Evaluation of the 3D Augmented Reality–Guided Intraoperative Positioning of Dental Implants in Edentulous Mandibular Models

Weipeng Jiang, PhD¹/Longfei Ma, PhD¹/Boyu Zhang, BS²/Yingwei Fan, PhD³/Xiaofeng Qu, MS⁴/Xinran Zhang, MS⁵/Hongen Liao, PhD⁶

**Purpose:** This research aimed to propose a three-dimensional (3D) augmented reality navigation method with point cloud–based image-patient registration that could merge virtual images in the real environment for dental implants using a 3D image overlay and to evaluate its feasibility. **Materials and Methods:** A total of 12 rapid prototyping mandibular models were fabricated using a 3D printing method and were divided into two groups: 3D augmented reality–guided group and traditional two-dimensional (2D) image-guided group. A point cloud–based preoperative image-to-patient registration method was introduced to replace the traditional point-to-point registration. After the registration, dental implant surgery was performed in the two model groups using an augmented reality–guided navigation method and a traditional two-dimensional image-guided navigation method. The planned and actual postoperative implant positions were compared for measuring positional implantation errors. The surgery time was also recorded and compared between the two groups. **Results:** In the model experiment, the root-mean-square deviation of registration was 0.54 mm, and the implant surgery results showed < 1.5-mm mean linear deviation and < 5.5-degree angular deviation. The augmented reality–guided implantation showed smaller horizontal, vertical, and angular errors in the apical areas of the central incisor and the canine region. The surgery time using the augmented reality–guided navigation method was significantly shorter than that using the two-dimensional (2D) image-guided navigation method (P < .05). Moreover, the volunteer experiment demonstrated that the preoperative 3D models in situ accurately overlaid onto the surgical site. **Conclusion:** The proposed point cloud–based registration method can achieve excellent registration accuracy. Dental implant placement guided by the proposed 3D augmented reality navigation method showed better accuracy and applicability, as well as higher efficiency, than the traditional 2D image navigation method. Int J Oral Maxillofac Implants 2018;33:1219–1228. doi: 10.11607/jomi.6638

**Keywords:** 3D augmented reality, dental implant, operative time consumption, point cloud registration, surgery accuracy, surgical navigation

For clinical success in oral and maxillofacial implant surgery, precise planning is essential. Improvements in surgical reconstructive methods, along with increased prosthetic demands, require high surgical accuracy regarding depth, angulation, and crestal position. The traditional freehand implant placement depends on clinical experience; furthermore, it results in more significant errors than the recent navigation-based methods.¹ Poor accuracy of implant positioning increases the risk of implant failure because of mechanical overload in the surrounding bone tissue²,³ and compromises the esthetics and function of the prosthetic rehabilitation.⁴ In various medical fields, the use of image navigation technology has facilitated performance of surgery with maximum accuracy and minimum invasiveness. Computer-aided surgery techniques have been

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proposed for the preoperative planning and intraoperative guidance of the correct implant position. Several researchers have reported on the efficaciousness of these systems with regard to achieving satisfactory implant positioning and preventing iatrogenic injury of anatomical structures, such as the mandibular nerve and maxillary sinus. The other main advantage of computer-aided surgery is the higher possibility of inserting implants more accurately in limited bony volumes. These recent techniques have facilitated using less-invasive approaches, such as flapless surgery, and simplified prosthetic procedures associated with immediate loading protocols.

Innovative imaging technology in the form of augmented reality techniques that can merge virtual images in the real environment has been recently introduced to help oral surgeons visualize surgical sites that cannot be directly observed. On the basis of two-dimensional (2D) imaging, Yamaguchi et al presented an augmented reality system for dental surgery, which required the surgeon to wear an additional head-mounted display to see the augmented view, leading to surgeons’ discomfort because of the bulky display. The tedious registration procedure, the lack of depth perception, and incomplete clinical workflow may limit its clinical application. As previously described, an autostereoscopic three-dimensional (3D) augmented reality surgical navigation system was developed using a real 3D image overlay based on integral videography technology, which differs from binocular stereoscopic display methods and can provide a full parallax naked-eye 3D view with depth perception for multiple observers. The present authors’ previous research showed that the 3D image-guided overlay system provided a more effective and accurate approach for oral maxillofacial surgery. The algorithms and conditions required for 3D virtual representation of the surgical area have been previously introduced.

In this study, a new augmented reality–guided clinical workflow was developed for dental implant surgery, from preoperative planning to the correct positioning of dental implants, and a new point cloud–based preoperative image-to-patient registration method was proposed. A model experiment and a volunteer experiment were performed to evaluate the feasibility of the point cloud–based registration and augmented reality–guided dental implant method.

MATERIALS AND METHODS

Configuration of Proposed Overlay System

Figure 1 shows the configuration of the overlay system. The 3D image display device comprises a 9.7-inch, 1,536 × 2,048-pixel, 264-ppi liquid crystal display and a micro convex lens array. The workstation is equipped with a 2.4-GHz Pentium Core 2 Duo processor and an NVIDIA Quadro Plex model 4 (Quadro FX 5600 × 2) graphics processing unit. The 3D image display device and the drill are tracked using an optical tracking device (Polaris, Northern Digital).

Finally, as previously described, 3D images are generated from acquired preoperative cone beam computed tomography data and displayed on liquid crystal display. No special glasses are required to view the 3D image, and motion parallax can be reproduced in all directions. 3D images are rendered at a rate of 15 frames per second by the system.

To prevent large deviations of operations and to guide the surgeon intuitively, an alarm system is designed. The deviation of displacement (D) is defined as the distance between the tip of drill and the planning path, and the deviation of angle (A) is defined as the vector angle of the planned path and the drill. Depending on the deviation of D and A, 3D images are displayed in green (D < 1 mm, A < 2 degrees), yellow (1 mm ≤ D < 2 mm, 2 degrees ≤ A < 4 degrees), and red (D ≥ 2 mm, A ≥ 4 degrees) (Fig 2). The surgeon can perform the implant surgery when the 3D image is green; otherwise, the surgeon needed to adjust the angle and direction of the dental implant machine in real time. A warning beep also helps alert the surgeon.

Markerless Registration Procedure Using Point Cloud

To accurately superimpose the 3D image of the preoperative images on the patient, a preoperative image-to-patient registration method is needed. Traditional surgical navigation systems in oral maxillofacial surgery are most frequently based on the point-to-point registration method or the tooth contour registration method. However, as the patient does not have any clear anatomical fiducial points, these methods are difficult to apply in clinical situations without placing markers on the patient’s body. In this study, markerless registrations are performed using point cloud data (Fig 3). A 3D scan device is used for acquiring point cloud data of the patient’s teeth. Preoperatively, an optical rigid marker is fixed on the 3D scan device, and the transformation matrix from the 3D scan device coordinate system to the optical tracking coordinate system is obtained by calibration. The software developed by the Visualization Toolkit is used to calculate the preoperative point cloud data of the patient’s teeth from the preoperative images, and the 3D scan device is used to obtain the intraoperative point cloud data of the patient’s teeth. The registration between the two-point cloud sets is performed using the iterative
closest point algorithm. The required initial alignment is obtained using four control points before the iterative closest point registration. After the point cloud registration, the transformation matrix $T_{\text{Img}}^{\text{Scan}}$ from the preoperative image coordinate system $\text{Img}$ to $\text{Scan}$ is obtained. Then, the registration matrix $T_{\text{Tra}}^{\text{Img}}$ from $\text{Img}$ to the patient in $\text{Tra}$ is determined using equation (1).

After registration, by tracking the 3D display device, the 3D image of the preoperative reconstructed model can be displayed on the surgical site in situ using equation (2).

$$T_{\text{Tra}}^{\text{Img}} = T_{\text{Tra}}^{\text{Scan}} \times T_{\text{Scan}}^{\text{Img}}$$

$$T_{\text{Dis}}^{\text{Img}} = T_{\text{Dis}}^{\text{Tra}} \times T_{\text{Tra}}^{\text{Img}}$$

This method may simplify the registration procedure, enhance the accuracy of registration, and facilitate dental implant surgery.

**Mandibular Models and Experimental Grouping**

In this research, rapid prototyping mandibular models were applied. The models were prepared using 3D printing (Western Time, 3D Systems) based on computed tomography data from patients’ edentulous mandibles. After obtaining informed consent, computed tomography images were acquired at Peking University School and Hospital of Stomatology under institutionally approved protocols. The images with no large defect or malformation suggesting a pathologic lesion were selected. In total, six sets of computed tomography data were used, and two rapid prototyping models were fabricated from each computed tomography data set. One model was introduced into the 3D augmented reality-guided group and the other into the 2D image-guided group. The two groups of mandibular models were then used for evaluating the implant accuracy and surgery time consumption.

The Digital Imaging and Communications in Medicine data set from cone beam computed tomography was uploaded to the image-overlay navigation system and entered into its planning system. The planning software (SimPlant, Materialise Dental) was used to define the arch, nerve mapping, and implant dimensional manipulation. To ideally orient the virtual implants, multiple views were used. Virtual 2.0 × 12.0-mm parallel wall dental implants were planned in
the mandibular models. On the basis of specific tooth sites, the positions and angles were determined.

### Real-time Surgical Navigation of Mandibular Models Using 3D Augmented Reality–Guided and 2D Image-Guided System

After point cloud–based registration, the 3D printed mandibular models were covered with dental plate wax (Fig 4a) to prevent the orientation of the implant drill entry point based on anatomical landmarks. During the surgery, a 3D image of the implant drill was overlaid on itself in real time, and the 3D image of the preoperative planned path was also displayed on the mandibular model in situ. The navigation was performed as follows: (1) the drill tip was aligned on the entry point of the implant socket through the observing window (Fig 4b); (2) the drill was moved forward along the 3D image of the path until it reached the apex of the path, and implant cavity preparation was then completed; and (3) the parallax pin was inserted in the implant cavity.

In the other group, 2D image guidance was also provided on the panel screen of the overlay system for surgeons during the dental implant surgery (Fig 4c). The display interface of the screen is similar to that of commercial navigation systems, such as the IGI (Image Navigation) and VISIT (University of Vienna, General Hospital) systems.

### Surgery Time Comparison and Postoperative Assessment

The surgery time was recorded from the start of matching the position of the drill with the preoperatively determined position to the end of implant hole preparation. After implant placement, the wax was removed, and the models underwent cone beam computed tomography scanning. The pre– and post–cone beam computed tomography scans were separately imported into the Mimics software and registered by aligning the six ring-shaped markers in each scan via a rigid transformation. The angular and positional deviations were calculated between the planned and actual positions.

The following deviations regarding planning with actual implants were calculated:

- **Lateral deviation (mm):** Deviations in the mesial/distal (y-axis) and buccal/lingual (x-axis) placement of the implant
- **Depth deviation (mm):** The difference in depth along the implant long axis between the planned and actual implants
- **Angular deviation (degree):** Largest angular errors in 3D space between center axes of pre- and post-implants

### Participant Bias Reduction

Participant biases were minimized using the following procedures: (1) the doctor was not involved in the accuracy evaluation process until the study was completed; (2) the operator who performed cone beam computed tomography scan alignment and determined the location of the implant in the postoperative cone beam computed tomography scan was blinded to the preoperative plan data; and (3) the final step of accuracy assessment was automatically executed by the computer.

### Statistical Analysis

Deviations in vertical error, horizontal error of the top and apex positions, and angular error were measured and collected for each osteotomy across surgical planning modality and reported by mean and standard deviations. A paired t test was used to compare the results of the 3D augmented reality–guided and 2D image-guided groups. Two examiners performed all calibrations, measurements, and analyses of the postoperative data (data combined together) after calibration.

### RESULTS

#### Evaluation of Point Cloud–Based Markerless Registration

The accuracy of point cloud–based registration was evaluated in the mandibular model experiment. For
acquiring the point cloud data, an Ensenso N10 (Ensenso) was used as the 3D scan device. After registration, using the optical tracking system, the center coordinates of the six circles on the mandibular model were measured using a tracked probe and were transformed to the preoperative image coordinate system through the registration matrix $T_{\text{Img}}$. The root-mean-square deviation was calculated by comparing the measured coordinates and the related preoperative coordinates $P$ using the following equation:

$$\text{Deviation} = \frac{1}{n} \sum_{i=1}^{n} (T_{\text{Img}} \cdot T_{\text{ip}} - P)$$

Figure 5a shows the point cloud–based registration procedure of the mandibular model. After the registration procedure was completed, by tracking the 3D image display device, the 3D image of the preoperative teeth, mandibular nerves, and jawbone could be displayed on the surgical site in situ. The root-mean-square deviation of registration was 0.54 mm via the model experiment. The consuming time of registration and the acquiring time of the point cloud were recorded as approximately 10 seconds and < 1 second, respectively. Moreover, a volunteer experiment was implemented to evaluate the accuracy of the point cloud registration (Fig 5b). The model and volunteer experiments demonstrated that the point cloud–based registration method was feasible.

### Accuracy of Comparison and Surgery Time Consumption

Six mandibular models were in the 3D augmented reality–guided group and the other in the 2D image-guided group, respectively. The implant positions included the central incisor, canine, first premolar, and second molar regions on both sides; thus, a total of 96 parallel pins were used. After 2-mm-diameter holes were drilled, eight parallel pins with 2-mm diameter and 12-mm length were inserted into these implant holes (Fig 6). All the implantation procedures were performed by two surgeons. The results of implant surgery accuracy and surgery time consumption are shown in Table 1. The horizontal distance errors in the top areas of the four tooth regions did not significantly differ between the two groups. The horizontal distance errors between the apical surface middle points were 1.30, 1.23, 0.95, and 0.88 mm in the central incisor, canine, second premolar, and second molar regions, respectively, for the overlay system; the errors for the 2D image-guided group were 2.08, 1.86, 1.17, and 1.26 mm, respectively. The errors associated with the 3D augmented reality–guided group were significantly smaller in the central incisor and canine regions.

The mean depth errors for the postoperative apical surface middle points were 1.17, 1.19, 0.95, and 1.01 mm, respectively, in the four tooth regions for the 3D augmented reality–guided group and 1.73, 1.36, 1.31, and 1.27 mm, respectively, for the 2D image-guided group. The errors were significantly greater in the central incisor region in the 2D image-guided group ($P = .029$).

The mean angular errors from the centerline were 5.04, 4.57, 3.95, and 3.37 degrees, respectively, in the four tooth regions for the overlay system and 7.02, 5.67, 4.92, and 4.37 degrees, respectively, for the 2D image-guided group. The 2D image-guided navigation resulted in significantly greater errors in the central incisor region ($P = .014$).

The times taken for cavity preparation and implant insertion in the four tooth regions were 27.79, 25.35, 23.56, and 22.2 seconds, respectively, for the 3D augmented reality–guided group and 38.27, 35.89, 33.27, and 32.7 seconds, respectively, for the 2D image-guided group.
35.68, and 33.15 seconds, respectively, for the 2D image-guided group. Thus, the time consumed for the 2D image-guided computer-aided surgery was significantly longer in the four tooth regions. Finally, the errors in the horizontal distances, angles, and depths to the postoperative apical surface middle points in the canine and central incisor regions significantly differed between the methods. The time taken by the 3D augmented reality–guided group was significantly less than that taken by the 2D image-guided group.

### Table 1 Comparison of Errors for Implantation Regions According to Implantation Method (mean ± SD)

<table>
<thead>
<tr>
<th>Surgical sitea</th>
<th>Overlay navigation group</th>
<th>CAS navigation group</th>
<th>P value</th>
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</thead>
<tbody>
<tr>
<td><strong>Horizontal distance errors in top surface area (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central incisor</td>
<td>1.21 ± 0.45</td>
<td>1.39 ± 0.56</td>
<td>.985</td>
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<tr>
<td>Canine</td>
<td>1.14 ± 0.23</td>
<td>1.52 ± 0.78</td>
<td>.229</td>
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<tr>
<td>Second premolar</td>
<td>0.99 ± 0.38</td>
<td>1.27 ± 0.67</td>
<td>.673</td>
</tr>
<tr>
<td>Second molar</td>
<td>0.74 ± 0.35</td>
<td>0.92 ± 0.43</td>
<td>.455</td>
</tr>
<tr>
<td><strong>Horizontal distance errors in apical surface area (mm)</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Central incisor</td>
<td>1.30 ± 0.68</td>
<td>2.08 ± 0.79</td>
<td>.018*</td>
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<tr>
<td>Canine</td>
<td>1.23 ± 0.54</td>
<td>1.86 ± 0.86</td>
<td>.032*</td>
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<tr>
<td>Second premolar</td>
<td>0.95 ± 0.37</td>
<td>1.17 ± 0.57</td>
<td>.704</td>
</tr>
<tr>
<td>Second molar</td>
<td>0.88 ± 0.29</td>
<td>1.26 ± 0.38</td>
<td>.331</td>
</tr>
<tr>
<td><strong>Vertical distance errors in apical surface area (mm)</strong></td>
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<td></td>
</tr>
<tr>
<td>Central incisor</td>
<td>1.17 ± 0.59</td>
<td>1.73 ± 0.82</td>
<td>.029*</td>
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<tr>
<td>Canine</td>
<td>1.19 ± 0.47</td>
<td>1.36 ± 0.85</td>
<td>.286</td>
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<tr>
<td>Second premolar</td>
<td>0.95 ± 0.35</td>
<td>1.31 ± 0.73</td>
<td>.267</td>
</tr>
<tr>
<td>Second molar</td>
<td>1.01 ± 0.39</td>
<td>1.27 ± 0.68</td>
<td>.453</td>
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<tr>
<td><strong>Angular errors from centerline (degree)</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Central incisor</td>
<td>5.04 ± 2.83</td>
<td>7.02 ± 3.68</td>
<td>.014*</td>
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<tr>
<td>Canine</td>
<td>4.57 ± 1.72</td>
<td>5.67 ± 3.23</td>
<td>.414</td>
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<tr>
<td>Second premolar</td>
<td>3.95 ± 1.64</td>
<td>4.92 ± 1.92</td>
<td>.537</td>
</tr>
<tr>
<td>Second molar</td>
<td>3.37 ± 1.38</td>
<td>4.37 ± 2.15</td>
<td>.99</td>
</tr>
<tr>
<td><strong>Time consuming (s)</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Central incisor</td>
<td>27.79 ± 11.34</td>
<td>38.27 ± 11.23</td>
<td>.013*</td>
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<tr>
<td>Canine</td>
<td>25.35 ± 8.39</td>
<td>35.89 ± 9.68</td>
<td>.026*</td>
</tr>
<tr>
<td>Second premolar</td>
<td>23.56 ± 7.59</td>
<td>35.68 ± 8.39</td>
<td>.018*</td>
</tr>
<tr>
<td>Second molar</td>
<td>22.2 ± 7.30</td>
<td>33.15 ± 9.38</td>
<td>.021*</td>
</tr>
</tbody>
</table>

*P ≤ .05.

**Surgery Procedure Simulation and Volunteer Experiment**

To simulate a real clinical environment, the models were mounted into a dental manikin frame having a limited opening mouth and a latex face to simulate limited visibility and pressure caused by soft facial tissues. The manikin frame was fixed on a surgical chair in the operatory, which was then set in the standard fashion for patient treatment (Fig 7a). Figure 7b shows the surgical area observed from the surgeon’s point of view. The 3D image was correctly superimposed on
the corresponding anatomical structure. Therefore, the surgeons could clearly view the inferior alveolar nerve and surgical pathway, both located in the mandibular bone. In this experiment, both surgeons correctly put the drill into the planned entry point under the guidance of this system, and the axis of the drill in accordance with the planned surgical path. In future clinical applications, surgeons only need to drive the drill along the planned surgical pathway to prepare the dental implant cavity.

A volunteer experiment was performed by the same two surgeons to evaluate the applications in real clinical dental implant surgery. The 3D overlay device was placed approximately 25 cm above the surgical area, giving the surgeon sufficient workspace (Fig 8a). After point cloud–based registration, the volunteer experiment demonstrated that the teeth, mandibular nerves, and jawbones that were reconstructed from the preoperative cone beam computed tomography images could be accurately overlaid onto the surgical site (Fig 8b). Thus, surgeons put the surgical drill on the entry point along the virtual surgical path.

**DISCUSSION**

**Principal Findings**

In this research, a new clinical workflow was proposed based on a recently developed advanced overlay system that can be used in dental implant surgery. The 3D image display device was placed approximately 25 cm above the surgical area, giving the surgeon sufficient workspace. The 3D image was accurately superimposed on the patient, giving the surgeon a fast and accurate understanding of the surgical area. Surgeons can move the 3D image display device away if the device interferes with the surgical operation and pull it back for visualization when necessary.

In this study, rapid prototyping models of edentulous mandibles were fabricated to reproduce the anatomical structures of patients. Furthermore, the models were covered by dental plate wax to avoid using anatomical structures for orientation during the preparation of the implant socket, thereby simulating a minimally invasive approach. The overall accuracy of a computer-aided intraoperative navigation system during implant surgery depends on the precision of the surgical navigation system and the skill of the surgeon in interpreting positional data displayed on the 3D image display device during the drilling of the implant socket hole.

In the registration procedure, a point cloud–based markerless registration method was applied instead of the traditional point-to-point registration method. The acquiring time of the point cloud was < 1 second, which helped the point cloud–based registration method greatly reduce patient discomfort compared with the traditional point-to-point registration method, which requires the patient to constantly keep his or her mouth open (≥ 10 seconds). The point cloud–based registration method could eliminate human error, accelerate registration speed, and increase registration accuracy. The experimental results demonstrated the feasibility of the point cloud–based registration method. The 0.54-mm deviation of registration met the clinical requirement. In the volunteer experiment, the point cloud data of the volunteer’s teeth were acquired, and there were no additional landmarks placed...
in the volunteer’s mouth before cone beam computed tomography scanning, accelerating the registration speed and reducing patient discomfort. In the future, the point cloud–based registration method will be tried in clinical situations.

This system was used to navigate a dental surgery in six models, and 48 parallel pins were successfully placed, instead of dental implant bodies, into the preoperatively planned positions. The 2D image-guided method was used to place another 48 parallel pins in the same mandibular models. For both the 3D augmented reality–guided and 2D image–guided methods, almost all errors were smaller in the posterior tooth regions than in the anterior tooth regions. This difference was probably due to the reduced stability of drilling in the anterior regions because the alveolar bone area in these regions of the edentulous mandible rapid prototyping models tends to be anatomically narrower and not flat compared with that in the molar region. This factor may also explain the smaller observed errors in the anterior tooth regions in the 3D augmented reality–guided group than in the 2D image–guided group. In addition, the autostereoscopic 3D images provided more angle and depth information to the surgeons than the 2D images, indicating that the overlay system helps decrease the time needed for correct positioning judgment and enhances the surgical accuracy. Similar to the pattern observed for location errors, significantly less time was used in the four tooth regions in the overlay–guided group compared with the 2D image–guided group. This result suggests that the surgeon can accurately and rapidly insert the implant bodies in real clinical operations, thereby enhancing the success rate and decreasing the healing time. Wagner et al have successfully placed 32 implants with the angle error of 0.4 to 17.4 degrees and the target error of 0.0 to 3.5 mm through the computer–aided navigation technology. In this study, the augmented reality–guided dental implant accuracy satisfied the above range.

**Agreements and Disagreements with the Previous Literature**

The insertion of dental implants requires accurate positioning, angulation, and insertion procedures to achieve results that are biomechanically, functionally, phonetically, and esthetically satisfactory. Several commercial navigation systems are currently available. Some are adaptable for dental implant placement, but others, such as the VISIT navigation system, the Virtual Implant Navigator (Medilibre Forschungs), and the RoboDent and LapDoc Systems (Robodont), were specifically developed for dental implant surgery. However, several limitations still exist in these systems and related technologies, particularly during their use in real dental implant surgery. First, the navigation methods for dental surgery presented by other groups rely on 2D image guidance. Second, the computer–generated virtual scene is displayed on a 2D screen away from the surgical site; therefore, surgeons have to divert their eyes from the surgical site to look at the monitor and find it difficult to maintain hand–eye coordination. Finally, compared with the visual perception of a 3D image, 2D projection lacks two important visual cues that give a viewer the perception of depth: stereo parallax and motion parallax. Depth perception in image–guided surgery enhances the surgical safety.

**Clinical Implications**

Innovative augmented reality imaging technology has been recently introduced. Augmented reality involves the co–virtualization of a virtual image and a real–time image so that the user can simultaneously observe and interact with the components of both images. This image–based navigation facilitates in situ visualization during surgical procedures because visual cues obtained from a preoperative radiologic image can enhance the visualization of surgical anatomy, improving preoperative planning and supporting the surgeon’s skill by simplifying the anatomical approach to complex procedures.

A previous study evaluated the application of a 3D augmented reality display system incorporating 3D application in oral maxillofacial surgery. The true 3D display generates naked–eye 3D images with no requirement for observers to wear any special glasses. Thus, it enables the observation of an autostereoscopic image as if the object is being viewed in real space. The main advantage of augmented reality is that the surgeon does not have to alternate attention between the surgical site and monitor, thus facilitating better focus, improved hand–eye coordination, and faster execution of surgical procedures.

**Limitations and Recommendations for Future Research**

In future clinical applications, surgeons can have the computed tomography scan and implant positions plan and perform dental implant surgery under the overlay system guidance on the same day. There is no need to fabricate a static guide template, which requires a few days. After a short time training on this system, surgeons with little or no experience can proficiently gain this skill and accurately perform dental implant surgeries, effectively reducing the learning curve to achieve this skill.

As computer–aided surgery has been widely used in surgical procedures, the need to provide information to the surgeon in a convenient and intuitive way becomes greater. The present prototype system for 3D
augmented reality–guided implant dentistry demonstrated the accuracy and reliability required for clinical application. It offers the possibility of improving the safety and efficiency of a widespread procedure. Technologically advanced methods for prosthetic planning and imaging, such as automatic segmentation of the mandibular nerve canal or fusion with other imaging modalities, such as dental magnetic resonance imaging, might further enhance the content of the radiologic information used for image guidance and can be directly introduced into the present system. The feasibility of the 3D augmented reality–guided navigation system in implant dentistry can be assessed in future clinical evaluations and comparisons with conventional splint techniques to show the effect of this system on the precision and speed of surgery and prosthetic procedures.

CONCLUSIONS

In this study, a 3D augmented reality–guided imaging navigation workflow was developed for dental implant surgery, and system feasibility in the model and volunteer experiments was proven. Dental implants can be placed using this proposed 3D augmented reality–guided system. The results of this preliminary study, in which 48 parallel pins were placed in six models, showed < 1.5 mm mean linear deviation and < 5.5-degree angular deviation. This technique shows the potential of computerized navigation in facilitating minimally invasive surgery in oral and maxillofacial implant surgery.

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REFERENCES