

Effect of Surgical Guide Design and Surgeon's Experience on the Accuracy of Implant Placement

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Implant position is a key determinant of esthetic and functional success. Achieving the goal of ideal implant position may be affected by case selection, prosthodontically driven treatment planning, site preparation, surgeon's experience and use of a surgical guide. The combined effect of surgical guide design, surgeon's experience, and size of the edentulous area on the accuracy of implant placement was evaluated in a simulated clinical setting. Twenty-one volunteers were recruited to participate in the study. They were divided evenly into 3 groups (novice, intermediate, and experienced). Each surgeon placed implants in single and double sites using 4 different surgical guide designs (no guide, tube, channel, and guided) and written instructions describing the ideal implant positions. A definitive typodont was constructed that had 3 implants in prosthetically determined ideal positions of single and double sites. The position and angulation of implants placed by the surgeons in the duplicate typodonts was measured using a computerized coordinate measuring machine and compared to the definitive typodont. The mean absolute positional error for all guides was 0.273, 0.340, 0.197 mm in mesial-distal, buccal-lingual, vertical positions, respectively, with an overall range of 0.00 to 1.81 mm. The mean absolute angle error for all guides was 1.61° and 2.39° in the mesial-distal and buccal-lingual angulations, respectively, with an overall range of 0.01° to 9.7°. Surgical guide design had a statistically significant effect on the accuracy of implant placement regardless of the surgeon's experience level. Experienced surgeons had significantly less error in buccal-lingual angulation. The size of the edentulous sites was found to affect both implant angle and position significantly. The magnitude of error in position and angulation caused by surgical guide design, surgeon's experience, and site size reported in this study are possibly not large enough to be clinically significant; however, it is likely that errors would be magnified in clinical practice. Future research is recommended to evaluate the effect of surgical guide design in vivo on implant angulation and position error.

Key Words: *surgical guide, implant placement*

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DOI: 10.1563/AAID-JOI-D-10-00046

INTRODUCTION

Surgical guides are advocated during dental implant surgery to assist in the accurate placement of implants.¹⁻⁷ Functional and esthetic problems may occur as a result of undesirable implant placement.^{6,8} The problems may result from inaccuracies in mesial-distal position, buccal-lingual position, vertical position, mesial-distal angulation, and buccal-lingual angulation.

Esthetic consequences of incorrect implant placement include excessive or inadequate interocclusal space, insufficient emergence profile, a visible implant collar, and reduced or missing papillae.^{6,8} Problems related to function may also arise and include increased soft tissue pocketing around the implant, difficulty with oral hygiene procedures, speech impairments, chronic discomfort, and nonaxial forces on the implant and prosthesis.⁹ Accurate implant placement may reduce surgical complications such as nerve damage and hemorrhage, and unintentional perforation of the sinuses, floor of the nose, and cortical plates.^{10,11}

The clinically acceptable position for an individual implant is not a single point but rather a zone.⁶ To develop an ideal emergence profile and to maintain buccal bone for support of soft tissue, the most facial surface of the implant should be approximately 1 mm palatal to the planned implant crown as it exits the gingiva.^{5,6} If bone has been lost from the facial aspect of the planned implant site, then hard tissue grafting to restore appropriate dimensions may be indicated. There is leeway to place the implant further palatally, but if the implant is more than 2 mm palatal to the ideal position, esthetics and function may be compromised.⁸ Guidelines for vertical positioning of the implant interface in esthetic zones include a 2-mm position apical to the cemento-enamel junction of adjacent teeth and 3 mm apical to the planned free gingival

margin of the implant, or in situations where there has been clinical attachment loss on adjacent teeth, at the level of the bone crest.^{5,6,12} The desired angulation may vary depending on whether the planned restoration is screw-retained or cement-retained. Screw-retained restorations in the esthetic zone require the screw access to emerge through the cingulum, while cement-retained restorations are less dependent on the emergence of the screw access.

Reported surgical guide designs include guides with metal tubes that only allow for the use of an initial pilot drill, guides with open channels that allow use of all drill sizes and give surgeons greater freedom, and guides that are computer designed and fabricated to direct all steps of the drilling sequence and may also direct placement of the implant.^{2-4,13-16}

The accuracy of implant placement subsequent to osteotomy preparation guided by simple surgical guide designs *in vivo* has not been reported. The effect of varying the diameter and length of the channel along with the distance between the intaglio surface of the surgical guide and the recipient site on the deviation of implant angulation has been assessed *in vitro*.¹⁷ Channel length was found to be the primary controlling factor in minimizing angulation error. The degree of implant angulation also increased significantly when the distance between the intaglio surface of the surgical guide and the recipient site was 2 mm compared with 4 mm.¹⁷ The greatest mean deviation reported was 3.16° with a standard deviation of 1.39°. Implant sites were prepared by 1 operator into acrylic resin blocks *in vitro*; therefore, the results may not be transferable to clinical practice.

The accuracy of computer-assisted design/computer-assisted machined (CAD/CAM) implant surgical guides has been reported.^{14,16,18-29} *In vitro* evaluation of implant placement using CAD/CAM guides (Nobel Guide, Nobel Biocare, Balsberg, Switzerland) found mean deviations of

217 μm (CI 200 to 275) horizontally and 254 μm (CI 185 to 320) vertically from the planned position. Axis deviations of 1.09° (CI 0.85 to 1.3) were detected.¹⁸ An *in vivo* evaluation of stereolithographic guides found the mean linear deviation to be 1.22 mm and the mean angular deviation to be 4.9° .¹⁹ Design features that are important for CAD/CAM guides may be different than those of non-CAD/CAM guides. An *in vitro* evaluation of the effect of tube height in CAD/CAM guides found no difference in planned and actual implant position between guides with 8-mm and 4-mm tube heights (250 and 240 μm , respectively).²³ Stability is a critical design feature of surgical guides regardless of the channel design with tooth-borne guides being more accurate than tooth-/tissue-borne guides.^{14,22}

Surgical experience has been demonstrated to increase the positional accuracy of implant placement^{30,31} in addition to the success rate of osseointegration.^{30,32} The success rates reported in these trials increased as experience was gained refining techniques in a rapidly developing field, so it is unknown if the increased success rates reported were due to the new techniques, the surgeon's experience, or a combination of both. There are limited reports available in the dental implant literature documenting the effect of surgical experience on the accuracy of implant placement. Surgical experience may have more impact in complex cases, especially if the bony anatomy at the implant recipient site varies significantly from the prosthetically planned position.³³ The effect of surgical guide design could be influenced by the number of missing teeth. For single edentulous sites, the adjacent teeth provide anatomic landmarks to guide implant position, whereas large edentulous spaces have fewer anatomic landmarks, and surgical guides may have a greater effect on placement accuracy.

The purpose of this study was to evaluate the effect of surgical guide design, surgeon's experience, and size of

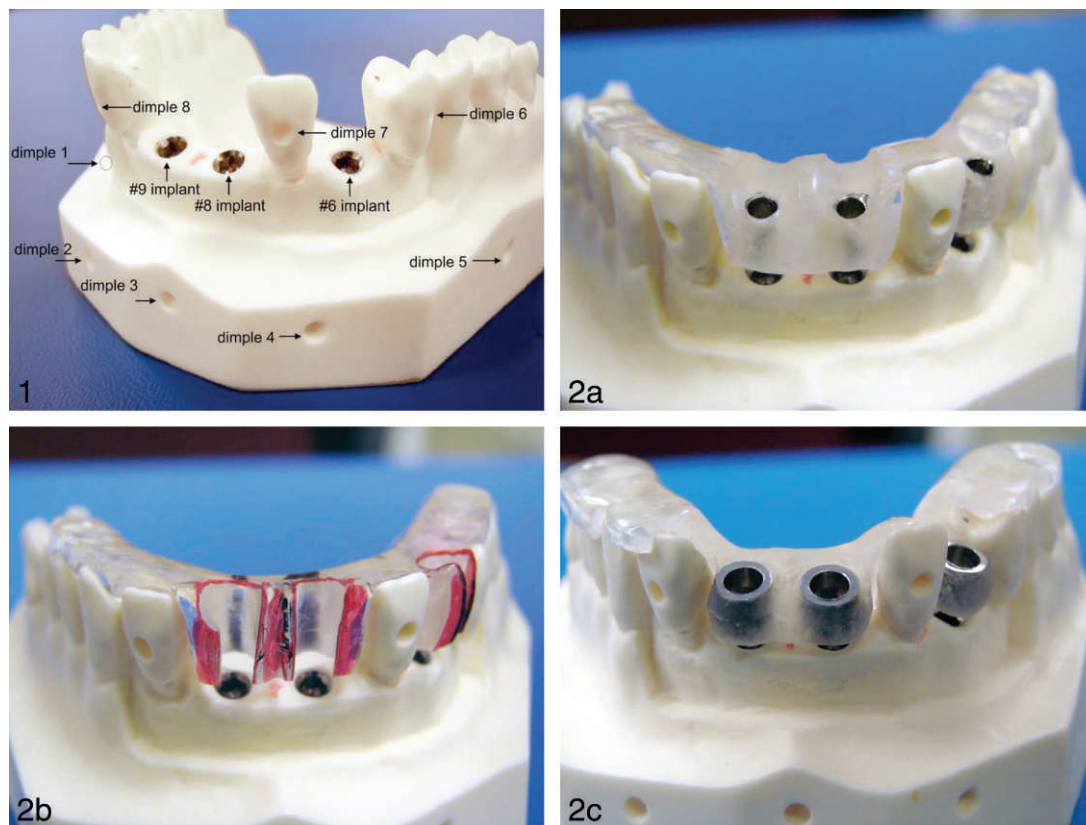
the edentulous site on the accuracy of implant placement. The null hypothesis was that surgical guide design, surgeon's experience, and size of the edentulous site do not affect the accuracy of implant placement.

MATERIALS AND METHODS

This study was a randomized, single blinded laboratory study using human subjects. Approval from the Internal Review Board of the University of Minnesota was obtained. Three groups of 7 subjects were recruited with different levels of dental implantology surgical experience. The first group (novice) included dental students with no clinical surgical implant experience. The Novice group completed an instructional laboratory course placing implants in typodonts. The second group (intermediate) included graduate periodontology residents who placed between 20 and 80 implants clinically. The third group (experienced) included periodontists who placed over 300 implants clinically.

Eighty-four duplicate maxillary typodonts (Models Plus, Kingsford Heights, Ind) were fabricated from a definitive typodont with edentulous spaces at the right canine (single site) and the right and left central incisors (double site) and 8 dimples (5 on the sides of typodont base and 1 each on the labial surfaces of the right first premolar and right and left lateral incisors) as positioning references for future measurements. Osteotomies were prepared in the definitive typodont, and 3 implants were placed in prosthetically determined ideal positions (Figure 1).

Three different surgical guide designs were fabricated retroactively from the definitive typodont (Figure 2). The first design (tube) included a 2.2-mm metal tube (Stent Guide Tubes, Biomet 3i, Palm Beach Garden, Fla) that was only wide enough for a 2-mm surgical drill to fit through. The second design (channel) included a guide channel that was wide



FIGURES 1 AND 2. **FIGURE 1.** Definitive typodont showing 8 reference dimples and 3 ideal implants in number 6, number 8, and number 9 area. **FIGURE 2.** Three surgical guide designs: (a) design 1 (tube), (b) design 2 (channel), and (c) design 3 (guided).

enough for all drill sizes, including the final drill, to fit through. The buccal part of the guide was removed to enhance visibility and access for irrigation. The third design (guided) included inserts that precisely fit each drill to guide the drill position, angulation, and drilling depth (guided surgery system, Dental Crafters, Marshfield, Wis). The guided design also directed placement of the implant. The fourth group did not use any implant surgical guide.

Twenty-one surgeons were each provided with 4 duplicate typodonts and were asked to place three 3.7×13 mm dummy implants (Zimmer Dental, Carlsbad, Calif) in each typodont, using 1 of 4 surgical guide techniques, for a total of 252 implants in 84 duplicate typodonts. All implant placement surgeries were performed following standard surgical protocol in the Minnesota Oral Health Clinical Research Center,

which is a fully equipped research clinic with 10 dental operators.

The ideal positioning was described to the surgeons in writing before they began the osteotomy preparations on the typodonts. The sequence of surgeries using the 3 surgical guides and no guide was randomized for each surgeon. The typodonts were held in a preclinical patient simulator head (M-1R-10 Simulation Manikin, Columbia Dentoform Corporation, Long Island City, NY) to simulate a clinical setting. Saline irrigation was required during the preparation.

The x, y, z coordinates of the 8 reference dimples and the implants placed in the duplicate typodonts were recorded using a coordinate measuring machine (CMM) (FARO Technologies Inc, Lake Mary, Fla) with a single point accuracy of $76 \mu\text{m}$. The x, y, z coordinates of each implant position were recorded by placing the

measuring stylus of the CMM in the center of a cover screw connected to the implant (Figure 3). In order to measure the angulation of the long axis of each implant, the coordinates of the top of an impression guide pin connected to the center of the implant were recorded and related to the coordinates of the center of the cover screw. The investigator who measured the position of the implants in the typodonts using CMM was blinded to the surgeon, surgeon group, and surgical guide design.

The x-axis was determined by a line connecting two reference dimples on the labial surfaces of the right first premolar and the right lateral incisor for the right canine implant site (single site) and by a line connecting the right lateral incisor and the left lateral incisor for both right and left central incisor implant sites (double site) (Figure 4).

Using the coordinates of the 8 identical reference dimples, each of the 84 duplicate typodonts was mathematically overlapped against the definitive typodont in such a way that the sum of absolute discrepancies between 8 pairs of dimples was minimized. Linear discrepancies in positions (Δx for mesial[+]-distal[-], Δy for buccal[+]-lingual[-], and Δz for coronal[+]-apical[-]) between the implants in the duplicate typodonts and the corresponding ideal implants in the definitive typodont were calculated and recorded. For the double implant site, the linear discrepancy for both right and left central incisors toward the midline or the mesial was recorded as positive (+).

Angular discrepancies (Δxz for mesial[+]-distal[-] and Δyz for buccal[+]-lingual[-] angulation) between the implants in the duplicate typodonts and the corresponding ideal implants in the definitive typodont were calculated and recorded.

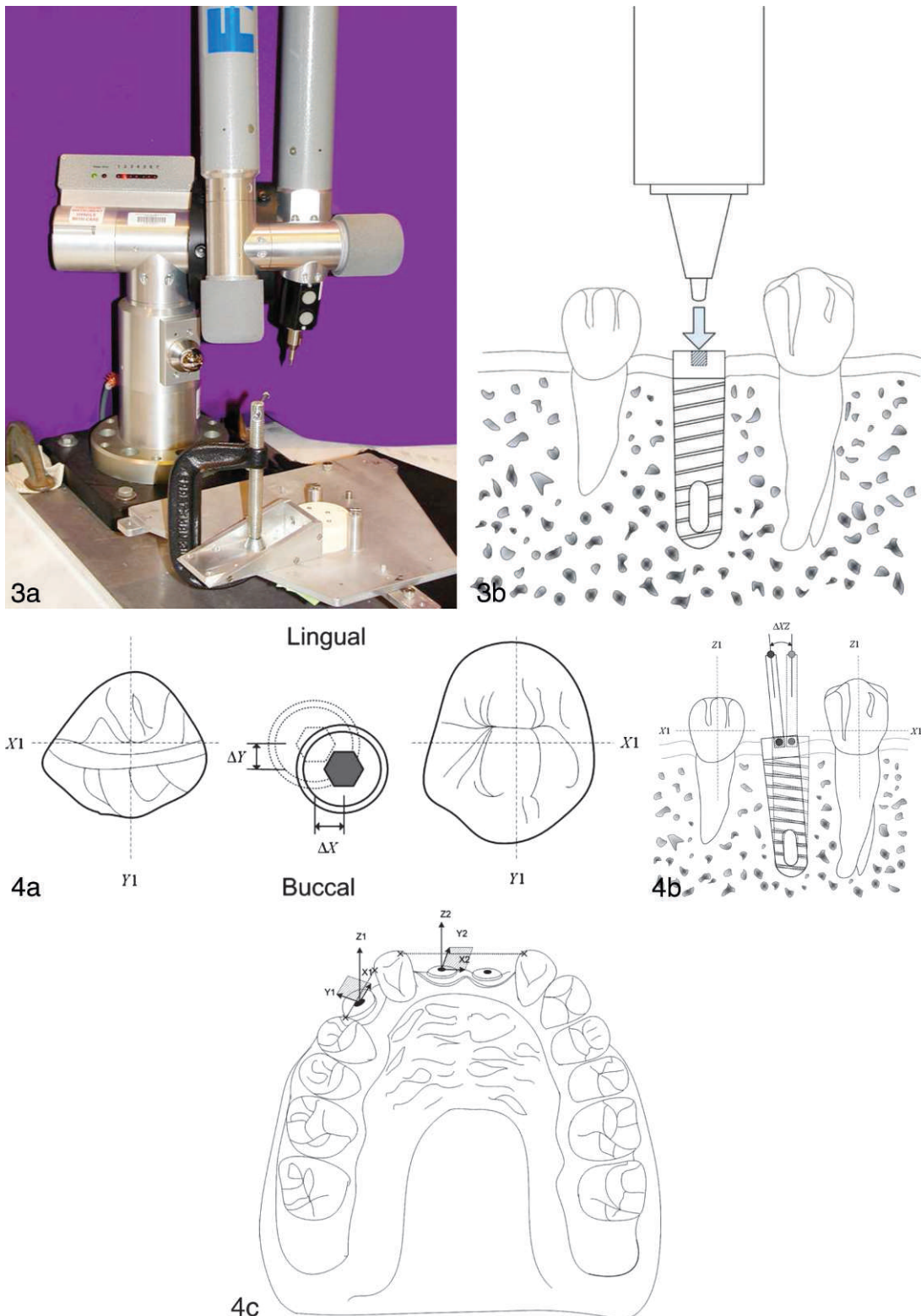
To determine the summative error level of duplicate cast fabrication, coordinate measurements, and overlapping procedures, a pilot study of measuring position

discrepancies of the 8 reference points in the definitive typodont and 2 duplicate typodonts was performed with 5 repeated measurements. The average discrepancy of 8 reference points after overlapping of duplicate typodonts to the definitive typodont was 38 μm .

Random intercept models were used to analyze the 5 dependent variables (Δx , Δy , Δz , Δxz , and Δyz). Independent variables, including the surgical guide design (4 groups), surgeon's experience (3 groups), size of the edentulous area (2 groups), and order of surgical guide usage (randomized), along with interactions between the variables were treated as fixed effects in each model. The random intercept was included to take into account the multiple measurements from each surgeon. In addition, the absolute value of the 5 dependent variables was calculated, and similar analyses were performed on the log-transformed absolute value of each dependent variable. When converting the outcome data to the absolute value, the distribution for each dependent variable became skewed (non-normal). To satisfy assumptions of the statistical analysis, a log transformation was performed to attempt to normalize the data. A Bonferroni adjustment was used to account for the modeling of the 5 dependent variables, so *P* values smaller than .01 (.05/5) were deemed statistically significant. If effects were significant, pairwise comparisons were made. Statistical software (SAS V9.1.3, SAS Institute, Cary, NC) was used to perform the statistical analysis.

RESULTS

P values of linear (Δx , Δy , Δz) and angular (Δxz , Δyz) discrepancies and their absolute values ($|\Delta x|$, $|\Delta y|$, $|\Delta z|$, $|\Delta xz|$, $|\Delta yz|$) for surgical guide design, surgeon's experience, and size of the edentulous sites are summarized in Tables 1 and 2. Least squared mean deviations (Δx , Δy , Δz , Δyz , Δxz) and median absolute value deviations ($|\Delta x|$, $|\Delta y|$, $|\Delta z|$, $|\Delta xz|$, $|\Delta yz|$) for



FIGURES 3 AND 4. FIGURE 3. (a) Coordinate measuring machine (CMM). (b) Stylus of CMM is placed in the center of an implant cover screw to record implant position in x, y, z coordinates. **FIGURE 4.** (a) Distance discrepancy measurement in right canine site between experimental implant (solid implant) and definitive implant (dotted implant) in x-axis (Δx) and y-axis (Δy). (b) Angular discrepancy measurement in right canine site between experimental implant (solid implant) and definitive implant (dotted implant) in xz-plane (Δxz). (c) Schematic drawing of typodont showing single (number 6) and double

TABLE 1

P values from random intercept models with interactions: linear discrepancies Δx , Δy , Δz , and absolute values of linear discrepancies $|\Delta x|$, $|\Delta y|$, $|\Delta z|$ *

Effect	<i>P</i> Value (Type III Test)					
	Δx M-D	$ \Delta x $ M-D†	Δy B-L	$ \Delta y $ B-L†	Δz C-A	$ \Delta z $ C-A†
Guide design	.0546	<.0001‡	<.0001	<.0001	<.0001	.6230
Surgeon experience	.2092	.1931	.0375	.1680	.6429	.6670
Site size	<.0001	.0973	.0053	.8873	.7639	.8602
Order	.9886	.7851	.1288	.3984	.6571	.1444
Guide^surgeon	.9108	.9595	.0767	.5143	.0677	.2702
Guide^site	<.0001	.0371	.0021	.1862	.2754	.3558
Surgeon^site	.4591	.3648	.0031	.6094	.9351	.6905
Guide^surgeon^site	.9520	.5091	.3543	.2901	.6397	.9551

*M-D indicates mesial-distal; B-L, buccal-lingual; C-A, coronal-apical.

†The dependent variable used in the model was the log-transformed absolute value of Δx , Δy , Δz .

‡Bold entries indicate statistically significant values ($P < .01$).

surgical guide design, surgeon’s experience, and size of the edentulous sites are summarized in Tables 3 through 5. The absolute deviation reported is the median deviation in the respective position/angle, regardless of direction.

The surgical guide design was found to significantly affect both the implant position and angle (Tables 1 and 2). Guided surgery differed significantly from all other groups in $|\Delta x|$, with the guided surgery producing the lowest absolute error (post hoc analysis not shown) (Figure 5). For guided surgery, Δy and $|\Delta y|$ were significantly greater than all other groups, and the error produced by guided surgery was positioned palatally for all 61 implants (Figure 6). Guided surgery produced Δyz angulation error to the buccal direction (double and single sites), whereas the tube, channel, and no guide groups all produced error to the palatal direction ($P < .0001$) (Table 3). When absolute angle deviation was compared, there were no significant differences between guides (Table 2).

The surgeon’s experience was found to statistically significantly affect only Δyz , with experienced surgeons being more

accurate than intermediate clinicians (Figure 7). There was no significant interaction between surgical guide design and surgeon’s experience.

The size of the edentulous sites was found to affect both angle and position. Greater error in position occurred in double sites compared to single sites in Δx (Table 5). For interaction between guide design and site size, the channel guide showed the biggest discrepancy between single and double sites for Δx (Figure 8). Greater angulation error occurred in single implant sites for Δxz ($P < .0001$), while greater angulation error occurred in double implant sites for Δyz ($P < .0001$) (Tables 2 and 5). The $|\Delta yz|$ was significantly less in single sites compared with double sites, and the error was distributed equally buccally and lingually, resulting in very small overall Δyz mean error. In double sites, Δyz tended toward the palate direction (Figure 9).

DISCUSSION

The data support rejection of the null hypothesis as the results of this study

(numbers 8 and 9) implant sites and their relative x-y-z axes. The x-axis was determined by the line connecting 2 reference dimples on the labial surfaces of the right second premolar and right lateral incisor for right canine implant (single site) and by the line connecting the right lateral incisor and left lateral incisor for both left and right central incisor implants (double site).

TABLE 2

P values from random intercept models with interactions: angular discrepancies Δxz , Δyz and absolute values of angular discrepancies $|\Delta xz|$, $|\Delta yz|$ *

Effect	<i>P</i> Value (Type III Test)			
	Δxz M-D	$ \Delta xz $ M-D†	Δyz B-L	$ \Delta yz $ B-L†
Guide design	.0005‡	.0409	<.0001	.3015
Surgeon experience	.0382	.0579	.0089	.6671
Site size	<.0001	<.0001	<.0001	.0014
Order	.7522	.1230	.1241	.9176
Guide^surgeon	.3012	.1260	.0221	.2322
Guide^site	<.0001	.0342	.0036	.0288
Surgeon^site	.0027	.1148	.0169	.9330
Guide^surgeon^site	.1389	.1522	.8325	.4173

*M-D indicates mesial-distal; B-L, buccal-lingual.

†The dependent variable used in the model was the log-transformed absolute value of Δxz , Δyz .

‡Bold entries indicate statistically significant values ($P < .01$).

demonstrate that surgical guide design can statistically significantly affect the accuracy of implant placement but only for some parameters. The greatest mean positional error was 0.62 mm that occurred in Δy (B-L position) using a guided surgical guide. The greatest mean position error for non-guided (ie, no guide, tube, or channel) was 0.29 mm in Δx (M-D position) using a channel guide. The overall range of absolute position error for all guides was 0.00 to 1.81 mm. The subject who produced the 1.81-mm error was an experienced surgeon using a channel guide placing an implant in a single site. The greatest mean angle error was 2.56° that occurred for Δyz (B-L angulation) in the channel group, while the greatest error for guided surgery was 1.91° for Δyz . The

range of absolute angle error for all guides was 0.01° to 9.70°. The subject who produced the 9.70° error was a novice using a channel guide placing an implant in a double site. Overall, our results were within the range of previous in vitro studies reporting error using non-guided surgery, where the greatest mean deviation reported was 3.16° with a standard deviation of 1.39°.¹⁷ The mean positional error found in our study was similar to reported mean positional error for guided surgery (0.5 to 1 mm).^{16,18}

Guided surgery (guided surgical guide) produced the smallest error in mesial-distal (Δx) position but the greatest error in buccal-lingual (Δy) position. All 61 implants placed using guided surgery deviated to the palatal from their ideal position

TABLE 3

Least squared mean deviations Δ (SE) and median absolute value deviation $|\Delta|$ (range) for surgical guide design*

Guide Design	Δx M-D, mm	Δy B-L, mm	Δz C-A, mm	Δxz M-D, Degree	Δyz B-L, Degree
None	Δ 0.22 (0.04)	-0.01 (0.05)	-0.06 (0.05)	1.06 (0.29)	-1.54 (0.33)
	$ \Delta $ 0.39 (0.01-1.64)	0.22 (0.00-0.98)	0.21 (0.00-1.07)	1.62 (0.06-7.56)	2.98 (0.03-8.54)
Tube	Δ 0.10 (0.04)	-0.15 (0.05)	-0.02 (0.05)	1.69 (0.29)	-1.17 (0.33)
	$ \Delta $ 0.21 (0.00-0.70)	0.27 (0.01-0.82)	0.20 (0.00-0.87)	1.73 (0.03-5.82)	1.72 (0.01-8.40)
Channel	Δ 0.29 (0.04)	0.06 (0.05)	-0.17 (0.05)	0.68 (0.29)	-2.56 (0.33)
	$ \Delta $ 0.34 (0.01-1.51)	0.32 (0.01-0.92)	0.17 (0.01-1.81)	1.42 (0.01-4.97)	2.97 (0.18-9.70)
Guided	Δ 0.09 (0.04)	-0.62 (0.05)	0.16 (0.05)	1.64 (0.29)	1.96 (0.33)
	$ \Delta $ 0.15 (0.00-0.42)	0.55 (0.13-1.48)	0.21 (0.00-0.70)	1.67 (0.02-7.64)	1.91 (0.05-6.88)

*M-D indicates mesial-distal; B-L, buccal-lingual; C-A, coronal-apical.

TABLE 4

Least squared mean deviations Δ (SE) and median absolute value deviation $|\Delta|$ (range) for surgeon's experience*

Surgeon's Experience	Δ x M-D, mm	Δ y B-L, mm	Δ z C-A, mm	Δ xz M-D, Degree	Δ yz B-L, Degree
Novice	Δ 0.16 (0.04)	-0.23 (0.06)	-0.07 (0.07)	1.05 (0.27)	-0.75 (0.37)
	$ \Delta $ 0.24 (0.00-1.51)	0.30 (0.01-1.48)	0.18 (0.01-1.07)	1.59 (0.02-7.64)	2.45 (0.03-9.70)
Intermediate	Δ 0.15 (0.04)	-0.06 (0.06)	-0.02 (0.07)	1.12 (0.27)	-1.61 (0.37)
	$ \Delta $ 0.22 (0.00-0.90)	0.28 (0.00-1.41)	0.17 (0.00-1.01)	1.44 (0.01-5.93)	2.49 (0.01-9.03)
Experienced	Δ 0.22 (0.04)	-0.24 (0.06)	-0.02 (0.07)	1.63 (0.27)	-0.12 (0.37)
	$ \Delta $ 0.24 (0.00-1.64)	0.44 (0.01-0.98)	0.24 (0.00-1.81)	2.06 (0.02-7.56)	1.70 (0.14-6.61)

*M-D indicates mesial-distal; B-L, buccal-lingual; C-A, coronal-apical.

with the mean absolute deviation being 0.55 mm. However, the standard deviations of both Δ x and Δ y of guided group implants were lowest (SD 0.13 mm and 0.31 mm, respectively) compared to the ones of the tube, channel and no guide group implants. One possibility for this greatest error in buccal-lingual (Δ y) position of the guided group may be due to a surgical guide fabrication error, whereby the guide tube was positioned approximately 0.5 mm too palatally. Another explanation for the error could be incorrect fit of the guided surgical guide on the typodonts or movement of the guide during surgical drilling, since stability is a critical design feature of surgical guides.¹⁴ During this experiment, it was noted that movement of the precision guide sometimes occurred during drilling or during seating of the implant. If the drill was not held perfectly straight, contact between the drill and their respective sleeves may have transferred force to the guide that was greater than the finger pressure holding the guide in place.

The tolerance of fit of drills within guide

tubes and the material the guide tube is made of (plastic or metal) may also affect precision of implant placement, but this has not been reported in the literature. It is possible that other guided surgery systems with metal inserts and less difference between the internal diameter of the tubes and the respective drills may be more accurate; however, the results of this study are within the range of the reported positional error for guides with these design features (0.5 to 1 mm).^{16,18} A further possibility is that the anatomy and strength of the palatal part of the osteotomy allowed the drills to sequentially drift toward the palate.

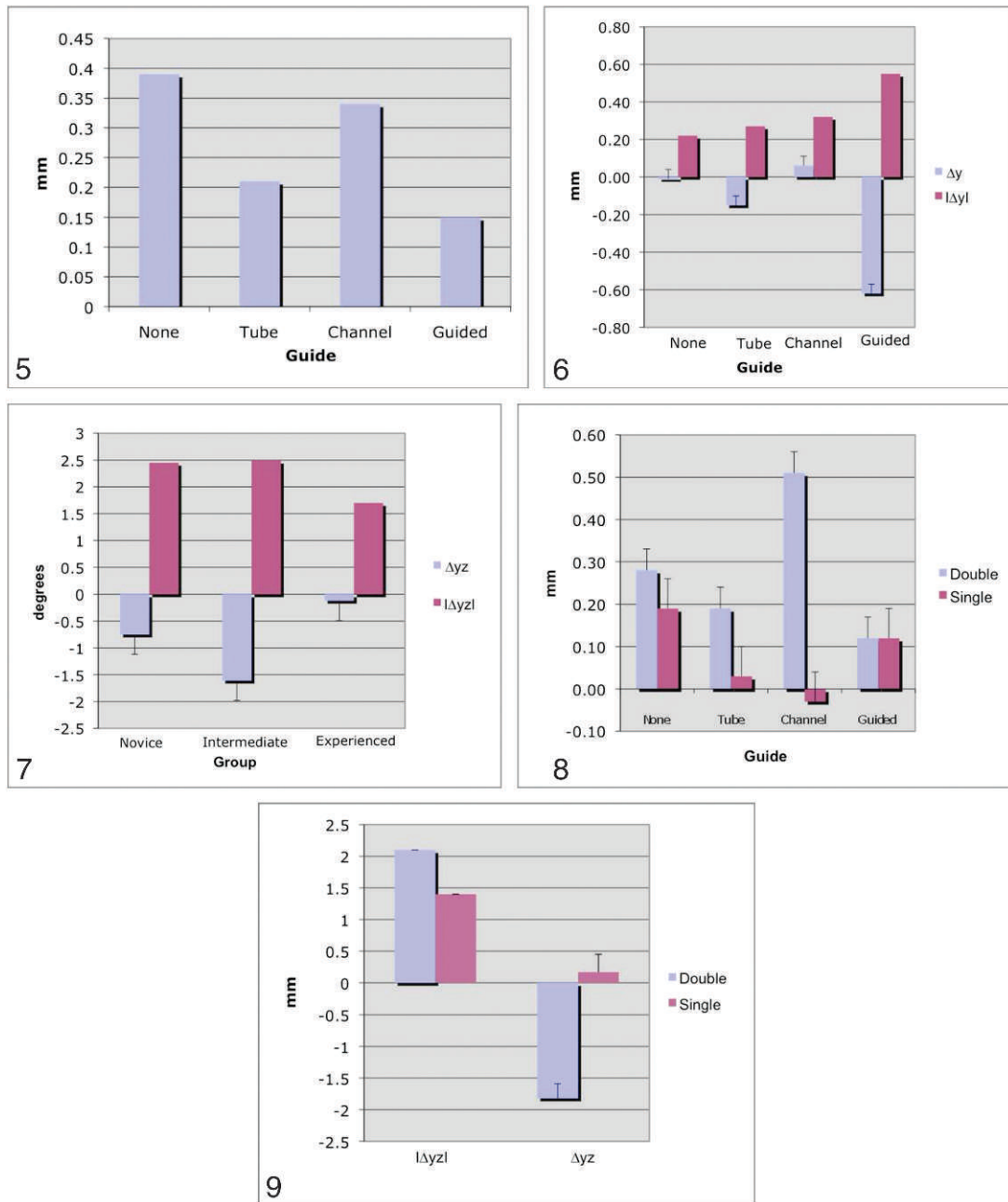
In this experiment, it was noted that if the first drill is incorrectly angled or positioned, subsequent drills have a tendency to be guided in that direction. In the guided surgery system used in this study, the first tube accommodated a 2.3-mm twist drill. Some surgeons used the 2.3-mm twist drill as their first drill, whereas others used narrower pilot drills to begin the osteotomy. If care is not taken to center a 1.6-mm drill within the center of the tube

TABLE 5

Least squared mean deviations Δ (SE) and median absolute value deviation $|\Delta|$ (range) for size of the edentulous sites*

Site Size	Δ x M-D, mm	Δ y B-L, mm	Δ z C-A, mm	Δ xz M-D, Degree	Δ yz B-L, Degree
Single	Δ 0.08 (0.04)	-0.23 (0.04)	-0.02 (0.05)	1.99 (0.25)	0.17(0.29)
	$ \Delta $ 0.21 (0.01-0.75)	0.33 (0.01-1.21)	0.20 (0.00-1.81)	2.66 (0.03-7.64)	1.83 (0.03-6.93)
Double	Δ 0.27 (0.03)	-0.12 (0.04)	-0.03 (0.04)	0.54 (0.18)	-1.82 (0.23)
	$ \Delta $ 0.27 (0.00-1.64)	0.37 (0.00-1.48)	0.20 (0.00-1.01)	1.26 (0.01-5.53)	2.76 (0.01-9.70)

*M-D indicates mesial-distal; B-L, buccal-lingual; C-A, coronal-apical.



FIGURES 5–9. **FIGURE 5.** Effect of surgical guide design on the absolute value of the distance discrepancy in x-axis ($|\Delta x|$). **FIGURE 6.** Effect of surgical guide design on the distance discrepancy in y-axis (Δy) and absolute value of the distance discrepancy in y-axis ($|\Delta y|$). **FIGURE 7.** Effect of surgeon’s experience on the angular discrepancy in the yz-plane (Δyz) and absolute value of the angular discrepancy in yz-plane ($|\Delta yz|$). **FIGURE 8.** Effect of surgical guide design and site size interaction on the distance discrepancy in x-axis (Δx). **FIGURE 9.** Effect of site size on the distance discrepancy in yz-plane (Δyz) and absolute value of the distance discrepancy in yz-plane ($|\Delta yz|$).

designed to accommodate the 2.3-mm drill, subsequent drills may have a tendency to follow the path of the first drill unless action is taken to correct the error. For tube and channel guides, the surgeon was not relying on the guide entirely so any

errors detected early in the drilling sequence could be corrected in subsequent drills. Removal of the simple guides between drills allowed surgeons to check the position and angle of osteotomies relative to adjacent teeth. This could also

be done with the guided surgery system; however, none of the subjects reported doing so. For the guided surgery, it appeared that most surgeons assumed they could rely entirely on the guide to control the drill position and angle throughout the drilling sequence, so action to correct early drilling errors did not appear to be taken as often. If the Δy (B-L position) error was due to guide fabrication error, fit or instability during drilling, then it can be concluded that the guided surgery was accurately inaccurate in buccal-lingual positioning of the implant; however, it was accurately accurate in mesial-distal positioning of the implant.

The effect of using no guide can be seen in Table 3. Overall, positional and angulation errors and absolute error of no guide are within the ranges of the tube and channel guides. This was true for all experience levels. From the results of our study, it appears that for simple surgical cases involving single and double implant sites, any guide option, including no guide, will produce equivalent accuracy regardless of the surgeon's experience level. The surgeon's personal preference and comfort zone may be the deciding factor.

Surgeon's experience had minimal effect on the accuracy of implant placement. The only difference that resulted from surgical experience was that experienced surgeons made the least amount of error in Δyz (B-L angulation). The mean difference between groups was about 1.5° , which may not be considered clinically significant. When the range of error within different experience groups is considered, it can be appreciated that the likelihood of having an esthetic or functional problem due to excessive buccal-lingual angulation error is lowest in the experienced group. The maximum Δyz error produced by experienced, intermediate, and novice surgeons was 6.6° , 9.0° , and 9.7° . An effort was made to simulate the clinical environment as much as possible, but invariably the laboratory environment is more controlled than in vivo surgery; therefore,

these differences in error occurring as a result of experience could be magnified in the clinical environment.

The main effect of site size was that double sites had more error in Δx (M-D position) ($+0.27$ mm). In this study, the resulting effect was that the 2 implants placed in the central incisor sites tended to both be placed closer to the midline. This probably occurs due to a tendency to want to avoid adjacent teeth. A surprising result was that greater angulation error in mesiodistal angulation (Δxz) occurred in single sites compared with double sites. The single site used in this study was a canine, whereas the double site was two central incisors. It is possible that surgeons found visualization of the position and angle of the canine more difficult compared to that of central incisors. The mesial-distal angulation of the central incisors was almost perpendicular to the occlusal plane, and the incisal edge could easily be imagined by referencing the incisal edges of the adjacent lateral incisors. In contrast, the mesial-distal angulation of the canine was not perpendicular to the occlusal plane. In retrospect, it may have been better to assign number 7 site as the single site and numbers 9 and 10 as the double site.

When interactions between surgical guide design and site size were analyzed, the channel guide produced significantly greater error than all other guides when used in a double site for Δx (M-D position) (0.51 mm) (followed by no guide, tube, and guided, which was the most accurate) (Figure 8). It is possible that this result occurred due to the channel guide providing the least mesiodistal guidance of all guides, while at the same time partially blocking vision of the surgical site. The channel guide also produced the greatest Δyz (B-L angulation) error in double sites, indicating that a channel type guide may not be the best choice in multiple implant sites.

The magnitude of error in position and angulation caused by surgical guide de-

sign, surgeon's experience, and site size reported in this study are possibly not large enough to be clinically significant; however, it is likely that errors would be magnified in clinical practice. Future research is recommended to evaluate the effect of surgical guide design in vivo on implant angulation and position error.

CONCLUSION

The results of this research found that surgical guide design, surgeon's experience, and size of edentulous site all statistically significantly affect the accuracy of implant placement. An angulation error in the buccal-lingual direction (Δyz) was shown to be less likely to occur in the experienced group. Overall, use of guided surgery does not improve accuracy of implant placement compared with simple guides or no guide in single or double implant situations.

ABBREVIATIONS

B-L: buccal-lingual
 CAD/CAM: computer-assisted design/computer-assisted machined
 C-A: coronal-apical
 M-D: mesial-distal

ACKNOWLEDGMENTS

Authors would like to gratefully acknowledge the American Academy of Implant Dentistry for their grant to support this research as well as Zimmer Dental for their generous donation of materials and equipment. We also would like to express our gratitude to the Minnesota Dental Research Center for Biomaterials and Biomechanics for the use of their coordinate measuring machine.

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