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Intraoperative clinical application of augmented reality in neurosurgery: A systematic review

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ABSTRACT

The interest and potential use of augmented reality (AR) in several medical fields since the early 90's has increased consistently. It provides intraoperative guidance for surgical procedures by rendering visible what cannot be seen directly, possibly affecting surgical outcomes. Our objective was to conduct a systematic review of the intraoperative clinical application of augmented reality in neurosurgery, in studies published during the last five years. We carried out an electronic search in the PUBMED database using the terms "Augmented Reality" and "Neurosurgery." After exclusions, 12 published articles that evaluated the utility of intraoperative clinical applications in surgical settings were included in our review. The results evaluated involved AR technique and visualization, time, complications, projection error, and located structures. We can conclude that the neurovascular application is the most frequent type of use for AR in neurosurgery (47.3%), followed by applications in neuro-oncological pathologies (46.7%), and non-vascular and non-neoplasic lesions (5.9%). The use of AR also allows a surgeon to maintain their view on the operative site permanently, and is useful for locating structures, guiding resections, and planning the craniotomy with more precision, decreasing the risk of injury. The intraoperative application of an augmented reality system helps to improve the quality and characteristics of the surgical field image. The injection of 3D images with AR allows for the successful integration of images in vascular, oncological and other lesions without the need of look away from the surgical field, improving safety, surgical experience, or clinical outcome. However, comparative studies are still required to determine its effectiveness.

1. Introduction

Augmented reality (AR) is the interaction of images which are generated by a device, with the real-world environment [1]. AR has been implemented in neurosurgery to project structures of interest from computed tomography (CT) or magnetic resonance onto the real surgical field [2]. Images can be observed in two or three dimensions (2D, 3D) through visualization techniques such as keeping a screen in hand or in the surgical area, injection of images in the surgical microscope, or projection of the image on the head of the patient [2–4]. AR allows for guidance with interactive images and intraoperative guidance by showing what cannot be seen directly [3,4]. It is a precise and safe system for images of the head, skull, and surface of the brain during surgical procedures [5] (Fig. 1).

The first AR system originated in Austria in 1938 [6], however, it was in 1968 that Sutherland created the head-mounted display (HMD) with the head position-tracking mechanism, which allowed the inclusion of drawings into the vision of reality of the user [7]. AR systems progressively improved over the years and, since 1995, there have been studies on their initial applications in various fields such as neurosurgery and neuroradiotherapy [8], general surgery [9], maxillofacial surgery [10,11], assisted bronchoscopy [12], ENT surgery [13], plastic surgery [14], and orthopaedics [15]. By 2000, it was tested as a training system for airway management procedures [16], echocardiography [17,18], guided ultrasound biopsies [19,20], and MRIs [21], among others. The first implementation of AR in neurosurgery corresponds to the projection and integration of CT images in a surgical monoscopic microscope, proposed in 1986 by Roberts et al [22]. Later, in 1994, HMD was developed with video augmentation along with 3D reconstructions of segments of CT or MRI superimposed using an external display [2,23]. In 1995, the first augmented stereo microscope was developed in the United Kingdom, solving the reported problems of

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Fig. 1. Shows an augmented reality-based application for brain surgery in situ. The clinician (Dr. WO) in the picture is holding an iPad through which a computarized brain model of the patient is being augmented in the real world. This model will be overimposed (or registered) onto the patient head, during the surgery, to provide the surgeon with an otherwise impossible referencial view of the inner surgical target (the brain), from the outside and non invasively.

depth perception. By 1998, an endovascular application was demonstrated by the projection of vascular structures with fluoroscopy [24], and in 2002 the first augmented neurosurgical endoscope was used for transsphenoidal approaches [25]. Applications of AR in neurosurgery have been studied with systematic reviews in recent years [26,27], however, conclusive information remains limited. As more articles have been published in the last five years, the objective of this review is to establish the intraoperative clinical application of augmented reality in neurosurgery by analyzing the latest studies.

2. Methods

An electronic search was carried out in the PUBMED database. Additionally, references of published systematic reviews that evaluated the use of AR in neurosurgery were manually verified to find additional studies. Two reviewers (PN and WC) examined titles and abstracts of relevant studies and obtained the full-text version of studies that could potentially be included. Later, they determined the inclusion and exclusion of studies according to established criteria. All original studies that evaluated the intraoperative application of augmented reality in patients undergoing a neurosurgery procedure were included. The types of studies included were observational and experimental in humans. All studies published in the last five years (2013–2018) were included. The results evaluated were, AR technique and visualization, time, complications, projection error, and located structures. Systematic reviews, topic reviews, and studies on cadavers were excluded. All publications included were in English. The search terms were: "Augmented Reality" and "Neurosurgery."

3. Results

3.1. Study Selection: *Fig. 2*

A total of 12 articles were included in our review. The PubMed search yielded 83 studies, and 20 studies were found in the references of the systematic reviews. The screening was done by title and summary and 44 studies were excluded because they did not meet the eligibility criteria, 28 duplicate studies were removed, and 2 were excluded because they were not available in full text. 29 articles were included in full text, according to the inclusion and exclusion criteria established, of which 17 articles were excluded because eight did not comply with the population described, one was a book, two were simulation studies, two were subject revisions, one was a maxillofacial surgery study, and three had an inadequate intervention.

3.2. Study characteristics: *table 1*

Table 1 summarizes the 12 included articles [3,5,28–37] published from 2013 to 2017. Among them, there were five case series [3,32–34, 37], three technical notes [28–30], one case report [31], two that compared the use of RA with the use of the neuronavigator [5,35], and one retrospective cohort of 79 cases [36]. The population of all studies were patients undergoing neurosurgical procedures. Three studies included, besides patients, an assessment with computer-generated simulation models in a phantom of the anatomical structures of interest [5,28,34]. The intervention of the included articles was the use of intraoperative virtual reality for the planning of a procedure, opening of the structures, resection, localization, or treatment. The visualization techniques were, superimposing images directly on the patient's head or spine in four articles [3,5,28,33], injection of images in the surgical microscope in five studies [29–3237], and image projection of AR in the neuronavigator and on the image of the patient in one study [36]. Furthermore, two studies obtained previous CT/MRI volumetric data and superimposed it on the image of the patient in the camera of an intelligent tablet or telephonic device [34,35].

3.3. AR in neurosurgery

Five of the 12 studies reported only neuro-oncological applications [3,5,31,34,35], four reported only neurovascular applications [29,30,32,33], one evaluated the applications associated with external ventricular drainage placement [37], one studied the use of AR in spinal

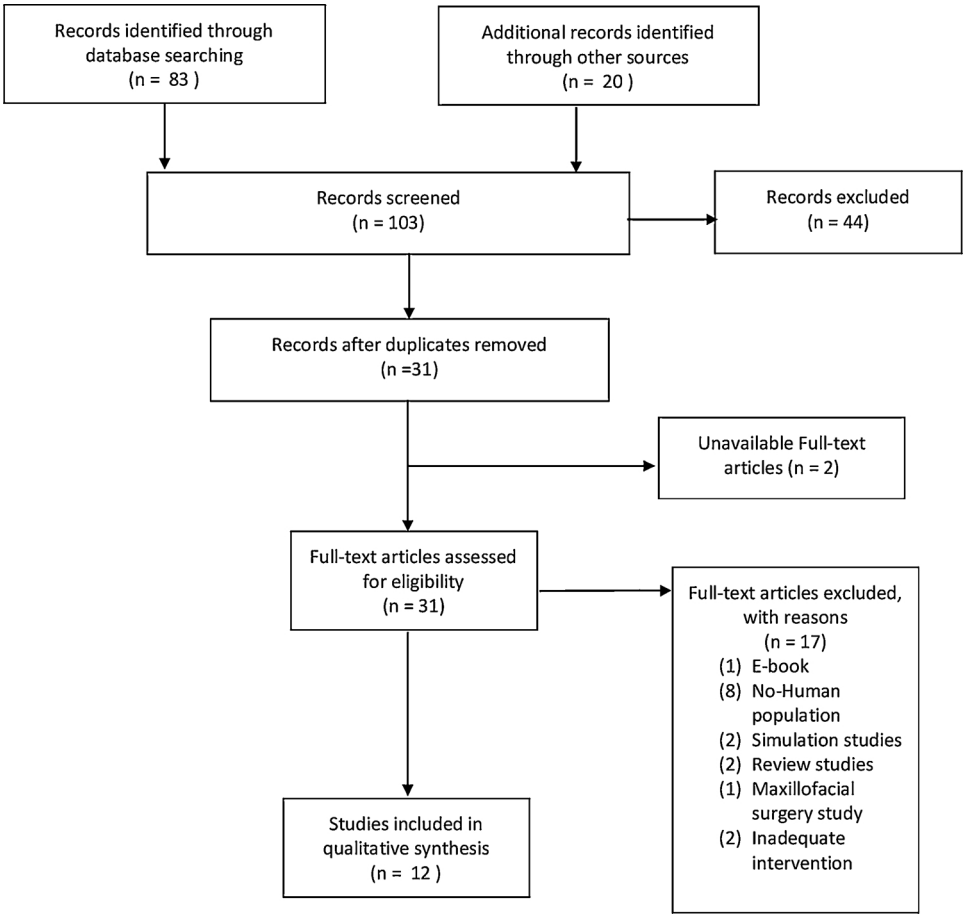

Fig. 2. PRISMA Flowchart.

surgery [28], and one combined the application in tumors, abscesses, and leakage of cerebrospinal fluid [36].

Table 2 lists the types of lesions classified by oncological, neurovascular, and other pathologies. A total of 169 lesions were found in the articles analyzed. Of these, 79 (46.75%) were oncological lesions, mainly meningiomas (34 lesions, 20.1%) and metastatic tumors (18 lesions, 10.7%). Less frequently, there were non-specified gliomas (4 lesions, 3.4%), craniopharyngiomas (4 lesions, 3.4%), glioblastomas (3 lesions, 1.8%), hemangioblastomas (3 lesions, 1.8%), schwannomas (3 lesions, 1.8%), lymphomas (1 lesion, 0.6%), osteoblastomas (1 lesion, 0.6%), and a choroid plexus papilloma (1 lesion, 0.6%). There were 80 (47.3%) neurovascular lesions, mainly aneurysms (55 lesions, 32.5% of the total), followed by arteriovenous malformations (AVM) (13 lesions, 7.7%), cavernoma malformations (5 lesions, 4.10%), intracranial stenosis (3 lesions, 1.8%), moyamoya disease (3 lesions, 1.8%), and an arteriovenous fistula (1 lesion, 0.6%). Among non-vascular and non-neoplastic lesions, there were 10 cases corresponding to 5.9% of the total, of which osteoporotic vertebral fractures were the main pathology (5 lesions, 3.0%), followed by hydrocephalus (2 lesions, 1.2%), cerebrospinal fluid leakage (1 lesion, 0.6%), abscess (1 lesion, 0.6%), and cerebellopontine angle Teflon granuloma (1 lesion, 0.6%). According to previous information, we can conclude that the neurovascular application is the most frequent type of use for AR in neurosurgery, followed by the application in neuro-oncological pathologies.

The image sources used to create the AR system varied depending on the type of pathology and the intervention required. In the included studies, one used only computed tomography (CT) [28]; two studies used only magnetic resonance imaging (MRI) [5,37]; three studies combined MRI and CT [31,34,35]; three studies used angio-magnetic resonance imaging (angio-MRI) and angio-computed tomography (angio-CT) [29,30,32]; one used angio-CT and X-ray angiography [33]; another study combined CT, angiography-CT, and MRI [36]; and one study used MRI and tractography [3]. These images were taken before the procedure to develop the 3D images and project them during surgery through an AR system.

In oncological lesion procedures, AR was useful for locating the structures, guiding the resection, planning the craniotomy, and incising the skin before surgery. In addition to superimposing the image of the tumors and the blood vessels, it allowed the visualization of the corticospinal tract to guide the neurosurgeon and avoid injury [3]. Precise identification of the edges and position of the tumor in relation to real anatomical structures such as convolutions, grooves, blood vessels, and nervous tracts was achieved, allowing to monitor these structures during the resection and to completely eliminate the tumor in all cases [3,5,31]. Eiju Watanabe et al. [34] reported that AR is especially useful in cases of suboccipital craniotomy because it is possible to locate the sinus directly. The use of AR has the advantage of merging neuronavigation data with the surgical field, which allows the neurosurgeon to permanently observe the operative site without the need to look at the navigation monitor and hold the pointer simultaneously [5,31,34] (Fig. 3).

In vascular neurosurgery, AR was useful for the adapted craniotomy in all studies. It allowed surgeons to guide the complete resection of lesions and to specify the location of donor vessels. [29,30,33] In cerebral artery baypass surgery, image injection of the recipient vessels allowed unequivocal identification in all cases of the real cortical vessels in the surgical field [32]. It also allowed guiding the dissection (in a study, it was particularly appreciated during the dissection of the occipital artery due to its sinuous trajectory), identification of drainage veins, and identification of feeders. In one study [32], only one patient

Table 1
Summary of studies on neurosurgical applications of AR.

Author and year	Study size	Condition	AR device/technique	Reported outcomes*
Abe et al, 2013 [28]	2 phantoms and 5 patients	Spine	Preplanned needle trajectory overlaid on patient image from tracked head-mounted webcam, displayed on HMD for percutaneous vertebroplasty.	• Significant improvement in insertion angle error in phantoms with AR vs without. • Insertion angle error $\leq 2.09^{\circ}$ in all planes in clinical trials. • No pedicle/vertebral body breach. • Bilateral needle insertion time: 14.8 minutes.
Inoue et al, 2013 [3]	3 patients	Tumor	Volumetric CT/MRI data overlaid on patient image from tracked head-mounted webcam displayed on external monitor.	• In one patient, accuracy could not be evaluated because the tumor was not on the surface. • In patients 2 and 3, the augmented reality error was 2 to 3 mm.
Cabrilo et al, 2014 [29]	5 patients	Vascular	AR stereomicroscope with overlaid NIR fluorescence for intraoperative ICG angiography, for AVM resection	• Was the AR useful for tailored craniotomy in the 5 patients, guided dissection in 4 cases, only in one case for the identification of the feeders, and in 2 cases for the identification of drainage veins.
Cabrilo et al, 2014 [30]	28 patients	Vascular	AR stereomicroscope, with overlaid NIR fluorescence for intraoperative ICG angiography, for aneurysm clipping.	• Registration error: 3 mm. • Smaller craniotomy in 63.3% of procedures. • Improved aneurysm exposition in 66.7% of aneurysms. • System useful in clip positioning in 92.3% of cases. • Clip correction required in 9.3% of cases with AR vs 11.7% of cases without AR. • No difference in 3-month mRS between cases with vs without AR.
Cabrilo et al, 2014 [31]	1 patient	Tumor	Application of AR in neuronavigation. Image-injection into the operating microscope.	• Allowed to “keep an eye” on these structures during the course of resection. • Spares the surgeon the task of mentally merging the neuro-navigational data with the operating field. Image-injection allows the surgeon to keep his/her eyes on the surgical field at all times.
Cabrilo et al, 2015 [32]	4 patients	Vascular	AR stereomicroscope, with overlaid NIR fluorescence for intraoperative ICG angiography, for STA-MCA or OAPICA bypass.	• Registration/microscope calibration time: 10 minutes. • Satisfactory localization of donor vessels without injury; comparable to localization by Doppler US or DSA roadmap and better than manual pulse palpation. • Satisfactory localization of pre-identified recipient vessels. • Useful for minimizing craniotomy size.
Tabrizi et al, 2015 [5]	10 phantoms and 5 patients	Tumor	Image projection of volumetric CT/MRI data directly onto phantom/ patient head.	• Registration time: 3.8 minutes (range: 2-7 minutes). • Projection error: 1.2 ± 0.54 mm (unaffected by tumor location or size).
Kersten-Oertel et al, 2015 [33]	4 patients	Vascular	Volumetric CTA overlaid on patient image from tracked video camera, displayed on external monitor.	• Patient-to-image fiducial registration error: 3.44 mm. • Camera calibration and re-projection error: 2.02 mm. • Overall AR misalignment: ~1-2 mm (based on subjective surgeon feedback).
Watanabe et al, 2016 [34]	1 phantom and 6 patients	Tumor	Volumetric CT/MRI data overlaid on patient image from tracked tablet camera, displayed on tablet screen.	• Projection error: ~1 mm in phantom model. • Mean registration time for clinical cases: 3 minutes.
Eftekhar, 2016 [35]	11 patients	Tumor	Volumetric CT/MRI data overlaid on patient image from smartphone camera on phone screen.	• Mean localization error: 10.2 mm difference between the smartphone app and standard frameless stereotactic neuronavigation systems, for localization of tumor center.
Justin R. Mascitelli et al [36]	79 patients	Tumor, vascular, abscess and cerebrospinal fluid leak	Navigation-Linked Heads-Up Display for identify and locate intracranial structures.	• Fifty-nine lesions were deep and 25 were superficial. • Structures identified included the injury (81), vessels (48), and nerves / brain tissue(31). • Accuracy was deemed excellent (71.4%), good (20.2%), or poor (8.3%). Deep lesions were less likely to have excellent accuracy (P = .029). • HUD was used during bed/head positioning (50.0%), skin incision (17.3%), craniotomy (23.1%), dural opening (26.9%), corticectomy (13.5%), arachnoid opening (36.5%), and intracranial drilling (13.5%). HUD was deactivated at some point during the surgery in 59.6% of cases.
Jang W. Yoon et al 2017 [37]	2 patients	Hydrocephalus	Application of AR in neuronavigation. Image-injection into the operating microscope.	• Shunt placements in two patients were completed successfully without complications. • The tip of the catheter ended well within the ventricles and away from the ventricular wall without obstruction in both patients.

*All values are presented as means or percentages.
AR = augmented reality; AVM = arteriovenous malformation; CTA = computed tomography angiography; FPS = frames per second; MCA = middle cerebral artery; mRS = modified Rankin score; NIR = near-infrared; OA = occipital artery; PICA = posterior inferior cerebellar artery; STA = superficial temporal artery; US = ultrasound; HUD = Head up display.

Table 2
Breakdown of pathologies.

Pathology	N	%
Oncologic	79	46,75
Glioblastoma	3	1,8
Meningiomas.	34	20,1
Clivus chordoma.	2	1,2
Metastasis	18	10,7
Hemangioblastoma	3	1,8
Craniopharygniomas	4	2,4
Gliomas	4	2,4
Schwannomas	3	1,8
Epidermoid/dermoids	3	1,8
Pituitary adenomas	2	1,2
Lymphoma	1	0,6
Osteoblastoma	1	0,6
Choroid plexus papilloma	1	0,6
Cerebrovascular	**80**	**47,3**
Intracranial Stenosis	3	1,8
Cavernous malformations	5	3
Arteriovenous malformations	13	7,7
Aneurysms	55	32,5
Arteriovenous fistulae	1	0,6
Moya-moya disease	3	1,8
Others	**10**	**5,9**
Abscess	1	0,6
Cerebellopontine angle Teflon granuloma	1	0,6
Cerebrospinal fluid leak	1	0,6
Hydrocephalus	2	1,2
Osteoporotic vertebral fractures	5	3
Total	**169**	**100**

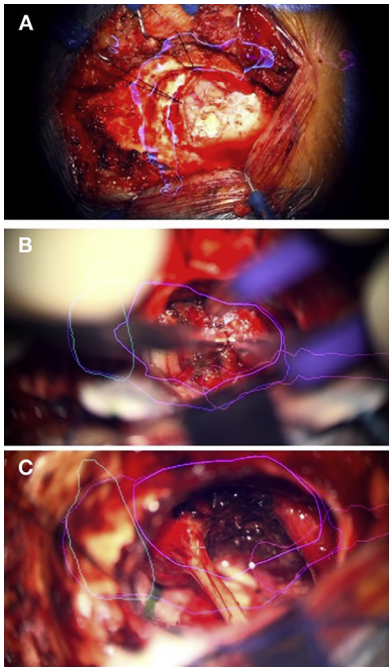

Fig. 3. Dural opening (A): A patient with a petrous meningioma involving CN V (B): The head up display was activated prior to craniotomy and was used to guide dural opening demonstrating the tumor (purple), sinus (blue), CN V (green) and vessel (pink), to guide the dural opening and tumor resection. Photo courtesy of Dr. Holly E. Oemke, Mount Sinai (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

allowed the identification of feeders of the AVM. However, in another study [33] the AR did allow it to do so, which can be attributed to Kersten-Oertel et al [33] using a marker to identify feeders. This allows the surgeon to easily identify their location even within the complexity of the AVM angioarchitecture. In the study with the largest number of patients—28 patients— [30], the intraoperative guide with AR had a registration error of 3 mm; also it was necessary to perform 11 surgeries to test and design the system with AR and build confidence in the procedure. The heads of the patients were repositioned in 10% of cases. It was useful for the adapted craniotomy in 63.3% of cases, and 66.7% of aneurysms had better exposure. AR was useful in clip positioning in 92.3% of the cases, with a correction of the clip required in 9.3% of cases with AR compared to 11.7% of cases without AR, showing no difference in the modified Rankin score of three months between cases with and without AR. In one study, it was considered that the use of AR had a significant impact on five surgeries (16.7%), in which the surgeon estimated that the trimming would have been significantly more laborious [30]. In another study, the surgeon considered that the information provided by the injection of images was useful in all cases, for helping to anticipate each step of the procedure and increase comfort by confirming the anatomical orientation without interrupting the workflow [32].

In the retrospective study [36] that included 84 lesions (59 deep and 25 superficial) of oncological, vascular, and other pathologies, the AR system allowed to identify lesions in 81 cases. Accuracy was better in superficial lesions as compared to deep ones; it was rated by neurosurgeons as excellent in 71.4%, good in 20.2%, and poor in 8.3% of cases. Additionally, it allowed the observation of surrounding vessels in 48 cases and tissue adjacent to the lesion in 31 cases. The AR was used during the positioning of the bed/head (50.0%), skin incision (17.3%), craniotomy (23.1%), dural opening (26.9%), corticotomy (13.5%), arachnoid opening (36.5%), and intracranial perforation (13.5%). The system was deactivated in 59.6% of cases because it was no longer useful (48.4%), it was distracting (38.7%), inaccurate (9.7%), or technical difficulties were presented (3.2%). There were no complications related to AR, inaccuracy, or overconfidence.

4. Discussion

The systematic review of studies published in the last five years that evaluated the intraoperative application of AR in neurosurgery reported articles with some similarities in design and heterogeneity in the report of the results and technique methodology, since AR in neurosurgery is an emerging system. Twelve articles were included, which were submitted for evaluation according to the eligibility criteria. The level of evidence for the intraoperative clinical applicability of AR is II.2 because the studies included were case reports, case series, and technical notes.

The application of AR in neurosurgery proves to be a useful element for different lesions in the brain. For the past five years, intraoperative application has been for oncological neurosurgery, vascular, and hydrocephalus. Currently, there are no prospective studies comparing and showing a significant difference between surgeries assisted by AR versus procedures guided by conventional navigation in terms of morbidity, mortality, and clinical effectiveness. Therefore, the result of this study is to provide a practical tool to analyze the different aspects and limitations of the implementation of an intraoperative AR system in neurosurgery.

According to this review, AR technology on patients was used the most on vascular neurosurgery field procedures, with aneurysms and AVM being the most frequent lesions. For these cases, the AR allowed planning the craniotomy, the resection runner, and the identification of the feeder and drainage vessels during the different stages of the surgery. In the case of Cabrilo et al [29], the intraoperative aid with 3D image injection and AR failed to allow the identification of feeder vessels of the AVM. However, for Kersten-Oertel [33], the system was useful for their identification. This discrepancy between articles may result because of Kersten-Oertel et al used a marker to identify feeders, which allowed the surgeon to easily identify the location even within the complexity of the angioarchitecture of the AVM. Therefore, it is considered that in vascular lesions, the application of AR in surgery

provides valuable information to achieve the surgical objective.

AR remains an experimental system with promising results, according to the articles included. It facilitates the selective and simplified representation of the anatomy, improving the accuracy and understanding of the lesion and adjacent structures and in-depth vision. This is exemplified in the results obtained in the articles on tumors and cavernomas, where AR was used to perform guided craniotomies and dissections. In cases of assisted neuronavigation with AR, there is evidence of an advantage over traditional neuronavigation since it avoids the work of mentally merging neuronavigation data with the operative field. AR-based neuronavigation integrates neuronavigator data with real-world images in a complete view, allowing the surgeon to keep their view permanently in the surgical field during the injection of images in the neuronavigator.

Within the study limitations, we found that it is necessary to assess the objectivity of the measures used to evaluate the results. There is no established method for accurate measurement of 3D error. Additionally, we show that the camera performance is limited in cases of deep injuries, so the AR system has greater utility in superficial injuries. It is important to acknowledge that the evidence is low in terms of the types of study and number of patients; prospective, comparative studies against traditional imaging techniques with larger samples are required.

5. Conclusions

The intraoperative application of augmented reality systems might improve quality and characteristics of the surgical field image. The injection of 3D images with AR allows for the successful integration of images in vascular, oncological, and other lesions. It can help adapt the craniotomy to the anatomy of the individual patient and is useful as a guide during dissection and resection. However, comparative studies are required to determine its effectiveness.

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Declarations of interest

None.

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