have been proposed

TABLE I
TECHNICAL SPECIFICATIONS OF AR-BASED GENERAL CRANIAL BASE PROCEDURES

Study	Application	Test Subjects	Hardware	Registration	Motion Tracking	Instrument Tracking	Display	Specifications
Murugesan et al. [7]	*Maxilla*	*8R*	*CT, stereocamera, translucent mirror*	*Enhanced ICP algorithm*	*TLD on bounded boxes followed by ICP*	*NS*	*IVD*	*OR: 0.2-0.6 mm FR: 13 fps*
Citardi et al. [4]	*Endoscopic sinus dissection*	*4C*	*CT, EM surgical navigation system*	*Contour based*	*Image based*	*EM*	*Monitor*	*TRE: 1.5 mm*
Wang et al. [59]	*Maxilla*	*1H, 1R, 1P*	*CT, camera,OTS*	*Enhanced ICP algorithm*	*Optical flow based TLD on bounded boxes followed by ICP*	*NS*	*NS*	*OR: 1 mm FR: 5 fps*
Cabrillo et al. [48]	*Inferior clivus chordoma*	*1H*	*CT, MRI, microscope*	*Surface matching*	*NS*	*NS*	*Ocular*	*NS*
Cho et al. [47]	*Middle and inner ear*	*5A*	*OCT, stereomicroscope, beam splitter*	*Beam splitter optics*	*Beam splitter optics*	*NS*	*Ocular*	*NS*
Dixon et al. [75]	*Transphenoi-dal skull base surgery*	*1C*	*CT, endoscope, OTS*	*Marker based*	*Optical*	*Optical*	*Monitor*	*TRE: 2.6 mm*
Inoue et al. [43]	*Brain tumour*	*3H*	*MRI, camera, OTS*	*Point matching (fiducial markers)*	*Optical*	*Optical*	*Monitor*	*FRE: 1.7 mm OR: 2-3 mm*
Essig et al. [60]	*Head and neck tumours*	*1H*	*CT, OTS*	*Point matching (fiducial markers)*	*Optical*	*Optical*	*Monitor*	*FRE: 1.3 mm*
Birkfellner et al. [66]	*Skull base surgery*	*1P*	*CT, binocular HMD, OTS, VISIT surgical*	*Point matching (fiducial markers)*	*Optical*	*NS*	*HMD*	*FRE: 0.9 mm FR: 40 fps*
Freysinger et al. [61]	*Paranasal and frontal skull base surgery*	*79H*	*(US, ISG viewing wand) OR (CT/MRI, ARTMA virtual patient and endoscope)*	*Point matching*	*Mechanical or EM*	*EM*	*Monitor*	*FRE: < 2 mm FRE: 3 mm*

NS = Not specified, H = Human, P = Phantom, C = Cadaver, A = Animal, R = Recoded video of human, IVD = Integral videography display, HMD = Head-mounted display, ICP = Iterative closest point, TLD = Tracking learning detection algorithm, FRE = Fiducial registration error, TRE = Target registration error, OR = Image overlay error, FR = Frame rate, fps = frames per second, EM = Electromagnetic, OTS = Optical tracking system.

for specific cranial base procedures that take into account the specific requirements of this surgery. Most of the systems adopted electromagnetic or optical tracking devices that require additional reference frames and markers attached to the patient and the surgical instruments. In most cases, the patient's head is immobilized in a clamp connected to a tracker.

Recent developments in hardware (e.g. more powerful graphic processing units), computer vision (e.g. new image processing algorithms such as feature and optical flow-based tracking [63, 64]), artificial intelligence (e.g. faster and more sophisticated neural networks [65]) and robotics are progressively integrated into the framework and have benefited the surgical domain. The details of different systems will be discussed in the following subsections.

A typical AR surgical system comprises the following processes: device calibration, initial registration, motion tracking, instrument identification and tracking, and visualization scheme. Reported systems differ in each of these processes and the following subsections provide a comparison.

A. Calibration

Calibration is one of the most important processes in such a system. It is the process of configuring different instruments so that they provide a result within an acceptable range. The basic idea is to use real world objects with pre-known positions as reference. Different subsystems such as image capture and display devices, navigational pointers, external tracking systems and surgical instruments need to be calibrated before they can be used.

Every computer assisted system requires a robust calibration procedure for accuracy. For some systems, calibration has to be performed before every surgery (e.g. systems that require patient specific calibration [48]) whereas for some it has to be performed on first use only (e.g. most of the systems that only require camera calibration [28, 66]).

Earlier AR systems employed point measurement stylus or ISG viewing wand (ISG Technologies, Ontario, Canada) to calibrate the measurement devices [57, 61, 67]. The process consisted of placing the tip of the stylus on different marker positions and recording their positions. Later similar systems

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TABLE II
TECHNICAL SPECIFICATIONS OF AR BASED MINIMALLY INVASIVE CRANIAL BASE PROCEDURES

Study	Application	Test Subjects	Hardware	Registration	Motion Tracking	Instrument Tracking	Display	Specifications
Hussain et al. [16, 8]	*Middle ear*	*4C, 5P*	*CT, microscope/endoscope*	*Point matching (fiducial markers)*	*Image features*	*Color markers followed by KF*	*Monitor*	*FRE: 0.21 mm TRE: 0.2 mm TE: 0.33 mm FR: 12 fps*
Chu et al. [45, 51]	*Endoscopic sinus and skull base surgery*	*3C, 1P*	*CT, endoscope, stereo depth camera, OTS*	*Convex hull based Point cloud matching*	*Optical*	*NS*	*Monitor*	*TRE: 0.77-1.36 mm*
Bong et al. [28]	*Endoscopic skull base surgery*	*1T*	*CT, endoscope, OTS*	*Point matching*	*Optical*	*Optical*	*Monitor*	*OR: 1 mm*
Lapeer et al. [44]	*Endoscopic sinus surgery*	*1C*	*CT, endoscope/microscope, OTS, passive coordinate measurement arm*	*ICP algorithm*	*Optical*	*Optical*	*Monitor*	*OR: 0.8-1.5 mm*
Liu et al. [49]	*Cochlear implant surgery*	*2C*	*CBCT, Da Vinci system*	*Point matching (fiducial markers)*	*NS*	*NS*	*Monitor*	*NS*
Thoranaghatte et al. [46, 68, 71, 86, 91]	*ENT, skull-base, cranio-maxillofacial surgery*	*1C, 1P, 5H*	*CT/MRI, endoscope/microscope, OTS, dental cast*	*Point matching followed by surface matching*	*Optical*	*Optical*	*Monitor*	*FRE: < 1 mm TRE: 2.25 mm OR: 0.7/2-3 mm TE: 1.1-1.8 mm*
Marmulla et al. [58, 81]	*Temporal fossa and intraorbital tumours*	*2H*	*CT, stereocamera, overhead projector, dental splint, OTS*	*Surface matching using structured light*	*Optical*	*NS*	*Projector*	*OR: 1 mm FR: 10 fps*
Kawamata et al. [56]	*Endonasal transsphenoidal surgery for pituitary tumors*	*12H*	*MRI, CT, endoscope, OTS, goggle frame*	*Optical*	*Optical*	*Optical*	*Monitor*	*NS*
Wagner et al. [57, 67, 76, 77]	*Cranio-maxillofacial surgeries*	*27H*	*CT, camera, EM tracking system, ARTMA virtual patient system*	*Point matching (fiducial markers)*	*EM*	*EM*	*HMD and monitor*	*NS*

NS = Not specified, H = Human, P = Phantom, C = Cadaver, T = Test board, HMD = Head-mounted display, ICP = Iterative closest point, KF = Kalman filter, FRE = Fiducial registration error, TRE = Target registration error, OR = Image overlay error, FR = Frame rate, fps = frames per second, TE = Tool error, EM = Electromagnetic, OTS = Optical tracking system.

employed neuronavigation style reference stars to calibrate the devices such as microscopes, endoscopes and navigation devices [48, 51]. These systems use reflective or optical marker arrays attached on a rigid support to the patient with pre-known positions to calibrate different devices and the patient. Different types of casts have been proposed to attach these markers e.g. rigid frames directly attached to the skull by screws or headband, frames attached to the Mayfield clamp which itself is attached to the skull or frames affixed in the teeth via a dental impression tray [57, 58, 68].

The most popular calibration approach in the medical domain is the photometric calibration technique [6, 43-45, 68]. It involves observing a calibration object (from different viewpoints) whose physical geometry in 3D space is pre-known to determine the intrinsic and extrinsic parameters of the cameras [69]. The calibration object may be a checkerboard pattern or a planar grid. A system that involves two cameras may be calibrated by extracting feature points from the two camera images and matching them [70].

Marker frame techniques provide good accuracies [46, 58]. However, introduction of external equipment introduces complications in surgery and limits instrument maneuverability. Photometric calibration eliminates the use of an external frame and provides a more user-friendly approach [69]. However, when the imaging devices are attached to a microscope, photometric calibration techniques often have limited performance due to the limited range of focus of the microscopic lens. Irrespective of the method that is being

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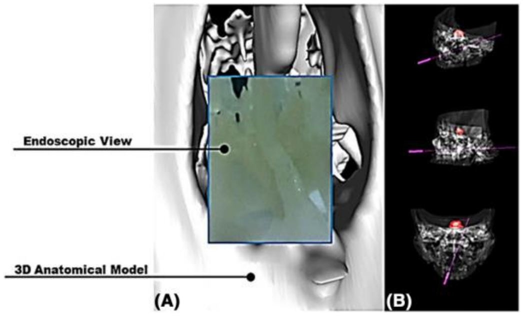

Fig. 3. An example of an AR endoscopic skull base surgical system with an extended field of view [28].

used, immense care needs to be given to the calibration process as it is very important to cover the entire workspace. Otherwise, the precision may be critically affected when subjects move outside the calibrated area. The ideal scenario would be the one which involves no calibration. However, to the best of our knowledge, such systems that comply with high cranial base surgical requirements (ergonomics, security, reliability) are not available.

B. Registration

The first main step in any AR surgical system is the registration which establishes correspondence between different objects and devices and homogenizes them into a single coordinate system. Registration is often represented as a transformation matrix that comprises of rotation, translation and skewing parameters. Registration can be classified in terms of objects (image-patient, patient-instrument), coordinates (2D-3D, 3D-3D) or degree (rigid, non-rigid). The type of registration that an AR system requires depends on the devices being used. Initial registration is the most crucial process in any AR surgical system as any error incurred during this step will propagate throughout the procedure. The most commonly used registration methods are point-based and contour-based approaches (Tables 1 and 2).

Anatomical landmarks may be used to establish patient-image correspondence during the registration [8, 28, 71]. Point-based registration schemes often are fast and require less time for registration. However, anatomical landmarks are difficult to ascertain and track once the procedure starts, as they may shift, or become obscured by fluid, blood or instruments. Furthermore, in cranial base regions, anatomical landmarks are not so apparent and complications may be introduced in selecting them. Moreover, this approach is not robust, as selecting the same landmarks is practically infeasible. Artificial markers that are visible on both preoperative scan and intraoperative imaging can be an alternate option [6, 43, 45, 60]. These may be glued on the skin or anchored on the bones. However, these markers are often required to be attached before the preoperative scan which typically takes place few days before the actual surgery. Markers need to remain static at the same position throughout the treatment process which limits the movements of the patient. Alternatively, markers can be housed on removable rigid frames attached to the patient's skull or teeth. In conventional cranial base procedures, the common choice is to use surgical skull Mayfield clamp for housing different markers. For AR procedures, different types of dental casts and occlusal splints have been proposed that fixate on upper or lower jaws [57, 58, 68, 72]. The reason for using a reference frame that is held by the teeth is so that the frame can be removed and reattached at exactly the same place without any screws or holes. These reference frames may also house markers for registration between patient and different devices. These frames may introduce difficulties in surgeon movement and tool manipulation. Image markers may also be attached to the patient's jaw and used for registration [73]. The use of such markers over fiducial points improves the accuracy as image objects are used instead of defining exact points which is prone to error [74].

Precision may improve by using sharp anatomical landmarks. Surface scanners are being used in surgery since early 2000s and seem to have overtaken fiducial markers as the first choice of registration. Contours formed by the facial skin, bone, entire surfaces or markers may be used for registration [4, 48]. These methods rely on a matching process such as convex hull or iterative closest point (ICP) algorithm [7, 44, 49, 51, 59]. Since, these algorithms use a lot of surface points for registration (typically 200-500), they are highly accurate but slow. Fiducial markers are seen to be the second choice if surface scanning is not possible. Alternatively, a combination of point-based and surface-based techniques can be adopted by firstly using artificial or anatomical landmarks to perform an initial registration and further refining the registration using surface matching techniques or vice versa [68, 74].

The combination of point and surface matching seems to be the best in terms of performance as it incorporates advantages of both the approaches however, it is computationally expensive. Alternatively, the least computationally expensive but complex registration approach is to register physically using splitting beam optics of the operating microscope [47]. Nevertheless, high precision is required in manufacturing the additional components.

C. Motion Tracking

After registration, it is important to track any movements of the patient or capture devices in order to maintain correspondence between different devices. Similar to the registration process, a transformation is sought after that depicts the difference between previous and current time steps. The vast majority of systems rely on electromagnetic and optical tracking systems [11, 28, 43, 44, 51, 56, 58, 61, 61, 66-68, 75]. When choosing a tracking system, different factors need to be taken into account: number of devices to be tracked, image refresh rate, workspace size, robustness, accuracy required, nature of interaction with environment and the placement of tracking markers (if required).

Optical tracking systems have been regarded as the state-of-the-art in surgical tracking for more than a decade now. Optical trackers work by detecting infrared rays reflected from retro-reflective markers attached to the patient or different devices. Although new systems have been developed that offer different types of advantages however, due to high precision, optical technology is still one of the most frequently used systems in the cranial base domain.

Electromagnetic and optical tracking systems require bulky reference frames that contain special markers. To counter this

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drawback, different vision-based techniques have been proposed to track any relative movements between patients and image capture devices [6, 7, 9, 59, 73]. To increase accuracy, image or fiducial markers may also be integrated into the tracking framework. The problem with image-based tracking schemes is that tracking is mainly performed in 2D and structures which are not in the image frame and in the current time-step are not taken into account.

Motion tracking is one of the key components of an AR system as the image refresh rate highly depends on it. So, great emphasis needs to be applied on choosing a performant tracker. Other processes that influence image refresh rates are image rendering and target/instrument detection. Based on the articles included in this study [4-7, 28, 43-49, 56-60, 66, 75] and commercially available trackers, it seems that optical trackers have shown the best precision whereas feature point matching techniques provide an ergonomic alternative, despite a slight compromise on precision. Improved vision-based techniques need to be developed specifically, in order for them to be widely accepted in this domain.

D. Instrument Identification

In most AR systems, the output is a 2D image display screen which leads to a loss of depth perception. Also, during MIS procedures, the target site is not directly visible. This raises a need for the AR system to detect all the surgical instruments and communicate their information to the surgeon in an interpretable manner.

Different instrument detection systems have been proposed to enable the surgeons to infer the exact position of the instruments in the 3D world space. Similar to motion tracking, earlier systems used electromagnetic and mechanical tracking systems to track the instruments [4, 67, 76, 77]. However, the trend has totally shifted towards optical tracking systems that are now regarded as the state-of-the-art in instrument tracking as well [11, 28, 43, 44, 56, 60, 68, 75]. These systems are highly accurate and are available in most of the operation rooms today.

Alternate instrument tracking systems have also been proposed that only rely on information from cameras [6, 9]. These usually involve attaching simple visual markers on the instrument that can be detected in the video frame to determine their 3D pose. Although these techniques do not require any bulky equipment or special markers, the instruments need to remain within the camera frame throughout the procedure. These systems are also limited by the number of instruments that can be simultaneously identified. Despite promising results with the image-based tracking, infra-red optical tracking systems are still the most preferred systems because of their optimum performance [27].

It is imperative to present instrument information using a user-friendly interface along with surgical planning and navigation data. The most conventional approach is to present the instrument tip on the three orthogonal planes of the pre-operative data [4, 28, 46, 56, 61, 77]. However, as previously explained, it is difficult for the surgeon to manipulate the instruments ergonomically. Alternate representations that display the instruments directly on the AR view can also be used. The 3D pose can be displayed in text on the screen to infer the required movements. However, this is not very ergonomic [6]. Alternatively, the instruments can be highlighted in different colors based on the distance between them and the target structures [4, 56, 61, 68]. New innovations that display the instrument information on 3D display screens or augmented/virtual 3D environments will be highly beneficial and ease the task of the surgeon.

E. Visualization Devices

Numerous options have been explored for visualization of the AR output such as traditional displays, wearable technology, see-through and projection devices; however no standard practice has been established for clinical practice. Some examples of AR displays are shown in Fig. 3-5.

The most popular display in cranial base AR systems is the traditional surgical monitor [8, 43, 49, 51, 56, 68, 75]. This choice is apparent when using endoscopes and when direct visualization is not possible such as in MIS procedures. The main advantage of this approach is that more than one surgeon can view the operative field at the same time. However, in cases of stereo microscopes and open surgery, the AR display is not in direct operative view making the surgeon look back-and-forth on the surgical field and the AR output which leads to time-consuming comparisons and interpretations. As a substitute to conventional display screens, tablets have also been utilized in different applications to display hidden structures that do not require large incisions in cranio-maxillofacial procedures [78]. However, they are not very useful in otology and rhinology applications due to small and intricate anatomy and relatively higher accuracy demands. Indeed, Nasal and external ear cavities have the shape of an irregular cylinder with a relatively larger height as compared to their diameters. In addition, the target structures are small and located deeply requiring lighting and magnification. Furthermore, the accuracy required for such surgery is not achievable with the conventional systems.

Another disadvantage of using traditional screens is that they do not provide any depth cue. The surgeons have to rely on color coding schemes to infer the distance between the surgical tip and the target structure. For this, additional processing has to be carried out in order to detect surgical instruments and targets. To facilitate the surgeons, text based information is often added to the display [6]. Alternatively, 3D displays can be used to counter the depth perception limitation [79]. It is important to understand that virtual information reduces visibility of the surgical site and consequently, displaying virtual objects during the entire surgical duration does not seem to be ergonomic. In contrast, the efficiency of the system may improve if virtual structures are overlaid only when they are required as proposed in [56].

Integral videography or immersive visualized surgical environment is another concept that has been utilized to intuitively visualize structures in 3D, providing enhanced realism [7]. A micro-lens array is placed in front of a high density LCD screen. Each pixel behind a lens emits light in a different direction. The surgeon only sees the set of emitted light rays that are projected directly to the surgeon through the lens. This enables different aspects of the object to be observed from different direction, thus giving a sense of depth. Surface based rendering or volume ray tracing is often used to render the display. In AR systems, a half-silvered mirror is

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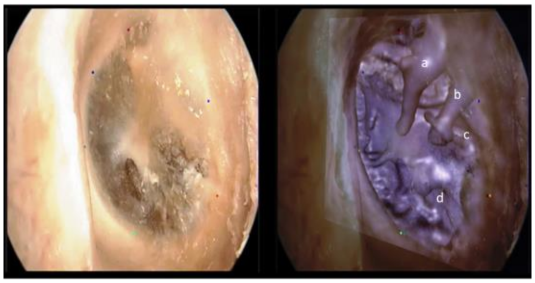

Fig. 4. An example of an AR display with image overlay. The image on the left is the endoscopic view of the tympanic membrane whereas the image on the right is the AR output which displays middle ear cleft structures overlaid on the endoscopic view. Potential middle ear targets, only visible by augmented reality, are indicated: a: malleus, b: incus, c: oval window, d: round window.

attached to the display through which surgeons can see the reflected image superimposed onto the patient. Integral videography is a promising alternative due to its simplicity and ability to produce motion parallax in both x-y and z directions. However, due to low rendering speed of the system, displaying enriched information is not possible.

Head-mounted display (HMD) is a device worn on the head that has a small display in front of one (monocular) or both (binocular) eyes. Some HMDs also have the ability to project images, allowing the user to see through them. HMDs used in surgery can superimpose computer generated virtual objects over real-time video. This can be done either electronically or using a partially reflective mirror. HMDs, like tablet screens, have been used in a limited number of applications related to cranial base interventions mainly in the cranio-maxillofacial domain which does not involve deep surgical areas. Hidden anatomical structures and navigation information can be overlaid onto the patient in a partially immersive environment.

Binocular HMDs have been found to have better performance as compared to singular HMDs. In a study on analyzing the impact of stereoscopic visualization on target localization in skull-base surgery, it was concluded that using binocular HMD yielded an average of 35% improvement in terms of both accuracy and time as compared to monoscopic vision [66]. The introduction of HMD did not seem to significantly affect target localization.

Although the HMDs provide ergonomic benefits, such as direct visualization, as compared to visualization on surgical monitors, they have been shown to increase inattentional blindness especially when an unexpected situation arises [75]. Inattentional blindness refers to the failure of noticing a fully-visible, but unexpected, object because attention was engaged on another task, event, or object [80]. HMDs, in general, have not been a popular choice among practitioners in clinical practice. This is due to the following factors [66]: (a) Focus: If the operative field and the virtual objects are not projected on the same plane, eyes fail to accommodate such out-of-focus images. (b) Latency: A lag in the display of the real and virtual information cannot be tolerated in a surgical environment. (c) Projection: A calibration process that determines the transformation between the 3D world coordinates to 2D image coordinates needs to be initially carried out. In the case of optical see-through HMDs, once the HMD moves from its

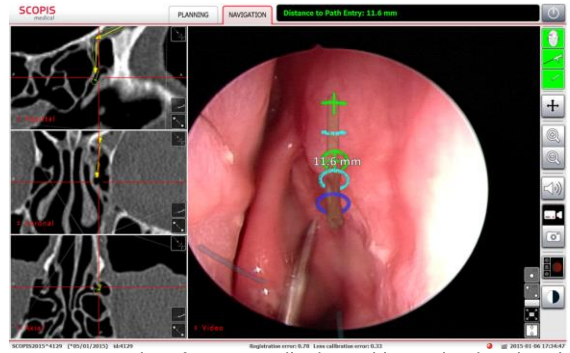

Fig. 5. An example of an AR display with navigational guidance depicting the frontal sinus outflow track [4].

original calibration position, the same transformation may no longer be valid. These factors coupled with the fact that HMDs are heavy and bulky devices are the reason that many surgeons are not comfortable wearing HMDs. Such systems may distract the surgeon so this technology should be carefully adopted.

Surgical planning and navigation data can also directly be projected onto the surgical site. Marmulla et al. developed an overhead projector that projected osteotomy lines and tumor contours onto the patient [58, 81]. However, this system is fixed. Gavaghan et al. developed a portable projection device based on RGB laser technology that was tracked using optical sensors [82]. This device allowed more freedom of movement to the surgeon. For procedures that employ surgical microscopes, the AR image can directly be projected onto their ocular lens [47, 48]. This allows for direct visualization of the structures in the surgeon's viewpoint.

In AR surgical systems, the best option indeed is one where the virtual information is directly projected on the surgical site as it allows for direct visualization and improved ergonomics. However when this is not possible, traditional screens seem to be the best option. Indeed, the choice of visualization strategy seems to be highly influenced by the degree of incision inside the body. HMDs and integral videography have been employed mainly in cranio-maxillofacial surgeries whereas traditional monitors are seen to be the popular choice when an endoscope is involved. In otology, microscope is preferred as it enables the surgeon to visualize micro-structures in great detail. Integration of 3D displays will help to improve the performance and intuitiveness of such systems.

F. Experimental Validation

Cranial base region involves some of the smallest and delicate structures in the human body. For an image-guided system to be useful, accuracy needs to be below 1-2 mm in the operating room environment [6, 8, 83]. AR systems that are commercially available have achieved target accuracies of around 1.5-2 mm. However, very often in the surgical routine the error is above this threshold [84]. Previously, most surgeons argued that without submillimetric precision, AR computer assisted systems will not be able to attain popularity among surgeons. However, recently researchers have realised that attaining surgical errors below 1 mm is infeasible due to physical limitations of the anatomy and system, thus maximum errors of 1.5-2 mm have been regarded as plausible [83, 85].

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In a normal working scenario, the developed system is first tested under laboratory conditions on phantoms and cadaver bones before it is operated under clinical conditions on animals and humans. In order to facilitate the evaluation process, in some specific cases, specially designed artificial markers may also be introduced to facilitate the evaluation process [44, 51, 58]. Alternatively, an intra or post-operative scan or complementary conventional tracking systems can also be used to compute target accuracy [11, 73]. It is important to mention that in a surgical application, results may differ significantly from those in laboratory conditions. Furthermore, the error increases with increase in distance between the camera and the target [68]. Due to the complex anatomy and workspace, it is often very difficult to measure the performance quantitatively. Thus, many studies on human subjects only provide a qualitative assessment [47-49, 56, 67]. Only few studies provide results on more than one type of test subjects [6, 51, 59, 68]. From these studies, it can be inferred that the accuracy almost drops by 45% when a shift is made from the laboratory to the operating room.

Different factors contribute to the final accuracy and evaluation of the system: (a) Fiducial registration error (FRE) depicts the difference between positions of fiducial points (often used for registration) in preoperative image and their corresponding points on the patient coordinate system. (b) Fiducial localization error (FLE) is the distance between measured and actual positions of the fiducial points caused by discrepancies in the image and patient coordinate systems. FLE is both heterogeneous and anisotropic in terms of magnitude and orientation. It is often difficult to compute directly and often determined by averaging over multiple localizations of the same point. (c) Target registration error (TRE) defines the intraoperative distance between actual positions of target localizations and their corresponding positions in the patient coordinate system. It is often regarded as the final accuracy of the system. (d) Overlay error (OR) is similar to TRE but defines the difference in overlap of projected virtual information and their corresponding structures in physical space. It is usually measured from the boundary points of the projections. (e) Tool error (TE) is the error in determination of the position and orientation of surgical instruments being used to carry out the procedure. Finally, the errors induced by the display (insufficient resolution, contrast, zoom factor or unadapted view) can also influence the surgical outcome. All of the above parameters are important characteristics of an AR system and necessary for evaluation.

For AR technology to be successful in cranial base procedures, researchers need to strive for errors below 1 mm for each of the above parameters. Tables 1 and 2 depict results of different types of error evaluations used in each study. The choice of evaluation parameter depends on anatomy, type of visualisation, degree of insertion and registration and tracking schemes used. However, it is recommended that TRE should always be quoted as it encompasses different types of error into one and provides a good intuition to the expected overall accuracy.

VI. Discussion

Surgeons have been taking advantage of image-guided schemes in variety of applications. From diagnosis and surgical planning to intraoperative imaging, navigation and post-operative analysis, image-guided systems have played a crucial role in improving the outcomes of the interventions. The clinical objective is to overcome the shortcomings of conventional techniques that may introduce hindrance in intraoperative evaluation and lead to suboptimal performance. AR technology has introduced new dimensions into such systems. The combination of AR with medical imaging and nuclear medicine (for tumor management) enables precise anatomical localization and unification of pre and intraoperative data in an ergonomic and efficient manner. The prerequisite for an AR system in cranial base domain is accurate information about high risk structures such as blood vessels and critical nerves so that an unsolicited situation may not arise. In an AR system, the virtual objects may be overlaid onto the real environment in two ways: (a) Annotations or virtual models extracted from preplanning process are projected onto the surgical video. (b) The real-world surgical video is fused with virtual images.

Earlier AR systems adopted conventional sensors like optical and electromagnetic devices to establish correspondence between different objects and to track any movements. The first applications in late 1990s utilized electromagnetic tracking systems based on hall sensors to track movements and instruments [61, 67]. The problem with this technology is that any object with magnetic properties could affect the output of the system. So, in 2000s, optical tracking systems gained popularity and replaced the electromagnetic systems as the first choice of developers [11, 28, 43, 45, 56, 59, 60, 66, 68, 75]. Optical trackers are still the state-of-the-art sensors in surgery today. Surgical instruments and visual devices can also be tracked using mechanical arms with passive coordinate measurement [44, 49, 61]. The advantage with using such systems is that they provide high degree of accuracy which is essential for cranial base procedures. Also, since they do not rely on image processing, the tracked objects do not necessarily need to be visible in the endoscopic frame during manipulation. However, such conventional systems require special markers and frames for tracking and an extensive calibration process before use. Although some systems may not require calibration before each surgery, however when they have to be used in another environment, calibration has to be carried out again. In addition, these systems require additional space in the operating room and are extremely heavy and bulky, causing discomfort during surgery [43, 59]. Also, these tracking systems are very expensive. These shortcomings have opened a way for a new generation of AR systems (without any physical tracking system) that only require digital cameras connected to a powerful computer.

The fact that space outside the endoscope view remains a blank space in vision-based AR procedures has restricted the potential of vision-based algorithms to track objects and instruments when they go outside the camera frame. Another major issue with vision-based AR is the low accuracy that has been achieved when using such systems. Therefore,

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conventional sensors have always been preferred in the cranial base domain due to high precision requirements. However, with recent advances in imaging technology and computer vision, different vision-based AR systems have been reported. The first applications did not achieve promising results in terms of accuracy (above 1 mm) [7, 47-49, 59, 73]. It is only recently that more successful applications of vision-based AR have emerged that are competent with optical and magnetic tracking systems [6, 8]. Shift towards vision-based AR is imminent but further advancements need to be carried out for it to establish a firm footing in the cranial base surgical domain.

In cranial base surgeries, endoscopic sinus and skull-base procedures seem to be the primary area of AR application. An ideal AR surgical system should comply with different requisites. The processes such as fixating markers on the patient and the instruments and calibration (that need to be carried out before the actual procedure) should be simple and few. Image-guided surgeries often have reduced depth perception. In order to improve safety, additional depth cues need to be provided. In applications where virtual objects are overlaid on the endoscopic video, 3D images should be provided so that parallax is retained when the viewing angle changes.

Careful attention should be payed to the design of an AR surgical system in order to display only the appropriate amount of virtual information as it may reduce on-site visibility by obstructing important structures or lead to visual discomfort. Moreover, virtual information is only required during certain time periods and not throughout the procedure [11, 86]. Inattentional blindness also increases with dependence on AR systems. By optimizing the spatial relationship between different structures and reducing occlusion, visual clutter can be reduced [86]. A major issue with MIS, tele-manipulated and robotic procedures is the lack of haptic information for the surgeon. Haptic feedback devices will certainly improve the acceptance of such systems. They can be used in both tele-manipulated and co-manipulated instruments to amplify the tactile perception of very delicate structures or prevent the surgeon to trespass security boundaries.

AR has been shown to not only facilitate surgical accuracy and help in decision making but also reduce operation time [45]. However, the overall surgical time is often increased due to preoperative processes, depending on the complexity of the AR system. Development of automatic systems will help in reducing the overall time of the surgery. Improvements in pre-operative planning procedures such as structure segmentation and trajectory planning also need to be addressed to improve ergonomics and accuracy. Furthermore, powerful computers are required to carry out complex image reconstructions. Advancements need to be made to optimize and automate the reconstruction algorithms. Real-time medical imaging devices will also be useful in this regard.

An ideal AR surgical system would be one that involves no (or very less) calibration process, and is devoid of external reference frames and tracking systems. However, with the current technology, carrying out a careful calibration process before surgery seems inevitable. Moreover, all devices need to be well-integrated with the environment so that the experience is seamless. The ability to qualitatively monitor any deviation from the desired workflow and re-register smoothly can be one of the major advantages of AR technology. Automatic alarm systems based on quantitative evaluation can also play an important role in safety management. Since portability and lightness play a huge role in making such systems desirable, processing power of portable systems is often limited. The processing speeds that have been achieved for AR systems range from 5-40 frames per second (fps). Although the more fps the better, most of the developed systems achieved around 10 fps. GPU implementations can significantly improve the processing times, yielding up to 60 fps [9, 79]. In order to perceive a continuous and flicker-free visual output, researcher should target a minimum processing speed of 17 fps [88].

Considering these issues, a number of requirements can be defined for a functional AR surgical system:

(a) simple installation and setup before surgery.
(b) minimum calibration process.
(c) common focus for virtual objects and real-world images.
(d) high accuracy (submillimetric for otology).
(e) short registration time.
(f) unified integration of surgical instruments.
(g) low encumbrance.
(h) depth cues for both virtual objects and instruments.
(i) virtual objects superimposed only when necessary.
(j) high resolution and frame rate.
(k) low latency.
(l) adaptable adequate image-object contrast during projection.

A recent study on endoscopic skull base surgery has shown that the impact of AR systems on the surgical output depends on the operative experience of the surgeon [45]: Although AR generally reduces surgical time and mental workload, the degree of improvement corresponds to the lack of experience of the surgeon. AR systems can elevate the performance of surgeons with low experience near to the level of highly experienced surgeons. The high technicity of most devices requires special expertise to be properly used. This also plays an important role in acceptability of such systems as potential consequences of improper use can be significant. Further in-depth studies should be conducted to demonstrate the superiority and usefulness of AR surgical systems as compared to standard practices. Apart from enhancing surgical experience, AR may also benefit education by redefining surgical training and teaching methodologies. Intuitive illustrations may be provided to students allowing a more thorough and comprehensive explanation of the anatomy and working principle of each organ. According to a recent survey, 81% students preferred the integration of such a system into their residency program while 93% approved its use in the operating room [55].

Machine learning based AR has been used for supporting diagnosis and detection in other similar fields. The maximum accuracy reached is 81% which is better than naive surgeons (~45%) but worse than experienced surgeons (~95%)

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according to a recent study [89, 90]. Advanced artificial intelligence techniques have not been applied successfully in the cranial base domain as these algorithms are highly sensitive to training data and the accuracy of current algorithms is not good enough to be applied in this domain. Currently, such systems are only being used in post-processing of medical images which do not incur instantaneous threat to patients (to classify or segment certain structures). This signifies the importance of improving the automatic computer vision algorithms before they can be applied in real-time surgical applications. Introduction of AR technology in surgical robotic systems will also greatly enhance the potential of such systems. New developments in micro and nano-robotics and autonomous surgical systems will be highly beneficial.

VII. Conclusion

AR is a powerful tool with a potential to revolutionize the cranial base surgery through enhancing the surgical experience and providing additional information in a safe, user-friendly and intuitive manner. Recent studies indicate that navigation systems integrating AR offer comparable results to traditional navigation systems in terms of precision but with improved ergonomics and visualization. AR has been applied to many steps of the surgical management such as diagnosis, surgical preplanning, navigation, intraoperative imaging, and MIS procedures. AR can also prove beneficial for teaching purposes. However, more work still needs to be undertaken to improve the current state, and achieve maximum security and reliability and reduce system cost. New developments in robotics, visualization, positional sensors, haptics, artificial intelligence and computer vision will all benefit the AR technology in its widespread acceptance among surgeons.

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