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Supporting mandibular resection with intraoperative navigation utilizing augmented reality technology – A proof of concept study

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ABSTRACT

Objective: The aim of this study was to compare the accuracy of simulated mandibular osteotomies performed with cutting guides and two different intraoperative navigation systems based on simple (sAR) and navigated (nAR) augmented reality technology.
Material and methods: A total of 126 osteotomies were performed on 21 identical mandible models according to a prespecified virtual surgery plan. The data from postoperative computed tomography (CT) images were fused with preoperative CT scans to objectively compare the outcomes, i.e. angular deviations from the osteotomy trajectory (°) and displacement of two control points (mm).
Results: Osteotomies performed with cutting guides turned out to be the most accurate, with mean angular deviation of 4.94 ± 4.62° and mean control point displacement of 1.65 ± 0.88 mm. Mandibular osteotomies assisted with sAR and nAR were less accurate in terms of mean angular deviations (5.34 ± 3.67° and 7.14 ± 5.19°, respectively) and control point displacements (1.79 ± 0.94 mm and 2.41 ± 1.34 mm, respectively).
Conclusion: Our findings imply that in future, AR-based intraoperative navigation systems may find application in everyday clinical practice. Although AR technology still requires some improvements, it can already be used for presentation of digital navigation data, enhancing surgeon's awareness and hand-eye coordination during mandibular resection and reconstruction procedures.

1. Introduction

In recent years, computer-assisted surgeries (CAS) have been gaining popularity among oral and maxillofacial oncologic surgeons. Nowadays, the most popular form of CAS is a combination of virtual surgical planning (VSP) and computer-assisted design and manufacturing (CAD/CAM) (Hirsch et al., 2009; Roser et al., 2010; Ciocca et al., 2012; Foley et al., 2013; Levine et al., 2013; Mazzoni et al., 2013; Rohner et al., 2013; Rodby et al., 2014; Yuan et al., 2016; Weitz et al., 2018). Thanks to a combination of these two methods, surgeons can prepare patient-specific cutting guides which are later used to perform planned osteotomies with high accuracy. Another intensively researched method of VSP execution is robotic surgery, aimed mainly at reconstructive procedures such as neomandible creation with free fibula flap (Chao et al., 2016; Lin et al., 2016; Zhu et al., 2016). Last but not least there is intraoperative navigation, also referred to as image-guided surgery (IGS). This technology has already found application in bone tumor resection, guided biopsies and reconstruction of acquired and congenital deformations of the craniomaxillofacial region, to mention a few (Ewers et al., 2005; Girod et al., 2008; Schramm et al., 2008; Feichtinger et al., 2010; He et al., 2012; Rana et al., 2012; Gui et al., 2013; Pietruski et al., 2016).

As a result of recent progress in hardware, augmented reality (AR) emerged as a technology that can revolutionize many diagnostic and operative procedures (Badiali et al., 2014; Vávra et al.,

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2017; Bosc et al., 2018). In AR, computer-generated two-dimensional and 3D images are superimposed onto the visual field of the user. This technology seems to be particularly attractive from the perspective of IGS. The operator whose perception is enhanced with the components of a virtual surgery plan no longer needs to focus on a monitor screen. The need to observe the monitor is a disadvantage of currently available intraoperative navigation systems, which negatively affects the eye-hand coordination of the surgeon. It is postulated that in improving the user's orientation within the operative field, the use of AR may contribute to shorter surgical time and lesser morbidity, and thus, may reduce overall treatment costs (Bosc et al., 2018).

In this study, we objectively compared the outcomes of simulated mandibular osteotomies performed with cutting guides and two novel AR-based intraoperative navigation systems. Aside from the study results, we also discuss structure and functionality of the systems, challenges to overcome and potential applications in the field of maxillofacial surgery.

2. Materials and methods

2.1. Image data acquisition and virtual surgery planning

A human mandible model made of plaster was scanned using a 32-slice CT scanner (Siemens Somatom Sensation 16, Siemens Medical Solutions, Erlangen, Germany); 512 × 512-pixel dataset was acquired at a resolution of 0.39 mm/pixel and 0.625 mm slice thickness. The image data were saved in Digital Imaging and Communication in Medicine (DICOM) format and imported to a virtual planning software of the MentorEye system (Wroclaw University of Science and Technology, Wroclaw, Poland).

The software was used to design a virtual surgery plan for six various mandibular osteotomies (Fig. 1A). Then, the VSP was uploaded into an intraoperative navigation module of the MentorEye system. Moreover, a 3D model of the mandible along with the information about the osteotomy locations was exported and sent to a company that specialized in CAD/CAM technology. Based on the provided data, the company designed and produced three region-specific surgical guides for the planned osteotomies (Fig. 1B).

2.2. Computer-assisted osteotomies

The osteotomies were performed on 21 identical mandibular models (7 mandibles per each CAS method), using a sagittal surgical saw.

2.3. CAD/CAM support

In the first method, three region-specific surgical guides were mounted onto the mandible in the areas of their ideal attachment. Then, the osteotomy was performed with a sagittal saw, the blade of which was led along the guides' apertures.

2.4. AR navigation system support

In another two methods, an original AR-based intraoperative navigation system developed by the authors was used, along with an optical see-through head-mounted display (HMD) (Fig. 2). To perform the assisted osteotomies, a dynamic reference frame (DRF) was fixed to the mandible, and a passive optical tracking adapter was mounted onto the handle of the sagittal saw. Each procedure started with the registration of seven fiducial points located on the mandibular surface. The registration, carried out with a tip-pointer,

Fig. 2. Experimental intraoperative navigation system setup.

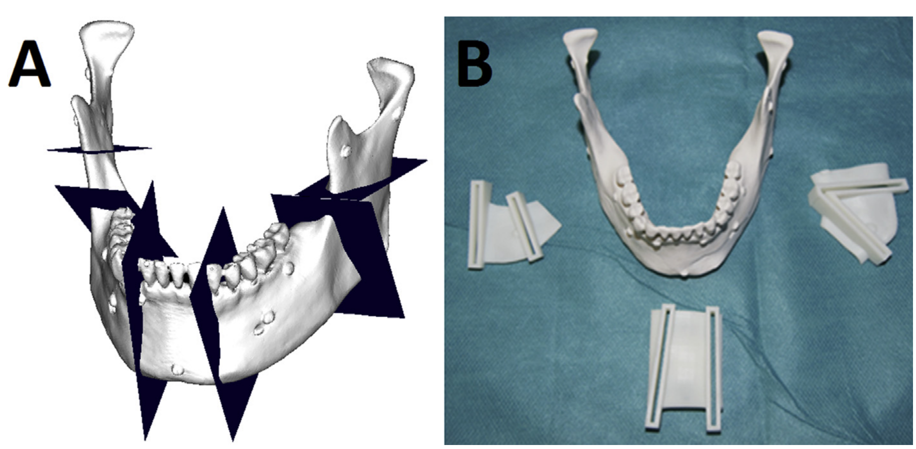

Fig. 1. (A) Three-dimensional view of six virtual osteotomies of the mandible. (B) A mandible model and three region-specific surgical guides for the planned osteotomies.

always followed the same protocol and was considered effective if the average fiducial registration error (FRE) parameter was less than 1 mm (Fitzpatrick and West, 2001). Then, the tip-pointer was used to calibrate the sagittal saw by determining the plane, length and edge width of its blade. Upon calibration, the operator could track the position and angulation of the blade in real time, displayed on the HMD as multiplanar two-dimensional cross-sections, three-dimensional image and digital coordinate system. The latter was the key component of the intraoperative navigation system, informing the operator about the distance and angulation of the blade in relation to the virtual trajectory of planned osteotomy. To our knowledge, it is the first report of usage of such a feature because the other navigation systems rely on the visual guidance of the pointers and the surgical tools.

In both AR-assisted methods, Movierio BT-200 Smart Glasses (Epson, Suwa, Japan) were used to display the navigation data. In simple AR (sAR) method, the data were acquired from the navigation system's screen. At any moment, the operator could choose between displaying solely a bar with the digital coordinate system presenting position of the blade against the virtual osteotomy trajectory or another bar with a 3D mandible image and contours of the navigated blade. In the second method, navigated AR (nAR), components of the virtual surgical plan were superimposed directly onto the surgeon's visual field. To achieve this, reflective passive marker spheres were mounted onto the eyewear's frames; the spheres that could be navigated against the patient's position were calibrated preoperatively to be coordinated with the visual field of the individual surgeon. During the procedure, aside from the bar with the digital coordinate system, the surgeon could also see from his own perspective a virtually generated osteotomy trajectory superimposed onto the mandible, and optionally, also a 3D mandibular model (Fig. 3).

2.5. Postoperative evaluation

Postoperative CT scans were obtained for all operated mandibles. Using the MentorEye software, the postoperative image data in DICOM format were fused with the virtual surgery plan, by labeling corresponding fiducial points on the mandible. Image fusion was considered acceptable if an average registration error was less than 0.8 mm. The following parameters were measured and analyzed for each procedure: the angular deviation from the planned osteotomy trajectory, and the deviation (calculated using the same formula as for the target registration error parameter) in the location of the control points labeled on the edges of the trajectory of the actual and planned osteotomy.

2.6. Statistical analysis

Normal distribution of the study variables was verified with Shapiro–Wilk test. The significance of differences between the actual and reference values was analyzed with Wilcoxon's signed rank test, and the significance of differences between the deviations from the reference values obtained with various methods was tested with Friedman's ANOVA. All calculations were carried out with Statistica 10 package (StatSoft, Tulsa, OK, United States), with the threshold of statistical significance set at $p < 0.05$.

3. Results

The data on angular deviations from planned osteotomy trajectories are presented in Table 1. The three methods did not differ significantly in terms of the deviations in the transverse plane. The use of CAD/CAM resulted in lesser deviations in the sagittal plane than in the case of the nAR method ($p = 0.023$). Moreover, both the

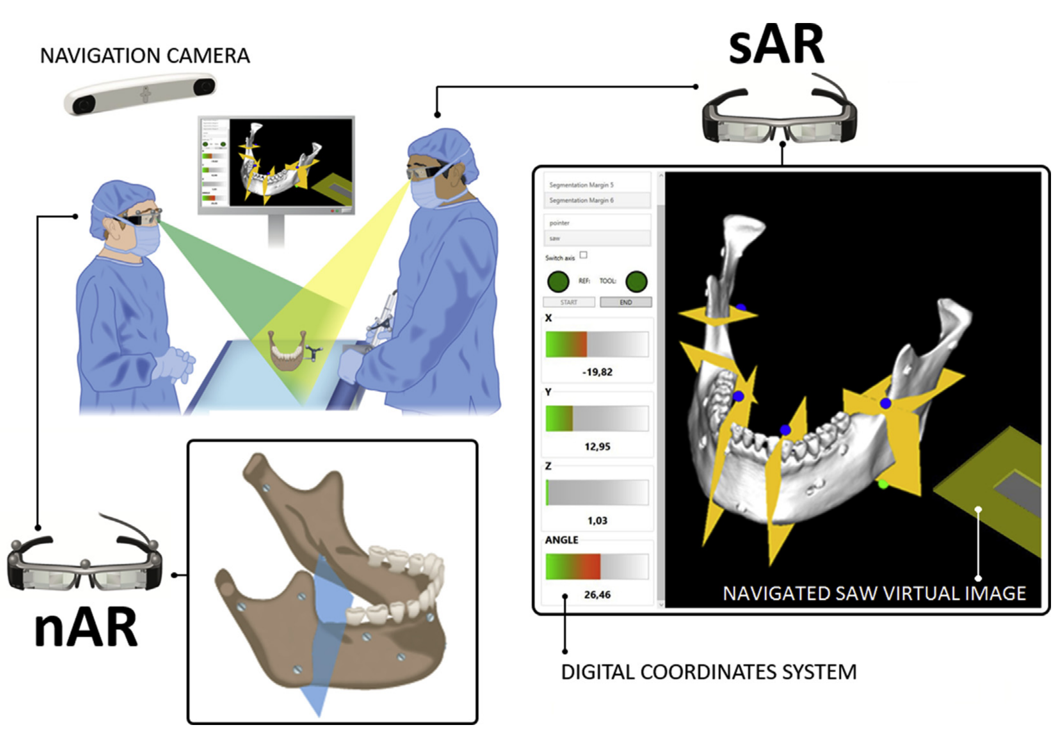

Fig. 3. The simple (sAR) and navigated (nAR) augmented reality concept. In the first method, the head-mounted display is simply used to display data from the navigation system monitor. The innovative digital coordination system provides the operator with information about the distance and angulation of the blade in relation to the planned osteotomy. In addition, the virtual image of the operative field, as well as the contours of the navigated saw, can be displayed. In the nAR method, due to the navigated AR head-mounted display, components of the virtual surgical plan are superimposed directly onto the surgeon's visual field.

Table 1
Angular deviations between the planned and actual osteotomies.

Plane	Method	Mean ± SD (°)	Median (°)	P
Transverse	CAD/CAM	2.65 ± 1.63	2.17	0.001
	Simple AR	3.55 ± 1.74	3.11	0.001
	Navigated AR	5.21 ± 2.72	5.28	0.001
Sagittal	CAD/CAM	2.67 ± 1.52	2.52	<0.001
	Simple AR	3.57 ± 1.96	3.00	<0.001
	Navigated AR	3.94 ± 2.33	3.73	<0.001
Frontal	CAD/CAM	7.22 ± 5.50	5.69	<0.001
	Simple AR	7.12 ± 4.15	5.52	<0.001
	Navigated AR	9.92 ± 5.70	8.33	<0.001

CAD/CAM and the sAR methods were shown to produce significantly lesser deviations in the frontal plane than the nAR method ($p = 0.031$ and $p = 0.014$, respectively; Table 2).

Statistical characteristics of deviations in the location of control points are presented in Table 3. Irrespective of the method, locations of the control points differed significantly from the respective reference values. Cumulative analysis of the results for all osteotomies demonstrated that CAD/CAM produced significantly lesser deviations in the location of point A than sAR and nAR methods ($p = 0.031$ and $p = 0.002$, respectively). Moreover, the use of either CAD/CAM or sAR method contributed to lesser deviations in the location of point B than in the case of nAR method ($p = 0.005$ and $p = 0.001$, respectively; Table 4).

Table 2
Inter-method comparison of osteotomy angular deviations.

Plane	Method	CAD/CAM	sAR	nAR
Transverse	CAD/CAM		ns	ns
	sAR	ns		ns
	nAR	ns	ns	
	Overall	0.071		
Sagittal	CAD/CAM		0.059	0.023
	sAR	0.059		0.705
	nAR	0.023	0.705	
	Overall	0.036		
Frontal	CAD/CAM		0.354	0.031
	sAR	0.354		0.014
	nAR	0.031	0.014	
	Overall	0.015		

ns, not significant.

Table 3
Differences between the preoperative and postoperative osteotomy control points positions.

Method	Control Point	Mean ± SD (mm)	Median (mm)	P
CAD/CAM	A	1.50 ± 1.04	1.13	<0.001
	B	1.80 ± 0.67	1.69	<0.001
sAR	A	1.80 ± 1.05	1.65	<0.001
	B	1.77 ± 0.82	1.71	<0.001
nAR	A	2.23 ± 1.17	2.01	<0.001
	B	2.59 ± 1.08	2.38	<0.001

Table 4
Inter-method comparison of osteotomy control points dislocations.

Method	Control Point A				Control Point B			
	CAD/CAM	sAR	nAR	Overall	CAD/CAM	sAR	nAR	Overall
CAD/CAM		0.031	0.002			0.537	0.005	
sAR	0.031		0.354	0.003	0.537		0.001	0.001
nAR	0.002	0.354			0.005	0.001		

4. Discussion

A complex 3D anatomy of the head and neck stimulated the development of various methods to support maxillofacial surgeries. One such method, gaining popularity nowadays, is CAD/CAM technology used to create surgical cutting guides supporting osteotomies, positioning and fixation of bone fragments (Hirsch et al., 2009; Roser et al., 2010; Ciocca et al., 2012; Foley et al., 2013; Rohner et al., 2013; Rodby et al., 2014; Yuan et al., 2016; Weitz et al., 2018). However, CAD/CAM technology has many drawbacks (Roser et al., 2010; Foley et al., 2013; Mazzoni et al., 2013; Rustemeyer et al., 2014; Pietruski et al., 2016). First, the time required to design, create and deliver the cutting guide by a specialized company precludes the use of this technology in many trauma and cancer patients (Roser et al., 2010; Mazzoni et al., 2013; Pietruski et al., 2015). Moreover, this technique generates high costs, up to 6,000 USD per procedure, and the cost-effectiveness of this method has not been confirmed unequivocally thus far (Mazzoni et al., 2013). The costs increase further if the procedure requires the use of more than one cutting guide. For example, when the decision to extend tumor resection margins was made intraoperatively, the surgical plan needs to be changed, which enforces the use of a new plan-specific guide, different than the one originally designed (Pietruski et al., 2015). Another drawback of CAD/CAM-assisted procedures stems from the fact that the cutting guide should ideally attach to a specific surface of the bone, which necessitates extensive dissection of soft tissues around the bone.

AR has a huge potential for application in the field of maxillofacial surgery, for both resections and reconstructive procedures (Badiali et al., 2014; Kim et al., 2017; Wang et al., 2017; Bosc et al., 2018). Due to the possibility to observe computer-generated anatomical structures, such as vessels and nerves, as well as the components of the VSP, the surgeon has a better orientation within the operative field, which results in greater safety of the procedure and its shorter duration. Also, intraoperative navigation technology is in many aspects superior to CAD/CAM-guided procedures in the field of trauma and oncologic maxillofacial surgery (Pietruski et al., 2015). A few documented attempts were made to incorporate the AR-based technologies into oral and maxillofacial surgery, primarily to support the orthognathic procedures and to visualize key anatomical structures (Mischkowski et al., 2006; Dixon et al., 2013; Zinser et al., 2013; Badiali et al., 2014; Choi et al., 2016; Lin et al., 2016; Kim et al., 2017; Wang et al., 2017; Bosc et al., 2018). However, none of the proposed solutions have been yet implemented into a routine clinical practice (Vávra et al., 2017; Bosc et al., 2018).

The primary aim of our study was to compare the accuracy of mandibular osteotomies assisted with cutting guides and two AR-based methods. Our findings suggest that CAD/CAM provides the greatest accuracy of the procedure, as shown by the smallest mean angular deviations from the planned osteotomy trajectory (2.65 ± 1.63 in transverse plane, 2.65 ± 1.52 in sagittal plane, 7.22 ± 5.50° in frontal plane) and the smallest mean deviation in the location of control points (mean 1.65 mm, Table 1). However, all previously mentioned drawbacks of CAD/CAM hinder widespread practical application of this technology. To overcome those limitations, we have developed two concepts of utilizing AR in the intraoperative system.

In the first approach, sAR, the data from the intraoperative navigation system's screen are presented on the AR display. Our findings imply that using sAR, the operator could accurately navigate surgical instrument against the predefined control points and was able to follow the osteotomy trajectory based on digital information about the metric and angular deviations. Mean angular deviations from the planned osteotomy trajectory in transverse, sagittal and frontal plane obtained with sAR method were

3.55 ± 1.74, 3.57 ± 1.96 and 7.12 ± 4.15°, respectively; these values did not differ significantly from the respective deviations obtained with the cutting guides. However, mean deviations from the locations of control points turned out to be significantly larger than those obtained with CAD/CAM cutting guides, 1.80 ± 1.05 mm for point A and 1.77 ± 0.82 mm for point B ($p = 0.031$). In addition, we noticed that the use of sAR improved performing the patient registration procedure. By displaying the image of 3D mandible model with marked registration points, the user was able to effectively identify and match them in the operative field without the need of turning his head away from it to observe the system monitor screen.

The second AR-based strategy, nAR, provided the lowest accuracy of all analyzed methods. Irrespective of the analyzed plane, mean angular deviations from the planned osteotomy trajectory were the largest, 5.21 ± 2.72 in transverse plane, 3.94 ± 2.33 in sagittal plane, and 9.92 ± 5.70° in frontal plane. The same referred to mean differences in the locations of control points, 2.23 ± 1.17 mm for point A and 2.59 ± 1.08 mm for point B. Probably, the lowest accuracy of nAR method can be explained by a high complexity of the solution, combining multiple technologies, as well as by imperfection of currently available HMD displays and still developing an individual user-oriented vision calibration algorithms. On the other hand, this method seems to pose tremendous potential in aiding ablative and reconstructive surgery. Without a doubt, it should become the main feature to obtain in next-generation intraoperative navigation systems.

According to the surveyed surgeons, the AR glasses provide good work ergonomics, even during long-term wear. The glasses are relatively inexpensive and can be used without compromising the operator's sterility. The surgeons praised low weight of the glasses and the fact that they did not generate excessive heat and noise. The run-time of the glasses without an external power supply reaches up to 3 h. In our present study, functioning of the intraoperative navigation system was controlled by an assistant. However, in the future, the system can also be controlled directly by the surgeon, with voice or gesture recognition function, or eye-tracking technology.

The sAR strategy deserves particular attention. Having access to digital navigation data shown on the display, the operator is able to localize each topographic landmark with adequate precision and can appropriately position the saw's blade on the mandibular surface without observing the screen. Compared with the nAR method, the process of data acquisition is very simple, as they are transmitted directly from the navigation system's screen to HMD. No user-specific vision calibration is needed. The only prerequisite is appropriate software for the navigation system. The software should include the digital coordinate system, to provide information about the position of surgical instrument against the control points and trajectory of planned osteotomy; such information may greatly facilitate the decision-making process. Since the AR display is transparent, the surgeon still can observe the operative field directly, even in the case of a sudden technical defect of the glasses or navigation system. Since the implementation of the sAR method requires only proper navigation software adaptation, it may soon become a standard feature of the next commercially available IGS systems.

Although the results of this study are promising, a number of issues need to be addressed before the implementation of the AR-based intraoperative navigation systems into clinical practice. From a surgeon's point of view, mounting DRF to the mandible through oral access seems impractical for most of the procedures. Percutaneous access is justified only for supporting large resections and reconstructions. Moreover, in those settings, a problem of limited visibility of DFR to the tracking exists. A miniature tracking camera that could be mounted on HMD would solve this problem. Perhaps such a concept will be realized in the next generation of intraoperative systems. For now, we propose to use wiring or dental acrylic splint containing titanium screws (for non-invasive registration process), which allow immobilization of the mandible to the upper jaw, therefore allowing fixation of the DRF to the skull (Lübbers et al., 2011). Improvement of the tracking process would allow using presented AR navigation to support mandible resection, its reconstruction with fibula free flap and dental implants insertion.

Perhaps the biggest challenge for AR is the improvement of image fusion accuracy and facilitation of appropriate 3D and depth perception by all users, irrespective of their visual acuity and interpupillary distance. Another technological aspect to be addressed is an increase in the dimensions of the active display matrix, which was postulated by surgeons who tested the system. The display of the Epson eyewear used in our present study has a 0.42-inch diagonal, and thus, the field of vision with the superimposed virtual image might be considerably narrowed down in the case of closely located objects. Another aspect, less important for optical-see-through displays than for video-see-through displays, is a potential input latency (Kim et al., 2017; Vávra et al., 2017). Both issues result from technological drawbacks of currently available AR displays, and hopefully, will be no longer inherent to new generation devices. Finally, the use of HMDs may cause nausea, vertigo and headache (Kim et al., 2017). Thus, prior to the first use, each surgeon should be examined for potential occurrence of those ailments.

5. Conclusion

Our novel AR-based navigation system provides good functionality and ergonomics. The results of simulated osteotomies imply that projection of the virtual surgery plan onto the surgeon's visual field improved hand-eye coordination and orientation within the operative field, and as a result, the outcomes of the procedures were similar to those obtained with the cutting guides. Eventual implementation of presented concepts to maxillofacial surgery needs to be preceded by further development and testing of the technology. However, our presented findings imply that the sAR method might already find application in some ablative and reconstructive surgery cases, serving as a transient form of IGS until the expected improvement of optical see-through displays.

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