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

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Dedication

I dedicate this thesis to my dear wife, **Susan Hinckfuss**, for her love and support, and for traveling with me around the globe, enabling me to pursue my education.

To my children, Daisy and Henry who are my proudest achievements

Abstract

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 volunteer surgeons were recruited to participate in this study. They were divided equally 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) utilizing 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 were 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 degrees in the mesial-distal and buccal-lingual angulations respectively with an overall range of 0.01 to 9.7 degrees. 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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1. 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 non-axial forces on the implant and prosthesis.[9] Accurate implant placement may reduce surgical complications such as nerve damage, hemorrhage and unintentional perforation of the sinuses, floor of nose, and cortical plates.[10,11]

The clinically acceptable position for an individual implant is not a single point but rather a zone.[6] In order 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 may be indicated to restore appropriate dimensions. 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 cementoenamel 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 (CAL) 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.

Surgical guide designs include guides constructed with metal tubes that allow for the use of only an initial pilot drill, guides with open channels that allow for 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 osteotomy preparation and subsequent implant placement in conjunction with 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 degrees with a standard deviation of 1.39 degrees. 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 (confidence interval (CI) 200 to 275) horizontally and 254 µm (CI 185 to 320) vertically from the planned position. Axis deviations of 1.09 degrees (CI 0.85 to 1.3) were detected.[18] An in vivo evaluation of stereolithic guides found the mean linear deviation to be 1.22 mm and the mean angular deviation to be 4.9 degrees.[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 between planned and actual implant position for guides with 8 mm and 4 mm tube heights (250 µm and 240 µm respectively).[23] Stability is a critical design feature of surgical guides regardless of the channel design with tooth-born 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 surgeons' 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 of an 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. While 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 hypothesis was that surgical guide design, surgeon's experience and size of the edentulous site all potentially affect the accuracy of implant placement.

Hypothesis and Aims

The purpose of this study is to evaluate the effect of surgical guide design, surgeon's experience and size of the edentulous site on the accuracy of implant placement.

H^0: The surgical guide design, surgeon's experience and size of the edentulous site do not affect the accuracy of implant placement.

H^1: The surgical guide design, surgeon's experience and size of edentulous site affect the accuracy of implant placement.

The specific aims of this study are to determine whether:

1) Surgical guide design affects the accuracy of dental implant placement.
2) The surgeon's experience level in dental implantology affects the accuracy of dental implant placement.
3) The size of the edentulous site (single- or double- tooth site) affects the accuracy of dental implant placement.
4) The combined effect of surgical guide design, surgeon's experience level, and size of edentulous space affects the accuracy of dental implant placement.

Methods and Materials

This study was a randomized, single blind laboratory study using volunteer dental surgeons. Approval from the Institutional Review Board of the University of Minnesota was obtained. Three groups of 7 surgeons were recruited with different levels of dental implantology surgical experience. The first group (Novice) included dental students (n=7) without clinical experience in surgical implant placement. The Novice group completed an instructional laboratory course placing implants in typodonts. The second group (Intermediate) included graduate Periodontology residents (n=7) who had previously placed between 20 and 80 implants. The third group (Experienced) included Periodontists (n=7) who had surgically placed over 300 implants.

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

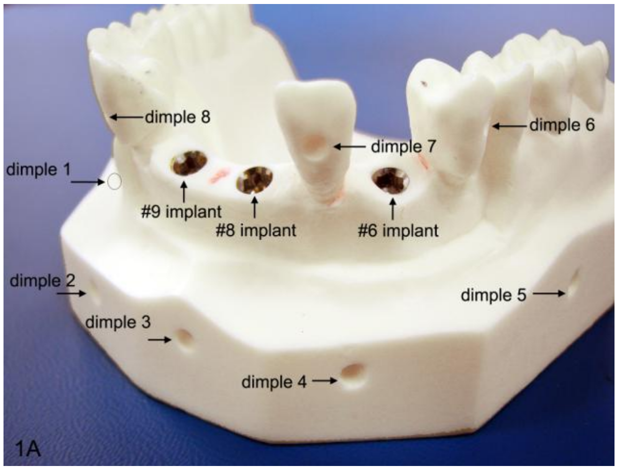


Figure 1. Definitive typodont showing 8 reference dimples and three ideal implants in #6, #8, and #9 area.

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, FL, USA) 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 enough for all the 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 (Model-based Zimmer Guided Surgery System: Dental Crafters, Marshfield, WI, USA). The Guided design also directed placement of the implant. The fourth group did not use any implant surgical guide.

(a) (b) (c)

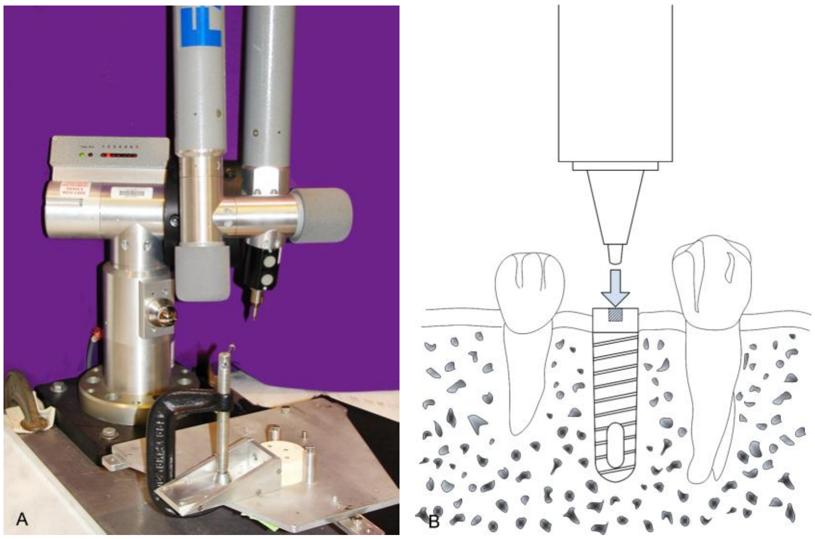
Figure 2. Three surgical guide designs; (a) Design 1 (Tube), (b) Design 2 (Channel), (c) Design 3 (Guided)

Twenty one surgeons were each provided with 4 duplicate typodonts and were asked to place three 3.7 x 13 mm dummy implants (Zimmer dental, Carlsbad, CA, USA) 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 operatories.

The ideal positioning was described to the surgeons via a written protocol before they began the osteotomy preparations on the typodonts. The sequence of surgeries was randomized among the 3 surgical guides and No guide 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, USA) 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, FL) with a single point accuracy of 76 μm. 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).



(a) (b)

Figure 3. (a) CMM (coordinate measuring machine), (b) Stylus of CMM is placed in the center of an implant cover screw to record implant’ position in x, y, z coordinates.

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. A single investigator completed all measurments of the position of the implants in the typodonts using CMM and was blind to the surgeon’s name, surgeon’s 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).

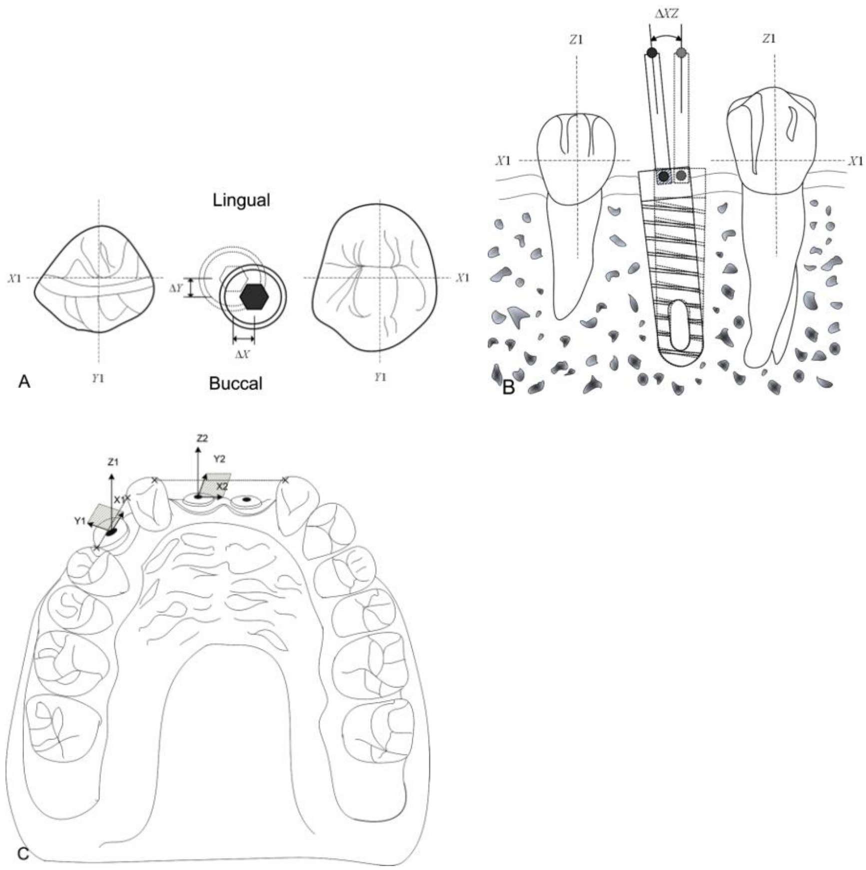


Figure 4. (A) Distance discrepancy measurement in right canine site between experimental implant (solid implant) and definitive implant (dotted implant) in X axis (Δx) and Y axis (Δy). (B) Angular discrepancy measurement in right canine site between experimental implant (solid implant) and definitive implant (dotted implant) in XZ plane (Δxz). (C) Schematic drawing of typodont showing single (#6) and double (#8 and #9) implant sites and their relative X-Y-Z axes. The x-axis was determined by the line

connecting two reference dimples on the labial surfaces of right 2nd premolar and right lateral incisor for right canine implant (single site) and by the line connecting right lateral incisor and left lateral incisor for both left and right central incisor implants (double site).

Using the coordinates of the 8 identical reference dimples, each of the 84 duplicate typodonts was mathematically overlapped against the master typodont in such a way that the sum of absolute discrepancies between 8 pairs of dimples was minimized. Linear discrepancies in position (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 level of the cummalative level of error 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, 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). In order 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 0.01 (0.05/5) were deemed statistically significant. In order to determine 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

Data for all 243 implants is shown in Appendix 1. P-values of linear (Δx, Δy, Δz) and angular (Δxz, Δyz) discrepancies and their absolute values (|Δx|, |Δy|, |Δz|, |Δxz|, |Δyz|) for surgical guide design, surgeon's experience, and size of the edentulous sites are summarized in Tables 1 and 2.

Table 1. P-values from Random Intercept Models with Interactions – linear discrepancies Δx, Δy, Δz, and absolute values of linear discrepancies |Δx|, |Δy|, |Δz|

	P-value (Type III test)					
Effect	**Δx M-D**	**|Δx|* M-D**	**Δy B-L**	**|Δy|* B-L**	**Δz C-A**	**|Δz|* C-A**
Guide Design	0.0546	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.6230
Surgeon Experience	0.2092	0.1931	0.0375	0.1680	0.6429	0.6670
Site Size	**<0.0001**	0.0973	**0.0053**	0.8873	0.7639	0.8602
Order	0.9886	0.7851	0.1288	0.3984	0.6571	0.1444
Guide*Surgeon	0.9108	0.9595	0.0767	0.5143	0.0677	0.2702
Guide*Site	**<0.0001**	0.0371	**0.0021**	0.1862	0.2754	0.3558
Surgeon*Site	0.4591	0.3648	**0.0031**	0.6094	0.9351	0.6905
Guide*Surgeon*Site	0.9520	0.5091	0.3543	0.2901	0.6397	0.9551

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

Table 2. P-values from Random Intercept Models with Interactions – angular discrepancies Δxz, Δyz and absolute values of angular discrepancies |Δxz|, |Δyz|

	P-value (Type III test)			
Effect	**Δxz M-D**	**|Δxz| * M-D**	**Δyz B-L**	**|Δyz| * B-L**
Guide Design	**0.0005**	0.0409	**<0.0001**	0.3015
Surgeon Experience	0.0382	0.0579	**0.0089**	0.6671
Site Size	**<0.0001**	**<0.0001**	**<0.0001**	**0.0014**
Order	0.7522	0.1230	0.1241	0.9176
Guide*Surgeon	0.3012	0.1260	0.0221	0.2322
Guide*Site	**<0.0001**	0.0342	**0.0036**	0.0288
Surgeon*Site	**0.0027**	0.1148	0.0169	0.9330
Guide*Surgeon*Site	0.1389	0.1522	0.8325	0.4173

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

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 surgical guide design, surgeon's experience, and size of the edentulous sites are summarized in Tables 3, 4, and 5. The absolute deviation reported is the median deviation in the respective position/angle regardless of direction.

Table 3. Least squared mean deviations Δ (SE) and median absolute value deviation |Δ| (range) for surgical guide design.

Guide Design		Δx (mm) M-D	Δy (mm) B-L	Δz (mm) C-A	Δxz (degree) M-D	Δyz (degree) B-L
None	Δ	0.22 (0.04)	-0.01 (0.05)	-0.06 (0.05)	1.06 (0.29)	-1.54 (0.33)
	|Δ|	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)
	|Δ|	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)
	|Δ|	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)
	|Δ|	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)

Table 4. Least squared mean deviations Δ (SE) and median absolute value deviation |Δ| (range) for surgeons' experience.

Surgeon's Experience		Δx (mm) M-D	Δy (mm) B-L	Δz (mm) C-A	Δxz (degree) M-D	Δyz (degree) B-L
Novice	Δ	0.16 (0.04)	-0.23 (0.06)	-0.07 (0.07)	1.05 (0.27)	-0.75 (0.37)
	|Δ|	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)
	|Δ|	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)
	|Δ|	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)

Table 5. Least squared mean deviations Δ (SE) and median absolute value deviation |Δ| (range) for size of the edentulous sites.

Site Size		Δx (mm) M-D	Δy (mm) B-L	Δz (mm) C-A	Δxz (degree) M-D	Δyz (degree) B-L
Single site	Δ	0.08 (0.04)	-0.23 (0.04)	-0.02 (0.05)	1.99 (0.25)	0.17(0.29)
	|Δ|	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 site	Δ	0.27 (0.03)	-0.12 (0.04)	-0.03 (0.04)	0.54 (0.18)	-1.82 (0.23)
	|Δ|	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)

The surgical guide design was found to significantly affect both the implant position and angle (Tables 1 & 2). Guided surgery differed significantly from all other groups in |Δx| with the guided surgery producing the lowest absolute error (Figure 5) Appendix 2(c) lists the full post hoc analysis with all statistically significant effects of guide for |Δx|.

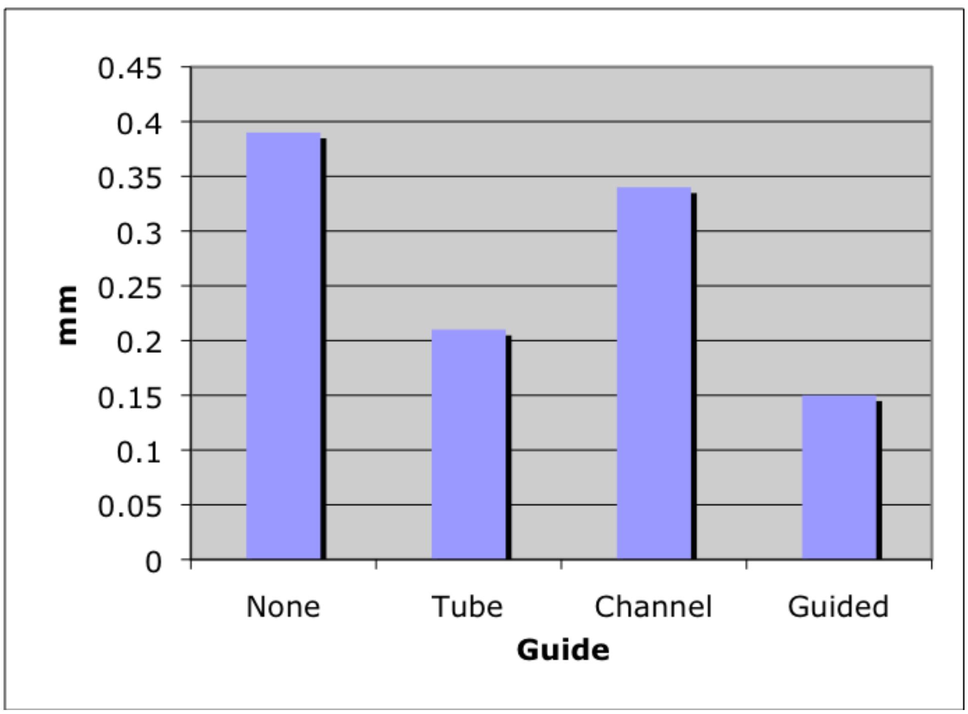


Figure 5. Effect of surgical guide design on |Δx|

For Guided surgery Δy and |Δy| were significantly greater than all other groups and the error produced by guided surgery was positioned palatally for all 61 implants (Fig 6). Appendix 2 (d) & (f) lists the full post hoc analysis of the effect of guide design on Δy and |Δy| with all statistically significant interactions.

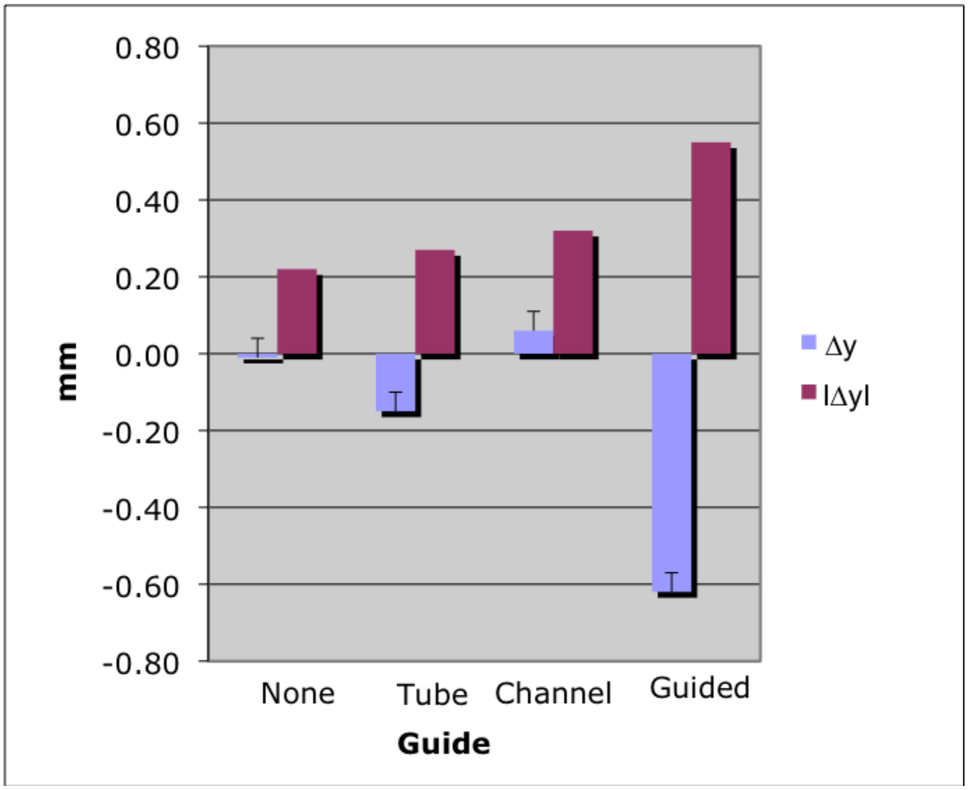


Figure 6. Effect of surgical guide design on Δy and |Δy|

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<0.0001*) (Table 3). When absolute angle deviation was compared there were no significant differences between guides (Table 2). Appendix 2 (k) lists the full post hoc analysis of the effect of guide design on Δyz with all statistically significant interactions.

Only the surgeon's experience was found to have a statistically significant affect on Δyz with experienced surgeons being more accurate than intermediate clinicians (Fig 7). Appendix 2 (k) lists the full post hoc analysis of the effect of surgeons' experience on Δyz with all statistically significant interactions. There was no significant interaction between surgical guide design and surgeon's experience.

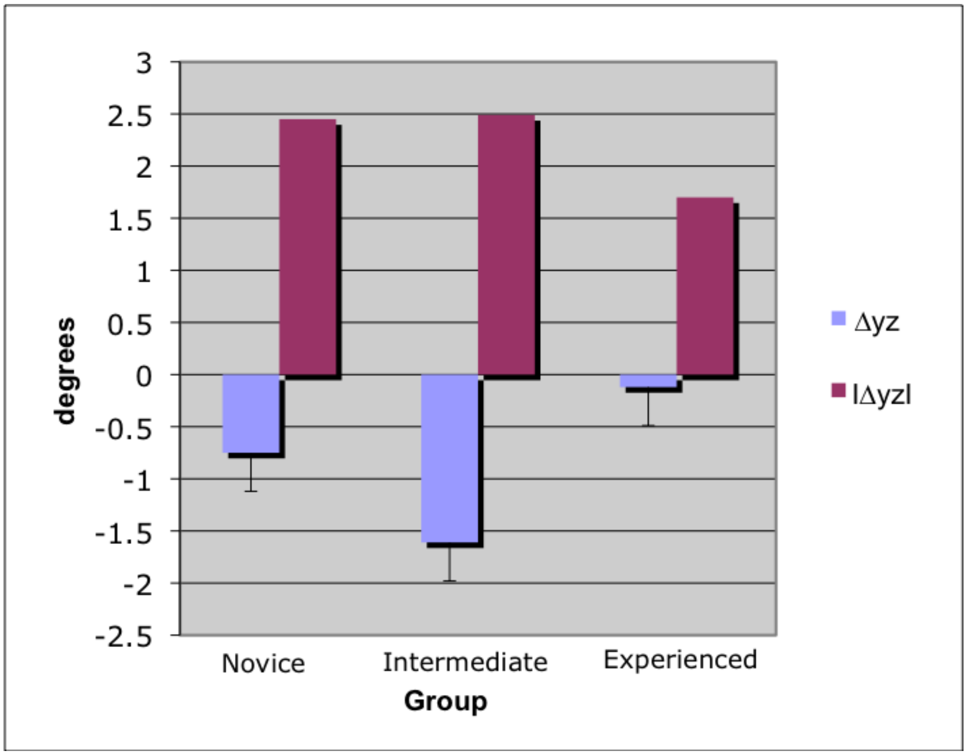


Figure 7. Effect of surgeon's experience on Δyz and lΔyzl

The size of the edentulous sites was found to affect both angle and position. Appendices 2 (a), (d), (h), (j), (k) and (m) list the full post hoc analysis of the effect of site size on Δx, Δy, Δxz, lΔxzl**,** Δyz and lΔyzl with all statistically significant interactions. The most clinically relevant finding was that 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 demonstrated the greatest discrepancy between single and double sites for Δx (Figure 8) (Appendix 2 (b)). Interaction between guide design and site size was also significant for Δy, Δxz, Δyz (Appendices 2 (e), (i) & (l)).

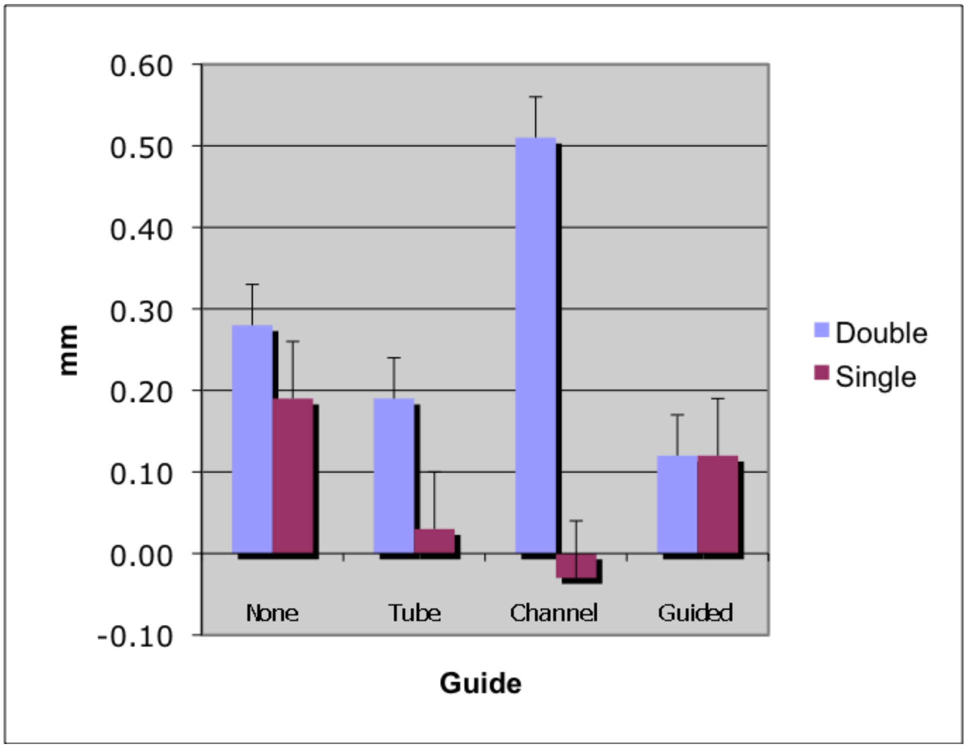


Figure 8. Effect of surgical guide design and site size interaction on Δx

Greater angulation error occurred in single implant sites for Δxz (*P<0.0001*) while greater angulation error occurred in double implant sites for Δyz (*P<0.0001*) (Table 2 and 5). The lΔyzl was significantly less in single sites compared with double sites, and the error was equally distributed buccally and lingually resulting in very small overall Δyz mean error. In double sites Δyz tended toward the palate direction (Figure 9).

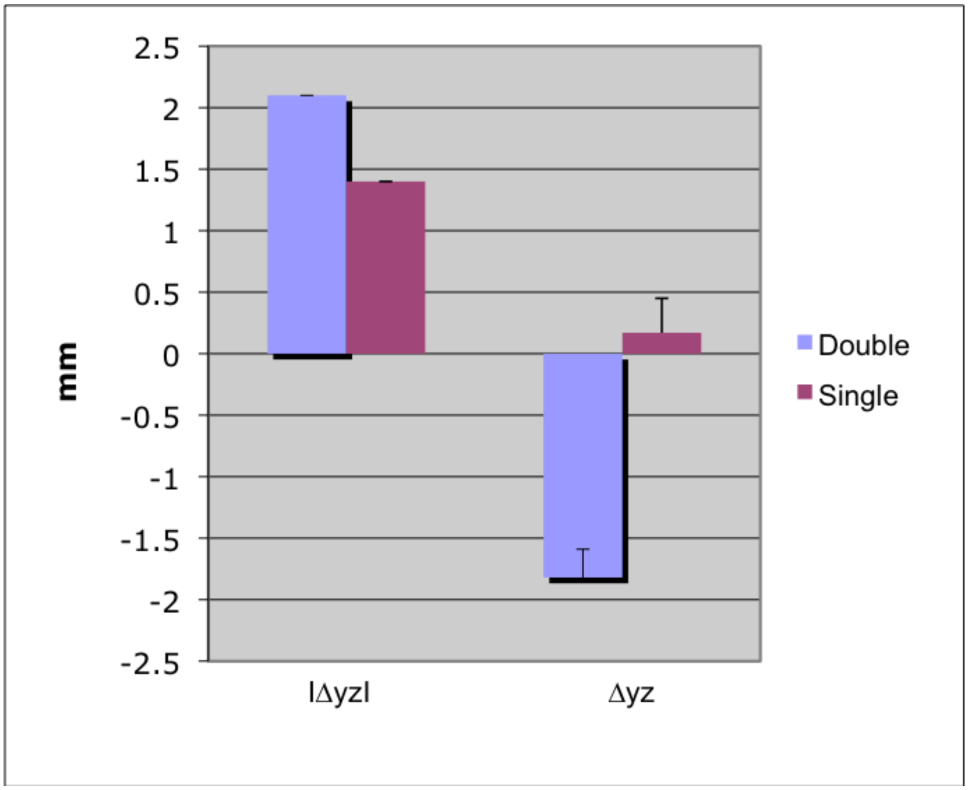


Figure 9. Effect of site size on |Δyz| and Δyz

Discussion

The data support rejection of the null hypothesis since the results of this study 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 surgeon who demonstrated 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 degrees that occurred for Δyz (B-L angulation) in the channel group while the greatest error for Guided surgery was 1.91 degrees for Δyz. The range of absolute angle error for all guides was 0.01 to 9.7 degrees. The surgeon who produced the 9.7 degree 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 degrees with a standard deviation of 1.39 degrees.[17] The mean positional error found in our study was similar to the previously reported mean positional error for guided surgery (0.5 to 1 mm).[16,18]

Guided surgery (Guided surgical guide) produced the smallest error in mesio-distal (Δx) position but greatest error in bucco-lingual (Δy) position. All 61 implants placed using Guided surgery deviated to the palatal from their ideal position with the mean absolute deviation being 0.55 mm. However, the standard deviations of both Δx

and Δy of Guided group implants were lowest (Standard Deviation 0.13 mm and 0.31 mm respectively) compared to the ones of Tube, Channel and No guide group implants (Appendix 3). One possibility for this greatest error in bucco-lingual (Δy) 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 far palatal. 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 then 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. However 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 mis-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 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 with subsequent drills. Removal of the simple guides between drilling steps allows 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 angulation throughout the drilling sequence so action to correct early drilling errors was not frequently employed. 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 consistantly inaccurate in buccal-lingual positioning of the implant; however, it was consistently accurate in the 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 with No Guide are within the ranges of the Tube and Channel guides. 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 surgeons' 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 degrees 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 bucco-lingual angulation error is lowest in the experienced group. The maximum Δyz error produced by experienced, intermediate and novice surgeons was 6.6 degrees, 9.0 degrees and 9.7 degrees. An effort was made to simulate the clinical environment as much as possible but invariably the laboratory environment was more controlled than in vivo surgery. Therefore, these differences in error occurring as a result of experience could be magnified in the clinical environment. Standard abutments are adequate to compensate for cases with angulation discrepancies less than 15 degrees. However, cases with greater than 15 degrees of angulation deviation may require use of a customized abutment. Usually this results in adequate esthetic and functional outcomes. However, the combination of an angulation error and a positional discrepancy (especially to the buccal) may result in an implant being non-restorable.

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 mesio-distal 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 mesio-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 mesio-distal angulation of the canine was not perpendicular to the occlusal plane. In retrospect, it may have been better to assign #7 site as the single site and #9 & #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 mesio-distal 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 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 of greater magnitude in clinical practice due to variability in technique and individual patient

circumstances. Considering the magnitude of error associated with use of No guide, Tube guide, Channel guided and Guided guide, surgeons need to question the merit of the addition costs associated with CAD/CAM guides for simple cases like those evaluated in this study. 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.

Bibliography

1. Akca K, Iplikcioglu H, Cehreli MC. A surgical guide for accurate mesiodistal paralleling of implants in the posterior edentulous mandible. *J Prosthet Dent*. 2002;87(2):233-235.

2. Almog DM, Torrado E, Meitner SW. Fabrication of imaging and surgical guides for dental implants. *J Prosthet Dent*. 2001;85(5):504-508.

3. Atsu SS. A surgical guide for dental implant placement in edentulous posterior regions. *J Prosthet Dent*. 2006;96(2):129-133.

4. Becker CM, Kaiser DA. Surgical guide for dental implant placement. *J Prosthet Dent*. 2000;83(2):248-251.

5. Belser U, Buser D, Higginbottom F. Consensus statements and recommended clinical procedures regarding esthetics in implant dentistry. *Int J Oral Maxillofac Implants*. 2004;19 Suppl:73-74.

6. Buser D, Martin W, Belser UC. Optimizing esthetics for implant restorations in the anterior maxilla: anatomic and surgical considerations. *Int J Oral Maxillofac Implants*. 2004;19 Suppl:43-61.

7. Dixon DL, Breeding LC. Surgical guide fabrication for an angled implant. *J Prosthet Dent*. 1996;75(5):562-565.

8. Belser UC, Schmid B, Higginbottom F, Buser D. Outcome analysis of implant restorations located in the anterior maxilla: a review of the recent literature. *Int J Oral Maxillofac Implants*. 2004;19 Suppl:30-42.

9. Rangert B, Sennerby L, Meredith N, Brunski J. Design, maintenance and biomechanical considerations in implant placement. *Dent Update*. 1997;24(10):416-420.

10. Paquette DW, Brodala N, Williams RC. Risk factors for endosseous dental implant failure. *Dent Clin North Am*. 2006;50(3):361-74, vi.

11. Goodacre CJ, Bernal G, Rungcharassaeng K, Kan JY. Clinical complications with implants and implant prostheses. *J Prosthet Dent*. 2003;90(2):121-132.

12. Buser D, Chen ST, Weber HP, Belser UC. Early implant placement following single-tooth extraction in the esthetic zone: biologic rationale and surgical procedures. *Int J Periodontics Restorative Dent*. 2008;28(5):441-451.

13. Cehreli MC, Sahin S. Fabrication of a dual-purpose surgical template for correct labiopalatal positioning of dental implants. *Int J Oral Maxillofac Implants*. 2000;15(2):278-282.

14. Di Giacomo GA, Cury PR, de Araujo NS, Sendyk WR, Sendyk CL. Clinical application of stereolithographic surgical guides for implant placement: preliminary results. *J Periodontol*. 2005;76(4):503-507.
15. Greenstein G, Cavallaro J. The relationship between biologic concepts and fabrication of surgical guides for dental implant placement. *Compend Contin Educ Dent*. 2007;28(4):196-203; quiz 204.
16. Jabero M, Sarment DP. Advanced surgical guidance technology: a review. *Implant Dent*. 2006;15(2):135-142.
17. Choi M, Romberg E, Driscoll CF. Effects of varied dimensions of surgical guides on implant angulations. *J Prosthet Dent*. 2004;92(5):463-469.
18. Dreiseidler T, Neugebauer J, Ritter L, et al. Accuracy of a newly developed integrated system for dental implant planning. *Clin Oral Implants Res*. 2009;20(11):1191-1199.
19. Ersoy AE, Turkyilmaz I, Ozan O, McGlumphy EA. Reliability of implant placement with stereolithographic surgical guides generated from computed tomography: clinical data from 94 implants. *J Periodontol*. 2008;79(8):1339-1345.
20. Kramer FJ, Baethge C, Swennen G, Rosahl S. Navigated vs. conventional implant insertion for maxillary single tooth replacement. *Clin Oral Implants Res*. 2005;16(1):60-68.
21. Nickenig HJ, Eitner S. Reliability of implant placement after virtual planning of implant positions using cone beam CT data and surgical (guide) templates. *J Craniomaxillofac Surg*. 2007;35(4-5):207-211.
22. Ozan O, Turkyilmaz I, Ersoy AE, McGlumphy EA, Rosenstiel SF. Clinical accuracy of 3 different types of computed tomography-derived stereolithographic surgical guides in implant placement. *J Oral Maxillofac Surg*. 2009;67(2):394-401.
23. Park C, Raigrodski AJ, Rosen J, Spiekerman C, London RM. Accuracy of implant placement using precision surgical guides with varying occlusogingival heights: an in vitro study. *J Prosthet Dent*. 2009;101(6):372-381.
24. Ruppin J, Popovic A, Strauss M, Spuntrup E, Steiner A, Stoll C. Evaluation of the accuracy of three different computer-aided surgery systems in dental implantology: optical tracking vs. stereolithographic splint systems. *Clin Oral Implants Res*. 2008;19(7):709-716.
25. Sarment DP, Sukovic P, Clinthorne N. Accuracy of implant placement with a stereolithographic surgical guide. *Int J Oral Maxillofac Implants*. 2003;18(4):571-577.
26. Valente F, Schiroli G, Sbrenna A. Accuracy of computer-aided oral implant surgery: a clinical and radiographic study. *Int J Oral Maxillofac Implants*. 2009;24(2):234-242.

27. Van Assche N, van Steenberghe D, Guerrero ME, et al. Accuracy of implant placement based on pre-surgical planning of three-dimensional cone-beam images: a pilot study. *J Clin Periodontol*. 2007;34(9):816-821.
28. Van Steenberghe D, Malevez C, Van Cleynenbreugel J, et al. Accuracy of drilling guides for transfer from three-dimensional CT-based planning to placement of zygoma implants in human cadavers. *Clin Oral Implants Res*. 2003;14(1):131-136.
29. Widmann G, Bale RJ. Accuracy in computer-aided implant surgery--a review. *Int J Oral Maxillofac Implants*. 2006;21(2):305-313.
30. Albrektsson T. A multicenter report on osseointegrated oral implants. *J Prosthet Dent*. 1988;60(1):75-84.
31. Preiskel HW, Tsolka P. Treatment outcomes in implant therapy: the influence of surgical and prosthodontic experience. *Int J Prosthodont*. 1995;8(3):273-279.
32. Adell R, Lekholm U, Rockler B, Branemark PI. A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. *Int J Oral Surg*. 1981;10(6):387-416.
33. Gunne J, Nystrom E, Kahnberg KE. Bone grafts and implants in the treatment of the severely resorbed maxillae: a 3-year follow-up of the prosthetic restoration. *Int J Prosthodont*. 1995;8(1):38-45.

Appendices

Appendix 1. Data for all 243 implant placed. For surgeon ID: N, I and E indicate Novice, Intermediate and Experienced groups

Surgeon ID	Guide	Order	Site	ΔX	ΔY	ΔZ	ΔXZ	ΔYZ
N1	None	NCTG	6	0.6281	-0.2708	-0.2323	-2.8545	-5.9000
N1	Tube	NCTG	6	-0.0436	-0.0476	0.1702	0.0313	-1.0268
N1	Channel	NCTG	6	0.1008	-0.3208	0.1542	0.2141	-0.7510
N1	Guided	NCTG	6	-0.0485	-0.2335	0.3513	2.8115	1.6952
N1	None	NCTG	8	0.2960	-0.1673	-0.3790	-1.5502	2.3594
N1	Tube	NCTG	8	0.4162	-0.0875	-0.1003	-1.2212	-2.7758
N1	Channel	NCTG	8	0.4546	-0.0696	-0.0433	-1.8954	-4.1845
N1	Guided	NCTG	8	0.1841	-0.8824	0.3210	-1.7391	4.0962
N1	None	NCTG	9	-0.2286	-0.3388	-0.4298	-3.7249	2.3323
N1	Tube	NCTG	9	-0.0438	-0.1552	0.0203	-1.7305	-2.2691
N1	Channel	NCTG	9	-0.1406	-0.7598	0.1061	-2.6466	0.1810
N1	Guided	NCTG	9	-0.2039	-0.4988	0.2239	0.9277	1.9566
N2	None	CTGN	6	-0.4729	0.2782	-1.0725	3.0719	-4.7687
N2	Tube	CTGN	6	-0.4464	0.2497	-0.6851	1.7155	-3.8567
N2	Channel	CTGN	6	-0.5030	-0.2953	-0.1996	3.2026	-2.4587
N2	Guided	CTGN	6	0.1773	-1.1106	-0.5130	7.6405	1.9277
N2	None	CTGN	8	-0.0657	-0.3988	-0.7475	5.5297	-4.2172
N2	Tube	CTGN	8	0.1506	0.0354	0.1727	3.4850	-3.8326
N2	Channel	CTGN	8	0.2877	0.5862	-0.3465	1.4234	-6.6292
N2	Guided	CTGN	8	0.1039	-1.4760	-0.0732	0.0526	4.7822
N2	None	CTGN	9	-0.7468	0.0155	-0.7911	-0.5490	-2.2974
N2	Tube	CTGN	9	-0.3184	-0.6741	0.2490	0.2452	-1.1569
N2	Channel	CTGN	9	-0.7188	0.0530	-0.1665	0.6434	-4.2354
N2	Guided	CTGN	9	-0.2340	-1.0624	-0.3745	0.0185	2.7400
N3	None	TGNC	6	0.5867	-0.2963	-0.1395	-2.6810	-0.2552
N3	Tube	TGNC	6	0.1101	-0.2172	-0.5326	0.4327	-2.7894
N3	Channel	TGNC	6	0.1900	-0.3624	-0.1023	2.0353	-0.2196
N3	Guided	TGNC	6	0.2129	-0.6593	0.0419	5.5814	3.4526
N3	None	TGNC	8	-0.0686	0.1873	-0.4125	-0.5814	-5.2673
N3	Tube	TGNC	8	-0.1365	-0.2220	-0.4397	1.5844	-3.6092
N3	Channel	TGNC	8	-0.0594	-0.2861	-0.2955	1.4458	-3.8115
N3	Guided	TGNC	8	0.0328	-1.0402	-0.2168	1.8163	0.6610
N3	None	TGNC	9	-0.2044	0.0778	-0.4326	-0.8702	-6.2826
N3	Tube	TGNC	9	-0.4475	0.0061	-0.3023	-1.2023	-2.3492
N3	Channel	TGNC	9	-0.7379	-0.2348	-0.3538	-0.1453	-2.3174
N3	Guided	TGNC	9	-0.2826	-0.8244	-0.1067	1.4477	2.9726
N4	None	GNCT	6	0.0280	-0.0581	0.1369	2.4100	-0.0288
N4	Tube	GNCT	6	0.0582	-0.5286	0.0618	3.3470	1.3536
N4	Channel	GNCT	6	-0.4722	0.5335	-0.4939	-2.6397	-2.4353
N4	Guided	GNCT	6	0.4193	-0.4647	-0.0572	-4.7126	1.8698

N4	None	GNCT	8	0.7111	-0.0794	0.1020	-2.5510	-3.8833
N4	Tube	GNCT	8	0.6969	-0.4256	-0.1376	-0.8154	-2.8491
N4	Channel	GNCT	8	1.5087	-0.0889	-0.2683	-0.6321	-3.8276
N4	Guided	GNCT	8	0.3164	-1.1187	0.3288	-2.5308	2.6574
N4	None	GNCT	9	-0.8632	-0.8247	0.2664	-4.5946	-1.3334
N4	Tube	GNCT	9	-0.1279	-0.7589	-0.1389	-4.6353	-0.7467
N4	Channel	GNCT	9	-0.0308	0.2763	-0.1363	-0.7812	-0.3473
N4	Guided	GNCT	9	-0.1622	-0.8649	0.1557	-1.4093	1.3360
N5	None	NCTG	6	0.3212	-0.2187	-0.3127	-1.7870	-1.4978
N5	Tube	NCTG	6	0.2526	-0.0873	-0.0292	1.9355	-0.1480
N5	Channel	NCTG	6	0.4113	-0.6461	-0.2265	0.4532	-1.2961
N5	Guided	NCTG	6	0.0376	-0.4226	0.5015	5.2350	2.7956
N5	None	NCTG	8	-0.7803	0.5015	-0.5054	2.6104	1.9867
N5	Tube	NCTG	8	0.3490	0.1122	-0.1222	1.1372	-4.6605
N5	Channel	NCTG	8	0.8371	-0.5424	-0.6302	-0.9180	-6.4823
N5	Guided	NCTG	8	0.0282	-0.6139	0.4436	-2.2456	6.8768
N5	None	NCTG	9	-0.6637	0.0736	-0.0776	-0.3715	0.0785
N5	Tube	NCTG	9	0.4131	-0.4589	0.0245	-4.2269	-0.6249
N5	Channel	NCTG	9	-0.1426	-0.3138	-0.4068	-2.7281	-2.8203
N5	Guided	NCTG	9	-0.1779	-0.6333	0.2608	-0.6476	4.1254
N6	None	CTGN	6	0.4361	0.0409	0.1177	-4.6825	5.0911
N6	Tube	CTGN	6	-0.0745	-0.1340	0.1875	0.0873	2.8638
N6	Channel	CTGN	6	0.0817	-0.0108	0.0746	-0.6114	2.4089
N6	Guided	CTGN	6	0.1111	-0.1345	0.1657	1.6180	2.0464
N6	None	CTGN	8	0.7367	-0.4194	0.0085	-1.3901	-6.1475
N6	Tube	CTGN	8	0.1991	-0.0085	-0.1160	-0.2092	-3.3594
N6	Channel	CTGN	8	0.5792	0.4122	-0.3073	-1.0146	-3.0841
N6	Guided	CTGN	8	0.0974	-0.1708	0.0905	-0.7962	-0.4013
N6	None	CTGN	9	-0.1466	-0.2334	0.1315	-2.0273	-2.9845
N6	Tube	CTGN	9	-0.1431	-0.6525	0.0244	-3.4822	-2.9800
N6	Channel	CTGN	9	-0.4077	-0.0246	-0.1677	-2.1813	-2.4046
N6	Guided	CTGN	9	0.0016	-0.2634	0.0230	-1.1810	-0.9264
N7	None	TGNC	6	-0.3834	0.1545	0.0695	0.7714	-3.4982
N7	Tube	TGNC	6	-0.6573	0.3025	0.1433	2.4463	-1.5653
N7	Channel	TGNC	6	-0.5559	0.3460	-0.0093	-0.0884	-5.8473
N7	Guided	TGNC	6	-0.2355	-0.3447	0.1495	6.6896	-1.3637
N7	None	TGNC	8	0.3256	0.8614	0.1450	1.5099	-0.4911
N7	Tube	TGNC	8	-0.3088	0.4516	0.2340	1.5859	-2.4417
N7	Channel	TGNC	8	0.3246	0.9193	-0.1566	-0.6220	-9.6985
N7	Guided	TGNC	8	-0.0042	-0.1979	0.4737	2.2060	-0.4980
N7	None	TGNC	9	-0.0276	0.5429	0.3428	0.9982	-0.8771
N7	Tube	TGNC	9	-0.4374	0.2554	0.2716	0.0937	-2.1563
N7	Channel	TGNC	9	-0.9047	0.5879	-0.0956	-0.5510	-5.5606
N7	Guided	TGNC	9	-0.1789	-0.2482	0.6186	2.7501	4.0151
I1	None	GNCT	6	0.3857	-0.1024	0.3457	1.5326	-2.4551
I1	Tube	GNCT	6	-0.2286	-0.4989	-0.3464	3.6026	-1.7460
I1	Channel	GNCT	6	-0.1412	0.3534	0.2110	-2.3016	-2.2236
I1	Guided	GNCT	6	0.2155	-0.4906	0.4490	5.6402	3.3251

I1	None	GNCT	8	0.9050	0.2132	0.0767	-1.3345	-6.8569
I1	Tube	GNCT	8	0.1894	0.1992	0.0291	0.4506	-3.9382
I1	Channel	GNCT	8	0.1648	0.4921	0.0862	-0.0121	-6.1063
I1	Guided	GNCT	8	-0.0323	-0.6995	0.2514	-1.1517	5.7583
I1	None	GNCT	9	0.0635	0.0013	0.2700	-0.4234	-3.2226
I1	Tube	GNCT	9	-0.1314	-0.3676	0.5113	-4.0010	1.7206
I1	Channel	GNCT	9	-0.3350	0.2761	0.5995	-1.6174	-2.3315
I1	Guided	GNCT	9	-0.2792	-0.4608	0.0663	0.8183	1.5585
I2	None	NCTG	6	-0.1573	0.5484	-0.1954	-0.4753	-3.7861
I2	Tube	NCTG	6	0.3209	-0.2431	0.0865	1.6432	1.4322
I2	Channel	NCTG	6	-0.3156	-0.1499	-0.0768	2.3977	-0.5162
I2	Guided	NCTG	6	0.2093	-0.4442	0.2060	3.8219	2.6472
I2	None	NCTG	8	-0.2823	0.4283	-0.3383	0.8735	-4.0353
I2	Tube	NCTG	8	-0.0049	0.3489	-0.1735	0.5974	-1.4394
I2	Channel	NCTG	8	0.0503	0.0891	-0.2458	1.8973	-3.7037
I2	Guided	NCTG	8	0.1044	-0.1614	-0.0676	-0.2349	-2.9362
I2	None	NCTG	9	-0.5340	0.0595	-0.1384	-0.2583	-3.0349
I2	Tube	NCTG	9	-0.0766	0.3239	-0.1339	-0.2182	-0.8301
I2	Channel	NCTG	9	-0.8392	-0.0331	-0.1313	1.5141	-3.1873
I2	Guided	NCTG	9	-0.1699	-0.7224	-0.1275	-1.6678	0.2866
I3	None	CTGN	6	0.0119	-0.3968	0.0550	3.1857	0.7278
I3	Tube	CTGN	6	0.0148	-0.1736	0.0572	5.6296	1.7506
I3	Channel	CTGN	6	0.2079	-0.1705	-0.1076	2.3931	0.7643
I3	Guided	CTGN	6	-0.0282	-0.5127	0.2473	5.2843	2.7366
I3	None	CTGN	8	-0.2232	0.0008	-0.1625	-0.5975	-6.3119
I3	Tube	CTGN	8	0.1221	0.0443	0.1526	-2.1192	-1.3748
I3	Channel	CTGN	8	0.7575	-0.3726	0.0814	0.5468	-1.0557
I3	Guided	CTGN	8	0.0786	-0.3587	0.4503	-0.5812	0.5526
I3	None	CTGN	9	-0.7461	-0.2292	-0.0280	-1.6172	-3.4773
I3	Tube	CTGN	9	-0.1198	-0.0690	0.3268	-3.1442	1.3928
I3	Channel	CTGN	9	-0.2579	0.3739	-0.0196	-0.2586	0.8753
I3	Guided	CTGN	9	-0.0919	-0.2212	0.2904	-0.8037	0.6921
I4	None	TGNC	6	0.2685	0.3299	-0.0816	-4.7591	-4.4221
I4	Tube	TGNC	6	0.2593	0.2849	-0.1978	-5.8188	-4.2377
I4	Channel	TGNC	6	0.0754	0.4405	-0.1554	-4.8316	-2.3686
I4	Guided	TGNC	6	0.3342	-0.6898	0.3807	2.3883	1.7838
I4	None	TGNC	8	-0.3681	0.2057	-0.2537	0.4680	-7.7560
I4	Tube	TGNC	8	0.5311	0.6288	-0.1184	-0.3310	-8.4026
I4	Channel	TGNC	8	0.2371	0.4965	-0.0489	-0.2973	-7.0575
I4	Guided	TGNC	8	0.0305	-1.0040	0.7017	0.1392	4.7539
I4	None	TGNC	9	-0.4767	-0.0398	-0.0406	-1.0129	-6.9429
I4	Tube	TGNC	9	-0.4101	0.1823	0.0734	0.5199	-5.9167
I4	Channel	TGNC	9	-0.4563	0.5192	-0.0370	-0.6888	-4.7671
I4	Guided	TGNC	9	-0.2637	-0.7512	0.6157	1.6659	3.8354
I5	None	GNCT	6	-0.0102	-0.0278	-0.0019	2.7454	0.9436
I5	Tube	GNCT	6	0.0565	-0.1229	-0.0677	3.7704	2.3458
I5	Channel	GNCT	6	0.0078	-0.2769	-0.1987	2.4821	0.8242
I5	Guided	GNCT	6	0.1207	-1.2089	-0.1501	5.9289	3.3961

I5	None	GNCT	8	-0.5518	0.3859	0.2522	2.4792	-0.9546
I5	Tube	GNCT	8	-0.1697	0.2692	-0.4899	0.7150	-2.2829
I5	Channel	GNCT	8	0.3058	0.1131	-0.1392	1.5251	-4.6598
I5	Guided	GNCT	8	-0.0038	-1.4053	0.1993	1.2470	1.9120
I5	None	GNCT	9	-0.7517	0.0159	0.4325	0.0627	-0.3199
I5	Tube	GNCT	9	-0.5014	0.0817	-0.2740	-1.1926	0.0083
I5	Channel	GNCT	9	-0.2197	0.0304	0.0064	1.3557	-2.9659
I5	Guided	GNCT	9	-0.2815	-1.0119	0.0937	-1.2115	-0.2386
I6	None	NCTG	6	-0.1587	0.3040	-0.1765	0.1603	-6.9287
I6	Tube	NCTG	6	0.2078	0.3366	-0.4661	1.6875	-2.6993
I6	Channel	NCTG	6	-0.2078	-0.0682	-0.4247	0.2034	-2.0458
I6	Guided	NCTG	6	-0.1715	-0.1755	-0.2633	0.1881	0.0464
I6	None	NCTG	8	0.5979	0.5903	-0.1636	1.3974	-8.5405
I6	Tube	NCTG	8	-0.3972	0.2623	-0.7464	3.5397	-2.7779
I6	Channel	NCTG	8	0.3912	0.0273	-1.0145	1.1290	-6.4267
I6	Guided	NCTG	8	0.0021	-0.3338	-0.3775	3.2089	-4.1784
I6	None	NCTG	9	-0.7608	0.7373	-0.5730	1.4811	-4.7935
I6	Tube	NCTG	9	-0.5324	-0.4524	-0.8668	-3.5623	-7.0307
I6	Channel	NCTG	9	-0.8295	-0.6633	-0.6479	-2.1236	-5.6380
I6	Guided	NCTG	9	-0.2072	-0.5332	-0.1197	-1.1015	-1.0275
I7	None	CTGN	6	0.3888	-0.0377	0.2853	2.2179	-0.1644
I7	Tube	CTGN	6	0.2313	-0.0735	0.2293	2.5697	0.6151
I7	Channel	CTGN	6	-0.2090	0.0803	-0.0115	2.0026	-2.5255
I7	Guided	CTGN	6	-0.0136	-0.2066	0.1023	3.5130	-0.3425
I7	None	CTGN	8	0.4517	0.1168	0.0654	-1.3380	-3.2584
I7	Tube	CTGN	8	0.2310	0.6248	0.0854	-0.4805	-2.3902
I7	Channel	CTGN	8	0.4746	0.4631	-0.1669	-1.2668	-9.0322
I7	Guided	CTGN	8	0.0939	-0.3829	-0.1127	0.8187	-0.6104
I7	None	CTGN	9	-0.3233	0.0507	-0.0641	2.3564	-0.2291
I7	Tube	CTGN	9	0.0939	-0.2191	-0.0032	-2.6032	1.0086
I7	Channel	CTGN	9	-0.6735	0.0270	0.1544	-0.1532	-3.3263
I7	Guided	CTGN	9	0.0104	-0.2513	0.1919	-0.8660	0.3721
E1	None	TGNC	6	-0.5203	-0.3897	-0.0556	7.5622	4.0419
E1	Tube	TGNC	6	0.0223	-0.4216	0.2917	1.7742	1.0827
E1	Channel	TGNC	6	-0.0781	-0.3328	0.0072	1.3284	1.1619
E1	Guided	TGNC	6	-0.0058	-0.6074	0.4753	7.1013	1.1777
E1	None	TGNC	8	-0.5963	0.0746	-0.2112	2.5983	1.7089
E1	Tube	TGNC	8	0.2792	-0.6031	0.3087	0.0719	-1.7240
E1	Channel	TGNC	8	0.6342	0.8785	-0.6104	-0.8231	-2.7337
E1	Guided	TGNC	8	-0.0081	-0.8174	-0.0102	2.7941	-1.3561
E1	None	TGNC	9	-1.6363	0.1950	-0.2363	1.2299	0.5224
E1	Tube	TGNC	9	-0.1477	-0.3026	0.4648	-2.5638	-0.8790
E1	Channel	TGNC	9	-0.1746	0.7412	-0.5330	-3.0117	-0.1946
E1	Guided	TGNC	9	0.0303	-0.5691	0.3027	-0.1426	1.5184
E2	None	GNCT	6	0.4882	-0.7015	0.3255	6.0936	5.0287
E2	Tube	GNCT	6	-0.1347	-0.1196	-0.2799	2.0007	1.3835
E2	Channel	GNCT	6	-0.1979	-0.0724	0.0389	0.8543	0.6366
E2	Guided	GNCT	6	0.1497	-0.5928	0.2085	7.4180	4.8677

E2	None	GNCT	8	-0.0223	0.8286	-0.1642	-3.8952	1.6421
E2	Tube	GNCT	8	0.3837	0.4506	-0.2727	-2.7497	-4.9005
E2	Channel	GNCT	8	1.2917	0.6504	-0.1732	-4.9718	-5.0149
E2	Guided	GNCT	8	0.0935	-0.5149	0.1455	-1.7604	4.6903
E2	None	GNCT	9	-0.1667	-0.1032	0.2899	-3.4807	3.4406
E2	Tube	GNCT	9	0.1473	-0.1927	0.1373	-3.5482	-0.7937
E2	Channel	GNCT	9	-0.0121	0.4141	-0.0487	-3.7084	-4.0598
E2	Guided	GNCT	9	-0.0702	-0.6138	-0.0015	-3.1432	1.0293
E3	None	NCTG	6	0.5926	-0.4479	0.3176	1.4824	-0.1405
E3	Tube	NCTG	6	0.0435	-0.4212	0.2321	3.6927	0.5513
E3	Channel	NCTG	6	0.4998	-0.5174	0.3731	1.4762	0.4322
E3	Guided	NCTG	6	0.2948	-0.4229	0.3825	3.3449	3.0476
E3	None	NCTG	8	0.2264	0.0296	0.1956	-1.0647	-3.7353
E3	Tube	NCTG	8	0.3359	0.0162	0.3094	-0.8135	-1.6833
E3	Channel	NCTG	8	0.6455	0.1305	0.0626	-1.0491	-3.8788
E3	Guided	NCTG	8	0.2273	-0.8655	0.4530	-0.6034	3.8504
E3	None	NCTG	9	-0.3585	-0.2845	0.4442	-0.3357	-0.4834
E3	Tube	NCTG	9	-0.1427	-0.5625	0.6269	-1.1728	1.6014
E3	Channel	NCTG	9	-0.6375	0.2165	0.0428	-0.9269	-3.1354
E3	Guided	NCTG	9	-0.1632	-0.5431	0.4160	0.5956	1.9871
E4	None	CTGN	6	0.7539	-0.9781	0.4097	3.1895	4.0651
E4	Tube	CTGN	6	0.2189	-0.7309	0.5066	5.4943	1.4761
E4	Channel	CTGN	6	0.2132	-0.5440	0.2247	3.7953	2.1425
E4	Guided	CTGN	6	0.3334	-0.5439	0.0701	1.4462	3.0402
E4	None	CTGN	8	-0.4673	-0.0866	-0.0037	-1.2366	-1.6279
E4	Tube	CTGN	8	0.1847	-0.4256	0.3521	-0.5009	-3.0158
E4	Channel	CTGN	8	0.2952	-0.2831	-0.0144	-1.5670	-4.9961
E4	Guided	CTGN	8	0.4040	-0.7197	0.5700	-3.1032	1.9626
E4	None	CTGN	9	-0.1205	-0.6906	0.3460	-2.1173	-1.5418
E4	Tube	CTGN	9	-0.2587	-0.5234	0.5493	-0.7165	0.6623
E4	Channel	CTGN	9	-0.3822	-0.5408	0.1379	-2.2626	-1.7769
E4	Guided	CTGN	9	-0.1001	-0.6496	-0.2037	-3.1602	-1.0465
E5	None	TGNC	6	0.4351	-0.3596	-0.0110	4.7240	-0.4605
E5	Tube	TGNC	6	0.0535	0.0665	-0.3105	3.7706	-0.1970
E5	Channel	TGNC	6	0.6826	-0.1371	0.2407	3.4006	2.3445
E5	Guided	TGNC	6	0.2166	-0.4119	0.2636	3.2379	0.8222
E5	None	TGNC	8	0.4819	0.2055	-0.3639	-0.2759	-4.3365
E5	Tube	TGNC	8	0.2247	0.0054	-0.1866	3.0273	-1.1677
E5	Channel	TGNC	8	0.4367	-0.2385	-0.1637	0.0176	-6.6073
E5	Guided	TGNC	8	-0.0014	-0.4870	0.2456	0.6412	-1.8047
E5	None	TGNC	9	-1.0239	0.1651	-0.2875	1.6782	-2.8354
E5	Tube	TGNC	9	-0.3472	0.3702	-0.0467	1.9291	0.7177
E5	Channel	TGNC	9	-0.9601	0.0262	-0.5055	-0.5716	-4.0477
E5	Guided	TGNC	9	-0.2043	-0.4358	0.1556	1.6002	-0.7692
E6	None	GNCT	6	0.0826	0.2300	-0.0884	3.2838	1.1536
E6	Tube	GNCT	6	0.5741	-0.8230	-0.5847	-0.6553	0.3211
E6	Channel	GNCT	6	-0.1665	-0.0429	-0.4058	-1.1915	0.9574
E6	Guided	GNCT	6	0.2183	-0.5998	0.2677	2.3790	3.6720

E6	None	GNCT	8	-0.4025	0.1170	-0.0384	0.0904	0.4630
E6	Tube	GNCT	8	0.3635	-0.3957	0.1157	-1.2817	-3.5179
E6	Channel	GNCT	8	1.0940	0.8080	-0.3285	-3.8579	-5.2590
E6	Guided	GNCT	8	0.2446	-0.9320	0.0762	-1.2396	1.1248
E6	None	GNCT	9	-0.3073	0.0872	0.2086	-1.2348	-3.0769
E6	Tube	GNCT	9	-0.1072	-0.7684	-0.2143	-3.4292	-4.8235
E6	Channel	GNCT	9	-0.4259	0.7321	-0.2366	-1.7853	-5.0443
E6	Guided	GNCT	9	0.0639	-0.6953	-0.1985	-5.1931	-1.5133
E7	None	NCTG	6	0.2074	-0.2995	-0.1975	3.0357	-4.4015
E7	Tube	NCTG	6	-0.1642	-0.5115	-0.3065	3.8261	-0.3894
E7	Channel	NCTG	6	-0.3258	-0.0402	-1.8090	0.6095	0.4788
E7	Guided	NCTG	6	0.0528	-0.5513	0.0221	4.4749	2.3694
E7	None	NCTG	8	-0.3733	-0.0774	-0.2583	2.6645	-2.8825
E7	Tube	NCTG	8	-0.0593	-0.1772	-0.1262	0.6182	-2.7259
E7	Channel	NCTG	8	0.9835	0.8085	-0.5425	-3.2111	-4.8768
E7	Guided	NCTG	8	-0.0580	-0.4602	0.1702	-0.7116	0.7178
E7	None	NCTG	9	-1.3356	0.5903	-0.2858	-4.1396	-1.0992
E7	Tube	NCTG	9	-0.5831	-0.2342	-0.0070	-3.0779	-1.0745
E7	Channel	NCTG	9	-0.2458	0.6470	-0.4932	-3.8817	-5.6059
E7	Guided	NCTG	9	-0.2389	-0.6060	0.1900	-0.3842	1.6040

Appendix 2. Post hoc analyses

A2 (a): Significant differences for Δx: Site size

Effect	SIZE	_SIZE	Estimate	StdErr	Probt
SIZE	Double	Single	0.20	0.04	0.0000

A2 (b): Significant differences for Δx: Site size*Guide design

Effect	SIZE	GUIDE	_SIZE	_GUIDE	Estimate	StdErr	Probt
SIZE*GUIDE	Double	Channel	Double	Guided	0.38	0.07	0.0000
SIZE*GUIDE	Double	Channel	Double	None	0.22	0.07	0.0018
SIZE*GUIDE	Double	Channel	Double	Tube	0.32	0.07	0.0000
SIZE*GUIDE	Double	Channel	Single	Channel	0.54	0.09	0.0000
SIZE*GUIDE	Double	Channel	Single	Guided	0.38	0.09	0.0000
SIZE*GUIDE	Double	Channel	Single	None	0.32	0.09	0.0003
SIZE*GUIDE	Double	Channel	Single	Tube	0.47	0.09	0.0000
SIZE*GUIDE	Double	Guided	Double	None	-0.16	0.07	0.0232
SIZE*GUIDE	Double	Guided	Double	Tube	-0.06	0.07	0.3676
SIZE*GUIDE	Double	Guided	Single	Channel	0.16	0.09	0.0718
SIZE*GUIDE	Double	Guided	Single	Guided	0.00	0.09	0.9860
SIZE*GUIDE	Double	Guided	Single	None	-0.06	0.09	0.4582
SIZE*GUIDE	Double	Guided	Single	Tube	0.09	0.09	0.2959
SIZE*GUIDE	Double	None	Double	Tube	0.10	0.07	0.1678
SIZE*GUIDE	Double	None	Single	Channel	0.32	0.09	0.0003

SIZE*GUIDE	Double	None	Single	Guided	0.16	0.09	0.0657
SIZE*GUIDE	Double	None	Single	None	0.10	0.09	0.2622
SIZE*GUIDE	Double	None	Single	Tube	0.25	0.09	0.0039
SIZE*GUIDE	Double	Tube	Single	Channel	0.22	0.09	0.0116
SIZE*GUIDE	Double	Tube	Single	Guided	0.06	0.09	0.4725
SIZE*GUIDE	Double	Tube	Single	None	0.00	0.09	0.9953
SIZE*GUIDE	Double	Tube	Single	Tube	0.15	0.09	0.0757
SIZE*GUIDE	Single	Channel	Single	Guided	-0.16	0.10	0.1150
SIZE*GUIDE	Single	Channel	Single	None	-0.22	0.10	0.0281
SIZE*GUIDE	Single	Channel	Single	Tube	-0.07	0.10	0.5100
SIZE*GUIDE	Single	Guided	Single	None	-0.06	0.10	0.5304
SIZE*GUIDE	Single	Guided	Single	Tube	0.09	0.10	0.3572
SIZE*GUIDE	Single	None	Single	Tube	0.15	0.10	0.1224

A2 (c): Significant differences for $|\Delta x|$: Guide design

Effect	GUIDE	_GUIDE	Estimate*	StdErr	Probt
GUIDE	Channel	Guided	1.28	0.20	0.0000
GUIDE	Channel	None	-0.02	0.20	0.9162
GUIDE	Channel	Tube	0.51	0.20	0.0120
GUIDE	Guided	None	-1.30	0.20	0.0000
GUIDE	Guided	Tube	-0.77	0.20	0.0002
GUIDE	None	Tube	0.54	0.20	0.0089
*log scale of absolute values					

A2 (d): Significant differences for Δy: Site size, Guide design

Effect	SIZE	GUIDE	_SIZE	_GUIDE	Estimate	StdErr	Probt
SIZE	Double		Single		0.11	0.04	0.0110
GUIDE		Channel		Guided	0.68	0.06	0.0000
GUIDE		Channel		None	0.07	0.06	0.2315
GUIDE		Channel		Tube	0.21	0.06	0.0005
GUIDE		Guided		None	-0.61	0.06	0.0000
GUIDE		Guided		Tube	-0.48	0.06	0.0000
GUIDE		None		Tube	0.14	0.06	0.0196

A2 (e): Significant differences for Δy: Guide*Site size, Surgeon group*Site size

Effect	GRP	SIZE	GUIDE	GRP	_SIZE	_GUIDE	Est	SE	Probt
SIZE*GUIDE		Double	Channel		Double	Guided	0.82	0.07	0.0000
SIZE*GUIDE		Double	Channel		Double	None	0.09	0.07	0.1498
SIZE*GUIDE		Double	Channel		Double	Tube	0.27	0.07	0.0000
SIZE*GUIDE		Double	Channel		Single	Channel	0.28	0.08	0.0005
SIZE*GUIDE		Double	Channel		Single	Guided	0.69	0.08	0.0000
SIZE*GUIDE		Double	Channel		Single	None	0.30	0.08	0.0002
SIZE*GUIDE		Double	Channel		Single	Tube	0.36	0.08	0.0000
SIZE*GUIDE		Double	Guided		Double	None	-0.73	0.07	0.0000
SIZE*GUIDE		Double	Guided		Double	Tube	-0.55	0.07	0.0000
SIZE*GUIDE		Double	Guided		Single	Channel	-0.54	0.08	0.0000
SIZE*GUIDE		Double	Guided		Single	Guided	-0.13	0.08	0.1060
SIZE*GUIDE		Double	Guided		Single	None	-0.52	0.08	0.0000
SIZE*GUIDE		Double	Guided		Single	Tube	-0.46	0.08	0.0000
SIZE*GUIDE		Double	None		Double	Tube	0.18	0.07	0.0070
SIZE*GUIDE		Double	None		Single	Channel	0.19	0.08	0.0201
SIZE*GUIDE		Double	None		Single	Guided	0.60	0.08	0.0000
SIZE*GUIDE		Double	None		Single	None	0.21	0.08	0.0095
SIZE*GUIDE		Double	None		Single	Tube	0.27	0.08	0.0010
SIZE*GUIDE		Double	Tube		Single	Channel	0.01	0.08	0.9050
SIZE*GUIDE		Double	Tube		Single	Guided	0.42	0.08	0.0000
SIZE*GUIDE		Double	Tube		Single	None	0.03	0.08	0.6921
SIZE*GUIDE		Double	Tube		Single	Tube	0.09	0.08	0.2635
SIZE*GUIDE		Single	Channel		Single	Guided	0.41	0.09	0.0000
SIZE*GUIDE		Single	Channel		Single	None	0.02	0.09	0.8106
SIZE*GUIDE		Single	Channel		Single	Tube	0.08	0.09	0.3866
SIZE*GUIDE		Single	Guided		Single	None	-0.39	0.09	0.0000
SIZE*GUIDE		Single	Guided		Single	Tube	-0.33	0.09	0.0004
SIZE*GUIDE		Single	None		Single	Tube	0.06	0.09	0.5310
GROUP*SIZE	1	Double		1	Single		-0.04	0.07	0.5623
GROUP*SIZE	1	Double		2	Double		-0.21	0.09	0.0202
GROUP*SIZE	1	Double		2	Single		-0.12	0.10	0.2109
GROUP*SIZE	1	Double		3	Double		-0.10	0.09	0.2553
GROUP*SIZE	1	Double		3	Single		0.19	0.10	0.0459
GROUP*SIZE	1	Single		2	Double		-0.17	0.10	0.0881
GROUP*SIZE	1	Single		2	Single		-0.08	0.10	0.4396
GROUP*SIZE	1	Single		3	Double		-0.06	0.10	0.5350
GROUP*SIZE	1	Single		3	Single		0.23	0.10	0.0261
GROUP*SIZE	2	Double		2	Single		0.08	0.07	0.2241
GROUP*SIZE	2	Double		3	Double		0.11	0.09	0.2316
GROUP*SIZE	2	Double		3	Single		0.40	0.10	0.0001
GROUP*SIZE	2	Single		3	Double		0.02	0.10	0.8286
GROUP*SIZE	2	Single		3	Single		0.31	0.10	0.0029
GROUP*SIZE	3	Double		3	Single		0.29	0.07	0.0000

A2 (f): Significant differences for l∆yl: Guide design

Effect	GUIDE	_GUIDE	Estimate*	StdErr	Probt
GUIDE	Channel	Guided	-0.84	0.19	0.0000
GUIDE	Channel	None	0.33	0.19	0.0759
GUIDE	Channel	Tube	0.08	0.19	0.6860
GUIDE	Guided	None	1.18	0.19	0.0000
GUIDE	Guided	Tube	0.92	0.19	0.0000
GUIDE	None	Tube	-0.26	0.19	0.1694
*log scale of absolute values					

A2 (g): Significant differences for ∆z: Guide design

Effect	GUIDE	_GUIDE	Estimate	StdErr	Probt
GUIDE	Channel	Guided	-0.33	0.04	0.0000
GUIDE	Channel	None	-0.11	0.04	0.0142
GUIDE	Channel	Tube	-0.15	0.04	0.0008
GUIDE	Guided	None	0.22	0.04	0.0000
GUIDE	Guided	Tube	0.19	0.04	0.0000
GUIDE	None	Tube	-0.04	0.04	0.3643

A2 (h): Significant differences for ∆xz: Site size, Guide design

Effect	SIZE	GUIDE	_SIZE	_GUIDE	Estimate	StdErr	Probt
SIZE	Double		Single		-1.45	0.27	0.0000
GUIDE		Channel		Guided	-1.51	0.38	0.0001
GUIDE		Channel		None	-0.44	0.38	0.2510
GUIDE		Channel		Tube	-1.09	0.38	0.0051
GUIDE		Guided		None	1.07	0.38	0.0059
GUIDE		Guided		Tube	0.42	0.38	0.2731
GUIDE		None		Tube	-0.64	0.38	0.0942

A2 (i): Significant differences for ∆xz: Guide*Site, Surgeon*Site

Effect	GROUP	SIZE	GUIDE	_GROUP	_SIZE	_GUIDE	Estimate	StdErr	Probt
SIZE*GUIDE		Double	Channel		Double	Guided	0.12	0.44	0.7865
SIZE*GUIDE		Double	Channel		Double	None	-0.26	0.44	0.5549
SIZE*GUIDE		Double	Channel		Double	Tube	-0.85	0.44	0.0566
SIZE*GUIDE		Double	Channel		Single	Channel	-0.43	0.54	0.4300
SIZE*GUIDE		Double	Channel		Single	Guided	-3.56	0.54	0.0000
SIZE*GUIDE		Double	Channel		Single	None	-1.05	0.54	0.0542
SIZE*GUIDE		Double	Channel		Single	Tube	-1.75	0.54	0.0014

SIZE*GUIDE		Double	Guided		Double	None	-0.38	0.44	0.3893
SIZE*GUIDE		Double	Guided		Double	Tube	-0.97	0.44	0.0298
SIZE*GUIDE		Double	Guided		Single	Channel	-0.55	0.54	0.3126
SIZE*GUIDE		Double	Guided		Single	Guided	-3.68	0.54	0.0000
SIZE*GUIDE		Double	Guided		Single	None	-1.17	0.54	0.0321
SIZE*GUIDE		Double	Guided		Single	Tube	-1.87	0.54	0.0007
SIZE*GUIDE		Double	None		Double	Tube	-0.59	0.44	0.1864
SIZE*GUIDE		Double	None		Single	Channel	-0.17	0.54	0.7585
SIZE*GUIDE		Double	None		Single	Guided	-3.30	0.54	0.0000
SIZE*GUIDE		Double	None		Single	None	-0.79	0.54	0.1477
SIZE*GUIDE		Double	None		Single	Tube	-1.49	0.54	0.0065
SIZE*GUIDE		Double	Tube		Single	Channel	0.42	0.54	0.4396
SIZE*GUIDE		Double	Tube		Single	Guided	-2.72	0.54	0.0000
SIZE*GUIDE		Double	Tube		Single	None	-0.20	0.54	0.7112
SIZE*GUIDE		Double	Tube		Single	Tube	-0.90	0.54	0.0971
SIZE*GUIDE		Single	Channel		Single	Guided	-3.14	0.63	0.0000
SIZE*GUIDE		Single	Channel		Single	None	-0.62	0.63	0.3225
SIZE*GUIDE		Single	Channel		Single	Tube	-1.32	0.63	0.0357
SIZE*GUIDE		Single	Guided		Single	None	2.51	0.63	0.0001
SIZE*GUIDE		Single	Guided		Single	Tube	1.81	0.63	0.0042
SIZE*GUIDE		Single	None		Single	Tube	-0.70	0.63	0.2631
GROUP*SIZE	1	Double		1	Single		-0.48	0.47	0.3039
GROUP*SIZE	1	Double		2	Double		0.14	0.44	0.7474
GROUP*SIZE	1	Double		2	Single		-0.99	0.52	0.0558
GROUP*SIZE	1	Double		3	Double		0.17	0.44	0.7064
GROUP*SIZE	1	Double		3	Single		-2.57	0.52	0.0000
GROUP*SIZE	1	Single		2	Double		0.63	0.52	0.2269
GROUP*SIZE	1	Single		2	Single		-0.51	0.58	0.3837
GROUP*SIZE	1	Single		3	Double		0.65	0.52	0.2097
GROUP*SIZE	1	Single		3	Single		-2.08	0.58	0.0004
GROUP*SIZE	2	Double		2	Single		-1.14	0.47	0.0165
GROUP*SIZE	2	Double		3	Double		0.02	0.44	0.9565
GROUP*SIZE	2	Double		3	Single		-2.71	0.52	0.0000
GROUP*SIZE	2	Single		3	Double		1.16	0.52	0.0259
GROUP*SIZE	2	Single		3	Single		-1.58	0.58	0.0075
GROUP*SIZE	3	Double		3	Single		-2.73	0.47	0.0000

A2 (j): Significant differences for $|\Delta xz|$: Site size

Effect	SIZE	_SIZE	Estimate*	StdErr	Probt
Size	Double	Single	-0.65	0.14	0.0000
*log scale of absolute values					

A2 (k): Significant differences for ∆yz: Surgeon group, Site Size and Guide design

Effect	GROUP	SIZE	GUIDE	GROUP	_SIZE	_GUIDE	Estimate	StdErr	Probt
GROUP	1			2			0.86	0.52	0.0984
GROUP	1			3			-0.63	0.52	0.2233
GROUP	2			3			-1.49	0.52	0.0043
SIZE		Double			Single		-1.98	0.30	0.0000
GUIDE			Channel			Guided	-4.52	0.40	0.0000
GUIDE			Channel			None	-1.02	0.40	0.0115
GUIDE			Channel			Tube	-1.39	0.40	0.0006
GUIDE			Guided			None	3.50	0.40	0.0000
GUIDE			Guided			Tube	3.13	0.40	0.0000
GUIDE			None			Tube	-0.37	0.40	0.3539

A2 (l): Significant differences for ∆yz: Guide*Site

Effect	SIZE	GUIDE	_SIZE	_GUIDE	Estimate	StdErr	Probt
SIZE*GUIDE	Double	Channel	Double	Guided	-5.45	0.45	0.0000
SIZE*GUIDE	Double	Channel	Double	None	-1.70	0.45	0.0002
SIZE*GUIDE	Double	Channel	Double	Tube	-1.92	0.45	0.0000
SIZE*GUIDE	Double	Channel	Single	Channel	-3.59	0.55	0.0000
SIZE*GUIDE	Double	Channel	Single	Guided	-6.23	0.55	0.0000
SIZE*GUIDE	Double	Channel	Single	None	-3.25	0.55	0.0000
SIZE*GUIDE	Double	Channel	Single	Tube	-3.93	0.55	0.0000
SIZE*GUIDE	Double	Guided	Double	None	3.76	0.45	0.0000
SIZE*GUIDE	Double	Guided	Double	Tube	3.54	0.45	0.0000
SIZE*GUIDE	Double	Guided	Single	Channel	1.86	0.55	0.0008
SIZE*GUIDE	Double	Guided	Single	Guided	-0.78	0.55	0.1551
SIZE*GUIDE	Double	Guided	Single	None	2.20	0.55	0.0001
SIZE*GUIDE	Double	Guided	Single	Tube	1.53	0.55	0.0060
SIZE*GUIDE	Double	None	Double	Tube	-0.22	0.45	0.6253
SIZE*GUIDE	Double	None	Single	Channel	-1.89	0.55	0.0007
SIZE*GUIDE	Double	None	Single	Guided	-4.54	0.55	0.0000
SIZE*GUIDE	Double	None	Single	None	-1.55	0.55	0.0051
SIZE*GUIDE	Double	None	Single	Tube	-2.23	0.55	0.0001
SIZE*GUIDE	Double	Tube	Single	Channel	-1.67	0.55	0.0026
SIZE*GUIDE	Double	Tube	Single	Guided	-4.32	0.55	0.0000
SIZE*GUIDE	Double	Tube	Single	None	-1.34	0.55	0.0159
SIZE*GUIDE	Double	Tube	Single	Tube	-2.01	0.55	0.0003
SIZE*GUIDE	Single	Channel	Single	Guided	-2.65	0.63	0.0000
SIZE*GUIDE	Single	Channel	Single	None	0.34	0.63	0.5934
SIZE*GUIDE	Single	Channel	Single	Tube	-0.34	0.63	0.5967
SIZE*GUIDE	Single	Guided	Single	None	2.98	0.63	0.0000
SIZE*GUIDE	Single	Guided	Single	Tube	2.31	0.63	0.0003
SIZE*GUIDE	Single	None	Single	Tube	-0.68	0.63	0.2883

A2 (m): Significant differences for |Δyz|: Site size

Effect	SIZE	_SIZE	Estimate*	StdErr	Probt
Size	Double	Single	0.41	0.13	0.0022
*log scale of absolute values					

Appendix 3. Standard deviations

Guide	N	Delta X Standard Deviation	Delta Y Standard Deviation	Delta Z Standard Deviation	XZ Angle Standard Deviation	YZ Angle Standard Deviation
Channel	63	0.43	0.43	0.34	1.99	2.77
Guided	63	0.13	0.31	0.26	2.81	2.17
None	63	0.48	0.38	0.31	2.54	3.23
Tube	63	0.27	0.36	0.32	2.15	2.33