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FATIGUE FRACTURE OF A NOVEL DESIGN FOR CERAMIC-NECK TITANIUM IMPLANT

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ABSTRACT

Statement of problem: The ceramic neck implant is a novel implant design for tooth replacement. The novel design has a ceramic shell that covers the neck of the titanium implant and masks its dark color, which gives an appearance that mimics natural dentition.

Purpose: The purpose of this study was to in vitro test an optimized version of the ceramic neck implant for future clinical testing in patients. The aim was to determine the fatigue resistance of the ceramic shell under cyclic loading to simulate chewing function. This is the third article in a three article series to test a novel dental implant design with a ceramic neck in-vitro.

Materials and Methods: Thirty4.1mm (D) X 10mm (H)Grade 4 commercially pure tissue level, endosseous implants were used. The implants were divided into two groups (n=15) Group I (control) and Group II which had a novel ceramic neck design. All implants were placed in type 3 saw bone. Single tooth abutments, 7mm in height were inserted and torqued to 35Ncm. Identical CAD/CAM crowns were milled and adhesively cemented to abutments. Specimens were fatigue tested until failure using a computer controlled universal testing machine. Cyclic compressive fatigue test was done according to the modified “staircase” method. Mean ± SD was calculated according to specific statistical equations. Student t-test was done between two groups ($\alpha = 0.05$).

Results: Implants without ceramic shell recorded a higher mean value of fatigue failure load (328.3±102.4) than novel design implants with ceramic shell (269.5±54.7). The difference between two groups was not statistically significant ($P= 0.18 > 0.05$).

Conclusions: No statistical significant difference between the two groups means that the mechanical fatigue failure test showed high fracture resistance to cause failure of the ceramic shell.

KEYWORDS: Titanium, Implant, Porcelain, Fatigue fracture, Cyclic loading

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INTRODUCTION

Current paradigms for treatment success in implant dentistry are based not only on true clinical outcomes such as implant survival and restoration survival but also on surrogate clinical outcomes such as dento-gingival esthetics and health of surrounding soft tissues. This is especially important for implant therapy in maxillary and mandibular anterior regions, where esthetics play a predominant role in treatment success. Esthetic outcomes of dental implants pose challenges for comparison of treatment outcomes across populations and studies. This is obviously because of variations in subjective assessments not only among clinicians but also because of variations between clinicians and patients. The predominant esthetic outcome attributable to the anterior implant restoration is the change in color of the peri-implant soft tissues.[1] Previous studies have implicated that the blue-grayish shimmering effect of titanium abutments, especially over thin peri-implant mucosal tissues can compromise the esthetic results of implant treatment.[2,3] It is common for the implant neck to show through the gums as a black or dark grey line and/or as a grayish discoloration of the peri-implant soft tissue.[4] This implant esthetic problem occurs when unfavorable soft tissue conditions exist such as thin peri-implant mucosa and soft tissue recessions or as a result of poor implant placement.

A novel design of ceramic neck implant has been developed by the authors. This design is aimed at improving the esthetic outcome of the implant treatment and offering a more natural looking dental prosthesis that will optimally blend-in with surrounding dentition and oral structures taking advantage of the proven record of favorable tissue response to ceramics[5-13] The key component of this novel design is the ceramic shell that covers the polished collar of the tissue level titanium implant and masks its dark color. Two previous studies were conducted to evaluate and optimize this novel design.[14,15] The first one determined the minimum porcelain thickness that is needed to mask the color of titanium to provide the esthetic advantage of this implant. It was found that 0.5mm thickness of the ceramic shell is enough to do so.[14] Thesecond study determined the maximum torque for fracturing the ceramic shell and compared it to clinical insertion torque values. It was found that the ceramic shells did not fracture. Instead, implants carriers have fractured at certain torque levels. These levels were sufficiently higher than the clinical torque values. This means that there are fewer chances that a fracture might happen while inserting the novel ceramic neck implant and/or the abutment.[15]

However, it still needs to be determined whether the novel design will provide proper clinical performance during function or not. Without a doubt, the knowledge of the expected functional life of an implant is a critical therapeutic parameter for prosthetic longevity. Such knowledge requires fatigue tests in order to measure the fatigue life of the implant. The mechanical behavior of a structure is one of the most important factors to consider through the optimization of a dental implant design. The study of mechanical behavior of the dental prosthesis/implant system is needed to predict the long-term clinical success of an implant-supported prosthesis. However, it is necessary to recall that the mechanical behavior of a structure under a static load might be noticeably different than under a cyclic load. A cyclic load could result in fatigue failure at stress levels below the yielding stress of a material.[16]Additionally, stress applied to teeth and dental restorations is generally low and repeated rather than being single impact in type.[17] From this standpoint, the study of the mechanical behavior of an implant structure under a cyclic load is required.

Therefore, the purpose of this study (the third in a three article series testing this novel design) was to estimate the load-bearing capacity of the ceramic shell by dynamic type of mechanical test, rather than by static loading test. The resulting information should provide insight into the question of whether the simulated function will result in cracking or fracture of the ceramic shell. These studies will provide feasibility data for a large clinical study to test this product in humans to assess the esthetic outcome, improved tissue response and bone preservation, and improved patient satisfaction with the new implant design. The clinical study will also assess the dentists' impression of the complexity/ simplicity of placement and restorative procedures.

MATERIALS AND METHODS

Specimen Preparation: Thirty, 4.1mm (D) X 10mm (H) tissue level, type 4 commercially pure endosseous implants were used. Half of the implants (n=15) had no ceramic shell as a control (Group I). The other half (n=15) had the novel design of ceramic shell covering the polished collar of the implant (Group II). All implants were measured and placed in type 3 saw bone so that 3.0 mm of the implant was exposed above the saw bone to simulate the worst case clinical scenario for crestal bone loss.[18] Single tooth abutments, 7mm in height were then inserted and torqued to 35Ncm as per the manufacturer's specifications.

Crowns were fabricated using Ceramill motion 2 CAD/CAM system (Amanngirrbach AG, Koblach, Austria). After designing the single tooth incisor crown, fifteen identical crowns were milled from an Empress e-max ceramic block (Ivoclar Vivadent, Schaan, Liechtenstein) this was to ensure the consistency of the fabricated crowns. The crowns were adhesively cemented to the abutments with dual polymerizing resin cement Panavia F 2.0 (Kuraray America Inc., New York, NY 10038) according to the manufacturer's instructions.

All samples were individually mounted onto the lower fixed compartment of a computer controlled universal testing machine (Model 3345; Instron Instruments Ltd., USA) with a load cell of 5 kN and data were recorded using computer software (Bluehill Lite; Instron Instruments Ltd., USA). The samples underwent cyclic loading by means of a metallic sphere of 3.6 mm diameter which was attached to the upper movable compartment of the machine. The load was applied at the middle third of the palatal surface using a custom-made 45^{o} angle jig to simulate the normal relationship between maxillary and mandibular anterior teeth. Load profile was in the form of a sine wave at a rate of 1 Hz. The load was cycled at first between a specified maximum (49N) and small but non-zero minimum (10N) to avoid lateral dislocation of the loading tip and help in stabilizing the specimens during the test. These values represent the average biting force in a patient who had a single crown restoring an incisor tooth.[19]A tin foil sheet was placed between the loading tip and the palatal surface of crown to achieve homogenous stress distribution and minimize of the transmission of local force peaks.

Fatigue Testing: Cyclic compressive fatigue test at 5000 load cycles[20] were applied according to the modified "staircase" method.[21] Inthis method, tests are conducted sequentially, with the maximum applied load increased by a fixed percentage in each succeeding test, when the previous load did not result in a failure. Since the specimen did not fail within the prescribed number (5000) of load cycles and the prescribed load (10N-49N), the load for the second specimen was increased by a fixed increment of 10% of static compressive load as reported in other studies.[22-24]

The mean compressive fatigue limit (CFL) was calculated using Equation (1) and standard deviation was calculated using Equation (2), respectively:[21]

$$\mathrm{CFL} = X_0 + d\left(\frac{\sum in_i}{\sum n_i} \pm 0.5\right) \quad \ldots(1)$$

$$\mathrm{S.D.} = 1.62d\left(\frac{\sum n_i \sum i^2 n_i - \left(\sum in_i\right)^2}{\left(\sum ni\right)^2} + 0.029\right) \quad \ldots(2)$$

Where X_0 is the lowest load level considered in the analysis and (d) is the fixed load increment. In Equation (1), the negative sign is used when the analysis is based on failures; otherwise the positive sign is used. The lowest stress level considered is designated as i= 0, the next as i= 1, and so on and n_i is the number of failures or non-failures at the given stress level.

Data analysis was performed in several steps. Initially, descriptive statistics for each group were calculated. Student's t-test was performed between the two groups. Statistical analysis was performed using Assistat 7.6 statistics software for Windows (Campina Grande, Paraiba state, Brazil). P values ≤0.05 are considered to be statistically significant for all tests at α= 0.05 significance level.

RESULTS

The results of the fatigue fracture testing of group I (control) under cyclic loading are presented in Tables 1 and 2. The results showed that five specimens failed at load of 50-245 N while four failures were obtained under 60-294 N load. In addition, three specimens failed at 70-343 N and the other three specimens failed under 80-392 N of dynamic load.

The results of the fatigue fracture testing of group II (Ceramic Neck) under cyclic loading are presented in Tables3 and 4. The results showed that five specimens failed at load of 40-196 N while the other five failures were obtained under 50-245 N load. In addition, five specimens failed at 60-294 N of dynamic load.

The equations used in this study revealed that traditional implants without ceramic shell (group I) recorded a higher mean value of fatigue fracture limit (328.3±102.4) than novel design ceramic neck implants (group II) (269.5±54.7). The difference between the two groups was statistically non-significant as indicated by t-test (p = 0.18) (Figure 1).

SN curve (load-number of cycles) demonstrated that as the applied load increased, the number of cycles decreased (Figure 2).

Additionally, the results of this study showed that the fatigue limit increased as the compressive load increased.

TABLE (1) Number of cycles to failure as a function of the applied dynamic load for group I.

i	Load (N)	Number of Cycles Till Failure														
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
i7	80-392	210									45					101
i6	70-343	5000	34							21	5000	415				5000
i5	60-294	5000	5000	120			1120		77	5000	5000	5000		12		5000
i4	50-245	5000	5000	5000	1	845	5000	83	5000	5000	5000	5000	201	5000	19	5000
i3	40-196	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
i2	30-147	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
i1	20-98	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
i0	10-49	5000	5000	5000	5000	5000	5000	5000	5000	198	5000	5000	5000	5000	5000	5000
Fatigue Failure Load					Mean = 328.3											
					SD = 102.4											

TABLE (2) Method for analyzing staircase test procedure data for group I.

I	Load (N)	Failures (n_i)	in_i	i^2n_i
i7	80-392	3	21	147
i6	70-343	3	18	108
i5	60-294	4	20	100
i4	50-245	5	20	80
i3	40-196	0	0	0
i2	30-147	0	0	0
i1	20-98	0	0	0
i0	10-49	0	0	0
		Sum=15	Sum= 79	Sum = 435

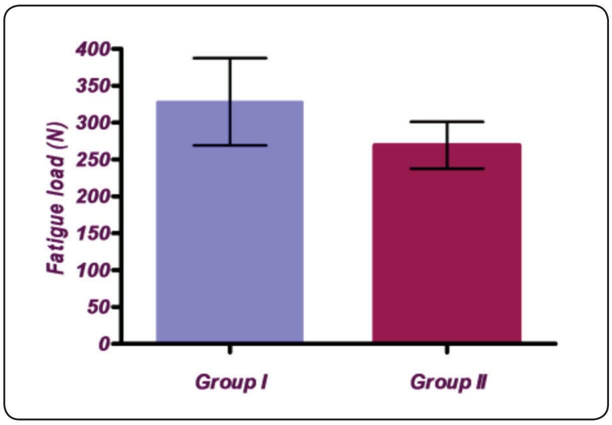

Fig. (1) Comparison of mean value of fracture failure load for two tested groups.

TABLE (3) Number of cycles to failure as a function of the applied dynamic load for group II.

i	Load (N)	Number of Cycles Till Failure														
		S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**
i5	60-294		1108	786	89			654								716
i4	50-245		5000	5000	5000			5000	2237	453		1298		293	719	5000
i3	40-196	311	5000	5000	5000	2187	965	5000	5000	5000	1285	5000	3102	5000	5000	5000
i2	30-147	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
i1	20-98	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
i0	10-49	5000	5000	5000	5000	5000	5000	5000	5000	198	5000	5000	5000	5000	5000	5000
Fatigue Failure Load					Mean = 269.5											
					SD = 54.7											

TABLE (4) Method for analyzing staircase test procedure data for group II.

i	Load (N)	Failures (n_i)	in_i	i^2n_i
i5	60-294	5	25	125
i4	50-245	5	20	80
i3	40-196	5	15	45
i2	30-147	0	0	0
i1	20-98	0	0	0
i0	10-49	0	0	0
		Sum=15	Sum= 60	Sum = 250

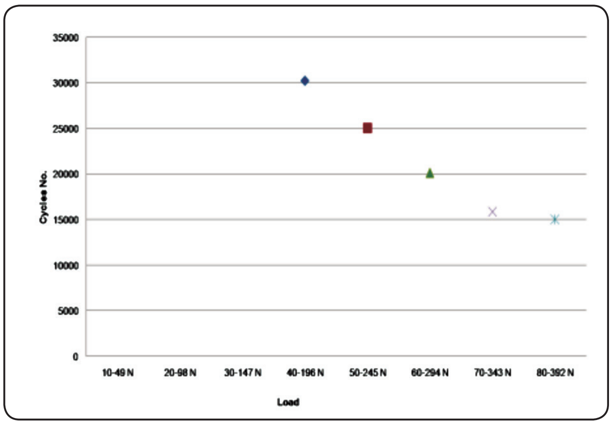

Fig. (2) Wholer graph for fatigue test on specimens.

DISCUSSION

Fracture of endosseous dental implants during placement or function will have serious implications for patients. Fracture of implants during insertion may occur as the insertion load exceeds the fracture strength of the implant. Such a failure is most unlikely to be the result of clinical misuse and is most probably due to a design or metal selection error. Errors in manufacturing and flaws in materials may also contribute to failure.[25] Our previous study[15] proved that the ceramic shell of the novel design of the ceramic neck implant did not fracture at the average clinical insertion torque value. This means that there are fewer chances that a fracture might happen while inserting the novel ceramic neck implant and/or the abutment.

The other mechanism of failure for implant components is fatigue failure. This occurs as a result of cyclic functional loading; the magnitude of which may be well below the ultimate strength of the components. Good adherence to sound biomechanical principles of prosthesis design should minimize the risks of fatigue failure, although component design may play a role.[25]Hence, it is of crucial importance to consider cyclic mechanical loading when evaluating the long-term behavior of implant-supported restorations in vitro.[26]Accordingly, the current study tested the fatigue fracture of our novel implant design. Fatigue testing until failure is accepted as a method to generate data on the implant longevity.[27,28] The "staircase" method was selected to be followed in this study because it provides a measure of the mean CFL and permits calculation of the standard deviation of that mean. Since the data was calculated around the mean stress, the number of specimens required was less than with other methods. A minimum of fifteen specimens was considered to be enough for accurate data analysis.[29] Therefore, we assigned 15 implants to each experimental group.

Fatigue limit depends not only on the nature of the material, but also on the nature of the applied stress and the frequency of cyclic loading.[30] Therefore, the rate of 1 Hz was used in the present study because it is equivalent to the average masticatory cycle of 0.8 – 1.[31]

The number of cycles used in this study was similar to other studies[20,32] using the stair case method. Some other studies[23,33] used cycles of 1000. The "staircase" method automatically concentrated testing nearer to the limit. In particular, when $[\Sigma n_i \Sigma i^2 n_i - (\Sigma i n_i)^2] / (\Sigma n_i)^2$ is larger than 0.3, the estimation of standard deviation becomes more accurate and when the value is less than 0.3, a more elaborate calculation must be employed.[23,34] The corresponding value in this study was 1.26 for group I and 0.6 for group II (i.e. larger than 0.30in both groups). In addition the data showed a linear relationship between compressive fatigue limit and load-bearing capacity which is in agreement with a study by Garoushiet al.[23]

The single-tooth implant situation demands the greatest degree of mechanical integrity in the implant-abutment interface.[27] The results of the present study showed high fracture resistance of the novel design ceramic neck implants that was not statistically different from traditional implants. This could be attributed to the fact that the internal hex was made of metal of sufficient thickness so that there are minimal stresses on the ceramic shell. The implant abutment is in complete contact with the internal metal connection of the implant, which is designed with sufficient moment of inertia to resist bending under occlusal forces, so that it does not exert any force on the ceramic shell to prevent fracture or chipping of the ceramic outer shell.

The surface properties of an object could affect its fatigue resistance. These include; surface roughness, variation in surface strength, and variation in surface residual stresses. Among these three factors, the influence of the surface roughness is of more interest for this study. A study by Fluck PG[35] investigated the influence of surface roughness on the fatigue resistance of steel specimens and showed that polished specimens with 0.05μm surface roughness had a fatigue life about 10 times more than specimens with 2.67μmsurface roughness. Another study[36] found that improving the surface roughness of dental implants could be one of the major factors that could increase the implant fatigue resistance. This could be an explanation for the good results of our novel implant design keeping in mind the smooth surface attained by the porcelain shell on the implant neck.

This study is the third in a series of three in vitro studies aimed at testing and optimizing the design of the ceramic neck implant before initiating the in vivo stage which will test this product in humans to assess the esthetic outcome, improved tissue response and bone preservation, and improved patient satisfaction with the new implant design. The clinical phase will also assess the dentists' impression of the complexity/simplicity of placement and restorative procedures.

CONCLUSION

Since there was no statistically significant difference between the new novel implant design and the control groups we can conclude-within the limitations of this study- that the mechanical fatigue failure test showed high fracture resistance to cause failure of the ceramic shell.

Within the limitations of this study we can also conclude that the novel implant design has very high chances to perform well clinically during chewing function.

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