A Novel Dental Implant Guided Surgery Based on Integration of Surgical Template and Augmented Reality

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ABSTRACT

Background: Stereoscopic visualization concept combined with head-mounted displays may increase the accuracy of computer-aided implant surgery.

Purpose: The aim of this study was to develop an augmented reality-based dental implant placement system and evaluate the accuracy of the virtually planned versus the actual prepared implant site created in vitro.

Materials and Methods: Four fully edentulous mandibular and four partially edentulous maxillary duplicated casts were used. Six implants were planned in the mandibular and four in the maxillary casts. A total of 40 osteotomy sites were prepared in the casts using stereolithographic template integrated with augmented reality-based surgical simulation. During the surgery, the dentist could be guided accurately through a head-mounted display by superimposing the virtual auxiliary line and the drill stop. The deviation between planned and prepared positions of the implants was measured via postoperative computer tomography generated scan images.

Results: Mean and standard deviation of the discrepancy between planned and prepared sites at the entry point, apex, angle, depth, and lateral locations were 0.50 ± 0.33 mm, 0.96 ± 0.36 mm, $2.70 \pm 1.55°$, 0.33 ± 0.27 mm, and 0.86 ± 0.34 mm, respectively, for the fully edentulous mandible, and 0.46 ± 0.20 mm, 1.23 ± 0.42 mm, $3.33 \pm 1.42°$, 0.48 ± 0.37 mm, and 1.1 ± 0.39 mm, respectively, for the partially edentulous maxilla. There was a statistically significant difference in the apical deviation between maxilla and mandible in this surgical simulation ($p < .05$).

Conclusions: Deviation of implant placement from planned position was significantly reduced by integrating surgical template and augmented reality technology.

KEY WORDS: accuracy, augmented reality, dental implants, guided implant surgery, surgical template

INTRODUCTION

Dental implant surgery using a computer-aided design (CAD)/computer-aided manufacturing (CAM) surgical template is a relatively recent concept designed to facilitate implant placement.[1,2] The surgical template has guided sleeves that are positioned according to the treatment plan to direct surgical positioning of the drills and implants clinically.[3,4] Stereolithographic (SLA) surgical template improves implant placement by outlining the ideal implant axis and visualizing the final restorative plan during implant surgery.[5–7] Navigation systems using image data from computerized tomography (CT) further enhance the process.[8,9] These computer-aided intraoperative navigation systems provide the surgeon with a direct visualization of

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DOI 10.1111/cid.12119

computer-planned graphical data over the operating field via monitors.[10,11] This visualization technique is generally referred to as augmented reality (AR).[12] Using this technique, the clinician may avoid potential surgical mishaps, such as placing an implant too close to significant anatomic structures, while optimizing the eventual prosthetic rehabilitation. The main drawbacks of current visualization technique are the low refreshing rate of two frames delivered by the hardware and visual distraction during surgery from focusing on both the operative site and the computer display.[13] To overcome this problem, a head-mounted display (HMD) can be used to increase the accuracy of computer implant surgery. However, HMDs are still not widely used in intraoperative navigation because of focal and projection transformation problems.[13] In addition, the need for additional training and difficulty in simultaneously managing both the patient and visual information lead to dissatisfaction with the real-time tracking system.[14] An optical see-through display system has been developed recently to superimpose the three-dimensional virtual models onto the existing scene during implant surgical simulation training.[15] With this integration, operators can appreciate combined display of oral anatomical structures, planned implants, and the intraoperative procedure simultaneously. A few studies have reported on the accuracy and clinical outcomes of computer-guided template-based implant placement.[13,16–21] Substantial deviations in three-dimensional direction have been found between virtual planning and actual-obtained implant position.[22,23]

In this investigation, dental implant surgery assisted by the integration of surgical guide and AR was proposed to overcome the aforementioned problems. With this novel system, dentists could see three-dimensional virtual anatomic structures and the implant with the surgical template to confirm whether the site preparation results matched the planning. The latest model of HMD also provides dentists with intraoperative visual assistance to achieve satisfactory implant position and to minimize the risk of iatrogenic injuries to the surrounding anatomic structures like the mandibular nerve or the maxillary sinus floor.[24,25] The aim of this study was to compare the geometric positioning of virtually planned implants with that of the actual osteotomy sites prepared by AR-guided surgery. The null hypothesis was that there would be no statistically significant difference in geometric accuracy between the planned and prepared sites.

MATERIALS AND METHODS

Surgical Template Manufacturing

Scans of a 54-year-old patient with fully edentulous mandible and a 45-year-old patient with missing maxillary anterior teeth were obtained with a high-resolution multi-slice CT scanner (Somatom Sensation 16; Siemens AG, Erlangen, Germany). Reconstructed voxel size was set to $0.35 \times 0.35 \times 0.60$ mm. Digital imaging and communications in medicine files were transferred and converted into three-dimensional models with SLA data format. One examiner (I.W.) planned the placement of dental implants using software (ImplantSmart, Changhua, Taiwan). Virtual treatment plans with six implants in the fully edentulous mandible and four implants in the partially edentulous maxilla were developed. The completed image data sets were sent electronically to the manufacturing facility (TDS Biotech, Changhua, Taiwan), and surgical CAD/CAM template guides were manufactured out of medically approved acrylic resin. Customized surgical templates, including one mucosa- and one tooth-supported template, containing metallic sleeves, were manufactured with rapid prototyping. Each drill guide was at least 20 mm in height (10 mm implant length, 9 mm for the distance between the top of the implant and the top of the guided metal sleeve, 1 mm for the height of the drill guide). In addition, a laser scanner (LSC 200, TDS Biotech) was used to scan the two patients' plaster casts as SLA data format, which were subsequently transferred to a computer-controlled 5-axis milling machine (TME-300, TDS Biotech). In total, four sets of maxillary and mandibular casts were manufactured using the SLA method. An acrylic resin marker measuring $60\ \text{mm} \times 60\ \text{mm} \times 2\ \text{mm}$ was designed by CAD software (Autodesk Inventor 3D CAD software; Autodesk, Inc., Arroyo Grande, CA, USA). It was then manufactured by laser cutting and its pattern printed using screen printing, Figure 1.

AR Assembly

A commercially available 1280×720 resolution HMD (Sony HMZ-T1 personal 3D viewer, Tokyo, Japan) with a video see-through binocular organic light emitting diodes (OLED) viewer was used. A charge-coupled device (CCD) (C950, Logitech, Newark, CA, USA) with

Figure 1 Surgical template mounted with the marker.

autofocus and zoom was attached to the HMD. User's vision was replaced by an image captured with the CCD, displaying directly onto the HMD. In addition, the image was used to compute transformation from three-dimensional camera coordinates to marker coordinates. Working distance of the CCD was set from 350 to 480 mm. In order to minimize the latency in the video see-through display and full screen effect, the 970×720 resolution was adopted to satisfy the operator requirement. The frame rate per second was approximately 15. The video see-through binocular OLED display and CCD were connected to a commercial laptop computer with an Intel® Core™ i7-2760QM 2.4GHz (Intel Company, Santa Clara, CA, USA). After capturing the images from the CCD, the image processing, tracking, and transformation of three-dimensional models were calculated on the computer. The displays of the HMD and laptop were driven by an Intel® high definition Graphics 3000. This allowed the operator to see the results via the HMD while other observers could simultaneously see the results on the laptop screen. To superimpose three-dimensional virtual models on real environment, two-dimensional camera screen coordinates were transferred to three-dimensional camera coordinates and then to marker coordinates. In this study, the algorithm from previous studies[15,26] was adopted. The transformation from CT coordinates to marker coordinates was calculated by point-to-point registration technique.[27] After achieving these transformations, the three-dimensional virtual objects could be projected accurately onto the real environment. The four positions of pattern corners were used as marker coordinates and CT coordinates. The marker was attached on the surgical template with metal screws, Figure 1. The scenery displayed on the HMD was generated from the preoperative planning data. After real world-to-CT registration, the planning data were matched with the real world coordinate system. AR with a common focus for the real world image and the computer graphics was achieved.

AR-Based Surgical Procedure Simulation

One experienced periodontist (I.W.) performed the simulation of implant surgical procedure with osteotomy site preparation on the casts. Osteotomy site-specific drills with rubber stops (Astra rubber EPDM, Mölndal, Sweden) were utilized to control the apico-coronal site preparation. During the surgical procedure simulation, the operator wore the HMD with CCD, and the surgical template was passively fitted on the fully edentulous mandibular cast. The operator could see the planned implants and adjacent anatomical structures of the virtual three-dimensional jawbone on the screen of HMD to confirm the position of the surgical template. Then, the drill guide, compatible with the 3.5 mm diameter drill, was inserted into the guided metallic sleeve of the surgical template. Six osteotomy sites were prepared with the surgical template and drill guide following the virtual guide line (in yellow color) of each planned implants that displayed continuously. The virtual drill stop was a small red-colored cylinder displayed at the top of the drill guide indicating the 10 mm implant length. In addition, the virtual nerve canal (in blue color) allowed the operator to recognize the spatial relationship between the osteotomy site and the vital structures. Virtual sinus portions (light purple color) were continuously displayed on the screen of the HMD. During surgical procedures, the operator could move his head to review and confirm the orientation of each planned implants in reality. The operator could not only feel the physical limitation from the drill stop, but also receive visual feedback during the operation. The osteotomy site preparations in partially edentulous maxillary casts were conducted in the same manner as above. Four osteotomy sites were planned and prepared

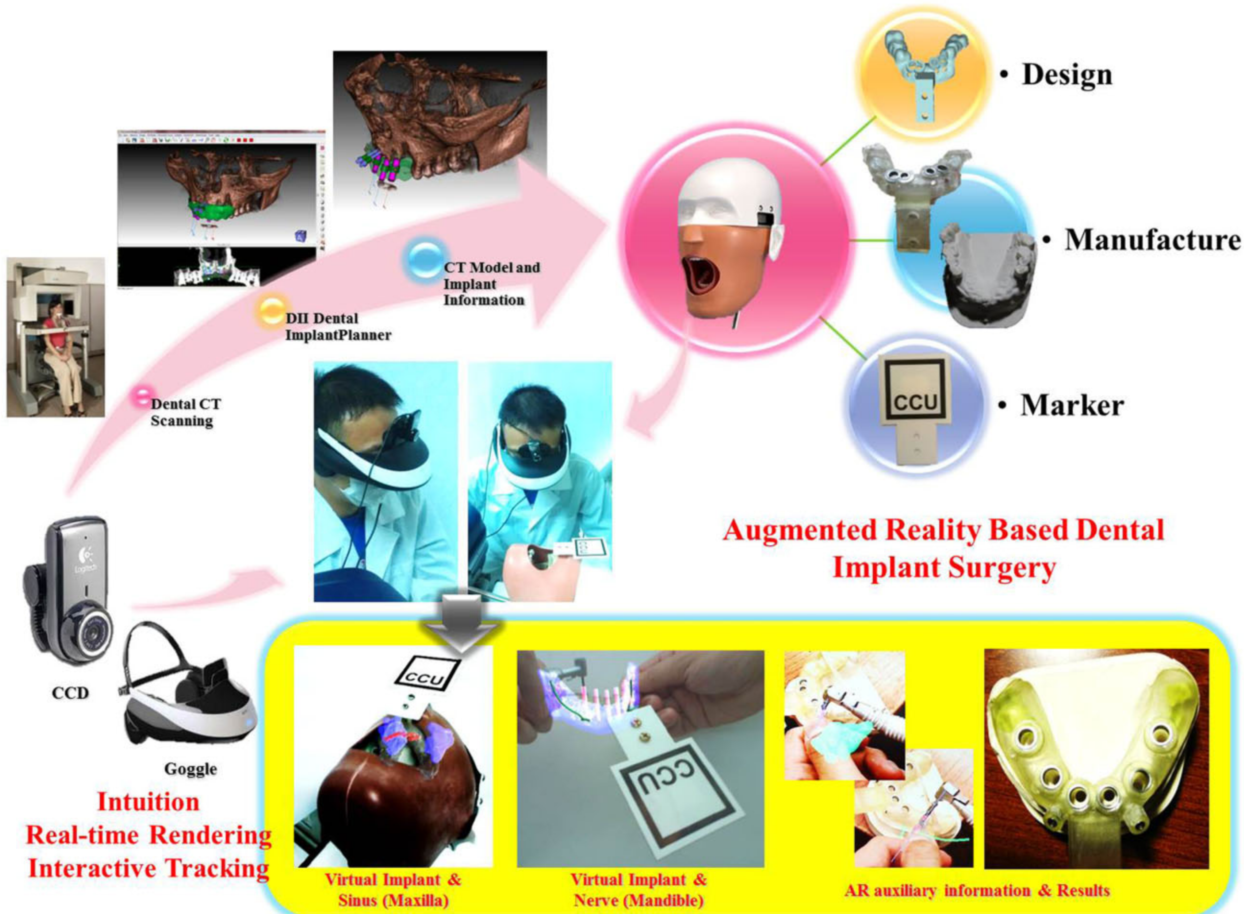

Figure 2 The flowchart of the proposed dental implant guided surgery.

with the surgical template and AR. The 2.8 mm drill guide was inserted into the surgical template to guide the drill during preparation. The entire flowchart of the proposed dental implant-guided surgery was shown in Figure 2.

Accuracy Assessment

All the prepared maxillary and mandibular casts underwent a second (postoperative) CT scan immediately after the surgical simulation. To determine the accuracy of the AR based drilling procedure, the position and angle differences between the planned and the osteotomy sites were measured on corresponding CT slices. The postoperative data were matched with the preoperative images using the fusion criterion of multimodality image registration.[28] First, a digital plaster cast and CT scans of the virtually planned implants were aligned. This allowed a prepared cast with drilled holes to be built from the postoperative CT slices. The postoperative images were geometrically aligned with the planned images by placing a set of landmark points and using point-to-point registration software (Designer 3.1; TDS Biotech). The software then calculated the transformation matrix applied to have the best fit between the casts with the planned implant locations and the casts with the drill holes. Once the casts with the planned implant locations and the casts with the drill holes were aligned, deviations of the global apical, coronal, as well as lateral, depth, and angular position could be calculated. The entire flowchart of the assessment is shown in Figure 3. A global deviation was defined as a three-dimensional distance between the coronal (or apical) center of the corresponding planned and placed implants. The angular deviation was calculated as a three-dimensional angle between the longitudinal axis of the planned and placed implant. To determine the lateral positional deviation, a plane perpendicular to the longitudinal axis of the planned

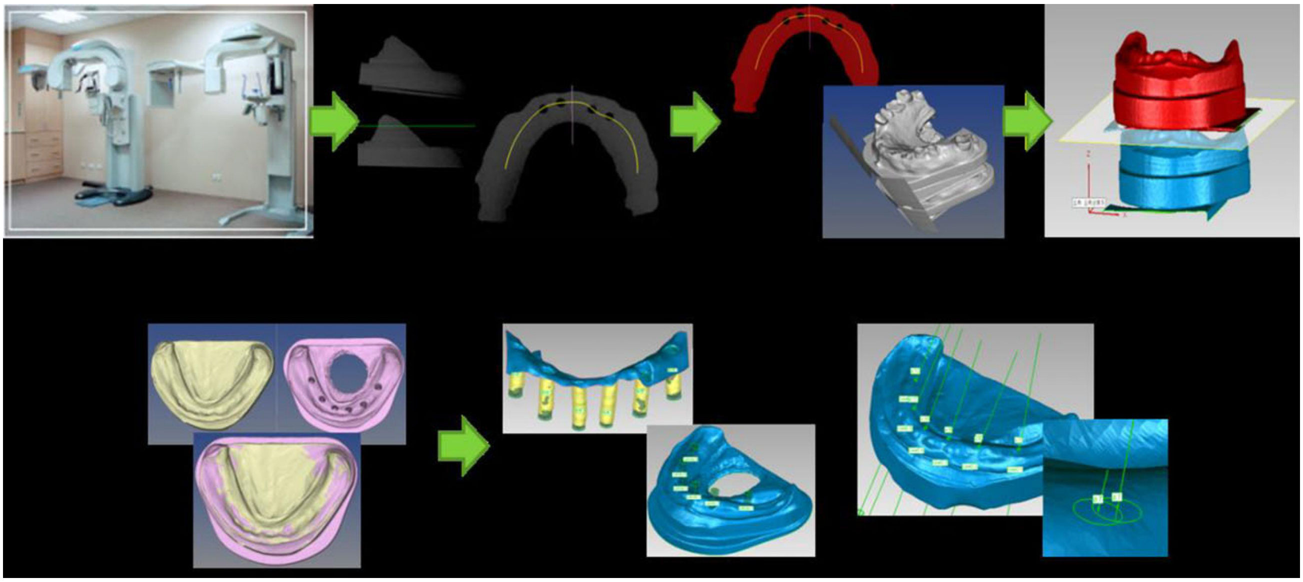

Figure 3 The flowchart of the accuracy assessment.

implant and through the coronal (or apical) center was defined as a reference plane. Lateral positional deviation was defined as the distance between the coronal (or apical) center of the planned implant and the intersection point of the longitudinal axis of the placed implant with the reference plane. Depth deviation was defined as the distance between the coronal (or apical) center of the planned implant and the intersection point of the longitudinal axis of the planned implant with a plane parallel to the reference plane and through the coronal (or apical) center of the placed implant according to a previous publication, Figure 4.[23]

Statistical Analysis

Computer software (SPSS Inc., Chicago, IL, USA) was used for data analysis. The Shapiro–Wilk test revealed that the data did not follow a normal distribution. Thus, a *Z*-test with robust standard error computed from sandwich estimator using generalized estimating equation was used for comparisons between planned implant positions and the actual prepared sites in terms of angular deviation and the position of the osteotomy site at the entry and apex. Differences were considered statistically significant if $p < .05$. ANOVA was conducted to test whether there was a difference in accuracy for the mandibular and maxillary casts.

RESULTS

After aligning the planned data with the prepared cast, the scenery on the HMD and computer screen displayed a pink virtual implant, a red drill stop, a blue auxiliary line, and a green inferior alveolar canal in order to create a simple AR environment as shown in Figure 5.

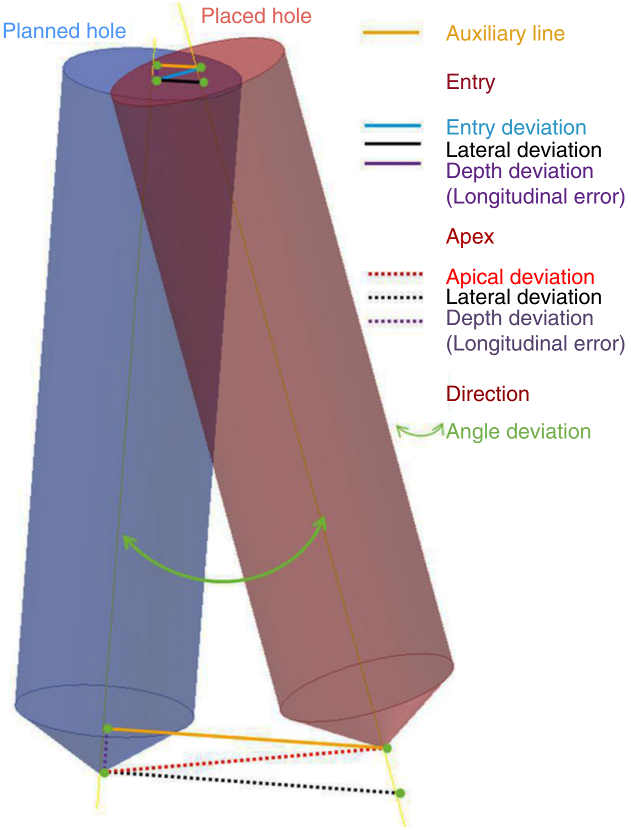

Figure 4 Three-dimensional evaluation of the virtual planned site and the augmented reality-based osteotomy site preparation.

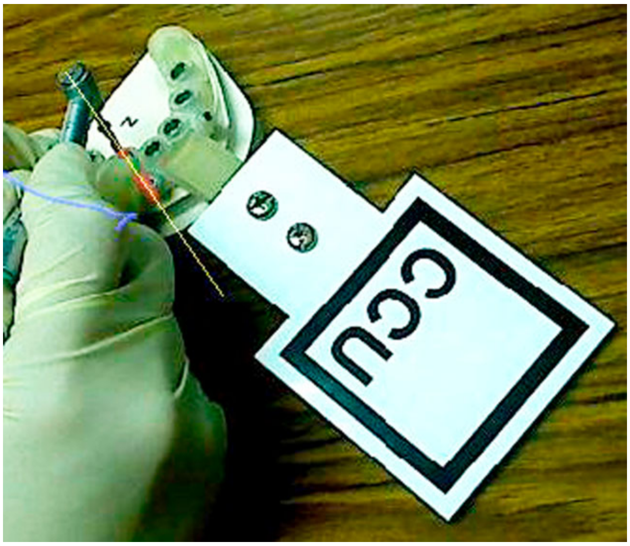

Figure 5 Augmented reality environment view through head-mounted display (HMD) during the simulation showing virtual drill stop, implant, auxiliary line, and mandibular canal.

Assessment of Accuracy

The distribution of the deviations is listed in Table 1. The mean and standard deviation of 24 mandibular osteotomy site preparations to the preoperatively planned positions at the entry point were 0.50 ± 0.33 mm (range: 0.04–1.24) and 0.96 ± 0.36 mm (range: 0.36–1.47) at the apex of the 10 mm long implants. The angulation accuracy showed a mean deviation of 2.70 ± 1.55° (range: 0.49–6.56). The lateral deviation between planned and prepared sites was 0.86 ± 0.34 mm (range: 0.36–1.46), and the depth deviation of the long axis was 0.33 ± 0.27 mm (range: 0.01–0.90).

TABLE 1 Distribution of the Global (Entry and Apex), Angular, Depth, and Lateral Deviations

Models	Entry (mm)	Angle (Degree)	Apex (mm)	Lateral* (mm)	Depth* (mm)
Mandible (24 Drill Holes):					
Mean	0.50	2.70	0.96	0.86	0.33
Maximum	1.24	6.56	1.47	1.46	0.90
Minimum	0.04	0.49	0.36	0.36	0.01
SD	0.33	1.55	0.36	0.34	0.27
Maxilla (16 Drill Holes):					
Mean	0.46	3.33	1.23	1.10	0.48
Maximum	0.89	6.47	1.98	1.68	1.24
Minimum	0.22	1.08	0.61	0.23	0.08
SD	0.20	1.42	0.42	0.39	0.37

*Apex.

The mean and standard deviation of 16 maxillary osteotomy site preparations to the preoperatively planned positions at the entry point were 0.46 ± 0.20 mm (range: 0.22–0.89) and 1.23 ± 0.42 mm (range: 0.61–1.23) at the apex of the 10 mm long implants. The angulation accuracy showed a mean deviation of 3.33 ± 1.42° (range: 1.08–6.47). The lateral deviation between the planned and prepared sites was 1.10 ± 0.39 mm (range: 0.23–1.68), and the depth deviation of the long axis was 0.48 ± 0.37 mm (range: 0.08–1.24).

A box plot analysis was used to show the deviations in the maxilla and mandible; the differences between the planned and actual sites of maxillary and mandibular implants at entry, apex, and in angular measurements are illustrated in different panels, Figure 6. There is a statistically significant difference in the apical deviation between maxilla and mandible during surgical simulation ($p < .05$), Table 2. The total deviations compared with previous studies between years 2002 and 2012 are listed in Table 3.

DISCUSSION

Generally speaking, osteotomies for implant placement always have deviations from planned positions in two image-guide systems especially in manual implantation. The accuracy of two navigation systems compared with manual implantation was reported by Brief and colleagues.[16] They placed pilot boreholes in a master cast, and the boreholes were reproduced in duplicate casts using one of two image-guide systems and manual implantation. Resulting positions were determined using a coordinate measurement device and compared with the pilot boreholes in the master cast. Results indicated that image-guide insertion of dental implants was significantly more accurate than manual implantation.

The present study evaluated whether the integration of surgical template and AR improved the accuracy of computer-assisted intraoperative navigation. An AR environment (Figure 5) was created by projecting a planned implant position and computer-generated essential structures onto the visual display and merging these with the operation field images to resolve the multiple displays and focus problems, thereby increasing intraoperative agreement. Currently, the proposed system is perhaps somewhat complicated in a clinical setting. The procedure can be simplified and customized to increase its feasibility within the surgical workflow. In fact, the proposed AR-based surgical planning is less

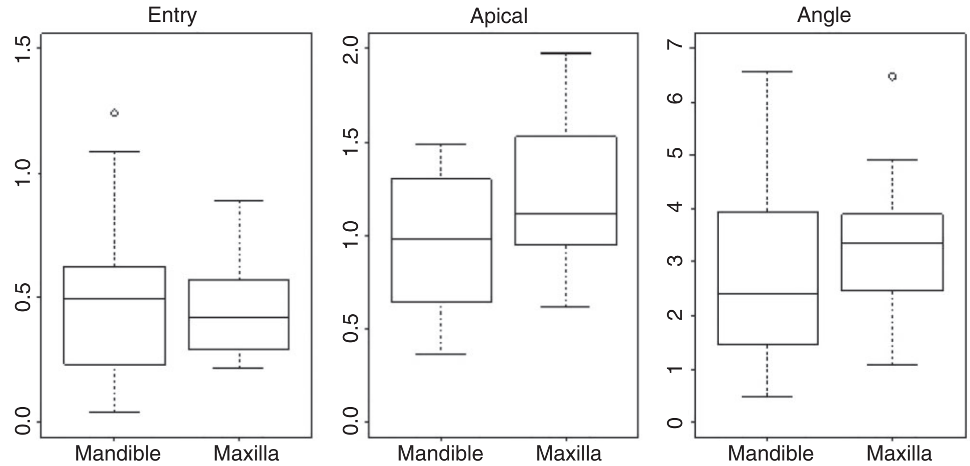

Figure 6 Boxplots of deviation in mandible and maxilla showing median, quartile, and extreme values of deviations. Boxes contain 50% of all values; the horizontal line inside the boxes indicates the median, vertical lines end at the minimum and maximum values excluding outlier (1.5 interquartile range away from first and third quartiles). Outliers are plotted by dots. Angle deviations are in degrees; all other deviations are in millimeters.

complicated than most of navigation systems that have already been commercially available. And through the integration of surgical template and tracking device, the proposed AR-based system should provide better visual feedback and physical guidance.

Based on the results of this study, the null hypothesis was rejected because of significant deviations in the created osteotomy sites' geometric positions compared with the virtually planned implant positions. However, similar mean values for maxillary and mandibular entry points and apices were observed, though there was a statistically significant difference in apical deviation mean values ($p = .04$), Table 2. The variation of model effect is comparable with the variation of random noise (0.11 vs 0.08, 0.23 vs 0.15, and 2.14 vs 2.33 for entry point, end point, and angle, respectively). The type effect is higher than the model effect and random noise for apical (0.71 vs 0.23 and 0.15) and degree (3.91 vs 2.14 and 2.33), while the model effect has the similar magnitude as random noise. In general, greater deviations were found using voxel-based registration at the apex than at the entry point, which mirrored findings in previous investigations.[29,30] Clinically, deviations at the entry or shoulder of the implants hinder correct fitting of a prefabricated prosthesis and require adaptation of fit or occlusion and deviations at the implant apex are to be expected. Therefore, consensus safety margins of 1.5 mm around planned implants and 2 mm around sensitive anatomical structures (e.g., alveolar inferior nerve, neighboring teeth, and maxillary sinus) have been recommended.[19,31]

Moreover, angular and depth deviations provide valuable information in avoiding damage to important anatomic structures and planning prosthetic construction.[30] Ersoy and colleagues used CT images and SLA guides to place 94 implants and determined that the placed implants had an angulation deviation of $4.90 \pm 2.36°$ and a linear deviation of 1.22 ± 0.85 mm at the implant neck and 1.51 ± 1.00 mm at the implant

TABLE 2 ANOVA Analyses for Type (Maxilla or Mandible) and Model Effects

	df	Sum Square	Mean Square	*F* Value	*p* Value
Deviation in Entry (mm)					
Type	1	0.02	0.02	0.24	0.63
Model	3	0.32	0.11	1.41	0.26
Interaction	3	0.37	0.12	1.63	0.20
Residuals	32	2.44	0.08		
Deviation in Apical (mm)					
Type	1	0.71	0.71	4.58	0.04
Model	3	0.70	0.23	1.52	0.23
Interaction	3	0.02	0.01	0.05	0.98
Residuals	32	4.94	0.15		
Deviation in Degree (°)					
Type	1	3.91	3.91	1.68	0.20
Model	3	6.43	2.14	0.92	0.44
Interaction	3	4.84	1.61	0.69	0.56
Residuals	32	74.49	2.33		

TABLE 3 Comparisons of Mean Deviations between Virtually Planned Positions and Augmented Reality-Based Preparation Sites with Other Studies

Study (Number of Drills/Implants)	Subject	System	Entry (mm) Mean/SD	Apex (mm) Mean/SD	Angle (Degrees) Mean/SD	Lateral (mm) Mean/SD	Depth (mm) Mean/SD	AR	NG	ST
Lin et al., present study ($n = 40$)	Model	ImplantSmart	0.49/0.28	1.07/0.40	2.95/1.52	0.47/0.27*	0.11/0.11*	✓		✓
						0.95/0.38†	0.39/0.32†			
Wanschitz et al.,[13] ($n = 15$)	Cadaver	VISIT	0.58/0.45	0.78/0.67	3.55/2.07	1.07/0.63		✓		
van Steenberghe et al.,[1] ($n = 10$)	Cadaver	LITORIM	0.80/0.30	0.90/0.30	1.80/1.00					✓
Sarment et al.,[6] ($n = 25$)	Model	SimPlant	1.50/0.70	2.10/0.97	4.50/2.00					✓
Wagner et al.,[11] ($n = 32$)	Human	VISIT	0.90/0.40	1.20/0.90	6.40/13.3				✓	
Brief et al.,[16] ($n = 15$)	Model	RoboDent	0.35/0.17	0.60/0.20	2.12/0.78				✓	
		DenX	0.65/0.58	0.94/0.40	4.21/4.76				✓	
		Manual	1.35/0.56	1.89/0.80	4.59/2.84					
Di Giacomo et al.,[2] ($n = 21$)	Human	SimPlant	1.45/1.42	2.99/1.77	7.25/2.67					✓
Wittwer et al.,[34] ($n = 78$)	Human	Medtronic	0.75/0.65	1.10/0.65						
Van Assche et al.,[4] ($n = 12$)	Cadaver	Nobel Guide	1.10/0.70	1.20/0.70	1.80/0.80					✓
Ersoy et al.,[29] ($n = 94$)	Human	Meliodnet	1.51/1.00	1.22/0.85	4.90/2.36					✓
Kalt & Gehrke,[31] ($n = 48$)	Cadaver	Med3D	0.83/0.49	2.17/1.02	8.44/3.98		0.20/0.54†			✓
Ruppin et al.,[18] ($n = 120$)	Cadaver	SimPlant	1.50/0.80		7.90/5.00		0.60/0.40*			✓
	Cadaver	RoboDent	1.00/0.50		8.10/4.60		0.60/0.30*		✓	
	Cadaver	ARTMA	1.20/0.60		8.10/4.90		0.80/0.70*		✓	
Horwitz et al.,[35] ($n = 54$)	Model	Med3D	0.49/0.36	0.63/0.38	2.17/1.06					✓
Ozan ert al.,[7] ($n = 110$)	Human	Rhinoceros	1.11/0.70	1.41/0.70	4.10/2.30					✓
Pettersson et al.,[33] ($n = 145$)	Cadaver	SimPlant	1.06/0.58	1.25/0.68	2.64/1.42		0.28/0.59†			✓
Cassetta et al.,[32] ($n = 227$)	Human	SimPlant	1.50/0.63	1.90/0.90	4.82/3.14	1.35/0.68†	0.82/0.59†			✓
Komiyama et al.,[30] ($n = 139$)	Model	Nobel Guide	0.80/0.80	1.10/1.09						✓
Cassetta et al.,[36] ($n = 111$)	Human	SimPlant	1.52/0.61	1.97/0.86	4.68/2.98	1.20/0.63†	0.75/0.55†			✓
Di Giacomo et al.,[37] ($n = 60$)	Human	ImplantViewer	1.35/0.65	1.79/1.01	6.53/4.31					✓
Cassetta et al.,[38] ($n = 116$)	Human	SimPlant	1.47/0.68	1.83/1.03	5.09/3.70	0.97/0.52†	0.98/0.71†			✓
Turbush &Turkyilmaz,[39] ($n = 150$)	Model	Mimics	1.18/0.42	1.44/0.67	2.20/1.20					✓
Behneke et al.,[20] ($n = 132$)	Human	Med3D	0.32/0.23	0.49/0.29	2.10/1.31					✓
Cassetta et al.,[40] ($n = 129$)	Human	SimPlant	1.55/0.59	2.05/0.89	5.46/3.38	1.36/0.58	0.63/0.43			✓
Pettersson et al.,[21] ($n = 139$)	Human	SimPlant	0.80/0.72	1.09/0.48	2.26/1.08		0.15/0.76			✓
D'haese et al.,[41] ($n = 79$)	Human	Astr Tech AB	0.91/0.44	1.13/0.52	2.60/1.61					✓
Dreiseidler et al.,[42] ($n = 108$)	Model	SKY-Plan X	0.89/0.44	1.09/0.69	2.01/1.94					✓

*Entry.
†Apex.
AR, augmented reality; NG, navigation guidance; ST, surgical template.

apex.[29] They concluded that the reported technique might be reliable for implant placement. In a meta-regression analysis of eight published studies, Schneider and colleagues presented results with a mean deviation of 1.07 mm (95% confidence interval [CI]: 0.76–1.22 mm) at the entry point and 1.63 mm (95% CI: 1.26–2 mm) at the apex.[22] D'haese and colleagues recently reported a mean apical deviation of 1.0 mm from one in vitro study, a range of 0.6 mm to 1.2 mm from three ex vivo studies, and a range of 0.95 to 4.5 mm from six in vivo studies.[23] Mean deviations from 25 studies were selected and compared with the present investigation (Table 3). The entry point and apical mean deviations as well as angle, lateral, and depth deviations obtained from this study were within the lower end of the comparison ranges. The deviations may be related to mechanical errors caused by the gap between the guiding sleeve and the bur during simulation procedures.[32] Comparing previous results listed in Table 3 with the data attained from this study, we conclude that computer-aided positioning of oral implants with an HMD and a computer-generated AR environment as well as a SLA surgical template exceeds presently available methods in accuracy. The accuracy of this technique appears to be superior to similar procedures reported earlier.[13,33] Any deviations that may occur clinically will remain within the safety zone, thus effectively minimizing the risk of encroaching on sensitive anatomical structures. All the deviations currently documented in the literature and obtained by this study may not have any adverse effects other than perhaps reducing the precision of fit of the superstructures involved. It means that a substantial improvement can be achieved in terms of controlling the implant drill during the surgical procedure with this novel technique. Even with these shortcomings, the AR-based guided surgery technique allows simulation surgery to closely represent reality.

One should consider that the present data were from casts, not from cadaver experimentation or human clinical study. Thus, attention should be paid to the limitations of the results presented because of the technique of this in vitro study. An *in vitro study* usually provides ideal conditions under parameters not easily controlled when placing implants in vivo. An *in vivo study* would most likely have varying levels of accuracy depending on the implant location and, consequently, the ability to access the surgical site. Human error remains an uncontrollable factor throughout all the steps involved in guided implant placement and three-dimensional planning. The total sum of potential errors during each step has not been fully evaluated.[30] The data obtained by this in vitro study demonstrate that the accuracy of the proposed system would be sufficient for clinical practice, particularly in terms of the transfer precision of three-dimensional implant planning. However, in vivo clinical trials need to be conducted to validate the clinical accuracy and treatment quality of the proposed system in the future. Future studies should focus on virtual variation simulation of CAD/CAM template combined with AR-based guided surgeries on actual patients to reveal surgical system limitations and errors as well as to gain more experience to minimize the geometric variation.

ACKNOWLEDGMENTS

This study was partially supported by the National Science Council, Taiwan (NSC 101-2917-I-194-005) and the University of Washington, Department of Restorative Dentistry (07-5840 Task 803). The authors thank Dr. Tijana Stijacic for her assistance in manuscript preparation.

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