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Systematic Review
Emerging Technologies

# Intraoperative augmented reality with heads-up displays in maxillofacial surgery: a systematic review of the literature and a classification of relevant technologies

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*Abstract.* Although the term augmented reality appears increasingly in published studies, the real-time, image-guided (so-called ‘hands-free’ and ‘heads-up’) surgery techniques are often confused with other virtual imaging procedures. A systematic review of the literature was conducted to classify augmented reality applications in the fields of maxillofacial surgery. Publications containing the terms ‘augmented reality’, ‘hybrid reality’, and ‘surgery’ were sought through a search of three medical databases, covering the years 1995–2018. Thirteen publications containing enough usable data to perform a comparative analysis of methods used and results obtained were identified. Five out of 13 described a method based on a hands-free and heads-up augmented reality approach using smart glasses or a headset combined with tracking. Most of the publications reported a minimum error of less than 1 mm between the virtual model and the patient. Augmented reality during surgery may be classified into four categories: heads-up guided surgery (type I) with tracking (Ia) or without tracking (Ib); guided surgery using a semi-transparent screen (type II); guided surgery based on the digital projection of images onto the patient (type III); and guided surgery based on the transfer of digital data to a monitor display (type IV).

Key words: augmented reality; virtual reality; immersive headset; mixed reality; smart glasses; 3D visualization.

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The first descriptions of augmented reality (AR) and mixed reality (MR) applications in interventional radiology[1,2] and maxillofacial surgery[3] appeared at the end of the 1980s. The number of articles describing the utility of AR for guided surgery has increased with the development of digital video-assisted surgery techniques in fields as varied as craniofacial surgical navigation, standard or robot-assisted laparoscopy surgery, arthroscopy, and endovascular and other types of surgery. To date, all of these techniques have required the use of monitors in the operating room, making it impossible for the surgeon to have a 'heads-up' and 'hands-free' view while operating, i.e., without the surgeon's eyes and hands being diverted from the operating field.

The problem is that the systems currently used for surgical navigation are often located outside the operating field on monitor displays with two-dimensional (2D) images or volume rendering. Consequently, the surgeon must coordinate his/her view of the monitor with the movements of his/her hands or instruments, without looking at them and without taking into account the patient's actual anatomical positioning. The result is a lengthy learning curve and, sometimes, difficulty in assessing the ongoing situation[4]. This may constitute an additional challenge for the surgeon and ultimately become an impediment to using these technologies.

Unlike most of the systems studied in the literature, AR and MR with a wearable heads-up device provides the surgeon with a three-dimensional (3D) visualization of virtual objects during the surgical procedure, overlaid onto the patient's anatomy in real time. This makes it possible to keep the surgical field in view and to rely on prepared information for guided surgery, without the need to divert the eyes from the operating field or use a physical cutting guide.

Hands-free devices have been used for many years in professional sectors (industrial, military) and for navigation purposes, allowing operators to remain continuously focused on what their hands are doing while at the same time receiving digital information that enriches their visual environment. Depending on their needs, they use headsets or glasses with a central or remote monitor and a simple or a binocular lens, and hands- or voice-command systems. Recently, improvements in the quality and choice of models of smart binocular glasses has increased the potential for use in more ordinary medical applications – not unlike the smartphone phenomenon[5–7] – and, in particular, their use in the operating room.

There is a vast disparity in the quality of the studies that have been published on this topic. In particular, there is a lack of consistency in the description and precise utilization of these technologies, making it difficult to assess, monitor, and compare the advantages and disadvantages of the devices. This review excluded studies on surgery guided by navigation or virtual reality (VR) and using computerized cutting guides, and only retained applications in maxillofacial surgery. The aim of this research was to specifically target AR use in the operating room (Fig. 1). In contrast to these techniques, the 'see-through' AR provides access to an unaltered visualization of the operative field and the body of the patient, with or without the addition of digital objects.

The aim of this review was to establish an exhaustive list of studies on humans published in the literature and to provide the level of evidence for AR applications in maxillofacial surgery in order to categorize these technologies and suggest avenues for further research in this field.

## Methods

A search of the MEDLINE (PubMed), Google Scholar, and Cochrane Library databases was conducted following the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (see **Supplementary Material**, Appendix S1).

The search was started with the key words ''augmented reality'' to broadly and systematically identify all available literature on this subject without search filters, and was then refined using the key words ''surgery'' or ''operation'' to retain only results concerning applications in fields related to operating room activities. The search yielded 622 results in PubMed; 109 in the Cochrane Library; and 1760 in Google Scholar for all publications between January 1, 1995 and January 1, 2018. The aim of this research was to specifically target AR or MR use in the operating room. The full search procedure is given in the **Supplementary Material** (Appendices S2–4).

The following inclusion criteria were applied: (1) the study had to include the use of a wearable heads-up visualization device in the operating room; (2) the study had to concern a field of application for maxillofacial surgery in adults or children.

Exclusion criteria were (1) studies about a visualization device for medical or surgical training purposes; (2) simulations without any surgical application actually being performed; (3) journals and editorials; (4) animal studies; (5) studies solely on cadavers or imaging phantoms; (6) studies published in a language other than English; (7) devices used solely to film or record the surgical procedure for

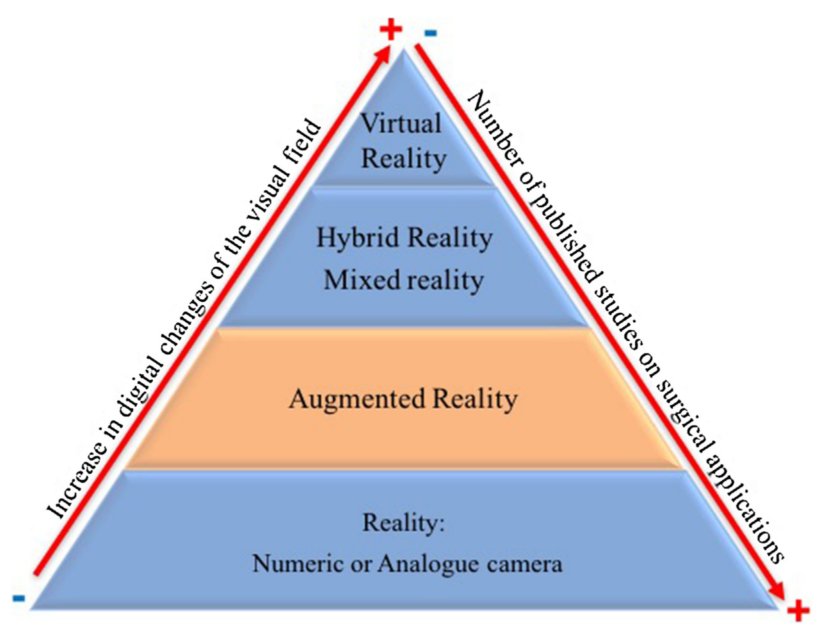


*Fig. 1.* Diagram of the technologies used for digital visualization according to the level of virtualization of the visual environment.

immediate or subsequent use for the purposes of telemedicine; (8) studies with a modification of the normal visual environment of the surgeon: mixed reality, hybrid reality, virtual reality.

Review Manager version 5.3 software was used for the article selection process (The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen, Denmark, 2014). The articles were ranked according to the GRADE guidelines8 : level I, randomized clinical trials or systematic reviews of the same; level II, cohort studies or systematic reviews of the same; level III, case–control studies or systematic reviews of the same; level IV, case series and case reports. This included a complete analysis with double reading of the title and the abstract by two medical practitioners who are familiar with these technologies (a surgeon specialized in maxillofacial surgery and an interventional radiologist). The concordance rate (κ) for exclusion was 88% and for inclusion was 100% (see detailed flowchart in Fig. 2). Five hundred and forty-five publications concerned pre-clinical applications, or were journal reviews or letters to the editor. The selection process excluded 14 duplicates. At the end of the selection process, 157 articles had been identified. After eliminating publications on neurosurgery ($n = 36$), laparoscopic digestive surgery ($n = 51$), laparoscopic thoracic surgery ($n = 4$), vascular surgery ($n = 18$), urological and gynaecological laparoscopic surgery ($n = 12$), and cardiac surgery ($n = 9$), a total of 27 articles about AR in relation to maxillofacial and craniofacial surgery were retained[3,9–34].

## Results

A complete analysis of the selected articles with extraction of the results was performed and 14 studies that did not address tests on actual patients were excluded; these studies were also removed from the final analysis. Of the 13 remaining articles selected for systematic analysis, two provided grade III level of evidence[9,10], while 11 provided grade IV level of evidence[3,12–20,22], based on the CEBM grading recommendations for clinical studies with a therapeutic objective.

The topics covered in the articles focused primarily on the technical procedures used and details about materials required. In particular, all selected articles described the workflow for data acquisition, tracking, transmission, and image projection[21] (see diagram, Fig. 3). The applications concerned head and neck cancer surgery and orthognathic surgery. Table 1 shows the different parameters for designing AR systems.

Table 2 provides information about the type of surgical intervention using AR. Of the 13 studies that underwent full analysis, 12 made use of computed tomography (CT) and one was based on cone beam CT prior to the surgical procedure.

None of the studies was based on using a hybrid operating room with real-time acquisition. Most of the tracking devices were made up of a high-definition optical sensor recognizing a device in two or three dimensions, attached to a stable structure: teeth or skull. None of the studies gave the exact cost of the material the researchers used or clearly stated the additional cost of the full system. The primary parameter examined in these articles was the correlation, measured in millimetres, between the structures projected in AR and the physical structures: patients or phantoms. Table 3 summarizes the degree of correlation and the number of patients studied.

A total of 141 patients received direct or indirect treatment using an AR-guided surgery technique. Only 11 publications provided a precise description of the degree of error measured for a total of 83 patients who underwent craniofacial bone surgery (Table 3). Most of the publications reported a minimum error of less than 1 mm between the virtual model and the patient. One study reported degrees of error of up to 6 mm (guided surgery to position dental implants in the upper jaw)[13]. The other studies did not provide a precise description of the degrees of error in the position of virtual objects in the surgeon's field of vision[3], or they did not set up a control device to check such positioning[20] .

The primary objective in undertaking a complete study of the texts of the articles was to identify the techniques that the surgeons used for AR visualization of digital data during the surgical procedure. Four categories were created to classify the procedures described in the articles: type I procedures involve devices worn by the surgeon, such as smart glasses or headsets, either with a tracking system (type Ia) or without a tracking system (type Ib); type II approaches concern guidance using a device with digital data projection on a half-silvered mirror; type III refers to techniques that project images directly onto the patient; finally, type IV procedures include AR techniques using a display monitor.

Smart glasses or headsets free up the surgeon's hands to perform the surgery. By comparison, devices and systems that come between the surgeon and the patient (i.e., semi-transparent mirrors and display monitors) alter the view of the surgeon's hands, much like laparoscopic and robot-assisted surgery.

Most of the studies reviewed provided a clear description of how to process tomographically acquired digital images in order to plan a surgical procedure. The software systems used to process and modify 3D images (Table 1) are the same tools that are used for 3D printing[35]. Several teams have made use of open-source software for semi-automatic segmentation (e.g., 3D Slicer, Harvard University, Boston, MA, USA; OsiriX, Pixmeo SARL, Geneva, Switzerland) and for computer-aided design (e.g., Meshmixer, Autodesk, San Rafael, CA, USA)[22],26. The authors of most of the articles indicated that they used licensed software (e.g., Mimics, Materialise, Leuven, Belgium; 3ds Max, Autodesk, San Rafael, CA, USA; Rhinoceros 3D, Robert McNeel & Associates, Seattle, WA, USA) or software that is specifically adapted for this purpose (e.g., AR Toolkits, AR Toolworks, Seattle, WA, USA).

## Discussion

This systematic study of the literature revealed that publications about real-life applications of AR in maxillofacial surgery remain rare. Among the techniques cited in publications, four types of procedure have already been tested: type I represent see-through projection systems using smart glasses or a headset with tracking (Ia) or without tracking (Ib); type II represent projection systems using a half-silvered mirror; type III are systems to project images directly onto the patient; type IV are systems to project digital data onto a display monitor. However, to date, no large-scale interventional or comparative studies have been conducted that demonstrate a level of evidence regarding the usefulness of the most recent technologies, namely types Ia and Ib. This is despite the fact that digital imaging has for many years been integrated into maxillofacial and craniofacial surgery.

For more than 20 years, computer-aided design after digital acquisition along with computerized planning have made it possible to use 3D printers to create customized cutting guides and prostheses. These processes are gradually replacing design techniques based on moulds or sculpting to make cutting guides, restraints, and

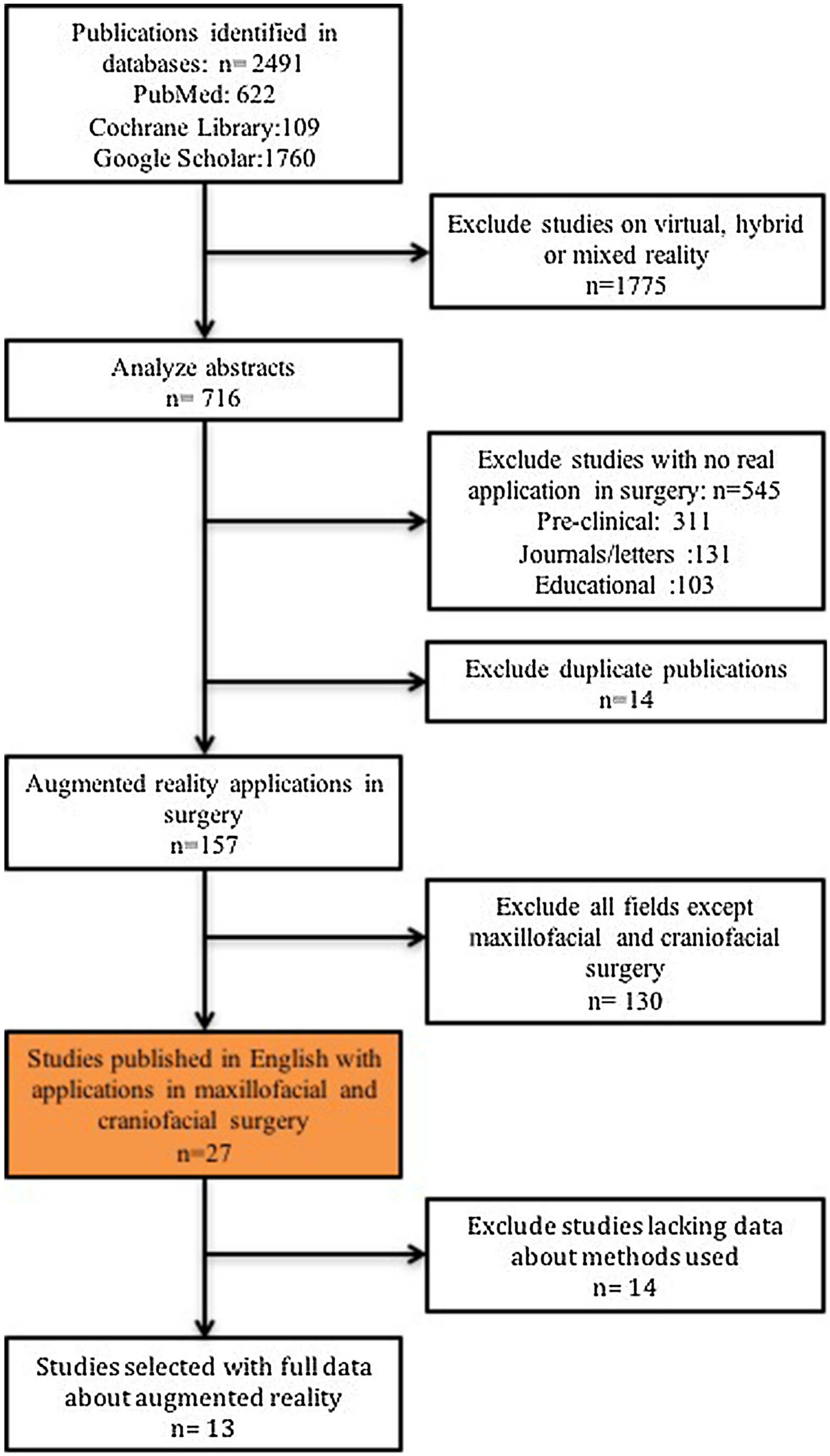


*Fig. 2.* Attrition flowchart showing the algorithmic elimination of studies through application of the exclusion and inclusion criteria.

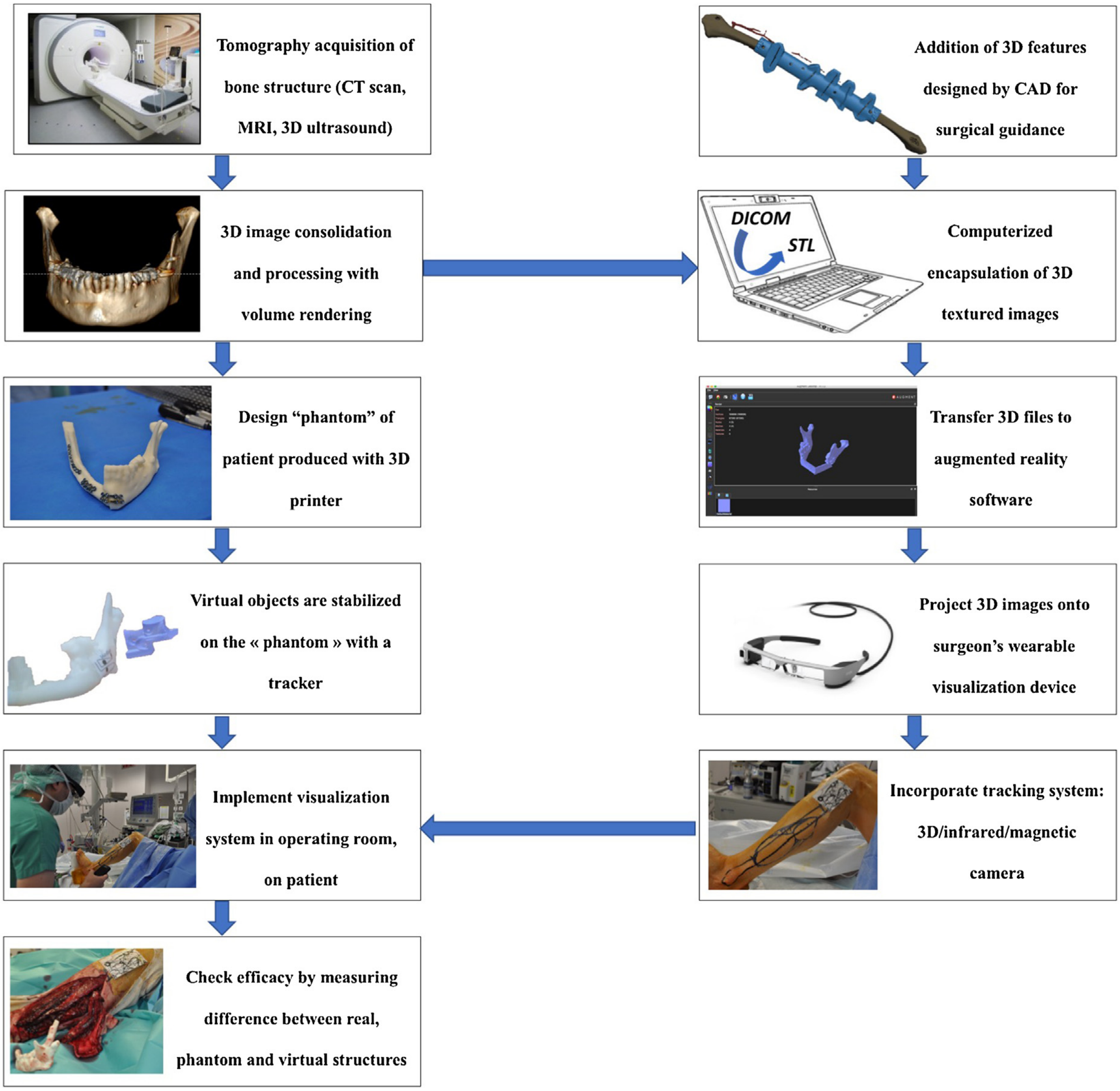


*Fig. 3.* Workflow showing the typical process of creating a reality augmented process for surgery with a tracking system.

dental devices. In a larger surgery field, this is also the case for custom-designed silicone thoracic implants[36] and skull prostheses made of porous titanium or polyether ether ketone[37].

Three primary factors have brought about this change: first, the substantial increase in power of PCs has enabled manufacturers, followed by surgeons, to process imaging data using volume rendering, to design and ultimately to test tools for digital image visualization and modification. Second, new developments in 3D image processing software[27], especially for computer-aided design and semi-automatic segmentation applied to ergonomics and compatibility, have meant that they are more accessible to all users. This change has come about thanks to the standardization of 3D digital encapsulation formats (standard tessellation language .STL or object .OBJ), and the availability of open-source volume-rendering software. Lastly, in the operating room, the widespread practice of using visualization tools (digital screens), digital acquisition (4K cameras), and more recently 3D printing[38] (3D printers), means that any surgeon anywhere in the world can adopt the end products of this design chain and use them during surgery.

Only those studies concerning an AR visualization technique combined with a tracking system were selected for this review. Without a tracking system to link virtual objects to the patient and to stabilize them during movement, the data remain in a corner of the surgeon’s field of vision. This means that surgeons must divert their eyes from the operating field in order take in the data, similar to how a display monitor provides information. In addition, the surgeon’s visual field is reduced.

By contrast, using see-through AR with glasses or a smart headset gives the surgeon a 3D view of the digital objects while freeing up his/her hands to perform the surgery. The present authors believe that integrating these tools into surgical procedures represents a valuable argument for using AR. Two of the 27 studies originally retained in the review were designed to project native digital images without image post-processing[22,25].

Only five studies (Table 4) in the literature combined a wearable heads-up, see-

*Table 1*. Detailed description of methods used in the 27 publications on the use of augmented reality in maxillofacial surgery.

| Variable | Number of articles |
|---|---|
| Image acquisition by CT scan/MRI | 27 |
| Software for processing of images | 27 |
| SolidWorks (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) | 6 |
| Mimics (Materialise, Leuven, Belgium) | 7 |
| Autodesk 3ds (Autodesk, San Rafael, CA, USA) | 11 |
| Rhinoceros (Robert McNeel & Associates, Seattle, WA, USA) | 2 |
| Ultra2 Creator 3D workstation (Sun Microsystems, Mountain View, CA, USA) | 1 |
| Material to project images | 27 |
| Head-mounted display | 9 |
| Half-silvered mirror | 7 |
| Projector | 10 |
| Smart glasses | 1 |
| Tracking | 13 |
| Plan | 10 |
| Three-dimensional | 3 |
| Monitoring control of 3D objects | 20 |
| Phantom | 8 |
| Phantom printed in 3D | 10 |
| Virtual | 2 |

3D, three-dimensional; CT, computed tomography; MRI, magnetic resonance imaging.

*Table 2*. Surgical interventions.

| |
|---|
| Le Fort osteotomy[9,10,14,18,19,22] |
| Sagittal osteotomy[12,16] |
| Mandibular angle split osteotomy[17] |
| Dental implants[13] |
| Orbital wall and floor surgery[15] |
| Maxillofacial tumour resection[3] |
| Orbital fractures[20] |

through technology and tracking[9],10,13,17,27. These were classified in the type Ia category. Previous authors have described the necessary technical devices as being complicated and costly[23], largely due to the need to have extensive IT equipment for the integration and projection of AR medical images. Several recent studies have referred to lighter and simpler equipment[10],17, both for AR visualization and for tracking. With the latest generation of smart glasses, it could be possible to render a high-definition filmed environment and to have any 3D virtual object with a 90° field of vision. Prices range from \$300 to \$3000, and they can operate for up to 8 hours before requiring recharging. Several devices are available that perform equally well or better; their prices vary (Moverio Epson, HoloLens Microsoft, Vive HTC).

Thanks to these new tools, it is possible to imagine a field of surgery applications that is broader than the field of craniofacial surgery. Today, with the availability of hands-free 3D imaging in the surgeon's line of sight, with a tracking procedure, different categories of AR-guided surgical procedure can easily be contemplated: perforated flap removal, or guided surgery for non-palpable tumours26. Moreover, due to continuous improvements in sensor quality and miniaturization, as well as high-definition display monitors, surgeons may enjoy an 'augmented' visualization of the operating field, i.e., better than can be seen with the naked eye.

In their comments, most authors also underline the complexity of tracking systems, which may be unstable in the operating room due to obstacles between the digital optical sensors and the tracker, or due to stroboscopic interactions between LED surgical lighting systems and the sensors. Moreover, recommendations and legislation on the use of such devices for medical purposes have not yet been developed. In particular, there is as yet no sterile tracking system with surgical standards for use in the operating field.

During the review of the literature, objective data were extracted, in particular the differential measurements between the position of the virtual objects and the real models (printed in 3D, phantoms, or patients). Most of the maximum differences observed were less than 2 mm (maximum 6 mm). These figures are not different from those typically observed in navigation for maxillofacial surgery in humans[39].

Only two of the studies in this review were comparative studies[18],20, and they looked at a small number of patients ($n$ = 20). Consequently, it is not yet possi-

*Table 3*. Data extracted from each paper studied.

| Study | Number of patients | Error between the virtual model and the phantom/patient; minimum–maximum (mm) |
|---|---|---|
| Wang et al. 2017[12] | 1 | 0.67–1.65 |
| Zhu et al. 2017[10] | 20 | 0.55–2.00 |
| Zhu et al. 2016[9] | 12 | 3.30–1.26 |
| Lin et al. 2016[17] | 5 | 1.10–2.41 |
| Suenaga et al. 2015[14] | 1 | 0.25–0.71 |
| Lin et al. 2015[13] | 2 | 0.04–6.56 |
| Qu et al. 2015[15] | 20 | 1.24–2.95 |
| Wang et al. 2014[16] | 1 | 0.19–1.41 |
| Suenaga et al. 2013[22] | 1 | 0.45–1.34 |
| Zhu et al. 2011[18] | 15 | 0–1.50 |
| Mischkowski et al. 2006[19] | 5 | 0.43–1.67 |
| Total | 83 | 0–6.56 |

*Table 4*. Detailed description of studies using a wearable heads-up system: type Ia.

| Study | Number of patients | Tracking device | Visualization device |
|---|---|---|---|
| Zhu et al. 2016 and 2017[9,10] | 20 + 12 | 2D marker fixed on teeth | Customized head-mounted display |
| Badiali et al. 2014[27] | 1 | 3D tracking: coloured spheres | Z800, eMagin (Bellevue, WA, USA) |
| Lin et al. 2015 and 2016[13,17] | 5 + 2 | 2D tracker fixed on jaw | nVisor ST60 (NVIS Inc., Reston, VA, USA) |

2D, two-dimensional; 3D, three-dimensional.

ble to demonstrate the efficacy of these techniques when compared to reference procedures.

AR is often confused with virtual reality or navigation. There are currently numerous applications for navigation in neurosurgery and in laparoscopic surgery, but they typically rely on the use of display monitors with an external video system (type IV). As is true in the case of laparoscopy and robot-assisted surgery, the surgeon's hands are not viewable during the operation, creating a major challenge and a lengthy learning curve for these techniques. Unlike these procedures, 3D visualization of virtual objects through a wearable device, which is integrated into the actual operating field, is very simple to incorporate into standard surgical techniques.In conclusion, applying AR technology in maxillofacial surgery is practiced by a limited number of surgeons today, although it is used increasingly by interventional radiologists and for laparoscopic surgery. The universe of modern imaging, which has become fully digital, and the use of a display monitor coming between the surgeon and the patient, obviously involves processing and incorporating digital data to facilitate technical procedures that require both accuracy and safety. Computer-assisted planning and 3D printing have been part of skull reconstruction procedures for some 20 years, yet still today they are not utilized routinely for AR-guided surgery. With access to binocular smart wearable devices, the widespread use of AR in maxillofacial surgery should be possible. The potential of AR to improve surgery outcomes and the conditions of surgical procedures will, however, need to be demonstrated in more studies involving a greater number of patients.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ijom.2018.09.010.

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