Overlay analysis of cone-beam computed tomography images acquired before and after guided bone regeneration surgery

by

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“Overlay analysis of cone-beam computed tomography images acquired before and after guided bone regeneration surgery”

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Overlay analysis of cone-beam computed tomography images acquired before and after guided bone regeneration surgery

This thesis is submitted by Dane T. Swenson and has been examined and approved by an appointed committee of the faculty of the Uniformed Services University of the Health Sciences.

The signatures that appear below verify the fact that all required changes have been incorporated and that the thesis has received final approval with reference to content, form and accuracy of presentation.

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DEDICATION

To my wife Aimee. You changed my life.

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ABSTRACT

"Overlay analysis of cone-beam computed tomography images acquired before and after guided bone regeneration surgery"

Dane T. Swenson, DMD, 2019

Thesis directed by: COL Kenneth J. Erley, COL Robert W. Herold,
LTC(P) Thomas M. Johnson and MAJ Jennette B. Obryhim

Background: Guided Bone Regeneration (GBR) has become one of the most common procedures utilized to augment a deficient edentulous site in preparation for dental implant placement. Success of implant placement depends on the volume of bone and ridge dimensions at the surgical site. Numerous biomaterials and membranes have been successfully used to augment deficient ridges. The purpose of this retrospective study was to evaluate possible associations between subject- and procedure-related variables and increased horizontal ridge dimension following GBR procedures specifically utilizing high density polytetrafluoroethylene (dPTFE) membranes and freeze-dried bone allograft (FDBA).

Methods: Pre- and Post-GBR cone beam computed tomography (CBCT) images acquired between July 1, 2012 and November 7, 2016 were included in this analysis. Cone-beam computed tomography images, from two different time-points, were overlaid and analyzed to measure the amount of ridge augmentation that was achieved. Gains in horizontal ridge dimension and change in vertical height of the crest were assessed with respect to subject- and procedure-related variables: gender, age, smoking status, number of missing teeth in site, anterior versus posterior site, healing time, titanium reinforcement of membrane, membrane fixation, tenting screw use, and membrane removal prior to implant placement.

Results: Thirty-one GBR sites (23 posterior, 8 anterior) in 31 subjects (22 male, 9 female) were included in the analysis where horizontal augmentation of the ridge was the primary goal of surgery. In the mesiodistal centers of anterior GBR sites, there was a vertical ridge height mean loss of 0.96 mm whereas posterior sites had a mean vertical gain of 0.27 mm. Significant increases were also found when using titanium strut reinforcement when evaluating percentage change of ridge width and vertical ridge height. When measuring 2 mm apical to the crest at the mesiodistal centers, those with titanium struts had a mean percent gain of 36.81% and those without titanium struts had a mean loss of 12.07%. Those with titanium struts had a mean gain in vertical ridge height of 0.40 mm; those without titanium struts had a mean loss of 0.76 mm. When measuring 2 mm apical to the crest at the mesiodistal centers, sites with no premature membrane removal had mean gains in ridge width of 2.23 mm, whereas sites that had a membrane removed pre-maturely had a mean loss of 0.36 mm.

Conclusion: GBR with dPTFE membranes and FDBA produced increases in horizontal ridge dimensions comparable with increases reported in studies utilizing other materials. In the study population evaluated, some patient- and procedure-related factors influenced the magnitude of augmentation achieved.

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LIST OF ABBREVIATIONS

BMP:	Bone morphogenetic proteins
CBCT:	Cone beam computed tomography
dPTFE:	High density polytetrafluoroethylene
DFDBA	Demineralized freeze-dried bone allograft
ePTFE	expanded polytetrafluoroethylene
FDBA:	Freeze-dried bone allograft
GBR:	Guided bone regeneration
GTR:	Guided tissue regeneration
HA:	Hydroxyapatite
MSC:	Mesenchymal stem cells
OPG	Osteoprotegerin
PLA:	Polylactides
PGA:	Polyglycosides
TCP:	Tricalcium phosphate

INTRODUCTION

STATEMENT OF THE PROBLEM

Despite current advances in dental treatment, approximately 20 million dental extractions are performed each year in the United States. Once a tooth is extracted, a decrease in the volume of bone at that site can be expected due to induced bone modeling and remodeling. Without application of ridge preservation techniques, a patient can expect a 50% decrease in ridge width following a posterior tooth extraction with two-thirds of that occurring in the first three months.(1) This bone loss following tooth extraction, as well as loss due to periodontal disease, trauma, and anatomical or congenital factors can preclude a patient from having a reliable and esthetic restorative treatment option for their edentulous span. Further, even with the use of ridge preservation techniques, some bone loss may still occur.

Dentists often need to manage deficient alveolar ridges in order to restore health, comfort, and function for their patients. In many cases, proper dental implant placement cannot proceed until the clinician augments the deficient ridge. The desired magnitude of horizontal augmentation is biologically driven. Human and animal studies suggest a minimum bone thickness of 2 mm around the implant is necessary for stability of peri-implant tissues. Consequently, bone augmentation, especially using guided bone regeneration (GBR), has become a common necessary preparatory step in the process of augmenting an edentulous ridge for dental implant placement.(2-5)

Data regarding increases in ridge dimensions following GBR have been reported. However, materials used in some early studies are no longer available, and newer materials with less supporting data are now employed extensively. Reported mean increases in horizontal ridge dimensions following GBR range from 2.7 mm to 5.6 mm, with considerable heterogeneity among studies in materials used, defect types, observation periods, ridge measurement techniques, and vertical position of ridge measurement.(6-11) Given the wide array of grafts, bone derivatives and substitutes, other biomaterials, membranes, and biologic amplifiers utilized in GBR procedures, data indicating results achieved with specific material combinations are clinically valuable.

In most previous GBR studies, measurements of horizontal bone gain following GBR were performed using manual calipers intraorally and therefore lack the accuracy of CBCT three-dimensional imaging measurements now available. This study utilized overlaid CBCT images to retrospectively evaluate GBR outcomes when the procedure involved a specific combination of materials: a dPTFE membrane and FDBA particulate biomaterial. The influences of subject- and procedure-related variables on the magnitude of horizontal ridge augmentation were assessed.

SIGNIFICANCE

Being able to reliably predict the amount of bone a practitioner can expect to gain following a GBR procedure would allow a provider to make an informed decision on when to proceed with potential implant treatment and when to consider other options. If a clinician knows how much bone they will gain following a GBR procedure, they will then be able to determine more definitively if implant placement is the right option for an edentulous site. This would allow clinicians to predictably treat a soldier in need of ridge augmentation and implant placement with a lower risk of having undesired outcomes. This knowledge can save the soldier time, save the US Army money and increase military health and readiness.

REVIEW OF THE LITERATURE

INTRODUCTION

Nyman et. al. performed a number of experimental studies in the early 1980's with a focus on regeneration of lost periodontal tissues which was subsequently called Guided Tissue Regeneration (GTR). They developed the technique of using barrier membranes to exclude undesired cells from a periodontal defect. This subsequently led to the technique of guided bone regeneration by applying these principles on edentulous ridges. A vertical or horizontal ridge deficiency could be augmented surgically with the use of a barrier membrane aiding in the containment of a particulate biomaterial as well as to maintain space for bone regeneration.(12-15)

Implant-supported restorations are an important treatment option for an edentulous site, providing an esthetic and long-lasting outcome. It is estimated that up to 40% of dental implants require ridge augmentation.(16,17) Importantly, as bone naturally goes through modeling and re-modeling, a minimum of 2 mm of bone thickness surrounding the site of implant placement allows for the most predictable long term stability of the implant and surrounding tissues.(2,3) For this reason, various ridge preservation techniques can be applied at the time of extraction in an effort to maintain adequate bone by minimizing the loss of bone that occurs following extraction.

However, due to the net loss of bone by resorption following tooth extraction, or as a result of other conditions such as disease activity or trauma, there can be insufficient bone to support an implant on an edentulous ridge. Therefore, bony ridge augmentation is a commonly needed step in preparation for implant placement.

RIDGE AUGMENTATION AND GUIDED BONE REGENERATION

There are many different strategies for ridge augmentation: autogenous block grafting, ridge expansion osteotomy, alveolar distraction osteogenesis, titanium mesh housing a bone morphogenetic proteins (BMP-2) saturated collagen sponge and GBR utilizing particulate graft, bone derivative or bone substitute have all been utilized to aid in areas of bone insufficiency. The goals of these therapies is to create enough ridge volume that allows an implant to be fully integrated and maintained during functional loading.

Autogenous block grafts are the only source of viable osteoprogenitor cells and can be harvested surgically from the patient’s mandibular symphysis or ramus buccal shelf to obtain a cortico-cancellous or a pure cortical bone block for alveolar ridge augmentation. Multiple surgical sites, donor site morbidity and unpredictable resorption rates are known disadvantages of block grafts.(18) The split crest technique involves expanding a narrow ridge following a mid-crestal osteotomy and using osteotomes of progressively larger diameters, then impacting them to mobilize and gradually expand the vestibular bony flap to create an implant bed.(19) Alveolar distraction osteogenesis involves mobilization of a healthy segment of bone adjacent to a deficient site utilizing a mechanical device to provide gradual, controlled transport of that mobilized alveolar segment. The distraction device is left in static mode once the segment is positioned, acting as a fixation device. This allows for simultaneous increase of hard and soft tissue, however recent studies have shown that there is not a significant difference in terms of bone gain between alveolar distraction osteogenesis and the more commonly utilized onlay bone grafting.(20) True bone regeneration can be accomplished on a deficient ridge utilizing by fixating a titanium mesh housing containing a BMP-2 collagen sponge.(21) Potential patient morbidity, surgical complications of removal of the titanium mesh as well as the extreme high cost of BMP-2 make this option less popular.

In GBR procedures, a crestal incision in made in the area of a deficient alveolar ridge. Intrasulcular incisions extend laterally to allow adequate access without undue intraoperative flap tension. A full thickness mucoperiosteal flap is elevated apically several millimeters past the ridge deficiency. Intramarrow penetrations through the buccal cortex are frequently performed to allow for blood supply and viable osteoprogenitor cells into the GBR site. A membrane is adapted to the ridge defect and tenting screws may be placed in the area of the deficiency to support the membrane and provide space maintenance so that bone regeneration can occur.

An autogenous particulate or block graft, or a particulate biomaterial (a xenograft, a mineralized or demineralized allogeneic bone, or a synthetic bone substitute) is placed to create the ideal ridge contour and shape. The membrane, properly trimmed and adapted, covers the particulate biomaterial or graft and the membrane is then often fixated utilizing 3-5 mm length titanium tacks or screws. Membranes used during GBR may be either resorbable or non-resorbable and some non-resorbable membranes also have integrated titanium struts to provide more rigidity to the membrane and get more exacting space maintenance. The membrane helps to contain the loose particulate graft material and also provides a barrier against infiltration of soft tissue healing into the biomaterial matrix.(22)

The surgical site is then typically closed after one to two vertical releasing incisions and a periosteal releasing incision has been made. The periosteal releasing incision is made with a horizontal incision that is approximately 1.5 mm deep through the fibrous layer of the periosteum. As the periosteal releasing incision proceeds, a several millimeter gap between the apical and coronal periosteal margins appears, with distinct submucosa intervening between the two fibrous segments. This allows for passive, tension free, flap closure that when sutured properly, allows mucosal healing by primary intention.(22)

HEALING OF BONE AT THE CELLULAR LEVEL

To gain an understanding of how bone can be regenerated in an alveolar defect, a practitioner must understand how bone heals on a cellular level. Skeletal bone goes through a process of renewal by turnover (remodeling) to maintain its vitality and structure. Osteoblasts, which have a mesenchymal origin, are bone cells that are active along the surfaces of bone; they produce a bone matrix (osteoid) which can mineralize. When an osteoblast is finished laying down the bone matrix, it will undergo apoptosis or mature into either an osteocyte or a bone lining cell. Osteoblasts secrete the protein osteoprotegerin (OPG) that inhibits bone resorption. OPG binds to the protein, RANKL (also produced by osteoblasts and other cells) to prevent the activation of bone breakdown through stimulation of osteoclastic activity. Thus the concentration ratio of RANKL to OPG, determined in large part by osteoblast activity, determines the formation and activity of osteoclasts, the cells that mediate bone resorption, and ensures a coupling of bone formation and resorption during remodeling.(23)

Endochondral ossification goes through a different process than intramembranous ossification. Endochondral ossification is the process where bone replaces a cartilage model (a hyaline cartilage precursor) whereas intramembranous ossification occurs when bone is laid down directly onto connective tissue (mesenchyme). Intramembranous ossification forms the flat bones of the skull, clavicle and mandible.(24)

For both forms of ossification, osteoblasts appear to originate from undifferentiated mesenchymal stem cells (MSCs): multipotent, extravascular cells that are not of hematopoetic or endothelial cell origin. MSCs are present in the bone marrow and periosteum and exhibit a high amount of activity at sites of injury. They exhibit numerous processes including migration, condensation, proliferation and differentiation to help repair and rebuild bone that has been injured. These stem cells differentiate to build bone by becoming a precursor cell with a bone morphogenetic protein (BMP) receptor. When a BMP protein binds to a BMP receptor, the cell further differentiates into a pre-osteoblast that can then attach to a bone surface via osteopontin and various ligand-receptor interactions. After differentiation to a secretory osteoblast the cell will lay down osteoid bone matrix that undergoes mineralization.(25)

Bone lining cells cover surface sites that are neither actively laying down nor resorbing bone. They lie flat, with an extended morphology when compared to osteoblasts, and are connected via gap junctions. They are involved in the homeostasis of bone, especially in adult skeletal bone. Bone lining cells send cell processes into surface canaliculi to contact osteocytes, establishing a communication network throughout the bone structure to the surface.(26)

When an osteoblast matures into an osteocyte, which is encased in mineralized tissue, it no longer secretes OPG and bone resorption is less inhibited. Osteoclasts, which are of hematopoetic origin, respond to elevation of parathyroid hormone levels as well as to the binding of RANKL to their surface receptor RANK. Active osteoclasts bind to the bone surface, seal the edges, and secrete hydrochloric acid to dissolve the inorganic matrix of bone.(27)

Pathways of Bone Healing

There are a number of different bone healing processes that take place within the human skeleton. Fracture healing, extraction socket healing, and guided bone regeneration each have similar core characteristics.

Fracture healing can take place in the maxilla and mandible. Much like the healing of an extraction socket, a clot within the fracture site is the first step toward healing. The clot is then replaced by granulation tissue. Around two weeks later, a callus forms, comprised of both mature and immature tissue, with active chondroblasts and osteoblasts laying down extracellular matrices of respectively cartilage and woven bone in a process resembling endochondral ossification. Within a week, the newly formed matrices begin mineralization. In the months following, the woven bone is replaced by lamellar bone to give strength and structure to the area and to allow for continuous remodeling of the bone.(28)

Healing of extraction sockets has some differences from the bone healing seen in fracture healing. When a tooth is extracted, there are four bony walls that contain the blood clot within. This clot is partially replaced with granulation tissue within the first 3-4 days, and then by a provisional matrix a week after the initial extraction. By Day 30, the matrix has been replaced by woven bone, forming coronally beginning from the apex, with the majority of the space being mineralized. By six months post-extraction, lamellar bone has replaced the woven bone and evaluation reveals that by volume, 85% of the socket has bone marrow and 15% is mineralized bone.(29)

Extraction socket healing is dissimilar from healing during GBR in a few ways. With healing during GBR there is a lack of the clot being contained within a four wall bony socket, and also lacks remnants of the periodontal ligament seen in fresh extraction sites. The extraction socket is generally left exposed to the oral environment during healing instead of having complete wound closure for primary intention healing that is a surgical goal of GBR. However, despite these differences, the sequence of events that occur during bone healing following a tooth extraction provides us information on normal bone healing of the alveolar ridge.(30) In GBR the same general principles and steps of healing are witnessed in extraction socket healing and fracture healing, but with the additional influence of surgical steps to promote bone formation and augmentation of the ridge. Requirements for bone regeneration include complete wound closure with primary intention healing, space maintenance in the desired area of augmentation, and wound stability during healing.(31) Many authors also recommend surgically creating bone perforations in the cortex in the zone of augmentation. This wounds the bone to stimulate a reparative response and allows blood supply and eventual vascularization of the augmented site.(22)

Implant Success in Newly Augmented Bone

Implant success rates have shown to be similar when placed in purely native bone when compared to sites that have had GBR performed. Similar survival rates are also achieved when GBR is combined with either simultaneous or staged implant placement.(32-34)

Histological analysis of a healed ridge that had previous GBR performed with hydroxyapatite (HA) biomaterial reveals certain characteristics when compared to the native bone, even years after placement. Specifically, there is a mixture of three main components: vital bone (consistent with the native bone), connective tissue and residual graft particles.(35) Other histological studies have demonstrated similar results when different biomaterials (xenografts and allogeneic particulate) are used.(36) Despite these modest differences in histological makeup between native and augmented bone, there have been numerous studies that have found that the survival rates of implants are similar in GBR sites when compared to implant survival rates in native bone.(37-39)

MATERIALS USED FOR GBR

Barrier Membranes

Membranes used in GBR procedures can be classified as resorbable and non-resorbable. They are made of natural polymers, synthetic polymers, metals and inorganic compounds.(40-41) Necessary characteristics of a barrier membrane intended for GBR must include: biocompatibility, cell occlusion, space maintenance, tissue integration, and clinically manageable handling properties.(42)

Polymeric membranes are synthetic materials, able to be created under strict laboratory conditions, and can be reproduced consistently. They are made of polyglycosides (PGAs), polylactides (PLAs), a combination of the two, or polydioxanones and triemethylene carbonates.(43) Occasionally, complications can occur with polymeric compounds that include inflammatory and foreign body reactions, sometimes even requiring surgical debridement or removal of the material. Membrane exposure during the healing phase has shown to be less problematic. Upon exposure, membranes quickly degrade within 3-4 weeks, possibly leading to spontaneous healing and closure of the tissue, which is not possible with a nonresorbable membrane.(44)

Commonly utilized natural bioresorbable membranes are collagen based. These membranes may be derived from type I collagen or of type I and type III collagen from porcine or bovine tissues. They are easily manipulated and have advantages over synthetic resorbable membranes that include hemostasis, weak immunogenicity, a direct effect on bone formation and an ability to augment tissue thickness. However, collagen membranes can be more unpredictable from one specimen to another in makeup and longevity, possibly limiting their barrier function to only a few weeks. Their rate of degradation can be extended by methods of physical/chemical cross-linking treatments. Many collagen membranes have suggested properties of potential to promote better wound healing and bone regeneration. However, although cross-linked collagen membranes have improved long term stability, residues of amides and aldehydes used in the cross-linking process have been reported to potentially induce severe inflammation at the implantation site. This also has led to a higher risk of membrane exposure during healing, which in turn, leads to decreased augmentation of the bony ridge.(41,45-47)

Nonresorbable synthetic membranes have been commonly used in dentistry since the 1980’s. The Expanded polytetrafluoroethylene (ePTFE) membranes are considered to be inert, stable polymers that resist breakdown by host tissues and does not elicit an immunologic response. ePTFE membranes are biologically inert and nondegradable due to their strong carbon and fluorine bond, for which there is no known enzyme in the body capable of cleaving.(48) When a bone defect heals underneath an ePTFE membrane, the soft tissues that form underneath and on top of the membrane are distinctly different. In an experiment on the canine mandible, soft connective tissue, dense in collagen with a covering of keratinized epithelium, made up the outer soft tissue layer adjacent to the nonresorbable membrane. Underneath the membrane was more delicate collagen and loose connective tissue that was derived from the bone marrow itself, illustrating the membrane’s ability to provide proper cell occlusion.(42,49) A frequent complication that arises with use of ePTFE membranes is a membrane exposure from soft tissue dehiscences during the healing phase. Mean bone regeneration rates are strongly reduced in cases of early exposure of the membrane.(50) The ePTFE membrane stiffness makes membrane exposure during healing more likely and increases possible post-operative complications of surgery such as wound infection.(51) Another drawback to these nonresorbable membranes is a required second surgery to remove the membrane after proper healing has occurred.

High density polytetrafluoroethylene (dPTFE) membranes have replaced most uses of the ePTFE membranes. dPTFE membranes are to be able used in situations where obtaining primary closure of a site is difficult, such as in instances of socket preservation, or when early exposure of GBR is probable. They have been shown to have predictable results in preservation of hard and soft tissues, even when partially exposed to the oral environment. dPTFE membranes were developed with much smaller pore size (sub-micron level) than the previous ePTFE membranes. This small pore size allows for exchange of gasses and nutrients, but is too small for bacterial colonization and infiltration, greatly reducing the risk of infection at the surgical site, even with membrane exposure. dPTFE membranes may also have titanium reinforcement struts integrated which allow for optimum space maintenance when manipulated.(52)

Bone Grafts and Biomaterials Used in Ridge Augmentation

Bone graft materials in use today include autogenous block and particulate grafts, xenogeneic (bovine, porcine and equine derived materials), synthetic bone substitute of various types commonly referred to as alloplastic materials, or allogeneic mineralized or demineralized particulate bone. When placed in a defect, the biomaterials act to give structural support to the membrane and serve as a scaffold that can support bone ingrowth from the recipient site.

Autogenous bone grafts are taken from an intraoral or extraoral site in the patient, and transferred to the recipient site. Bone-stimulating growth factors and viable osteogenic cells are brought to the site when using an autogenous graft.(53) Blocks of cancellous bone more readily contain and release growth factors than blocks of compact bone. Greater concentrations of growth factors are released as a result of the greater blood supply, marrow space and surface area of trabecular bone.(54) Autogenous block grafts are a treatment option that offers mechanical stability against pressures from tissue overlying it, and are usually held in place with fixation screws. Block grafts harvested from the iliac crest revascularize faster than blocks taken from the mandibular body, because of their greater content of cancellous bone.(53) However, block grafts harvested from the patient's mandibular symphysis or ramus buccal shelf have shown greater resistance to resorption than iliac crest and particulate autografts during the healing phase because of their higher cortical and mineralized content. The shortcomings of using autogenous grafts, such as donor site morbidity and longer surgeries, have led to bone graft substitutes, alone or in combination with autogenous bone grafts, becoming the standard treatment in bone augmentation procedures.

Xenogeneic biomaterials come from non-human sources, bone mineral derived from animals as well as minerals collected from calcifying corals or algae (from which the organic components have been removed). Coral- and algae-derived bonelike minerals are seldom used for GBR procedures because studies have shown them to have less osteoconductive potential than other bone substitute materials, even though their HA is nearly identical to that seen in the mineral content of bone.(60) Animal-derived bone materials have been used in GBR with good evidence of bone formation from experimental and clinical studies. The organic component of animal bone is removed by either heat treatment, chemical extraction, or a combination of the two during processing while preserving the inorganic mineral composition. Cancellous bovine particulate biomaterials have been used extensively due to their extremely similar makeup to cancellous human bone.(61) These materials have shown very slow resorption rates which assures their long-term stability.

Alloplastic bone substitutes are made up combinations of calcium phosphate, bioactive glass, or are polymeric in nature. Calcium phosphates, which include HA, have been studied intensively as their composition is extremely similar to inorganic bone. HA is osteoconductive and nonresorbable, making it suitable for more demanding defect morphologies, such as lateral ridge augmentation. Another compound, tricalcium phosphate (TCP) is often added together with HA because of its greater and faster facilitation of osteoconduction. TCP releases raw material calcium and phosphate ions into the space upon its degradation, which may promote faster bone healing than when HA is used alone.(62)

Allogeneic biomaterials come in many forms of preparation and are commercially available, allowing an essentially limitless supply of biomaterial that can be used to aid in bone regeneration. Bone substitutes must demonstrate biocompatibility, osteoconductivy, and provide adequate mechanical support to allow for regeneration of bone. Some materials show greater amounts of biodegradability and replacement of the biomaterial by the patient’s own bone, but non-resorption of the biomaterial may aid in maintenance of the augmented ridge.(55)

FDBA and demineralized freeze-dried bone allograft (DFDBA) are produced by harvesting cadaver bone, and processed by freeze-drying, and sterilizing bone. They are supplied by licensed tissues banks as both block and particulate bone. There have been no reported cases of disease transmission from the use of FDBA or DFDBA during the 30 year history of their use and the likelihood of disease transmission is extremely low.(56) DFDBA has an added step of demineralizing the donor bone, which has shown to have more osteoinductive potential due to a greater exposure of BMP's on the particulate surface of DFDBA.(57,58) However, comparative studies in ridge preservation models have shown similar results when using either FDBA or DFDBA.(59)

GBR MEASURING TECHNIQUES

When comparing the accuracy of measuring bone width with digital calipers vs software generated calculations of distance on a CBCT, studies have found limitations with both techniques.

Many of the previously discussed studies utilized calipers that were placed on the ridge intraorally to measure various dimensions and gains following GBR. If calipers are precisely calibrated, a direct method of measurement is an accurate way to visualize the bone currently present at that time. However, when evaluating a site that has had GBR performed, this method likely fails to take into account the vertical change in the ridge height and caliper accuracy is limited from the imprecision of replicating the pre- and post-GBR measuring position on the ridge. For example, if a surgical site has gained or lost bone during the surgery and healing process, the clinician can only give their best estimation of consistent measurement points.

Overlay analysis of two CBCT images taken at two different time points gives more accuracy of the change in ridge morphology. The positioning of the palatal and lingual cortical plates rarely changes following GBR procedures and provides a consistent starting point when making measurements at two different time points. Measurements can be obtained, even in areas that might be difficult to clearly see or access with direct measuring techniques in the mouth.

CBCT measuring software does have limitations. For instance, if the patient is not motionless while an image is obtained it can lead to irregularities in precision measurements. Device-specific exposure parameters, the type of software used, manual vs automated procedures, and difficulty in deciphering areas surrounding metallic artifacts complicate measurements on CBCT images.(63)

SUMMARY

Previous imaging methods have limited our understanding of treatment predictions because of their two-dimensional orientation. Few studies have been performed utilizing the three-dimensional measurements of CBCT imaging to evaluate GBR treatment. Measuring lateral ridge augmentation allows for much more precision than past studies that have utilized intraoral caliper measurements. Orientation of the bony ridge and precision of measurements is more consistent utilizing CBCT imaging.(64)

PURPOSE

The purpose of this project is to determine the expected horizontal gain in bone following GBR and compare the results of dPTFE membranes with and without titanium reinforcement as well as expected gain in interproximal sites vs distal extension sites. We will be measuring patients at Tingay dental clinic who had a CBCT taken both before and after GBR was performed.

MATERIALS AND METHODS

ETHICAL GUIDELINES

This study was reviewed and approved by the Regional Health Command Central (Provisional) Human Research Protections Office, Joint Base San Antonio, Fort Sam Houston, TX (Ref. #C.2017.006e) and was determined to be exempt from regulatory requirements of 32CFR§219.

INCLUSION AND EXCLUSION CRITERIA

Pre- and Post-GBR CBCT images acquired from patients undergoing GBR procedures at Tingay Dental Clinic, Fort Gordon, GA, from July 1, 2012, to November 7, 2016, were evaluated. All images were acquired on a single CBCT scanner. GBR sites were included for analysis if the site had both a pre- and post-operative CBCT scan, the surgical goal was horizontal ridge augmentation in preparation for dental implant placement and the procedure utilized a dPTFE membrane (with or without titanium reinforcement) and FDBA. Sites were excluded if no implant was planned, the surgical goal was primarily vertical ridge augmentation, or the surgeon employed materials other than dPTFE membranes and FDBA.

SUBJECT- AND PROCEDURE-RELATED VARIABLES

Patient records were reviewed to confirm the treatment plan and record subject- and procedure-related variables: gender, age, smoking status, number of missing teeth in site, anterior versus posterior site, healing time, titanium reinforcement of membrane, membrane fixation, tenting screw use, and membrane removal prior to implant placement.

CBCT IMAGE EVALUATION

A single examiner (DTS) exported DICOM images from the CBCT scanner (3D Accuitomo 170, J. Morita USA Inc., Irvine, CA) and imported both the pre- and post-GBR CBCT's into a designated computer with CBCT overlay software (Dolphin 3D Imaging software, Patterson Dental Supply Inc., Chatsworth, CA). The images from two different time points were overlaid by using consistent anatomical points (i.e. mental foramen, anterior nasal spine, unique nodules and tori, CEJ's of teeth in the same arch) to ensure accurate measurements when comparing the pre- and post-GBR scans. Since patients are often open at varying degrees for the pre- and post- scan, only one arch (maxilla or mandible) can be overlaid at a time. The examiner recorded buccolingual ridge width measurements at six points for each GBR site. Specifically, ridge width was assessed at two vertical levels (2 mm and 4 mm apical to the osseous crest) at each of 3 mesiodistal positions (M1, M2, and M3). M2 was defined as the mesiodistal midpoint within the GBR site. M1 and M3 were the mesiodistal positions located 2 mm toward the midpoint measured from the mesial and distal membrane margins, respectively (Figure 1). A seventh measurement was recorded to document the change in vertical height of the crest at the M2 position. If the membrane was removed prior to the post-GBR CBCT image acquisition, M1 and M3 were established 2 mm from the mesial and distal margins of the FDBA observed on the CBCT image. The method of positioning CBCT images prior to measurement described by Block and colleagues was adapted for use in this study population.(11) Landmarks such as the occlusal plane, the nasal spine, the floor of the maxillary sinus, the inferior border of the mandible, the mandibular canal, the mental foramen, adjacent teeth, and dental restorations were used to place images in anatomic position and set the spline of the alveolar ridge. Cross-sectional CBCT images of the ridge (perpendicular to the arch form) at the M1, M2, and M3 positions were selected for measurement. The metric ruler included in the CBCT system software was used to establish the measurement location 2 mm and 4 mm apical to the osseous crest. Baseline ridge width at each position was determined by measuring from the palatal/lingual extent of the ridge to the buccal extent of the native cortical bone, and the post-GBR ridge width was determined by measuring from the palatal/lingual extent of the ridge to the buccal/facial limit of the augmented ridge

(Figure 1). To establish reproducibility of the measurement technique, a second examiner (DJP) repeated measurements for the first 10 subjects.

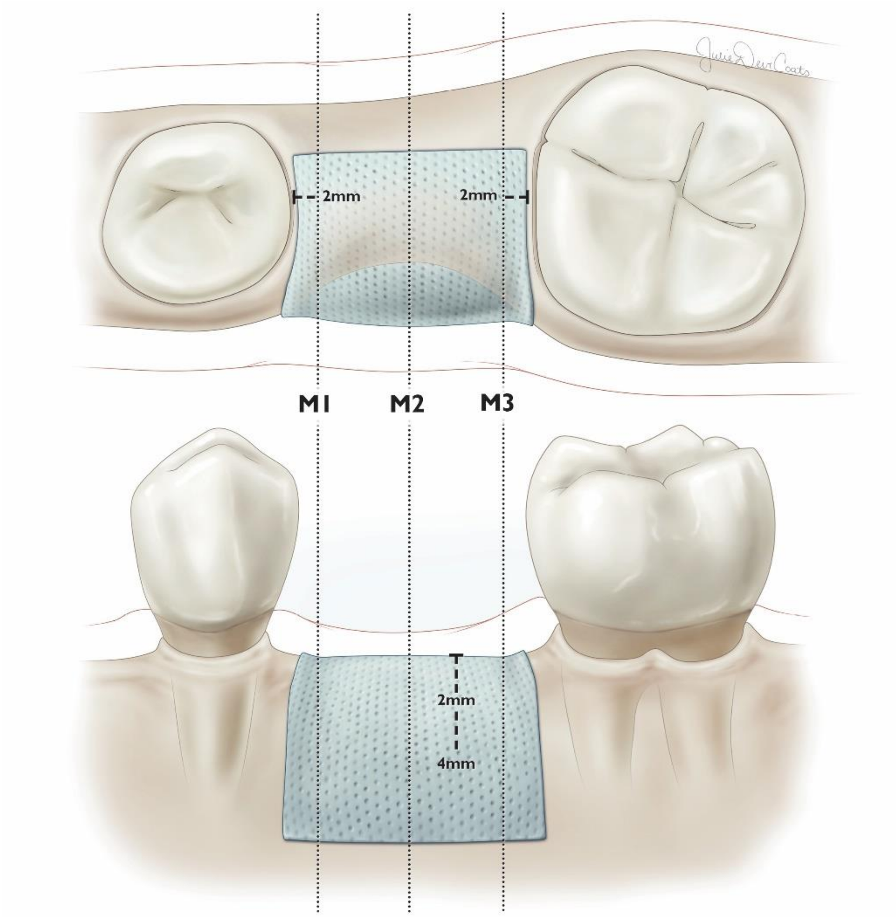

Figure 1. Diagram delineating six horizontal CBCT measurement points (M1, M2, and M3 positions, 2 mm and 4 mm apical to the osseous crest). A change in vertical height of the crest was also taken at the M2 position

RESULTS

Statistical Methods

SAS 9.4 was used for all statistical analyses. An alpha level of 0.05 was used to assess statistical significance. Descriptive statistics were calculated for all qualitative and quantitative variables.

A two-sample t-test was performed to determine if differences between groups of interest were significant. Pearson's Correlation Coefficient was calculated to examine associations between initial ridge width measures with absolute and percent change from baseline.

Overview

There were 31 patients with data (22 males and 9 females) with a mean age of 40.1 years (SD=10.5). All subjects were non-smokers. Table 1 illustrates the study population characteristics. Table 2 shows the individual subject data collected. Tables 3a and 3b give the descriptive statistics for quantitative and qualitative variables, respectively.

Significant Findings

Significant differences were found between anterior vs. posterior sites for vertical ridge height change at M2. Anterior sites had a mean loss of 0.96 mm and posterior sites had a mean gain of 0.27mm.

There was a significant difference between Titanium Strut Reinforcement (Y vs. N) groups for vertical ridge height at M2 and percent change in ridge width when measuring 2 mm apical to the crest at the mesiodistal centers [M2 (2mm)]. Those sites with titanium struts had a mean percent gain of 36.81% and those without titanium struts had a mean loss of 12.07%. It is worth noting that the sites that had complete loss of the ridge 2mm from the original crest of bone were factored into that mean value. Those with titanium struts had a mean gain in vertical ridge height of 0.40 mm whereas those without titanium struts had a mean loss of 0.76 mm. Figures 3a and 3b illustrate an example of measurements taken on a subject where vertical loss of the ridge was greater than 2mm.

Significant difference were found between premature membrane removal (Y vs. N) groups for percent change in ridge width at M1 (2mm), M2 (2mm), percent change in ridge width at M2 (2mm), and vertical ridge height change at M2. Those with no premature membrane removal had significantly greater ridge augmentation at M2 (2mm), percent change at M1 (2mm) and M2 (2mm) and vertical ridge height change at M2. Figures 4a and 4b illustrate an example of measurements taken on a subject where no premature membrane removal occurred and significant horizontal augmentation is noted.

Posterior ridge width, change in ridge width and percent change in ridge width at M1 (2mm), M2 (2mm), M3 (2mm) were significantly correlated with vertical ridge height.

Table 1. Study Population Characteristics

Gender	9 Female	22 Male
Age [years]	Mean age of 40.1 (SD = 10.5 years)	
Smoking status	All subjects were non-smokers	
Site type	8 Anterior	23 Posterior
GBR site terminal position in arch	12 interproximal GBR sites	19 Distal Extension GBR sites
Number of missing teeth in GBR site	13 subjects - 1 tooth 12 subjects - 2 teeth 4 subjects - 3 teeth 2 subjects - 4 teeth	
Tenting screw use	8 - Yes	23 - No
Membrane fixation	29 - Yes	2 - No
Membrane reinforcement (titanium)	19 - Yes	12 - No
Membrane removal prior to implant placement	14 - Yes	17 - No
Interval between GBR and CBCT image [months]	Mean = 5.2, Range = 1.2 to 23.2	

Table 2. Individual subject data

											Measured 2mm from osseous crest						Measured 4mm from osseous crest								
Subject	Pre- and Post-GBR images [Y/N]	Sex [M/F]	Age [Integer]	Smoker [Y/N]	Distal extension [Y/N]	Anterior (A), Posterior (P)	Number of missing teeth in site [#]	Tenting screw [Y/N]	Titanium struts [Y/N]	Membrane fixation [Y/N]	$M1_{i2}$ [mm]	$M1_{GBR2}$ [mm]	$M2_{i2}$ [mm]	$M2_{GBR2}$ [mm]	$M3_{i2}$ [mm]	$M3_{GBR2}$ [mm]	$M1_{i4}$ [mm]	$M1_{GBR4}$ [mm]	$M2_{i4}$ [mm]	$M2_{GBR4}$ [mm]	$M3_{i4}$ [mm]	$M3_{GBR4}$ [mm]	Premature membrane removal [Y/N]	Healing time post-GBR image [days]	Change in vertical ridge height at M2 [mm]
S1	Y	F	29	N	N	P	1	N	N	N	4.1	0	4.3	0	4.5	0	4.9	5.3	5.2	4.7	5.5	4.7	Y	346	-2.6
S2	Y	F	31	N	N	P	2	Y	Y	Y	4.4	6.6	4.3	7.1	4.1	8.3	5.2	6.7	6.9	8.2	7.1	9.5	Y	121	+3.5
S3	Y	F	32	N	Y	P	2	N	Y	Y	4.2	5.6	4.3	9.4	2.5	2.5	6.6	9	6.7	9.9	5.8	6.3	N	198	+1.3
S4	Y	M	40	N	N	P	1	N	Y	Y	5.3	7.9	5.6	8.3	5.9	8.9	7.1	9.9	7.2	9.2	7.8	10	N	169	+0.4
S5	Y	M	22	N	N	A	1	N	N	Y	2	0	2.2	0	2.5	0	3.2	6.1	3.3	5.9	3.9	6.4	Y	125	-2.3
S6	Y	M	49	N	N	A	1	N	N	Y	3.9	5.1	4.4	5.5	4.5	5.5	4.8	6.1	5.7	7.3	6.2	7.4	N	125	0.2
S7	Y	M	31	N	Y	P	3	N	N	Y	4.3	0	4.2	0	3.8	6	6.6	7.1	5.7	7.2	5.4	8.7	Y	139	-2
S8	Y	M	31	N	Y	P	3	N	N	Y	5.2	7.2	4.4	7	5	6.6	7.1	9.4	6.4	8.6	6.6	6.9	Y	139	+0.6
S9	Y	M	36	N	N	P	1	N	N	Y	4	4	4.5	5.4	4.4	4.8	5.8	6.4	6.2	7.5	7.4	7.9	Y	133	-1
S10	Y	M	33	N	N	A	2	N	Y	Y	3.3	4.5	3.1	4.9	3.5	5.2	2.7	4.8	2.3	4.9	2.7	5.2	N	80	0
S11	Y	M	49	N	N	P	2	Y	Y	Y	4.1	7	5.5	8.1	4.3	9.1	5.3	7.6	7.8	8.8	6.9	10.3	N	152	+3
S12	Y	M	27	N	Y	P	2	N	Y	Y	4.5	6.2	5.1	4.3	5.5	0	6.5	8	8	7.5	7.9	5.6	N	110	0
S13	Y	M	27	N	Y	P	2	N	Y	Y	5.6	1.7	4.4	6.4	4.9	4	7.7	7.8	6.7	9.1	5.7	8	N	199	0
S14	Y	M	30	N	N	P	1	N	Y	Y	5.7	9.6	4	9	5.5	9	8.2	11.1	8	11.3	8.2	11	N	118	+1.6
S15	Y	M	55	N	Y	P	2	N	Y	Y	6.1	7.3	6.4	8.2	4.8	4.4	7.1	9.4	6.4	9.2	6.8	8.1	Y	52	-0.7
S16	Y	M	55	N	Y	P	3	N	Y	N	6.8	8.4	6.7	9.1	5.6	8.7	7.5	9.9	8.1	10.7	7.8	11.5	Y	39	-1.3
S17	Y	F	47	N	Y	P	4	Y	N	Y	9.2	9.2	7.8	9.8	6.4	7.5	10.1	10.1	9.3	10	9.2	9.2	N	215	+0.5
S18	Y	F	47	N	Y	P	4	Y	N	Y	8	8	7.7	0	6.4	0	9.2	11.4	8	11	8	8.1	Y	171	-1.8
S19	Y	F	47	N	N	P	2	N	Y	Y	8.4	8.6	7.5	8.4	7.4	8.4	8.3	8.6	8.9	9.8	10	11.1	Y	695	-0.2
S20	Y	M	49	N	N	P	2	N	Y	Y	5.3	9	6.4	8.7	4.3	5.3	7.2	10.4	8.8	10.1	9.7	10.9	N	35	+1
S21	Y	M	37	N	N	P	1	Y	N	Y	5.1	8.7	5.2	10.1	6.4	8.9	6.9	11.1	7	11.6	7.5	11.5	N	152	-0.5
S22	Y	M	43	N	N	A	1	Y	N	Y	6.4	6.4	6.4	6.4	7	7	6.4	11.3	6.5	11.1	7.4	11.5	N	160	-1.4
S23	Y	M	36	N	Y	P	1	N	Y	Y	6.8	8.7	6.4	8.2	6.3	8.4	8.8	9.5	9.7	10	10.1	11.9	N	201	+0.3
S24	Y	M	37	N	N	A	1	N	Y	Y	5.2	6.8	5	6.4	5.5	7.2	6.5	8.2	6.7	8.2	7.4	8.7	N	168	0
S25	Y	F	34	N	Y	P	1	N	Y	Y	6.1	10.2	6.1	11.1	6.6	11.5	8.2	10.9	8.8	11.5	10.3	13.2	N	197	+2.9
S26	Y	F	58	N	Y	P	3	N	Y	Y	7.4	8.9	5.9	7.5	6.6	7.7	9.2	11.4	8.2	11.7	8.5	10.2	N	140	0
S27	Y	M	56	N	N	A	2	Y	Y	Y	3.8	0	5.7	5.1	5.4	0	4.7	4.7	6.3	7.4	9.2	7.6	N	55	-1.1
S28	Y	M	56	N	N	A	2	Y	Y	Y	5	6	5.4	7.6	4	3.5	5.5	7.4	6.6	8.6	6.2	7.8	Y	55	-0.7
S29	Y	M	25	N	N	A	1	N	Y	Y	5.5	4.1	2.8	0	5.9	3.4	8.4	6.1	3.2	2.7	7.3	5.6	Y	151	-2.4
S30	Y	F	47	N	N	P	2	N	N	Y	6.2	6.2	6.5	6.5	6.6	6.6	8.4	8.4	9.3	11.1	8.7	10.4	Y	126	-0.3
S31	Y	M	46	N	N	P	1	N	N	Y	8.9	9.8	8	10.5	8.5	9.9	10.7	12	11	12.5	10.7	11.8	Y	109	+1.5

M = male, F = female, Y = yes, N = no, A= anterior, P = posterior, M1 = mesiodistal position within the GBR site 2 mm from the mesial margin of the dPTFE membrane/FDBA, M2 = mesiodistal center of the GBR site, M3 = mesiodistal position within the GBR site 2 mm from the distal margin of the dPTFE membrane/FDBA

Table 3a. Descriptive Statistics for quantitative variables (N = 31)

Variable	Mean	SD	Min	Max
Age	40.06	10.52	22	58
Number of Missing Teeth	1.84	0.90	1	4
M1@2mm (pre)	5.51	1.67	2	9.2
M1@2mm (post)	6.18	3.08	0	10.2
M1@2mm (chg)	0.67	2.32	-4.3	4.1
M1@2mm (%chg)	9.10	52.21	-100	70.73
M2@2mm (pre)	5.36	1.45	2.2	8
M2@2mm (post)	6.42	3.31	0	11.1
M2@2mm (chg)	1.06	2.89	-7.7	5.1
M2@2mm (%chg)	17.89	61.53	-100	125
M3@2mm (pre)	5.31	1.38	2.5	8.5
M3@2mm (post)	5.75	3.30	0	11.5
M3@2mm (chg)	0.44	2.92	-6.4	4.9
M3@2mm (%chg)	7.64	58.08	-100	111.63
M1@4mm (pre)	6.93	1.86	2.7	10.7
M1@4mm (post)	8.58	2.14	4.7	12
M1@4mm (chg)	1.65	1.43	-2.3	4.9
M1@4mm (%chg)	27.28	25.35	-27.38	90.63
M2@4mm (pre)	7.06	1.91	2.3	11
M2@4mm (post)	8.95	2.29	2.7	12.5
M2@4mm (chg)	1.88	1.30	-0.5	4.6
M2@4mm (%chg)	29.55	26.49	-15.63	113.04
M3@4mm (pre)	7.48	1.84	2.7	10.7
M3@4mm (post)	8.94	2.28	4.7	13.2
M3@4mm (chg)	1.45	1.64	-2.3	4.1
M3@4mm (%chg)	22.50	27.13	-29.11	92.59
M2 Vert. Ridge Ht chg	-0.05	1.53	-2.6	3.5

Table 3b. Descriptive Statistics for qualitative variables (N = 31)

Variable	N	Percent
Sex		
Male	22	70.97
Female	9	29.03
Distal Extension		
Yes	12	38.71
No	19	61.29
Site		
Anterior	8	25.81
Posterior	23	74.19
Number of Missing Teeth		
1	13	41.94
2	12	38.71
3	4	12.9
4	2	6.45
Tent Screw Use		
Yes	8	25.81
No	23	74.19
Titanium Strut Reinforcement		
Yes	19	61.29
No	12	38.71
Membrane Fixation		
Yes	29	93.55
No	2	6.45
Premature Membrane Removal		
Yes	14	45.16
No	17	54.84
Actual Implant Placement		
Yes	30	96.77
No	1	3.23
Both pre- and post-GBR images		
Yes	31	100
No	0	0

Figure 2. Example of anterior GBR site measurements

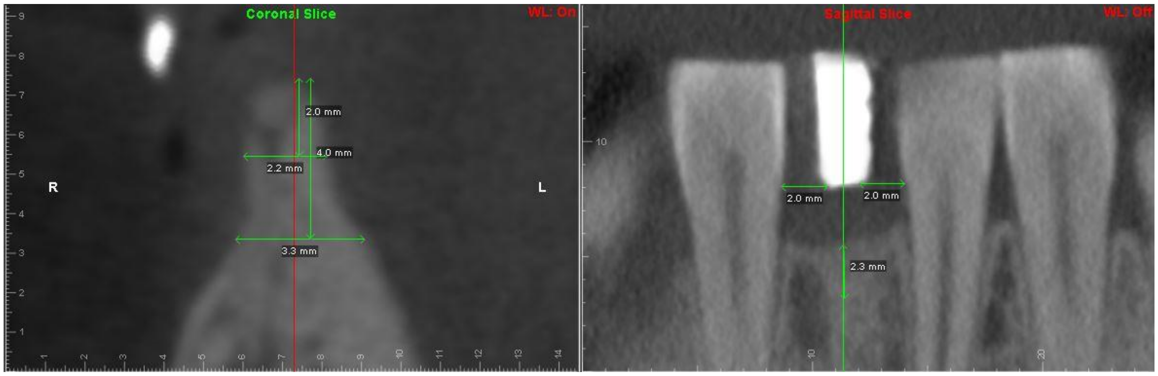

Figure 3a. Anterior Pre-GBR measurements performed at $M2_{i2}$ (2.2 mm) and $M2_{i4}$ (3.3 mm).

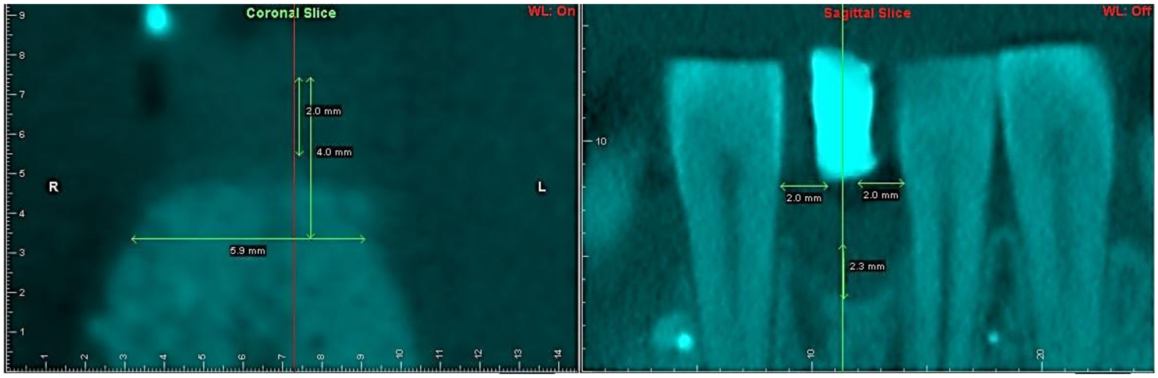

Figure 3b. Anterior Post-GBR GBR site measurements performed at $M2_{GBR2}$ (0 mm) and $M2_{GBR4}$ (5.9 mm). A vertical change (loss of 2.3 mm) at the M2 site was also noted.

Figure 3. Example of posterior GBR site measurements

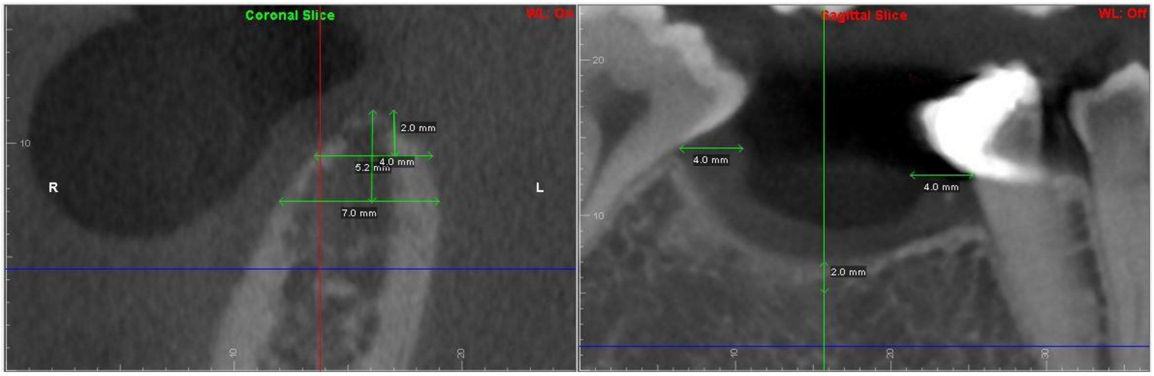

Figure 4a. Posterior Pre-GBR measurements performed at $M2_{i2}$ (5.2 mm) and $M2_{i4}$ (7.0 mm).

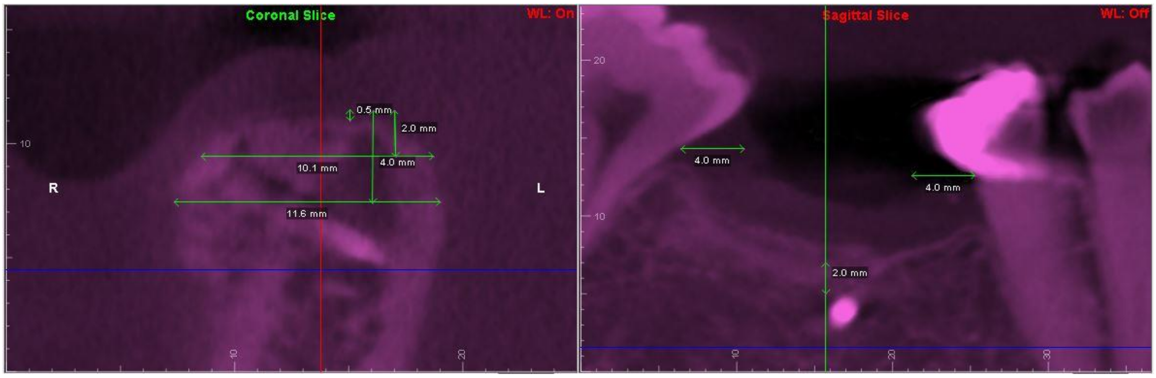

Figure 4b. Posterior Post-GBR GBR site measurements performed at $M2_{GBR2}$ (10.1 mm) and $M2_{GBR4}$ (11.6 mm). A minimal vertical change (loss of 0.5 mm) at the M2 site was also noted.

DISCUSSION

In some respects, mean post-GBR increase in horizontal ridge dimension is a misleading indicator of clinical success. The wide range of post-GBR ridge width increases observed in this study was not unexpected. Indeed, practitioners tend to aim for a magnitude of horizontal ridge augmentation that will ultimately yield at least 2 mm of circumferential peri-implant bone, and maximizing ridge width is not always the goal. Moreover, edentulous ridges vary widely in degree of deficiency. The amount of augmentation needed to reach the ideal horizontal dimension is thus variable. Even so, multiple studies have reported mean changes in horizontal ridge dimensions following GBR surgery. In most studies, only one postsurgical measurement was recorded for each site, and these studies employed a variety of measurement techniques.(6-11) Mean post-GBR ridge width increases determined in the present study are comparable with mean ridge width increases of previously reported values. Procedural and methodological details in previous reports are important for placing the present observations in context.

Buser and coworkers performed ridge augmentation on 66 sites in 40 subjects using expanded PTFE membranes, membrane fixation screws, autogenous block grafts from the chin or ramus, block fixation/tenting screws, and bone chips. Calipers were used to measure the ridge to the nearest quarter millimeter at a point 2mm apical to the osseous crest at the site of planned implant placement. The distance from the measurement site to the adjacent tooth was recorded in order to repeat the measurement upon re-entry. The mean horizontal augmentation attained was 3.53 mm (range 1.0 mm to 6.5 mm).(6)

Von Arx and Buser augmented 58 deficient alveolar ridge sites in 42 patients using a combination of block grafts with anorganic bovine bone matrix (ABBM) and collagen membranes. Preoperative and postoperative ridge measurement locations were not standardized with a guide or template. For single-tooth edentulous sites, the middle of the edentulous span was utilized. A protocol was utilized to determine measurement locations for multiple adjacent missing teeth and distal extension situations. Measurements were recorded 1 mm apical to the osseous crest using calipers to the nearest half millimeter. The calculated mean gain in horizontal ridge thickness was 4.6 mm (range 2 mm to 7 mm).(7)

Geurs et al. laterally augmented 98 potential dental implant sites in 51 patients using synthetic membranes and a combination of DFDBA and cortical cancellous chips in a thermoplastic biologic carrier. The alveolar ridge was measured at a single horizontal position along the deficient ridge both at the crest and 4 mm apical to the crest before augmentation and at reentry. The mean ridge width increased from 2.4 mm to 5.2 mm at the crest and from 4.4 mm to 7.5 mm at a vertical position 4mm apical to the crest.(8)

Beitlitum and coworkers performed GBR utilizing a ribose cross-linked collagen membrane and FDBA with or without the addition of autogenous bone chips in a bilayered grafting technique. There were 27 subjects in the FDBA group and 23 subjects in the bilayered graft group. Addition of autogenous bone chips did not statistically enhance horizontal or vertical ridge augmentation. The mean horizontal ridge augmentation was 5.0 mm and 3.6 mm for the FDBA and bilayered graft groups, respectively. During the GBR procedure, the minimum ridge width was measured clinically, and the point of measurement was indexed to the nearest tooth or implant for repeat measurement at the second surgery (implant placement or implant uncovering).(9)

Urban and colleagues published a prospective GBR case series utilizing a resorbable polymer membrane and particulate autogenous bone with or without addition of anorganic bovine bone. Twenty-five surgical sites were evaluated in 22 subjects, with 58 implants placed after GBR healing. Intrasurgical initial (at GBR surgery) and final (prior to implant placement) horizontal ridge width was recorded using calipers at a single point, 2 mm apical to the osseous crest. The mean gain in ridge width following GBR was 5.56 mm.(10)

Block and coworkers evaluated a series of 12 patients who received GBR procedures in the anterior maxilla using particulate bovine xenograft and resorbable membranes. Eight patients received collagen membranes placed under the flap (not fixed with tacks). Four patients received polyglyolic acid/polylactic acid (PGA/PLA) foils fixed with PGA/PLA tacks. The width of the alveolar ridge was measured at three vertical positions from the osseous crest (designated as crestal, midway, and apical ridge thickness) using a CBCT scanner. CBCT images were acquired at 5 time points (pre-operatively, immediately after augmentation, 3 to 6 months after augmentation, immediately after implant placement, and after osseointegration). At the crest, the mean change in ridge with was minimal (< 1 mm) at all postoperative time points. At the longest postoperative time point, the mean changes in ridge width at the midway and apical vertical positions were 2.69 mm and 2.75 mm, respectively.(11)

This study was able to directly monitor if modeling of the resident bone after surgery altered the baseline measurements to varying degrees. The overlay analysis of pre- and post-GBR ridge width measurements and calculated ridge width increases may capture the most accurate magnitude of augmentation. Prior studies analyzed changes in ridge dimensions over time, and most authors utilized calipers intraoperatively to measure the ridge dimensions at various points. In most cases, these investigations involved direct measurement of the ridge at GBR and again at implant placement. This information, though useful clinically, fails to capture the variations of the healing process following surgery, especially if there is a change in vertical height of the ridge following GBR procedures.

Cone Beam scans can be utilized to compare images side by side to try to estimate the dimensional changes of the ridge following GBR, however small variations in angulation, rotation and positioning while orienting CBCT images can lead error in reported measurements.

Utilizing Dolphin 3D imaging software allows measurements of dimensional changes before and after surgery by superimposing two CBCT scans on the same patient from two different time points. This allows for a more accurate report on both the horizontal and vertical dimensional changes of the ridge following GBR therapy. Many studies in the past performed a measurement at only one position of the augmented site while this study captured a more comprehensive seven points.

Some GBR surgeries resulted in little change in vertical height of the ridge. However, other surgeries had significant loss in vertical ridge height when GBR was performed when horizontal augmentation was the primary goal. Many of these cases resulted in significant horizontal gains 4mm apical to the original pre-surgical crest, but the width of the ridge 2mm apical to the original crest of bone was either significantly reduced or not present at all. Prior studies would have reported those surgeries as a great success when measuring 2mm from the osseous crest because they failed to account for the significant change in vertical height after healing. If the site loses some of the vertical ridge dimension the repeat measurement will have been recorded at a very different vertical level and, usually, the ridge is wider apically than it is near the crest, thus inflating prior studies reported gains as a result of GBR surgery.

The present study utilized a convenience sample from existing CBCT images to assess GBR treatment outcomes. A study of this type is inherently biased toward clinically successful procedures. Practitioners acquired CBCT images after GBR in order to plan for dental implant placement. Thus, the chosen method of identifying subjects selected for procedures not encountering complications prohibitive of implant placement.

FUTURE STUDIES

Future studies utilizing overlay analysis of CBCT imaging could include numerous combinations of biomaterials, membranes and surgical techniques for ridge augmentation. Analysis of data when a practitioner's goal is vertical augmentation, or combination defects could be analyzed using this same methodology to ensure accuracy of reported results.

Although taking numerous measurements of different mesio-distal points of the GBR site could potentially provide more information to the examiner, the most significant changes of horizontal augmentation were witnessed at the midpoint (M2) of the sites examined in this study population. If performing a similar study where analysis of horizontal augmentation is desired, an examiner could measure the GBR site at the midpoint at 3 different vertical levels (2mm, 4mm, and 6mm) from the crest of the ridge as well as the vertical change of the ridge at that site. This would ideally emphasize the vertical and horizontal changes of the ridge in their greatest magnitude, without time consuming unnecessary measurements at other mesio-distal sites (M1 and M3) where the magnitude of change was less significant.

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APPENDICES

Table 4. Variables by Sex

Variable	Female (N = 9)				Male (N = 22)				df	t	p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max			
Age	41.33	10.04	29	58	39.55	10.90	22	56	29	0.42	0.675
Number of Missing Teeth	2.33	1.12	1	4	1.64	0.73	1	3	29	2.07	0.048
M1@2mm (pre)	6.44	1.92	4.1	9.2	5.13	1.43	2	8.9			
M1@2mm (post)	7.03	3.04	0	10.2	5.84	3.10	0	9.8			
M1@2mm (chg)	0.59	2.22	-4.1	4.1	0.71	2.41	-4.3	3.9	29	-0.13	0.898
M1@2mm (%chg)	8.13	47.37	-100	67.21	9.50	55.12	-100	70.73	29	-0.06	0.949
M2@2mm (pre)	6.04	1.47	4.3	7.8	5.08	1.38	2.2	8			
M2@2mm (post)	6.64	4.03	0	11.1	6.33	3.07	0	10.5			
M2@2mm (chg)	0.60	4.19	-7.7	5.1	1.25	2.26	-4.2	5	9.9518	-0.44	0.672
M2@2mm (%chg)	14.49	74.73	-100	118.60	19.28	57.23	-100	125	29	-0.19	0.848
M3@2mm (pre)	5.68	1.60	2.5	7.4	5.16	1.29	2.5	8.5			
M3@2mm (post)	5.83	4.04	0	11.5	5.72	3.05	0	9.9			
M3@2mm (chg)	0.16	3.64	-6.4	4.9	0.56	2.66	-5.5	4.8	29	-0.34	0.733
M3@2mm (%chg)	2.67	67.73	-100	102.44	9.67	55.28	-100	111.63	29	-0.3	0.767
M1@4mm (pre)	7.79	1.82	4.9	10.1	6.58	1.80	2.7	10.7			
M1@4mm (post)	9.09	2.11	5.3	11.4	8.38	2.16	4.7	12			
M1@4mm (chg)	1.30	1.12	0	2.7	1.80	1.54	-2.3	4.9	29	-0.88	0.386
M1@4mm (%chg)	17.53	14.57	0	36.36	31.28	27.92	-27.38	90.63	29	-1.39	0.174
M2@4mm (pre)	7.92	1.39	5.2	9.3	6.71	2.01	2.3	11			
M2@4mm (post)	9.77	2.19	4.7	11.7	8.61	2.30	2.7	12.5			
M2@4mm (chg)	1.84	1.35	-0.5	3.5	1.90	1.31	-0.5	4.6	29	-0.11	0.916
M2@4mm (%chg)	22.76	18.60	-9.62	47.76	32.33	29.03	-15.63	113.04	29	-0.91	0.370
M3@4mm (pre)	8.12	1.70	5.5	10.3	7.22	1.86	2.7	10.7			
M3@4mm (post)	9.19	2.55	4.7	13.2	8.83	2.21	5.2	11.9			
M3@4mm (chg)	1.07	1.22	-0.8	2.9	1.61	1.78	-2.3	4.1	29	-0.84	0.407
M3@4mm (%chg)	11.98	15.14	-14.55	33.80	26.81	29.95	-29.11	92.59	29	-1.4	0.171
M2 Vert. Ridge Ht chg	0.37	1.98	-2.6	3.5	-0.22	1.32	-2.4	3	29	0.96	0.343

Females had significantly greater average number of missing teeth compared to males in this study population.

Table 5. Variables by Distal Extension Status

Variable	No Distal Extension (N = 19)				Distal Extension (N = 12)				df	t	p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max			
Age	40.11	10.09	22	56	40.00	11.63	27	58	29	0.03	0.979
Number of Missing Teeth	1.42	0.51	1	2	2.50	1.00	1	4	14.63	-3.47	0.004
M1@2mm (pre)	5.08	1.64	2	8.9	6.18	1.55	4.2	9.2			
M1@2mm (post)	5.81	3.11	0	9.8	6.78	3.07	0	10.2			
M1@2mm (chg)	0.72	2.32	-4.1	3.9	0.60	2.43	-4.3	4.1	29	0.14	0.890
M1@2mm (%chg)	9.66	56.30	-100	70.73	8.21	47.39	-100	67.21	29	0.07	0.942
M2@2mm (pre)	5.09	1.52	2.2	8	5.78	1.30	4.2	7.8			
M2@2mm (post)	6.21	3.19	0	10.5	6.75	3.60	0	11.1			
M2@2mm (chg)	1.12	2.39	-4.3	5	0.97	3.65	-7.7	5.1	29	0.14	0.891
M2@2mm (%chg)	16.86	61.13	-100	125	19.52	64.86	-100	118.60	29	-0.12	0.909
M3@2mm (pre)	5.27	1.48	2.5	8.5	5.37	1.26	2.5	6.6			
M3@2mm (post)	5.84	3.23	0	9.9	5.61	3.54	0	11.5			
M3@2mm (chg)	0.57	2.74	-5.4	4.8	0.24	3.29	-6.4	4.9	29	0.3	0.767
M3@2mm (%chg)	9.30	60.69	-100	111.63	5.00	56.20	-100	74.24	29	0.2	0.845
M1@4mm (pre)	6.33	1.97	2.7	10.7	7.88	1.20	6.5	10.1			
M1@4mm (post)	8.01	2.36	4.7	12	9.49	1.38	7.1	11.4			
M1@4mm (chg)	1.68	1.67	-2.3	4.9	1.61	1.00	0	2.7	29	0.14	0.889
M1@4mm (%chg)	31.16	30.35	-27.38	90.625	21.15	13.35	0	36.36	26.63	1.26	0.219
M2@4mm (pre)	6.68	2.17	2.3	11	7.67	1.27	5.7	9.7			
M2@4mm (post)	8.47	2.62	2.7	12.5	9.70	1.45	7.2	11.7			
M2@4mm (chg)	1.79	1.35	-0.5	4.6	2.03	1.26	-0.5	3.5	29	-0.5	0.619
M2@4mm (%chg)	30.57	31.38	-15.63	113.04	27.95	17.28	-6.25	47.76	28.64	0.3	0.767
M3@4mm (pre)	7.36	1.97	2.7	10.7	7.68	1.66	5.4	10.3			
M3@4mm (post)	8.91	2.30	4.7	11.8	8.98	2.33	5.6	13.2			
M3@4mm (chg)	1.55	1.64	-1.7	4.1	1.30	1.69	-2.3	3.7	29	0.41	0.683
M3@4mm (%chg)	25.17	29.16	-23.29	92.59	18.27	24.17	-29.11	61.11	29	0.68	0.500
M2 Vert. Ridge Ht chg	-0.07	1.67	-2.6	3.5	-0.02	1.36	-2	2.9	29	-0.09	0.929

Those with distal extension had significantly greater average number of missing teeth compared to those without distal extension.

Table 6. Variables by Missing Single/Multiple Teeth

	Single Missing Tooth (N = 13)				Multiple Missing Teeth (N = 18)				df	t	p-value
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**			
Age	35.69	7.86	22	49	43.22	11.25	27	58	29	-2.07	0.047
Number of Missing Teeth	1.00	0.00	1	1	2.44	0.70	2	4	17	-8.7	<.0001
M1@2mm (pre)	5.31	1.67	2	8.9	5.66	1.71	3.3	9.2			
M1@2mm (post)	6.25	3.46	0	10.2	6.13	2.88	0	9.2			
M1@2mm (chg)	0.95	2.44	-4.1	4.1	0.48	2.28	-4.3	3.7	29	0.55	0.588
M1@2mm (%chg)	9.96	56.81	-100	70.59	8.48	50.31	-100	70.73	29	0.08	0.940
M2@2mm (pre)	4.99	1.56	2.2	8	5.63	1.35	3.1	7.8			
M2@2mm (post)	6.22	3.98	0	11.1	6.56	2.83	0	9.8			
M2@2mm (chg)	1.23	2.98	-4.3	5	0.93	2.90	-7.7	5.1	29	0.28	0.783
M2@2mm (%chg)	13.98	73.36	-100	125	20.71	53.51	-100	118.60	29	-0.3	0.770
M3@2mm (pre)	5.65	1.48	2.5	8.5	5.06	1.29	2.5	7.4			
M3@2mm (post)	6.50	3.61	0	11.5	5.21	3.04	0	9.1			
M3@2mm (chg)	0.85	2.67	-4.5	4.9	0.15	3.13	-6.4	4.8	29	0.65	0.521
M3@2mm (%chg)	7.50	56.02	-100	74.24	7.74	61.13	-100	111.63	29	-0.01	0.991
M1@4mm (pre)	6.92	1.99	3.2	10.7	6.94	1.82	2.7	10.1			
M1@4mm (post)	8.77	2.47	5.3	12	8.45	1.92	4.7	11.4			
M1@4mm (chg)	1.85	1.86	-2.3	4.9	1.51	1.06	0	3.2	17.60	0.6	0.557
M1@4mm (%chg)	30.79	31.49	-27.38	90.63	24.75	20.43	0	77.78	29	0.65	0.522
M2@4mm (pre)	6.81	2.26	3.2	11	7.24	1.66	2.3	9.3			
M2@4mm (post)	8.73	3.01	2.7	12.5	9.10	1.68	4.9	11.7			
M2@4mm (chg)	1.92	1.65	-0.5	4.6	1.86	1.03	-0.5	3.5	29	0.14	0.889
M2@4mm (%chg)	29.07	29.19	-15.63	78.79	29.90	25.23	-6.25	113.04	29	-0.09	0.933
M3@4mm (pre)	7.67	1.91	3.9	10.7	7.34	1.82	2.7	10			
M3@4mm (post)	9.35	2.75	4.7	13.2	8.63	1.89	5.2	11.5			
M3@4mm (chg)	1.68	1.70	-1.7	4.1	1.29	1.62	-2.3	3.7	29	0.66	0.515
M3@4mm (%chg)	22.87	25.63	-23.29	64.10	22.24	28.89	-29.11	92.59	29	0.06	0.951
M2 Vert. Ridge Ht chg	-0.25	1.68	-2.6	2.9	0.10	1.45	-2	3.5	29	-0.63	0.534

Significant difference in age between those with single vs. multiple missing teeth

Table 7. Variables by Tent Screw Use

Variable	No Tent Screws (N = 23)				Tent Screws (N = 8)				df	t	p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max			
Age	38.09	10.54	22	58	45.75	8.66	31	56	29	-1.84	0.075
Number of Missing Teeth	1.70	0.76	1	3	2.25	1.16	1	4	29	-1.54	0.135
M1@2mm (pre)	5.43	1.60	2	8.9	5.75	1.95	3.8	9.2			
M1@2mm (post)	6.08	3.21	0	10.2	6.49	2.86	0	9.2			
M1@2mm (chg)	0.65	2.38	-4.3	4.1	0.74	2.31	-3.8	3.6	29	-0.09	0.930
M1@2mm (%chg)	7.43	52.30	-100	69.81	13.91	55.21	-100	70.73	29	-0.30	0.768
M2@2mm (pre)	5.14	1.48	2.2	8	6.00	1.23	4.3	7.8			
M2@2mm (post)	6.30	3.40	0	11.1	6.78	3.20	0	10.1			
M2@2mm (chg)	1.16	2.59	-4.3	5.1	0.78	3.82	-7.7	4.9	29	0.32	0.754
M2@2mm (%chg)	17.05	63.62	-100	125	20.31	59.14	-100	94.23	29	-0.13	0.900
M3@2mm (pre)	5.24	1.45	2.5	8.5	5.50	1.22	4	7			
M3@2mm (post)	5.83	3.18	0	11.5	5.54	3.84	0	9.1			
M3@2mm (chg)	0.58	2.48	-5.5	4.9	0.04	4.11	-6.4	4.8	29	0.45	0.657
M3@2mm (%chg)	7.78	50.75	-100	74.24	7.23	79.74	-100	111.63	29	0.02	0.982
M1@4mm (pre)	7.02	1.85	2.7	10.7	6.66	1.98	4.7	10.1			
M1@4mm (post)	8.51	2.05	4.8	12	8.79	2.52	4.7	11.4			
M1@4mm (chg)	1.49	1.31	-2.3	3.2	2.13	1.75	0	4.9	29	-1.08	0.288
M1@4mm (%chg)	25.12	25.04	-27.38	90.63	33.52	26.89	0	76.56	29	-0.80	0.429
M2@4mm (pre)	6.98	2.15	2.3	11	7.30	1.01	6.3	9.3			
M2@4mm (post)	8.72	2.49	2.7	12.5	9.59	1.55	7.4	11.6			
M2@4mm (chg)	1.74	1.19	-0.5	3.5	2.29	1.60	0.7	4.6	29	-1.02	0.316
M2@4mm (%chg)	28.49	27.74	-15.63	113.04	32.62	23.97	7.53	70.77	29	-0.37	0.711
M3@4mm (pre)	7.41	2.05	2.7	10.7	7.69	1.07	6.2	9.2			
M3@4mm (post)	8.76	2.48	4.7	13.2	9.44	1.57	7.6	11.5			
M3@4mm (chg)	1.35	1.49	-2.3	3.7	1.75	2.10	-1.6	4.1	29	-0.59	0.562
M3@4mm (%chg)	21.57	27.48	-29.11	92.59	25.19	27.72	-17.39	55.41	29	-0.32	0.752
M2 Vert. Ridge Ht chg	-0.13	1.37	-2.6	2.9	0.19	2.01	-1.8	3.5	29	-0.50	0.621

No significant differences between Tent Screw Use (Y vs. N) groups for any variables.

Table 8. Variables by Site

	Anterior (N = 8)				Posterior (N = 23)				df	t	p-value
Variable	Mean	SD	Min	Max	Mean	SD	Min	Max			
Age	40.13	13.14	22	56	40.04	9.80	27	58	29	0.02	0.985
Number of Missing Teeth	1.38	0.52	1	2	2.00	0.95	1	4	29	-1.75	0.090
M1@2mm (pre)	4.39	1.40	2	6.4	5.90	1.60	4	9.2			
M1@2mm (post)	4.11	2.70	0	6.8	6.90	2.92	0	10.2			
M1@2mm (chg)	-0.28	1.94	-3.8	1.6	1.00	2.39	-4.3	4.1	29	-1.36	0.184
M1@2mm (%chg)	-13.44	57.09	-100	36.36	16.94	49.30	-100	70.73	29	-1.44	0.160
M2@2mm (pre)	4.38	1.52	2.2	6.4	5.70	1.29	4	8			
M2@2mm (post)	4.49	2.90	0	7.6	7.09	3.23	0	11.1			
M2@2mm (chg)	0.11	1.86	-2.8	2.2	1.39	3.14	-7.7	5.1	29	-1.08	0.290
M2@2mm (%chg)	-7.34	61.09	-100	58.06	26.66	60.53	-100	125	29	-1.37	0.183
M3@2mm (pre)	4.79	1.44	2.5	7	5.49	1.34	2.5	8.5			
M3@2mm (post)	3.98	2.82	0	7.2	6.37	3.28	0	11.5			
M3@2mm (chg)	-0.81	2.49	-5.4	1.7	0.88	2.98	-6.4	4.9	29	-1.44	0.161
M3@2mm (%chg)	-19.15	57.11	-100	48.57	16.95	56.66	-100	111.63	29	-1.55	0.132
M1@4mm (pre)	5.28	1.85	2.7	8.4	7.50	1.51	4.9	10.7			
M1@4mm (post)	6.84	2.15	4.7	11.3	9.19	1.81	5.3	12			
M1@4mm (chg)	1.56	2.10	-2.3	4.9	1.69	1.18	0	4.2	8.6	-0.16	0.877
M1@4mm (%chg)	38.17	41.11	-27.38	90.63	23.50	16.74	0	60.87	7.8	0.98	0.356
M2@4mm (pre)	5.08	1.82	2.3	6.7	7.75	1.41	5.2	11			
M2@4mm (post)	7.01	2.54	2.7	11.1	9.62	1.81	4.7	12.5			
M2@4mm (chg)	1.94	1.46	-0.5	4.6	1.87	1.27	-0.5	4.6	29	0.13	0.895
M2@4mm (%chg)	43.15	41.15	-15.63	113.04	24.83	18.10	-9.62	65.71	8.0	1.22	0.258
M3@4mm (pre)	6.29	2.09	2.7	9.2	7.90	1.58	5.4	10.7			
M3@4mm (post)	7.53	1.99	5.2	11.5	9.43	2.20	4.7	13.2			
M3@4mm (chg)	1.24	2.01	-1.7	4.1	1.53	1.53	-2.3	4	29	-0.43	0.670
M3@4mm (%chg)	29.27	39.81	-23.29	92.59	20.15	21.84	-29.11	61.11	8.5	0.62	0.554
M2 Vert. Ridge Ht chg	-0.96	1.02	-2.4	0.2	0.27	1.57	-2.6	3.5	29	-2.07	0.048

Significant difference between anterior vs. posterior site for vertical ridge height change at M2.

Table 9. Variables by Titanium Strut Reinforcement Status

Variable	No Titanium Struts (N = 12)				Titanium Struts (N = 19)				df	t	p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max			
Age	38.75	8.98	22	49	40.89	11.55	25	58	29	-0.55	0.589
Number of Missing Teeth	1.92	1.24	1	4	1.79	0.63	1	3	14.6	0.33	0.747
M1@2mm (pre)	5.61	2.20	2	9.2	5.45	1.29	3.3	8.4			
M1@2mm (post)	5.38	3.64	0	9.8	6.69	2.65	0	10.2			
M1@2mm (chg)	-0.23	2.29	-4.3	3.6	1.24	2.21	-3.9	4.1	29	-1.78	0.086
M1@2mm (%chg)	-12.51	56.92	-100	70.59	22.75	45.34	-100	70.73	29	-1.91	0.066
M2@2mm (pre)	5.47	1.80	2.2	8	5.29	1.23	2.8	7.5			
M2@2mm (post)	5.10	4.13	0	10.5	7.25	2.43	0	11.1			
M2@2mm (chg)	-0.37	3.59	-7.7	4.9	1.96	1.96	-2.8	5.1	15.2	-2.06	0.057
M2@2mm (%chg)	-12.07	69.60	-100	94.23	36.81	48.73	-100	125	29	-2.30	0.029
M3@2mm (pre)	5.50	1.66	2.5	8.5	5.19	1.20	2.5	7.4			
M3@2mm (post)	5.23	3.44	0	9.9	6.08	3.25	0	11.5			
M3@2mm (chg)	-0.27	2.77	-6.4	2.5	0.89	2.99	-5.5	4.9	29	-1.08	0.290
M3@2mm (%chg)	-8.84	57.29	-100	57.89	18.04	57.62	-100	111.63	29	-1.27	0.215
M1@4mm (pre)	7.01	2.25	3.2	10.7	6.88	1.63	2.7	9.2			
M1@4mm (post)	8.73	2.45	5.3	12	8.49	1.98	4.7	11.4			
M1@4mm (chg)	1.72	1.62	0	4.9	1.62	1.34	-2.3	3.2	29	0.19	0.852
M1@4mm (%chg)	29.14	30.63	0	90.63	26.11	22.21	-27.38	77.78	29	0.32	0.752
M2@4mm (pre)	6.97	2.11	3.3	11	7.12	1.83	2.3	9.7			
M2@4mm (post)	9.04	2.51	4.7	12.5	8.88	2.21	2.7	11.7			
M2@4mm (chg)	2.08	1.48	-0.5	4.6	1.76	1.20	-0.5	3.5	29	0.64	0.524
M2@4mm (%chg)	32.78	26.72	-9.62	78.79	27.51	26.87	-15.63	113.04	29	0.53	0.598
M3@4mm (pre)	7.21	1.85	3.9	10.7	7.65	1.85	2.7	10.3			
M3@4mm (post)	8.71	2.25	4.7	11.8	9.08	2.34	5.2	13.2			
M3@4mm (chg)	1.50	1.64	-0.8	4.1	1.43	1.68	-2.3	3.7	29	0.12	0.905
M3@4mm (%chg)	23.43	27.49	-14.55	64.10	21.92	27.63	-29.11	92.59	29	0.15	0.883
M2 Vert. Ridge Ht chg	-0.76	1.30	-2.6	1.5	0.40	1.52	-2.4	3.5	29	-2.18	0.038

Significant difference between Titanium Strut Reinforcement (Y vs. N) groups for vertical ridge height at M2 and percent change in ridge width for M2@2mm.

Table 10. Variables by Membrane Fixation Status

Variable	No Membrane Fixation (N = 2)				Membrane Fixation (N = 29)				df	t	p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max			
Age	42.00	18.38	29	55	39.93	10.31	22	58	29	0.26	0.793
Number of Missing Teeth	2.00	1.41	1	3	1.83	0.89	1	4	29	0.26	0.798
M1@2mm (pre)	5.45	1.91	4.1	6.8	5.51	1.69	2	9.2			
M1@2mm (post)	4.20	5.94	0	8.4	6.32	2.94	0	10.2			
M1@2mm (chg)	-1.25	4.03	-4.1	1.6	0.81	2.21	-4.3	4.1	29	-1.22	0.231
M1@2mm (%chg)	-38.24	87.35	-100	23.53	12.36	49.77	-100	70.73	29	-1.34	0.190
M2@2mm (pre)	5.50	1.70	4.3	6.7	5.35	1.47	2.2	8			
M2@2mm (post)	4.55	6.43	0	9.1	6.55	3.16	0	11.1			
M2@2mm (chg)	-0.95	4.74	-4.3	2.4	1.20	2.80	-7.7	5.1	29	-1.02	0.318
M2@2mm (%chg)	-32.09	96.04	-100	35.82	21.34	59.47	-100	125	29	-1.20	0.241
M3@2mm (pre)	5.05	0.78	4.5	5.6	5.33	1.42	2.5	8.5			
M3@2mm (post)	4.35	6.15	0	8.7	5.85	3.18	0	11.5			
M3@2mm (chg)	-0.70	5.37	-4.5	3.1	0.52	2.83	-6.4	4.9	29	-0.57	0.576
M3@2mm (%chg)	-22.32	109.85	-100	55.36	9.70	55.81	-100	111.63	29	-0.75	0.460
M1@4mm (pre)	6.20	1.84	4.9	7.5	6.98	1.88	2.7	10.7			
M1@4mm (post)	7.60	3.25	5.3	9.9	8.65	2.11	4.7	12			
M1@4mm (chg)	1.40	1.41	0.4	2.4	1.67	1.46	-2.3	4.9	29	-0.26	0.800
M1@4mm (%chg)	20.08	16.86	8.16	32	27.78	25.96	-27.38	90.625	29	-0.41	0.685
M2@4mm (pre)	6.65	2.05	5.2	8.1	7.09	1.94	2.3	11			
M2@4mm (post)	7.70	4.24	4.7	10.7	9.03	2.21	2.7	12.5			
M2@4mm (chg)	1.05	2.19	-0.5	2.6	1.94	1.26	-0.5	4.6	29	-0.94	0.357
M2@4mm (%chg)	11.24	29.50	-9.62	32.10	30.82	26.37	-15.63	113.04	29	-1.01	0.320
M3@4mm (pre)	6.65	1.63	5.5	7.8	7.54	1.86	2.7	10.7			
M3@4mm (post)	8.10	4.81	4.7	11.5	8.99	2.16	5.2	13.2			
M3@4mm (chg)	1.45	3.18	-0.8	3.7	1.46	1.58	-2.3	4.1	29	0.00	0.997
M3@4mm (%chg)	16.45	43.83	-14.55	47.44	22.92	26.78	-29.11	92.59	29	-0.32	0.750
M2 Vert. Ridge Ht chg	-1.95	0.92	-2.6	-1.3	0.08	1.48	-2.4	3.5	29	-1.89	0.068

No significant differences between Membrane Fixation (Y vs. N) groups for any variables.

Table 11. Variables by Premature Membrane Removal Status

Variable	No Premature Membrane Removal (N = 17)				Premature Membrane Removal (N = 14)				df	t	p-value
	Mean	SD	Min	Max	Mean	SD	Min	Max			
Age	40.24	9.69	27	58	39.86	11.82	22	56	29	0.10	0.923
Number of Missing Teeth	1.71	0.85	1	4	2.00	0.96	1	4	29	-0.90	0.373
M1@2mm (pre)	5.41	1.49	3.3	9.2	5.64	1.92	2	8.9			
M1@2mm (post)	6.79	2.80	0	10.2	5.44	3.35	0	9.8			
M1@2mm (chg)	1.39	2.33	-3.9	4.1	-0.19	2.06	-4.3	2.2	29	1.98	0.058
M1@2mm (%chg)	26.08	47.89	-100	70.73	-11.52	51.30	-100	50	29	2.11	0.044
M2@2mm (pre)	5.37	1.13	3.1	7.8	5.35	1.82	2.2	8			
M2@2mm (post)	7.60	2.00	4.3	11.1	4.99	4.03	0	10.5			
M2@2mm (chg)	2.23	1.87	-0.8	5.1	-0.36	3.31	-7.7	2.8	19.6	2.61	0.017
M2@2mm (%chg)	44.85	40.57	-15.69	125	-14.85	67.88	-100	65.12	29	3.03	0.005
M3@2mm (pre)	5.36	1.22	2.5	7	5.25	1.59	2.5	8.5			
M3@2mm (post)	6.34	3.23	0	11.5	5.04	3.36	0	9.9			
M3@2mm (chg)	0.98	2.88	-5.5	4.9	-0.21	2.93	-6.4	4.2	29	1.13	0.268
M3@2mm (%chg)	18.42	54.05	-100	111.63	-5.46	62.06	-100	102.44	29	1.15	0.261
M1@4mm (pre)	6.88	1.83	2.7	10.1	6.99	1.97	3.2	10.7			
M1@4mm (post)	8.94	2.20	4.7	11.4	8.16	2.06	5.3	12			
M1@4mm (chg)	2.06	1.39	0	4.9	1.16	1.37	-2.3	2.9	29	1.79	0.083
M1@4mm (%chg)	32.74	23.78	0	77.78	20.66	26.46	-27.38	90.63	29	1.34	0.191
M2@4mm (pre)	7.28	1.71	2.3	9.7	6.80	2.17	3.2	11			
M2@4mm (post)	9.39	1.88	4.9	11.7	8.41	2.68	2.7	12.5			
M2@4mm (chg)	2.11	1.44	-0.5	4.6	1.61	1.09	-0.5	3	29	1.08	0.290
M2@4mm (%chg)	33.85	29.06	-6.25	113.04	24.34	22.95	-15.63	78.79	29	0.99	0.329
M3@4mm (pre)	7.68	1.90	2.7	10.3	7.24	1.80	3.9	10.7			
M3@4mm (post)	9.32	2.34	5.2	13.2	8.46	2.19	4.7	11.8			
M3@4mm (chg)	1.65	1.76	-2.3	4.1	1.22	1.50	-1.7	3.7	29	0.72	0.480
M3@4mm (%chg)	25.34	28.68	-29.11	92.59	19.07	25.73	-23.29	64.10	29	0.63	0.531
M2 Vert. Ridge Ht chg	0.48	1.19	-1.4	3	-0.69	1.69	-2.6	3.5	29	2.27	0.031

Significant difference between Premature Membrane Removal (Y vs. N) groups for percent change in ridge width at M1 (2mm), M2 (2mm), percent change in ridge width at M2 (2mm), and vertical ridge height change at M2.

Table 12. Correlation of Variables with Vertical Ridge Height

Variable	Pearson's r	p-value
M1@2mm (pre)	0.11	0.5648
M1@2mm (post)	0.56	0.0010
M1@2mm (chg)	0.67	<.0001
M1@2mm (%chg)	0.69	<.0001
M2@2mm (pre)	0.17	0.3632
M2@2mm (post)	0.70	<.0001
M2@2mm (chg)	0.72	<.0001
M2@2mm (%chg)	0.75	<.0001
M3@2mm (pre)	0.06	0.7462
M3@2mm (post)	0.60	0.0003
M3@2mm (chg)	0.65	<.0001
M3@2mm (%chg)	0.68	<.0001
M1@4mm (pre)	0.15	0.4202
M1@4mm (post)	0.29	0.1152
M1@4mm (chg)	0.24	0.2011
M1@4mm (%chg)	0.10	0.5878
M2@4mm (pre)	0.47	0.0074
M2@4mm (post)	0.43	0.0168
M2@4mm (chg)	0.06	0.7549
M2@4mm (%chg)	-0.06	0.7609
M3@4mm (pre)	0.33	0.0728
M3@4mm (post)	0.44	0.0129
M3@4mm (chg)	0.25	0.1792
M3@4mm (%chg)	0.10	0.5847

Post ridge width, change in ridge width and percent change in ridge width at M1 (2mm), M2 (2mm), M3 (2mm) were significantly correlated with vertical ridge height. Also, baseline value for ridge width at M2 (4mm) and post value for ridge width at M3 (4mm) are also significantly correlated with vertical ridge height.