Quantification of Image Artifacts from Navigation Markers in Dynamic Guided Implant Surgery and the Effect on Registration Performance in Different Clinical Scenarios

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Purpose: Different navigation markers in dynamic guided implant surgery could cause different degrees of artifacts, which would affect the accuracy and efficiency of the implant navigation system. This study aimed to quantify artifacts caused by navigation markers made of different materials and to evaluate their effects on registration accuracy under various oral conditions. Materials and Methods: Four U-shaped tubes with different navigation markers (440c stainless steel, silicon nitride, zirconium oxide, and aluminum oxide) were produced by three-dimensional printing. Four kinds of maxillary plaster models were prepared to simulate four tooth crown conditions. U-shaped tubes combined with different tooth models were scanned using cone beam computed tomography. The size of artifacts from different navigation markers and registration rate were measured. Abrasion performance of navigation markers was evaluated by scanning electron microscopy images. Results: Aluminum oxide navigation markers showed the fewest artifacts. Silicon nitride markers caused fewer artifacts than zirconium oxide and 440c stainless steel ones (P < .05) and had the best registration performance under all tooth crown conditions with the lowest volume of abrasion. Registration data suggested aluminum oxide worked badly under artificial crown and natural tooth conditions for its lower radiopacity, and zirconium oxide worked undesirably in edentulous conditions. 440c stainless steel was worst in all dental conditions. Conclusion: Navigation markers made of silicon nitride have the best overall performance and perform the best in registration under all circumstances owing to less artifact generation, better radiopacity, and desirable abrasion resistance. Silicon nitride can be regarded as an ideal material, including but not limited to oral implant navigator-guided surgery. INT J ORAL MAXILLOFAC IMPLANTS 2019;34:726–736. doi: 10.11607/jomi.7179

Keywords: artifacts, cone beam computed tomography, dental implants, dynamic guided, navigation marker, registration

In the past decade, prosthodontic-driven implant dentistry has gradually been accepted by both dental clinicians and patients. It focuses on predictable aesthetic design and precise implant positioning, which can lead to long-term success of implant surgeries.¹ ² Surgical guides have been widely used in implant dentistry, but it is difficult for water to adequately cool down the drill due to guide obstruction, which increases the risk of thermal damage to the surgical bone area. Moreover, changing the drilling position and angulation according to the real-time situation is also difficult and time-consuming when the surgical guide has been fixated by fixation pins.³ ⁴ ⁵ Surgical guide fracture has also been reported during implant placement.⁶ ⁷

With the progress of three-dimensional diagnostic and motion capture technology, such as cone beam computed tomography (CBCT) and third-party preoperative implant planning software, computer-aided navigation dynamic guided implant surgery gradually became another choice, in addition to static-guided

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implant surgery with traditional surgical guides. No significant difference in accuracy has been found between static and dynamic guided implant surgery. In addition, without the aforementioned limits of the traditional surgical guides, computer-aided navigation provides real-time navigation to monitor the depth and angle of the drill, which provides a more adjustable and flexible situation for surgeons. Computer-aided navigation also assesses the relationship between instruments and important anatomical structures, such as the inferior alveolar nerve and the maxillary sinus, during the operation. The advantages of dynamic guided implant surgery are clear: it decreases the failure rates of implanting and leads to more precise outcomes compared with the freehand method. Moreover, dynamic guided implant surgery helps the surgeon apply the digital plan from the computer to the patient in an integrated process. Problems of current dynamic guided systems include higher early investment of equipment and lack of enough strong clinical evidence. In addition, a limitation of the current visualization technique is the need for the operator to manage both the patient and visual information displayed on the traditional computer screen, which may lead to dissatisfaction with restoration and more additional training.

In most computer-aided navigation systems, data acquisition and registration are important steps and are subject to several sources of error. Previous studies indicated that the presence of artifacts from metallic restorations in radiographic data might cover anatomical structures or reference markers and result in registration failure. Practically speaking, navigation markers used in dynamic guided implant surgery can also cause different degrees of artifacts themselves, which in turn compromise the accuracy of data registration and subsequent implant surgery. Despite the increasing amount of research designed to improve clinical accuracy, there is a lack of studies centered on the clinical effects of artifacts caused by the navigation marker materials themselves. However, it is essential to study these effects because the marker is the key media used to identify and register any targeted surgical areas.

This study aimed to quantify artifacts caused by different types of navigation markers that are made from different materials (440c stainless steel, silicon nitride, zirconium oxide, and aluminum oxide), and to evaluate their effects on registration accuracy under different oral conditions. To simulate different oral conditions, the maxillary plaster models were pretreated with different crowns on each second premolar. The abrasion of navigation balls during the preoperative procedure may also result in registration error. The abrasion performance of different navigation markers was checked by scanning electron microscopy (SEM).

**Materials and Methods**

**Navigation System**

The Digital-care Implant Surgery Navigation System (Yizhimei, Dcarer) is an optical-based navigation system, consisting of a detector, monitor, host computer, and navigators (Fig 1). It uses a U-shaped tube as a registration template. Each U-shaped tube has nine pits (inner diameter: 2.0 mm) in its interior surface for placing navigation markers. The navigation system also contains preoperative implant planning software for surgical planning and navigation. Data can be collected in real-time and exported for analysis.

In the data registration step, the Digital-care Implant Surgery Navigation System has set a standard of successful registration that at least six markers must be identified, which maintains the accuracy of the navigation system. In other words, not necessarily all markers are identified, but at least six of them are identified to ensure a successful registration.

**Specimen Preparation**

To study the size of artifacts under different tooth conditions, four maxillary plaster models were obtained from one of the investigators (Y.D.) with normal occlusion. The natural maxillary right second premolar of each model was led through the following pretreatments: (1) a porcelain fused to metal crown (PFM) condition made from cobalt-chromium (Co59%, Cr28%); (2) zirconia all-ceramic crown; (3) an edentulous condition where the plaster tooth was removed with no substitutes; and (4) the natural tooth condition, where a natural second premolar was implanted to replace the plaster tooth.

Four U-shaped tubes made of different materials were produced by three-dimensional printing. For each tube, there are nine identical navigation markers.
from one of the following materials: group 1, 440c stainless steel; group 2, silicon nitride; group 3, zirconium oxide; and group 4, aluminum oxide (Table 1).

### Obtaining CBCT and Registration Data

In order to place the U-shaped tube on the plaster model, silicone rubber (Express STD, 3M) was squeezed into the peripheral region of the groove, and the center was filled. Then, the U-shaped tube was pressed onto the region that contained the right second premolar and gently nudged into place to seat evenly from palate to tongue in the target region, eliminating any abnormal protrusion in contact with the tooth.

The entire maxillary tooth model, including the U-shaped tube, was scanned, using CBCT (PaX-Uni3D, VATECH). All CBCT scans were repeated three times by one professional technician to reduce manual operation error. Exposure protocol was set at 85 kVp/5.5 mA, a common setting for maxillary scanning. The field of view (FOV), exposure time, and voxel size were fixed at 80 × 80 mm, 15,000 ms, and 0.3 × 0.3 × 0.3 mm, respectively. In total, 48 data sets were collected and exported in Digital Imaging and Communications in Medicine (DICOM) format.

Following the scans, the aforementioned built-in oral implant surgery navigation system was used for registration, adopting 3,500 as the registration threshold value. DICOM files were downloaded and registered, with results appearing as the images that were being researched.

All the former procedures in this section followed the clinical protocol, except there was no bite registration because only maxillary models were used.

### Quantification Evaluation of Artifacts

Data sets stored in DICOM format were imported in open source image software: ImageJ ver. 1.51j8 (NIH; http://rsb.info.nih.gov/ij/) as sequences with default settings. Each axial slice was selected, including the middle-most cross section of each navigation marker or crown, because it is the most representative slice. A fixed region of interest (ROI) surrounding the outline of each U-shaped tube was selected and saved using built-in tools “Polygon selections” and “ROI manager.”

According to the supplier’s guide, when quantifying the navigation marker–induced or prosthetic crown–induced local image degradation, only hyperdense areas should be taken into consideration. Artifact areas were quantitatively measured by adjusting attenuation threshold values, modified from the previously reported methods.20-23 Within the ROI, a background area without the distortion of artifacts was selected, and the mean attenuation value of this area was obtained with standard deviation (SD). Attenuation threshold values of artifact areas were calculated by adding three times the SD of the background to the mean attenuation value of the background (Fig 2). Then, the “Threshold” and “Measure” tools of ImageJ were utilized to establish and measure hyperdense areas in square millimeters.

In brief, artifact areas were calculated from areas already measured earlier, subtracting the middle cross-sectional area of navigation markers or prosthetic crowns. For each navigation marker, the middle cross-sectional area was calculated using the formula $\pi r^2$, where $r$ represented the radius of the ball. For each prosthetic crown, the mean middle cross-sectional area of the natural teeth in the same group was used for reference.

Two experienced observers (L.L., L.L.) finished the above steps twice independently. In each set of DICOM data, 10 study materials (9 navigation markers and a crown) were measured. For the research objective, 960 evaluations were done in total, corresponding to four different models using four different navigation markers, and each combination of models and navigation markers had three DICOM data sets obtained on different dates.

### Qualitative Evaluation of Abrasion Performance

Another set of four different navigation markers (440c stainless steel, silicon nitride, zirconium oxide, and aluminum oxide) were sent to be observed by scanning electron microscope (Inspect F50, FEI), which obtained images of the surface morphology. Then, the surfaces of the four balls were cleaned and ground, and scanned once again, to investigate the microstructures after grinding. Raw emery paper was selected as the abrasive material.

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### Table 1 Group Setting of Four Different Marker Materials

<table>
<thead>
<tr>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Silicon nitride</td>
<td>Zirconium oxide</td>
<td>Aluminum oxide</td>
</tr>
<tr>
<td>Composition</td>
<td>Si₃N₄</td>
<td>ZrO₂</td>
<td>Al₂O₃ (99.50%); MgO (0.20%); SiO₂ (0.10%)</td>
</tr>
</tbody>
</table>

Four different kinds of navigation markers made of these materials were assembled on four U-shaped tubes. For each tube, there are nine identical navigation markers. Note that some impurity constituents are not listed.
Statistical Analysis

The artifact size of navigation markers and registration rate were quantitatively evaluated. Data analyses were performed using SPSS 21 for Windows (SPSS). Quantitative data were described with means and SDs, analyzed by two-tailed t test. P < .05 was considered statistically significant. Exposure parameters in CBCT scanning (kVp and mA), pretreatments for the maxillary right second premolar of each model, and other materials, such as temperature, served as irrelevant variables.

The difference between artifacts from different navigation markers or artificial crowns was analyzed using

Fig 2 Artifact quantification in CBCT scans. (a) Artifact of a navigation marker in clinical setting. (b) Background attenuation value: mean and SD. (c) Area of hyperdense artifact enclosing all voxels with attenuation value > 3,431.81 (mean + 3*SD).

Fig 3 SEM images of different navigation markers (a to h) before and (i to p) after grinding. (a to d, i to l) ×2,000 magnification. (e to h, m to p) ×40,000 magnification. (a, e, i, m) ZrO₂. (b, f, j, n) Al₂O₃. (c, g, k, o) 440c stainless steel. (d, h, l, p) Si₃N₄.
two-way analysis of variance (ANOVA), followed by the Tukey method post hoc analysis test, to find statistically significant factors or interactions between them that interfered with the response variables.

Meanwhile, the registration performance of different kinds of navigation markers was exported with statistics analyzed by the Kruskal-Wallis H test. In this part, both quality (“registration results”) and quantity (“numbers of different markers identified in different pretreatments”) of the registration were assessed.

The Kruskal-Wallis H test is an alternative nonparametric test for a one-way ANOVA if the assumptions of the latter are violated. It uses “mean rank” as its statistical description parameter. The mean rank is the mean value of serial numbers (ranks) derived from sorting and numbering the data from small to large. Thus, the navigation marker groups with higher mean rank demonstrated they performed better in registration.

**Reporting Guidelines**
SQUIRE 2.0 guidelines have been considered and followed.24

**RESULTS**

SEM images of different navigation markers before and after grinding are shown in Fig 3. For the qualitative evaluation of abrasion performance, SEM images showed that under the same circumstances, the surface of the navigation marker made of aluminum oxide changed the most after grinding. Among the remaining three navigation markers, evaluated by two experienced observers (L.L., L.L.), the navigation marker made of silicon nitride appeared to have the least obvious strip scratches compared with the other two.

Figure 4 shows the artifacts produced by different navigation markers. For the statistical analysis, results from SPSS are summarized in Table 2. The artifacts caused by the navigation markers made of aluminum oxide and silicon nitride were much less noticeable than those caused by zirconium oxide and 440c stainless steel, and this difference was statistically significant (mean ± SD: 0.3 ± 0.8 mm² and 0.8 ± 0.9 mm², vs 38.0 ± 13.1 mm² and 25.6 ± 9.5 mm²). Meanwhile, there were significant differences between the mean artifact areas of all navigation markers (P < .05), except between silicon nitride and aluminum oxide (0.8 mm² vs 0.3 mm²).

Artifacts from the different tooth crowns were also measured, as shown in Fig 5. For the statistical analysis, results from SPSS are summarized in Table 3. Results indicated that there were significant differences between the mean size of every type of tooth crown (P < 0.5). The zirconia all-ceramic crown demonstrated the largest of the artifacts (mean ± SD: 88.0 ± 24.8 mm²),
Table 2  Area of Hyperdense Artifacts for Navigation Markers Studied

<table>
<thead>
<tr>
<th>Pretreatments</th>
<th>PFM crown</th>
<th>Zirconia crown</th>
<th>Edentulous</th>
<th>Natural tooth</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum oxide (mm²)</td>
<td>0.5 ± 1.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.8 ± 0.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>26.5 ± 7.0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>40.0 ± 12.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Silicon nitride (mm²)</td>
<td>1.0 ± 1.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>28.9 ± 11.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>37.4 ± 11.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>440c stainless steel (mm²)</td>
<td>0.7 ± 0.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>27.6 ± 8.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td>38.7 ± 12.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconium oxide (mm²)</td>
<td>0.2 ± 0.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.7 ± 0.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.4 ± 7.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td>35.9 ± 15.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>PFM crown</td>
<td>0.3 ± 0.8</td>
<td>0.8 ± 0.9</td>
<td>25.6 ± 9.5</td>
<td>38.0 ± 13.1</td>
<td></td>
</tr>
<tr>
<td>Zirconia crown</td>
<td>0.3 ± 0.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.0 ± 1.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>28.9 ± 11.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>37.4 ± 11.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Edentulous</td>
<td>0.3 ± 0.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.7 ± 0.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>27.6 ± 8.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td>38.7 ± 12.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Natural tooth</td>
<td>0.2 ± 0.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.7 ± 0.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.4 ± 7.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td>35.9 ± 15.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.3 ± 0.8</td>
<td>0.8 ± 0.9</td>
<td>25.6 ± 9.5</td>
<td>38.0 ± 13.1</td>
<td></td>
</tr>
</tbody>
</table>

Different superscript letters indicate statistically significant differences among navigation marker groups (P < .05); no statistically significant differences were found between the aluminum oxide group and silicon nitride group, so they share the same superscript letter “a”; statistically significant differences were found between the aluminum oxide group and 440c stainless steel group, so their superscript letters are different. Uppercase superscript letters indicate statistically significant differences among different artificial crown pretreatments (P < .05). PFM crown = porcelain fused to metal crown.

Table 3  Area of Hyperdense Artifacts for Tooth Crowns Studied

<table>
<thead>
<tr>
<th>Markers</th>
<th>PFM crown (mm²)</th>
<th>Zirconia crown (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum oxide</td>
<td>59.7 ± 9.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>75.9 ± 13.4&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>49.8 ± 9.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>92.9 ± 29.3&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>440c stainless steel</td>
<td>55.4 ± 8.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>96.1 ± 36.7&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Zirconium oxide</td>
<td>54.1 ± 7.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>87.3 ± 12.8&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total</td>
<td>54.7 ± 9.0</td>
<td>88.0 ± 24.8</td>
</tr>
</tbody>
</table>

Different superscript letters indicate statistically significant differences between different artificial crown pretreatments (P < .05). No statistically significant differences were found among different navigation markers in the same artificial crown group. Natural tooth or edentulous pretreatments did not demonstrate artifacts themselves.
followed by the cobalt-chromium metal-ceramic crown (54.7 ± 9.0 mm$^2$), the natural second premolar, and the edentulous space (0.0 mm$^2$).

Images of registration are shown in Fig 6. Note that registration of navigation markers made of silicon nitride succeeded in all experiments. As for the registration results (Table 4), times of successful registration of different marker groups were evaluated, and there were significant differences among the four kinds of navigation markers ($P < .05$). According to their mean rank derived from the Kruskal-Wallis H test, navigation markers made of silicon nitride had the best registration result (3.33), followed by 440c stainless steel (2.50) and zirconium oxide (2.17), while aluminum oxide performed the worst (2.00).

Numbers of navigation markers in different pre-treatment conditions identified by the implant surgery navigation system are summarized in Table 5. On the whole, for the Kruskal-Wallis H test, the number of silicon nitride markers that were identified in registration came first (mean rank: 38.50), followed by 440c stainless steel (24.33), zirconium oxide (20.00), and...
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aluminum oxide (15.17), and there were significant differences between them ($P < .05$). Furthermore, this was in accordance with the aforementioned registration results.

It is important to evaluate the performance of the different navigation markers under the different tooth crown conditions (Tables 4 and 5). In the natural tooth condition, the number of successful registrations was 10 in 12. However, navigation markers made of aluminum oxide performed the worst, and they were responsible for the only two failed registrations. Additionally, the numbers of aluminum oxide navigation markers recognized were the lowest, and there were significant differences noted ($P < .05$). In the edentulous condition, the number of successful registrations was 7 in 12, with navigation markers made of silicon nitride performing the best. In this case, all registrations succeeded, every marker was recognized in registration compared with others, and there were significant differences ($P < .05$). Silicon nitride also worked well and received the highest mean rank in the PFM crown group (10.00) and zirconia crown group (11.00). However, there were no significant statistical differences in both groups.

### DISCUSSION

Dynamic guided surgery systems were introduced to the field of implant dentistry in 2000. The CBCT scanning works with three-dimensional imaging tools, which has led to a breakthrough in virtual implant treatment planning. Recently, the intraoral scanning devices have been introduced in treatment planning. It can be predicted that real-time navigation and new developments will have a positive impact on guided surgery.

With the rapid development of digital dentistry and the wildly expanding applications of CBCT, nowadays, interferences are not limited to diagnosis. In oral dynamic guided implant surgery, the present study confirmed that artifacts affect the data registration as well, which can in turn disturb follow-up surgery procedures.

High-density matter, such as metals, alloys, and their oxides, is the main cause of artifacts in radiology images. This effect was also confirmed in the present experiment in the field of dental implant radiology images. Artifacts lead to interference in clinical radiologic diagnosis. The sizes of artifacts and registration performance of different navigation markers were compared among different aspects, including variable textures of navigation markers and crowns. In addition, abrasion performance was studied because abrasions may change the shape of markers and affect the recognition of navigation markers.

Purely based on the texture of navigation markers, aluminum oxide generated a minimum artifact size. Silicon nitride was a little bigger followed by 440c stainless steel, while the maximum size was zirconium oxide. However, the registration success rate

<table>
<thead>
<tr>
<th>Pretreatments</th>
<th>Aluminum oxide</th>
<th>Silicon nitride</th>
<th>440c stainless steel</th>
<th>Zirconium oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFM crown</td>
<td>0/3</td>
<td>3/3</td>
<td>1/3</td>
<td>0/3</td>
</tr>
<tr>
<td>Zirconia crown</td>
<td>0/3</td>
<td>3/3</td>
<td>2/3</td>
<td>2/3</td>
</tr>
<tr>
<td>Edentulous</td>
<td>3/3</td>
<td>3/3</td>
<td>1/3</td>
<td>0/3</td>
</tr>
<tr>
<td>Natural tooth</td>
<td>1/3</td>
<td>3/3</td>
<td>3/3</td>
<td>3/3</td>
</tr>
<tr>
<td>Total</td>
<td>4/12</td>
<td>12/12</td>
<td>7/12</td>
<td>5/12</td>
</tr>
</tbody>
</table>

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of aluminum oxide was quite unsatisfactory because it is less radiopaque (Fig 7). Compared with silicon nitride, aluminum is lighter in the CBCT image. It is indistinguishable from the surrounding structures. At the same time, the registration success results indicated that navigation markers made of silicon nitride registered the most successfully in all registration tasks, thus demonstrating a superior registration rate compared with the other three kinds (Table 3).

In clinical practice, the present study found that the presence of crowns also impacted the registration rate. In this study, zirconia all-ceramic crowns and cobalt-chromium metal-ceramic crowns obtained quite large sizes of artifacts, thus complicating clinical radiologic diagnosis and navigator-guided surgeries. Natural tooth and edentulous conditions provided less interference. The influence of different markers on the registration success for different crowns is seldom discussed. Thus, the present study first investigated the registration rates of different markers in all-ceramic, PFM, natural teeth, and the edentulous condition. For natural teeth, silicon nitride had the highest registration rate (100%, 12 successes/12 total).

The present experiment used CBCT scanning of the plaster models with U-tubes, which is the same process as in the clinic. However, there is a new idea that if the registration software is changed slightly, registration can also be done by surface scanning. Although this cannot be done right now, because the DICOM registration process in the computer is based on the identification of the markers on the U-tube, this idea is technically feasible. Therefore, the markers’ position can be obtained through CBCT or through surface scanning. Although the scan provides only the two-dimensional (2D) position for each marker, theoretically, based on at least four markers, the three-dimensional (3D) position of the U-tube can be obtained.

Dental stone was used in this study to fabricate models that simulate human jaws during preparation. If healthy human volunteers are used in the experiments, there is too much CT radiation. For human safety reasons, the present study could not be conducted on real patients, nor was it necessary to do so. Also, all the samples need a similar radiation barrier baseline. Thus, the plaster model was used in the present experiment, and the process of registration is the same as in the clinic. Thus, it does not matter whether a plaster model or real people are used to get a CBCT scan. Dental stone was a reasonable alternative material and has been used by previous similar research, as dense bone and dental stone have similar calcium content. However, it is known that the presence of anatomical structures outside the jaw and soft tissues may also influence the gray value measurements of the jaws in CBCT, and this may be a limitation of the present study.

In terms of clinical application, it has been reported that oral implant surgery navigation systems can attain surgical accuracy of 0.5 mm, which guarantees both the stress direction and the protection of surrounding tissue. Now, silicon nitride, which has been used as navigation markers during dynamic guided implant surgery, can increase the efficiency, accuracy, and security of surgery according to the results of the present study.

It is necessary to investigate how to reduce artifacts generated from navigation markers. Artifacts were usually seen in the images of radiopaque materials predominantly, and they could be observed when intraoral objects were positioned near the facial surface. The causes of artifacts can be divided into scattering, beam hardening, photon starvation, and quantum noise (poison noise). In view of the influence of artifacts in surgery, scholars have studied how to reduce artifacts for a long time. It has been reported that low-dose CBCT imaging can be helpful to reduce metal and beam hardening artifacts in CBCT, though it can result in poor soft tissue resolution, and image intensifier may improve the quality of images. The present study discussed one of the possible methods: to make markers using materials with acceptable artifacts. Materials cause different artifacts under different
dental conditions. For the first time, the present study analyzed the most suitable marker materials in dynamic guided implant surgery. The results of the present study suggested that silicon nitride markers are the most suitable for all four dental conditions. The data also suggested that aluminum oxide did not work well under natural tooth conditions, and zirconium oxide did not work well in edentulous conditions. As a traditional marker material, 440c stainless steel is the least favorable in all four dental conditions. To focus on the comparison of materials and dental conditions, the present study used the most common clinical setting parameters for CBCT.

Some groups have studied the effects of exposure parameters and algorithms. Adjusting exposure parameters, such as increasing the FOV size, kVp, or the mAs, may contribute to artifact reduction, but several studies have revealed that this solution is limited and not clinically feasible because of subsequent potential risks of high radiation dosages, which is less desirable than changing the materials of the markers.

A new method to reduce the artifacts of metal is to use complementary magnetic resonance images, which can correct reconstructed CT images, and the missing projections will be restored by data from a corresponding magnetic resonance image; however, its weakness is that this method is limited by bone tissue, which has high density, thus appearing on CT images brightly, and there are quite a few bones in the oral-maxillofacial region.

Meanwhile, augmented reality can be regarded as a kind of tool to avoid the effect of artifacts in implant surgery. It also has the problem that the surgeon may be distracted due to focusing on both the operative site and the computer display.

In addition, there is a novel method to remove artifacts originated by dental restorations in 3D CT images by recovering the damaged areas of images using dental cast model images obtained by CT. The damaged region in CT images regarded as an obstacle for implant surgery was removed and replaced with the trimmed images of the dental cast. Nevertheless, problems arise because it is difficult to measure dental casts from plural directions and keep data linkup to compensate the undercut, as well as to acquire the 3D images with satisfactory precision.

Clinical implementation of metal artifact reduction algorithms, however, shows more promise for artifact reduction. Different methods, such as iterative metal artifact reduction, projection interpolation, image filtering, and their combinations, have been under investigation in this area. The iterative metal artifact reduction technique is a fully automatic algorithm without specific hardware type requirements. It is easily applicable to implant surgery and other fields of dental surgery. However, the cone beam geometry may become an additional challenge of implementation compared with normal reconstruction. Based on all the methods and their features, more studies are needed in this field to generate comprehensive solutions.

CONCLUSIONS

Although navigation markers made of aluminum oxide showed the fewest artifacts, navigation markers made of silicon nitride have the best overall performance and perform the best in registration under all circumstances, owing to moderate artifact generation, better radiopacity, and desirable abrasion resistance. Silicon nitride should be regarded as the ideal material for registration, including, but not limited to, oral implant navigator-guided surgery.

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