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Accuracy of computer-guided implantation in a human cadaver model

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Abstract

Objectives: To examine the accuracy of computer-guided implantation using a human cadaver model with reduced experimental variability.

Materials and methods: Twenty-eight (28) dental implants representing 12 clinical cases were placed in four cadaver heads using a static guided implantation template. All planning and surgeries were performed by one clinician. All radiographs and measurements were performed by two examiners. The distance of the implants from buccal and lingual bone and mesial implant or tooth was analyzed at the apical and coronal levels, and measurements were compared to the planned values.

Results: No significant differences were seen between planned and implanted measurements. Average deviation of an implant from its planning radiograph was 0.8 mm, which is within the range of variability expected from CT analysis.

Conclusions: Guided implantation can be used safely with a margin of error of 1 mm.

More than 2 million dental implants are inserted into patients in the United States annually, and this number is expected to increase each year (American Dental Association 2007). As dental implants become the preferred choice for patients to restore missing teeth, methods for improving implant surgery have also been developed (Cibirka et al. 1997; Esposito et al. 2012; Vogel et al. 2013).

The development of cone-beam computed tomography (CBCT) has allowed dentists to plan surgical procedures based on a three-dimensional (3D) model of the patient's mouth. A major advantage that 3D imaging offers in planning procedures is preventing disruption of anatomic structures, in particular the lower mandibular nerve and upper sinus Schneiderian membrane (Brief et al. 2005). Compared with traditional CT imaging, CBCT has similar resolution but with lower radiation dosage (Liang et al. 2010). However, manual placement of implants with prior CBCT planning is still limited by the ability to insert the implant in the correct position and angulation. Manual implantation also requires an open flap surgery that results in alveolar crest bone loss from a decrease in supraperiosteal blood supply during surgery (Rousseau 2010).

The introduction of computer-guided surgery templates allows for minimally invasive flapless surgery and immediate loading, resulting in reduced postoperative pain for the patient (Hultin et al. 2012). Guided surgery has gained much popularity with a mean implant survival rate of 96% after 36 months (Valente et al. 2009). The technology can also be used to reduce the number of bone augmentation and sinus lifts. Implants can be inserted into a narrow ridge; angulated implants can be used, and the insertion of an implant into non-bony tissues such as nerve can be avoided. Other advantages of computer-guided implantation include a reduced surgical time of <1 h, better alignment between implants, and the ability to plan more precisely for implants (Balshi et al. 2006; Jabero & Sarment 2006). The use of guided implantation has been concluded to be more accurate than freehand insertion (Park et al. 2009). In a direct comparison study between guided implant placement vs. manual freehand placement, use of CBCT and an implant guide resulted in significantly smaller variation between the treatment plan

and the actual clinical placement (Nickenig et al. 2010). Deviation at the implant shoulder ranging from 0 to 4.5 mm was detected with use of an implant guide, while manual placement resulted in a much larger deviation ranging from 0 to 7.0 mm.

The accuracy of computer-guided implantation varies between studies due to different clinical and experimental setups (Hultin et al. 2012). A review of surgical template accuracy provides different values and ranges for *in vitro*, *ex vivo*, and clinical studies (D'Haese et al. 2012). It has also been shown previously that the experience level of the clinician can result in significant differences in accuracy (Van de Velde et al. 2008). Because error can arise from various steps in the process, it is unclear whether deviation of the resulting implant location from the planned location was a result of the guiding template (resolution from CBCT or template manufacturing) or environmental factors. The experience of the surgeon, regional location in the mouth, type of software and template, and transfer of information between entities can all contribute to deviation from the initially planned implant location.

The purpose of this study was to analyze accuracy of computer-guided dental implantation in a reduced-variability environment. We hypothesized that using computer-guided implantation with reduced human variability will increase accuracy of implant insertion and the implanted location will not be statistically different than the planned implant location. In this study, 12 clinical cases with 28 implants were implanted in human cadaver heads. All CT scans were performed in the same machine and by the same operator, and surgical procedures were planned by one clinician and executed by one surgeon. Measurements were made and analyzed by two examiners and were compared to the original plans for each implant.

Material and methods

Four whole human cadaver heads were retrieved and their mouths were examined. An impression of both jaws was taken, and a cast was made. The specimens were obtained from the USA bone bank for research only, and the study was performed in Israel under approval by the Ministry of Health. A specific CT guide with facial markers was created and used for pre-implantation scans of each cadaver head. The CT scan was used with a specific setup to obtain the CBCT radiographic scans, which allowed for scan-

ning the heads before and after implantation without altering alignment.

AB Guided Service (Ashdod, Israel) was used to plan the insertion of each implant using guided implantation. The treatment plan for each case and the plan of the AB Guide models were approved by one clinician. The AB Guided models were ordered using the AB Denpax software program. AB Guided surgical templates, an AB Guided surgical kit, and suggested implants and crowns were provided as a gift by AB Dental and were used for implantation.

Twelve (12) implantation cases were planned in four cadaver heads, with a total of 28 implants (Table 1). Cases were planned in edentulous areas only, with each cadaver head accommodating 2–4 cases. Implant length and diameter were planned according to anatomic structures on the CBCT scan. Implants were placed in the incisive, premolar, and molar areas of the mouth, covering both the upper and lower jaws (Table 2). The implantation of all implants was performed by one clinician according to the original plan. The guide was inserted and stabilized by pins, and the implant was inserted through the gingiva according to the company's guidance to the appropriate depth.

After implantation, CBCT scans were retaken. Measurements between the location of implants in CT at the time of planning and after implantation were made at the coronal and apical levels to determine the distance between the implant and buccal bone, lingual bone, and adjacent (mesial) implant/teeth by two independent examiners, which were previously calibrated (Fig. 1). All

CBCT scans were performed by the same individual to reduce user variation.

Statistical analyses: Paired *t*-test was used to compare between planned and implanted groups, while unpaired *t*-test was used for comparison between regional implant location and across groups. All planned vs. implanted analyses were performed on different CBCT scans and analyzed separately to be considered independent. One way analysis of variance with Bonferroni post-test correction was used to compare across three groups, with significance for all statistical analyses set at $P < 0.05$. All cases were planned and implanted by the same clinician. All calibration, measurements, and analyses were performed by two examiners (data combined together) after calibration between them.

Results

Two of the twelve cases are presented as case studies in Figs 2 and 3. In the first case (Fig. 2), teeth 24–26 were extracted and the plan to rehabilitate this area with three implants can be seen in the panoramic figure obtained from the CT scan in Fig. 2a. The location of the implants on the CT at the coronal occlusal plane can be seen in Fig. 2c, and on the apical plane in Fig. 2d. A cross section of the CT shows the three implants in Fig 2g–i. The surgery guide was then produced and can be seen in the buccal view in Fig. 2m, and occlusal view in Fig. 2n. The superposition of the planned and inserted implants is presented in panoramic, occlusal (coronal and apical), and cross-sectional

Table 1. Cases and implants per case for each cadaver head

Case no.	Head no.	Implant site	Anterior	Posterior	Length (mm)	Diameter (mm)
1	1	44 45 46		3	13 10 8	3.2 3.2 3.75
2	1	36		1	11.5	3.75
3	1	11	1		13	3.2
4	1	24 25 26		3	13 13 11.5	3.75 3.75 4.2
5	2	46 47		2	13 13	4.2 4.2
6	2	35 36 37		3	13 13 13	3.75 4.2 5
7	2	24		1	13	3.75
8	3	36 37		2	10 8	3.2 3.75
9	3	46		1	8	3.75
10	4	34 35 36 37		4	13 10 10 8	4.2 3.2 3.75 3.75
11	4	45 46 47		3	11.5 10 8	3.2 3.75 4.2
12	4	11 15 21 25	2	2	13 16 11.5 16	3 3.2 3 3.2

Table 2. Total number of cases, implants, and regional placement

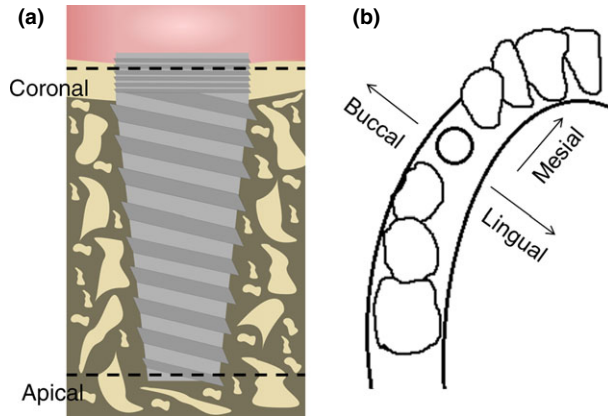| No. of case	No. of implant	No. of implant incisive	No. of implant premolar	No. of implant molar	No. of implant upper jaw	No. of implant lower jaw
12	28	3	11	14	9	19

Fig. 1. Apical and coronal direction of the implant (a) and buccal, lingual, and mesial direction of analysis from implant (b).

views in Fig. 2b,e,f,j,k,l, respectively. The implant restoration bridge was examined first in the model in Fig. 2o and then inserted in the mouth for implantation as shown in Fig. 2p.

In the second case (Fig. 3), teeth 46–47 were extracted and the rehabilitation plan for this area with two implants can be seen in the panoramic figure obtained from the CT scan in Fig. 3a. The location of the implants

on the CT at the coronal-occlusal plane can be seen in Fig. 3c, and the apical plane in Fig. 3d. A cross section of the CT shows the two implants in Fig 3g,h. The surgery guide was produced and can be seen in buccal view in Fig. 2k and occlusal view in Fig. 2l. The superposition of the planned and inserted implants are present in panoramic, occlusal (coronary and apically) and on cross sectional views in Fig. 2b,e and 2f,i, and 2j, respectively.

To reduce statistical bias, analyses were performed by case and by implant. Analyses per case revealed no significant differences between planned and implanted locations in buccal, lingual, and mesial directions, both at the coronal and apical levels (Fig. 4, Table 3). Although the deviation in distance was higher at the apex compared to the coronal plane, deviation from each direction was not statistically significant in either plane.
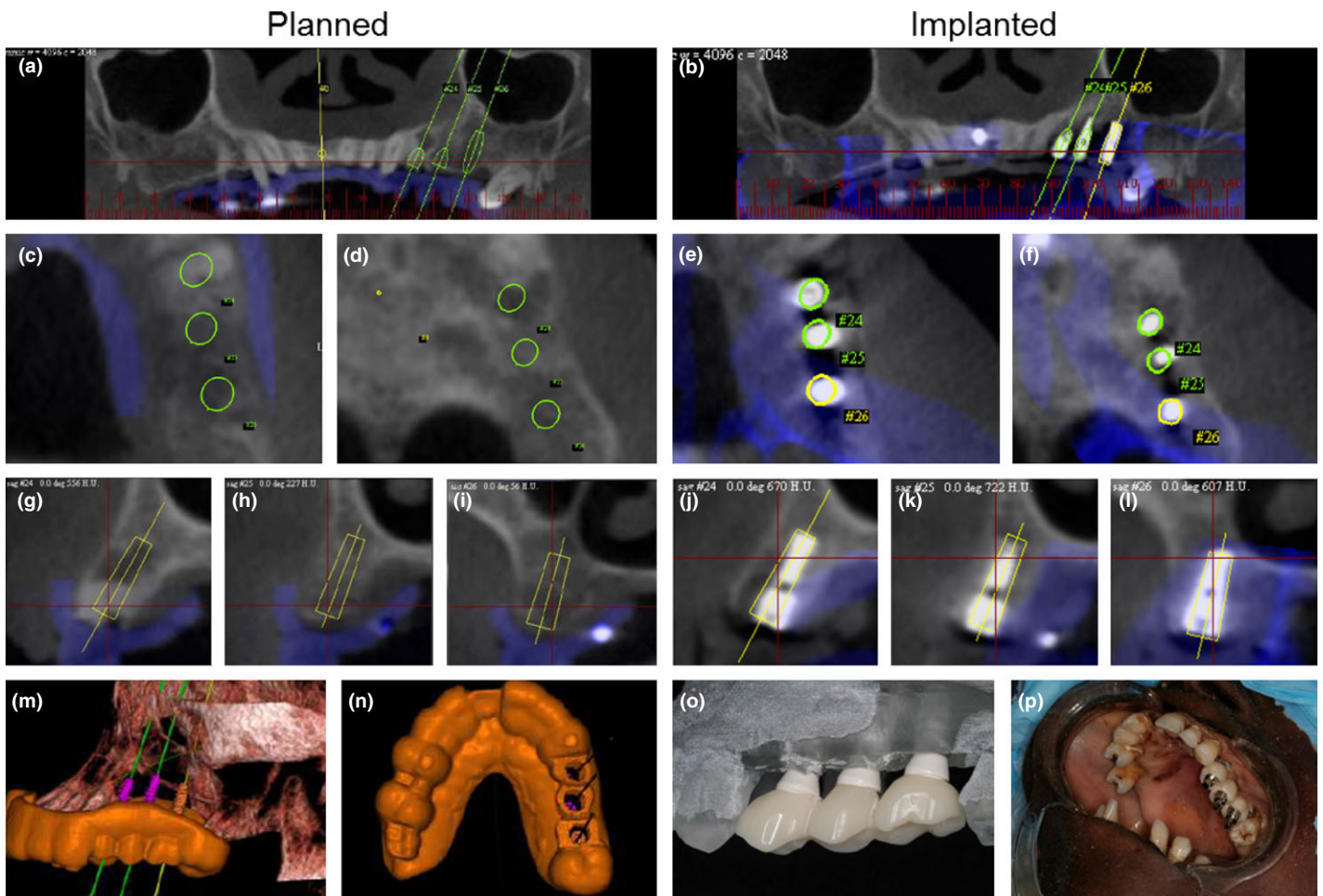

Fig. 2. Case showing planned (a, c, d, g, h, i, m, n) and implanted (b, e, f, j, k, l, o, p) images of guided implant placement in the maxilla. CBCT scans were taken of patients before (a) and after (b) implant placement, showing outline of planned implant (a, b) and location of the actual implant (b). Cross-sectional slices for location analysis were performed for planned (c, d) and implanted (e, f) implants at the coronal (c, e) and apical (d, f) levels. Close-up images of each implant placed from original CBCT scans (a, b) are shown before (g–i) and after implantation (j–l). A 3D reconstructed view of the maxilla with surgical guide (m, n) was used for implant placement. A model of the maxilla with planned implants (o) was used in selection of appropriate crown size that transferred to each finished case (p).
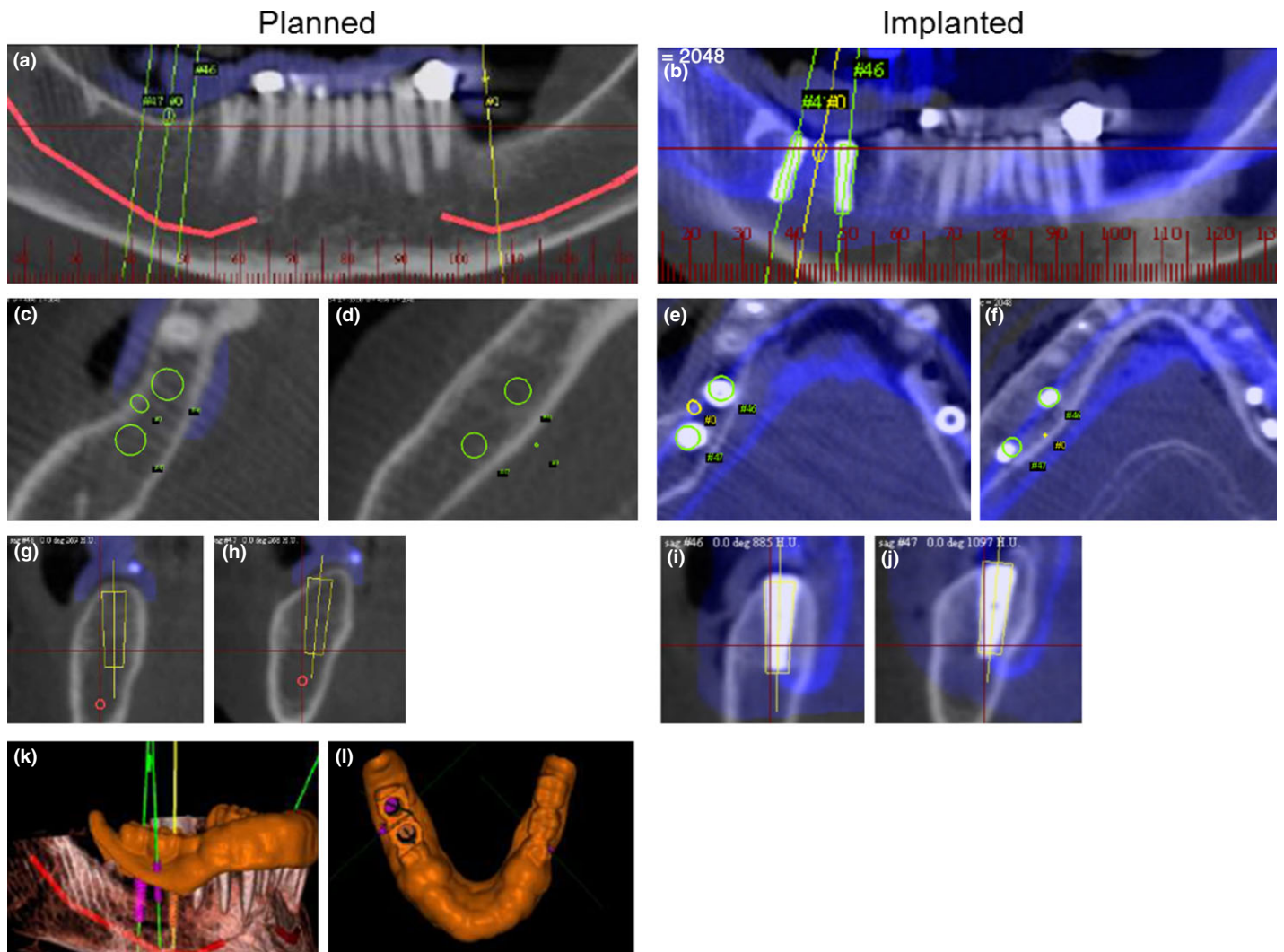
Fig. 3. Case showing planned (a, c, d, g, h, k, l) and implanted (b, e, f, i, j) images of guided implant placement in the mandible. CBCT scans were taken of patients before (a) and after (b) implant placement, showing outline of planned implant (a, b) and location of actual implant (b). Cross-sectional slices for location analysis were performed for planned (c, d) and implanted (e, f) implants at the coronal (c, e) and apical (d, f) levels. Close-up images of each implant placed from original CBCT scans (a, b) are shown before (g, h) and after implantation (i, j). A 3D reconstructed view of the mandible with surgical guide (k, l) was used for implant placement.
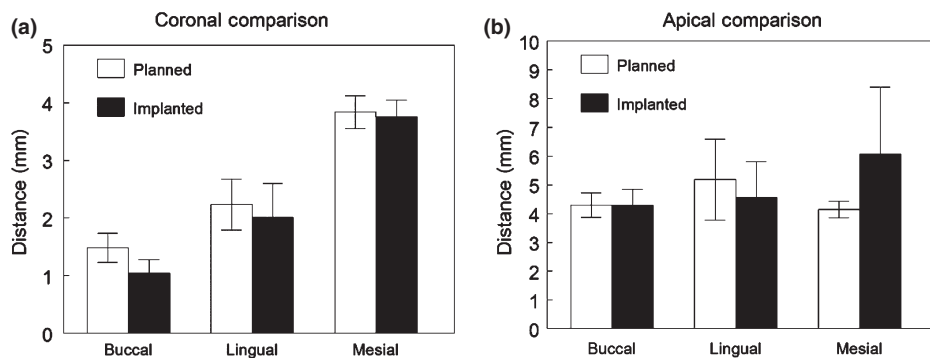

Fig. 4. Coronal and apical location analysis by case. Implant location was analyzed at the coronal (a) and apical (b) levels for planned and implanted sites. Student's *t*-test across planned and implanted locations showed no significant differences between groups.

Analyses per implant also showed no significant differences between planned and implanted locations in any direction (Fig. 5). Per implant analysis revealed a higher range of deviation from planned locations, but deviations were not significantly different in buccal, lingual, or mesial directions. Apical deviation in the mesial direction was the highest compared with buccal and lingual directions and the coronal plane.

Analyses per implant comparing implant locations between the premolar and molar areas did not show significant deviation from planned locations in the coronal plane (Fig. 6). Analyses were not performed for the incisive area due to the low number of implants that were placed in the region. Molar implant placement was characterized by a high standard deviation in the mesial direction. Analyses per implant comparing locations between the upper and lower jaw also did not show statistical significance from planned locations in the coronal plane.

The overall average error was 0.8 mm across all directions. The average error and standard deviation per case was 0.8 ± 0.1 mm and per implant was 0.9 ± 0.1 mm. The range of deviation between implanted and planned locations

Table 3. Difference between planned and implanted locations

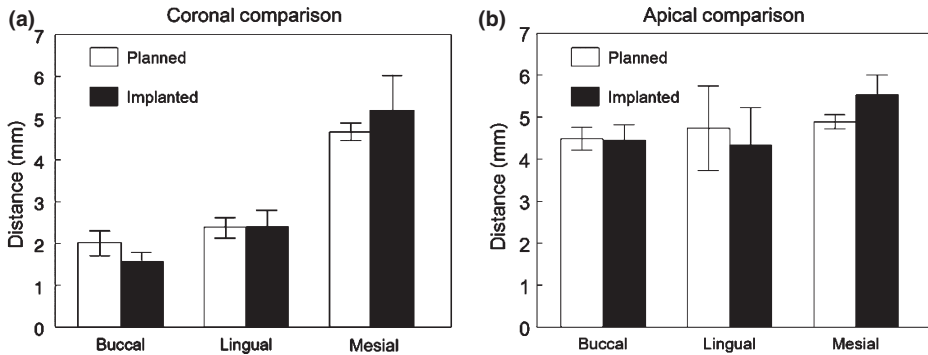| Difference between measurement (mm)		Buccal			Lingual			Mesial		
Analysis per	Location	Mean	SEM	Median	Mean	SEM	Median	Mean	SEM	Median
Case	Apical	0.70	0.19	0.65	0.86	0.26	0.88	1.13	0.42	0.98
Case	Coronal	0.74	0.13	0.55	0.78	0.22	0.78	0.41	0.09	0.59
Implant	Apical	0.72	0.12	0.48	0.82	0.20	0.98	2.1	1.10	1.76
Implant	Coronal	0.78	0.10	0.69	0.89	0.25	0.69	1.06	0.54	0.86

Fig. 5. Coronal and apical location analysis by implant. Implant location was analyzed at the coronal (a) and apical (b) levels for planned and implanted sites. Student's *t*-test across planned and implanted locations showed no significant differences between groups.
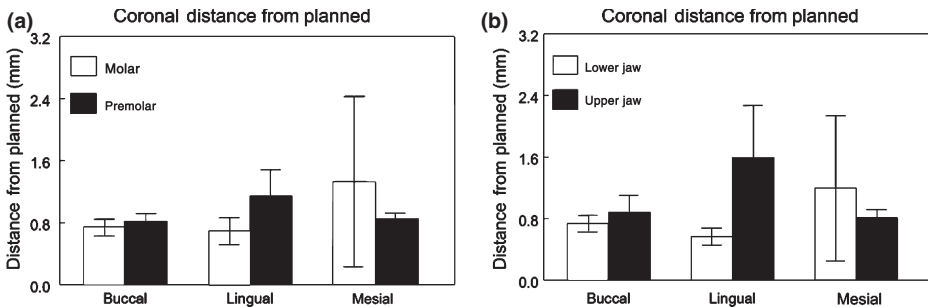

Fig. 6. Regional analysis by implant. Distance from buccal and lingual bone and mesially to adjacent tooth/implant was evaluated for planned and inserted implants in the molar and premolar regions (a) and lower and upper jaw (b). Student's *t*-test across molar vs. premolar and lower vs. upper jaw showed no significance differences between groups.

was greater mesially, as indicated by higher standard deviations in Figs 4d, 5b,d, 6a,b.

Discussion

With an increasing number of dental implant guides being used, it is important to analyze the accuracy of these systems in a controlled clinical environment. To reduce experimental variability while still remaining biologically relevant, we assessed placement accuracy for implants that were planned and performed consistently by the same clinician. Our results show that when using this guided implant system, final implant locations are not statistically different from planned locations, corroborating our original hypothesis.

Our novel cadaveric model provides a clinically relevant analysis of implant placement error resulting from the use of surgical guides, while upholding scientific rigor by reducing experimental variance.

In this study, average deviation was 0.8 mm, which is well accepted and within the lower range of error in the literature. It was also observed that the range of deviation was higher at the apex compared to the coronal plane. This has also been observed in the literature, and is due to changes in the placement angle, which was not measured in this study (Ersoy et al. 2008; Schneider et al. 2009; Van Assche et al. 2012). It has also been suggested that higher error in the apical plane could be attributed to the type of drill (cylindrical or tapered) being using (Arisan

et al. 2010). Careful planning can help ensure an appropriate implant length to prevent damage to the maxillary sinus or mandibular nerve.

The number and distribution of remaining teeth as well as the number of steps in producing and using the template can contribute to error (Behneke et al. 2012). In addition, implants placed with the same guide are not independent from each other and errors are interactive and possibly cumulative (Widmann & Bale 2006). It has been shown that error occurring during image acquisition and data processing ranges from 0.5 to 1 mm (Reddy et al. 1994; Abad-Gallego et al. 2011). A comparison study of linear measurement error between CBCT scans and direct measurements in an *ex vivo* porcine model found that overestimation occurred in 36% of the sites when using CBCT, with 0.8% of sites having an overestimation error of over 0.5 mm (Kurtz et al. 2007). Error during surgical template production can be up to 0.2 mm for transfer of the computer-assisted design to guide manufacturing axes (Champleboux et al. 1998). Error can also occur during template positioning and be increased if there is movement during drilling.

In addition, mechanical error caused by the bur-cylinder gap can lead to deviations up to 1 mm at the apex in surgical templates (Valente et al. 2009). However, this is less than axial deviation caused by freehand drilling (Nickenig et al. 2010). Axial deviation could also occur from human error, such as setting the bur at the incorrect position. Because tolerance is dependent on bone mass and location to critical anatomic structures, among other patient factors, there are no universal tolerance values established for dental implant placement. With the ability of errors to compound, it is important to still maintain safety margins when planning implant placement.

In this study, experimental variability was reduced significantly by allowing only one clinician to plan and perform all surgeries in the same surgical environment. In contrast to other studies on guided implantation accuracy using human cadaver jaws, this study was performed on whole human cadaver heads (Van Assche et al. 2007; Ruppin et al. 2008). Another study using two whole human cadaver jaws was performed only in the maxilla and could not provide quantitative assessments of accuracy for different regions in the mouth (van Steenberghe et al. 2002). The *ex vivo* use of entire cadaver heads allows a more clinical representation of surgical conditions while being able to eth-

ically control for environmental variability. However, due to preservation, cadaveric bone can be softer than live bone. In this study, limited bone was observed in the posterior mandible in one cadaver. This contributed to the large placement difference and deviation seen in Fig. 5d. We believe that this deviation was specific to the cadaver and would not translate to a healthy patient clinically. Although there may be slight biological differences between an *ex vivo* cadaver model and an *in vivo* clinical study, using this model allows us to much better control for other more important clinical variables. To the best of our knowledge, this is the first instance of a qualitative guided implant accuracy study in which an entire cadaver head was used.

In clinical studies, the most frequent problem encountered is limited access in posterior areas (Schneider et al. 2009). However, reducing the surgical guide occusogingival height from 8 to 4 mm did not significantly affect implant placement (Park et al. 2009). The cadaver head model used in the present study enables assessment of surgical guide design with respect to accuracy, but it cannot determine postoperative complications and see trends based on patient variability over time.

Conclusion

With the emergence and refinement of new technologies, the accuracy and popularity of computer-guided implantation will continue to grow. Before the advent of guided templates, safety margins of 2 mm were recommended to reduce damage to vital structures during implantation (Worthington 2004). Within the past 10 years, guided implantation has increased implant accuracy to 1.07 mm at the entry point and <0.5 mm in vertical deviation (Schneider et al. 2009).

In this study, we took a unique approach to analyzing guided implant placement accuracy through a biological model while controlling for clinician experience, hospital setting, equipment usage, and other experimental variability. This effective experimental model was able to isolate the true error of guided implant systems from the general compounded error due to clinical variation. The average deviation of placed from planned implants in this study was 0.8 mm, which is well accepted within the literature for computer-guided implantation. No statistical differences were found between the planned and implanted locations. To factor in clinician variability and patient type, the authors advise that implant planning with 3D and guided templates should include a safety distance of 1 mm. This study suggests that guided implantation can be used safely in difficult cases near anatomic structures.

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