Strain analysis and fracture strength of Nine Different Abutments for Cement-Retained Crowns on an Internal Hexagon Implant

Thesis

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By

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Abstract

Purpose: Many aftermarket abutments for cement-retained crowns are available for the Tapered Screw-Vent implant (Zimmer Dental, Carlsbad, CA, USA). Of these aftermarket abutments this is wide variation, from stock to custom abutments, as well as material differences such as zirconia, titanium, or a combination of the two. This study was performed in two parts: the aim of Part I was to measure and compare different strains conferred to the bone around the implants for nine different abutments for cement-retained crowns on an implant with an internal hexagon platform. The aim of Part II was to measure and compare the force required to cause fracture of ten different abutments for cement-retained crowns on an implant with an internal hexagon platform.

Material and Methods: Nine 4.1mm x 11.5mm Tapered Screw-Vent implants were placed into a 12” x 2” x 8mm resin block for strain measurements. Five abutment specimens of each of the nine different abutments (n = 44 total) were tried into one of the nine implants. Monolithic zirconia crowns were then fabricated for each of the nine different abutments and the crowns were cyclically loaded at thirty degrees two times at a frequency of 2Hz and strain was measured and recorded. Ten Tapered Screw-Vent Implants were then individually secured in a loading apparatus, and three abutment specimens of each of the ten different abutments (n = 30 total) were loaded at a 30 degree angle until fracture of the implant abutment complex was achieved. The strain to the resin block was determined using three-dimensional digital image correlation (3D DIC), an optical measurement technique. Commercial image correlation software (VIC 3D v7.0,
Correlated Solutions, Inc. Columbia, SC, USA) was used to analyze the strain around the implants. Data for maximal and minimal principle strains as well as load to fracture were compared using analysis of variance with a Tukey-Kramer post-hoc test (alpha = .05).

**Results:** Strain measurements showed no significant difference between any of the abutments when looking at minimal (compression) principle strains (p>.05). For maximal (tensile) principle strains the Atlantis Zirconia abutment and the Zimmer Patient Specific Abutment showed the highest and second-highest strain around the implant, respectively, with the Atlantis Zirconia being significantly greater than all abutments excluding the Zimmer PSA, and the PSA being significantly greater than the AstraTech ZirDesign and Legacy Straight Contoured abutment in titanium as well as zirconia (p<.05). For load to fracture tests, the Inclusive Custom Abutment in Zirconia and AstraTech ZirDesign zirconia abutment showed the lowest and second lowest load to fracture, respectively, which were significantly lower than all other abutments (p<.05). The highest overall fracture strength were the Legacy Straight Contoured Abutment in Titanium and Legacy Straight Contoured Abutment in Zirconia, which were significantly greater than all other abutments (p<.05). The Zimmer PSA abutment was the only abutment that showed no fracture of any of the components. Overall the full contour zirconia abutments fractured at an average of 278.03N vs 589.69N load to fracture of all ten abutments and 699.32N load to fracture of titanium abutments.

**Conclusion:** When selecting an abutment for a cement-retained crown on a Tapered Screw-Vent implant, the material selection of full contour zirconia vs titanium as well as off-market brands vs. the implant brand being used should be considered heavily. When comparing the strain to the implants, the Zimmer PSA and Atlantis Zirconia abutments
conferred the most tensile strain. For load to fracture the AstraTech ZirDesign and Inclusive Custom Implant Abutment in zirconia showed significantly less fracture resistance than any of the other implants. For zimmer vs. aftermarket brands, the Zimmer PSA abutment was the only abutment that had no fracture of any of the components. The Zimmer Contour Abutment in Zirconia had a significantly greater fracture resistance than the full zirconia abutments without titanium components.
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Fields of Study

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Table of Contents

Abstract..........................................................................................................................ii

Vita.....................................................................................................................................v

List of Tables..................................................................................................................vii

List of Figures...................................................................................................................viii

Chapter 1: Introduction...................................................................................................1

Chapter 2: Materials and Methods................................................................................6

Chapter 3: Results............................................................................................................10

Chapter 4: Discussion.....................................................................................................12

Chapter 5: Conclusion....................................................................................................17

References......................................................................................................................18

Appendix A: Tables.......................................................................................................22

Appendix B: Figures.......................................................................................................27
List of Tables

Table 1. Specifications of ten abutments for cement-retained prosthesis……………23

Table 2. Average Load to Fracture and Mode of fracture for abutments………………..24

Table 3. Statistically significant abutments for maximal principle strains………………..25

Table 4. Statistically significant name brand abutment differences vs aftermarket 
abutments for load to fracture ……………………………………………………………….26
List of Figures

Figure 1: The 12” x 2” x 8mm resin block with nine pilot holes.........................28
Figure 2: Resin block with Tapered Screw-Vent implants placed.........................29
Figure 3: Abutments attached to Tapered Screw-Vent Implants..........................30
Figure 4: Wax-up for crown fabrication on abutments.....................................31
Figure 5: Experimental Set-Up for Strain Tests.............................................32
Figure 6: Loading portion of strain measurements........................................33
Figure 7: DIC information for various strain tests.........................................34
Figure 8: Loading apparatus for load to fracture tests.................................35
Figure 9: Loading for load to fracture tests..................................................36
Figure 10: Example plots of the load to fracture tests....................................37
Figure 11: modes of fracture for zirconia abutments.......................................38
Figure 12: Plot of Load to Fracture for each abutment.................................39
Figure 13: Plot of maximal (tensile) principle strains around the implant...........40
Chapter 1: Introduction

Initially implants were used to treat only people who were completely edentulous. In these patients, implants were restored where the prosthesis was replacing an entire arch with the prosthetic components splinted together. Today, with long-term clinical success as high as 100% in some studies, replacement of single teeth with implants is now also a predictable and frequently used treatment, no matter what tooth in the mouth is being replaced.\textsuperscript{1-4} With this high success rate and common use, there are predictably a number of restorative options for the single unit implant prosthesis, namely in regard to screw versus cement retained implant crowns.

Historically, screw-retained implant crowns were used with good long-term success and were considered the restorative treatment of choice. However, as more patients were being treated for partial edentulism, more restorative options became available.\textsuperscript{5,6} There are limitations with the use of screw-retained restorations however, as improperly angled implants, or in situations where ideal placement is not possible the cement retained implant crown is the treatment option of choice.\textsuperscript{7,8} The main advantage of a screw-retained prosthesis is that of retrievability, which is desirable due to possible prosthetic complications that may occur in the lifetime of an implant, such as screw loosening and breakage.\textsuperscript{9-13} However, in the case that cement retained restorations are needed, retrievability could possibly be reached depending upon the type of cement
used, and the greater esthetics, more predictable occlusion, and ease of passivity of cement-retained restorations make it a very ideal treatment option.14-18

Although predictably of implant treatment has increased significantly, loosening of the abutment screw still remains a common complication that occurs frequently in comparison to other prosthetic complications.19 This can become quite problematic as loosening of the abutment screw can lead to fracture of the implant screw which not only can result in destruction of the implant crown, but may deem the implant non-restorable. With loosening or fracture of an abutment screw, especially with a cement retained implant crown, destruction of the porcelain and underlying metal or reinforced substructure might be necessary to gain access to the screw in order to retrieve the prosthesis.

Even with torqueing with a mechanical torqueing device, screws still become loose, with single tooth implant restorations being the most commonly affected.20 The only way to achieve screw loosening is for joint separating forces to be greater in magnitude than the clamping forces. Several factors, however, have been shown to contribute to screw loosening, one being a misfit of the implant/abutment hex that results in a non friction-fit between the implant and abutment surfaces.21 Other joint separating forces are also working constantly on the screw-joint interface to cause screw-loosening, such as excursive contacts as well as off-axis central contacts. In most cases these forces on implant restorations cannot be avoided – so only the fit of the abutment and implant can be controlled by the operator – making abutment selection a very important factor in the prevention of screw loosening.
In addition to screw loosening, bone loss around the implant is also of major concern and a complication that could lead to loss of the implant. The forces that act on a prosthesis are referred to as stresses, and these stresses are then transferred to the bone in the form of strain. These stresses and strains, in addition to causing prosthetic problems such as the aforementioned screw loosening or breakage can also cause biologic problems, such as bone loss. Although physiologically bone needs a certain amount of strain to stay viable and avoid atrophy, too much strain can result in microfractures and resultant bone loss. This excessive strain has been shown to result in bone loss around dental implants and even result in loss of osseointegration around the implant when taken beyond its physiologic threshold. This concept of overloading and limiting stresses and strains to both the prosthesis and the surrounding bone has resulted in many leading clinicians developing occlusal schemes as well as the implant company themselves developing different designs, from internal hexes to conical connections, in order to reduce these forces.

Internal hexes have become a key design for many of the leading implant manufacturers, with one of the most common being the Zimmer tapered screw-vent (TSV) implant (Zimmer Dental Carlsbad, CA, USA). This implant features a 1.5 mm deep internal hexagon (hex) below a 0.5 mm-wide 45° lead-in bevel. Even with the standardized design of the Zimmer Tapered Screw Vent implant, the abutment choices for a cement-retained restoration still remain abundant. Not only can one choose between a stock and custom abutment, but there are a number of different manufacturers that make them and different materials that can be used. In addition to choosing between a stock or custom abutment, the number of companies that make
abutments for cement-retained crowns is plentiful, from Atlantis (Dentsply, York, PA, USA) to Glidewell Laboratories (Glidewell Laboratories, Newport Beach, CA, USA) to Implant Direct (Implant Direct, Calabasas, CA, USA) to Zimmer Dental themselves. In addition to the different manufacturers, different materials can also be used in abutment selection: titanium (commercially pure Grades 1-4 and alloy Grade 5) and zirconium dioxide (ZrO₂), with the choice typically being dictated by esthetics for zirconium dioxide (zirconia). Although cost and marketing plays an important part in what clinicians typically use, some abutment types may provide advantages, with the Zimmer patient specific abutment (zimmer PSA) abutment claiming a “friction fit” between the implant and the abutment interface. Such a friction fit can result in not only a more stable screw joint, but may confer less harmful strains to the bone surrounding the implant. Some third party components for implants – abutments included- have a significant financial benefit to the practicing clinician, making them a very attractive treatment option. However, third party manufactured components do not require independent fatigue testing if the design is based on substantial equivalence based on the US Food and Drug administration 510(k) guidelines despite studies showing decreased fatigue resistance of third party components as well as variations in machining tolerances.²⁹-³¹

The purpose of this study was two-fold: Part 1 of the study was aimed to test the strain to resultant bone after cyclically loading crowns that have been fabricated to fit on nine different abutments for cement-retained restorations on the Zimmer TSV implant after a 30 NCm torque was applied. The null hypothesis was that there would be no differences in strain between the 9 different abutments. Part II aimed to measure at what force either abutment fracture or screw fracture was achieved. The second null hypothesis
was that there would be a higher load to fracture for the titanium vs. zirconia abutments but no difference within the zirconia or titanium groups.
Chapter 2: Materials and Methods

A 12” x 2” x 8mm block of resin (ABS transparent resin, DSM Somos, Elgin, IL, USA) was fabricated by Accudental Inc, (Golden, CO, USA). Approximating published estimates for cancellous bone (1,507 MPa), the resin has an elastic modulus of 2,000 MPa. Nine pilot holes approximately 5 mm deep were drilled one inch apart from each other using a drill press to ensure parallelism (Figure 1). Nine implant sites were then prepared by an experienced periodontist using a 3.8mm tap drill with a surgical implant handpiece (Surgical Motor System, Zimmer Dental, Carlsbad, CA, USA) set to 900 rpm taken to a 12mm depth. The threads of nine 4.1mm x 11.5mm Tapered Screw-Vent implants (Zimmer Dental, Carlsbad, CA, USA) were coated with a thin layer of metal bonding cyanoacrylate adhesive (Permabond 910, Permabond LLC Pottstown, PA, USA) and placed using the same surgical implant handpiece set to 35 Ncm. The implants were driven into the prepared implant sites manually with wrench attached to a digital torque indicator (Model M5i, Mark-10,Long Island, NY, SA) until the implant platforms were flush with the resin surface (Figure 2).

Nine different abutments were selected for testing for strain testing and ten for fracture testing based on the available options for abutments for cement-retained crowns on Tapered Screw-Vent implants from a local dental laboratory(Slagle and Kiser Dental Ceramics Reynoldsburg, OH) (Figure 3). After abutment fabrication resultant monolithic
zirconia crowns were milled for each group of abutments based on an initial wax-up and then scan (figure 4). The abutments can be grouped into 4 categories: Stock Titanium, Stock Zirconia, Custom Titanium, and Custom Zirconia. The abutments varied based on manufacturer, stock or custom, material, type of connection to the implant, and cost. Each type of abutment was assigned to only one of the nine implants.

The three-dimensional digital image correlation technique was used to measure strain to the transparent resin when loading forces were applied to the crown/abutment interface. Commercial image correlation software (Vic-3D v7.0 Digital Image Correlation Version 2009.1.0, build RC 2009.448, Correlated Solutions, Inc., Columbia, SC, USA) was used to collect and analyze data from images collected by two Point Gray Research GRAS-20S4M-C cameras (Point Grey, Richmond, B.C., CAN). These digital cameras have a 2048 pixel by 2048 pixel resolution and were equipped with Schneider-Kreuznach 35 mm lenses (Jos. Schneider Optische Werke GmbH, Bad Kreuznach, GER). The cameras were mounted on a tripod with a custom fixture directed at the specimens on the resin block that was fixed to a x-y table at thirty degrees to the crown (Figure 5). The high-resolution digital cameras provided a synchronized stereo view of the specimens during the experiment. Each camera was independently calibrated by taking images of the same calibration grid in different views. For each calibration image captured, a system of equations relating the sensor position of the calibration grid points to the camera parameters was formed. The solutions of these equations provided the cameras with parameters to transform camera sensor coordinates to a common world coordinate system. This world coordinate system provided the basis for relating image positions in both cameras to a common three-dimensional location.33
A non-repetitive, high contrast dot pattern was applied to the external surface of the resin block model. First, a white spray paint base coat was applied and allowed to dry. Secondly, a contrasting black spray paint was lightly spattered on the white base layer and allowed to dry. The two digital cameras recorded images of the resin as the crowns were cyclically loaded with a torque at a thirty-degree angle to the abutment. Two force cycles at a maximum of 225N at 2Hz were used to load the fabricated zirconia crowns with a steel hemispherical loading apparatus attached to an Instron 1321 (Instron corporation Norwood, MA) hydraulic load frame (Figure 6). This was done five times for each abutment for a total of 44 trials. Force measurements were recorded from the load cell equipped on the Instron frame. After strain measurements were finalized, ten additional implants were attached to a 30 degree fixture mount (figure 8) and the abutments were loaded without the crown until either fracture of the screw or abutment was reached (3 trials for each abutment) (Figure 9).

**Data Processing and Statistical Analysis**

Once all the images were captured the data was collected and processed using the Vic-3D Version 7.0 Digital Image Correlation software (Figure 7). First the displacement field was calculated from the images, and then the resultant strain field was calculated from the resultant displacements. A rectangular area directly apical to the implant platform was selected and strain measurements during the 2 cycles of loading were extracted from the data. Specifically minimal principle strains as well as maximal principle strains at 100N were looked at for each of the nine abutments. For load to fracture tests the load at which fracture of either the abutment or retentive screw was recorded (Figure 10). The Statistical Analysis System (SAS) software (SAS Institute Inc.,
Cary, NC, USA) was used to perform the statistical analysis. Data for maximal and minimal principle strains as well as load to fracture were compared using analysis of variance with a Tukey-Kramer post-hoc test (alpha = .05).
Chapter 3: Results

STRAIN MEASUREMENTS

In this study, maximal (major) and minimal (minor) principle strains around the implants were analyzed at 100N. Maximal principal strains were generally positive (tensile), whereas minimal principal strains were generally negative (compressive). There was no significant difference found between any of the abutments minimal (compressive) principle strains when compared to one another. For maximal (tensile) principle strains, significant differences were found (p<.05) (Figure 13). The Atlantis zirconia abutment conferred the highest strains that were significantly higher compared to all other abutments except the Zimmer Patient Specific Abutment (PSA) (p<.05). The Zimmer PSA abutment had the second highest strain values that were significantly greater than 3 other abutments: the AstraTech ZirDesign zirconia abutment, the Legacy Straight Contoured Abutment in titanium, and the Legacy Straight Contoured Abutment in Zirconia.

LOAD TO FRACTURE

In addition fracture of the abutment was analyzed. In this study fracture was considered to either be a fracture of the abutment itself or the retentive screw – whichever occurred first. Of the ten implant abutments used for fracture testing, five were entirely
titanium, three were full contour zirconia, and two were zirconia with titanium elements with the Legacy Straight Contoured abutment having an titanium hex and core and the Zimmer Zirconia Contour having a titanium ring in the hex. The overall average force to fracture for all abutments was 589.69N (Figure 12). The average load to fracture for the titanium abutments was 699.32N, that for the full contour zirconia was 278.03N and for the Zirconia with titanium component 842.39N. Of the ten abutments, five pairs made by the same manufacturer but only differing in material were looked at. Of those, three pairs had significant differences, with the AstraTech TiDesign, Inclusive Custom Abutment, and Zimmer Zirconia Contour needing significantly more load to fracture than the AstraTech ZirDesign, and Inclusive Custom Zirconia Abutment, respectively. The AstraTech ZirDesign, Inclusive Custom Abutment in Zirconia, Zimmer Zirconia Contour, and Atlantis Zirconia abutment had fracture of either the zirconia hex, coronal abutment, or both (Figure 11). The Zimmer PSA did not have a fracture of any of the components, and only exhibited retentive screw bending. All other abutments mode of fracture was breakage of the retentive screw.
Chapter 4: Discussion

The first null hypothesis, that all abutments would impart equal amounts of strain around the implant, was rejected due to the Atlantis Zirconia abutment having significantly greater principle tensile strains around the implant than all other abutment except for the Zimmer PSA abutment, which had the second highest tensile strains around the implant (p < .05). The Zimmer PSA abutment had significantly higher principle tensile strains than the AstraTech ZirDesign abutment and Legacy Straight Contoured Abutment in Titanium and Zirconia.

The second null hypothesis, that all abutments would have similar load to fracture values, was also rejected with multiple abutment varying significantly from each other (p < .05). The Inclusive Custom Abutment in Zirconia as well as the AstraTech ZirDesign abutments failed at significantly lower loads than all other abutments. The Legacy Straight Contoured Abutment in Titanium and Legacy Straight Contoured Abutment in Zirconia had significantly greater failed at significantly greater load values than all other abutments. The Zimmer PSA abutment was the only abutment to not have fracture of any of the components.

STRAIN MEASUREMENTS
Strain distribution around implants has been studied before, primarily with either strain gauges or photoelastic measurements.\textsuperscript{34,35} Unfortunately these techniques have their limitations – with strain gauges only giving quantitative data and photoelastic studies only providing qualitative data. Recently digital image correlation began to be used for implant biomechanics, providing both visual as well as quantitative data for the entire surface of a model.\textsuperscript{36-38} The magnitude of strains around the implants was looked at for nine different abutments attached to Zimmer TSV implants in this study. Both compressive as well as tensile principle strains were measured. The minimal principle (compressive) strains measured around the implants were found to not be statistically significant when comparing the nine different abutments. The maximal strains, being tensile, however did have two abutments that showed significantly higher strains than the other abutments, the Atlantis zirconia abutment showed the highest magnitude of principle tensile strains, while the Zimmer PSA showed the second highest magnitude of strains. Although too much strain to the bone induces micro fractures and bone loss, too little results in loss of bone homeostasis and bone atrophy.\textsuperscript{39} It is beyond the scope of this paper to determine whether any of the abutments conferred a strain that was past the homeostasis point, which has been estimated to be around 50 Megapascals, however the force of 100N that was analyzed relates to the average bite force on a single anterior tooth in a female, and is unlikely to induce strains that would result in microfractures to the bone around the implant.\textsuperscript{40} It has also been shown that bone has less tolerance for tensile forces than compressive forces, with bones normally tolerating 4,000 μe in compression and 2,500 μe in tension.\textsuperscript{41,42} More strain to the area around the implant may indicate a more tight connection, or friction-fit, of the abutment to the implant. By having a tight
connection of the abutment to the implant during loading, the strain might be transferred directly to the bone around the implant, as if the implant and abutment were all one unit. Lower strains may indicate more force transmission to the abutment/connection complex vs. the resultant bone around the implant, which would support Zimmer’s claims of a friction fit for its Zimmer PSA, as well as indicate a precise fit of the Atlantis Zirconia abutment.

LOAD TO FRACTURE

Ten different abutments were tested for load to fracture, with fracture being either a fracture of abutment or retentive screw. Our results indicate a significantly lower fracture resistance for the full zirconia abutments, specifically the Inclusive Custom Abutment in Zirconia as well as the full contour ZirDesign zirconia abutment from AstraTech. Fracture resistance of zirconia abutments has been studied previously, with results showing a Zirconia abutment with a Titanium core having significantly higher resistance fracture than full contour zirconia abutments. In that previous study, a full contour zirconia abutment was fabricated specifically for the implants used via CAD/CAM fabrication and showed an average fracture resistance of 525N. Of the five Zirconia abutments used in this study, three were full contour zirconia, one was a zirconia abutment with a titanium core, and one was a full contour zirconia with a titanium washer (Zimmer dental). The full contour zirconia abutment fabricated via CAD/CAM (Atlantis zirconia abutment, Dentsply) had a fracture resistance of 465.38N on average. The zirconia abutments that were full contour and also manufactured by a third party (ZirDesign by AstraTech and Inclusive Custom Abutment in Zirconia by Glidwell labs)
had fracture resistances of 236.22 N and 123.49 N, respectively. The zirconia abutment with titanium washer (Zimmer dental) had a fracture resistance of 667.82 N on average, and the zirconia abutment with titanium core resisted fracture more so than any of the other zirconia abutments, with an average force to fracture of 1016.96N, which correlates with results from a previous study that compared full contour zirconia abutments vs. zirconia abutments with a titanium core. The maximal bite force for a single anterior tooth has been reported to be as high as 233N, with the average mean for a male of around 146N. All abutments load to fracture was beyond this point except for the Inclusive Custom Abutment in Zirconia, and the AstraTech ZirDesign abutment fractured at an average of 266N. These results indicate caution should be exercised when using full contour zirconia abutments, especially from third party manufacturers. In addition, the overall load to fracture of 589.69N for all ten abutments indicates caution should be used if using 4.1mm implants with abutments to restore posterior dentition. With an average bite force of 720N in the posterior reported by Gibbs in 1981, only the Legacy Contour Abutments had a fracture resistance higher, although the Zimmer PSA abutment did not have fracture of any of the components, screw deformation occurred below this bite force. Although all crowns were loaded at thirty degrees, this does emphasize that any excursive contacts should be minimized if not altogether removed in implant restorations, especially in the posterior. However, this study was limited as it was an in-vitro study that was not able to replicate dynamic occlusion, multiple layers of bone, or clinical osseointegration. In addition, the mechanism to induce fracture was through constant force, unlike function in the mouth. In previous in vitro studies, fracture resistance for all zirconia crowns was found to be 457N to 525N. This force to
fracture corresponds to our overall zirconia abutment results, however those results were obtained with cyclic loading, a more possibly relevant test that more closely replicates intraoral conditions. Overall we found that the Zimmer abutment in zirconia had a significantly higher load to fracture versus the zirconia aftermarket brands with the zimmer PSA abutment having no fracture of any components, indicating better fracture resistance for the Zimmer abutments. The Zimmer PSA abutment was the only abutment that did not have a fracture of any component, but only bending of the screw, indicating it acting as a one-piece unit with all forces conferred to the abutment screw. In addition, each abutment had a screw provided by the respective manufacturer, adding an additional source of variation. The Zimmer Contour Abutment in Zirconia failed due to fracture of the zirconia hex, but the titanium washer surrounding the hex would have resulted in slight micro-movement and not the friction-fit the PSA would have. For our study, both stock and custom abutments were chosen, without a standardized contour or morphology. To this respect, some abutments had a greater thickness of material compared to others, with the Legacy Straight Contour Abutments in Titanium as well as Zirconia having some of the most bulk, possibly explaining fracture resistance differences between some of the implants. For the strain tests all abutments had crowns fabricated for them, which standardized the overall contour. Also, strains to the bone were only measured on the outside surface of the model, as opposed to three dimensionally. Clinical studies of different abutments and possible mechanisms of fracture would help to determine a more relevant load to fracture test, as well as analyze strains in a three dimensional manner.
Chapter 5: Conclusion

Our results showed no significant differences when comparing minimal principle strains (p > .05), however for maximal principle strains the Atlantis Zirconia abutment and Zimmer PSA abutment showed the most strains around the implant. The Atlantis Zirconia abutment had maximal principle strains that were significantly higher than all other abutments except the Zimmer PSA abutment (p < .05), and the Zimmer PSA abutment had significantly higher strains than the AstraTech ZirDesign as well as the Legacy Straight Contour abutments in titanium and zirconia.

Our results also showed significantly greater resistance to fracture of the Legacy Straight Contour Abutments in titanium and zirconia (p < .05), and no fracture of any component for the Zimmer PSA abutment. Overall load to fracture of the titanium abutments was found to be significantly higher than for the zirconia abutments. (p < .05). Load to fracture of zirconia abutments with titanium components vs full zirconia abutments was found to be significantly higher (p < .05).
References


47. Wohlwend AS. The zirconium oxide abutment: an all ceramic abutment for esthetic improvement of implant superstructures 1997
Appendix A: Tables
<table>
<thead>
<tr>
<th>Abutment Name</th>
<th>Manufacturer</th>
<th>Material</th>
<th>Stock/Custom</th>
<th>Connection to Implant</th>
<th>Cost ($)</th>
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<td>Titanium Alloy (6Al4V)</td>
<td>Custom</td>
<td>Friction-fit titanium</td>
<td>209</td>
</tr>
</tbody>
</table>

Table 1: Specifications of ten abutments for cement-retained prosthesis
<table>
<thead>
<tr>
<th>Type of Abutments</th>
<th>Name of Abutments</th>
<th>Mode of Fracture</th>
<th>Load to Fracture (N)</th>
<th>Average (N)</th>
<th>Overall Average (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>AstraTech TiDesign</td>
<td>Screw fracture</td>
<td>661.64</td>
<td>699.32</td>
<td>589.69</td>
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<tr>
<td></td>
<td>Atlantis Titanium</td>
<td>Screw fracture</td>
<td>506.62</td>
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<tr>
<td></td>
<td>Inclusive Custom Abutment in Titanium</td>
<td>Screw fracture</td>
<td>524.09</td>
<td></td>
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<tr>
<td></td>
<td>Legacy Straight Contoured Abutment in Ti</td>
<td>Screw fracture</td>
<td>1104.96</td>
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<tr>
<td></td>
<td>Zimmer PSA</td>
<td>DNF</td>
<td>DNF</td>
<td></td>
<td></td>
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<tr>
<td>Full Zirconia</td>
<td>AstraTech ZirDesign</td>
<td>Abutment fracture</td>
<td>236.22</td>
<td>275.03</td>
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<tr>
<td></td>
<td>Atlantis Zirconia</td>
<td>Abutment fracture</td>
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</tr>
<tr>
<td></td>
<td>Inclusive Custom Abutment in Zirconia</td>
<td>Abutment fracture</td>
<td>123.49</td>
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<td></td>
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<tr>
<td>Zirconia with Titanium Elements</td>
<td>Legacy Straight Contoured Abutment in Zr</td>
<td>Screw fracture</td>
<td>1016.96</td>
<td>842.39</td>
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</tr>
<tr>
<td></td>
<td>Zimmer Contour in Zirconia</td>
<td>Abutment fracture</td>
<td>667.82</td>
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</table>

Table 2. Average Load to Fracture and mode of fracture for each abutment, and put into groups
### Significantly Different Abutments For Maximal Principle Strains

<table>
<thead>
<tr>
<th>Atlantis Zirconia</th>
<th>Atlantis Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inclusive Custom Zirconia</td>
</tr>
<tr>
<td></td>
<td>Inclusive Custom Titanium</td>
</tr>
<tr>
<td></td>
<td>Legacy Straight Zirconia</td>
</tr>
<tr>
<td></td>
<td>Legacy Straight Titanium</td>
</tr>
<tr>
<td></td>
<td>AstraTech Ti Design</td>
</tr>
<tr>
<td></td>
<td>AstraTech Zir Design</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zimmer PSA</th>
<th>AstraTech Zir Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Legacy Straight Zirconia</td>
</tr>
<tr>
<td></td>
<td>Legacy Straight Titanium</td>
</tr>
</tbody>
</table>

Table 3: Statistically significant abutments for maximal principle strains
<table>
<thead>
<tr>
<th>Significantly Different Abutments for Load to Fracture</th>
<th>Significant Differences* (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zimmer Contour Zirconia</td>
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</tr>
<tr>
<td>Legacy Straight Titanium</td>
<td>-437.15</td>
</tr>
<tr>
<td>Legacy Straight Zirconia</td>
<td>-349.15</td>
</tr>
<tr>
<td>Inclusive Custom Zirconia</td>
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<tr>
<td>Inclusive Custom Titanium</td>
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</tr>
<tr>
<td>Atlantis Zirconia</td>
<td>+202.44</td>
</tr>
<tr>
<td>Atlantis Titanium</td>
<td>+161.20</td>
</tr>
<tr>
<td>AstraTech ZirDesign</td>
<td>+431.60</td>
</tr>
</tbody>
</table>

*All values are statistically different (P<0.05)

Table 4: Statistically significant name brand abutment differences vs aftermarket abutments for load to fracture
Appendix B: Figures
Figure 1: The 12” x 2” x 8mm resin block with nine pilot holes
Figure 2: Resin block with Tapered Screw-Vent implants placed
Figure 3: Abutments attached to Tapered Screw-Vent implants
Figure 4: Wax-up made for crown fabrication for each abutment
Figure 5: Experimental set-up for strain testing
Figure 6: Loading portion of strain measurements
Figure 7: DIC information of strain data for various abutments
Figure 8: Loading apparatus made for load to fracture tests
Figure 9: Load to fracture testing for abutments
Figure 10: Plot of Load to Fracture for Zimmer PSA (top) vs. Legacy Straight Titanium (bottom)
Figure 11: Mechanism of fracture for (from left to right) AstraTech ZirDesign, Inclusive Custom Abutment in Zirconia, Atlantis Zirconia, Zimmer Contour in Zirconia
Figure 12: Plot of Load to Fracture for each abutment
Figure 13: Plot of maximal (tensile) principle strains around the implant