Effect of the Configurations of Fiducial Markers on the Accuracy of Surgical Navigation in Zygomatic Implant Placement: An In Vitro Study

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Purpose: Real-time surgical navigation has been increasingly applied in implant placement. The initial registration procedures were found to substantially affect the overall accuracy, but the number and distribution of fiducial markers are yet undetermined. This study aimed to determine the minimal number and optimal distribution of fiducial markers to achieve clinically acceptable accuracy in surgical navigation for zygomatic implant placement by systematically analyzing the effects of different setups of fiducial markers on target registration error (TRE).

Materials and Methods: A maxillary phantom with bone-anchored fiducial markers was scanned using cone beam computed tomography, followed by data processing on Brainlab, a commercially available navigation system. A total of 10 miniscrews were inserted in the edentulous maxilla for the configuration of the fiducial markers, with another two miniscrews as implant targets to assess the TRE in zygomatic bone. Data were then collected in nine configurations with distinct fiducial numbers and positions. Statistical analyses were performed with SPSS.

Results: The accuracy of the surgical navigation system was found to depend on both the number and the position of fiducial markers. No significant difference was observed in accuracy among groups with eight fiducials and with a polygon span distribution (P > .05). When the fiducial number decreased to less than six, the markers inserted in a regular triangle were more precise than those in an inverse triangle configuration. When the number of fiducials was five with a polygonal distribution, a low TRE value of 0.59 mm was detected, which was comparable to the accuracy with more than eight fiducials in this study. Conclusion: A scattered distribution with a polygon span with at least five fiducial markers in the edentulous maxilla for registration seems to achieve acceptable TRE values with high accuracy for navigation in zygomatic implant placement. Int J Oral Maxillofac Implants 2019;34:85–90. doi: 10.11607/jomi.6821

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Zygomatic implants have been effectively used in rehabilitation of the atrophic maxilla and regarded as an alternative to large bone grafting wherever bone resorption inhibited conventional implant placement.1–3 In the 1990s, a trans-sinus implant placement approach to engage the body of the zygomatic bone in severely resorbed maxillae was introduced by Bränenmark and was later modified to the so-called quad approach.4 With the anatomical intricacies of zygomatic processes and the limited intraoperative visibility, placing multiple zygomatic implants certainly made this surgery more difficult and risky to perform. Real-time surgical navigation systems have been developed and applied to optimize preoperative planning and constant visualization of the trajectory during implant insertion.5,6

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The accuracy of intraoperative navigation is very important for computer-aided surgery in terms of reliability. The accuracy of navigation systems depends on parameters such as the computed tomography (CT) layer thickness, the voxel size of cone beam computed tomography (CBCT), the registration accuracy, the precision of the optical tracking system, and the rigid fixation of calibration for tracking.7 As a crucial part of navigation surgery, registration is defined as the determination of the spatial relationships between the virtual coordinate system and the intraoperative patient coordinate system, and its precision is vital to the actual navigation surgery.9,10 After the registration procedure, information can be provided on the target registration error (TRE). This value represents the error between target points after registration, and it is the most representative indicator of registration accuracy.9,10 In very few previous studies, when researchers evaluated registration errors in implant navigation surgery, they only focused on its distribution in extraoral cranial-facial areas.11–13 However, from a clinical point of view, this focus seemed less practical during implant insertion because of scar formation in the facial areas. Therefore, it is much more realistic to think about some intraoral regions in placed bone-anchored fiducial markers for implant placement. Furthermore, previous research failed to focus on the arrangement of fiducial markers for zygomatic implant insertion accuracy in navigation surgery.

Registration methods can be divided into two groups, which are invasive bone screw markers and noninvasive markers.9,11,13–17 Compared with noninvasive techniques, the advantage of an invasive technique (bone-anchored fiducial markers) is its precision for edentulous arches.15,17

The challenge of choosing an adequate intraoral area for fiducial markers is the limited anatomical area in an extremely atrophic maxilla. These areas must be noncritical but able to provide bone anchorage and not interfere with implant insertion. Meanwhile, for geometric consideration, the span of the markers should be as large as possible to achieve a wide field for maximum accuracy. Therefore, the present study aimed to determine the minimal number and optimal distribution of fiducial markers in maxillary atrophic edentulous arches to achieve clinically acceptable accuracy in surgical navigation for zygomatic implant placement.

MATERIALS AND METHODS

Placement of Fiducial Markers
A phantom based on a real patient’s CBCT scan (i-CAT, Imaging Sciences International) with a resolution of 0.39 mm/pixel and 0.5-mm slice thickness to simulate the edentulous maxilla was fabricated according to rapid prototype with fused deposition modeling (FDM) technology (Fig 1). In the phantom, the bilateral maxillary tuberosity, the midline palatine suture, and both sides of the anterior nasal spine were chosen as the bone anchorage areas for the fiducials. Bone-anchored fixed titanium miniscrews (diameter: 1.0 mm, length: 9.0 mm, square cavity: 1.0 mm) (CIBEI) served as fiducials, and a total of 10 fiducial markers were inserted in the aforementioned five areas (Fig 2a). There were two miniscrews in each area, with a distance of 3 mm. Another two screws of the same size were anchored on both zygomatic bone surfaces and were defined as “registration targets” (Fig 2b).

CBCT Scanning and Importing DICOM Data
After being prepared in this standardized manner, the model was fixed on the chin rest. A CBCT (i-CAT, Imaging Sciences International) scan was performed with a resolution of 0.39 mm/pixel and 0.5-mm slice thickness. The DICOM data were transferred to the planning software of one commercially available navigation system (iPlan Navigator, Brainlab), and all titanium miniscrews were identified and labeled in the coronal, axial, and sagittal views with this program.
Registration
In the registration procedure, the combination of 10 fiducial markers was first selected on the CBCT images, reconstructed, and then visualized in 3D; these markers served as the “registration fiducials” (Fig 3). The configuration was chosen from 4 to 10 points at any of the five regions (both sides of the anterior nasal spine, bilateral maxillary tuberosity, midline palatine suture). There were a total of nine groups of configurations with different fiducial numbers and positions. The different configurations of these nine groups are listed in Figs 4 and 5, and they were examined one by one using a probe for TRE measurement. All registration procedures were performed by two well-trained surgeons experienced with the navigation system (S.F., K.H.).

Measurement of TRE
After each registration procedure, all 10 target labels were checked one-by-one using a probe. The navigation system calculated the distance between the actual position and the registration target whenever the probe was positioned on a titanium screw. The TRE was calculated automatically by the system, which was the distance between the corresponding points and the registration markers after registration.

The TRE used the root mean square formula (RMS) specified as the distance between the image fiducial markers (fm) and the phantom targets (pt). The RMS was calculated by the navigation system as follows:

\[\sqrt{(X_{fm} - X_{pt})^2 + (Y_{fm} - Y_{pt})^2 + (Z_{fm} - Z_{pt})^2}\]

The complete experiment was repeated 10 times by each observer with a variety of selected fiducial configurations and target fiducial locations. From the nine different fiducial configurations, one target fiducial on each side of the zygomatic bone was determined.

Statistical Analysis
The data were maintained in Excel (Microsoft). Statistical analysis was performed with SPSS for Windows (16.0) (SPSS). Before all the parameter tests were carried out, the samples were tested for normality and homogeneity of variance. All data were reported as mean ± SD. Paired t tests were used to compare each side of the target. One-way analysis of variance (ANOVA) was used to test the differences among groups. In all tests, a significance level of .05 was chosen.

RESULTS
All fiducial markers and target markers were highly visible on the CBCT images. Nine different fiducial configurations were evaluated. A high consistency (reproducibility) of the interobserver measurements was observed (kappa value: 0.82).

Fig 3 Indication of fiducial markers for registration procedure on the axial, coronal, and sagittal reconstructions and a three-dimensional view in planning software (iPlan Navigator, Brainlab).

Fig 4 A total of nine groups of configurations with different fiducial numbers and positions.

Fig 5 The shape of distribution of fiducial markers. Inverse triangle span (blue area): fiducial markers distributed in anterior region and midline palatine suture. Regular triangle span (red area): fiducial markers distributed in maxillary tuberosity and midline palatine suture. Polygon span (green area): fiducial markers distributed in anterior region, maxillary tuberosity, and midline palatine suture.
The difference in TRE between the left and right zygoma target markers was insignificant ($P = .07$). The results of the registration for each fiducial configuration are shown in Table 1. Comparing the nine different fiducial configurations of TRE values (Table 1), the lowest mean TRE value was $0.44 \pm 0.12$ mm, when 10 fiducial markers were well-distributed on the anterior, posterior, and midpalatal areas at the same time (group 1). The highest mean TRE value was $1.53 \pm 0.20$ mm, when four fiducial markers were only distributed in the anterior and mid-palatal areas (group 9).

Statistically significant differences in the TRE values were observed ($P < .0001$) among these nine groups. However, when nine fiducial configurations were classified, there were no significant differences in accuracy among groups 1, 2, 3, and 4 ($P > .05$) (Table 1). When there were fewer than six fiducials, the markers inserted in a regular triangle area were more precise than those in an inverse triangle configuration (group 5 vs group 6, $P < .0001$; group 8 vs group 9, $P < .0001$) (Table 1).

To classify the configuration by the distributed regions, the nine groups were divided into two subgroups (Table 2). The mean value of TRE in the first subgroup, which included five distributed regions, was $0.49$ mm compared with $1.23$ mm in the second subgroup with three distributed regions. Significant differences were found between these two subgroups ($P < .0001$), and the polygonal distribution was the most precise distribution.

The TRE value increased as the number of fiducials decreased (Table 2). However, when there were five fiducials with a polygonal distribution, a low TRE value of $0.59$ was detected, which was comparable to the accuracy with more than eight fiducials in this study.

**DISCUSSION**

The overall reported frequency of complications when using zygomatic implants was $9.9\%$. The extraoral symptom of infraorbital nerve paresthesia and subcutaneous malar emphysema might be primarily related to the surgeon's performance and surgical accuracy. In placement of zygomatic implants, the drilling path is approximately four times longer than the path for regular dental implants, and exit deviation may increase proportionally due to the length of the drilling path. However, with the aid of a surgical navigation system, one case report demonstrated that three zygomatic implants were placed on one side of the zygoma with acceptable deviation of each zygomatic implant and no complications.

Navigation systems allow preoperative planning into an actual surgical path to guide the placement of implants. During the registration process, some errors may occur during point-based registration. The main sources of localization errors come from fiducial localization error (FLE), fiducial registration error (FRE), and target registration error (TRE). The FLEs were analyzed by the inaccuracy of the identified fiducial markers on the computer software, which depends on the image voxel size and the size of the fiducials. The FRE

**Table 1** TREAT Value of Zygoma Target by Different Fiducial Amounts and Configurations

<table>
<thead>
<tr>
<th>Group</th>
<th>Distributed regions</th>
<th>Shape of distribution</th>
<th>No. of fiducial markers</th>
<th>Mean ± SD TRE (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>Polygon</td>
<td>10</td>
<td>0.44 ± 0.12</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>Polygon</td>
<td>8</td>
<td>0.47 ± 0.09</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>Polygon</td>
<td>8</td>
<td>0.49 ± 0.08</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>Polygon</td>
<td>6</td>
<td>0.49 ± 0.07</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>Regular triangle</td>
<td>6</td>
<td>0.88 ± 0.12*</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>Inverse triangle</td>
<td>6</td>
<td>1.40 ± 0.13*</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>Polygon</td>
<td>5</td>
<td>0.59 ± 0.14</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>Regular triangle</td>
<td>4</td>
<td>1.10 ± 0.16**</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>Inverse triangle</td>
<td>4</td>
<td>1.53 ± 0.20**</td>
</tr>
</tbody>
</table>

TRE = target registration error; *$P < .05$; **$P < .0001$.

**Table 2** Nine Fiducial Configurations Classified According to Distribution and Number

<table>
<thead>
<tr>
<th>Fiducial distribution</th>
<th>Group numbers</th>
<th>Mean ± SD TRE (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5 (Groups 1, 2, 3, 4, 7)</td>
<td>0.49 ± 0.18*</td>
</tr>
<tr>
<td>3</td>
<td>4 (Groups 5, 6, 8, 9)</td>
<td>1.23 ± 0.30*</td>
</tr>
<tr>
<td>Fiducial number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1 (Group 1)</td>
<td>0.44 ± 0.12</td>
</tr>
<tr>
<td>8</td>
<td>2 (Groups 2, 3)</td>
<td>0.48 ± 0.09</td>
</tr>
<tr>
<td>6</td>
<td>3 (Groups 4, 5, 6)</td>
<td>0.92 ± 0.39</td>
</tr>
<tr>
<td>5</td>
<td>1 (Group 7)</td>
<td>0.59 ± 0.14</td>
</tr>
<tr>
<td>4</td>
<td>2 (Groups 8, 9)</td>
<td>1.32 ± 0.28</td>
</tr>
</tbody>
</table>

*$P < .05$.
is usually calculated by the RMS formula between homologous fiducials, which represent its own accuracy. The TRE is the best measurement for evaluating registration accuracy. The TRE refers to the discrepancy between the real-world coordinates of the navigated surgical tool during the real-time navigation surgical procedure and the corresponding real-world coordinates of the surgical target, which is of vital importance for the safe and precise performance of the surgery. Moreover, the TRE is also related to the geometry of the fiducial marker configuration and its relation to the surgical target.

Previous studies have been investigated using different methods for fiducial registration. The method of implanted bone screws serving as fiducials has shown high precision and is regarded as the gold standard of point-to-point registration. The placement and number of fiducials used in the present study were based on the general guidelines for registration by West et al: (1) broadly spread fiducial markers, (2) the placement of the centroid of the configurations as close as possible to the critical surgery region, (3) the avoidance of linear or near-collinear marker configurations, and (4) more markers placed around the target field. The consideration of the site for insertion of bone screw fiducials depended on the remaining bone quantity and density. Within the edentulous maxilla with severe bone atrophy, to acquire stable anchorage or split off during open-flap surgeries. Therefore, it is recommended that surgeons check the rigid anchorage of bone screws after placement or insert two more bone screws in regions with sufficient bone to ensure high accuracy for registration if necessary.

Implanted bone screws serving as fiducials have shown great outcomes and are regarded as the gold standard of point-to-point registration. The principle of using bone screws as fiducial markers is that the procedure effectively avoids the flexibility of soft tissue and skin shift and can decrease the FRE during registration. In the present study, customized fiducial screw markers were used in the phantom, and its central point was a cross intersection. It was easy for the researcher to accurately use the probe tip to detect the location of fiducial markers and decrease the FLE. Therefore, what the present study focused on most was the number and the manner of fiducial markers placed, which is most related to the TRE. Meanwhile, the clinical relevance of the configuration was significant because the number and alignment of fiducials were easy for the surgeon to plan and control.

In a previous study, six anatomical landmarks on the zygoma and anterior maxilla in a skull model achieved an overall accuracy of 0.93 mm. In the present study, the mean TRE value of the configuration with the same number of fiducial markers (group 4) was 0.49 ± 0.07 mm. The difference between the two studies might be explained by the different fiducial marker morphologies, different navigation systems, and different variations in arrangement of the fiducials. Another study investigated TRE in the zygomatic process by placing six bone screw fiducials around the maxillofacial area for cranio-maxillofacial surgery, which resulted in a value of 1.38 ± 0.36 mm. In this study, DICOM data were obtained from spiral CT scanning, and the navigation system was also different. Currently, there is no standard value for the minimum accuracy error. For anterior skull surgery and paranasal sinuses, accuracies of up to 2 mm were defined as “acceptable.” This error was obviously higher than all nine configurations in the present study and does not satisfy the requirements for zygomatic implant surgery.

However, the error may be underestimated in ex vivo research using phantom heads or skulls. One reason is that the registration process might be more complicated in a clinical setting due to saliva or blood or even losing fiducials during the operation, which might have a negative impact on the accuracy. In clinical procedures, the anchorage of bone screws is always limited by the remaining bone quantity and quality (stability). Some of the fiducial markers may displace or split off during open-flap surgeries. Therefore, it is recommended that surgeons check the rigid anchorage of bone screws after placement or insert two more bone screws in regions with sufficient bone to ensure high accuracy for registration if necessary.

**CONCLUSIONS**

A scattered distribution with a polygon span of five regions (both sides of the anterior nasal spine, bilateral maxillary tuberosity, midline palatine suture) with...
at least five fiducial markers in the edentulous maxilla for registration seems to achieve an acceptable TRE value for navigation surgery in zygomatic implant placement.

**ACKNOWLEDGMENTS**

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