Received: 5 December 2021 | Revised: 24 December 2021 | Accepted: 29 December 2021

DOI: 10.1002/rcs.2362

ORIGINAL ARTICLE

The International Journal of Medical Robotics and Computer Assisted Surgery

WILEY

Marker-free registration for intraoperative navigation using the transverse palatal rugae

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Funding information

Open access funding enabled and organized by Projekt DEAL

Abstract

Background: Registration is most important in navigation-assisted-surgery including the matching between the coordinates of the actual patient space and the medical image. Marker-based techniques mostly include marker application with subsequent radiography. In the edentulous patient, maker-free methods are generally less accurate and reproducible.

This new method of a marker-free registration uses the transverse palatal rugae as registration structures.

Methods: (1) Segmentation of bone and hard palatal mucosa from initial 3D imaging (DICOM), (2) Maxillary intraoral-scan with transfer to the 3D imaging using an Iterative-Closest-Point-Algorithm (ICP), (3) Marking digital registration points with holes within IOS-stl, (4) Transformation of the spatially aligned IOS-stl to LabelMap and storage in DICOM (IOS-DICOM), (5) Alignment of DICOM and IOS-DICOM, (6) Controlled positioning of digital reg. points and clinical correlation.

Results: Fiducial localization error (0.48 mm) and Target registration error (0.65 mm) is comparable to those of tooth-supported registration methods.

Conclusion: This approach of marker-free registration for navigation-assisted-surgery could improve the treatment in edentulous patients avoiding additional imaging and invasive marker insertion.

KEYWORDS

anatomical landmark, dose reduction, edentulous maxilla, marker-free registration, transverse palatal rugae, zygoma

1 | INTRODUCTION

In order to increase surgical precision and patient safety, intraoperative navigation and virtual surgical planning have become frequently used methods in craniomaxillofacial surgery (CMFS). It has a variety of possible applications including tumour surgery, dental implantology, endoprosthetic surgery of the temporomandibular joint (TMJ) and trauma surgery.[1-3] Intraoperative navigation allows the surgeon to visualise the actual position of surgical instruments in real time on the monitor displaying the Computed Tomography (CT) or Magnetic Resonance Imaging 3D data of the patient. These systems have recently evolved to improve precision, simplify the surgical procedure by minimising intraoperative invasiveness and increase predictability through greater precision.[4] To achieve this, valid patient registration is a crucial basic requirement. The accuracy of the navigation system depends to a large extent on the accuracy of the registration process, during which the relationship between the image space (preoperative image coordinate system) and the patient space (surgical field coordinate system) is established.[5] The registration procedure links the patient space (physical space) and image space. Ideally, a registration method should be non-invasive, simple, automatic, little time consuming, and with no requirement for additional exposure to radiation. Registration techniques can be categorised into two main groups: marker-based[6,7] and marker-free.[8] Currently, several registration concepts exist in CMFS including headbands that can be easily displaced intraoperatively, fiducial markers, splints, or a combination of the two may be used in point-based registration.[9-12] Besides to the splint-supported registration in the maxilla, which requires the presence of teeth, the presurgical insertion of osteosynthesis screws in the maxilla or forehead with subsequent 3D imaging allows intraoperative registration with high accuracy even in the edentulous maxilla.[13,14] However, this method requires invasive marker insertion and an additional pre-operative 3D imaging for marker detection.

In contrast, the marker-free technique is based on anatomical landmarks (e.g. bony prominences or dental cusps) which are hard to reproduce and less precise than artificial markers.[15] This is especially relevant for the edentulous maxilla, as the regional crestal mucosa has little to no reproducible structures for registration. Therefore, there is a need for innovative, non-invasive yet reproducible and accurate methods for the registration of intraoperative navigation systems. The registration at prominent and reproducible points of the transverse palatal rugae represents an easy-to-use and innovative technique for intraoperative registration, avoiding artificial marker application and additional 3D imaging. The primary objective of this technical note was to prove the techniques' feasibility in vitro on a stereolithographic skull with a rubber-elastic mucosal mask.

2 | MATERIALS AND METHODS

The planning is based on a cone beam computed tomography (CBCT) scan (OP 3D^{TM} Vision, KaVo Dental GmbH, Germany, Field of View: 13 cm 16 cm, tube-voltage: 120 [kVp], tube current: 5 [mA], voxel size: 300 [µm], Acquisition time: 8.9 s, file format: DICOM), which was made as a diagnostic image for TMJ resorption. (1) DICOM data extracted from the CBCT scans were imported into the open source software 3DSlicer (Version: 4.11.20210226r29738/7a593c8; https://www.slicer.org) and further used for facial bone and hard palatal mucosa segmentation using 3DSlicer's thresholding tool (intensity values ranging from −570.70 to 1163.37). 3DSlicer was chosen due to being free, open-source and cross platform. 3DSlicer offers a wider range of segmentation tools and scripting capabilities through a python console and segmentation module. In order to be able to delineate the soft tissue palate, the tongue must not touch the palate during the scan. This is a fundamental precondition for sufficient segmentation. It can be achieved by having the patient either bite on a wax plate or by asking the patient to point the tip of his tongue towards the floor of the mouth during the scan (Figure 1).

(2) An intra-oral scan (TRIOS 3 intraoral scanner, 3Shape) was acquired to obtain a detailed virtual stereolithographic model (stl) of the palate. To transfer the IOS into the coordinate system of the CBCT scan, it was made solid (Meshmixer®, Version: 3.5.474, Autodesk inc., USA) and then aligned to the stl model of the

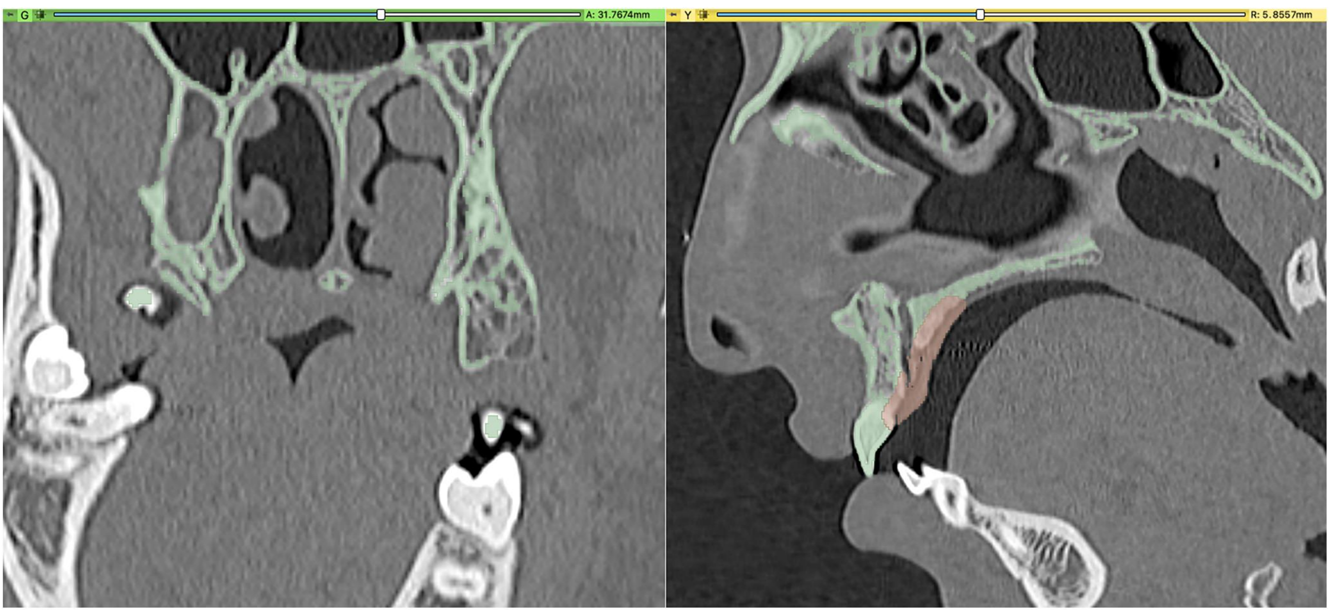

FIGURE 1 Shows the intensity regulated segmentation of the skull bone (green) as well as the soft tissue palate (brown) in 3DSlicer

pre-segmented soft tissue palate using the Iterative Closest Point Algorithm alignment tool from blender (https://www. blender.org). Accordingly, the intraorsal scan was defined as the "moving part" along with the segmented palate selected as "destination"[16] (Figure 2). (3) To allow identification of the corresponding reference points of the transverse palatal rugae in the cross-sectional view of the Kick® (Brainlab AG), we placed holes in the intraoral scans' stl models using a boolean operation (Meshmixer®, Autodesk inc., USA). (4) Since the current version of Brainlab's planning software Elements (Version: 1.0, Brainlab AG) no longer provides the option of setting registration points preoperatively, a methodical intermediate step was implemented in which an stl model was transferred to a DICOM data set using the 3DSlicer module "Model To LabelMap" which intersects an input model with a reference volume and produces an output label map, filling voxels inside the model with the specified label value (Figure 3). (5) Then, cone beam CT DICOM data and the newly created and prepared intraoral scans' DICOM dataset are loaded in and fused with Elements (Brainlab AG). To make the navigation procedure as realistic as possible using the stereolithographic skull, we printed a rubber-elastic gingival mask.

2.1 | Gingival mask

A gingival mask was digitally designed based on the IOS using the Meshmixer® software (Autodesk Inc., USA). The resulting. stl file was prepared for 3D printing with freely available Chitubox® slicer (Chitubox, Guangdong, China) with the following settings: layer

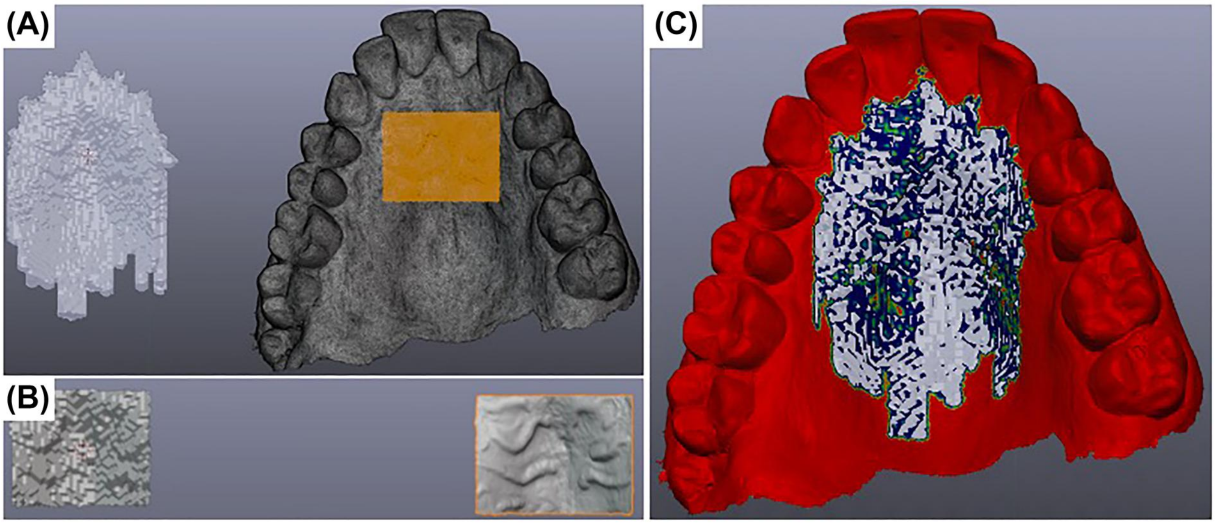

FIGURE 2 (A) Segmented soft tissue palate (left) and intraoral-scan (IOS) with Iterative Closest Point Algorithm (ICP) marking (right) in blender (https://www. blender.org). (B) Labelled surface for alignment and (C) matching of IOS and segmented soft tissue palate

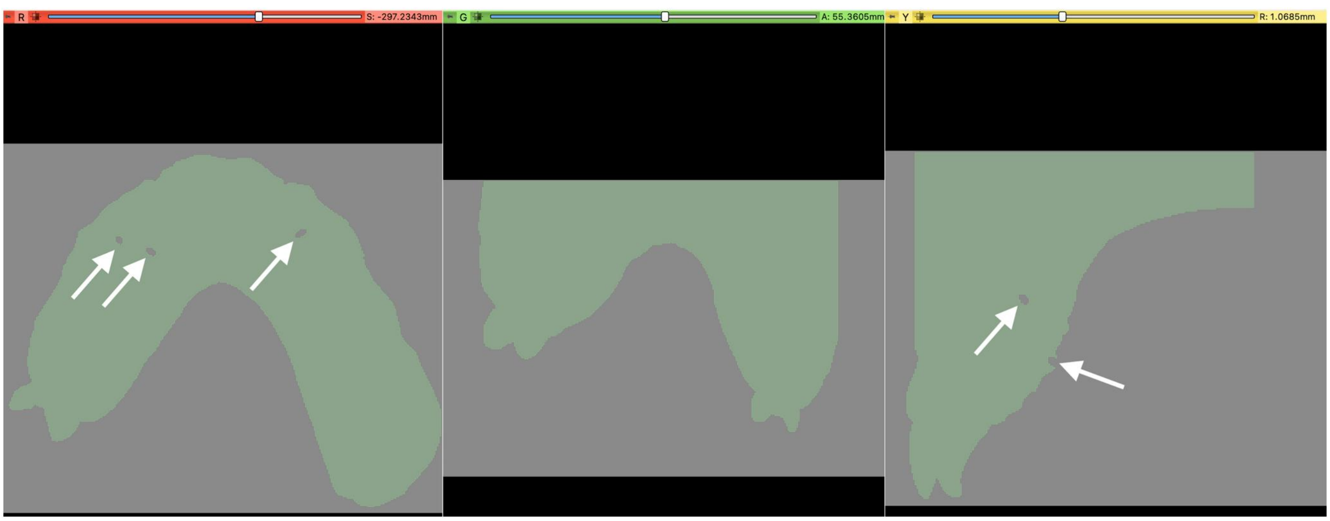

FIGURE 3 Labelmap of the intraoral-scan (IOS) prepared with maker holes in multiplanar representation (MPR) in 3DSlicer (https://www. slicer.org)

thickness 0.2 mm, exposure time 20 s. The gingival masks were then printed using the Dual Light Processing (DLP) technique. In the DLP technique a UV light source cures a photopolymerising resin layer by layer into a component (Figure 4). This manufacturing technique is relatively inexpensive, starting at 150 € for a consumer market printer. The gingival mask was then printed with the Anycubic Photon (Anycubic, Longgang District Shenzhen, 518000, China) printer using NextDents® flexible gingiva mask resin (NextDent B.V., Soesterberg, The Netherlands). Afterwards the printed gingival masks were glued to the base model.

2.2 | Registration

Digital positioning of referencing points was performed using the hole-prepared DICOM dataset of the IOS (Figure 5). The merged DICOM is loaded in Brainlab and the alignment is performed. According to Maurer et al. a classification into (1). The fiducial localization error (FLE), that is the error in locating the fiducial points (transverse palatal rugae), (2). Fiducial registration error, that is the distance between corresponding fiducial points after registration, and (3). Target registration error (TRE), that is the distance between

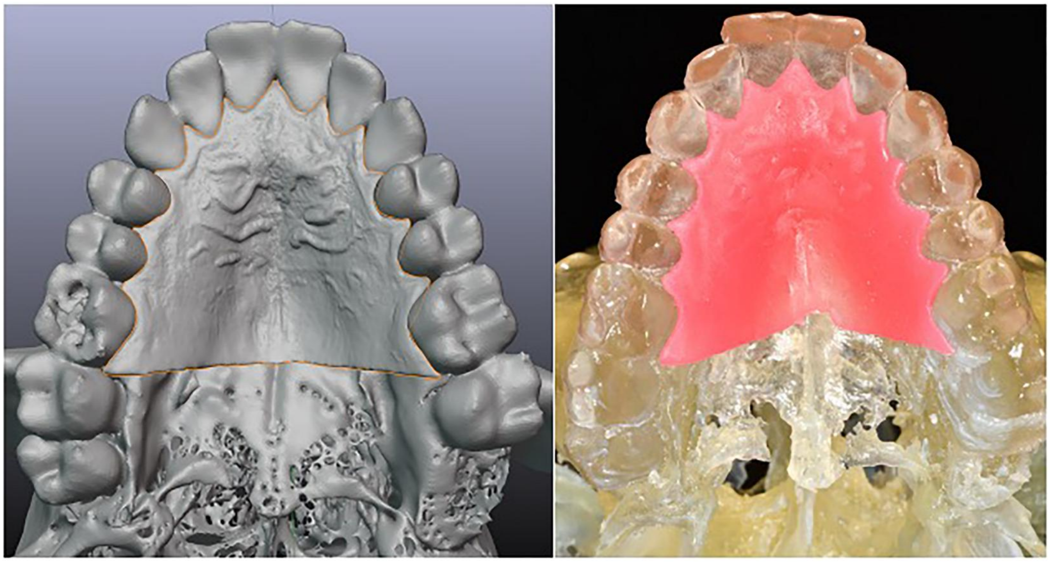

FIGURE 4 3D view of the segmented model of the soft tissue palate as well as the bone model (without intraoral-scan (IOS) overlay) in blender (https://www. blender.org) (left). Right skull stereolithography model with dental arch (IOS) and inserted flexible gingiva mask made of NextDents(R) flexible gingiva mask resin (NectDent B.V., Soesterberg, The Netherlands) (right)

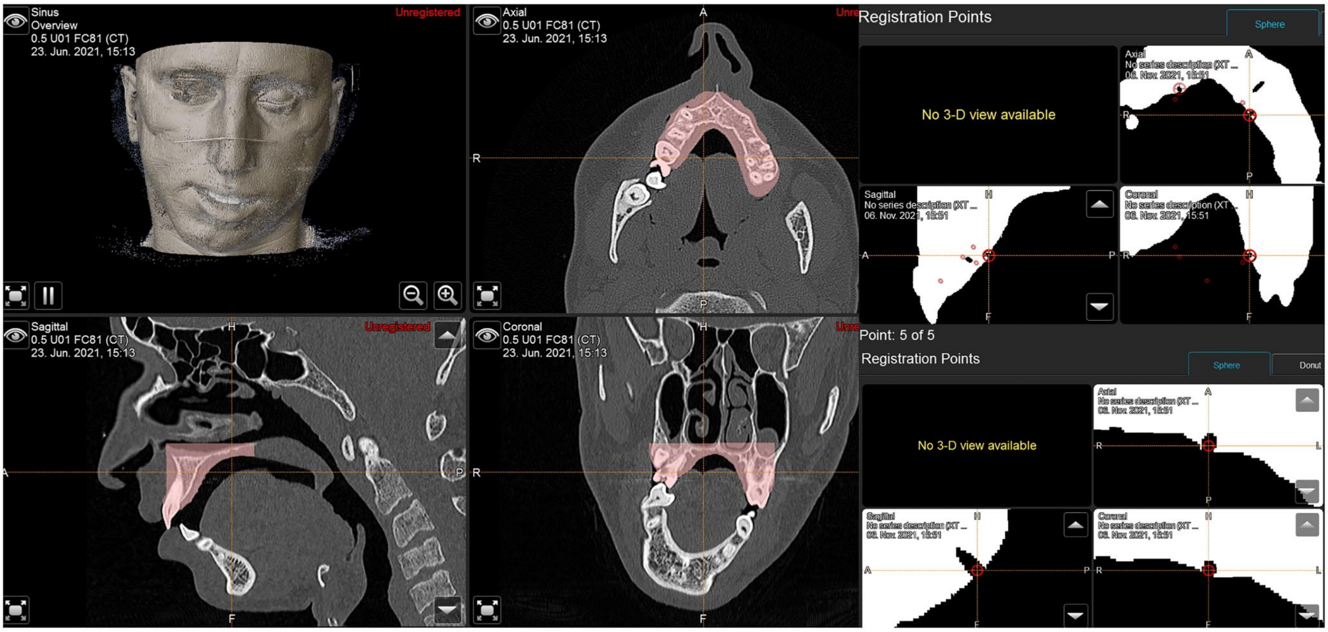

FIGURE 5 Shows the digital positioning of the reference points based on the hole-prepared intraoral scans' DICOM dataset

corresponding points other than the fiducial points (posterior and anterior nasal spine, infraorbital rim, tip of the right canine, entrance of foramen magnum, post-glenoid process) after registration.[17]

3 | RESULTS

3.1 | Measurements

Registration was performed on the basis of at prominent, clinically identifiable points of the transverse palatal rugae. The discrepancies between the model based reference point position and manually planned preoperative reference points were quantified using Elements (Brainlab AG) as FLE. The average FLE describes the discrepancy between the actual and digitally planned registration points on the transverse palatal rugae) was 0.48 mm (Figure 6) which is in accordance with the current literature[18] and possibly caused by misidentification of in situ landmark placement due to human error.[18] TRE was as follows: 0.5 mm to the posterior nasal spine (Point #01, Figure 7), 0.8 mm to the anterior nasal spine (Point #02; Figure 8) 0.3 mm point on the infraorbital rim (Point #03), 0.6 mm to the tip of the right canine (point #02 Figure 9) 0.9 mm at the entrance of the foramen magnum (point #06, Figure 10) and 0.8 mm at the post-glenoid process (point #07, Figure 11) which corresponds to a mean deviation of 0.65 mm.

4 | DISCUSSION

In this technical note, we described a new technique for the marker-free registration of intraoperative navigation systems. The key advantage of this technique is the avoidance of additional marker placement and subsequent pre-operative 3D imaging (CT or CBCT) in the edentulous maxilla. Registration is the task of obtaining the

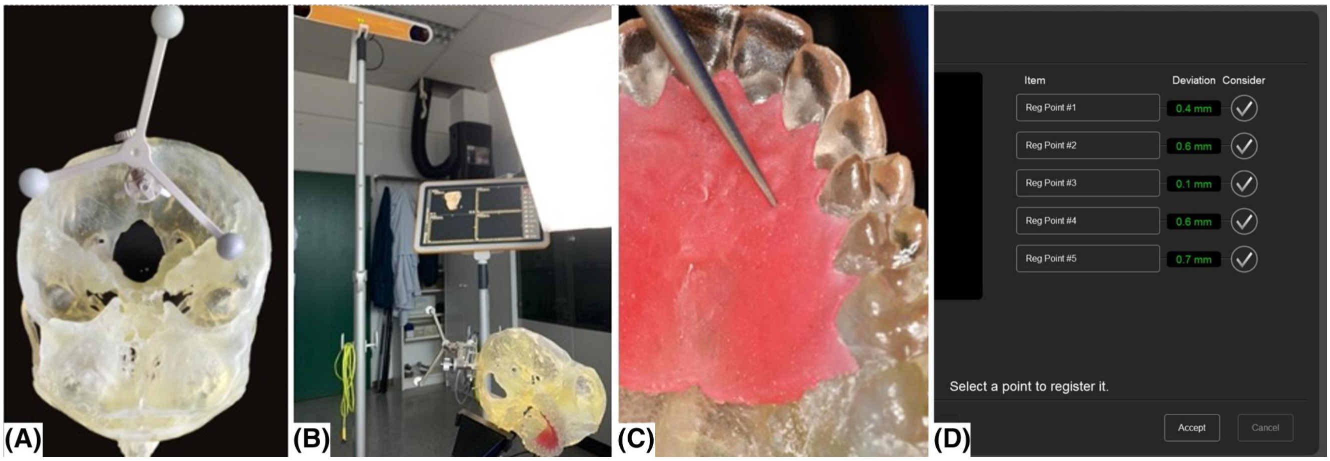

FIGURE 6 (A) Stereolithography skull model with attached referencing star with navigation markers, (B) Setup with fixed skull model and navigation unit, (C) Registration via fiducial points on transverse palatal rugae on the flexible gingival mask, and (D) Quantification of fiducial localization error (FLE) using a pointer

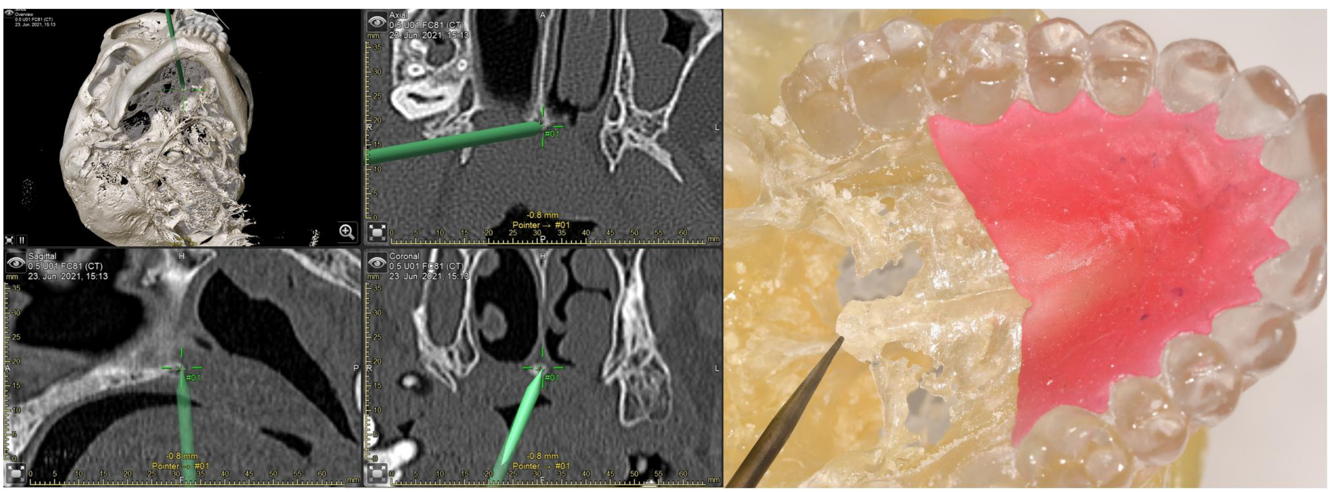

FIGURE 7 Navigation of the posterior nasal spine and demonstration of the achieved accuracy between digitally set fiducial points and intraoperative (stereolithography model) landmark (0.5 mm)

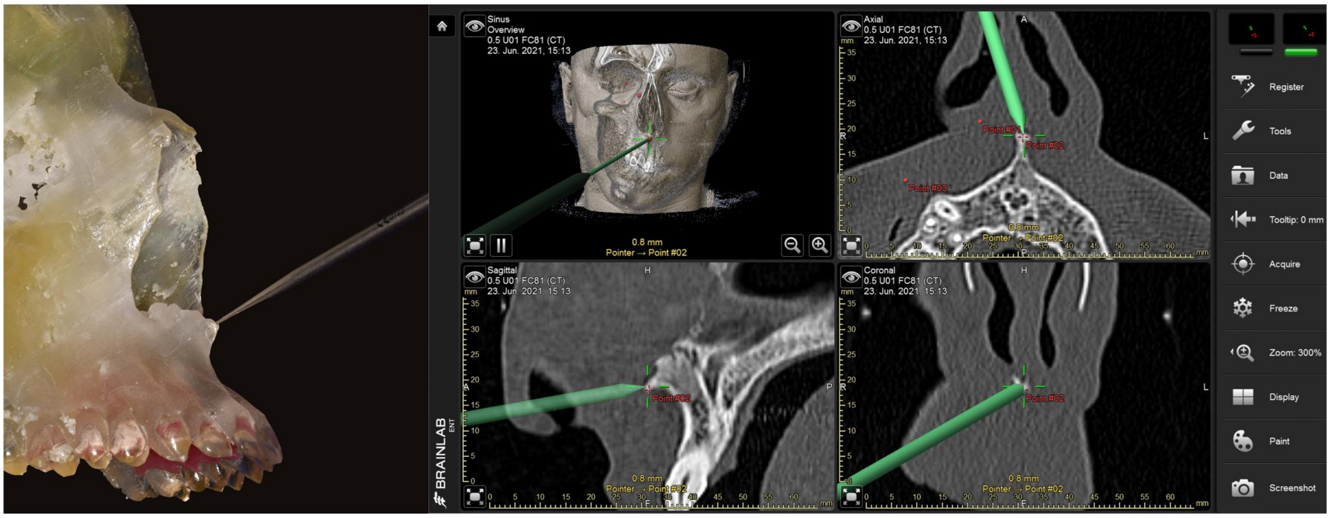

FIGURE 8 Navigation of the anterior nasal spine and demonstration of the achieved accuracy between digitally set fiducial points and intraoperative (stereolithography model) landmark (0.8 mm)

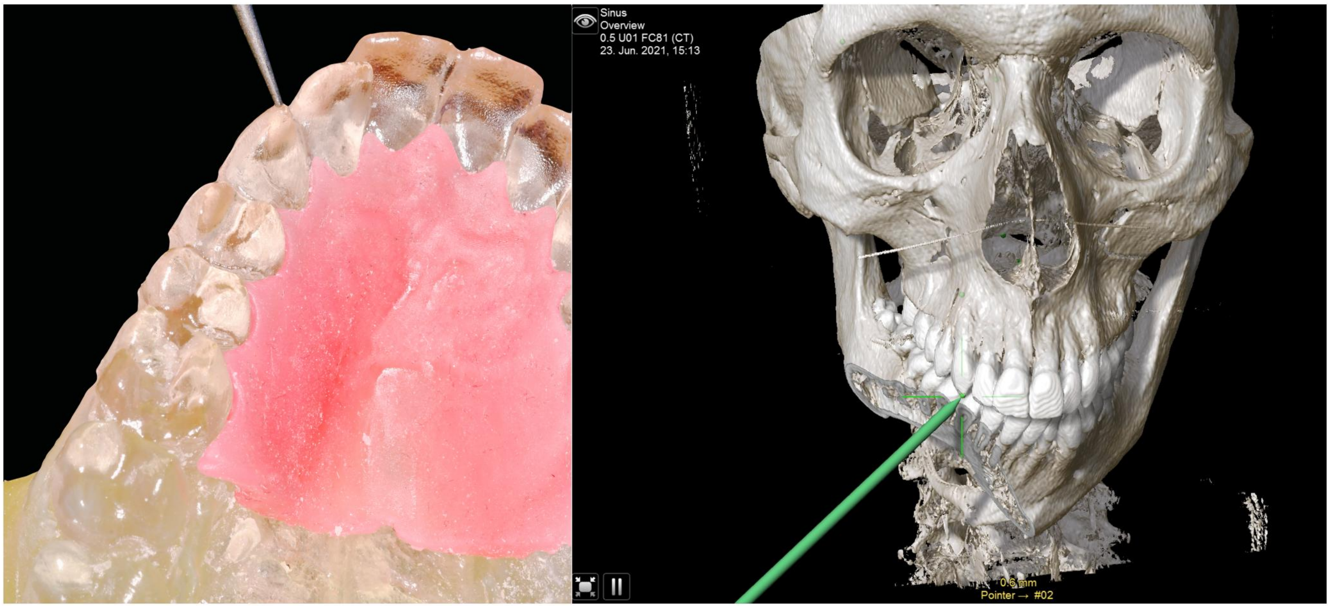

FIGURE 9 Navigation of the upper rights canines' tip and demonstration of the achieved accuracy between digitally set fiducial points and intraoperative (stereolithography model) landmark (0.6 mm)

mutual transformation matrix by calculating the relationship between the coordinates of the actual patient space and the coordinates of the medical image and is therefore the most important step when performing surgical navigation. While skin surface based registration methods in CMFS like the laser surface scanning are subject to wide variations due to regular intraoperative swelling, anatomical landmarks are often hard to reproduce and bone-supported markers require invasive insertion as well as additional 3D imaging for their detection.[8,19] Although they are soft-tissue in origin the use of the transverse palatal rugae for registration is advantageous because its structure is prominent and therefore clinically detectable, and its level of mobility is relatively low due to its high cross-linked collagen content. The precondition when using the transverse palatal rugae for registration is the low level positioning of the tongue during the CT or CBCT scan to ensure error-free segmentation of the palatal mucosa, hence this technique is limited to cases in which the maxilla and, in particular the transverse palatal rugae are present and freely accessible (e.g. unrestricted mouth opening and undamaged palatal mucosa). In our case, there was no special reason for using a CBCT scan; rather, the patients' dataset with a low-lying tongue already existed. Of course, contrasting or differentiating the palatal mucosa from the bone is better with a CT scan compared to a CBCT scan, but only with a higher radiation dose.

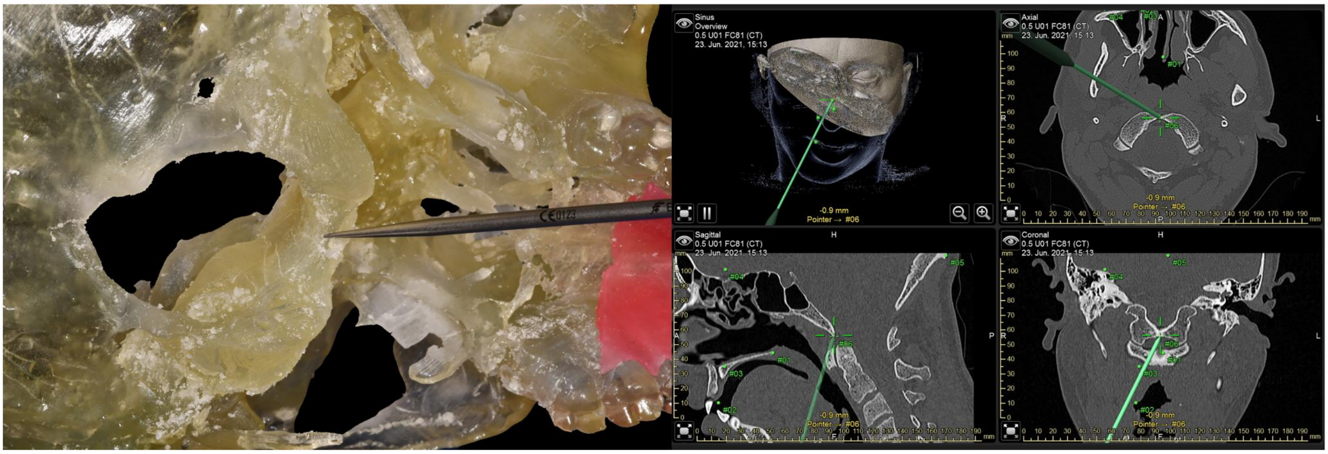

FIGURE 10 Navigation at the foramen magnum and demonstration of the achieved accuracy between digitally set fiducial points and intraoperative (stereolithography model) landmark (0.9 mm)

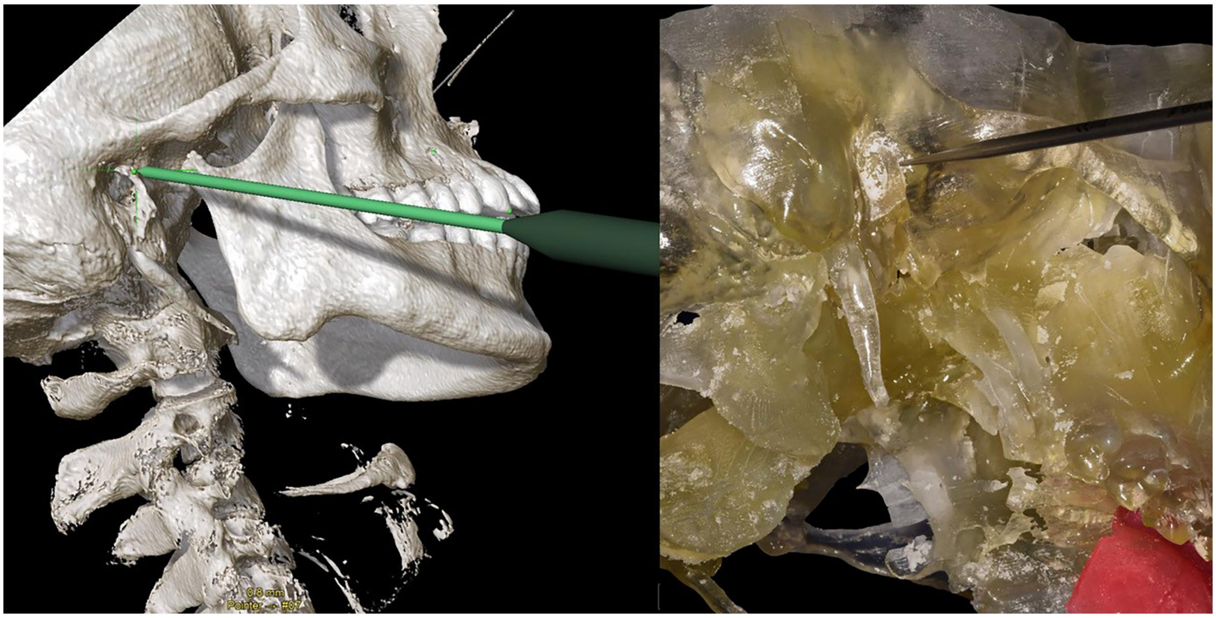

FIGURE 11 Navigation at the post-glenoid process and demonstration of the achieved accuracy between digitally set fiducial points and intraoperative (stereolithography model) landmark (0.8 mm)

Therefore, the advantages of a CBCT scan are the usually better availability compared to CT and at the same time lower radiation exposure for the patient. With regard to the application of the described methodology in the context of implantology, the use of the CBCT scan thus offers a simplification of the workflow due to the applicability of imaging in the dental and maxillofacial surgery practice.

In contrast to another recently described approach for the registration of intraoperative navigation systems via a tooth-supported splint with predefined reference points based on an IOS and the initial trauma CT,[19] our technique shows comparable accuracy. Despite increasing distance from the reference polygon (palate), TRE was 0.65 mm in average which is in line with the literature.[19,20]

As with any method, the one presented here has limitations/restrictions. Despite the rigidity of the palatal mucosa, the main limitation is clearly the existing mobility when a target pointer is applied. The use of laser-assisted surface marking could provide a remedy here. Furthermore, although rather rarely, the clinical identification of the registration points may be reduced due to excessive dehydration of the patient with subsequent decrease in volume of the transverse palatal rugae. However, this scenario is relatively unlikely, as it has already been shown in cadavers in forensic studies that the shape of the transverse palatal folds persists. Furthermore, the use of more distant registration points would further reduce the inaccuracy that necessarily occurs when navigating more distant regions of the skull.

5 | CONCLUSIONS

The described workflow appears to be a feasible approach for navigation-assisted surgery in the viscero- and neurocranium avoiding additional radiographic imaging and additive reference body insertion. A particularly interesting application could be the navigation-assisted insertion of zygoma implants in edentulous patients with severely atrophied maxilla since the maxillary regional crestal mucosa has little to no reproducible structures for registration.

ACKNOWLEDGEMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST

All the authors declares that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors of this manuscript had substantial contribution to conception and design or acquisition, analysis and interpretation of data; all revised it critically for important intellectual content and did final approval of the version to be published. All authors read and approved the final manuscript. D.G.E. Thiem (daniel.thiem@uni-mainz.de) takes responsibility for the integrity of the work as a whole, from inception to finished article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

1. Heiland M, Habermann CR, Schmelzle R. Indications and limitations of intraoperative navigation in maxillofacial surgery. *J Oral Maxillofac Surg*. 2004;62(9):1059-1063.
2. Neuhaus M, Zeller A, Bartella A, Sander A, Lethaus B, Zimmerer R. Accuracy of guided surgery and real-time navigation in temporomandibular joint replacement surgery. *Dent J*. 2021;9:87.
3. Westendorff C, Gülicher D, Dammann F, Reinert S, Hoffmann J. Computer-assisted surgical treatment of orbitozygomatic fractures. *J Craniofacial Surg*. 2006;17(5):837-842.
4. Azarmehr I, Stokbro K, Bell RB, Thygesen T. Surgical navigation: a systematic review of indications, treatments, and outcomes in oral and maxillofacial surgery. *J Oral Maxillofac Surg*. 2017;75(9):1987-2005.
5. Widmann G, Stoffner R, Bale R. Errors and error management in image-guided craniomaxillofacial surgery. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2009;107(5):701-715.
6. Howard MA, Dobbs MB, Simonson TM, LaVelle WE, Granner MA. A noninvasive, reattachable skull fiducial marker system. *J Neurosurg*. 1995;83(2):372-376.
7. West JB, Fitzpatrick JM, Toms SA, Maurer CR, Jr, Maciunas RJ. Fiducial point placement and the accuracy of point-based, rigid body registration. *Neurosurgery*. 2001;48(4):810-817. discussion 816-7.
8. Hoffmann J, Westendorff C, Leitner C, Bartz D, Reinert S. Validation of 3D-laser surface registration for image-guided cranio-maxillofacial surgery. *J Craniomaxillofac Surg*. 2005;33(1):13-18.
9. Schreurs R, Baan F, Klop C, et al. Registration-free workflow for electromagnetic and optical navigation in orbital and craniofacial surgery. *Sci Rep*. 2021;11(1):18080.
10. Schnutenhaus S, Edelmann C, Rudolph H, Dreyhaupt J, Luthardt RG. 3D accuracy of implant positions in template-guided implant placement as a function of the remaining teeth and the surgical procedure: a retrospective study. *Clin Oral Investig*. 2018;22(6):2363-2372.
11. Wong R, Jivraj J, Yang V. Current limitations and opportunities for surgical navigation. *Univ Tor Med J*. 2014;92(1):7-9.
12. Wu Y, Wang F, Huang W, Fan S. Real-time navigation in zygomatic implant placement: workflow. *Oral Maxillofac Surg Clin North Am*. 2019;31(3):357-367.
13. Wang F, Bornstein MM, Hung K, et al. Application of real-time surgical navigation for zygomatic implant insertion in patients with severely atrophic maxilla. *J Oral Maxillofac Surg*. 2018;76(1):80-87.
14. Fan S, Hung K, Bornstein MM, Huang W, Wang F, Wu Y. The effect of the configurations of fiducial markers on accuracy of surgical navigation in zygomatic implant placement: an in vitro study. *Int J Oral Maxillofac Implants*. 2019;34(1):85-90.
15. Villalobos H, Germano IM. Clinical evaluation of multimodality registration in frameless stereotaxy. *Comput Aided Surg*. 1999;4(1):45-49.
16. Hess R. *The Essential Blender: Guide to 3D Creation with the Open Source Suite Blender*. No Starch Press; 2007.
17. Maurer CR, Jr, Fitzpatrick JM, Wang MY, Galloway RL, Jr, Maciunas RJ, Allen GS. Registration of head volume images using implantable fiducial markers. *IEEE Trans Med Imag*. 1997;16(4):447-462.
18. Eckstein FM, Zeller A-N, Neuhaus M-T, et al. Referencing for intraoperative navigation: evaluation of human bias. *J Stomatol Oral Maxillofac Surg*. 2021(21):S2468-S7855.
19. Zeller AN, Zimmerer RM, Springhetti S, et al. CAD/CAM-based referencing aids to reduce preoperative radiation exposure for intraoperative navigation. *Int J Med Robot*. 2021;17(3):e2241.
20. Hoffmann, J, Westendorff, C, Schneider, M, Reinert, S. Accuracy assessment of image-guided implant surgery: an experimental study. *Int J Oral Maxillofac Implants*. 2005;20(3):382-386.

How to cite this article: Thiem DGE, Seifert L, Graef J, Al-Nawas B, Gielisch M, Kämmerer PW. Marker-free registration for intraoperative navigation using the transverse palatal rugae. *Int J Med Robot*. 2022;18(3):e2362. https://doi.org/10.1002/rcs.2362