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ORIGINAL ARTICLE

Utilization of a 3D printed dental splint for registration during electromagnetically navigated mandibular surgery

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Abstract

Purpose A dental splint was developed for non-invasive rigid point-based registration in electromagnetically (EM) navigated mandibular surgery. Navigational accuracies of the dental splint were compared with the common approach, that is, using screws as landmarks.

Methods A dental splint that includes reference registration notches was 3D printed. Different sets of three points were used for rigid point-based registration on a mandibular phantom: notches on the dental splint only, screws on the mandible, contralateral screws (the side of the mandible where the sensor is not fixated) and a combination of screws on the mandible and notches on the dental splint. The accuracy of each registration method was calculated using 45 notches at one side of the mandible and expressed as the target registration error (TRE).

Results Average TREs of 0.83 mm (range 0.7–1.39 mm), 1.28 mm (1.03–1.7 mm), 2.62 mm (1.91–4.0 mm), and 1.34 mm (1.30–1.39 mm) were found, respectively, for point-based registration based on the splint only, screws on the mandible, screws on the contralateral side only, and screws combined with the splint.

Conclusion For dentate patients, rigid point-based registration performs best utilizing a dental splint with notches. The dental splint is easy to implement in the surgical, and navigational, workflow, and the notches can be pinpointed and designated on the CT scan with high accuracy. For edentate patients, screws can be used for rigid point-based registration. However, a new design of the screws is recommended to improve the accuracy of designation on the CT scan.

Keywords Mandibular surgery · Electromagnetic surgical navigation · Rigid point-based registration · Dental splint · Target registration error

Introduction

Computer-aided-design/computer-aided-manufacturing (CAD/CAM) techniques are routinely used in mandibular surgery. To prepare for surgery, the surgeon uses a 3D rendered model of the mandible, that is, constructed from a preoperative computed tomography (CT) scan. The exact positions of the osteotomies are planned virtually, in order to achieve adequate tumor margins and to ensure an accurate fit of the bone segments that will be used for reconstruction after resection. To translate the positions of the osteotomies to the clinical situation in the operating room, patient-specific cutting guides and bone segment fixation plates are designed and manufactured by a certified producer. Besides the fact that this is a costly procedure, the preparation time can take up to several weeks before surgery. If tumor progression occurred in the meantime, the cutting guide cannot be adapted during surgery. Therefore, there is a need for a technology that is more adaptable than the patient-specific 3D printed cutting guides [1].

Surgical navigation provides real-time visual feedback regarding the position and orientation of surgical instruments in relation to the patient's anatomy. This could potentially be used to translate the preoperative planning to the operating room, thereby eliminating the use of cutting guides. Electromagnetic (EM) navigation is used routinely in neurosurgery

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or surgery of the sinonasal cavity, but not in mandibular surgery so far: the fact that the mandible is mobile challenges accurate navigational tracking. In a previous study, we evaluated the accuracy of an in-house developed EM navigation system, as a first step toward EM navigated assisted bone resection in mandibular tumor surgery [2]. In a total of eleven patients, EM navigation approached clinically acceptable accuracies to guide resections in mandibular surgery. However, we hypothesize that the accuracy could be improved further. One possible improvement could be achieved in the registration procedure: the method on how the virtual 3D rendered model is registered to the actual patient's mandible at the OR table.

In rigid point-based registration, or fiducial registration, the rotation and translation between the virtual model and the real-time situation is determined by pinpointing at least three points on the patient's mandible with an EM trackable instrument and matching those tracked locations with the corresponding points on the CT scan that is used for the virtual 3D model. This is challenging for the mandible, due to the lack of clear and precise anatomical landmarks on the mandibular surface: Naujokat et al. evaluated rigid point-based registration using interdental bone structures as anatomical landmarks, but found that the use of anatomical landmarks does not provide sufficient accuracy (error of 1.7 mm) [3]. As an alternative to anatomical landmarks, several studies have reported on the use of titanium screws fixated to the bone for rigid point-based registration [4–6]. Fixated screws would offer maximum accuracy due to the fixation, and in addition, screws are easily detectable on a CT scan and on the patient. However, the method is invasive: the screws have to be implanted prior to the acquisition of the preoperative CT and are subject to causing discomfort.

In order to improve the accuracy of EM navigated mandibular surgery, a dental splint was developed for rigid point-based registration in this study. The TRE obtained after registration based on the dental splint was compared to the TRE obtained with the use of fixated screws in different configurations.

Materials and methods

A mandible phantom was printed with a Form 2 3D printer (Formlabs, Somerville, Massachusetts, USA) and the standard Formlabs material, using a clear resin. Along the complete outer surface of the mandible, notches are located (Fig. 1). These notches are designed in such a way that they fit the EM trackable pointer of the navigation system exactly: The notches are cone shaped with a maximum diameter of 3 mm that equals the largest diameter of the pointer. In addition, five titanium 1.5×5 mm Drill-Free maxDrive® (KLS Martin, Freiburg, Germany) screws were drilled into the mandible at various locations along the body and the ramus of the mandible.

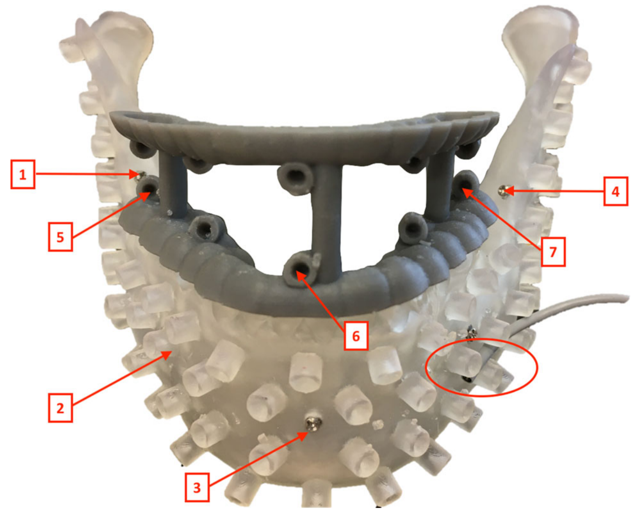

Fig. 1 The mandible model with the dental splint in position and a 6DOF sensor (in gray, circle) attached. The numbers indicate the points used for registration (1, 2, 3 and 4 indicate screws, 5, 6, 7 indicate notches on the dental splint)

A 3D printed dental splint was designed to exactly fit the teeth of the mandible phantom, using Meshmixer (2017 Autodesk, Inc. version 3.5.474). The spacing between the teeth's surface and the splint was 0.1 mm. The dental splint fits the teeth on the mandible and the upper jaw; however, only the mandible side was used for this study. Five notches (3 mm diameter) were added to the mandibular side of the 3D dental splint for registration purposes.

A computed tomography (CT) scan was acquired of the mandible phantom with the dental splint in position (pixel spacing of 0.68 mm and a 1 mm slice thickness, Siemens Somatom Confidence® (Siemens Healthineers, Erlangen, Germany)). On this CT scan, the notches and the screws were visible to allow rigid point-based registration (Fig. 2).

A 6 DOF EM tracked sensor was used to track the position of the mandible (Fig. 1). The sensor remains fixed to the mandible phantom during, and after, the registration procedure, so that the position of the mandible is tracked throughout the whole procedure. The positions of both the sensor and a trackable pointer were tracked by a planar EM field generator of NDI Aurora (Northern Digital Inc., Waterloo, Ontario, Canada). The distance between the sensor and the field generator was approximately 25 cm during the measurements, to simulate an intraoperative situation.

Rigid point-based registrations

Several configurations of registration points were used for different methods of rigid point-based registration, i.e., screws on the mandible, and notches on the dental splint

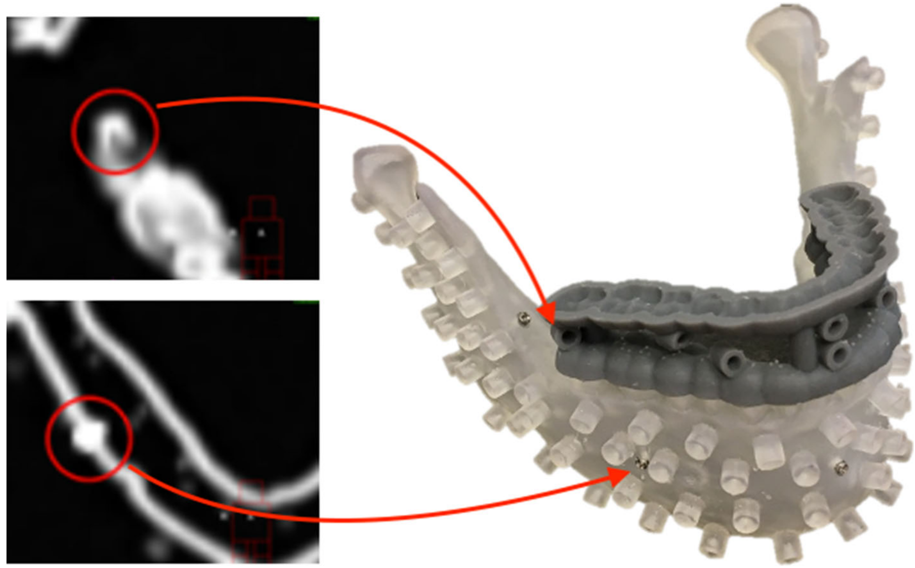

Fig. 2 Axial CT slices of the phantom. The upper CT image shows a notch; the lower CT image shows a screw

Table 1 The sets of points that were used for the different point-based registration procedures

Registration method	Registration points (see Fig. 1)
Screws	1–3–4
Contralateral screws	1–2–3
Screws and notches on the dental splint	1–3–7
Notches on the dental splint	5–6–7

(Table 1, Fig. 1): screws on the mandible, contralateral screws (the side of the mandible where the sensor is not fixated), a combination of screws on the mandible and notches on the dental splint, and notches on the dental splint only. The registration points were pinpointed using an EM tracked pointer on the mandible phantom with the dental splint. Corresponding points on the CT scan were manually indicated simultaneously, using coronal, sagittal and axial views in an in-house developed software program. The root mean squared error of the Euclidean distance between the pinpointed registration points on the mandible and the virtual registration points was calculated as the fiducial registration error (FRE).

Accuracy measurement

The accuracy of each registration method was calculated using 45 notches at one side of the mandible, assuming that when the tumor is located on that side of the mandible, this is the side where the technique is of clinical value. The 45 notches were virtually indicated on the CT scan (Fig. 3) and pinpointed with the trackable pointer at the actual mandible phantom. The location of the notches in the CT data was compared to the pinpointed location of the corresponding notches on the mandible phantom. The resulting difference was expressed as the target registration error (TRE), meaning the Euclidean distance between the virtual and pinpointed location.

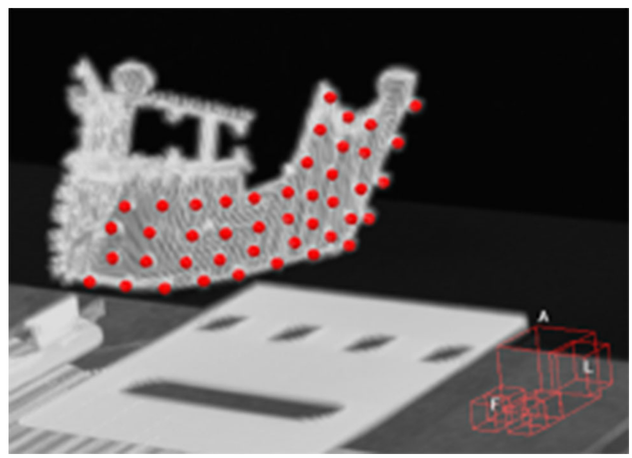

Fig. 3 The 45 points at the affected side of the mandible that are used to calculate the TRE, shown on the CT scan

Each registration method was repeated five times, and for each time, the TRE was calculated for all 45 notches. The average TRE of the five repetitions was calculated for each of the 45 notches. This average TRE was mapped onto a 3D surface model of the mandible using color coding. For the latter, Matlab 2017b (MathWorks, Natick, Massachusetts, USA) was used. The 3D surface model, consisting of small polygons, was colored using triangulation-based nearest neighbor interpolation, where each polygon received a color corresponding to the average TRE of the nearest notches. This results in small single-colored areas around the notches, indicating their corresponding average TRE (Fig. 4).

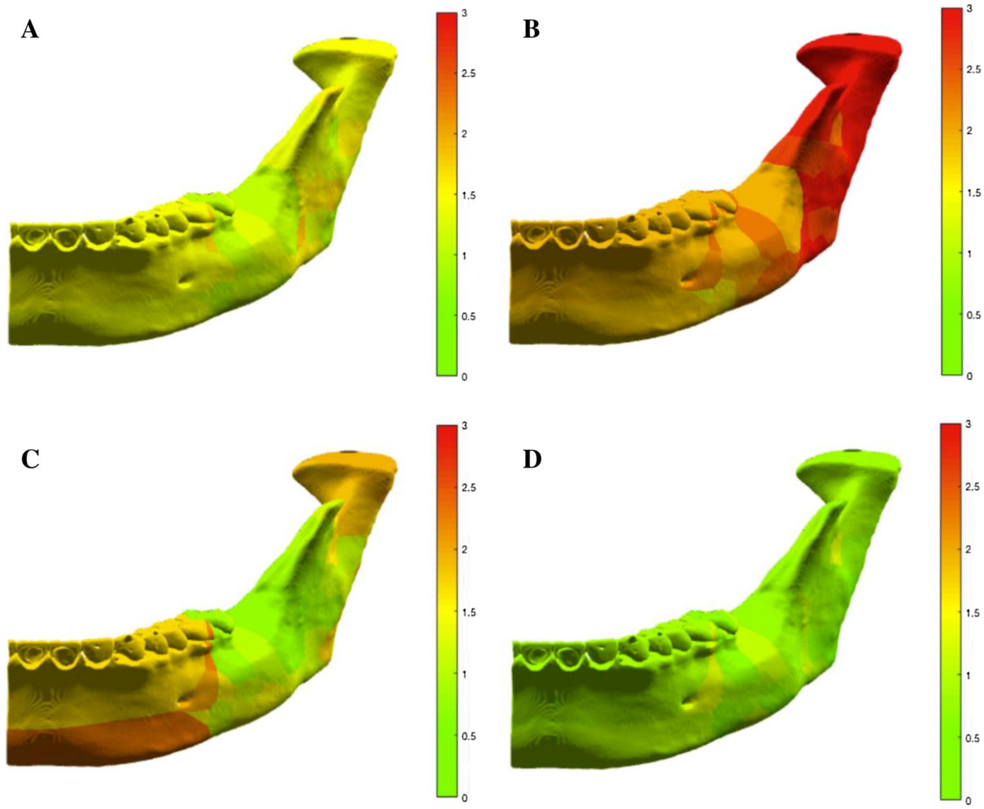

Fig. 4 Colormaps indicating the TRE (in mm) for the affected side of the mandible after point-based registration using the screws (**a**), only the contralateral screws (**b**), using a combination of the screws and the notch on the dental splint (**c**) and using the notches on the dental splint only (**d**)

Repeatability in designating the registration points (screws and notches) on the CT data

During the different registration methods, the registration points were repeatedly pinpointed on the phantom and designated on the CT data. To evaluate the reproducibility of the registration methods, the repeatability of designating the screws on the CT data was compared to the repeatability of designating the notches on the CT data.

There were a total of four screws that were designated as a registration point for forty times (over all methods and all repetitions), whereas three notches were designated as a registration point for twenty times. The centroid was calculated for each of the four screws and three notches individually, using their designations on the CT data. Then, the centroids of all screw registration points were superimposed on each other, and standard deviation (STD) of all screw designations with respect to the centroid was calculated. This was also done for the notches. The STD in Euclidean distance between the designation and the centroid was used as a measure to compare the repeatability of marking the screws and notches on the CT data.

Results

The FREs and TREs calculated from the outcomes of the five repetitions of accuracy measurements are shown in Table 2. Figure 4 provides insight into the areas of the affected mandible where high accuracies of the EM navigation technique can be achieved for each different type of registration method used. The use of a 3D printed dental splint demonstrated the smallest error and thus resulted in the most accurate method for EM navigational mandible tracking.

Regarding the repeatability of designating notches and screws on the CT scan, designating the notches on CT was more consistent (STD = 0.27 mm), compared to the screws (STD = 0.39 mm).

Discussion

In this phantom study, different variants of rigid point-based registration were evaluated, in order to investigate the accuracy of EM navigation for mandibular surgery. With a mean error of 0.83 mm, measured over the target surface of the

Table 2 FRE and TRE calculated after point-based registration using the different registration methods

Registration method	Average FRE (mm)	Average TRE (mm)	Minimum TRE (mm)	Maximum TRE (mm)
Screws	0.73	1.28	1.03	1.70
Contralateral screws	0.59	2.62	1.91	4.00
Screws and notches on the dental splint	0.74	1.34	1.30	1.39
Notches on the dental splint	0.36	0.83	0.70	1.39

mandibular phantom, the use of a dental splint has shown to achieve the highest accuracy.

The design, production and intraoperative use of a dental splint shows high potential for implementation within the EM navigation workflow. For the design of the dental splint, a non-invasive intra-oral scan of the mandibular teeth can be acquired during the first visit of the patient in the outpatient clinic. Using a handheld scanner, the physician or the dentist can acquire the scan within a few minutes. The intra-oral scanner acquires a 3D surface map of the mandibular teeth that can be inverted to design the dental splint. Subsequently, the dental splint can be printed using a sterilizable resin. The 3D virtual model of the dental splint can be added to the 3D reconstructed model of the mandible using two approaches: (a) the dental splint can be positioned on the patients teeth during the acquisition of the preoperative CT scan, or (b) the digital version of the dental splint can be added to the 3D model virtually. In the latter, the transformation found after surface registration of the intra-oral scan with the preoperative CT can be used to position the splint accurately. In the intraoperative setting, the 6 DOF reference sensor is fixated to the mandible and the dental splint can be placed on top of the patient's teeth. Rigid point-based registration can be performed by pinpointing the notches on the dental splint on the patient with the trackable pointer and linking them with the corresponding points on the virtual model which includes the surgical plan, e.g., cutting planes. After the registration procedure, the dental splint can be removed, and the EM navigation would be ready for use. Because the splint only has to be in place during the registration procedure to set up the surgical navigation, it will not hinder the use of other surgical instruments that are needed to perform the resection for example. The sensor remains in place and allows tracking of the position of the mandible throughout the whole procedure, thereby eliminating the need for immobilization of the mandible.

The described method could be used for different types of mandibular procedures for which surgical navigation is indicated, such as tumor resection surgery and reconstructive surgery, as long as the patients are dentate so that a splint can be designed, and there is an area on the mandible that allows fixation of the sensor. The dental splint is easy to implement in the EM navigation workflow, and it is a non-invasive method. However, its employment requires a patient-specific preparation (the splint can be designed in less than 30 min, and printing time is approximately 60 min.)

The use of screws would be a possibility for point-based registration in edentate patients. With the design of this study, we hypothesized that the screws would show a high accuracy due to the fact that they are fixated to the mandibular bone and clearly visible on the CT scan. The registration accuracy of the screws only method, however, was not superior, and our analysis on the variability of indicating the screws on the CT data confirms that the exact screw heads visible on the CT scan could be interpreted with a high variety (i.e., high STD). To perform rigid point-based registration using screws, special screws should be designed with, e.g., an attachable notch so that similar accuracies can be achieved as reported with the dental splint. Concerning the position of the screws, the current study implies that the smallest errors are reached when screws are positioned on the anterior surface and on both lateral surfaces of the mandible, making the methods accuracy dependent on the location of the tumor. Regarding the workflow for edentate patients, one should keep in mind that the screws need to be positioned prior to the acquisition of the preoperative CT scan and must remain in the mandible until the surgery.

In 2001, West et al. described four guidelines to achieve optimal TRE with rigid point-based registration: (1) avoid (near) linear configurations, (2) arrange the registration points so that the center of their configuration (centroid) is as close as possible to the target region, (3) increase the distance between the registration points, and (4) use as many registration points as possible [7]. Regarding the latter, they found that the increase in accuracy diminishes after using five or six registration points. However, in 2011, Shamir et al. suggested that the TRE would not necessarily improve by adding or deleting registration points, nor does the TRE increase as the target is further away from the center of the registration points [8]. In a recent study, Hwang et al. also demonstrated that an increase in the number of registration points was not necessarily associated with a decrease in the TRE [9]. Using from three up to seven screws as registration points distributed over a mandible phantom, and TREs calculated at various anatomical locations, they found that the minimum number of registration points to achieve optimal TREs, depends on the location of the target site. In the current study, small TREs were achieved with the use of only three registration points that were located near each other, in an almost linear configuration, but with their centroid near the target area. Thus, our results suggest that the position of the centroid of the registration points near the target area, contributes most to the accuracy.

In order to improve accuracy results with a splint by enlarging the distance between the registration points, Lee et al. designed a registration body for EM surgical navigation, in such a way that it could be fixated to the mandible as a symmetrical arch [9]. The registration body had 24 holes of different depths and in different positions. The holes contained 1 mm in diameter ceramic balls that served as fiducial points for registration. For point-based registration, six points at the registration body were used. TRE was measured on three condylar landmarks. Using the registration body, they found that highest accuracies (~ 0.7 mm) were found when the six registration points were located near the condyle that was used for accuracy measurement. This is comparable with the results obtained for the dental splint in this study and confirms that the position of the registration points is important for the accuracy.

Naujokat et al. also used different registration methods for the mandible and reported a superior registration accuracy when a splint manufactured on the occlusal surface was used [3]. However, they used an optical navigation system and required large optical markers attached to the splint. This challenges the way the splint is fixated to the mandible. Within the study they fixated the splint with the optical marker using wires around the mandibular bone, which challenges the application and fixation in patients.

Soteriou et al. found that after a rigid point-based registration with four titanium screws, a TRE of 0.94 ± 0.06 mm measured at 26 titanium screws was achieved on a skull model using EM navigation [5]. Kristin et al. also used an EM navigation system and measured an overall accuracy of 0.6 ± 0.3 mm after point-based registration with six titanium screws on a cadaver skull [6]. Both studies positioned the screws on the mastoid for navigation purposes on the ENT area or skull base, not the mandible. Our TRE of 1.28 mm, obtained with the screws only registration, needs improvement when compared to these results (< 1 mm). Main differences between our study and those studies are the number of registration points used, and the distance between the registration points. Both studies utilized the whole skull and therefore could extend the distance between the registration points. Due to the fact that the mandible is movable with respect to the skull, registration points are limited to the mandibular surface, limiting the distance between the registration points. Hwang et al. utilized screws positioned at the mandible only and obtained comparable results as our study; however, they used optical navigation, which is clinically less practical for use in a small surgical field as the oral cavity due to the required line of sight [9].

According to Wang et al., augmented reality shows great promise for image registration [10]. They used an intraoral 3D scanner to acquire the patient's teeth shape intraoperatively. The 3D shape of the teeth is registered with the 3D model obtained from the preoperative CT scan using a custom-made stereo camera system. In jaw phantom experiments, they found an average TRE of 0.50 mm.

Future studies will focus on translating this phantom study to a patient study: utilizing patient-specific dental splints during EM navigation in patients undergoing mandibular surgery.

Conclusion

In this phantom study, different variants of rigid point-based registration were evaluated, in order to facilitate EM navigation during mandibular surgery. For dentate patients, a method was developed to obtain high navigational accuracies after rigid point-based registration using a dental splint with notches. The dental splint is easy to implement in the surgical, and navigational, workflow, it is non-invasive, and the notches can be pinpointed and designated on the CT scan with high accuracy. For edentate patients, screws can be used for rigid point-based registration. However, a new design of the screws is recommended to improve the accuracy of designation on the CT scan.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Availability of data and materials The authors are willing to share the data and material for further research purposes.

Code availability The authors are willing to share the code and material for further research purposes.

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