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Review on Augmented Reality in Oral and Cranio-Maxillofacial Surgery: Toward "Surgery-Specific" Head-Up Displays

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ABSTRACT In recent years, there has been an increasing interest towards the augmented reality as applied to the surgical field. We conducted a systematic review of literature classifying the augmented reality applications in oral and cranio-maxillofacial surgery (OCMS) in order to pave the way to future solutions that may ease the adoption of AR guidance in surgical practice. Publications containing the terms ''augmented reality'' AND ''maxillofacial surgery'', and the terms ''augmented reality'' AND ''oral surgery'' were searched in the PubMed database. Through the selected studies, we performed a preliminary breakdown according to general aspects, such as surgical subspecialty, year of publication and country of research; then, a more specific breakdown was provided according to technical features of AR-based devices, such as virtual data source, visualization processing mode, tracking mode, registration technique and AR display type. The systematic search identified 30 eligible publications. Most studies (14) were in orthognatic surgery, the minority (2) concerned traumatology, while 6 studies were in oncology and 8 in general OCMS. In 8 of 30 studies the AR systems were based on a head-mounted approach using smart glasses or headsets. In most of these cases (7), a video-see-through mode was implemented, while only 1 study described an optical-see-through mode. In the remaining 22 studies, the AR content was displayed on 2D displays (10), full-parallax 3D displays (6) and projectors (5). In 1 case the AR display type is not specified. AR applications are of increasing interest and adoption in oral and cranio-maxillofacial surgery, however, the quality of the AR experience represents the key requisite for a successful result. Widespread use of AR systems in the operating room may be encouraged by the availability of ''surgery-specific'' head-mounted devices that should guarantee the accuracy required for surgical tasks and the optimal ergonomics.

INDEX TERMS Augmented reality, surgical navigation, maxillofacial surgery, 3D planning, virtual reality, headsets.

I. INTRODUCTION

Oral and cranio-maxillofacial surgery (OCMS) is the surgical specialty treating the pathological alterations of the mouth, jaws, face, head and neck area. This surgical specialty is often based on complex surgical procedures and involves delicate anatomical regions. For this reason, patients often undergo a Computer Tomography (CT) scan before surgery, which allows the surgeons the possibility to plan the appropriate surgical approach based on patient imaging data and the reproduction of this planning during treatment (e.g. drilling position, implant position, resection margins, reconstructive planning). Although surgeons have good knowledge and perception of the underlying structures, a beforehand more

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precise determination of the three-dimensional (3D) anatomical structure involved during surgery would greatly facilitate the procedure. Research efforts in this direction have generated lots of new techniques and instruments that allow the surgeon to directly visualize and manipulate the surgical site, such as image-guided navigation systems [1]. However, navigation systems present some shortcomings the major of which is due to the intrinsic incompatibility between the 3D representation of the real world and the nature of the computer-generated content, rendered as a two-dimensional (2D) image and showed on an external display [2]. This leads the surgeon to perform frequent hand-eye transformations whilst switching his own attention back and forth between real surgical tasks and the navigation data presented on the external display of the navigation system. Moreover, in OCMS, the small operating field and the presence of moveable temporo-mandibular joints make it particularly difficult to perform the image-to-patient switch without the invasive preoperative placement of skull-fixed fiducials and/or locking acrylic dental stents. However, real-time image registration without the use of fiducial markers (i.e., marker-less registration) and external trackers is highly preferable.

Augmented Reality (AR) has been recently introduced in OCMS with the intent of overcoming the above described problems [3], [4]. AR merges the virtual and real images into one single scene, allowing the direct observation of the patient imaging overlaid to the surgical field which smoothly enhances the perception of the physical environment. In this way, the surgeon can avoid alternate viewing of the displayed images and the surgical field, as both can be simultaneously visualized at once. Furthermore, these systems may improve the speed of execution of the surgical procedures [5]. During the last years, many tools and devices employing AR have been created and tested in several surgical fields [6]–[12]. The different experiences have led to AR views presented on traditional displays such as tablets and/or wearable headsets [4], [13], [14]. Although this wide variety of devices and solutions have not yet permitted the standardization of the optimal AR visualization mode in the context of OCMS [1]. To the authors's knowledge, today only two ''surgery-specific'' headsets for AR-based intraoperative guidance, VOSTARS (https://www.vostars.eu/) and XVision Spine (https://www.augmedics.com/), are undergoing clinical investigation. Particularly, for the Xvision Spine system, the company has recently announced the U.S. FDA 510(k) clearance and hopes to earn CE mark approval in the coming year.

We present a literature review aimed at analyzing different AR-based systems recently introduced in OCMS. We also outline future research directions that may favor the routine adoption of AR guidance in the surgical room.

II. METHODS

We conducted a systematic review of existing literature about the AR in OCMS. The review has been carried out according to the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) statement criteria [15]. The search was performed by using the PubMed database through the terms ''augmented reality'' AND ''maxillofacial surgery'', and the terms ''augmented reality'' AND ''oral surgery''. The search was performed and updated to May 2019. No other temporal criteria were used. The search included either human or in vitro studies. We performed the study selection based on the following inclusion criteria: (1) report of human in vivo AR applications in OCMS procedures;(2) in vitro studies on AR application in OCMS. Exclusion criteria were the following: (1) language of publication other than English, (2) lack of new original experiments or duplicates, (3) field of application other than OCMS, (4) commentaries and abstracts, (5) literature reviews. Two reviewers performed the eligibility assessment independently in an unblinded standardized way. In case of disagreement between the two reviewers, the dispute was resolved by consensus.

We classified the resulting eligible papers by means of a set of classes and sub-classes derived partly from the Data Visualization processing and View (DVV) taxonomy published by Kersten-Oertel *et al.* [16] and similarly expressed by Meola *et al.* [17] and by Fida *et al.* [18], and partly from our interest on some features that we considered as relevant.

In detail, we performed: (1) a general breakdown of the studies according to the AR systems diffusion in the OCMS community (i.e. distribution by OCMS subspecialty; distribution by country; distribution by year of publication); (2) a breakdown of the studies according to technical features of the AR-based devices (i.e. virtual data source (VDS), visualization processing mode (VPM), tracking mode (TM), registration technique (RT), AR display type (DT) and visualization mode, accuracy of image registration (Acc), and frame rate (FR) of the AR application).

III. RESULTS

The initial PubMed search provided 48 items. After going through the selection process (PRISMA), 24 papers were included in our review. Twenty-four studies out of the total 48 were discarded because they did not meet the inclusion criteria: 4 papers were duplicates; 4 papers were written in languages other than English; 8 papers involved specialties other than OCMS (i.e., neurosurgery, ENT surgery, endodontics, surgical training); 3 were abstracts; 5 papers were reviews. The authors added 6 papers [9], [19]–[23] according to the supplementary manual search on PubMed they performed, based on the best of their knowledge. The total number of works included, for which we obtained the full text, was 30 (**Figure 1**). No additional citations were included after going through the papers' bibliography.

In the following paragraphs, an analytic overview of the selected papers and their classification were presented, while a summary is shown in **Tables 1-3**.

A. GENERAL BREAKDOWN OF THE STUDIES

1) DISTRIBUTION BY OCMS SUBSPECIALTY

Figure 2 shows the distribution of studies by the three major subspecialties in OCMS: malformations/orthognatic surgery,

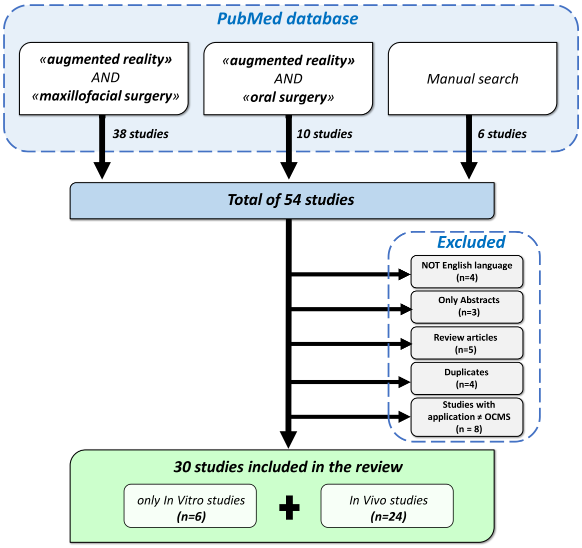


FIGURE 1. **A flowchart showing inclusion and exclusion criteria used for the search.**

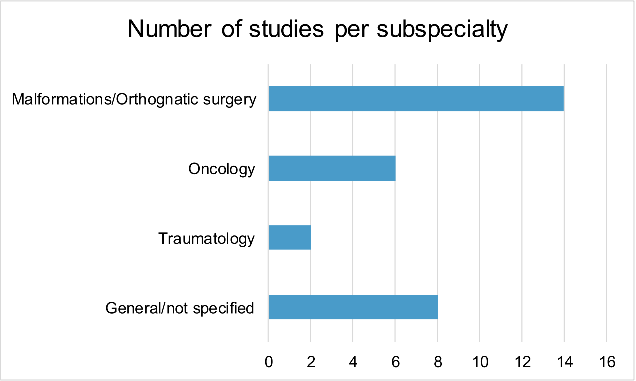


FIGURE 2. **Distribution of studies by OCMS subspecialties.**

oncology, and traumatology. Most of studies were in orthognatic surgery (14 studies), while the minority were in traumatology (2 studies). Six studies were in oncology and 8 in general OCMS.

2) DISTRIBUTION BY COUNTRY OF ORIGIN OF THE RESEARCH GROUP

Figure 3 shows the distribution of studies by country of the research groups involved in AR applications for OCMS. The research groups with more background and longer experience in this field come from Germany and Japan (6 studies each) followed by Austria and China (5 and 4 studies, respectively).

Six out of the 30 included studies deal with only *in vitro* tests, whereas the remaining 24 papers were about *in vivo* studies, involving both healthy volunteers and patients. *In vivo* studies with the most significant number of patients come from German, Austrian and Chinese research groups (**Table 1**).

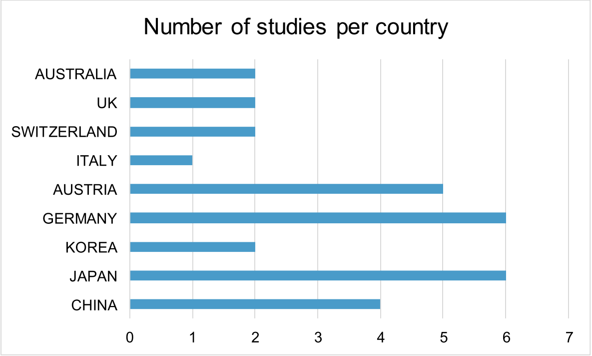


FIGURE 3. **Distribution of studies by country.**

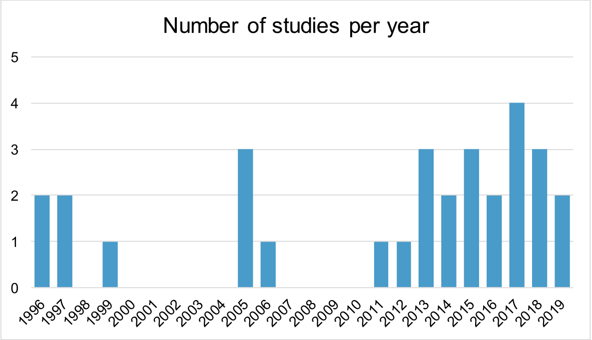


FIGURE 4. **Distribution of studies by year.**

3) DISTRIBUTION OF STUDIES BY YEAR OF PUBLICATION

Figure 4 shows the distribution of the selected studies by year. After the first experiences of AR application to OCMS coming from early pioneer groups in the late 1990s, there was a peak of interest in 2005 (3 studies), followed by an increasing trend started in 2013.

B. BREAKDOWN OF THE STUDIES ACCORDING TO TECHNICAL IMPLEMENTATION

1) VIRTUAL DATA SOURCE (VDS)

The starting point for the development of AR-based applications is the generation of virtual data which is to be displayed and overlaid onto the real content. Typically, for AR applications in the medical field, the virtual data are 3D reconstructions of anatomical structures performed by processing the radiological patient images that we define Virtual Data Source (VDS). In twenty-one out of 30 studies the VDS was represented by the preoperative CT or CBCT (Cone Beam CT) scan; in two studies [24], [25], a 3D scanner was used to acquire the patient's teeth shape to be used in combination with CT images; in two studies [20], [26], the data was obtained from SPECT/CT; in four studies the data was elaborated both from CT scan and MRI scans [3], [6], [8], [27].

The predominance of CT scans as source of pre-operative images is motivated by the particular OCMS subspecialties in the studies (e.g. orthognathic surgery), which mainly involved rigid bony structures. The use of CT scans assures a very accurate 3D reconstruction of the virtual bony models used in the AR visualization. In terms of feasibility, CBCT provides a dose and cost-effective alternative to helical CT scan for the diagnostic evaluation of osseous abnormalities or defects, and it is a widely used diagnostic imaging technique for preoperative planning in orthognatic and dental surgery.

In some cases, the multimodality imaging (CT/MRI, CT/SPECT) is required, especially in tumor surgery applications, where it is also important to have diagnostic information on soft tissues. In this case, the major drawbacks are the more time-consuming processes for medical image registration and fusion.

The raw imaging data are then processed using dedicated software for medical image segmentation, in order to generate the virtual content of the AR scene.

2) VISUALIZATION PROCESSING MODALITY (VPM)

The visualization processing mode (VPM) represents the type of virtual content introduced in the real scene used to aid the surgeon during the surgical task. In most studies, the virtual content was presented as wireframes or mesh representations of the anatomic structures involved in the surgery, e.g. maxilla, mandible, tooth roots, critical nerve channels, lymph nodes [8], [13], [14], [20]–[24], [27]–[33]. In thirteen of these studies ([3], [7], [9], [20]–[22], [24], [25], [31], [34]–[37]) additional computer-generated elements, such as preoperatively planned osteotomy lines, reference planes, planned resections, position of potential implants or representations of hot spots, were added to the virtual anatomical content for aiding the surgical procedure. Similarly, simple geometrical primitives constituted the core of the virtual content in the other studies. In Wagner *et al.* [35] and in Marmulla *et al.* [6] the projected virtual content consisted again of preoperatively planned osteotomy lines and skin incision lines. In Badiali *et al.* [4], a novel task-oriented visualization mode was presented. The visualization mode was based on a set of simple virtual elements (virtual asterisks), whose goal was to promote the implementation of an ergonomic interaction paradigm with the AR content whose final goal was the manual placement of a rigid body (e.g. upper maxilla) within the space [2]. Finally, in 2 studies [20], [26], the real view of the patient was enriched with purely textual elements (displaying the depth of specific target structures) and with three-dimensional virtual representations of the hot spots detected by freehand SPECT.

3) TRACKING MODALITY (TM)

The tracking modality (TM) plays a fundamental role in assessing the accuracy, usability and reliability of a specific surgical navigation system since it represents the core of the registration technique implemented. In seven papers, the AR systems adopted a marker-less method ([13], [14], [19], [24], [29], [33], [38]. In two studies ([13], [33]), the patient's teeth were tracked directly while the surgical instrument was tracked by means of a template marker attached to it. In nineteen studies a tracker was used. The tracking method was mostly based on either template markers or spherical markers (i.e., marker frames). One paper [30] presented the static superimposition of intraoral photographs with the preoperative 3D reconstruction of the mandibular bone from CT scans. In this study, no tracker was necessary since no real time augmentation was performed. Of the 19 studies using a tracker, all except 5 were based on an optical tracker. These five studies [3], [35], [36], [39], [40] used electromagnetic tracking technology.

Surgical navigation systems based on optical tracking solutions have the main drawback of introducing unwanted line-of-sight constraints into the operating room and of adding technical complexity to the surgical workflow [41], [42]. Yet, they are still preferred over electromagnetic trackers for the accuracy they can provide, and because they generally do not require wires for connecting the tracked body to the tracker. Electromagnetic trackers are particularly suited for tracking hidden structures [43], but both accuracy and reliability are severely affected by the presence of ferromagnetic and/or conductive materials [44]. Furthermore, to achieve tracking accuracy comparable to that obtained through standard optical trackers, the distance of the tracking body (patient or surgical tool) from the field generator should be limited to 30 cm [45]. All these aspects pose serious challenges for their smooth integration in the surgical workflow. Recently, a promising solution, which offers simultaneously both optical and electromagnetic tracking on the same system, has been proposed by a German company specialized in surgical navigation and AR (ScopisGmbh, now part of Stryker, MI, US). Their hybrid tracking allows the surgeon to opt for one of the two approaches during a specific task during the procedure. The Scopis tracking system has been tested in endoscopic sinus surgery [46] and in endoscopic neurosurgery [47].

Among the studies in which optical tracking solutions were proposed, 11 relied on infrared (IR) cameras. In six studies, standard digital RGB cameras, with visible light as source of information, were adopted. At the present state of technology, IR tracking, as provided by commercial workstations for surgical navigation, is still intrinsically more robust than visible-light tracking under non-controllable lighting conditions as in a standard surgical room. Nevertheless, IR tracking systems are generally cumbersome and add error-prone technical complexity to the whole registration procedure. This applies especially when similar off-the-shelf IR solutions are used in conjunction with standard RGB cameras (hand-held, wearable, endoscopic or external) whose task in an AR-based system is that of capturing the real scene.

In all the studies involving IR tracking, the tracked body was anchored to an array of spherical and reflective markers by means of a standard reference structure. In case of patient tracking, the reference structure was non-invasively fixed on the patient's maxilla through a dental splint [7], [22], [25], [28], [31], [35] or simply attached to the patient's forehead or skull [20], [25], [26], [35], [39]. When optical tracking was performed through RGB cameras, marker-based solutions were adopted in three of the six studies. In particular, the solution proposed in Badiali *et al.* [4] featured the stereo tracking of three undistinguishable markers anchored to the patient's head and whose position in the CT dataset was known a priori. Differently, the video-based tracking solution proposed in [21], [22], [31] was based on a template marker fixed to an occlusal dental splint. Nevertheless, video-based tracking methods, featuring the use of such large template-based markers, provide sufficiently good results in non-stereoscopic systems, despite being affected by the orientation of the camera viewpoint with respect to the template. In relation to this, they are not perfectly suited for use in a surgical setting because they limit the surgeon's line of sight given their planar structure, and they may occlude the visibility of the surgical field.

In the remaining studies, promising marker-less tracking solutions were implemented. In [13], [14] the 3D contour of the front teeth was retrieved as follows: first, the regions of interest enclosing the teeth contour were extracted from pairs of stereo images with sub pixel accuracy and using a template matching approach; then, image points on the extracted edges are stereo-matched using epipolar constraints and finally the 3D contour was determined through stereo triangulation.

Wang *et al.* [29] the authors addressed some of the limitations brought about by their previously proposed stereo-matching and tracking method: 1) the strict conditions imposed on the viewing angle of the stereo camera that limits the trackable area and 2) the need for frequent re-calibrations to cope with the degradation of the stereo calibration over time. Thus, as a solution they use a single RGB camera for tracking the teeth. The tracking method integrates a 3D-2D shape matching method into a tracking-learning-detection framework.

4) REGISTRATION TECHNIQUE (RT)

Registration is an important step in computer-assisted surgical navigation in order to correlate the computer-generated content and the real surgical scene. Regarding the registration technique (RT), in three studies, the authors described a standard point-based registration procedure on anatomic fiducials [35], [39], [40]. The surgeon performed the registration manually through an electromagnetic stylus. Even if it is not explicitly described in the text, a similar method was adopted by the authors in [8], [23], although they used an IR pointer of a commercial surgical neuro-navigation system (VectorVision, Brainlab AG, Munich Germany). In three studies [4], [22] and [31], the patient-to-image registration step was not described since it was inherent to the marker-based tracking solution adopted. In [21], [22] and [31], the registration was achieved by anchoring the position of the physical markers (template) to the patient by means of an occlusal-splint. Differently, the *in vitro* nature of the study described in [4] allowed the spherical markers to be directly implanted into the mannequin, hence at a given position with respect to the CT data.

In [20], the image-to-patient registration was achieved through a set of IR markers anchored to the patient's head and worn during SPECT/CT acquisition.

In [6] and [7] a surface-based patient-to-image registration was implemented. A surface scanning of the patient's facial soft tissue was performed through a structured light scanner and the obtained 3D surface was then registered with the preoperative 3D dataset. In [13], [14], [24], [29], [33] and [38] the authors relied on an automatic registration method based on the previously mentioned marker-less tracking solutions of the 3D contour of the patient's teeth [48]. Finally, in two works [26], [27], no method for image-to-patient registration was described whereas in [30] the registration was performed manually by aligning the position of the teeth between intraoral photographs and 3D models of the mandible.

5) AR DISPLAY TYPE (DT)

The AR display type (DT) is the particular technology used to present AR data to the end user.

Various types of AR visualization technologies are available, and they can be broadly divided into three categories: Video-See-Through (VST) mode, Optical See-Through (OST) mode and projection-based mode. VST mode superimposes virtually generated images onto a real-time video stream and generates an augmented 3D view that helps to improve the viewer's perception with regards to depth, motion and stereo parallax. OST visualization technology overlays the images onto a translucent mirror/device for the user's direct view and it allows the user to see what is shown on the glass screen while still being able to see through it. Projection-based mode works similarly to OST mode and overlays the virtual images onto projectors that can be directly viewed by the users. Projection-based AR visualization is appropriate for large operative field overlays; however, it lacks depth perception.

Wearable AR systems based on head-mounted displays (HMDs) were quite common among the studies included in our review (8 out of 30 studies). HMDs intrinsically provide the user with an egocentric viewpoint and they do not limit his/her freedom of movement around the patient [49]. Standard HMDs provide binocular parallax and motion parallax and smoothly augment the user's perception of the surgical scene throughout the specific procedure.

In HMDs, the see-through capability can be provided through either a VST or an OST paradigm. Of the 8 studies using an HMD, all except 1 [31] were based on VST paradigm (Figure 5a). Unfortunately, a full description of the specific HMD used in the study has been provided only in [4]. In that study, the authors used a custom-made VST stereoscopic visor. The visor was assembled by mounting a pair of stereo cameras on a commercial visor for virtual reality [42]. In [3], the authors used a see-through HMD but in the text it is not clearly stated whether it is VST or OST, nor how the mechanism for augmentation is implemented. In [22] and in [31], the augmented information was displayed on a

TABLE 1. General data of the included papers.

Ref.	Study (Author, year)	Country	In vivo/in vitro	No. of patients	OCMS subspecialty	Pathology
[31]	Zhu et al., 2017	China	In vivo	20	General OCMS	Mandibular diseases
[38]	Murugesan et al., 2018	Australia	In vivo	9	General OCMS	general (face defects/diseases)
[24]	Wang et al., 2019	China	In vitro/In vivo	1 (volunteer)	Orthognatic surgery	front toothloss
[6]	Marmulla et al., 2005 (a)	Germany	In vivo	1 (volunteer)	Notspecified	benign tumor of the left orbit.
[8]	Mischkowski et al., 2006	Germany	In vivo	1	Orthognatic surgery	translocation of bony segments
[30]	Won et al., 2017	Korea	In vivo	5	General OCMS	dentalprocedures
[4]	Badiali et al., 2014	Italy	In vitro	-	Orthognatic surgery	n.a.
[39]	Wagner et al., 1996 (a)	Austria	In vivo	1 (volunteer)	Orthognatic surgery	n.a.
[13]	Wang et al., 2014	Japan	In vitro	-	Orthognatic surgery/Dental surgery	n.a.
[32]	Tran et al., 2011	Japan	In vitro/In vivo	1 (volunteer)	General OCMS	n.a.
[26]	Profeta et al., 2016	United Kingdom	In vivo	1	Tumor surgery	image-guided sentinel lymph node biopsy
[36]	Wagner et al., 1999	Austria	In vivo	27	Reconstructive surgery	post-traumatic deformities of facial skeleton, defects of maxilla/mandible positions
[40]	Watzinger et al., 1997	Austria	In vivo	5	Reconstructive surgery	post-traumatic deformities of the zygomaticomaxillary complex
[37]	Gavaghan et al., 2012	Switzerland	In vivo	1	Tumor surgery	mandibular tumor
[3]	Wagner et al., 1996 (b)	Austria	In vivo	4	Tumor surgery	foreign body in left zygoma; recurrence of infraorbital osteosarcoma; defects of maxilla/mandible positions
[7]	Marmulla et al., 2005 (b)	Germany	In vivo	2	Tumor surgery	temporal/intraorbital tumors
[33]	Wang et al., 2015	Japan	In vitro	-	General OCMS	n.a.
[28]	Suenaga et al., 2013	Japan	In vitro/In vivo	1 (volunteer)	General OCMS	n.a.
[27]	Scolozzi et al., 2017	Switzerland	In vivo	1	Tumor surgery	epithelial tumour of lacrimal gland
[25]	Ahn et al., 2019	Korea	In vitro	-	Orthognatic surgery	n.a.
[29]	Wang et al., 2017	Japan	In vitro/In vivo	1 (volunteer)	Orthognatic surgery	n.a.
[35]	Wagner et al., 1997	Austria	In vitro/In vivo	1	General OCMS	osteotomies of facial skeleton
[14]	Suenaga et al., 2015	Japan	In vitro/In vivo	1 (volunteer)	Orthognatic surgery	n.a.
[34]	Kahrs et al., 2005	Germany	In vitro	-	Orthognatic surgery	n.a.
[19]	Basnet et al., 2018	Australia	In vitro	-	Orthognatic surgery	n.a.
[20]	Chand et al., 2018	United Kingdom	In vivo	1	Tumor surgery	head and neck tumor
[9]	Zinser, 2013 (a)	Germany	In vivo	16	Orthognatic surgery	skeletal Class III patients
[21]	Qu et al., 2015	China	In vivo	20	Orthognatic surgery	Hemifacial microsomia
[22]	Zhu et al., 2016	China	In vivo	12	Orthognatic surgery	orbital hypertelorism
[23]	Zinser, 2013 (b)	Germany	In vivo	30	Orthognatic surgery	dentofacial or orthognathic deformities

"semi-transparent helmet" but in neither of the two papers any description of the system is provided.

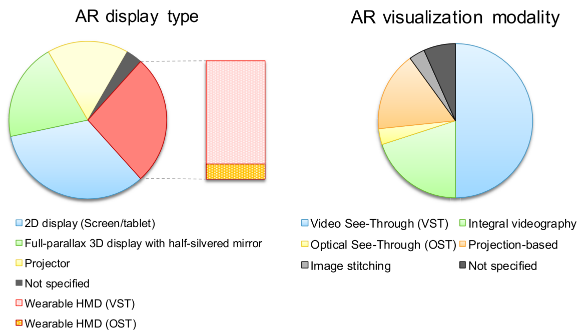
In ten studies, the AR was displayed on a traditional 2D screen and the AR paradigm was implemented under the VST mode. In two papers [8] and [9], the authors used a hand-held display (tablet) while in [20], [21], [24], [26] and [29] the display unit was a standard external monitor.

In five studies [6], [7], [21], [34] and [37], the virtual content was directly projected onto the surgical area through the scanner used for image-to-patient registration.

The major shortcomings of both the VST and OST paradigms implemented in the above-described AR displays are due to the intrinsic incompatibility between the 3D representation of the real world and the nature of the virtual content, rendered as a 2D image. To cope with these issues, alternative and promising 3D imaging approaches, based on the integral imaging technology (Integral Videography), were proposed in [13], [14], [28], [32], [33], [38]. The integral imaging autostereoscopic displays presented in these studies use a set of 2D elemental images with an array of micro convex lenses in order to generate a full parallax visualization of the 3D content. Therefore, with integral imaging-based displays, a proper 3D overlay between virtual content and real scene can be obtained.

6) ACCURACY AND FRAME RATE

As for the accuracy of the AR systems (i.e. the accuracy of the positioning of the virtual scene over the surgical real scene), we could not use it as a valid benchmark given the fact that its definition was not consistent across the different papers analyzed in this review and this hindered a meaningful comparison. The same considerations apply to the frame rate of the AR systems. Anyway, we reported the accuracy and frame rate values that were cited in the analyzed papers in **Table 2**.



(a) (b)

FIGURE 5. Distribution of studies by AR display type (a) and AR visualization mode (b).VST: Video See-Through; OST: Optical-See-Through.

C. COMPARISON BETWEEN APPLICATION SCENARIOS AND TECHNICAL ASPECTS

We reported in **Table 3** a comparative analysis aimed to outline any possible correlation of the different application scenarios (i.e. OCMS subspecialty, pathology) with the different tracking modalities, tracking bodies and registration techniques reported in the papers.

TABLE 2. Data on AR technical implementation extracted from each paper studied.

Ns ref.	Study (Author, year)	Virtual Data Source (VDS)	Visualization Processing Modality (VPM)	Tracking Modality (TM)	Tracking body site	Registration Technique (RT)	AR display type/visualization modality	Accuracy (Acc)	Frame rate
[31]	Zhu et al., 2017	CT	3D mesh representations of anatomic structures and task-oriented geometrical primitives (osteotomy lines)	Optical monoscopic tracking (visible light) of the patient	Maxilla (tracking marker on occlusal splint)	Marker-based registration through template marker anchored to occlusal splint	Wearable semi-transparent glass OST modality	Avg error 0.96±0.51mm	Not specified
[38]	Murugesan et al., 2018	CT	3D mesh representations of anatomic structures (nerve channels, tissue areas, teeth, mandible, maxilla)	TLD (Tracking Learning Detection) algorithm - bounding box tracking method	Not specified	Ulrich's method for initial registration [48] and then refinement using an ICP (Iterative Closest Point) algorithm	Translucent mirror for AR display Integral Videography (IV)	Improvement of Video accuracy by 0.30-0.40mm	10-13 fps
[24]	Wang et al., 2019	CT/3D scanner	3D mesh representations of anatomic structures (nerves, tooth roots), implants, and task-oriented geometrical primitives (cutting lines)	Optical stereo tracking (visible light) of the patient	Teeth	Ulrich's method for initial registration [48] and then refinement using an ICP (Iterative Closest Point) algorithm	Screen VST modality	Less than 0.5mm	30 Hz
[6]	Marmulla et al., 2005 (a)	CT/MRI	Task-oriented geometrical primitives (osteotomy lines, skin incision lines, tumor margins)	Optical tracking (infrared light) of the patient	Head (set of infrared markers)	Initial surface registration (face) before intervention through structured light and marker-based tracking (fiducial markers on splints) during the intervention	Projected (data directly displayed on the patient) Projector-based modality	Not specified	Not specified
[8]	Mischkowski et al., 2006	CT/MRI	3D mesh representations of anatomic structures	Optical tracking (infrared light) of the display	Display (set of infrared markers)	Point-based registration through anatomic fiducials and infrared pointer (provided by the navigation system)	Tablet VST modality	Avg error 0.97mm	Not specified
[30]	Won et al., 2017	CT	3D mesh representations of anatomic structures (mandible)	Not specified	Not specified	Manual registration	Screen Not specified	Not specified	Static Images
[4]	Badiali et al., 2014	CT	Task-oriented geometrical primitives (asterisks or crosses) and 3D mesh representations of anatomic structures	Optical stereo tracking (visible light) of the patient	Head (set of visible markers)	Marker-based registration through visible markers anchored to the patient	Wearable stereoscopic HMD VST modality	Avg Target Registration error 1.70mm on target points	25 fps
[39]	Wagner et al., 1996 (a)	conventional axiography/ cephalograms /radiography	3D mesh representation of anatomic structures (temporomandibular joint axiogram/virtual condyle and fossa)	Electromagnetic sensor tracking	Forehead, mandible	Electromagnetic sensors; fiducial markers and electromagnetic stylus	HMD VST modality	Not specified	Not specified
[13]	Wang et al., 2014	CT	3D mesh representations of anatomic structures	Optical stereo tracking (visible light) of the patient and the surgical instrument	Surgical instrument through template marker and patient's front teeth (tracked without markers)	Automatic registration using 3D contour of the patient's teeth (ARTMA);	Full-parallax 3D display (with half-silvered mirror) Integral Videography (IV)	Avg error 0.71mm	more than 60 fps
[32]	Tran et al., 2011	-	3D mesh representations of anatomic structures (osseous structures and soft tissues such as vessels)	Not specified	Lower jaw	Marker-based registration (marker frame on lower jaw) + a calibration object with six feature points.	Full-parallax 3D display (with half-silvered mirror) Integral Videography (IV)	An overall positional error of less than 1mm.	minimum 5 fps; in most cases more than 10 fps
[26]	Profeta et al., 2016	SPECT/CT	Textual elements and 3D mesh representations of the hot-spots	Optical tracking (infrared light) of the patient and the probe	Head and probe (2 sets of infrared markers)	Not specified	2D Display VST modality	Not specified	Not specified
[36]	Wagner et al., 1999	CT	Task-oriented geometrical primitives (osteotomy lines)	Electromagnetic tracking and optical tracking	Not specified	ARTMA Biomedical software for registration	Computer monitor or a see-through HMD VST modality	Not specified	Not specified
[40]	Watzinger et al., 1997	CT	Graphic lines representing zygoma outer surfaces	Electromagnetic tracking	Sensor 1 (fiducial marker on a 3D-splint) + sensor 2 (marker on patient's head) + sensor 3 (marker on frontal zygomatic bone)	ARTMA Biomedical software for registration	TV monitor and see-through HDM Not specified	Not specified	Not specified
[37]	Gavaghan et al., 2012	CBCT	3D mesh representations of anatomic structures (mandible, facial nerve) and task-oriented geometrical primitives (planned resections)	Optical tracking (infrared light)	Portable projector itself	Registration and tracking capabilities of the navigation system into which the device is integrated (point matching with fiducial markers).	Projected (a new portable image overlay projector) Projector-based modality	Mean projection accuracy of 1.3mm	Update rate of projector: 60 Hz
[35]	Wagner et al., 1996 (b)	CT/MRI	Task-oriented geometrical primitives (access path, osteotomy lines), numeric information on maxilla/mandible spatial position	Electromagnetic tracking	3D sensors positioned on patient's head, and occlusal splint	Electromagnetic sensors + electromagnetic stylus	See-through HDM VST modality	Not specified	Not specified
[7]	Marmulla et al., 2005 (b)	CT	Task-oriented geometrical primitives (osteotomy lines and tumor margins)	Optical tracking (passive reflecting markers – probably infrared)	Maxilla (tracking body on dental splint)	Initial marker-less registration (surface matching of the skin contour between preoperative CT and intraoperative surface scan), then marker-based registration	Projected Projector-based modality	Intraoperative accuracy of 1mm	Not specified
[33]	Wang et al., 2015	CT	3D mesh representations of anatomic structures (tooth roots, nerve channels, wisdom roots)	Optical tracking	Surface of the jaw model	Automatic image registration method using teeth contour tracking; the stereo camera can serve as a 3D tracking device	3D display and translucent mirror Integral Videography (IV)	0.9-1.1mm	50–60 fps (for surface models, 5–8 fps (for large volumes)
[28]	Suenaga et al., 2013	CT	3D mesh representations of anatomic structures (maxillary/mandibular jaws, teeth)	Optical tracking (infrared light)	Teeth (tracking markers on dental splint); tracking of surgical instruments	Marker-based registration	Videography display and half-silvered mirror Integral Videography (IV)	< 1mm	5 fps

TABLE 2. ***(Continued.)*** **Data on AR technical implementation extracted from each paper studied.**

[27]	Scolozzi et al., 2017	CT/MRI	3D mesh representations of anatomic structures (tumor and skull)	Optical tracking of the microscope (probably infrared)	Not specified	Not specified	Microscope eyepiece VST modality	Not specified	Not specified
[25]	Ahn et al., 2019	CT/3D scanner	3D mesh representations of anatomic structures (maxilla) and task-oriented geometrical primitives (midsagittal reference plane and Frankfort horizontal plane)	Optical stereo tracking	Frontal area of the patient; maxilla movement (marker in the intermediate splint)	Marker-based registration	Display VST modality	<0.5mm	Not specified
[29]	Wang et al., 2017	CT	3D mesh representations of anatomic structures	Optical monoscopic tracking (visible light) of the patient -	Teeth tracked without markers	Ulrich's method for initial registration [48] and then refinement using an ICP (Iterative Closest Point) algorithm;	2D Display VST modality	Avg error 1mm. Target registration error between indicated target points	3-5 fps (7-10 fps)
[3]	Wagner et al., 1997	CT	3D mesh representations of anatomic structures and geometrical primitives (planned osteotomy lines)	Electromagnetic tracking	3D sensors positioned on patient's head	Electromagnetic sensors; fiducial markers + Electromagnetic stylus	See-through HMD VST modality	Not specified	Not specified
[14]	Suenaga et al., 2015	CT	3D mesh representations of anatomic structures	Optical stereo tracking (visible light) of the patient	Teeth tracked without markers	Automatic registration via tracking of the 3D contour of the patient's teeth;	Full-parallax 3D display and half-silvered mirror Integral Videography (IV)	Avg error< 1mm	5 fps
[34]	Kahrs et al., 2005	Notspecified	Position of bone segment; position of potential implant	Not specified	Not specified	Not specified	Projected Projector-based modality	Not specified	Not specified
[19]	Basnet et al., 2018	CT	Not specified	TLD (Tracking Learning Detection) algorithm - bounding box tracking method	Not specified	Ulrich's method for initial registration [48] and then refinement using an ICP (Iterative Closest Point) algorithm	Not specified VST modality	Image overlay accuracy of 0.23-0.35mm	8-12 fps
[20]	Chand et al., 2018	SPECT/CT	Task-oriented geometrical primitives (the beam of the hand-held fluorescence probe and mesh)	Optical tracking (infrared light)	Head and probe (2 sets of infrared markers)	Marker-based registration through infrared markers anchored to the patient's head and worn during SPECT/CT image acquisition	Screen VST modality	Not specified	Not specified
[9]	Zinser et al., 2013 (a)	CT/CBCT	Task-oriented geometrical primitives (reference planes to obtain facial symmetry)	Optical tracking (infrared light) of the display	Display (set of infrared markers)	Wafer-less superimposition of real time and virtual intraoperative data, using a rear-mounted VGA camera on IGV display	Portable Image-guided visualization (IGV) display VST modality	Precision of planning transfer: <0.67mm, <0.41◦	Not specified
[21]	Qu et al., 2015	CT	3D mesh representations of anatomic structures and task-oriented geometrical primitives (osteotomy lines)	Optical monoscopic tracking (visible light) of the patient	Head through template marker	Marker-based registration through template marker anchored to occlusal splint	Projected Projector-based modality	about 1mm	Not specified
[22]	Zhu et al., 2016	CT	3D mesh representations of anatomic structures and task-oriented geometrical primitives (osteotomy lines)	Optical monoscopic tracking (visible light) of the patient	Maxilla (tracking marker on occlusal splint)	Marker-based registration through template marker anchored to occlusal splint	Wearable semi-transparent glass Not specified	Errors less than 2.5mm in translation	Not specified
[23]	Zinser et al., 2013 (b)	CT	3D mesh representations of anatomic structures	Optical tracking (infrared light) of the display	Display (set of infrared markers)	Point-based registration through anatomic fiducials and infrared pointer	Portable Image-guided visualization (IGV) display VST modality	Precision of the maxillary planning transfer <0.61 mm	Not specified

Regarding the tracking modality, we can observe that electromagnetic tracking is used more in tumor/reconstructive surgery (3/8 papers, i.e. 37%) than in orthognatic surgery (1/14 papers, i.e. 7%). This is mainly because patients undergoing orthognatic surgery typically have brackets on teeth for an orthodontic treatment associated to surgery, therefore the metal brackets create disturbances to the electromagnetic fields.

About the tracking body (when specified), we found that 14/24 papers (i.e. 58%) use the splint (or teeth) as tracking body. In general, the tracking of the splint (or teeth via anatomical fiducial markers) is the preferred solution since the closer you stay with the tracking body to the working area, the better is for the effectiveness and reliability of the tracking. In half of these studies (7/14), regardless of the type of surgical application, the tracked splint (or teeth) are used in combination with the tracking of the patient's head. Probably this combined approach is the most complete solution in maxillofacial applications.

Regarding the registration technique, we can observe that in orthognatic surgery the use of a marker-less registration is predominant (8/14, i.e. 57%) over a marker-based registration (5/14, i.e. 36%), while in tumor/reconstructive surgery it is the opposite (2/8, i.e. 25% for marker-less; 5/8, i.e. 62% for marker-based). Probably in orthognatic surgery the marker-less approach is more viable since the anatomical fiducial markers are more accessible and unaffected by pathology if compared with tumor surgery.

IV. DISCUSSION

This review focused on clinical research related to AR technologies in oral and cranio-maxillofacial applications.

Recently, a review on intraoperative augmented reality with heads-up displays in maxillofacial surgery has been

TABLE 3. Comparison between application scenarios and technical aspects.

Study	In vivo / In vitro	OCMS subspecialty	Pathology	Tracking modality	Tracking Body	Registration Technique
Zhu et al., 2017	In vivo	General OCMS	Mandibular diseases	Optical monoscopic tracking (visible light) of the patient	Patient maxilla (tracking marker on occlusal splint)	Marker-based registration through template marker anchored to occlusal splint (*marker-based*)
Murugesan et al., 2018	In vivo	General OCMS	general (face defect/diseases)	TLD (Tracking Learning Detection) algorithm - bounding box tracking method	Not-specified	Ulrich's method for initial registration [48] and then refinement using an ICP (Iterative Closest Point) algorithm (*marker-less*)
Wang et al., 2019	In vitro/In vivo	Orthognatic surgery	front toothloss	Shape tracking using a customized stereo camera	Teeth	Ulrich's method for initial registration [48] and then refinement using an ICP (Iterative Closest Point) algorithm (*marker-less*)
Marmulla et al., 2005 (a)	In vivo	Not-specified	benign tumor of the left orbit	Optical tracking (infrared light) of the patient	Head (markers)	Initial surface registration (face) before intervention through structured light and marker-based tracking (fiducial markers on splints) during the intervention (*marker-based*)
Mischkowski et al., 2006	In vivo	Orthognatic surgery	translocation of bony segments	Optical tracking (infrared light) of the display	Display (markers)	Point-based registration through anatomic fiducials and infrared pointer provided by the navigation system (*marker-less*)
Won et al., 2017	In vivo	General OCMS	Dental procedures	Not-specified	Not-specified	Manual registration
Badiali et al., 2014	In vitro	Orthognatic surgery	n.a.	Optical stereo tracking (visible light) of the patient	Head (markers)	Marker-based registration through visible markers anchored to the patient (*marker-based*)
Wagner et al., 1996 (a)	In vivo	Orthognatic surgery	n.a.	Electromagnetic tracking	Forehead, mandible	Electromagnetic sensors; fiducial markers + electromagnetic stylus (*marker-based*)
Wang et al., 2014		Orthognatic surgery/ Dental surgery	n.a.	Optical stereo tracking (visible light) of the patient and the surgical instrument	Surgical instrument through template marker Patient front teeth (tracked without markers)	Automatic registration via marker-less tracking of 3D contour of the patient's teeth (*marker-less*)
Tran et al., 2011	In vitro/In vivo	General OCMS	n.a.	Not-specified	Lower jaw	Marker-based registration (marker frame on lower jaw) + a calibration object with six feature points (*marker-based*)
Profeta et al., 2016	In vivo	Tumor surgery	image-guided sentinel lymph node biopsy	Optical tracking (infrared light) of the patient and the probe	Head and probe (2 sets of infrared markers)	Not-specified
Wagner et al., 1999	In vivo	Reconstructive surgery	post-traumatic deformities of facial skeleton, defects of maxilla/mandible positions	Electromagnetic tracking/ Optical tracking	Not-specified	Electromagnetic sensors; fiducial markers + electromagnetic stylus (*marker-based*)
Watzinger et al., 1997	In vivo	Reconstructive surgery	post-traumatic deformities of tzygomaticomaxillary complex	Electromagnetic tracking	Sensor 1 (fiducial marker on a 3D-splint) + sensor 2 (marker on patient's head) + sensor 3 (marker on frontal zygomatic bone)	ARTMA Biomedical software for registration (*marker-less*)
Gavaghan et al., 2012	In vivo	Tumor surgery	mandibular tumor	Optical tracking (infrared-based)	Portable projector itself	Registration and tracking capabilities of the navigation system into which the device is integrated (point matching with fiducial markers). (*marker-based*)
Wagner et al., 1996 (b)	In vivo	Tumor surgery	foreign body in left zygoma; recurrence of infraorbital osteosarcoma; defects of maxilla/ mandible positions	Electromagnetic tracking	3D sensors positioned on patient's head, and occlusal splint	Electromagnetic sensors; fiducial markers + electromagnetic stylus (*marker-based*)
Marmulla et al., 2005 (b)	In vivo	Tumor surgery	temporal/intraorbital tumors	Optical tracking (probably infrared)	Maxilla (tracking body on dental splint)	Initial marker-less registration (surface matching of the skin contour between preoperative CT and intraoperative surface scan), then marker-based registration (*marker-less*) +(*marker-based*)
Wang et al., 2015	In vitro	General OCMS	n.a.	Optical tracking (optional)	Surface of the jaw model	Automatic marker-less image registration method using teeth contour tracking (the stereo camera can serve as a 3D tracking device) (*marker-less*)
Suenaga et al., 2013	In vitro/In vivo	General OCMS	n.a.	Optical tracking (infreared)	Subject's teeth (tracking markers on dental splint); tracking of surgical instruments	(*marker-based*)
Scolozzi et al., 2017	In vivo	Tumor surgery	epithelial tumour of lacrimal gland	Optical tracking of the microscope (infrared probably)	Not-specified	Not-specified
Ahn et al., 2019	In vitro	Orthognatic surgery	n.a.	Optical tracking (stereo camera-based)	Frontal area of the patient; maxilla movement (marker in the intermediate splint)	(*marker-based*)
Wang et al., 2017	In vitro/In vivo	Orthognatic surgery	n.a.	Optical tracking (monoscopic with visible light) of the patient	Patient's front teeth tracked without markers	Ulrich's method for initial registration [48] and then refinement using an ICP (Iterative Closest Point) algorithm (*marker-less*)
Wagner et al., 1997	In vitro/In vivo	General OCMS	osteotomies of facial skeleton	Electromagnetic tracking	3D sensors positioned on patient's head	Electromagnetic sensors; fiducial markers + electromagnetic stylus (*marker-based*)
Suenaga et al., 2015	In vitro/In vivo	Orthognatic surgery	n.a.	Optical tracking (stereo with visible light) of the patient	Patient's front teeth tracked without markers	Automatic registration via marker-less tracking of the 3D contour of the patient's teeth (*marker-less*)
Kahrs et al., 2005	In vitro	Orthognatic surgery	n.a.	Not-specified	Not-specified	Not-specified
Basnet et al., 2018	In vitro	Orthognatic surgery	n.a.	TLD (Tracking Learning Detection) algorithm - bounding box tracking method	Not-specified	Ulrich's method (*marker-less*)
Chand et al., 2018	In vivo	Tumor surgery	head and neck tumor	Optical tracking (infrared)	Head and proble (markers)	Marker-based registration through infrared markers anchored to the patient's head and worn during SPECT/CT image acquisition (*marker-based*)

TABLE 3. ***(Continued.)*** **Comparison between application scenarios and technical aspects.**

Zinser, 2013 (a)	In vivo	Orthognatic surgery	skeletal Class III patients	Optical tracking (infrared)	Display	Wafer-less - superimposition of real time an virtual intraoperative data, using a rear mounted VGA camera on IGV display (*marker-less*)
Qu et al., 2015	In vivo	Orthognatic surgery	Hemifacial microsomia	Optical tracking (visible light) of the patient	Head (template marker)	Marker-based registration through template marker anchored to occlusal splint (*marker-based*)
Zhu et al., 2016	In vivo	Orthognatic surgery	orbital hypertelorism	Optical tracking (visible light) of the patient	Maxilla (marker on occlusal splint)	Marker-based registration through template marker anchored to occlusal splint (*marker-based*)
Zinser, 2013 (b)	In vivo	Orthognatic surgery	dentofacial or orthognathic deformities	Optical tracking (infrared) of the display	Display	Point-based registration through anatomic fiducials and infrared pointer (*marker-less*)

published by Bosc *et al.* [50]. In that case, the analysis has been focused only on wearable heads-up displays for applications in maxillofacial surgery, while the present review is aimed to provide a more comprehensive overview of the state-of-the-art in AR-based solutions in the field of oral and cranio-maxillofacial surgery.

Results from our analysis revealed that most of the AR applications in OCMS are used for assisting orthognatic surgical procedures and were based on a video-see-through (VST) paradigm.

In VST displays the direct view of the world is mediated by one or two external cameras anchored to the display. The camera frames are digitally blended with the virtual content and the resulting video streams are displayed onto the display (external display or HMD). The pixelwise blending between the camera frames and the computer-generated content is intrinsically parallax-free (i.e., devoid of the influence of the user's viewpoint), and this fact confers a clear advantage over the OST mechanism, for which a dedicated eye-to-display calibration procedure is required to achieve proper AR image registration. Projection-based AR solutions as the one used in [37] appear to offer more freedom of movement to the surgeon, yet they are particularly suited for augmenting only the exposed surfaces of the patient (or of the anatomical structures), since displaying structures that are positioned below the projection surface is not parallax-free. In this regard, autostereoscopic 3D see-through displays based on integral videography [13] represent a valid alternative to enhance depth perception and yield a proper virtual-to-real 3D image registration without the need for tedious pre-operative eye-to-display calibrations. However, such systems were/are still characterized by a degradation of the viewing quality owing to the trade-off of the viewing parameters [51] such as the viewing angle, the depth-of-field, the spatial resolution, and a light throughput of the display. This is the main reason that has hampered the actual commercialization of such systems.

Finally, about one third of the studies we reviewed reported the use of wearable HMDs, which seem to have on the contrary great potential for widespread use of augmented reality in the surgical practice. These systems bring about many benefits but also present some drawbacks that should be addressed in future research. In the following subsection, we will outline the main benefits and drawbacks of such AR displays in the field of image-guided surgery.

A. BENEFITS AND DRAWBACKS OF HEAD-MOUNTED DISPLAYS

The use of AR in surgical procedures impacts the clinical outcome in terms of treatment efficacy and accuracy since it provides surgeons with a virtual navigation aid contextually blended with the physical surgical field (i.e., in situ) [52]. Under AR guidance, the surgeon increases his/her own spatial awareness and perception of the underlying 3D anatomical structures, with the possibility of benefiting from a sort of "X-ray view" of the patient anatomy. In addition, AR allows the projection of preoperative planning data in the form of task-oriented geometrical primitives such as tumor contour margins, skin incision lines, and craniotomy/osteotomy lines. This property greatly facilitates the performance of high-precision surgical tasks both in terms of time efficiency and accuracy.

Another potential clinical impact of AR is to make open surgery tasks more ≪mini-invasive≫, since in some cases the exposure of deep anatomical structures, non-visible to the naked eye, can be prevented as they can be projected onto the patient's skin surface. A less invasive surgical approach implies a reduction in the surgical operating time, therefore a reduced post-operative recovery time for the patient.

The major benefit of HMDs for AR surgical applications is that they intrinsically provide the surgeon with an egocentric viewpoint and offer improved ergonomics if compared to traditional computer-assisted surgical systems. Indeed, head-up displays allow surgeons to concentrate on the task at hand without having to turn their heads away from the surgical field constantly shifting visual focuses between the surgical field and the imaging monitor [53]–[55]. This leads to efficient decision making and time saving in the workflow inside the operating room, which, as previously reported [56], can allow for more surgeries to be performed and it improves the overall productivity of the workforce.

One of the major problems currently experienced for surgical guidance, related to HMDs, is due to the limited registration accuracy between the virtual content and the real scene.

One of the head-mounted devices furthest along in development for AR applications is the HoloLens (Microsoft, Redmond, WA). This device projects a hologram in a user's line of vision when the visor is worn. In fact, the number of experiences with HoloLens and Google Glass used for surgical applications is growing [55]–[59]. However, since these head-up displays were developed for general-purpose applications, their technical requirement specifications are suboptimal for needs inherent to certain surgical tasks that require extreme precision.

Another problem related to HMDs may involve eye strain associated with concentration on a small screen for prolonged periods of time. This may lead to visual discomfort [54], [60].

The true wearability and ergonomics associated to heads-up displays, as well as the effective implementation of hands-free commands, are also important issues to be considered for the full acceptance and use of these systems by surgeons, especially in case of long operative times inherent to certain surgeries.

B. TOWARDS "SURGERY-SPECIFIC" HEAD MOUNTED DISPLAYS

In order to really favor the routine use of AR-based navigation systems in the operating room, the future research should be concentrated on the development of heads-up displays specifically designed for surgery. Nowadays, OST HMDs are the leading edge and the major output medium of wearable AR technology, and several heads-up display are entering the market following the success of the Microsoft HoloLens [61]. Nevertheless, technological and human-factor limitations still hinder the routine use of such devices in routine clinical practice [62]. The most relevant technological flaws of consumer level heads-up displays are: the presence of a small augmentable field of view, the low contrast image they can offer, and the need for a robust and possibly automatic eye-to-display calibration to achieve an accurate and reliable AR image registration [61], [63].

In addition, commercial heads-up displays were, and still are, mostly designed for parallel viewing with the focal plane commonly projected by the collimation optics of the display between 2 m and infinity. This feature causes perceptual conflicts such as the vergence-accommodation conflict, when the binocular triangulation distance conflicts with the focusing distance, and the focus rivalry, when the focusing distance of the real scene is significantly different from the one of the virtual content.

From a general perspective, the major requirements for a ''surgery specific'' HMD are related to its ergonomics, safety, and reliability. As reported in a recent review work on the use of AR in minimally invasive cranial base surgery [64], and in a work focused on OST-HMD technologies for specific clinical scenarios [65], the requirements that define a functional AR surgical system are:

- simple installation and setup
- minimum calibration process (inevitable for OST-HMD technologies)
- common focus for virtual objects and real-world images
- high accuracy (submillimetric for some specific tasks)
- short registration time
- unified integration of surgical instruments
- low encumbrance (wearability/low weight for HMDs)
- depth cues for both virtual objects and instruments
- virtual objects superimposed only when necessary
- high resolution and frame rate
- low latency
- adaptable and adequate image-object contrast during projection.

About safety requirements, automatic alarm systems based on quantitative evaluation of the registration accuracy should be used, as well as mechanisms ensuring that the direct vision of the surgical field is preserved even in presence of fault, thus allowing the surgeon to safely continue the operation [52].

A typical AR surgical system comprises some processes (device calibration, initial registration, patient or instrument tracking) that should hinder the surgical workflow as little as possible. Two aspects influencing the progress of surgery are registration time and tracking accuracy. Some previous works [66], [67] report that clinically 5–10 min is an acceptable registration duration, and 1-2 mm tracking precision are regarded as acceptable ranges in cranial base domain [64].

To the authors's knowledge, today two ''surgery-specific'' headsets for AR-based intraoperative guidance are under development and investigation.

The first is Xvision Spine system (XVS), an AR surgical navigation system based on a headset developed by Augmedics (Yoqneam, Israel) [68]. This system incorporates AR eyeglasses that project images onto the retina, infrared cameras, processors and algorithms and accomplishes all of the intraoperative functions, as for example tracking, image registration, and displaying the virtual images. The surgeon sees two little screens floating just above the patient and can intuitively see the 3D image without looking aside or up and down, and when he inserts an instrument within the patient, he can see the 2D planes to verify that the tool is inserted correctly. The images can be zoomed in and out, flipped and rotated, and the contrast can be adjusted. Very recently, the FDA cleared the XVS system, with XVS software, as an aid for precisely locating anatomical structures in either open or percutaneous spinal procedures. Their use is indicated for any medical condition in which the use of stereotactic surgery may be appropriate, and where reference to a rigid anatomical structure, such as the spine, can be identified relative to CT imagery of the anatomy. The predicate for the 510(k) submission was the Medtronic StealthStation S8 Surgical Navigation System.

The second system is VOSTARS: a new wearable AR-based system designed as a hybrid Optical-See-Through (OST)/Video-See-Through (VST) HMD capable to offer a highly advanced navigation tool for OCMS and other open-surgeries [71], [72]. The HMD is being designed to fulfill strict technical and human-factor requirements towards the realization of a functional and reliable AR-based surgical navigator [62]. Among the many features, the VOSTARS HMD has a robust egocentric optical tracking mechanism suited for use in the operating room and it is capable to yield both the see-through mechanisms (VST and OST) through a pair of electro-optical liquid-crystal (LC) shutters placed in front of the beam combiner of the see-through displays [70]: the system can therefore offer an accurate registration under VST modality and that of a natural view under OST modality.

VOSTARS development and validation are currently ongoing in the European H2020 project [69]. An early prototype of the VOSTARS system has been already evaluated in phantom tests taking into account surgical needs during maxillofacial orthognathic surgery [71], [72], and has demonstrated a submillimetric accuracy (0.5÷1 mm) in the execution of AR-guided maxilla osteotomies. In vivo clinical trials with VOSTARS system have recently started.

V. CONCLUSION

AR applications are of increasing interest and adoption in oral and maxillofacial surgery. However, the quality of the AR experience and the ability to smoothly integrate the surgeon's perceptive efficiency, represent the key requisites for a successful result. Widespread use of AR guidance in the operating room may be encouraged by the availability of ergonomic head-mounted devices that may guarantee the accuracy required for surgical tasks. Future research should be focused in this direction.

COMPLIANCE WITH ETHICAL STANDARDS

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

RESEARCH INVOLVING HUMAN PARTICIPANTS AND/OR ANIMALS

The authors confirm that no animal nor human testing were performed in this study.

INFORMED CONSENT

No informed consent is required.

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