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Effect of the number of short implants used for rehabilitation of posterior mandible on stress and strain distribution in bone: A finite element analysis

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Abstract

Objectives: This study aimed to assess the effect of number of short implants used for rehabilitation of posterior mandible on stress and strain distribution in bone using finite element analysis (FEA).

Materials and Methods: In three-dimensional (3D) finite element models, short implants with 4 mm diameter and 6 mm length were placed at the site of mandibular first premolar to second molar teeth. The designed models were as follows: (I) two implants at the site of teeth #4 and #7 with two pontics at the site of teeth #5 and #6, (II) three implants at the site of teeth #4, 5 and 7 with one pontic at the site of tooth #6, (III) three implants at the site of teeth #4, 6 and 7 with one pontic at the site of tooth #5, and (IV) four implants at the site of teeth #4, 5, 6, and 7 with no pontic. Next, 100 N load was applied vertically and with 30° angle to the occlusal surface of the crowns. The pattern of stress and strain distribution in bone was evaluated in certain points in cortical and cancellous bone using ANSYS Workbench version 16.1 software.

Results: The highest maximum von Mises and shear stress and strain values in vertical and off-axial loadings were noted in the model with two short implants at the site of teeth #4 and 7 with two pontics at the site of teeth #5 and 6. Generally, the highest maximum stress and strain values were noted following application of off-axial loads compared with vertical loads. In all models, the highest maximum stress was noted in cervical part of implants while maximum strain was noted in apical part of implants.

Conclusion: It seems that increasing the implant number significantly decreases the stress and strain values in peri-implant bone.

Keywords: Short Implants; Stress; Strain; Finite Element Analysis

Introduction

In the recent years, use of implant-supported restorations has increased in patients with complete or partial edentulism with successful results [1,2]. In severe bone resorption, use of dental implants requires extensive surgical procedures for bone augmentation. On the other hand, posterior anatomical landmarks such as the maxillary sinus and the mandibular canal may complicate implant placement in these areas.

Implant placement in the posterior parts of the jaws is associated with some complications such as limited access, limited visibility, limited inter-arch space, and post-extraction bone loss [3,4]. Short implants have been recommended as a less-invasive alternative for rehabilitation of posterior edentulous areas requiring sinus floor elevation, bone augmentation or nerve repositioning. In use of short implants, it has been recommended to increase the number and diameter of implants to minimize bone loss [5]. Several meta-analyses have confirmed the efficacy of implants with a minimum of 8 mm of length [6-8]. However, information about shorter implants is limited. They reportedly have a survival rate of around 94%, mainly due to early failure [5]. Short implants are easy to use and have a high safety margin due to low risk of interference with anatomical landmarks.

Some previous studies have reported lower success rate of short implants compared with standard-length implants [9,10]. However, studies conducted after 2005 have reported that the survival rate and success rate of short and standard-length implants are the same. Thus, use of short implants increased from 1% to 10% in the recent years [11]. However, information regarding the success rate of implants shorter than 7 mm is still limited.

Some considerations need to be taken into account in placement of short implants such as increasing the diameter and number of implants and their splinting. Considering the absence of periodontal ligament (PDL) around dental implants and osseointegration of titanium implants, correct distribution of loads applied to bone through the implant, especially the crestal bone, is highly important in success of implant treatment and prevention of bone loss. Correct distribution of loads in short implants (with higher crown/implant ratio) is more important than standard-length implants. Thus, it is recommended to splint the crowns in cases with high crown/implant ratio in order to evenly distribute the stress among the implants [12]. Aside from splinting and increasing the diameter of implants, use of higher number of implants is also recommended for better distribution of loads and in order to minimize bone loss around short implants [13]. Moreover, it has been reported that short implants well tolerate prosthetic restorations [14-16]. A photo-elastic assessment by Guichet et al. [17] evaluated the stress distribution in splinted and non-splinted restorations supported by external hexagon implants and reported optimal stress distribution in bone around splinted implants.

Considering the increasing use of short implants as a non-invasive alternative for rehabilitation of the posterior mandible, it is imperative to find the factors affecting the success of this treatment. Tabrizi et al. [13] assessed the relationship of the number of short implants and bone loss in the posterior mandible and reported that increasing the number of implants decreased marginal bone loss.

The significance of biomechanical factors in implant treatment has been previously emphasized [18]. Stress distribution per unit area is among the important biomechanical factors that affects the success rate of implant treatment. Finite element analysis (FEA) is commonly used for assessment of stress and strain distribution patterns [19]. It quantifies the amount of distributed stress and strain in bone around the implant three-dimensionally.

Controlled studies regarding optimal rehabilitation by use of short implants are limited, and no consensus has been reached regarding the number, diameter, crown to implant ratio, and splinting of short implants for this purpose. Thus, this study aimed to assess the effect of number of short implants for rehabilitation of posterior mandible on stress and strain distribution in peri-implant bone.

Materials and Methods

In this FEA, three-dimensional (3D) finite element models of short SIC implants (SIC invent AG, Basel, Switzerland) with 6 mm length and 4 mm diameter (abutment platform: 4 mm) placed in the posterior mandible were designed to calculate the maximum von Mises stress, maximum shear stress, maximum von Mises strain and maximum shear strain values around splinted and non-splinted implants following the application of 100 N load vertically and obliquely (30°).

The following four models with regard to placement of implants in the posterior mandible were designed:

(I) Two short implants placed at the site of teeth #4 and 7 with two pontics at the site of teeth #5 and 6

(II) Three short implants placed at the site of teeth #4, 5 and 7 with one pontic placed at the site of tooth #6

(III) Three short implants placed at the site of teeth #4, 6 and 7 with one pontic placed at the site of tooth #5

(IV) Four short implants placed at the site of teeth #4, 5, 6 and 7 without a pontic

Three-dimensional scanning:

ATOS II (GOM GmbH, Braunschweig, Germany) scanner and ATOS Viewer version v6.30 were used in this study for 3D scanning of teeth along with implants. CATIA software version R21

(Daso Systems, France) was used for 3D modelling and montage. ANSYS software version 16.1 was used for FEA. Implants with 4 mm diameter and 6 mm length were modelled and montaged in different situations explained earlier. Eight geometries and loading conditions were simulated and modelled as follows:

Model 1: Implants placed at the site of teeth #4, 5, 6 and 7, no pontic, 100 N load applied vertically

Model 2: Implants placed at the site of teeth #4, 5, 6, and 7, no pontic, 100 N load applied at 30° angle

Model 3: Implants placed at the site of teeth #4, 5 and 7, one pontic, 100 N load applied vertically

Model 4: Implants placed at the site of teeth #4, 5 and 7, one pontic, 100 N load applied at 30° angle

Model 5: Implants placed at the site of teeth #4, 6 and 7, one pontic, 100 N load applied vertically

Model 6: Implants placed at the site of teeth #4, 6 and 7, one pontic, 100 N load applied at 30° angle

Model 7: Implants placed at the site of teeth #4 and 7, two pontics, 100 N load applied vertically

Model 8: Implants placed at the site of teeth #4 and 7, two pontics, 100 N load applied at 30° angle

ANSYS software version 16.1 was used for load application and calculation of stress and strain values. The materials used were considered linearly elastic. Table 1 shows the behavioral properties of the materials used [20]. ANSYS meshing was employed for meshing. Smaller elements were used in critical areas to obtain more accurate results. Tetrahedral elements were used for meshing of all components. Hexahedral elements were used for meshing of the bar. All elements were quadratic with high precision. Table 2 presents the element data. The models were subjected to application of 100 N vertical and off-axial loads at 30° angle. Compressive loads were applied to the occlusal surface of porcelain. In order to prevent movement of the jaw, its inferior border was considered to have fixed support. Since the geometry and loading conditions were symmetrical, only half of the modelled jaw was considered. At the site of sectioning, the frictionless support boundary condition was considered. The contacts between the components were linearly bounded, which did not allow sliding or separation of the two components and only sticking could occur between them. In order to increase the accuracy of measurements at the critical contact points, tiny elements measuring 0.1 mm in size were used for modelling of these areas. In order to obtain more accurate results, a series of points were used in important areas. These points were selected at the middle of each implant in order for the results to be comparable. The selected points were located in cortical and cancellous bone and also at the end of implant threads. In each plane, two threads were clearly visible on the top (coronal part of the implant, which was located in cortical bone) and two threads were clearly visible at the bottom (apical part of the implant, which was located in cancellous bone) (Figure 1). The selected points were referred to as upper left (UL), upper right (UR), lower left (LL) and lower right (LR) points.

The equivalent (von Mises) stress, the maximum shear stress, the equivalent (von Mises) strain and the maximum shear strain were calculated at each point. The results obtained for each implant included 16 pieces of data including two stress and two strain values calculated at four points.

No statistical analysis was performed on the data and only the maximum von Mises stress and strain and the maximum shear stress and strain values in bone at the site of implants were calculated and reported for different models under 100 N vertical and off-axial (30°) loads.

Results

First model (implants placed at the site of teeth #4, 5, 6 and 7, no pontic, 100 N load applied vertically):

The highest maximum von Mises stress (1.9055 MPa) and maximum shear stress (1.0801MPa) values were noted in cortical bone around implant #7 (UR point of second molar). The highest maximum von Mises strain (713 με) and maximum shear strain (1010 με) values were recorded in cancellous bone around implant #6 (LL point of first molar).

The lowest maximum von Mises stress (0.1354 MPa) and maximum shear stress (0.0778 MPa) values were noted in cancellous bone around implant #4 (LL point of first premolar). The lowest maximum von Mises strain (53 με) and maximum shear strain (77 με) values were noted in cortical bone around implant #4 (UR point of first premolar).

Second model (Implants placed at the site of teeth #4, 5, 6 and 7, no pontic, 100 N load applied at 30° angle):

The highest maximum von Mises stress (4.2742 MPa) and maximum shear stress (2.4465 MPa) values were noted in cortical bone around implant #6 (UR point of first molar). The highest maximum von Mises strain (1140 με) and maximum shear strain (1640 με) values were noted in cancellous bone around implant #6 (LR point of first molar).

The lowest maximum von Mises stress (0.7066 MPa) and maximum shear stress (0.4041 MPa) values were recorded in cancellous bone around implant #4 (LR point of first premolar). The lowest maximum von Mises strain (48 με) and maximum shear strain (69 με) values were noted in cortical bone around implant #5 (UL point of first premolar).

Third model (implants placed at the site of teeth #4, 5 and 7, with one pontic and 100 N load applied vertically):

The highest maximum von Mises (3.1487 MPa) and maximum shear stress (1.7718 MPa) values were noted in cortical bone around implant #7 (UR point of second molar). The highest maximum von Mises strain (890 με) and maximum shear strain (1292 με) values were noted in cancellous bone around implant #7 (LR point of second molar).

The lowest maximum von Mises stress (0.5706 MPa) and maximum shear stress (0.3281 MPa) values were noted in cancellous bone around implant #4 (LR point of first premolar). The lowest maximum von Mises strain (52 με) and maximum shear strain (74 με) values were noted in cortical bone around implant #4 (LR point of first premolar).

Fourth model (implants placed at the site of teeth #4, 5 and 7, with one pontic and 100 N load applied at 30° angle):

The highest maximum von Mises stress (5.5191 MPa) and maximum shear stress (3.1678 MPa) values were noted in cortical bone around implant #5 (UR point of second premolar). The highest maximum von Mises strain (1150 με) and maximum shear strain (1680 με) values were noted in cancellous bone around implant #5 (LR point of second premolar).

The lowest maximum von Mises stress (0.29102 MPa) and maximum shear stress (0.15666 MPa) values were noted in cancellous bone around implant #4 (LL point of first premolar). The lowest maximum von Mises strain (67 με) and maximum shear strain (99 με) values were noted in cortical bone around implant #5 (UL point of second premolar).

Fifth model (implants placed at the site of teeth #4, 6 and 7, with one pontic and 100 N load applied vertically):

The highest maximum von Mises stress (2.45 MPa) and maximum shear stress (1.38 MPa) values were noted in cortical bone around implant #6 (UR point of first molar). The highest maximum von Mises strain (834 με) and maximum shear strain (1140 με) values were noted in cancellous bone around implant #4 (LL point of first premolar). The lowest maximum von Mises stress (0.10 MPa) and maximum shear stress (0.057 MPa) values in cancellous bone were noted around implant #7 (LR point of second molar).

Sixth model (implants placed at the site of teeth #4, 6 and 7, with one pontic and 100 N load applied at 30° angle):

The highest maximum von Mises stress (2.96 MPa) and maximum shear stress (1.71 MPa) values were noted in cortical bone around implant #7 (UR point of second molar). The highest maximum von Mises strain (1690 με) and maximum shear strain (2450 με) values were noted in cancellous bone around implant #6 (LR point of first molar).

The lowest maximum von Mises stress (0.0897 MPa) and maximum shear stress (0.051 MPa) values were noted in cancellous bone around implant #6 (LL point of first molar). The lowest maximum von Mises strain (71 με) and maximum shear strain (98 με) values were noted in cancellous bone around implant #6 (LL point of first molar).

Seventh model (implants placed at the site of teeth #4 and 7, with two pontics and 100 N load applied vertically):

The highest maximum von Mises stress (4.8167 MPa) and maximum shear stress (2.6885 MPa) values were noted in cortical bone around implant #7 (UR point of second molar). The highest maximum von Mises strain (1213 με) and maximum shear strain (1779 με) values were noted in cancellous bone around implant #7 (LR point of second molar).

The lowest maximum von Mises stress (0.6328 MPa) and maximum shear stress (0.36513 MPa) values were noted in cancellous bone around implant #7 (LL point of first molar). The lowest maximum von Mises strain (83 με) and maximum shear strain (124 με) values were noted in cortical bone around implant #4 (UL point of first premolar).

Eighth model (implants placed at the site of teeth #4 and 7, two pontics, 100 N load applied at 30° angle):

The highest maximum von Mises stress (7.9679 MPa) and maximum shear stress (4.5929 MPa) values were noted in cortical bone around implant #4 (UR point of first premolar). The highest maximum von Mises strain (1847 με) and maximum shear strain (2687 με) values were noted in cancellous bone around implant #4 (LR point of first premolar).

The lowest maximum von Mises stress (0.4084 MPa) and maximum shear stress (0.2339 MPa) values were noted in cancellous bone around implant #7 (LL point of second molar). The lowest maximum von Mises strain (266 με) and maximum shear strain (381 με) values were noted in cortical bone around implant #7 (UL point of second molar).

Discussion

This study assessed the effect of number of short implants used for rehabilitation of posterior mandible on stress and strain distribution in bone using FEA. Maximum stress and strain values in vertical and off-axial loadings were noted in the model with two short implants at the site of teeth #4 and 7 with two pontics at the site of teeth #5 and 6. Generally, maximum stress and strain values were noted following the application of off-axial loads compared with vertical loads. In all models, maximum stress was noted in upper parts of implants while maximum strain was noted in lower parts of implants.

Bone adapts to mechanical loads applied to it and undergoes constant remodeling, which helps preserve its mechanical properties [21]. Stress leads to strain and deformation of bone in the form of increase or decrease in bone length. A strain equal to 1000 με causes 1% change in bone. The amount of strain depends on the magnitude of applied stress and mechanical properties of bone [22]. If strain exceeds the bone tolerance threshold, fatigue fracture occurs. Normally, bone preserves its function in presence of 50-1500 με [21]. In 1500-3000 με, bone is slightly overloaded, which can lead to mechanical fatigue injury in bone. However, it heals by bone remodeling. Bone overload increases the frequency of micro-damage and leads to subsequent healing. Repetition of stress applied to bone can cause deformation and strain over 3000 με, which increases the micro-damage. Some strains may impair healing and cause fatigue failure. Sudden bone fracture often occurs in presence of 25000 με, which translates to 2.5% deformation in bone. Thus, moderate increase in optimal stress would increase bone regeneration. In 50 με strain, the bone is no longer stimulated and consequently, resorption occurs. On the other hand, occlusal forces all affect peri-implant bone; this effect can be positive or negative. After the first year of implant function in the oral cavity, slight bone resorption occurs around the implant; however, this resorption may be considerable around some implants. Thus, occlusal forces can cause marginal bone resorption and adversely affect osseointegration even after long periods of time [23].

Bone is a porous material with complex, tiny micro-structures. It is anisotropic and its different parts have different physical properties [24]. Primary mechanical distribution of stress occurs at the bone-implant contact [25]. First, the stress generated by the occlusal forces is transferred from implant to cervical bone. Limited amount of residual stress is distributed around the apical part of implant in trabecular bone. Also, high amounts of strain are generated in cortical bone in contact with the implant because its modulus of elasticity is higher than that of trabecular bone and has high capability for stress transfer [26]. However, in the present study, the highest maximum stress values were noted in cortical bone while maximum strains were noted in trabecular bone in all models.

One major reason for bone loss around the implant neck is inappropriate loading conditions. Inappropriate loading causes excessive accumulation of stress and subsequent initiation of bone resorption. Since stress distribution is an important factor in bone resorption following implant rehabilitation, this stress should be well distributed around dental implants to decrease the risk of bone resorption and improve the prognosis of treatment. These observations are highly important in long-term clinical service of implants because bone resorption at the cervical area can negatively affect implant stability and enhance the penetration of pathogenic microorganisms and subsequent inflammation, which could lead to implant loosening. Waskewicz et al. [27] reported that stress generation starts following placement of prosthesis over the abutment; however, it can be decreased if a precise structure is designed. Considering the complexity of bone structure and its mechanical and heterogeneous properties, we cannot determine a certain stress or strain threshold for it. Since micro-deformation is an important factor in implant survival, determining the level of stress and strain is critical [28].

Aside from its advantages, FEA has some shortcomings as well, which include unrealistic simulation of properties of the materials, the assumption of homogeneity, elasticity and isotropic nature of bone, tooth and PDL, and the assumption of tight contact between the bone and implant; whereas, the implant-bone contact is dynamic and it is impossible to perfectly simulate the natural behavior of different structures. The values obtained in FEA are unrealistic and are only suitable for the purpose of comparison. Nonetheless, use of 3D models yields more reliable results than 2D models [19]. FEA provides a general idea about the biomechanical aspects of treatment in normal conditions. Obviously, such mechanical results should be interpreted in combination with related clinical findings. FEA has been used for assessment of the pattern of stress distribution in bone around implants under different loading conditions [29-31]. In this study, vertical and off-axial loads with 30° angle was applied. Previous studies applied off-axial loads in the range of 35° to 45° [29]. Melsen and Lang [32] performed histomorphometric analysis to assess the tissue response around implants to load application. They compared the results with regional strain calculated by FEA. They found a significant correlation between strain values and cellular activity on trabecular bone surface. Maximum bone resorption was noted in areas with low or high strain. Surfaces with bone deposition had the highest frequency of strain values between 3400 and 6600 με. In our study, maximum strain did not exceed this range in any point. Due to linear nature of FEA data, higher loads were not tested in our study. However, there is a possible risk in the eighth model under bigger loads or larger angles.

Most FEA studies only report data at one point as the site of maximum stress. Although this method is simpler, it is not highly accurate since some sharp points may be present in meshing and the maximum stress points may be superimposed on these sharp points. Since these points are mainly singular, their data are not accurate. Thus, we also determined some reference points in cortical and cancellous bone adjacent to implant threads and measured the stress and strain values in these points as well. This was a strength of this study, which yielded more reliable data.

Wang et al. [33] used FEA and reported that higher stress values were related to application of horizontal loads rather than vertical loads, which was related to stress distribution pattern due to rigidity of splinting. In our study, stresses at the bone-implant contact were greater when off-axial load was applied. Our current findings indicated that increasing the number of implants decreased the maximum stress and strain values, which was in line with the clinical study by Tabrizi et al, [13] who reported that increasing the number of short implants decreased marginal bone loss. Our FEA findings can be translated to decreased bone loss in the clinical setting. Gumrukçü and Korkmaz [34] reported that placement of higher number of implants was associated with the lowest von Mises stress values, which was in line with our findings. Toniollo et al. [35] stated that use of higher number of implants to support fixed partial denture is preferred due to stress reduction in implant structure and the surrounding bone. El-Anwar et al. [36] in their study on the effect of number of implants and attachment type on stress distribution in mandibular bone reported that although the number of implants and attachment type had no significant effect on peri-implant bone, it would be preferred to use locator attachments where two abutments are used at the site of canines. Sousa et al. [37] reported that increasing the number of implants had no significant effect on strain in bone. According to the results of the aforementioned two studies, it seems that in mandibular overdentures, increasing the number of abutments does not cause a significant change in stress distribution pattern in bone. However, the current study showed that in fixed partial dentures of the mandible, increasing the number of implants would decrease and improve the distribution of stress in bone. In our study, the highest maximum stress values were noted in the upper parts of implants (UR) while the maximum strain values were noted in the apical part of implants (LR, LL). Also, the results showed reduction in maximum stress and strain values and more homogenous stress and strain distribution patterns in models with three implants placed at the site of teeth #4, 6 and 7, with one pontic at the site of first premolar. Further prospective clinical studies are required to confirm the results of this study. Also, stress and strain distribution patterns around short implants placed in other parts of the jaw should be evaluated in future studies.

Conclusion

The current results revealed that increasing the number of short implants resulted in lower stress and strain values under vertical and off-axial loads. The highest maximum stress values were noted in cortical bone while the maximum strain values were recorded in trabecular bone in all models. In 3-implant models with implants placed at the site of teeth #4, 6 and 7 and one pontic at the site of first premolar, the maximum stress and strain values decreased and more uniform stress and strain distribution patterns were achieved.

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Tables

Table 1. Behavioral properties of the materials

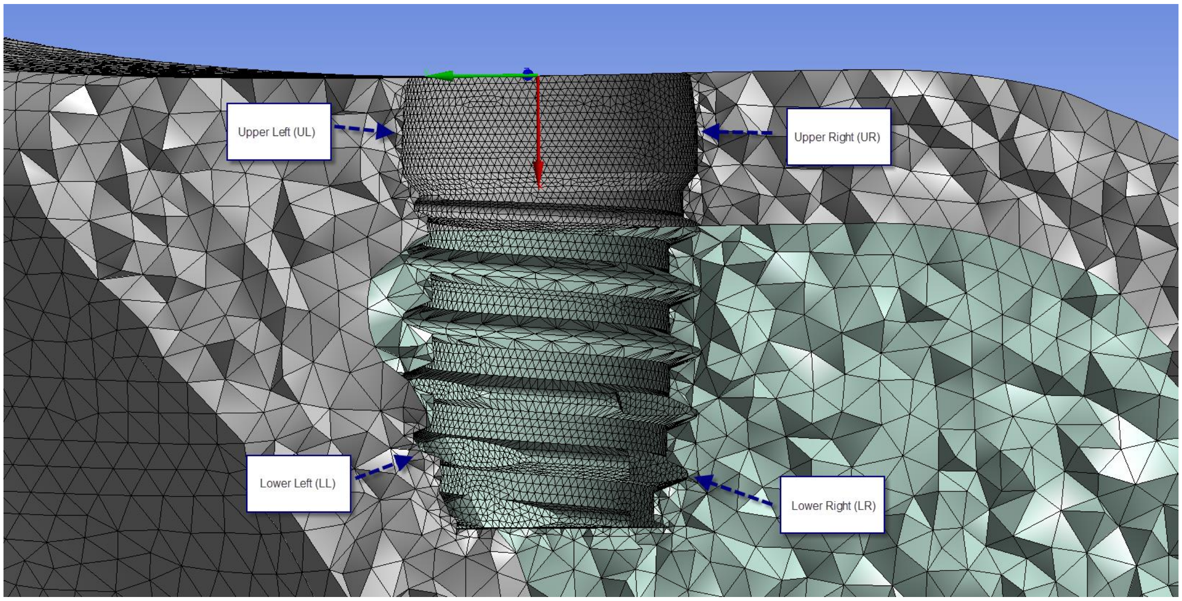
Material	Modulus of Elasticity (MPa)	Poisson's Ratio
Cortical	13 400	.3
Porcelain	68 900	.28
Cancellous Bone	1 370	.3
Titanium	110 000	.35

Table 2. Element data

Number of elements	2227491
Number of nodes	3380796
Type of elements	Tetrahedral + hexahedral
Element order	quadratic

Size of elements for the bar	0.25 mm
Size of elements for the porcelain	0.5 mm
Size of elements for the fixture and abutment	0.25 mm
Size of elements for cortical bone	0.5 mm
Size of elements for cancellous bone	0.5 mm
Size of elements for the external surface of fixture	0.1 mm
Size of elements for the internal surface of cortical bone and cancellous bone	0.1 mm

Figure 1. Selected four points for measurement of stress and strain in peri-implant bone (the two lower points are in the cancellous bone while the two upper points are in the cortical bone)



Upper Left (UL)
Upper Right (UR)
Lower Left (LL)
Lower Right (LR)