Augmented reality in neurosurgery: a systematic review

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Abstract

Neuronavigation has become an essential neurosurgical tool in pursuing minimal invasiveness and maximal safety, even though it has several technical limitations. Augmented reality (AR) neuronavigation is a significant advance, providing a real-time updated 3D virtual model of anatomical details, overlaid on the real surgical field. Currently, only a few AR systems have been tested in a clinical setting. The aim is to review such devices. We performed a PubMed search of reports restricted to human studies of in vivo applications of AR in any neurosurgical procedure using the search terms "Augmented reality" and "Neurosurgery." Eligibility assessment was performed independently by two reviewers in an unblinded standardized manner. The systems were qualitatively evaluated on the basis of the following: neurosurgical subspecialty of application, pathology of treated lesions and lesion locations, real data source, virtual data source, tracking modality, registration technique, visualization processing, dis- play type, and perception location. Eighteen studies were included during the period 1996 to September 30, 2015. The AR systems were grouped by the real data source: microscope (8), hand- or head-held cameras (4), direct patient view (2), endoscope (1), and X-ray fluoroscopy (1) head-mounted display (1). A total of 195 lesions were treated: 75 (38.46 %) were neoplastic, 77 (39.48 %) neurovascular, and 1 (0.51 %) hydrocephalus, and 42 (21.53 %) were undetermined. Current literature confirms that AR is a reliable and versatile tool when performing minimally invasive approaches in a wide range of neurosurgical diseases, although prospective randomized studies are not yet available and technical improvements are needed.

Keywords: Augmented reality, Virtual reality, Tumor, Aneurysm, Arterovenous malformation, Cavernous malformation, Navigation

1. Introduction

During the last 15 years, neuronavigation has become an essential neurosurgical tool for pursuing minimal invasiveness and maximal safety.[14] Unfortunately, ergonomics of such devices are still not optimal.[23] The neurosurgeon has to look away from the surgical field into a dedicated workstation screen. Then, the operator is required to transfer the information from the "virtual" environment of the navigation system to the real surgical field. The virtual environment includes virtual surgical instruments and patient-specific virtual anatomy details (generally obtained from pre-operative 3D images). Augmented reality (AR) allows merging data from the real environment with virtual information and vice-versa.[33] In the context of surgical navigation, AR may represents the next significant technological development because AR complements and integrates the concepts of traditional surgical navigation that rely solely on virtual reality.[1] The main goal of AR systems is to provide a real-time updated 3D virtual model of anatomical details, overlaid on the real surgical field. In this sense, the AR reality is the process of enrichment of reality with additional virtual contents.

In neurosurgery, there is a special need for AR to enhance the surgeon's perception of the surgical environment. The surgical field is often small and the neurosurgeon has to develop a "X-ray" view through the anatomical borders of the surgical approach itself[37] in order to avoid unnecessary manipulation or inadvertent injuries to vascular or nervous structures, which becomes even more important with the introduction of minimally invasive neurosurgery mandating the smallest possible accesses for a given intracranial pathology.[35] Although the benefits to patients of minimally invasive neurosurgery are well established, the use of small approaches still represents a surgical challenge.

Although AR in neurosurgery is a promising frontier, and several devices have been tested in vitro, [21,19] the clinical experience with such systems appears to be quite limited. [17,22,11,29,23,14,32,4,3,15,8,5] We present a literature review aiming to: describe and evaluate the advantages and shortcomings of each of the different AR setups tested in vivo in humans; to understand the efficacy of AR in the treatment of neurosurgical diseases; and, to define potential future research directions.

2.   Materials and Methods

The present review was conducted according to the PRISMA statement criteria.[27] The literature search was updated to September 30th, 2015. No other temporal limits were applied. The search was restricted to human studies. Inclusion criterion was: report of a human in vivo application of AR in any neurosurgical procedure. Exclusion criteria were: surgical simulation in virtual environment, in vitro studies, language of publication other than English, lack of new original experiments on humans, field of application other than neurosurgery, commentaries, and abstracts. The search was performed using the PubMed database and scanning reference lists of the resulting articles. The search terms were "Augmented reality" and "Neurosurgery". Eligibility assessment was performed independently in an unblinded standardized manner by two reviewers (AM and FCa). Disagreements between reviewers were resolved by consensus. The following clinical data were extracted from each paper: neurosurgical subspecialty of application (neurovascular surgery, neuro-oncological surgery, non neurovascular, non-neuro-oncological), lesion pathology, and lesion location. We evaluated a number of additional relevant technical aspects, as listed, in part, in the Data, Visualization processing and View (DVV) taxonomy published in 2010:[19] real-data source, virtual-data source, tracking modality, registration technique, visualization processing (AR visualization modality), display type where the final image is presented, the perception location (where the operator focused).

Unfortunately, qualitative parameters concerning the clinical usefulness and feasibility of the presented systems were not gathered primarily because of the subjective nature of the evaluation by the operators and the lack of consensus as to the definition of the qualitative parameters and consequently, the

evaluation tools, such as questionnaires. In a similar fashion, the accuracy of the AR systems was not included because, when reported, its definition was not consistent across different papers, obviating a meaningful comparison.

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 the same reasons, no statistical analysis was performed.

3. Results

A total of 18 studies were included in our review. The PubMed search provided 60 items. No duplicates were identified. Of these, 44 studies were discarded because they did not meet the inclusion criteria: four papers were written in languages other than English, seven were in vitro studies, five were virtual reality studies, nine were reviews or commentaries, 12 papers were about disciplines other than neurosurgery (i.e., maxillofacial surgery, ENT surgery), seven papers were not pertinent to AR. The full text of the remaining 16 citations was obtained. After carefully reviewing the bibliography of each of the papers, two additional citations were included. No other relevant unpublished studies nor congress abstracts were included. To the best of authors' knowledge, no other pertinent papers are available today.

Table 1 summarizes the 18 papers published from 1996 to September, 2015. The specific technical advantages and shortcomings of each system in the clinical setting are reported in section 3.1 and in table 1; the clinical applications of AR in neurosurgery are illustrated in section 3.2 and Table 2.

Table1.

Studies about Augmented Reality in Neurosurgery

Author	Date	Subspecialty	Lesions	Pathology/ location	Real data source	Virtual data source
Doyle W.K.	1996	NO (Epilepsy)	40	N/A	See Visualization Processing and display type	CT, MRI
Iseki H. et al.	1997	NO/NV	6	Glioblastoma/ frontal x2, Hematoma/ frontal, Meningioma/ frontal, Meningioma/ ventricle, Meningioma/ skull base,	Unaided view of the patient	CT, MRI
Masutani Y. et al.	1998	NV (endovascular)	3	Aneurysm MCA, Aneurysm MCA+ basilar apex	X-ray fluoroscopy	CTA, MRA
King A.P et al.	1999	NO/NV	4	Cyst/bilateral petrous apex, AVM/ central sulcus, Unknown lesion/ facial nerve,	Microscope	CT, MRI
Kawamata T. et al.	2002	NO	12	Adenoma/ pituitary x12	Endoscope	CT, MRI

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Acomm, anterior communicating artery; AVM, arterovenous malformation; CTA, angio-CT; MCA, middle cerebral artery; MEG, magnetoencephalography; MRA, angio-MRI, Nav, neuronavigator; NO, neuro-oncology; NV, neurovascular; nNO-nNV, non neuro-oncology non-neurovascular; Pcomm, posterior communicating artery; PCA, posterior cerebral artery; SCA, superior cerebellar artery; semitrans., semitransparent.

Table 2.

Neurosurgical lesions treated with the aid of Augmented Reality

PATHOLOGY	# LESIONS	% LESIONS
Neoplastic lesions	**75**	**38.46**
Glioma/GBL[*] supratentorial[23,15,34,29,14,16,31]	14	7.17
Glioma/GBL[*] infratentorial	0	0
Meningioma/supratentorial[15,11,23,30,14]	12	6.15
Meningioma/infratentorial-skull base[15,11,23]	7	3.58
Pituitary adenoma[17]	12	6.15
Metastasis[29,23,16]	11	5.64
Schwannoma, vestibular[11]	2	1.02
Ependymoma[29]	1	0.51
Oligodendroglioma[29]	1	0.51
Hemangioblastoma[29]	1	0.51
Neuroepitelial tumors[29]	1	0.51
Other neoplastic lesions[22,11,8]	13	6.66
Vascular lesions	**77**	**39.48**
Aneurysm ant.circul.[32,3]	39	20.00
post.circul.[3,23]	4	2.05
Cavernoma[23,34,38]	20	10.25
AVM[**][22,11,23,4]	8	4.10
Moya-Moya disease (by-pass)[5]	3	1.53
Stroke[29,15]	2	1.02
Arterial dissection (By-pass)[5]	1	0.51
Non-neoplastic, non vascular	**1**	**0.51**
Hydrocephalus[29]	1	0.51
Undetermined	**42**	**21.53**
Epileptogenic lesions[***][9]	40	20.51
Others	2	1.02
Total	*195*	*100*

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[*]Glioblastoma
[**]Arterovenous malformation
[***]The Author reports these lesions as mainly oncological, although an histological classification (Tumor or vascular) of the treated cases was not provided.

3.1. AR in Neurosurgery: technical implementations.

AR systems are composed of functionalities and devices that may be the same although used in different implementations. The real and virtual data source, its registration with the real content, the visualization of the AR content, and all the other factors shown in Table 1 are often performed with similar or exactly the same approach in different systems as described in the reported papers. Therefore, the discussion of some parts of selected papers reported here may appear somewhat redundant. [20] We describe the papers grouping them by function of the real-data source as the type of capturing device used during the actual procedure is, from a surgical point of view, most important.

Real data source. Overall, the real-data sources were the microscope (eight studies), different types of cameras (four studies in total), including hand-held cameras (four studies) and head-held cameras (two studies), direct patient view with or without the interposition of a semitransparent mirror (one study each), endoscope (one study), X-Ray fluoroscopy (one study) and finally, a rudimentary head-mounted display (one study).

In most of the systems, the real data source is a surgical microscope. These systems allow overlaying 3D projections derived from preoperative surgical images into bilateral eyepieces of the binocular optics of the operating microscope, precisely aligned with the surgical field.[22,11,4,3,5,38,16,34] To achieve a coherent fusion between real images and virtual content, these systems monitor microscope optics pose, focus, zoom, and all internal camera parameters.[13] This is an important advantage as other, simpler, systems require manual alignment with the surgical field.[29] The microscope based AR system represented by MAGI (microscope-assisted guided interventions), requires an invasive preoperative placement of skull-fixed fiducials and/or locking acrylic dental stents. More recently, surface based registration approaches have been used[4] without any additional referencing device as traditional modern neuronavigation systems.

It is significant that a microscope based AR system does not require the bayonet pointer typical of the common neuronavigation systems. In traditional neuronavigation systems, the bayonet pointer, tracked and shown in the external display, is the sole link between the real and the virtual environment. In fact, in order to see the correspondence between a real and a virtual point, the surgeon places the pointer tip on a real anatomical target and observes its correspondence with the virtual one. In an AR scene, the correspondence between the real and virtual worlds is shown on the augmented images themselves without any additional physical device as a pointer, which might be a potential source of damage in the surgical field. Additionally, when brain shift occurs during intradural maneuvers, the AR view can be used as a guide for a limited correction of the initial image coregistration.[16,10]

A special type of microscope based AR system is created by a neuronavigation-tracked microscope that serves uniquely as an input source for software integrating the data with preoperative virtual models. [34] The image is not displayed in the microscope, but rather, on a screen separate from the actual surgical scene. This is probably due to technical issues related to the re-send of the augmented images as input data to the microscope display. These microscope based AR systems have two main shortcomings: first, the microscope itself is not practical for the initial macroscopic part of the surgical procedure, consisting of skin incision, craniotomy, and dural opening; second, current microscopes display only a monoscopic visualization of the surgical field.[23] As a consequence, a potential stereoscopic virtual image is superposed on a bidimensional field. From a practical point of view, there are perceptual issues particularly related to depth perception of an AR scene.[23]

In four papers, the real data source was an additional hand-held and/or head-held camera.[23,30,14,29] These systems are based on the use of a camera connected to a neuronavigation system. Currently, four main set-ups have been reported.

The Dex-Ray[23,30] consists of a small, lipstick-shaped video-camera positioned on a tracked handheld pointer. The AR scene consists of the virtual rendering of a 3D dimensional virtual model superimposed on a bidimensional (monoscopic) view of the surgical field. Finally, the scene is shown on a display remote from the patient. Dex-Ray has several advantages and some limitations. There is a perfect alignment between the pointer and the camera so the surgeon is aware of the spatial relationship between the tip of the pointer, the borders of the surgical corridor, and the target. Nevertheless, this feature has two limitations: first, in deep and narrow corridors, the camera has a limited ability to depict the anatomical structures due to lack of light and unsatisfactory magnification. Second, the surgeon's viewpoint is different from that of the camera resulting in two main consequences: first, oculomotor issues occur due to camera movement, and second, the different point-of-view raises uncertainty as to the actual position of camera-recorded objects (parallax problem).

Additionally, the Dex-Ray requires the surgeon to look away from the surgical field to a screen where the AR scene is shown, rendering this setup quite similar to common neuronavigation systems. Unlike the microscope, the Dex-Ray can be handled easily without obstruction of the surgical field, and can be conveniently used in all steps of the surgery, from skin incision to tumor resection.

The second camera based set-up is a quite similar one. The AR created overlapping intraoperative pictures (taken using a standard digital camera) on a 3D virtual model of the brain.[29] The virtual model was elaborated by dedicated neuroimaging 3D rendering software. The "real" intraoperative picture and the virtual model were matched using anatomical landmarks --sulci and gyri -- and shown to the surgeon with a bit of delay. The AR system was then validated by verifying the actual position of the surgical target with intraoperative US or stereotactic biopsy. The main advantage of this system is that it is extremely cost-effective, making it a suitable option in developing countries where traditional commercially available neuronavigation systems are not available.[29] The two main disadvantages are that the image-guidance is not displayed in real-time so the delay depends on the frequency of acquired pictures and that the guidance becomes unreliable when lesions are far from the cortical surface because the sole anatomical landmark is almost lost. Conversely, it works surprisingly well for lesions hidden in the depth of a sulcus.

Recently, a new system was designed by using a hand-held or head-held camera tracked by a classical neuronavigation system.[14] The AR scene was displayed on a separate monitor by overlapping the 3D virtual model, as acquired by the camera, onto the real bidimensional surgical field.. The head mounted camera partially resolves the issues related to a conflicting point of view for at least camera movement. Nevertheless, it still requires that the surgeon look away from the actual surgical scene to observe the AR scene on a separate screen. Additionally, the point of view of the camera is not aligned with surgeon's line of sight. Consequently, the eye-hand coordination may constitute a challenge.

More recently, a tablet based-AR system[8] was applied to neurosurgery. It consists of a navigational tablet that superimposes a virtual 3D model on the surgical field as it is recorded by the tablet's posterior camera. In this case, the camera's point of view can be considered aligned with the surgeon's line of sight, offering favorable ergonomics in terms of eye-hand coordination. However, the tablet cannot be draped so a second surgeon needs to hold the tablet while the operator performs the surgery. Although the tablet allows magnification of the surgical field, it cannot provide the magnification and resolution necessary for microsurgical use.

The real-data source can be represented by the direct view of the patient's head. Two systems were proposed with this aim in mind. One is based on commercially available video projectors with LED technology.[2] The virtual image is projected onto the patient's head and it is rigidly and statically manually registered by moving the head or the projector up to align fiducial points. The main advantage is a potential intuitive visualization of the site of the skin incision and craniotomy (not

explained by the authors) with a highly ergonomic setup, potentially resolving the eye-hand coordination problem. Unfortunately, the point-of-view of the operator is not the same as that of the projector, so that a parallax error is created, primarily for deep structures.[12]

In 1997, a new, interesting AR system was created,[15] with a paradigm completely different from the previously described systems. It has continuously been improved during the ensuing years until the present. [39,40] It consists of a semi-transparent mirror positioned at 45° in front of a light field display[26] developed with the integral imaging approach.[28] The display technology is the same as that employed in glass-free 3D television and allows obtaining a realistic full-parallax view of a virtual scene. The user can perceive motion parallax moving in respect to the display. The half mirror allows the user to see the patient's head with his/her unaided eyes and it is mixed with the full parallax light field rendering of the virtual information. The registration of the CT or MRI patient specific 3D model with the patient's head is manually performed aligning artificial markers.[7] The main advantage of the system is the full parallax visualization of the virtual information and the unaided view of real surgical environment, an advantage in a camera mediated view in cases of open surgery.

The application of the AR to endovascular surgery consisted of the superimposition of a CT or MRI-derived 3D model of the vascular tree and its lesions on the real bidimensional image acquired, in this case, with angiography.[32] Since the craniotomy is not needed, the brain shift is null in this application field. Accordingly, it can be considered the one AR system that is completely reliable for surgical access into the brain.

The use of an endoscope with AR consists of the superimposition of virtual 3D models, obtained, as in the previous case, from CT or MRI images on the bidimensional view of the surgical field as acquired by the endoscopic camera.[17] It requires registration of the patient's head and the tracking of the rigid endoscope itself. Two types of information were shown on the traditional endoscopic monitor: the surgical target (and surrounding critical structures), and the position of the endoscope inside the nasal cavities. The second aspect may be especially important when an angled endoscope is used as the endoscope axis is different from the surgeon's view of the axis. Typical limitations of common endoscopes still persist, including the bidimensional view of the operative field and a limited magnification ability in respect to the surgical microscope.

The oldest system reported in our review in 1996, did not show the virtual information superimposed and aligned with the real anatomy.[9] The graphic user interface essentially shows the surgeon the tip of a magnetic tracked digitizer in respect to the CT or MRI pre-operative images as in traditional (non-AR) neuronavigators. The system, a pioneer, can be considered a first example of AR as the authors employed a semi-transparent head mounted display so as to offer the user the possibility of seeing the navigator images and the real patient at the same time.

Tracking. Overall, tracking was not needed in four setups, but, as performed, optical trackers were generally used (13 studies). Magnetic tracking was reported as used in only one of the oldest reports in 1996.[9]

There is a wide consensus that the optical tracking was the best option for AR systems in neurosurgery, [6]. In fact, optical tracking is very practical because it does not require wires to connect the tracked object. Additionally, it is promptly available because it can rely on widely available cameras included in smartphones, tablets,[8] digital recording cameras.[14] The main shortcoming is that tracked objects have to be in line of sight of the tracking system.

Registration Technique. Patient registration was mainly based on superficial fiducial markers (six studies), on face surface matching systems (six studies), or on manual procedures/refinement (five studies). Skull-implanted or dental-fixed fiducials were used in two older reports in 1999 and 2004. [22,11]

Thus, in the largest part of the reported studies the image registration is based on fiducial markers or on skin surface identification. Indeed, these two techniques demonstrated to be faster and more accurate respect to the manual registration,[25] as well as less invasive and laborious than skull-implanted or dental-fixed fiducials.

Visualization processing. It allowed for the representation of virtual reality in several different ways including: surface mash (eight studies), texture maps (four studies), wireframes (three studies) and transparencies (three studies). Older reports described rudimentary visualizations: in one case,[9] the MRI slices were directly visualized in a fashion similar to the current neuronavigation devices; in another case,[15] a light field object rendering was performed.

The visualization processing affects the global manner ("style") that is used to represent the virtual content. From a practical point of view, visualization processing should be as simple and intuitive as possible, resembling the real-life experience: wireframes and texture maps are less intuitive than surface meshes because the latter realistically clearly represent the margin and shape of the object of interest. Indeed, they were used in seven of the more recent studies (Table 1).

Display Type and Perception Location. The Dysplay type determines the perception location that can be a remote monitor (eight studies) or the patient himself (10 studies). The first type of perception location is provided by hand-held camera (two studies), a head-held camera (two studies), digital camera (one study), endoscope (one study), X-ray fluoroscopy (one study) and microscope when the AR scene is projected on an external monitor (one study) instead of eyepieces. The latter kind of perception location is achieved by using several different displays, including microscope eyepieces (five studies) or oculars via an external beam (two studies), tablet display, light field display with a 45 degree-oriented mirror, or an image created by a common video-projector (one study each).

The perception location has two main practical consequences. First, when the AR is displayed on an external monitor,[34,29,23,30] the surgeon has to move his/her attention from the actual surgical field to the monitor, in order to gather information that will be "mentally" transferred to the real surgical field, as currently occurs with the neuronavigation systems. In contrast, perception localization on the patient is much more intuitive. The goal can be achieved both by the unaided eye,[2] or by devices presenting the AR scene in the line of view between the surgeon and the surgical field, as in the case of the microscope,[4,3,5,16,38] the tablet,[8] and the light field display.[15]

The second crucial aspect is the different points-of-view of the same surgical target that can be achieved by the surgeon's eye and optic devices (the parallax problem). When the surgeon's point-of-view is the same as that of the real-data source, there is no mismatch between what the operator sees and what the device actually captures. Conversely, when the operator and the data-source have different points-of-view, there may be uncertainty as to the actual position of the target.[23] The position of the AR display in relation to the surgeon is very important also for future developments.

3.2. AR in Neurosurgery: clinical applications

Six of the 18 studies reported neuro-oncological applications only (one of them mainly reported epileptogenic tumors)[9], six reported neurovascular applications only, five reported both neuro-oncological and neurovascular applications , and one reported a neuro-oncological, neurovascular, non-neuro-oncological non neurovascular application, the use of AR for external ventricular drainage placement.[29]

The lesions listed in Table 2 are classified by pathology type. A total of 195 treated lesions were analyzed in the selected works. Of these, 75 (38.46%) were neoplastic lesions, mainly gliomas (14 lesions, 7.17%) and meningiomas in supratentorial (12 lesions, 6.15%) or infratentorial/skull base (7 lesions, 3.58%) locations, pituitary adenomas (12 lesions, 6.15%) and metastases (11 lesions, 5.64%).

There were 77 (39.48%) neurovascular lesions, mainly aneurysms of the anterior circulation (39 lesions, 20% of the total), and posterior circulation (four lesions, 2.05% of the total), cavernomas (20 lesions, 10.25%), AVMs (eight lesions, 4.10%). Non neoplastic, non vascular lesions included just one case (0.51% of total) of external ventricular drainage under AR guidance. The histology was not specified for 42 lesions (21.53%). The "epileptogenic lesions" (40 lesions, 20.51%) were reported to be mainly tumors. Adding these lesions to the neoplastic lesions listed above (75), we may conclude that the neuro-oncological application is the most frequent type of use for AR in neurosurgery.

Accordingly to the pathological process and the type of intervention required, the Virtual-reality sources were: CT (13 studies), angio-CT (four studies), MRI (14 studies), angio RM (seven studies), functional MRI (one study), tractography (one study), and angiography (one study).

Although AR has been applied to a wide range of diseases, including neoplastic, vascular, and other lesions (non-neoplastic non-vascular), the small number of cases in each series allowed only a qualitative assessment of the usefulness of AR in such neurosurgical procedures.

In neuro-oncological surgery, the AR has been applied in open treatment, mainly of gliomas and meningiomas. The largest tumor series[11,23] reports an advantage in minimizing skin incisions and craniotomies. When the dura is to be opened, the AR allows a clear visualization of the venous sinuses underneath: for example, in the case of falcine meningiomas,[23,30] the sagittal sinus can be seen as a virtual model, and spared. In addition, when tumors are hidden in the depths of a cerebral sulcus, the visualization of the tumor shape under the brain surface can aid in the selection of the sulcus to be dissected.[29] When the surgeon performs the corticectomy and tumor resection, the relevant surrounding vascular and nervous structures can be visualized, including eloquent areas and white matter tracts.[14] In an older, yet broad series of mixed oncological and epilepsy cases, AR allowed reducing craniotomy size needed to position subdural electrodes monitoring cortical activity.[9] In skull base surgery, the AR provides an optimal visualization of cranial nerves and major vessels and their relationships with bony structures,[11] potentially reducing morbidity and mortality. This advantage is especially relevant in endoscopic endonasal approaches. In fact, AR allows the surgeon to orient his tracked instruments in the nasal cavities perfectly, having a precise awareness of the midline position and, when the approach moves laterally, visualizing the carotids and optic nerves.[17] Such an advantage is particularly relevant when the endonasal anatomy is distorted by previous interventions.

In vascular neurosurgery, the AR was mainly applied to the open treatment of aneurysms[3,5] and AVMs,[4] and to the endovascular treatment of aneurysms.[32]

The microscope based AR systems were found to be a particularly useful asset in neurovascular surgery because they improve the craniotomy placement and dural opening[4,3,5] as also demonstrated in neuro-oncological cases.[11,22] Specifically, microscope based AR systems were useful in aneurysm treatment because they allowed optimal adjustment of the head position, minimizing subarachnoid dissection, and selecting the proper clip placement by a thorough visualization of the vascular anatomy near the aneurysm itself.[3] Furthermore, when by-pass surgery was the selected treatment option for multiple aneurysms, the microscope based AR systems allowed for a reliable identification of the donor vessel and of the recipient intracranial vessel.[5] In the case of AVMs, results were less encouraging. In fact, microscope-based AR systems allowed a reliable visualization of the main arterious feeders of an AVM, indicating precisely where proximal control should be performed in case of an intraoperative AVM rupture. However, microscope-based systems were not able to reveal the detailed anatomy of vessels surrounding or actually feeding the AVM, a detail of critical importance during AVM resection. The information about AVM venous drainage seems to be irrelevant because a large number of cases underwent preoperative embolization.

Microscope-based AR systems were found to be a useful tool for resecting cavernomas close to eloquent areas or deeply-seated.[38] Unfortunately, the virtual component may partially obstruct the surgeon's point of view and not function when the cavernoma itself has been reached surgically.

AR also dramatically improved the endovascular treatment of cerebral aneurysms. In fact, the angiographic visualization of cerebral vessels does not allow the observer any intuitive deduction about the spatial relationship between structures. A 3D model of one or more vascular branches is a valuable aid for the surgeon.[32]

Finally, AR can also improve the treatment of non-neoplastic non-vascular pathology, as in the case of hydrocephalus secondary to subarachnoid hemorrhage.[29] The external ventricular drain positioning can be easier and faster, especially if the lateral ventricle is not well dilated yet due to sudden obstruction of the ventricular system.

4. Discussion

AR in neurosurgery was demonstrated as a useful asset in different subspecialties. Nonetheless, there are a number of uncertainties limiting the introduction of AR in the daily practice. Currently, there are no prospective studies showing a significant difference between AR-aided surgeries versus navigation guided procedures in terms of morbidity, mortality, and clinical effectiveness.

Thus, the aim of the present study was not to drag definitive conclusions on the "best" AR system, but to provide a practical tool to analyze the different aspects and limitations of existing neuronavigation systems and to stimulate the development of new solutions for AR in Neurosurgery. The most relevant parameters, and their main current options, are summarized in table 3.

Table 3.

A practical 10-point multi-parametric assessment for AR systems in Neurosurgery.

Field of use	Options (examples)
1- Open Neurosurgery	**Macroscopic** (allowed by all systems) **Microscopic** (only microscope and endoscope)
2- Endoscopy	**Endoscope**
3- Endovascular Neurosurgery	**X-ray fluoroscopy**
AR system features	
4- Real data source	**Microscope** **Video-camera** (hand-held or head-held) **Tablet-camera** **Unaided view** (Projector; light field display and half mirror at 45°, LFD) **Endoscope** **X-ray fluoroscopy**
5- Tracking modality	**Optical** (broadly used for all the systems) **Magnetic** (used only by Doyle WK, 1996) **None**
6- Registration technique	**Fiducial markers** (applied to: skin, teeth, skull) **Skin surface registration** **Manual**
7- Display type	**Microscope oculars** **Semitransparent head-up display** (used only by Doyle WK, 1996 and questionable) **External monitor** (hand video-camera, camera, microscope, endoscope, X-ray fluoroscopy) **Tablet monitor** **LFD** **Projector**
8- Perception location	**Patient** (microscope, tablet, projector, LFD) **External monitor**
AR scene parameters	
9- Virtual image source	**CT** **MRI** (and related techniques) **Angiography**
10- Visualization	**Wireframe** **Texture map**

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First, the field of use must be defined. Indeed, the adequacy of an AR system should be primarily evaluated in respect to the different procedures or steps in the procedure. When only a macroscopic view of the surgical field is required (i.e., ventricular drain placement, standard craniotomy), microscope-based AR systems are potentially impractical because of the ergonomics of the microscope itself. When a relevant magnification is required, the microscope-based AR systems appear to be the best option. In a similar fashion, the endoscope and the endoscope represent the main, and sole, tool to perform respectively endoscopic and endovascular surgeries.

Then, the AR set-up in the operating room should consider 5 parameters: the real data source, the tracking modality, the registration technique, the display type and the perception location. As described above, there is quite an unanimous agreement across different neurosurgical subspecialties that the best tracking method is the optical tracking and that the easiest as well as accurate registration technique is represented by fiducial markers or skin surface registration. All the other parameters must be tailored on the specific surgical needs, as well as on the available tools.

Unfortunately, the monetary cost of the different systems has not yet been determined. The necessary equipment for microscope based AR systems is primarily based on a neuronavigation system and a surgical microscope that are available in most modern operating rooms and their introduction into daily practice would not require additional costs. Some AR systems may also be cheaper than a standard neuronavigation system. In fact, in developing countries, very rudimentary AR systems, composed of a 3D rendering software running on a computer and a digital camera[29] have partially replaced the use of neuronavigation systems, although with evident limitations.

The third main aspect to define in an AR system is the layout of actual surgical scene, as provided by different visualization techniques. The depth perception of the overlaid 3D models is still quite difficult for all the AR systems.[24,36] Binocular cues, partially offered by 3D stereoscopic displays, are not always sufficient for inferring the spatial relationships between objects in a three-dimensional scene. The 3-D perception is necessarily associated not only with the binocular perception of the scene, but also with the different visualization techniques, as reported above. For this reason, many researchers try to improve depth perception by means of visualization processing techniques.[19] For example, specific color-coding, one of several methods, can be associated with the distance from the surgical target.[17] Other more sophisticated tools consist of progressive transparency of colors as the structures are deeper.[18]

On the other hand, the crowding of the surgical view must be avoided. The virtual models should be presented to the surgeon, in the most intuitive as well as most effective way.. Only essential virtual details should be presented because the overlapped models may hide a part of the actual surgical field. This issue could be a potential source of morbidity and mortality. Similarly, all AR systems that require the surgeon to look away from the surgical field eliminate this risk.

Great effort should be invested in not only improving the visualization of 3D models, but also in introducing information derived from new advanced imaging techniques. AR systems represent a suitable option for multimodal imaging integration involving not only CT, MRI (and related techniques), and angiography, but also other techniques such as magnetoencephalography and transcranial magnetic stimulation.

Further, when the arachnoid is opened, the resulting brain shifts irreversibly, progressively compromising the reliability of both virtual models of AR systems and neuronavigation. This problem was recently addressed by manually optimizing the overlay of the virtual model in the surgical microscope. It has been reported,[16] that when severe deformation occurs during advanced tumor resection, compensation of any sort becomes impossible because of the parenchymal deformation. The

brain shift problem could be dealt with by refreshing the virtual 3D models with intraoperative imaging, such as intraoperative MRI and intraoperative ultrasound, as with traditional neuronavigation systems.

4. Conclusions

AR represents a meaningful improvement of current neuronavigation systems. The prompt availability of virtual patient-derived information superimposed onto the surgical field view aids the surgeon in performing minimally invasive approaches. In particular, the large variety of technical implementations provides the neurosurgeon valid options for different surgeries (mainly neuro-oncological and neurovascular) for different treatment modalities (endovascular, endonasal, open), and for different steps of the same surgery (microscopic part and macroscopic part). Current literature confirms that AR in neurosurgery is a reliable, versatile, and promising tool, although prospective randomized studies have not yet been published.

Efforts should be invested in improving the AR systems setup, making them user friendly throughout all the different steps of the surgery (microscopic and macroscopic part) and across different surgeries. The virtual models need to be refined, perfectly merging with the surrounding real environment. Finally, new imaging techniques such as magnetoencephalography, transcranial magnetic stimulation, intraoperative MRI, and intraoperative ultrasound have the potential for providing new details for virtual models and improved registration.

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