Accuracy Evaluation of Computed Tomography–Derived Stereolithographic Surgical Guides in Zygomatic Implant Placement in Human Cadavers

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Presurgical planning is essential to achieve esthetic and functional implants. For implant planning and placement, the association of computer-aided design (CAD) and computer-aided manufacturing (CAM) techniques furnishes some advantages regarding tridimensional determination of the patient’s anatomy and fabrication of both anatomic models and surgical guides. The goal of this clinical study was to determine the angular deviations between planned and placed zygomatic implants using stereolithographic surgical guides in human cadavers. A total of 16 zygomatic implants were placed, 4 in each cadaver, with the use of stereolithographic (SLA) surgical guides generated by computed tomography (CT). A new CT scan was made after implant insertion. The angle between the long axis of the planned and actual implants was calculated. The mean angular deviation of the long axis between the planned and placed implants was $8.06 \pm 6.40$ (mean $\pm$ SD) for the anterior-posterior view, and $11.20 \pm 9.75$ (mean $\pm$ SD) for the caudal-cranial view. Use of the zygomatic implant, in the context of this protocol, should probably be reevaluated because some large deviations were noted. An implant insertion guiding system is needed because this last step is carried out manually. It is recommended that the sinus slot technique should be used together with the CT-based drilling guide to enhance final results. Further research to enhance the precision of zygomatic implant placement should be undertaken.

Key Words: zygomatic implant, atrophic maxilla, image-based surgery, stereolithography, customized drill guides

INTRODUCTION

Presurgical planning is essential to achieve excellent esthetic and functional outcomes with dental implants. Many conflicting variables such as the mandibular canal, maxillary sinus, and adjacent teeth...
must be considered before implant surgery is performed. Practitioners generally have used conventional dental radiographs (panoramic and periapical radiographs) and conventionally fabricated surgical guides for implant placement. The panoramic radiographs that are commonly used in implant treatment planning are limited by their characteristics of magnification and distortion, as well as by lack of sharpness of the image. Also, a panoramic radiograph is a 2-dimensional image that provides little information about the buccal-lingual width of the jawbones. The surgical guides conventionally fabricated on diagnostic stone casts do not provide information about the varying thicknesses of the mucosa, the topography of underlying bone, or the anatomic structures, and they do not remain stable during surgery because of reflected soft tissue.

Computed tomography (CT) is a helpful tool for implant patients, especially in situations with anatomic limitations, insufficient bone dimensions, and poor bone density. The use of CT imaging enhances the correlation between implant planning and actual implant placement compared with conventional radiographic methods.

Currently, few software systems use CT scans to aid in planning surgery and to produce surgical drilling guides. These guides are manufactured in such a way that they match the location, trajectory, and depth of the planned implant with a high degree of precision. As the dental practitioner places the implants, the guides stabilize the drilling by restricting the degrees of freedom of the drill trajectory and depth. Earlier studies concluded that 3-dimensional (3D) planning resulted in implant positioning with improved biomechanics and esthetics. Use of such a system usually prevents complications such as mandibular nerve damage, sinus perforations, fenestrations, or dehiscences. Also, computer-aided design (CAD) and computer-aided manufacturing (CAM) software may improve the association between dental implant planning and insertion, in terms of 3D determination of the patient’s jaw anatomy and fabrication of both anatomic models and surgical guides.

Some studies have recently illustrated promising results with stereolithographic (SLA) surgical guides. The SLA consists of a vat containing a liquid photopolymerized resin. A laser mounted on top of the vat moves in sequential cross-sectional increments of 1 mm, corresponding to the slice intervals specified during the CT formatting procedure. The laser polymerizes the surface layer of the resin on contact. Once the first slice is completed, a mechanical table immediately below the surface moves down 1 mm, carrying with it the previously polymerized resin layer of the model. The laser subsequently polymerizes the next layer adjacent to the previously polymerized layer. In this manner, a complete SLA model of the maxilla and the surgical guides is created.

Restoration of the atrophied edentulous maxilla poses a great dilemma to the oral and maxillofacial surgeon and the restorative dentist. Patients with adequate maxillary bone are ideal candidates for implants, but they are the exception. Patients with moderate to severe atrophy challenge the surgeon to discover alternative ways to use existing bone or resort to augmenting the patient with autogenous or alloplastic bone materials.

Various techniques have been described for approaching the atrophic maxilla, including the use of tilted implants in the paranasal region and implants in the pterygoid apophysis, grafting of the maxillary sinus floor, and the use of short, wide implants, different types of grafts, and zygoma implants. The incidence of implant loss in the severely resorbed pos-
terior maxilla is approximately 15% without a sinus bone graft.41

The zygoma implant has been designed by Branemark33,34,42 for those situations in which there is insufficient bone in the upper jaw, which would otherwise require onlay or inlay (sinus) bone grafts. Zygomatic bone is excellent for the anchorage of implants, as has been validated in several anatomic studies.43–46 These authors agree that the quality of zygomatic bone is superior to that of the posterior maxilla, and the importance of the cortical portion of the zygomatic bone for anchoring implants43 has been described. Furthermore, zygomatic implants display initial primary stability, because it has been demonstrated that the zygomatic bone area where the implant is inserted has wider and thicker trabecular bone.45

Implant placement in the zygoma bone, however, can be difficult because of the variable anatomy and varying degrees of atrophy possible in the maxillofacial region.47 The technique is not performed without risk because the drill path is close to important anatomic structures. A significant error can be induced by only a slight deviation of the drill path direction.48

The clinical effectiveness of the use of the drill guide and the important advantage for aesthetic outcome have been described.49 For zygoma implants, the accuracy of the transfer of the preoperative plan to the surgical field is even more crucial. Given an appropriate visualization, 3D CT images provide an unparalleled depiction of the complex anatomic topography that has to be respected when the trajectory of a zygoma implant is decided.

Personalized drilling templates may be fabricated by a computer-based transfer from the available 3D CT planning data50; this allows incorporation of all predetermined biomechanical, esthetic, and anatomic factors during the surgical procedure.

The goal of this clinical study was to determine the angular deviations between planned and placed zygomatic implants in human cadavers by using SLA-based drilling guide technology.

MATERIALS AND METHODS

The study protocol was approved by the Institutional Ethics Committee of the Federal University of Minas Gerais. Four human cadavers were considered for the study.

Standardized CT scanning procedures were followed for each cadaver and were performed by the same radiologist operating a CT machine (Classic i-CAT, Imaging Sciences International, Hatfield, Pa). CT data for each cadaver were imported to the planning software (Dental Slice software, BioParts Prototipagem Biomédica, Brasília, Brazil), allowing the surgical team to simulate implant placement on the 3D model. While taking into consideration the anatomic structures, the surgical team interactively simulated the position of the implant on each plane. Once the implant is planned, its angulation can still be adjusted and its dimensions adapted to obtain the optimal position of the implant (Figure 1). The implant is directed in a lateral and upward direction with an angulation of 45 degrees from a vertical axis. The end point has to encroach into the zygomatic bone, which has a thickness of about 10 mm. The zygoma implant thus follows an intrasinusal trajectory. After initial positioning of the implant, several minor adjustments can be made until the implant is surrounded by bone at its entry and end points, to ensure that the intermediate part does not perforate the anterior maxillary wall. A rapid prototyping machine based on the principle of stereolithography was used to fabricate the SLA models and guides. The aim was to create an individualized drill guide that is suited to the bone profile.
The SLA machine also read the diameter and angulation of the simulated implants and selectively polymerized resin around them, forming a cylindrical guide corresponding to each implant. Surgical grade stainless steel tubes were attached to the cylindrical guide. To prevent lateral angulation of the drill during the drilling process, drill guides (made by Peclab Ltda, Belo Horizonte, Brazil) that perfectly adapted to the stainless steel tubes were made (Figure 2). Drilling of the zygoma implants was performed with the use of 4 drills. Consequently, 4 sets of drill guides were provided. The inner diameter of the drill guides is 0.3 mm greater than the diameter of the corresponding drill. The angulation and mesiodistal and buccolingual positioning of each implant as planned with the use of 3D computer simulation software were transferred to the SLA surgical guide.

The SLA bone-supported surgical guide type was used. The surgical drill guide was fitted onto the maxilla and was fixated with 2 or 3 osteosynthesis screws (10.0 × 1.5 mm). The drilling procedures were performed with the use of appropriate drills for each corresponding implant according to the manufacturer’s instructions. A total of 16 zygomatic implants were placed (SIN Sistema de Implante, São Paulo, Brazil), all 4.0 mm of diameter ranging from 37.5 to 57.5 mm in length. Four implants were placed in each cadaver, 2 in the canine region, 2 in the first molar region, with the use of SLA surgical guides generated from CT. A new CT scan was made for each cadaver after implant insertion.

Figure 1. The 3-dimensional computed tomography (CT) planning system. Axial, transversal, panoramic, and tridimensional CT slices are possible. Clinically relevant covisualization can be obtained.

Figure 2. Drill guides to every corresponding drill were made to perfectly adapt into the cylindrical guide.
Adobe Photoshop Elements software (version 2.0, Adobe Systems Incorporated, San Jose, Calif) was used to match images of planned and placed implants, and their positions and axes were compared. Preoperative and postoperative CT scans in anterior-posterior (Figure 3) and caudal-cranial (Figure 4) views were aligned to allow observation of the superposition of anatomic markers. The angle between the long axes of the planned and the actual implant (Figures 5 and 6) was calculated with the VistaMetrix software (version 1.36.0, Skill-Crest, Tucson, Ariz). Basic descriptive statistics was employed to analyze the data obtained using standard software (Excel, Microsoft Corporation, Redmond, Wash).

**RESULTS**

In the right posterior implant of cadaver 4 (C4), the angular deviation between planned and actual implant position in an anterior-posterior view was 0.35 degrees, the smallest deviation, but the left posterior implant of cadaver 3 (C3) in a caudal-cranial view showed the largest deviation (37.60 degrees). A more detailed presentation of the angular deviation between planned and placed implants in an anterior-posterior and a caudal-cranial view in the 4 cadavers is found in the Table.

The mean angular deviation of the long axis between planned and placed implants was $8.06 \pm 6.40$ (mean ± SD) for the anterior-posterior view, and $11.20 \pm 9.75$ (mean ± SD) for the caudal-cranial view. Minimal and maximal values for the anterior-posterior view were 0.35 degrees and 21.20 degrees, and 0.76 degrees and 37.60 degrees for the caudal-cranial view.

**DISCUSSION**

The strength of the anchorage in the zygoma compensates for the bad quality of the bone, mostly type IV in the posterior maxilla. From a biomechanical point of view, it has been demonstrated that if the zygoma fixtures are connected to the anterior...
implants, masticatory forces applied to the fixed prosthesis are transferred to the zygoma.\textsuperscript{44}

The CT scanning template is the principal key to the system because it permits the transfer of the predetermined prosthetic setup to the actual implant planning. The scanning template is an exact replica of the desired prosthetic outcome; this allowed both surgeon and restorative dentist to base implant planning on the desired prosthetic outcome. The treatment plan is thus driven by the prosthetic end result.\textsuperscript{16,51}

Other studies have assessed the magnitude of error in transferring the planned position of implants from CT scans to a surgical guide. In the in vitro study by Besimo et al,\textsuperscript{52} the deviation between the positions of the apex of proposed implants on cross-sectional CT images and on the corresponding study cast was measured at 77 sites. Transfer errors for the maxilla and mandible were 0.6 ± 0.4 mm and 0.3 ± 0.4 mm. However, investigators concluded that the transfer errors noted in their study were not clinically relevant because other factors involved in transferring positional and angular measurements from CT images to the actual surgical area may result in greater errors. Another in vitro study by Sarment et al\textsuperscript{12} included 50 implants placed into 5 epoxy resin edentulous mandible models. Each epoxy resin mandible received 5 implants on each side. On the right side, 5 implants were inserted using a conventional surgical guide, whereas on the left side, 5 implants were inserted using an SLA surgical guide. When compared with conventional guides, significant improvements were evident in all measurements taken with SLA surgical guides. Investigators stated that the clinical significance of this result may be relevant when multiple parallel distant implants are placed, and where the degree of accuracy is critical for obtaining a single prosthetic path of insertion. Their studies, although very relevant, were made with normal dental implants only in the jaws, not in the zygoma.

Van Assche et al\textsuperscript{53} placed 12 implants in 4 formalin-fixed cadaver jaws. Upon comparison with the planned implants, investigators noted average angular deviation of 2 ± 0.8 degrees and mean linear deviation of 1.1 ± 0.7 mm at the neck and 2 ± 0.7 mm at the apex in the placed implants. Another human cadaver study by Van Steenberghe et al\textsuperscript{44} included 6 zygoma implants with surgical drilling guides based on CT data. Researchers matched preoperative CT scans with postoperative CT scans to evaluate the deviation between planned and placed zygoma implants. Investigators reported that the angular deviations in the axis for 4 planned and placed implants were less than 3 degrees, whereas 1 implant showed 3.1 degrees and the last one showed 6.9 degrees angular deviation in the axis.

Di Giacomo et al\textsuperscript{15} evaluated the match between the positions and axes of planned

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{Cadaver} & \textbf{View} & \textbf{C1} & \textbf{C2} & \textbf{C3} & \textbf{C4} \\
\hline
\textbf{Region} & & \textbf{A-P} & \textbf{C-C} & \textbf{A-P} & \textbf{C-C} & \textbf{A-P} & \textbf{C-C} \\
\hline
First right superior molar & A-P & 12.30 & 4.20 & 1.46 & 14.80 & 6.66 & 14.20 & 0.35 & 8.59 \\
Right canine & C-C & 2.70 & 14.70 & 4.22 & 18.30 & 11.20 & 0.76 & 5.05 & 6.30 \\
Left canine & C-C & 8.79 & 5.74 & 4.99 & 14.10 & 18.50 & 1.22 & 16.50 & 4.41 \\
\hline
\end{tabular}
\caption{Angular deviations between planned and actual zygomatic implant positions in 4 human cadavers\textsuperscript{*}}
\end{table}

\textsuperscript{*A-P indicates anterior-posterior view; C-C, caudal-cranial view.}
and inserted implants when an SLA surgical guide was used. They inserted 21 implants in 4 patients using 6 SLA surgical guides and CT data, measuring the deviation between planned and inserted implants. Investigators noted an average angular deviation of 7.25 ± 2.67 degrees between planned and inserted implant axes. This average angular deviation was higher in the study of Vrielinck et al—10.46 degrees (range: 0–21.0 degrees)—also an in vivo study. Other in vivo studies tried to determine deviations in the position and inclination of planned and placed implants using SLA surgical guides and to compare 3 different types (tooth-supported, bone-supported, and mucosa-supported) of SLA surgical guides. Under the guidelines of this study, CT-derived SLA surgical guides supported by tooth, bone, or mucosa provided a precise tool for both flapless and conventional flap implant insertion. Naitoh et al found angular deviations between planning and placement ranging from 0.5 to 14.5 degrees, with an average of 5.0 degrees, using teeth-supported conventional guides. The CT data were used to transfer only the position and/or inclination of the implants to a laboratory-made template placed on working plaster models.

The main goal of the study was to evaluate the possibilities of skeletally supported drill guides for zygomatic implant placement in patients with severely atrophic maxillas, while still providing a predictable, permanent, and successful treatment result. The mean angular deviation of the long axis between planned and placed implants was 8.06 ± 6.40 (mean ± SD) for the anterior-posterior view, and 11.20 ± 9.75 (mean ± SD) for the caudal-cranial view. This aim was not completely met by this treatment concept, in terms of angular deviations between planned and placed implants. Despite the fact that deviations between planned and placed implants could be quite substantial, in some cases this may not affect the ability of the restorative dentist to design and fabricate a prosthetic suprastructure onto these deviated implants. Deviations with good clinical results also occurred, as can be observed with the left side on cadaver 1 (Figures 7 and 8).

It is not easy to make direct comparisons between in vitro studies and the present human subject, as in vitro studies provide improved control of all contributing parameters. However, it was observed as large angular deviations, probably because of
poor fit of the surgical guide, between other causes. The precision of the whole procedure depends largely on the ability to position accurately the drill guide on top of the bone, and to maintain that stable position during the whole procedure. The difference of osteosynthesis screws in fixing the surgical guide onto the maxilla bone can also have an important role. In this study, 1 mm length screws were used—a half length when compared with the study of Vrielinck et al.\textsuperscript{48} The number of screws was also lesser: 2 or 3 against 4 or 5 in the study of Vrielinck et al.\textsuperscript{48} Asymmetric distribution of the screws or uneven tightening of the screws could bring the drilling template out of balance. Furthermore, a certain error is induced as the diameter of the steel tubes is slightly larger than the drill diameter. Finally, the largest error is probably due to the fact that the final step in the procedure is carried out manually. Implant placement cannot be done through the surgical drill guide because of present mechanical limitations. The drill guide, therefore, has to be removed before the implant is actually inserted, leaving the possibility of additional deviation.

The original Branemark protocol creates a sinus window technique for placement of these zygoma dental implants. Stella and Warner’s\textsuperscript{55} published “sinus slot technique” significantly simplified the original Branemark protocol. The “sinus slot” is a guide window made directly through the buttress wall of the maxilla, whereby the zygoma implant is guided through the maxilla to the apex insertion at the junction of the lateral orbital rim and the zygomatic arch. This lateral sinus slot allows greater potential for bone-to-implant interface because of this lateral position, and eliminated the sinus window and sinus lining elevation for placement of the implant. This lateral window allows direct vision to the base of the zygoma bone and helps control the implant position by direct vision.\textsuperscript{56} The fact that we have done these surgeries in a cadaver without direct vision through the maxillary sinus may also have influenced the results.

Moreover, some deviation may occur when the actual implant entry point is considered compared with initial treatment planning. This may be due to the brittle and soft consistency of bone in the maxillas with severe bone atrophy.\textsuperscript{48}

On the left side of cadaver number 3, 1 implant emerged in the infratemporal fossa (Figure 9) and the other one inside the orbit (Figure 10).
This great deviation of course occurred because of the long length of the zygomatic implants (37.5–57.5 mm)—3 to 4 times that of oral implants—which means that even minute angular deviations lead to important discrepancies at the extremity. According to Vrielinck et al, it should be noted that the common practice today is to position zygoma implants without any form of physical control of the drilling trajectory. However, care has to be taken to ensure a proper mesiocranial direction for the implant. If the implant is planned too much laterally, it would emerge in the infratemporal fossa. If, on the contrary, it is planned too much mesially it would end up in the nasopharynx or the sphenoid sinus. If the inclination of the implant is too much in the cranial direction, it would enter the fossa pterygopalatina. For an implant directed too much horizontally, no bony structures will be encountered. Based on the dimensional variability of the zygoma bone, such errors might, even with accurate 3D CT-based planning and transfer, create potential dangers.

It must be emphasized that in the preliminary feasibility study, implant planning may be done solely on the basis of available bone volume (ie, implant planning may not take into account information conveyed through a preoperative prosthetic set-up, because the quantity of present bone may be minimal because of the atrophy). Consider that the “wrong” implants position should not affect the ability to design and fabricate a prosthetic suprastructure onto these deviated implants, despite the angular deviation.

**Conclusions**

The results of this study demonstrate that the use of the zygomatic implant, in the context of this protocol, should probably be reevaluated because some large deviations were noted. An implant insertion guiding system is needed because this last step is carried out manually. It is recommended that utilization of the sinus slot technique together with the CT-based drilling guide would enhance the final results. The tridimensional CT is a helpful tool for patient candidates to zygomatic implants, because the drill path is close to important anatomic structures. The reported results may be surprising and should stimulate further research to enhance the precision of zygomatic implant placement, even given that better results were obtained by former studies.

**Abbreviations**

CAD: computer-aided design  
CAM: computer-aided manufacturing  
CT: computed tomography  
SLA: stereolithographic  
3D: three-dimensional

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354 Vol. XXXVI/No. Five/2010


