Accuracy of augmented reality navigated surgery for placement of zygomatic implants; *a human cadaver study* (#102174)

First submission

Guidance from your Editor

Please submit by **31 Jul 2024** for the benefit of the authors (and your token reward) .

Structure and Criteria
Please read the 'Structure and Criteria' page for guidance.

Custom checks
Make sure you include the custom checks shown below, in your review.

Raw data check
Review the raw data.

Image check
Check that figures and images have not been inappropriately manipulated.

If this article is published your review will be made public. You can choose whether to sign your review. If uploading a PDF please remove any identifiable information (if you want to remain anonymous).

Files

Download and review all files from the materials page.

3 Figure file(s)
1 Table file(s)
1 Raw data file(s)

Custom checks

Human participant/human tissue checks

- Have you checked the authors ethical approval statement?
- Does the study meet our article requirements?
- Has identifiable info been removed from all files?
- Were the experiments necessary and ethical?

Structure and Criteria

Structure your review

The review form is divided into 5 sections. Please consider these when composing your review:

1. **BASIC REPORTING**
2. **EXPERIMENTAL DESIGN**
3. **VALIDITY OF THE FINDINGS**
4. General comments
5. Confidential notes to the editor

You can also annotate this PDF and upload it as part of your review

When ready submit online.

Editorial Criteria

Use these criteria points to structure your review. The full detailed editorial criteria is on your guidance page.

BASIC REPORTING

- Clear, unambiguous, professional English language used throughout.
- Intro & background to show context. Literature well referenced & relevant.
- Structure conforms to PeerJ standards, discipline norm, or improved for clarity.
- Figures are relevant, high quality, well labelled & described.
- Raw data supplied (see PeerJ policy).

EXPERIMENTAL DESIGN

- Original primary research within Scope of the journal.
- Research question well defined, relevant & meaningful. It is stated how the research fills an identified knowledge gap.
- Rigorous investigation performed to a high technical & ethical standard.
- Methods described with sufficient detail & information to replicate.

VALIDITY OF THE FINDINGS

- **Impact and novelty is not assessed.** Meaningful replication encouraged where rationale & benefit to literature is clearly stated.
- All underlying data have been provided; they are robust, statistically sound, & controlled.
- Conclusions are well stated, linked to original research question & limited to supporting results.

Standout reviewing tips

The best reviewers use these techniques

Tip	*Example*
Support criticisms with evidence from the text or from other sources	*Smith et al (J of Methodology, 2005, V3, pp 123) have shown that the analysis you use in Lines 241-250 is not the most appropriate for this situation. Please explain why you used this method.*
Give specific suggestions on how to improve the manuscript	*Your introduction needs more detail. I suggest that you improve the description at lines 57- 86 to provide more justification for your study (specifically, you should expand upon the knowledge gap being filled).*
Comment on language and grammar issues	*The English language should be improved to ensure that an international audience can clearly understand your text. Some examples where the language could be improved include lines 23, 77, 121, 128 – the current phrasing makes comprehension difficult. I suggest you have a colleague who is proficient in English and familiar with the subject matter review your manuscript, or contact a professional editing service.*
Organize by importance of the issues, and number your points	*1. Your most important issue* *2. The next most important item* *3. …* *4. The least important points*
Please provide constructive criticism, and avoid personal opinions	*I thank you for providing the raw data, however your supplemental files need more descriptive metadata identifiers to be useful to future readers. Although your results are compelling, the data analysis should be improved in the following ways: AA, BB, CC*
Comment on strengths (as well as weaknesses) of the manuscript	*I commend the authors for their extensive data set, compiled over many years of detailed fieldwork. In addition, the manuscript is clearly written in professional, unambiguous language. If there is a weakness, it is in the statistical analysis (as I have noted above) which should be improved upon before Acceptance.*

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

Sander Tabernée Heijtmeijer Corresp., 1, 2 , **Haye Glas** [1] , **Nard Janssen** [3] , **Nathalie Vosselman** [1] , **Sebastiaan De Visscher** [1] , **Fred Spijkervet** [1] , **Gerry Raghoebar** [1] , **Remco de Bree** [4] , **Antoine Rosenberg** [3] , **Max Witjes** [1] , **Joep Kraeima** [1, 2]

[1] Department of Oral and Maxillofacial Surgery, University Medical Center Groningen, Groningen, Netherlands
[2] 3D-Lab, University Medical Center Groningen, Groningen, Netherlands
[3] Department of Oral and Maxillofacial Surgery & Special Dental Care, Utrecht University Medical Center, Utrecht, Netherlands
[4] Department of Head and Neck Surgical Oncology, University Medical Center Utrecht, Utrecht, Netherlands

Corresponding Author: Sander Tabernée Heijtmeijer
Email address: s.j.c.tabernee.heijtmeijer@umcg.nl

Purpose. Placement of zygomatic implants in the most optimal prosthetic position is considered challenging due to limited bone mass of the zygoma, limited visibility, length of the drilling path and proximity to critical anatomical structures. Augmented reality (AR) navigation can eliminate some of the disadvantages of surgical guides and conventional surgical navigation, while potentially improving accuracy. In this human cadaver study, we evaluated a developed AR navigation approach for placement of zygomatic implants after total maxillectomy.

Methods. The developed AR navigation interface connects a commercial 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, postoperative scans were virtually matched with preoperative 3-dimensional virtual surgical planning, and distances in mm from entry-exit points and angular deviations were calculated as outcome measures. Results were compared with a previously conducted study in which zygomatic implants were positioned with 3D printed surgical guides.

Results. The mean entry point deviation was 2.43 ± 1.33 mm and a 3D angle deviation of 5.80 ± 4.12° (range 1.39 - 19.16°). The mean exit point deviation was 3.28 mm (± 2.17). The abutment height deviation was on average 2.20 ± 1.35 mm. The accuracy of the abutment in the occlusal plane was 4.13 ± 2.53 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. Despite the higher precision of surgical guides, AR navigation demonstrated acceptable accuracy, with potential for improvement and specialized applications. The study highlights the feasibility of AR navigation for zygomatic implant placement, offering an alternative to conventional methods

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

Sander J.C. Tabernée Heijtmeijer[1,2], Haye H. Glas[1], Nard G. Janssen[3], Nathalie Vosselman[1], Sebastiaan A. H. J. de Visscher[1], Fred K. L. Spijkervet[1], Gerry M. Raghoebar[1], Remco de Bree[4]. Toine J. W. P. Rosenberg[3], Max J. H. Witjes[1], Joep Kraeima[1,2]

[1] Department of Oral and Maxillofacial Surgery, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands

[2] 3D-Lab, University Medical Centre Groningen, University of Groningen, the Netherlands

[3] Department of Oral and Maxillofacial Surgery, University Medical Center Utrecht, University of Utrecht, Utrecht, The Netherlands

[4] Department of Head and Neck Surgical Oncology, University Medical Center Utrecht, University of Utrecht, Utrecht, The Netherlands

Corresponding Author:
Sander Tabernée Heijtmeijer[1,2]
Hanzeplein 1, Groningen, 9713 GZ Groningen, The Netherlands
Email address: s.j.c.tabernee.heijtmeijer@umcg.nl

Abstract

Purpose. Placement of zygomatic implants in the most optimal prosthetic position is considered challenging due to limited bone mass of the zygoma, limited visibility, length of the drilling path and proximity to critical anatomical structures. Augmented reality (AR) navigation can eliminate some of the disadvantages of surgical guides and conventional surgical navigation, while potentially improving accuracy. In this human cadaver study, we evaluated a developed AR navigation approach for placement of zygomatic implants after total maxillectomy.

Methods. The developed AR navigation interface connects a commercial 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, postoperative scans were virtually matched with preoperative 3-dimensional virtual surgical planning, and distances in mm from entry-exit points and angular deviations were calculated as outcome measures. Results were compared with a previously conducted study in which zygomatic implants were positioned with 3D printed surgical guides.

Results. The mean entry point deviation was 2.43 ± 1.33 mm and a 3D angle deviation of 5.80 ± 4.12° (range 1.39 - 19.16°). The mean exit point deviation was 3.28 mm (± 2.17). The abutment height deviation was on average 2.20 ± 1.35 mm. The accuracy of the abutment in the occlusal plane was 4.13 ± 2.53 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. Despite the higher precision of surgical guides, AR navigation demonstrated acceptable accuracy, with potential for improvement and specialized applications. The study highlights the feasibility of AR navigation for zygomatic implant placement, offering an alternative to conventional methods

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[1–3]. 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, accurate placement of osteosynthesis materials and dental- or patient specific implants[4]. Traditionally, the 3D VSP is translated towards surgery using surgical guides or image guided therapy techniques like navigation.

Navigation is often used during tumour resection surgery in less accessible locations such as the maxilla and base of the skull. Although reconstruction of maxillary defects with vascularized free flaps appears to yield better speech and swallowing outcomes for extensive defects than conventional prosthetic obturation, not all patients are fit for vascularized free flap reconstruction[5]. In these patients, an obturator prosthesis supported by dental or zygomatic implants significantly improves oral function rehabilitation outcomes. [6, 7]. 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, guides or navigation are increasingly used in zygomatic implant surgery nowadays.

Vrielinck et al. was one of the first to use drill guides for zygomatic implant surgery [8]. 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 [9, 10]. One challenge in using 3D printed drill guides is that the bone must be stripped of periosteum to provide 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 not as 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[11]. 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[12]. Several AR navigation systems for OMFS have been described, including applications in orthognathic surgery, temporomandibular joint arthrocentesis and dental implantology.[13–16] 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 & Methods

Five formalin fixated human cadaver skulls were obtained and scanned using cone beam computed 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 was 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 Fig. 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. This study followed the Declaration of Helsinki on medical protocol and ethics ~~and~~ the local Medical Ethics Committee (METc of the University Medical Center Groningen, 2021/504) granted written permission for the retrospective anonymized use of human cadaver data in this study.

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, Redmond WA, United States) 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[11]. This augmented reality visualisation enables the surgeon to visualize and interact with the VSP and navigation data while in the operating room. It collects 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 Fig. 2.

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 of the surgeons participated in a training session where dental implants were placed in sawbones using the same workflow and augmented reality visualization. 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 postoperative CBCT scan was made. A 3D model was made in a similar fashion as for the 3D VSP. Hereafter the postoperative 3D skull was 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[9, 10]. Both coordinate systems are illustrated in Fig. 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[9, 10]. The accuracy was compared to the accuracy of guided placement, on which we have reported earlier[9]. 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 postoperative analysis, based on the postoperatively performed CBCT, was performed identically to that study.

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 ± 1.33 mm and a 3D angle deviation of 5.80 ± 4.12° (range 1.39 - 19.16°). The mean exit point deviation was 3.28 mm (± 2.17), and the abutment height deviation was on average 2.20 ± 1.35 mm. The accuracy of the abutment in the occlusal plane was 4.13 ± 2.53 mm. The complete accuracy results can be seen in Table 1. No significant differences were found between ventral and dorsal implants ($P > 0.05$) nor between left or right implants ($P > 0.05$).

Compared to the results of our previous study on the accuracy of zygomatic implants with 3D-printed surgical guides[9], all three accuracy measurements of the abutment and the entry-point were significantly more accurate with the use of surgical guides. For the exit-point there was no statistical significant difference. All results of the AR navigation (this study) vs guides (previous work) are found in Table 1.

~~**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

Discussion

This study shows a novel AR dynamic navigation system for placement of zygomatic implants. Using AR navigation 20 zygomatic implants have been placed in 5 cadavers. Surgical guides perform significantly better for the entry-point (1.20 ± 0.61 mm vs. 2.43 ± 1.33 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 to 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 [17–21]. Some studies use clinically available navigation systems [17, 22, 23], some used dental navigation systems or developed their own[18, 19, 24–27], extended reality systems are also described [27, 28]. 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 ± 0.54 mm, exit-point of 1.87 ± 0.63 mm (exit point), and an angle deviation of 2.52 ± 0.84° [29]. Chrcanovic et al. placed 16 zygomatic implants in human cadavers with an angle accuracy of 8.06 ± 6.40° for the anterior-posterior view and 11.20 ± 9.75° for the caudal cranial view[30]. Vrielinck et al. report on an entry-point accuracy of 2.77 mm (range 1.0 – 7.4) and exit-point accuracy of 4.46 mm (range 0.3 - 9.7) in a patient cohort[8]. 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[9]. 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 ± 0.75 mm (entry-point), 2.15 ± 0.95 mm (exit-point), and 2.05 ± 1.02° angle deviation[31]. 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.

Conclusions

This study shows a novel AR dynamic navigation system for placement of zygomatic implants. Despite the fact that patient specific 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. The study highlights the feasibility of AR navigation for zygomatic implant placement, offering an alternative to conventional methods

Acknowledgements

N/A

References

1. Kraeima J, Dorgelo B, Gulbitti HA, Steenbakkers RJHM, Schepman KP, Roodenburg JLN, Spijkervet FKL, Schepers RH, Witjes MJH (2018) Multi-modality 3D mandibular resection planning in head and neck cancer using CT and MRI data fusion: A clinical series. Oral Oncol 81:22–28. https://doi.org/10.1016/j.oraloncology.2018.03.013
2. Kraeima J, Schepers RH, Van Ooijen PMA, Steenbakkers RJHM, Roodenburg JLN, Witjes MJH (2015) Integration of oncologic margins in three-dimensional virtual planning for head and neck surgery, including a validation of the software pathway. Journal of Cranio-Maxillofacial Surgery 43:1374–1379. https://doi.org/10.1016/j.jcms.2015.07.015
3. Witjes MJH, Schepers RH, Kraeima J (2018) Impact of 3D virtual planning on reconstruction of mandibular and maxillary surgical defects in head and neck oncology. Curr Opin Otolaryngol Head Neck Surg 26:108–114. https://doi.org/10.1097/MOO.0000000000000437
4. Glas HH, Vosselman N, de Visscher SAHJ (2020) The use of 3D virtual surgical planning and computer aided design in reconstruction of maxillary surgical defects. Curr Opin Otolaryngol Head Neck Surg 28:122–128. https://doi.org/10.1097/MOO.0000000000000618

5. Moreno MA, Skoracki RJ, Hanna EY, Hanasono MM (2010) Microvascular free flap reconstruction versus palatal obturation for maxillectomy defects. Head Neck 32:860–868

6. Buurman DJM, Speksnijder CM, Engelen BHBT, Kessler P (2020) Masticatory performance and oral health-related quality of life in edentulous maxillectomy patients: A cross-sectional study to compare implant-supported obturators and conventional obturators. Clin Oral Implants Res 31:405–416. https://doi.org/10.1111/clr.13577

7. Schmidt BL, Pogrel MA, Young CW, Sharma A (2004) Reconstruction of extensive maxillary defects using zygomaticus implants. Journal of Oral and Maxillofacial Surgery 62:82–89. https://doi.org/10.1016/j.joms.2004.06.027

8. Vrielinck L, Politis C, Schepers S, Pauwels M, Naert I (2003) Image-based planning and clinical validation of zygoma and pterygoid implant placement in patients with severe bone atrophy using customized drill guides. Preliminary results from a prospective clinical follow-up study. Int J Oral Maxillofac Surg 32:7–14. https://doi.org/10.1054/ijom.2002.0337

9. Vosselman N, Glas HH, de Visscher SAHJ, Kraeima J, Merema BJ, Reintsema H, Raghoebar GM, Witjes MJH (2021) Immediate implant-retained prosthetic obturation after maxillectomy based on zygomatic implant placement by 3D-guided surgery: a cadaver study. Int J Implant Dent 7:. https://doi.org/10.1186/s40729-021-00335-w

10. Vosselman N, Glas HH, Merema BJ, Kraeima J, Reintsema H, Raghoebar GM, Witjes MJH, de Visscher SAHJ (2022) Three-Dimensional Guided Zygomatic Implant Placement after Maxillectomy. J Pers Med 12:. https://doi.org/10.3390/jpm12040588

11. Glas HH, Kraeima J, van Ooijen PMA, Spijkervet FKL, Yu L, Witjes MJH (2021) Augmented Reality Visualization for Image-Guided Surgery: A Validation Study Using a Three-Dimensional Printed Phantom. Journal of Oral and Maxillofacial Surgery 79:1943.e1-1943.e10. https://doi.org/10.1016/j.joms.2021.04.001

12. Sielhorst T, Feuerstein M, Navab N (2008) Advanced Medical Displays: A Literature Review of Augmented Reality. Journal of Display Technology 4:451–467. https://doi.org/10.1109/JDT.2008.2001575

13. Zinser MJ, Mischkowski RA, Dreiseidler T, Thamm OC, Rothamel D, Zöller JE (2013) Computer-assisted orthognathic surgery: waferless maxillary positioning, versatility, and accuracy of an image-guided visualisation display. British Journal of Oral and Maxillofacial Surgery 51:827–833. https://doi.org/10.1016/j.bjoms.2013.06.014

14. Tran HH, Suenaga H, Kuwana K, Masamune K, Dohi T, Nakajima S, Liao H (2011) Augmented reality system for oral surgery using 3D auto stereoscopic visualization. Med Image Comput Comput Assist Interv 14:81–88. https://doi.org/10.1007/978-3-642-23623-5_11

15. Wang J, Suenaga H, Yang L, Kobayashi E, Sakuma I (2017) Video see-through augmented reality for oral and maxillofacial surgery. Int J Med Robot 13:. https://doi.org/10.1002/rcs.1754

16. Wang Y-Y, Liu H-P, Hsiao F-L, Kumar A (2019) Augmented reality for temporomandibular joint arthrocentesis: a cadaver study. Int J Oral Maxillofac Surg 48:1084–1087. https://doi.org/10.1016/j.ijom.2018.12.011

17. Wang F, Bornstein MM, Hung K, Fan S, Chen X, Huang W, Wu Y (2018) Application of Real-Time Surgical Navigation for Zygomatic Implant Insertion in Patients With Severely Atrophic Maxilla. Journal of Oral and Maxillofacial Surgery 76:80–87. https://doi.org/10.1016/j.joms.2017.08.021

18. Pellegrino G, Tarsitano A, Basile F, Pizzigallo A, Marchetti C (2015) Computer-Aided Rehabilitation of Maxillary Oncological Defects Using Zygomatic Implants: A Defect-Based Classification. J Oral Maxillofac Surg 73:2446.e1-2446.e11. https://doi.org/10.1016/j.joms.2015.08.020

19. Gasparini G, Boniello R, Laforì A, De Angelis P, Del Deo V, Moro A, Saponaro G, Pelo S (2017) Navigation System Approach in Zygomatic Implant Technique. Journal of Craniofacial Surgery 28:

20. Pellegrino G, Lizio G, Basile F, Stefanelli LV, Marchetti C, Felice P (2020) Dynamic navigation for zygomatic implants: A case report about a protocol with intraoral anchored reference tool and an up-to-date review of the available protocols. Methods Protoc 3:1–10. https://doi.org/10.3390/mps3040075

21. Fan S, Sáenz-Ravello G, Diaz L, Wu Y, Davó R, Wang F, Magic M, Al-Nawas B, Kämmerer PW (2023) The Accuracy of Zygomatic Implant Placement Assisted by Dynamic Computer-Aided Surgery: A Systematic Review and Meta-Analysis. J Clin Med 12:12. https://doi.org/10.3390/JCM12165418/S1

22. Hung K-F, Wang F, Wang H-W, Zhou W-J, Huang W, Wu Y-Q (2017) Accuracy of a real-time surgical navigation system for the placement of quad zygomatic implants in the severe atrophic maxilla: A pilot clinical study. Clin Implant Dent Relat Res 19:458–465. https://doi.org/10.1111/cid.12475

23. Hung K, Huang W, Wang F, Wu Y (2016) Real-Time Surgical Navigation System for the Placement of Zygomatic Implants with Severe Bone Deficiency. Int J Oral Maxillofac Implants 31:1444–1449. https://doi.org/10.11607/jomi.5526

24. González Rueda JR, García Ávila I, de Paz Hermoso VM, Riad Deglow E, Zubizarreta-Macho Á, Pato Mourelo J, Montero Martín J, Hernández Montero S (2022) Accuracy of a Computer-Aided Dynamic Navigation System in the Placement of Zygomatic Dental Implants: An In Vitro Study. J Clin Med 11:. https://doi.org/10.3390/jcm11051436

25. Kreissl ME, Heydecke G, Metzger MC, Schoen R (2007) Zygoma implant-supported prosthetic rehabilitation after partial maxillectomy using surgical navigation: A clinical report. J Prosthet Dent 97:121–128. https://doi.org/https://doi.org/10.1016/j.prosdent.2007.01.009

26. Panchal N, Mahmood L, Retana A, Emery R (2019) Dynamic Navigation for Dental Implant Surgery. Oral Maxillofac Surg Clin North Am 31:539–547. https://doi.org/https://doi.org/10.1016/j.coms.2019.08.001

27. González-Rueda JR, Galparsoro-Catalán A, de Paz-Hermoso VM, Riad-Deglow E, Zubizarreta-Macho Á, Pato-Mourelo J, Hernández-Montero S, Montero-Martín J (2023) Accuracy of zygomatic dental implant placement using computer-aided static and dynamic navigation systems compared with a mixed reality appliance. An in vitro study. J Clin Exp Dent 15:e1035–e1044. https://doi.org/10.4317/JCED.61097

28. Fan X, Feng Y, Tao B, Shen Y, Wu Y, Chen X (2024) A hybrid robotic system for zygomatic implant placement based on mixed reality navigation. Comput Methods Programs Biomed 249:108156. https://doi.org/10.1016/J.CMPB.2024.108156

29. Zhou W, Fan S, Wang F, Huang W, Jamjoom FZ, Wu Y (2021) A novel extraoral registration method for a dynamic navigation system guiding zygomatic implant placement in patients with maxillectomy defects. Int J Oral Maxillofac Surg 50:116–120. https://doi.org/10.1016/j.ijom.2020.03.018

30. Chrcanovic BR, Oliveira DR, Custódio AL (2010) Accuracy evaluation of computed tomography-derived stereolithographic surgical guides in zygomatic implant placement in human cadavers. J Oral Implantol 36:345–355. https://doi.org/10.1563/AAID-JOI-D-09-00074

31. Hung KF, Wang F, Wang HW, Zhou WJ, Huang W, Wu YQ (2017) Accuracy of a real-time surgical navigation system for the placement of quad zygomatic implants in the severe atrophic maxilla: A pilot clinical study. Clin Implant Dent Relat Res 19:458–465. https://doi.org/10.1111/cid.12475

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

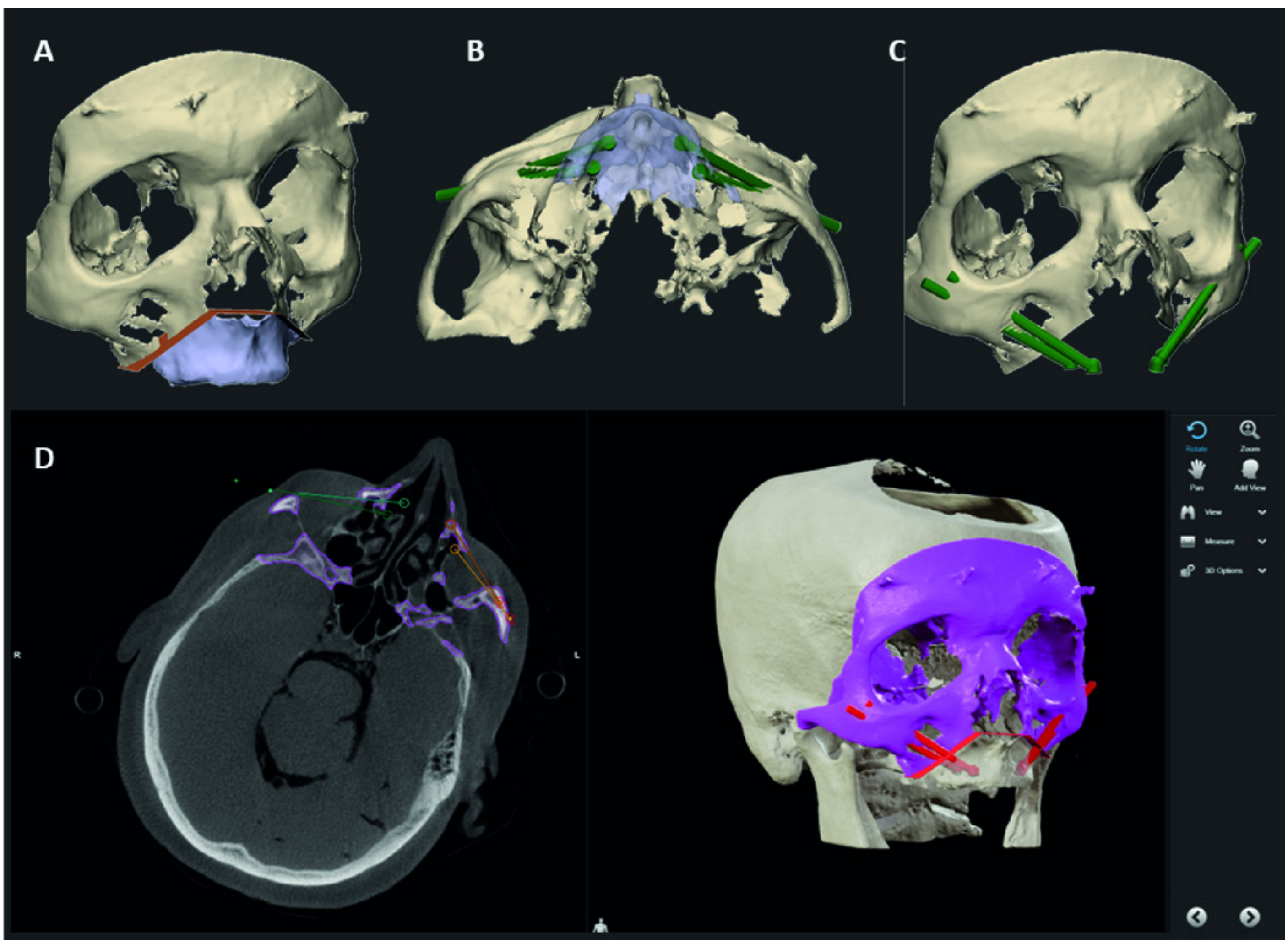

Figure 2

AR navigation system and interface

(A) Image of the setup during the cadaver experiment. The surgeon wearing the HoloLens with a custom made reference array attached. Fiducial markers on the reference arrays of the HoloLens, surgical drill and skull enable the navigation system to track the objects and project the visualisation on the patient. **(B)** An example of the AR visualisation as seen by the surgeon during the phantom setup. 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.

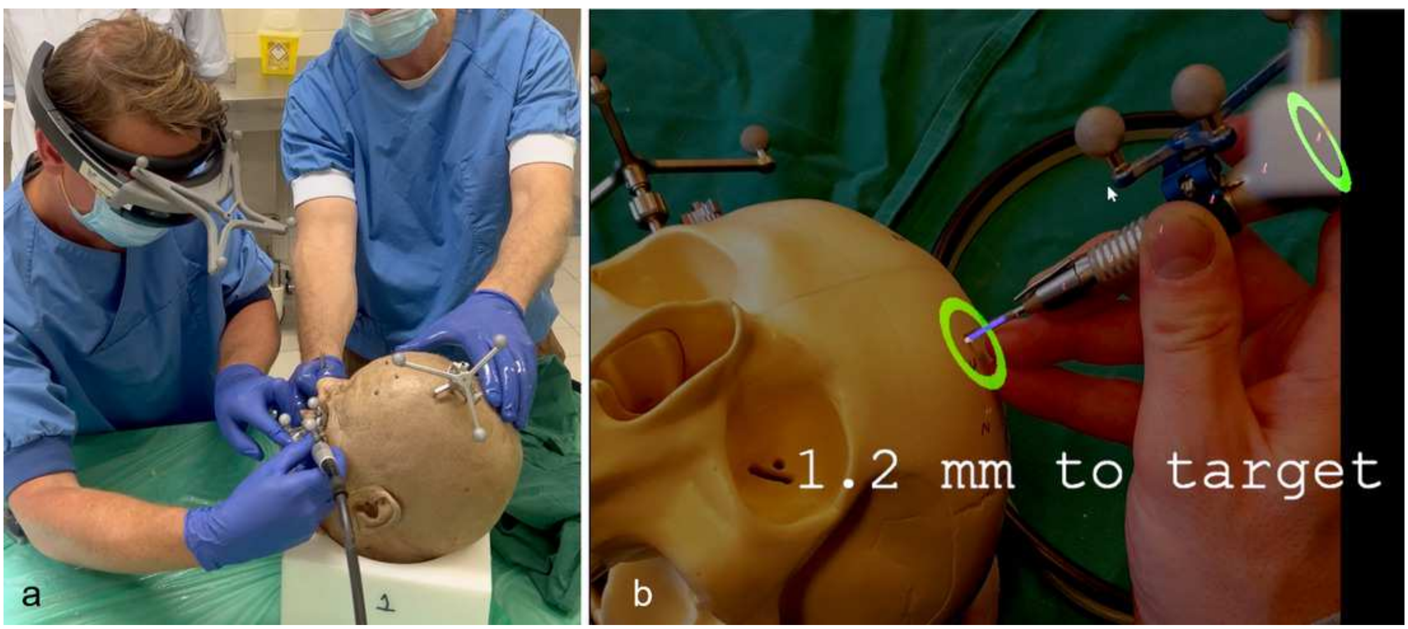

Figure 3

Reference planes and coordinate systems

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

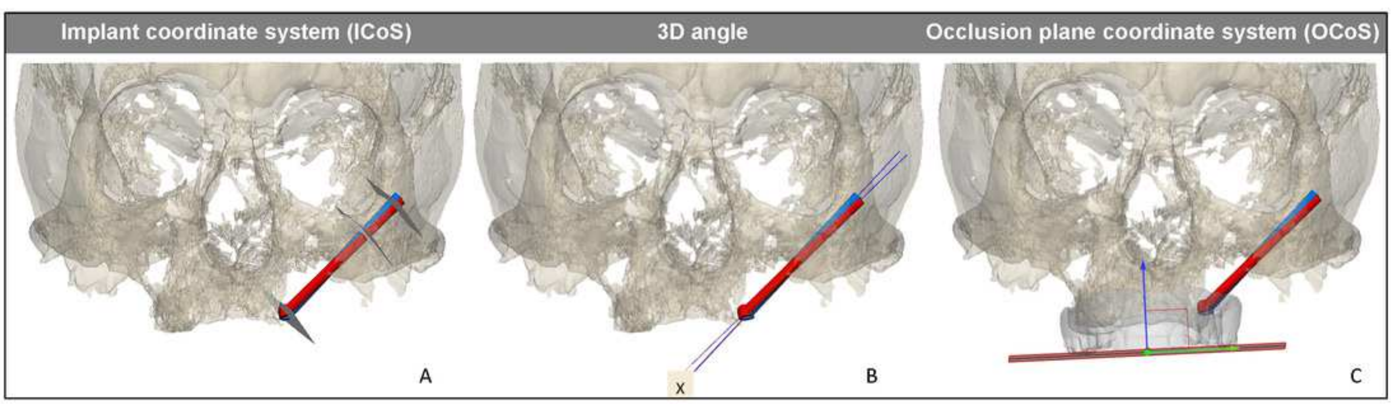

Table 1 (on next page)

Accuracy data

Results of the postoperative analysis of the Implant coordinate system (IcoS) and occlusion coordinate system (OcoS) measurements for the Augmented reality system (this paper) and with the use of patient-specific guides (previous work) [9] . Statistical significant differences are highlighted in blue.

		Augmented Reality		Guides	
		Mean (±SD)	Range	Mean (±SD)	P value
ICoS deviation	**Abutment (mm)**	3.34 (± 2.11)	0.60 - 8.63	1.19 (± 0.63)	0.005
	Entry-point (mm)	2.43 (± 1.33)	0.60 - 5.96	1.20 (± 0.61)	0.012
	Exit-point (mm)	3.28 (± 2.17)	1.36 - 11.65	2.12 (± 1.24)	0.143
OCos deviation	**Abutment in occlusal plane (mm)**	4.13 (± 2.53)	1.09 – 2.53	1.77 (± 1.31)	0.012
	Abutment height from occlusal plane (mm)	2.20 (± 1.35)	0.08 – 4.63	1.03 (± 0.85)	0.021
	Axial angle (°)	5.76 (± 4.74)	1.04 – 21.63	2.07 (± 2.63)	0.062
	Coronal angle (°)	2.44 (± 2.02)	0.27 – 7.63	0.99 (± 2.32)	0.682
	Sagittal angle (°)	7.62 (± 6.55)	0.39 – 25.27	1.48 (± 3.59)	0.047
	3D angle (°)	5.80 (± 4.12)	1.39 – 19.16	2.97 (± 1.43)	0.051