Anatomic Customization of Root-Analog Dental Implants With Cone-Beam CT and CAD/CAM Fabrication: A Cadaver-Based Pilot Evaluation

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Existing root-analog dental implant systems have no standardized protocols regarding regenerative design, surface manipulation, or prosthetic attachment design relative to the site’s unique anatomy. Historically, existing systems made those design choices arbitrarily. For this report, strategies were developed that deliberately reference the adjacent anatomy, implant and restorative path of draw, and bone density for implant and retentive design. For proof of concept, dentate arches from human cadavers were scanned using cone-beam computed tomography and then digitally modeled. Teeth of interest were virtually extracted and manipulated via computer-aided design to generate root-analog implants from zirconium. We created a stepwise protocol for analyzing and developing the implant sites, implant design and retention, and prosthetic emergence and connection all from the pre-op cone-beam data. Root-analog implants were placed at the time of extraction and examined radiographically and mechanically concerning ideal fit and stability. This study provides proof of concept that retentive root-analog implants can be produced from cone-beam data while improving fit, retention, safety, esthetics, and restorability when compared to the existing protocols. These advancements may provide the critical steps necessary for clinical relevance and success of immediately placed root-analog implants. Additional studies are necessary to validate the model prior to clinical trial.

Key Words: dental implants, immediate implants, root-analog implants, zirconia implants, dental anatomy

INTRODUCTION

Root-analog implants (RAIs) may improve the clinical ease, success, and esthetic outcomes compared to traditional root-form titanium implants. Numerous attempts at shaping implants to mimic the native root anatomy have seen varied rates of success. The main theories behind failure are trauma to the cortical plates at the time of implant placement and the inability to gain initial stabilization of the implant, thus prohibiting osseointegration. By creating implants that only approximate the dimensions of the extracted root, we place undue stressors on the supporting bone. This impedes the sufficient initial implant stability required for osseointegration, which can result in failure rates greater than 50%.1–3 With RAIs, a static fit of the fixture is considered essential for success. Attempts to increase the implant size to compensate for the lost width of the periodontal ligament have also resulted in failure.2,4–6

Various systems of root-analog type implants have been published, and some have become commercially available. Some rely on stabilization by splinting the implant body to adjacent teeth during the osseointegration phase, while Pirker et al7–10 have shown promising results with RAI systems using retentive elements in their implant designs along with areas of reduction to reduce risk of alveolar fracture. This approach resulted in 1–2-year success rates exceeding 90%.7–10 Although preliminarily successful, the clinical relevance of the RAI system is limited. This protocol requires extraction of the affected tooth, which then needs to be modified by hand-layering arbitrary retentive elements directly to the root surface and, further, hand-prepped for a crown. The modified tooth then must be scanned, milled, and the implant inserted at a later date when it is ready. The retention and restorative preparation are subjectively designed, which also may limit clinical success.

For immediately placed RAIs to be clinically and commercially successful, the location, size, and shape of the implant body, retentive elements, and restorative abutment surfaces must be customized to the patient’s unique anatomy, esthetics,
prosthetic requirements, and path of draw. Equally important is the goal of implantation at the time of extraction. With the cadre of dental technology currently available—including cone-beam computerized tomography (CBCT), computer-aided design (CAD) software, and computer-aided manufacturing (CAM)—immediate implantation can now be a clinical reality.\textsuperscript{11–13} Specifically, Moin et al demonstrated the accurate digital extraction and fabrication of RAI from CBCT data.\textsuperscript{13,14} Yttrium-stabilized zirconium dioxide (zirconia, ZrO\textsubscript{2}), has emerged as an excellent choice for material for RAIs as it is biocompatible, mechanically favorable, tooth colored, and capable of osseointegration.\textsuperscript{12,15–20} The purpose of this study was to develop methods to create custom immediate zirconia RAIs with retentive elements capable of primary stabilization using existing dental diagnostic and laboratory technologies.

**MATERIALS AND METHODS**

**Human cadaver specimens**

This study was approved by the Medical University of South Carolina Institutional Review Board. A total of six maxillae and six mandibles were harvested from 10 different preservation-fixed (formalin, phenol) dentate human cadavers. CBCT images were captured from these specimens (SCANORA, SOREDEX, Tuusla, Finland), and digital imaging and communications in medicine (DICOM) files were rendered using CT visualization software (In Vivo, Anatomage, San Jose, Calif). Specimens were selected for the presence of natural single-rooted teeth that were flanked by natural teeth, all with 50% bone loss. In addition, only those teeth were accepted that had no evidence of labial or lingual plate fenestration or dehiscence. Images captured teeth, their roots, and the supporting and adjacent anatomical structures. The 3-dimensional (3D) images of the existing roots served as the templates for the future implant design.

**Implant design**

3D surface mesh models of 12 teeth and roots were virtually extracted from the DICOM files using medical modeling software (Anatomage) in stereolithography (.stl) format. Each surface mesh was manipulated in CAD software (SketchUp Make, Trimble, Sunnyvale, Calif) to allow surface reduction, creation of retentive elements, and creation of the prosthetic-mating surfaces.

For analysis of the implantation site, measurement of bone density based upon approximate Hounsfield units (aHU) was completed rather than true calibrated HU. “Relative” bone density (dense to cancellous) was therefore available over the entire implant site. Density at specific areas of the implant were defined by mapping regions of the root/implant surfaces with mean aHU measurements for each region, referenced when designing the implant surfaces and retentive elements. To account for anatomical root complexity, we identified concavities or undercuts because these areas could limit the path of implant insertion or cause trauma to the alveolar bone upon insertion. This problem is especially evident as protrusive elements are added to the implant surface to engage the bone beyond the dimensions of the natural tooth root. In addition to these issues, interfering areas of bone may create vector forces perpendicular to the path of insertion, thereby increasing the chance for alveolar trauma or implant dislocation during implantation. To improve the design, we carried out an analysis of the implant and the implant site bone. Due to the potential complexity, we attempted to simplify the task through the following steps:

1. Virtual tooth extraction: DICOM images were examined and the teeth of interest were marked, their volumes and surfaces predicted by the modeling software. The predictions were refined by examining the defined areas in 1-mm slices in the axial and sagittal orientations, and the areas were manually corrected as necessary. Modeling was finally confirmed virtually in situ and the .stl surface mesh files were exported (Figure 1).

2. Analysis of path of insertion: For each digitally extracted tooth, sagittal and coronal sections were analyzed with respect to the implant’s path of insertion. Path of insertion was calculated based upon the 3D rendering of the root model to allow direct placement with minimal physical interference (ie, direction of path of least resistance), based upon a central axis defined within the rendering of the root using modeling software. Therefore, the direction for insertion limits the volume of implant prominence that is affected by interferences, such as convexities or curvatures of the extraction socket walls during insertion. Also, this direction allows reference for the design of retention perpendicular to that axis.

3. Analysis of the implant site for constrictions: Incremental axial slices of the CBCT for each tooth/root site at 1-mm increments were evaluated for circumferential deviation compared to the central axis. In the axial slices, length measurements were calculated from the implant surface to the central axis at specific circumferential degree reference points. This was facilitated via the software, allowing for marking a point at the root’s edge that could be referenced at each slice. These measurements were compared to points more coronally positioned. Any measurement coronal to the point of interest was considered a constriction if it was less than the apical measurement at the point of interest (ie, the edge of the root was closer to the central axis compared to an apical point). We did not factor in expansion of the extraction socket, assuming that the socket should be identical to the conformation seen on the CBCT prior to extraction. Once the root was analyzed circumferentially, 3D areas that lie outside a constriction based upon path of draw could be assigned. These areas were defined as an implant “prominence” and considered for removal on the root model rendering in conjunction with the next step.

4. Analysis of the implant site for bone density: The decision to relieve potential interferences or prominences was related to bone density at the constriction. Density is inversely proportional to the need to relieve implant surfaces to allow path of insertion. In less dense bone, a higher degree of plastic deformation is possible, while insertion forces on denser or cortical bone may result in fracture. Therefore, we considered the approximate HUs for the bone with respect
to path of draw in the decision to relieve implant surfaces. The alveolar bone that existed in the area of a root/implant constriction was defined as an “insertion interference.” If the density of bone or the overall dimension was not thought to allow active insertion of the implant, the apical prominence of the implant was removed to allow placement (Figure 2).

5. Limiting surface area and pressure: Thin cortical plates of bone—especially the labial plate in the anterior—are critical for support of the implant and support of the soft tissues for functional and ideal esthetics. To avoid fracture of these plates, a minimum reduction of the implant surface was established irrespective of path-of-draw concerns. This allowed a minimum gap between the cortical bone and the implant surface during the active phase of implant placement as well as after the implant was seated. Fracture risk is inversely proportional to the thickness and directly proportional to the total area of the cortical plate. To combat this risk, we reduced the implant surface by 0.5 mm in areas in close proximity to spots where the cortical plate thickness was less than 2 mm, assuming the area was not already reduced in the previous step. In addition, the apex of the implant was reduced by 1 mm if it was in contact with the inferior cortical border of the maxillary sinus.

Retentive element design and placement

Retentive elements were virtually designed on the 3D implant renderings after the alterations. Retentive elements are protrusive structures designed to engage the alveolar bone to provide stability during the integration phase of implant healing, as well as increase the total implant surface area. Previous finite analysis of ROIs with different methods of retention had identified ideal stress distribution and stability properties when using “fins;” which were a starting point for design.21 The retentive elements were designed based on the bone morphology adjacent to the implant site, tooth-root shape and contour, proximity to adjacent roots and structures, path of draw, and requirement to avoid movement. Pressure or retention should be avoided in the presence of cortical or dense bone to avoid alveolar bone fracture or necrosis.3,17,22 Therefore, retention was avoided at the cortical bone and limited in dense noncortical bone. Width and depth of elements were determined by the density and dimension of bone in each region. The size, shape, and exact placement were dependent upon the desired vector forces, estimation of native retention, and perceived need for additional retention. The goal was to utilize the least number and areas of retentive elements possible, while providing sufficient retention to achieve primary implant stability. The profile of the illustrated feature and our adopted system was based on a cross-sectional modified-butress thread design but could assume any retentive form (Figure 3). Figure 3 also represents the proportional relationships between retentive element size and angulation parameters compared to bone density.

Steps for retentive element design:

1. Define the areas of alveolus beyond the tooth-root that are safe for retentive elements to protrude, ranging from the root surface to 1 mm from the adjacent PDL or to the internal border of the cortical plates: Safe-zones were limited by the area of the zone more coronal to avoid the construction of larger elements apically in the effort to avoid trauma upon insertion. Therefore, the areas are defined in a coronal to apical sequence (Figure 4).

2. We placed 3 or 4 retentive elements on the mesial and the distal surfaces, extending beyond the root surface into the safe zones, angled to allow insertion and prevent movement. The apex of the virtual root was used as a reference point for vertical positioning of the retentive elements when comparing the CBCT to the .stl model. Flanking of the elements was utilized to stay within the safe zones, and the offset angle was set to make the elements perpendicular to...
the implant long axis (Figure 5). The proportions of each retentive element parameter correlated to bone density, as seen in Figure 3. The most coronal elements were placed ≥3 mm from the crest of bone in anticipation of future crestal bone loss.

Design of the prosthetic abutment surface

The supercresal dimension exactly mimicked the tooth form, and a “crown preparation” was designed at the natural cementoenamel junction (CEJ) located on the extracted .stl models. For each RAI, the prosthetic abutment surface was created at an ideal angle and dimension to serve as an abutment for a single unit CAD/CAM crown, compatible with standard fixed prosthetic restorative principles.23 An occlusal plane was defined from the adjacent teeth to aid in the definition of a perpendicular restorative path of draw. A restorative shoulder margin (0.8–1.2 mm) was placed at the CEJ, while the body of the preparation was designed to be appropriate in relation to the adjacent dentition, path of draw, restorative thickness, and emergence. Axial walls tapered inward by a minimum of 3°, and the restorative abutment angle did not necessarily parallel the long-axis of the implant body (Figure 6).

Implant fabrication

The RAIs were milled from medical-grade 3% yttria-stabilized tetragonal zirconia polycrystal blocks with a computer aided
manufacturing 5-axis machine and sintered (Sherer Dental Lab, Rock Hill, SC; Figure 7). For this study, no surface preparations (etching, blasting) or sterilization processing were completed. Dimensional error from .stl to milled sample was confirmed to be ±0.050 mm in any direction.

**Tooth extraction and immediate implant placement**

Selected single-rooted teeth from the cadaver specimens were extracted using perirotomes, luxators, and forceps to limit damage to the soft tissue, bone, and extraction sockets, with careful attention paid to the lingual and facial cortical alveolar plates. The extraction sockets were thoroughly curetted with Molt and Gracey curettes to prepare the site for implantation, and analysis of the integrity of cortical plates was conducted prior to implantation.

**Implant placement and evaluation**

RAIs were placed in the extraction sockets immediately following tooth extraction. The implants were manually seated into the socket under finger pressure and driven to depth with gentle tapping with a mallet and straight implant impactor with a head designed for safe delivery of zirconia implants using 3–4 gentle blows (Cera-root, Santa Monica, Calif). Implant seating was confirmed with finger pressure, periapical radiography, and stability testing. Following implantation, full-thickness mucoperiosteal flaps were reflected around the implant sites to expose the alveolar bone in the effort to identify fractures, dislocations, and/or expansion of alveolar bone. Implant stability was measured with the Periotest M instrument (Medizintechnik Gulden, Modautal, Germany) as directed by the manufacturer, and stability measurements were reported in Periotest units corresponding to stability as previously reported.24–26 Photographs pre- and postoperatively were taken with a Nikon D70s 105 mm at f/32. Photographs were cropped and optimized for brightness and contrast with Adobe Photoshop CS5. Postoperative CBCTs generated too much artifact for analysis. Data points for each specimen indicate an average of 5 readings.

**Statistical analysis**

Statistical analysis was completed with PSPP (Gnu Statistics, Free Software Foundation, Boston, Mass). Data were presented...
FIGURE 7. Implant design: left to right for natural tooth #7: .stl surface mesh images of the extracted tooth, .stl images of the designed implant, and photograph of the implant. Top: distal view. Bottom: lingual view.
in box plot format, and comparisons between groups were made with the Student’s t-test. An alpha value of 0.05 was defined as the limit for statistical significance.

**RESULTS**

**Implant design**

Computerized tasks were completed manually, accomplishing the analytical and design steps outlined above. Virtual tooth extraction was relatively easy as the radiographic differentiation between the root surfaces and PDL spaces were easily distinguishable. CEJ levels were not easily identifiable on the .stls of the virtually extracted teeth. In cases where large restorations were present or around the tooth of interest, the CEJs were obscured from radiographic artifact and had to be estimated. In general, radiographic artifact was present throughout the specimens at the coronal aspect, whether or not restorations were present. The crown shapes on the virtually extracted teeth were distorted as a result (Figures 2 and 7). However, once the CEJ was defined, the clinical crown was reduced using the preparation guidelines for an all-ceramic crown, establishing a prosthetically compatible surface. Implant surface reduction and path-of-draw restrictions were incorporated into the implant surface and, finally, retentive elements were placed (Figures 5 and 7). Each step was cross-referenced to the original CBCT with respect to anatomy, bone quality, and implant insertion path.

**Implant placement**

After extractions, the implants were self-guided and easily seated with tapping. Depth of placement was evident when implant progress stopped and was confirmed as firmly seated when palpated. Radiographic findings suggest accurate placement and fit of the implants (Figures 8 and 9). The implant bodies matched the extraction socket minus the areas of intentional reduction, while the retentive elements extended into the adjacent bone. No fractures or dislocations of cortical plates were observed post-insertion. Photographs indicated that the digital interpretation of the CEJ was accurate, placing the designed margin at or just below the free gingival margin. The cadaver gingiva lacked elasticity due to fixation, and residual soft-tissue gaps between the implant surface gingiva can be seen, but the restorative margin and abutment surfaces appear appropriate.

**Stability**

Implant stability was assessed immediately postimplantation. Measurements indicated that 11/12 implants were theoretically stable enough for immediate temporization while the remaining implant was stable enough to expect osseointegration. No statistical differences were noted for stability between implants in maxillary and mandibular arches (Figure 10). Subjectively, the implants were stable enough that significant buccal/lingual forced expansion with forceps was necessary to remove the implants prior to retirement of the cadaver specimens. However, we do acknowledge that the cadaver specimens were fixed, which could affect the alveolar elasticity compared to fresh or live alveolar bone.

**DISCUSSION**

Previous work demonstrates the potential for success for RAIs, especially when retention and risk of pressure to the cortical plates are accounted for. Pirker and colleagues have designed their system with the understanding that there is room for enlargement and retention only in the interradicular spaces. By developing a systematic approach for analyzing the 3D data of the CBCT, our work takes this concept further. In our postoperative periapical radiographs, it may appear as though the retentive elements protrude only to contact the lamina dura when, in reality, they extend significantly farther into the available spaces facial and lingual but short of the cortical plates. However, in this study, we did not account for the expansion of the socket and alveolus related to the extraction process, which is in the range of 0.6–5.9% volumetrically. We were able to design the body of each RAI to have a favorable path of insertion while restricting pressures on cortical bone and limiting impingement on critical anatomy. In addition, we could mimic the natural emergence of the tooth/root and add a prosthetic abutment surface—all while generating implant stabilization.

The clinical success of immediately placed implants is well documented and is a standard clinical practice. However, cylindrical root-form implants are not sized-matched to the socket walls, thus creating gaps and potential for traumatic and resorative processes. Sufficient bone must exist to allow enough primary implant stability to permit osseointegration, which significantly decreases the cases where this therapy is appropriate, such as meager interradicular bone or critical anatomy near the tooth-root apex. Root-analog implants may help overcome some of these problems, and our system may offer advantages compared to the current root-form and RAI systems and protocols through the following:

1. Custom-made implants can be delivered at the time of extraction, using existing radiographic data for implant design and fabrication.
2. Immediate implant placement may reduce the extent of surgical intervention, risk of morbidity, discomfort, and cost for the patient.
3. RAI immediately placed implants do not require osteotomy preparation.
4. RAI immediately placed implants may be done in areas where traditional root-form implants cannot be placed due to lack of apical bone.
5. Resorption of alveolar bone and soft tissue recession may be reduced due to the hard and soft tissue support congruent with the natural dentition and due to elimination of the implant-to-abutment microgap.
6. Resorption may also be decreased due to a lack of macrosurface structure at the implant to crestal interface (ie, threads), which may reduce plaque biofilm retention.
7. Esthetics may be improved given the material color of zirconia and natural emergence profile of the implant, as
well as support of crestal bone and papilla due to immediate implant placement.

8. Technical expertise for placement and for restoration will not exceed standard dental skillsets and will likely be less than current implant systems.

9. Overall safety may be improved as the surrounding anatomy is considered when designing the implant.

The results from this study demonstrated that 3D data from standard CBCT equipment can be utilized for the design and fabrication of self-retentive RAls. Perhaps most important is that these implants can be designed and manufactured preoperatively. The majority of labor to produce the implants was dedicated to the CBCT evaluation CAD processes. Fabrication and materials were inexpensive, and if the design process can be streamlined and upscaled, these implants may compete with traditional implants in cost. The design tasks were accomplished manually in this study, with no specialized CAD expertise. Ideally, future software systems will be capable of automating the digital extraction and design processes.

An area of future improvement in both software and technique revolves around the identification and use of the central/long axis position of the implant in the fixture creation model. This is important because much of the implant body analysis and design relies on the definition of this central axis.

**Figure 8.** Case 1. Panel photographs on the top 3 rows from top to bottom showing labial, occlusal, and lingual views of implant site #9. From left to right: pre-op, extraction, and implantation. On the bottom row left to right: periapical radiographs taken pre-op, after extraction, and after implantation. Implant .stl surface mesh models and matching implant photographs distal and lingual are shown.
The goal is to define the axis that results in the lowest inertia tensor for the object. The inherent problem in this process is that the .stl models are surface mesh and not true volumetric representations of the area. Therefore, the analysis must be based on the vertices or nodes of the surface mesh. One potential option in mathematical terms is to take the mesh nodes as data points in n-dimensional space and perform a principal component analysis, assigning the accompanying eigenvector as the major axis. In clearer terms, imagine the nodes of the surface mesh in 3D space and creating an average of center-point positions for all levels of the object in space. The weighted average is used as the central axis. Due to the irregularity of the surface mesh, the nodes must be “weighted” to avoid over influence of areas where the nodes are concentrated. Another option may be to create orthographic projections (changing all z-coordinates to 0 and doing linear regression analysis on the resulting x and y coordinates, then combining those axes. For both methods, decreasing the “resolution” of the surface mesh to reduce the nodal concentration per unit area may eliminate areas of complex surface irregularity and reduce the risk of artifact. Work on this will be a continuing endeavor.

The next logical step with our system would be to superimpose an intraoral optical scan with the CBCT, which would greatly improve the ability to model the native tooth and to define the ideal prosthetic margin placement with respect to gingival esthetics and biologic width. Furthermore, the rapid improvement in 3D printing technology will undoubtedly increase the available options for methods and material, including direct laser metal forming of titanium that has been deployed clinically with excellent 1-year survival.29

**Figure 9.** Case 2. Panel photographs on the top three rows from top to bottom showing facial, occlusal, and lingual views of implant site #5. From left to right: pre-op, extraction, and implantation. On the bottom row left to right: periapical radiographs taken pre-op, after extraction, and after implantation. Implant .stl surface mesh models and matching implant photographs distal and lingual are shown.
None of the authors have any business, research, or personal aided manufacturing phase of this project. We would like to thank Jimmy Stegall at Sherer Dental Lab for support for these emerging RAI design strategies.

CONCLUSIONS

Although RAI systems exist, the true potential of clinical success for this design system is unknown. Osseointegration will require surface preparation and sterilization processing that were not done in this study. Similarly, restorative success with respect to esthetics, maintenance of crestal bone, soft-tissue health, and prosthetic connection based upon the design of the implant can be anticipated but are equally unknown and need assessment to make better implant and restorative design decisions. However, we believe that detailed customization of RAI's based upon site anatomy is necessary as defined in this study. We anticipate that by completing these tasks, overall success will improve as well as increase the likelihood of clinical and commercial viability. Further efforts are needed to provide support for these emerging RAI design strategies.

ABBREVIATIONS

aHU: approximate Hounsfield unit
CAM: computer-aided design
CBCT: cone-beam computed tomography
CEJ: cementoenamel junction
DICOM: digital imaging and communications in medicine
RAI: root-analog implant

ACKNOWLEDGMENT

We would like to thank Jimmy Stegall at Sherer Dental Lab for his invaluable assistance and expertise with the computer-aided manufacturing phase of this project.

NOTE

None of the authors have any business, research, or personal interests that represent any conflict of interest to this study.


