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## Three-dimensional virtual surgical planning in head and neck oncology surgery

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# 8

## **Accuracy of augmented reality navigated surgery for placement of zygomatic implants; a human cadaver study**

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## Abstract

**Introduction** Zygomatic implants can be used in patients with maxillary defects after maxillectomy to improve the retention and stability of obtural prostheses. Placement of zygomatic implants in the most optimal prosthetic position is considered challenging due to the limited bone mass of the zygoma, limited visibility, length of the drill path and proximity to anatomical structures like the content of the orbital cavity. In this human cadaver study, we used an augmented reality (AR) navigation approach to place zygomatic implants after total maxillectomy. AR navigation can eliminate some of the drawback of surgical guides and conventional surgical navigation, while potentially improving accuracy.

**Materials & method** An AR navigation interface was developed connecting a commercially available navigation system with the Microsoft HoloLens. AR navigated surgery was performed to place 20 zygomatic implants using 5 human cadaver skulls after total maxillectomy. To determine accuracy, post-operative scans were virtually matched with the preoperative 3-dimensional virtual surgical planning (3D VSP), where after distances in mm of entry- exit-points and angle deviation were calculated as outcome measures. Results were compared with a previously performed study that made use of 3D virtual surgical planning with 3D printed surgical guides.

**Results** The mean entry point deviation was  $2.43 \text{ mm} \pm 1.33 \text{ mm}$  and a 3D angle deviation of  $5.80^\circ \pm 4.12^\circ$  (range  $1.39^\circ - 19.16^\circ$ ). The mean exit point deviation was  $3.28 \text{ mm} (\pm 2.17 \text{ mm})$ . The abutment height deviation was on average  $2.20 \text{ mm} \pm 1.35 \text{ mm}$ . The accuracy of the abutment in the occlusal plane was  $4.13 \text{ mm} \pm 2.53 \text{ mm}$ . Surgical guides perform significantly better for the entry-point ( $P = 0.012$ ) and 3D angle ( $P = 0.05$ ), however there is no significant difference in accuracy for the exit-point ( $P = 0.143$ ) when using 3D printed drill guides or AR navigated surgery.

**Conclusion** This study shows a novel AR dynamic navigation system for placement of zygomatic implants. Despite the fact that guides lead to a more accurate placement compared to AR navigation, the accuracy of AR navigation is acceptable as well and authors are convinced that it will continue to improve and will find its specific application.

**Keywords:** zygomatic implants, 3D virtual surgical planning, augmented reality, navigation, guided surgery

## Introduction

Ablative surgery in the maxilla is complicated and is accompanied with profound consequences for the patient's function and appearance. To improve accuracy of surgical outcome, nowadays the surgeon relies on 3-dimensional virtual surgical planning (3D VSP) when bone cuts (osteotomies) are required. 3D VSP typically includes the planning of osteotomies for ablative surgery with a sufficient margin from the tumour borders. Because of the high accuracy of 3D VSP, surgical resections with tumour margin control can be obtained<sup>1-3</sup>. When one-stage reconstruction surgery is indicated, the 3D VSP also includes the plan for reconstruction. For example, reconstruction and rehabilitation can include location of osteotomies, precise placement of osteosynthesis materials and dental- or patient specific implants<sup>4</sup>. Traditionally, the 3D VSP is translated towards surgery using surgical guides or image guided therapy techniques like navigation. Navigation is frequently used during tumour resection surgery in less accessible locations like the maxilla and skull base area.

While maxillary defects reconstruction using vascularized free flaps seem to provide better speech and swallowing results for extensive defects than conventional prosthetic obturation, not all patients are suitable for vascularized free flap reconstruction<sup>5</sup>. For these patients an obturator prosthesis supported with dental or zygomatic implants significantly improves the results of oral function rehabilitation<sup>6,7</sup>. Placement of dental implants is often not possible due to lack of bone of the maxilla. Placement of zygomatic implants is considered challenging due to the limited bone mass of the zygoma, limited perioperative visibility, length of the drill path and proximity to anatomical structures like nerve bundles and the orbital cavity. Therefore, nowadays guides or navigation are increasingly used in zygomatic implant surgery.

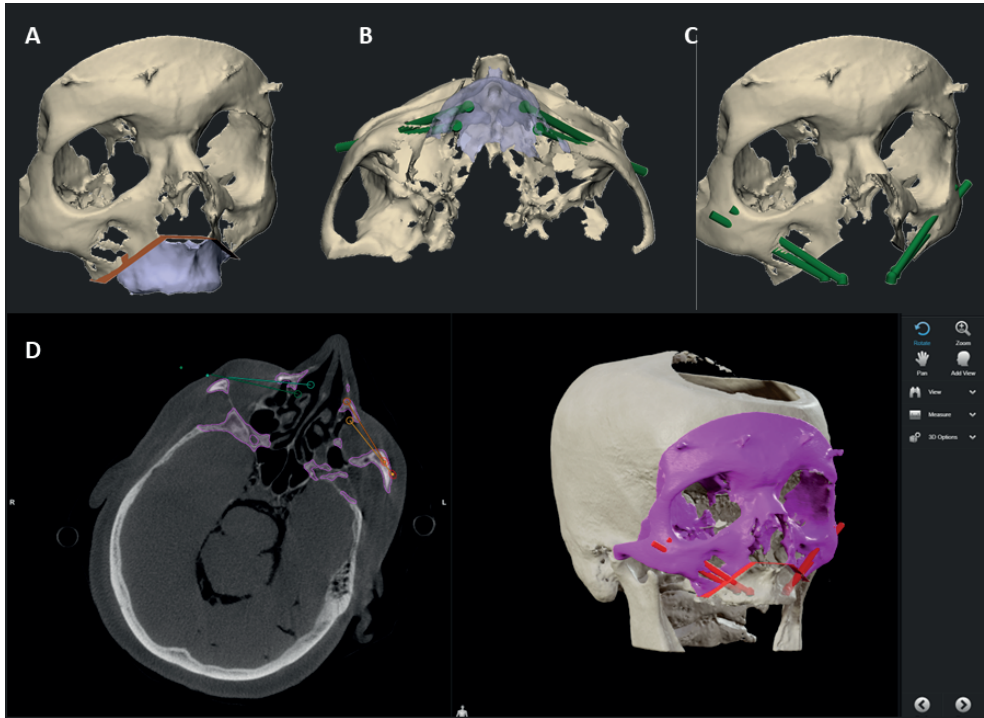
Vrielinck et al. was one of the first to use drill guides for zygomatic implant surgery<sup>8</sup>. Since then, multiple improvements have been made. Vosselman et al. reported on a 3D printed guide using an metal insert for drilling, showing high accuracy in vitro as well as in vivo<sup>9,10</sup>. A challenge in the use of 3D printed drill guides is that a large proportion of the bone needs to be denuded in order to provide a stable support for the surgical template. Moreover, 3D

printed drill guides can only properly provide control over the entry point of the trajectory, while the deeper trajectory is less controlled because real time feedback is not possible. Therefore, surgical navigation is considered a promising addition and can even potentially substitute 3D printed drill guided zygomatic implant surgery, mainly due to its real time guidance and feedback.

Augmented reality (AR) assisted navigation techniques hold the promise to improve navigation performance during surgery in terms of speed, accuracy and user friendliness<sup>11</sup>. AR navigation provides in situ visualisation, fusing navigation information directly with the (anatomy of the) patient. Therefore the surgeon does not have to split his attention between the patient and multiple screens in the operating room<sup>12</sup>. Several AR navigation systems for OMFS have been described, including applications in orthognathic surgery, temporomandibular joint arthrocentesis and dental implantology<sup>13-16</sup>. In this human cadaver study, we use an AR navigation approach to place zygomatic implants after total maxillectomy to estimate the accuracy of AR compared to surgical guides.

## Materials and methods

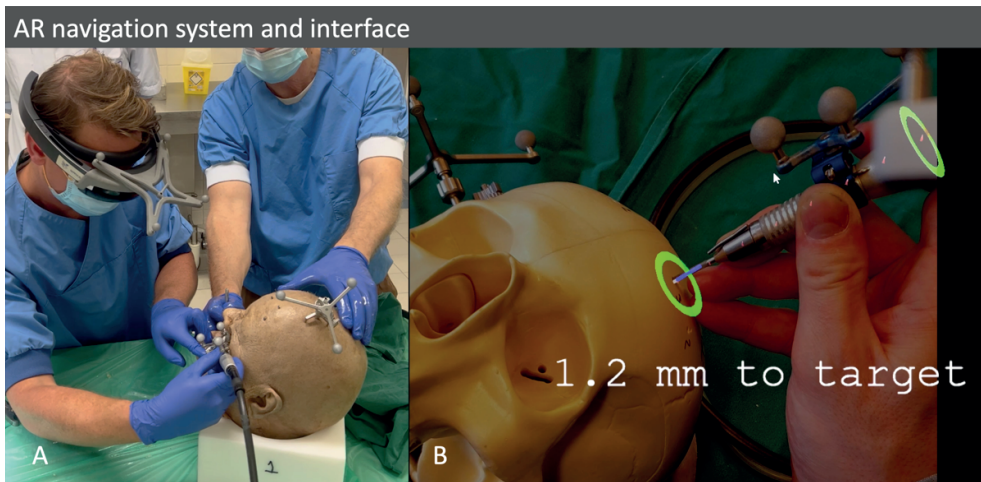
Five formalin fixated human cadaver skulls were obtained and scanned using cone beam computer tomography (CBCT) (Planmeca, ProMax 3D Max, Helsinki, Finland). The settings were in accordance with the clinical settings used for 3D VSP (voxel size 0.4mm). The scans were converted into a 3D model using ProPlan CMF 3.0 (Materialise, Leuven, Belgium). To mimic the clinical condition and to be able to implant four zygomatic implants per cadaver, a total maxillectomy has been included in the 3D VSP. The four zygomatic implants (Southern Implants, Irene, South Africa) were planned towards the most ideal prosthodontic positions based on the pre-maxillectomy situation, in a slightly palatal direction from the occlusal plane. An overview of the 3D VSP can be seen in figure 1. The tip of the implant was planned in the lateral cortical bone of the zygomatic complex, with a minimum distance of 2mm to the orbital cavity. Also, the minimally planned distance between two unilateral implants was 2mm to ensure sufficient bone around each implant. Hereafter, the 3D models were imported into the navigation software (Brainlab Elements, Brainlab AG, Munich, Germany), in which the drill trajectories for the implants were planned.



**Figure 1.** Overview of the 3D VSP. (A) The osteotomy of the maxillectomy is planned. (B) The abutment positions of the zygomatic implants are based on the pre-maxillectomy situation, in a slightly palatal direction from the occlusal plane. (C) The tip of the implant is planned in the lateral cortical bone of the zygomatic complex, with a minimum distance of 2mm between implants and to the orbital cavity. (D) The 3D VSP is uploaded into the navigation system where the drill trajectories are defined.

In the anatomical lab, the 3D VSP is downloaded on the navigation hardware (Brainlab Curve, Brainlab AG, Munich, Germany), subsequently the patients reference array was attached to the cadaver skulls and registration of imaging data and the cadaver is performed. The registration is performed using a minimum of four preoperatively placed 1.5 mm miniscrews (KLS Martin, Tuttlingen, Germany) which were used as landmarks. Hereafter, the surgical drill was calibrated using the instrument calibration matrix (Brainlab AG, Munich, Germany). We used the Microsoft HoloLens I (Microsoft) as an AR head-mounted-display (HMD). Before the surgical procedure started the HoloLens was connected to the navigation system using an in-house developed workflow, based on previous work described by Glas et al<sup>11</sup>. This augmented reality visualisation enables the surgeon to visualize and interact with the VSP and navigation data while in the operating room. It downloads the VSP from the

navigation system and visualises it in the surgical field, while updating the visualisation with real time navigation data. In addition, fiducial markers were added to the HMD using a special made 3D printed reference array. By doing this, the position of the surgeon is tracked by the navigation system as well, enabling a semi-automated registration of the virtual overlay onto the patient and surgical tools. A quick manual registration had to be performed before each use, when the HMD was put on. The virtual overlay enabled visualizing directions of the planned trajectories and navigation directions of the instruments, real live in the surgical field. An example of the AR navigation setup is seen in figure 2.



**Figure 2.** AR navigation system and interface. (A) The surgeon wearing the Microsoft HoloLens with a special reference array attached. Fiducial markers on the reference arrays of the HoloLens, surgical drill and skull enable the navigation system to track the different object and project the visualisation on the patient. (B) An example of the AR visualisation as seen by the surgeon. Virtual navigational indicators are projected into the surgical area. The colour and size of the green circles change with manipulating the direction of the drill. The depth to target is also updated real time.

### Tasks & participants

The surgery was performed by OMF surgeons skilled in 3D VSP and navigated surgery. Three OMF surgeons (NJ, SV, GR) drilled the implant trajectories and placed the zygomatic implants. All but one surgeon participated in a training session where dental implants have been placed in sawbones, using the same workflow and augmented reality visualisation. After the cranial resection margin of the maxilla was marked using the AR navigation, a total



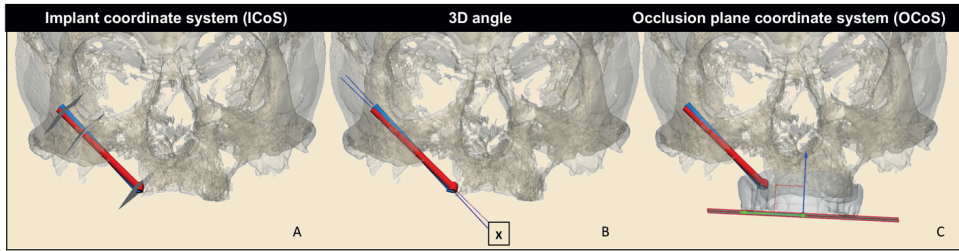
maxillectomy was performed. Hereafter, a total of 20 zygomatic implants were placed in five cadavers using the AR navigation.

### **Implant placement accuracy**

For determining the zygomatic implant accuracy, a post-operative CBCT was made. A 3D model was made in a similar fashion as for the 3D VSP. Hereafter the post-operative scans were matched virtually with the preoperative 3D VSP. Subsequently, bone entry and exit positions in the zygomatic bone were defined by the intersection of the long axis of the implant with the bone. Accuracy was assessed in an identical way to the method used by Vosselman et al., where two coordinate systems have been used<sup>9,10</sup>. Both coordinate systems are illustrated in figure 3 and defined as:

1. The Implant's Coordinate System (ICoS); the z-axis runs along the long axis of each planned implant.
2. The Occlusion Coordinate System (OcoS); congruent with the axial, sagittal and coronal planes. The axial plane is defined by the occlusion plane derived from the positions of the planned abutments.

Accuracy of the abutment, the entry and exit points were measured in the ICoS. The distance between planned and postoperative position was measured in a plane perpendicular to the long axis of the implant. Other accuracies were measured in the OcoS, these include the height deviation of the abutment in the occlusal plane, the displacement of the abutment in the occlusal plane, the axial, coronal, sagittal and 3D angle. A placement accuracy of 3 mm in the occlusal plane for the abutment was considered to be successful, and is assumed to result in a passive fit for a prosthesis<sup>9,10</sup>. The accuracy was compared to the accuracy of guided placement, on which we have reported earlier<sup>9</sup>. This study was performed in a similar fashion, the VSP was followed by guided placement of 10 zygomatic implants using 5 fresh frozen human cadavers. The post-operative analysis, based on the post-operatively performed CBCT, was performed identically to that study.



**Figure 3.** Description reference planes and coordinate systems for assessing the accuracy of zygomatic implant. In red the planned zygomatic implant position, in blue the postoperative zygomatic implant position derived from CBCT. **(A)** the implant coordinate system (ICoS) including the three reproducible reference planes in which the accuracy is measured; the centre of the abutment, the bone entry point, and bone exit point of the implant. **(B):** 3D angle deviation between the planned position and post-op position. **(C):** Visualisation of the Occlusion plane coordinate system (OCoS). The occlusal plane is defined parallel to a plane intersecting the planned abutment positions. Perpendicular to this plane is the blue arrow which indicates the direction the abutment height accuracy is calculated.

## Results

With the aid of the VSP, the navigated drill and AR navigation a total 4 maxillectomies were performed and 20 zygomatic implants were placed in 5 cadaver heads. In one of the cadavers, a maxillectomy had previously been performed. This maxillectomy has been digitally copied preoperatively into the 3D VSP.

The implant lengths varied between 40 mm and 55mm. The mean entry point deviation was  $2.43 \text{ mm} \pm 1.33 \text{ mm}$  and a 3D angle deviation of  $5.80^\circ \pm 4.12^\circ$  (range  $1.39^\circ - 19.16^\circ$ ). The mean exit point deviation was  $3.28 (\pm 2.17)$ , and the abutment height deviation was on average  $2.20 \text{ mm} \pm 1.35 \text{ mm}$ . The accuracy of the abutment in the occlusal plane was  $4.13 \text{ mm} \pm 2.53 \text{ mm}$ . The complete accuracy results can be seen in table 1. No significant differences were found between the mean values of the ventral and dorsal implants ( $P > 0.05$ ). No significant differences were found between left and right sided placed implants ( $P > 0.05$ ). All three accuracy measurements of the abutment were significantly more accurate using surgical guides, so was the entry-point. The exit-point was not significantly different. All results of AR navigation vs guides are found in table 2.

**Table 1** Accuracy data. Results of the post-operative analysis of the Implant coordinate system (IcoS) and occlusion coordinate system (OcoS) measurements.

ICoS deviations Cadavers		Mean ( $\pm$ SD)	Min	Max
Abutment (mm)		3.34 ( $\pm$ 2.11)	0.60	8.63
Entry-point (mm)		2.43 ( $\pm$ 1.33)	0.60	5.96
Exit-point (mm)		3.28 ( $\pm$ 2.17)	1.36	11.65
OCoS deviations Cadavers		Mean ( $\pm$ SD)	Min	Max
Abutment in occlusal plane (mm)		4.13 ( $\pm$ 2.53)	1.09	2.53
Abutment height from occlusal plane (mm)		2.20 ( $\pm$ 1.35)	0.08	4.63
Axial angle ( $^{\circ}$ )		5.76 ( $\pm$ 4.74)	1.04	21.63
Coronal angle ( $^{\circ}$ )		2.44 ( $\pm$ 2.02)	0.27	7.63
Sagittal angle ( $^{\circ}$ )		7.62 ( $\pm$ 6.55)	0.39	25.27
3D angle ( $^{\circ}$ )		5.80 ( $\pm$ 4.12)	1.39	19.16

**Table 2** Accuracy data of AR-navigation vs surgical guides. Statistical differences are highlighted in blue.

	AR-Navigation	Guided	
ICoS deviations Cadavers	Mean ( $\pm$ SD)	Mean ( $\pm$ SD)	P value
Abutment (mm)	3.34 ( $\pm$ 2.11)	1.19 ( $\pm$ 0.63)	0.005
Entry-point (mm)	2.43 ( $\pm$ 1.33)	1.20 ( $\pm$ 0.61)	0.012
Exit-point (mm)	3.28 ( $\pm$ 2.17)	2.12 ( $\pm$ 1.24)	0.143
OCoS deviations Cadavers	Mean ( $\pm$ SD)	Mean ( $\pm$ SD)	P value
Abutment in occlusal plane (mm)	4.13 ( $\pm$ 2.53)	1.77 ( $\pm$ 1.31)	0.012
Abutment height from occlusal plane (mm)	2.20 ( $\pm$ 1.35)	1.03 ( $\pm$ 0.85)	0.021
Axial angle ( $^{\circ}$ )	5.76 ( $\pm$ 4.74)	2.07 ( $\pm$ 2.63)	0.062
Coronal angle ( $^{\circ}$ )	2.44 ( $\pm$ 2.02)	0.99 ( $\pm$ 2.32)	0.682
Sagittal angle ( $^{\circ}$ )	7.62 ( $\pm$ 6.55)	1.48 ( $\pm$ 3.59)	0.047
3D angle ( $^{\circ}$ )	5.80 ( $\pm$ 4.12)	2.97 ( $\pm$ 1.43)	0.051

## Discussion

This study shows a novel AR dynamic navigation system for placement of zygomatic implants. Using the AR navigation 4 maxillectomies have been performed and 20 zygomatic implants have been placed in 5 cadavers. Surgical guides perform significantly better for the entry-point ( $1.20 \text{ mm} \pm 0.61 \text{ mm}$ ), however no statistical differences could be found for the exit-point or 3D angle. Placement of zygomatic implants at time of ablative surgery has been shown to be an effective means of accelerating oral function rehabilitation, along with early loading protocols. Placement of zygomatic implants is challenging, due to the length of zygomatic implants (40 tot 55mm), a minor angular deviation can lead to relatively large positional errors at the exit point.

Navigated zygomatic implant placement was described before in multiple studies<sup>17-20</sup>. Some studies use clinically available navigation systems<sup>17,21,22</sup>, some used dental navigation systems or developed their own<sup>18,19,23-25</sup>. Zhou et al. report on 14 navigated placed zygomatic implants in patients with maxillectomy defects, with an mean accuracy at the entry-point of  $1.56 \pm 0.54 \text{ mm}$ , exit-point of  $1.87 \pm 0.63 \text{ mm}$  (exit point), and an angle deviation of  $2.52 \pm 0.84^\circ$ <sup>26</sup>. Chrcanovic et al. placed 16 zygomatic implants in human cadavers with an angle accuracy of  $8.06^\circ \pm 6.40^\circ$  for the anterior-posterior view and  $11.20^\circ \pm 9.75^\circ$  for the caudal cranial view<sup>27</sup>. Vrielinck et al. report on an entry-point accuracy of 2.77 mm (range 1.0 - 7.4 mm) and exit-point accuracy of 4.46 mm (range 0.3-9.7 mm) in a patient cohort<sup>8</sup>. In our study the accuracy of implant placement in human cadavers after total maxillectomy was slightly higher both for the surgical guides from our previous study and the AR navigation<sup>9</sup>. Hung et al. have placed 40 zygomatic implants in severe atrophic maxillae using the Brainlab navigation system (Brainlab AG, Munich, Germany), reporting an accuracy of  $1.35 \pm 0.75 \text{ mm}$  (entry-point),  $2.15 \text{ mm} \pm 0.95 \text{ mm}$  (exit-point), and  $2.05 \pm 1.02^\circ$  angle deviation<sup>28</sup>. However, accuracy of zygomatic implantation in a resorbed maxilla might be higher due to a more stable drill entry point. While drilling the trajectory after (total) maxillectomy, the bone entry location is not a stable flat surface. Most likely the tip of the drill approaches the anterior wall of the maxillary sinus in an oblique fashion, making an exact entry-point difficult due to sliding of the drill tip along this cortical bone. Using navigation guidance, the surgeon is likely to correct for this entry-point deviation by manipulating the direction of the drill, in order to

get back on the planned trajectory. One observation we made, is that manipulating the drill could subsequently cause the drill to bend, mainly due to the length of the drill bits. As a result, the tip of the drill no longer matches the virtual drill in the navigation, which in turn leads to additional inaccuracy. In none of the 5 cases the placement of the implants was complicated by an orbital perforation. Therefore, accuracy in this small sample seems to be accurate enough for safe application in human patients of both investigated methods; drilling guides as well as AR navigation. Additionally, the abutment height was within the 3 mm limit for both surgical guides as well as for AR navigation.

Multiple factors impact the accuracy of surgical navigation, including imaging techniques, registrations procedures of the patient as well as the surgical tools, how rigid these surgical tools are, and moreover the human machine interface which influences the surgeon's performance. Using surgical guides, an accurate result can be obtained, however, sufficient bone has to be exposed for the guide to be stable during the entire drilling procedure. Moreover, the guide has to be designed such that it minimises the risk of deforming during drilling. This means sufficient support area and sometimes a bulkier guide. In ablative oncological surgery, the surgical area might be more easily accessible while this is more restricted in elective procedures. When a minimal invasive procedure is warranted AR navigation could be used as an alternative. However, based on the results of this cadaver study probably the best results may be obtained, if surgical guides are used for control of the entry point and AR navigation for trajectory control. While this study focused on augmented reality navigation in one stage resection and reconstruction surgery for placement of zygomatic implants, the AR-navigation might also be used in other craniomaxillofacial indications such as maxilla, orbital, and cranial base resections.

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