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# Optimal selection of dental implant for different bone conditions based on the mechanical response

SANDIPAN ROY[1, 3], MAINAK DAS[1], PRATYAYA CHAKRABORTY[1], JAYANTA KUMAR BISWAS[1],
SUBHOMOY CHATTERJEE[1], NILOY KHUTIA[1], SUBRATA SAHA[2], AMIT ROY CHOWDHURY[1]*

[1] Department of Aerospace Engineering &Applied Mechanics,
Indian Institute of Engineering Science and Technology, Shibpur, India.
[2] SUNY Downstate Medical Center, Brooklyn, New York.
[3] Department of Mechanical Engineering, SRM University, Kattankulathur.

*Purpose*: Bone quality varies from one patient to another extensively. Young's modulus may deviate up to 40% of normal bone quality, which results into alteration of bone stiffness immensely. The prime goal of this study is to design the optimum dental implant considering the mechanical response at bone implant interfaces for a patient with specific bone quality. *Method*: 3D models of mandible and natural molar tooth were prepared from CT scan data, while dental implants were modelled using different diameter, length and porosity and FE analysis was carried out. Based on the variation in bone density, five different bone qualities were considered. First, failure analysis of implants, under maximum biting force of 250 N had been performed. Next, the implants that remained were selected for observation of mechanical response at bone implant interfaces under common chewing load of 120 N. *Result*: Maximum Von Mises stress did not surpass the yield strength of the implant material (TiAl4V). However, factor of safety of 1.5 was considered and all but two dental implants survived the design stress or allowable stress. Under 120 N load, distribution of Von Mises stress and strain at the bone-implant interface corresponding to the rest of the implants for five bone conditions were obtained and enlisted. *Conclusion*: Implants exhibiting interface strain within 1500–3000 microstrain range show the best bone remodelling and osseointegration. So, implant models having this range of interface strains were selected corresponding to the particular bone quality. A set of optimum dental implants for each of the bone qualities were predicted.

*Key words*: *bone condition, porous dental implant, FE analysis, patient specific*

## 1. Introduction

Dental implants have turned out to be very popular choice among partially and fully edentulous patients [37] to regain ample dental performance as well as to get an aesthetic appearance. As a result of huge clinical success, the demand of these artificial surgical components is increasing day by day [36].

The quality of the adjacent jaw-bone is significant factor in dental implant design [15]. The human bone, applying its inherent capability of renovating its biomechanical property by altering its geometry and/or material characteristics holds the dental implant and makes it compatible and accustomed with human body. This intricate phenomenon is described as osseointegration [31]. Improved performance and prime stability of the dental implant are obtained at higher degree of osseointergration [25], which varies with bone implant interface strain that depends on bone quality of the patient and stiffness of the implant. So, it is very important to design and carry out analysis of dental implant considering the patient specific bone quality.

Often a marginal bone loss, a serious issue regarding dental implant occurs due to the lack of application of mechanical simulation [39]. Unlike experimental approach, numerical techniques, especially FEA have turned out to be immensely effective to analyze these biomechanically complicated phenomena [24], [27], [37]. Using 3D FEA it was found from the stress

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* Corresponding author: Amit Roy Chowdhury, Department of Aerospace Engineering and Applied Mechanics, Indian Institute of Engineering Science and Technology, 711103 Shibpur, Howrah, India. Tel: +919830465710, fax: +913326682916, e-mail: arcbesu@gmail.com

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distribution at bone-implant interface that transverse mechanical loading plays more significant role in stability of dental implant [15]. Tao-Li et al [23] and El-Anwar and El-Zawahry [16] noticed that selection of implant diameter and length higher than 4 mm and 12 mm, respectively, for an uniform bone quality results into improved stress distribution at bone implant interface, which leads to firm locking and anchoring. Similar conclusion was drawn by Toniollo et al. [35] when they incorporated Morse taper into the FEA model of the dental implant. The stress level at the bone implant interface can be reduced by employing of angled abutment for occlusal loading [34]. Shigemitsu et al. [33] discovered that at neck area of an implant of the cortical bone the stress is significantly high. Achour et al. [1] compiled a modern notion of attaching a bio-elastomer between the crown of the skeleton and the abutment. It caused that the occlusive shock loads got reduced and the stress concentration at the bone implant interface reduced, which significantly enhanced the long term stability.

FEA has also proved to be extremely useful in research other than failure and stability analysis. Incoherent number, placement and design of the dental implants could not only be infelicitous, but also may result into tooth loss [8]. Chih-Ling Chang et al. [10] applied topology optimization in search of optimal material distribution and found that retaining the same biomechanical properties the volume of the implant can be reduced up to 17.9% compared to traditional bone, which is advantageous for bone growth due to space availability and enhancement of stability. However, designing dental implants using FEA for specific patient with a specific bone condition is yet to be carried out. So far, much importance has not been given in this aspect.

It is well understood that bone quality varies from patient to patient in wide range due the difference of bone mineral density [17], [29]. For example, Young's modulus of bone of an osteoporotic patient may vary up from 40 to 50% of that of normal bone. Hence, stiffness of the dental implant should be adjusted accordingly to achieve proper osseointegration against such large variation in bone quality, as loosening or failure of implants mostly depends on mechanical behavior of bone implant interface. Similar variation in bone quality exists in mandible bone for different patients.

The main objective of this study is to find out the optimum stiffness of a dental implant for a patient with a specific bone quality, which will generate ossieointegration friendly mechanical situation at bone implant interface. The stiffness of the implants was varied by introducing porosity at implant stem. From weak to stronger, five different categories of bone, with different mandible sizes were considered for analyses aimed at finding out the optimum size and stiffness of implant for respective bone quality. Strain generated at bone implant interface was considered as index for ossiointegration at bone implant interface.

## 2. Materials and methods

To execute the FEA study, first, the geometry of the mandible, natural molar tooth and dental implant were fetched into computer environment and corresponding material properties were embarked using specialized software. ANSYS Workbench 14.0, ANSYS Mechanical APDL 14.0 and Mimics 11.0 were used in modelling and 180 different FEA models were con-

Table 1. Various combination of implant diameter, length and porosity

| Implant | Length (mm) | Diameter (mm) | Pore Dia (mm) | | Elastic modulus (GPa) | Poisson's ratio |
|---|---|---|---|---|---|---|
| Solid<br>(0% porosity) | 9<br>10<br>11<br>12 | 4<br>5<br>6 | – | Molar Tooth<br>Enamel<br>Dentin<br>Cementum | 80<br>22<br>2.5 | 0.3<br>0.3<br>0.3 |
| Solid<br>(10% porosity) | 9<br>10<br>11<br>12 | 4<br>5<br>6 | 0.4–0.6 | Molar Tooth<br>Enamel<br>Dentin<br>Cementum | 80<br>22<br>2.5 | 0.3<br>0.3<br>0.3 |
| Hollow<br>(20% porosity) | 9<br>10<br>11<br>12 | 4<br>5<br>6 | 0.4–0.6 | Dental Implant<br>TiAl6V4 | 117 | 0.3 |

sidered in this analysis. Various combination of implant diameter, length and percentage of porosity were taken into account to prepare the implant models. Table 1 shows the list of different values of diameter, length and porosity taken under consideration (pitch: 0.7 mm) [16].

Nowadays, for intricate formations, Computer Tomography (CT) technology is a thriving and efficient technology for dental implant design [11]. 3D models of mandible were created from the DICOM data based on 120 set of computerized tomography (CT) scan data which allowed for the individual scan to be processed in Mimics 11.0, and the final 3D solidmodel of mandible was created. Then, the scanned 3D models were imported in ANSYS Workbench 14.0 as .IGES files. In order to assess material property (i.e., density and Young's modulus) of mandible, the element and node file of the mandible bone were imported in Mimics with the help of PREP7 file and, material property was assigned [22] using equation 1 where HU is the Hounsfield unit.

$$\begin{gathered} \rho = 0.000769\text{HU} + 1.028 \\ E = 2349\rho^{2.15} \end{gathered} \tag{1}$$

3D models of molar tooth were hatched primarily using computer tomography (CT) images, digital edge detection technique and computer aided design (CAD) methods (Fig. 1c). The periodontal ligament (PDL) represented considerably small volume of 0.2 mm of the molar tooth system and was assimilated into the volume of the alveolar bone. Those were imported into ANSYS in .IGES format afterwards and the material properties of natural molar tooth were assigned. Indeed there is very little data concerning muscular action during mastication in literatures. In this study, both condyle head zones of the mandible were considered motionless, i.e., fixed. Masseters muscles were modeled as a truss element and considered at proper anatomical zone. Temporal muscles and medial pterygoid muscles were modeled as membrane elements. Muscular action was simulated by contraction of this elements. [13]. Then, those were placed within our region of interest, i.e., the molar region of the mandible (Fig. 2a) and stress and strain exhibited in the interface zone under loaded condition were duly studied.

At the next stage, 3D models of dental implants with different combination of dimensions (e.g., dx1Lx2, d4L10, d5L9, d6L12 etc., where d – diameter, x1 – the magnitude of diameter, L – length of the implant and x2 – magnitude of length of the implant) and porosity (e.g., solid, 10% porosity, 20% porosity) (Figs. 1a, 1b) were constructed 180 such different models were developed. Every single implant was inserted into the very location in the molar region where, previously, the natural molar tooth was established. After placing the implant in molar position of mandible bone, they were meshed with solid 187 elements in ANSYS workbench (Fig. 2b) and the element and node file were transferred into ANSYS Mechanical APDL as a .DAT file. The material property (i.e., Young's Modulus) of titanium alloy (Ti6Al4V) was assigned for implant. In line with the last approach, the interface stress and strain were observed and compared with the set of data obtained for natural molar tooth.

During the analysis, it was assumed that the materials were linearly elastic in nature for both mandible and implant. Based on post tooth extraction bone resorption and other factors, five different

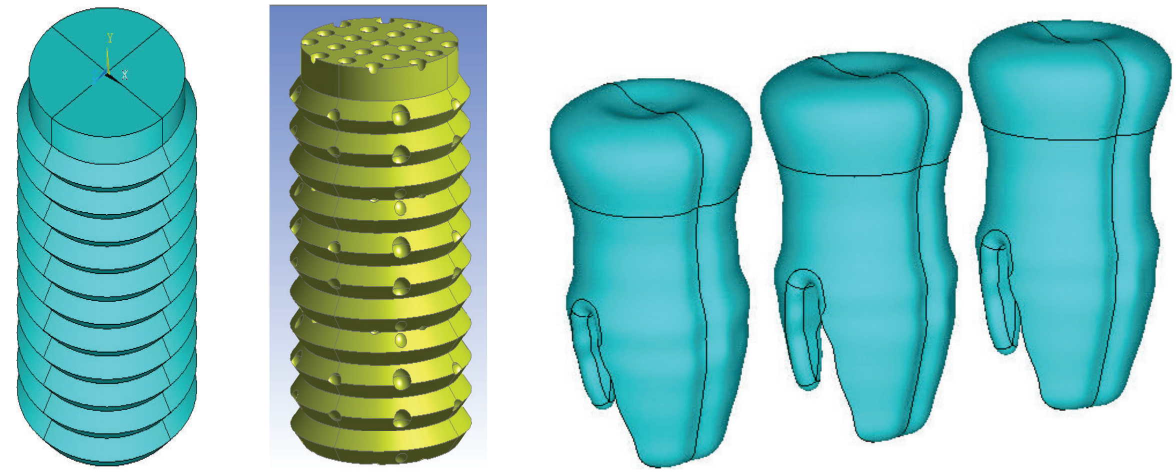
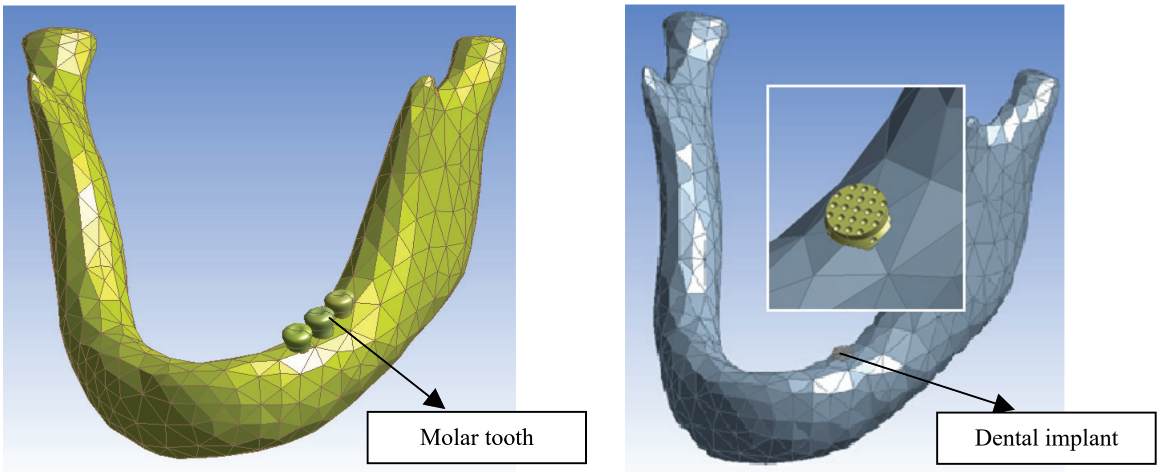

(a) Solid dental implant (b) Porous dental implant (c) Natural molar tooth

Fig. 1. 3D CAD models of Natural molar tooth and different dental implants



(a) with molar tooth (b) with implant

Fig. 2. Model of mandible

bone conditions were considered [30]. Eighty Nine (89) set of CT scan data were collected and analyzed in MIMICS software for calculating the Young's modulus which depends on Hounsfield Unit (HUs). The average bone density is found to be varying which results into about 22% variation of Young's modulus to either side of mean value [3]. The one having average bone density neighboring the mean is normal. Cases having bone densities nearing 10% and 20% higher than normal are considered strong and very strong respectively. Similarly, cases with 10% and 20% lower bone densities than normal are termed as weak and very weak. Mandibles with very strong, strong, normal, weak and very weak bone conditions were assigned. Calculation of young's modulus of each pixel point of CT image data can be done as the youngs modulus value was calculated from intensity value (HU unit) of the pixel of CT scan image slice data. For the very strong bone calculated average young modulus value for all the pixels of cancelous bone are about 4.369 GPa. These data can be obtained directly from image processing software, i.e., MIMICS. This way, for strong, normal, week and very week bone the average Young's modulus are 3.745, 3.121, 2.497 and 1.872 GPa, respectively. We have assumed that, to simulate real clinical situations upper portion of the mandible was fixed for all five cases. Also, the interface between implant and bone was modelled as a continuous bond. Contact element was used with fully bonded condition. This implies ideal osseointegration, without any relative motion at the interface. In other words, the implant was rigidly anchored in the bone, showing a fixed and the same type of bond at all prosthesis material interfaces.

# 3. Results

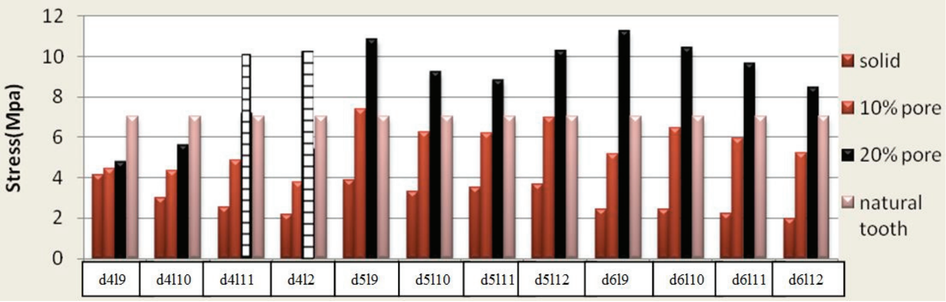
In the simulated model of natural and implanted mandible, loads and boundary conditions, similar to the previous work [8] have been applied. Stress and strain results observed in our model are very close to those reported literature. Maximum difference of 5% to 6% is observed at implant and places adjacent to the implanted bone.

At first, 250 N static load [31], corresponding to maximum biting force had been applied onto each of the simulated models of dental implants for natural bone condition and it was observed whether the implants were managed to endure. Respective Von Mises stress contours are shown in Fig. 8a, 8b. Maximum stress for implant under different bone conditions is 749.84 MPa, which occurs in d4L12 (20% porous) implant, which is lower than compressive yield value (970 MPa) of implant material (Ti6Al4V). Only in few cases (d4L11 and d4L12 (20% porous)), the stress generated at implants went beyond the permissible limit (≈ 647 MPa) which is 66.67% of yield stress of Ti6Al4V alloy (In other words, factor of safety = 1.5). Those failed implants were rejected.

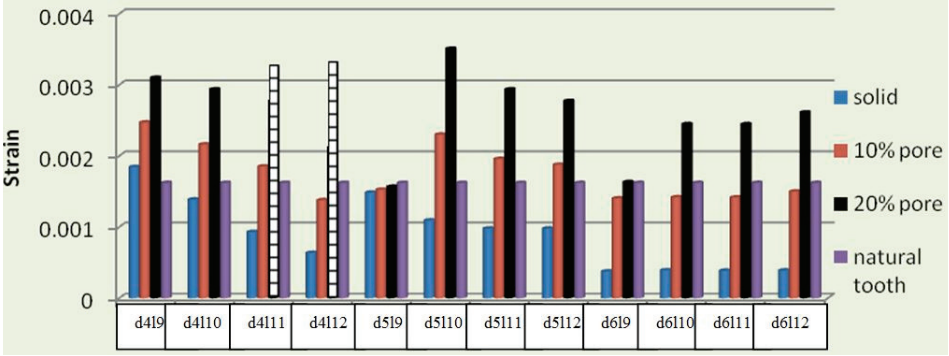
In the rest of the implants 120 N load [16], corresponding to common loading for chewing, had been applied for bone of five different conditions to understand the prospect of bone remodelling in each case, which will assure higher degree of osseointegration in the long run.

The model of mandible with natural molar tooth and with implants of different diameter (4, 5, 6 mm) and length (9, 10, 11, 12 mm) [23] were loaded vertically with 120 N. Load was applied on the crown of natural molar tooth and implants. After application of load, the solutions of each model has been compared accenting maximum implant stress, implant-bone interface strain and stress in cancellous bone area.

Implant strain is one of the most important key factors in the design of dental implants [18]. Von Mises criterion is considered for calculating maximum stress and maximum strain, measured at the adjacent bone.

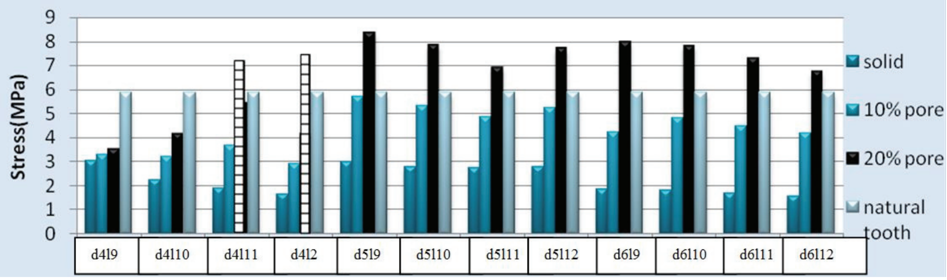


(a) Interface Stress

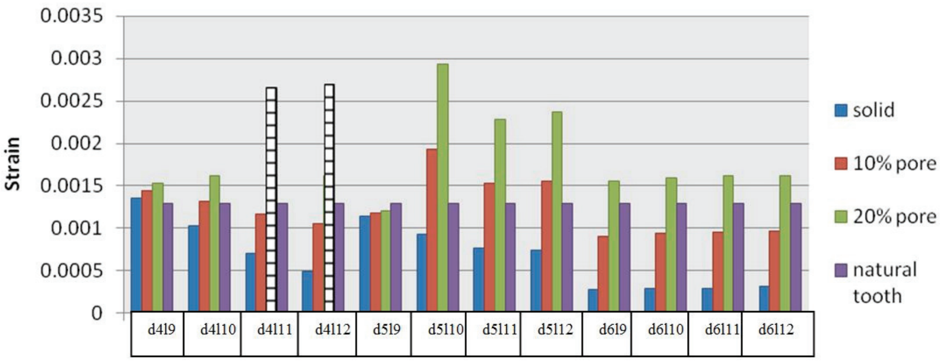


(b) Interface Strain

Fig. 3. Comparison of values of Interface Stress and Interface Strain of implants with different diameter and length for very weak bone condition

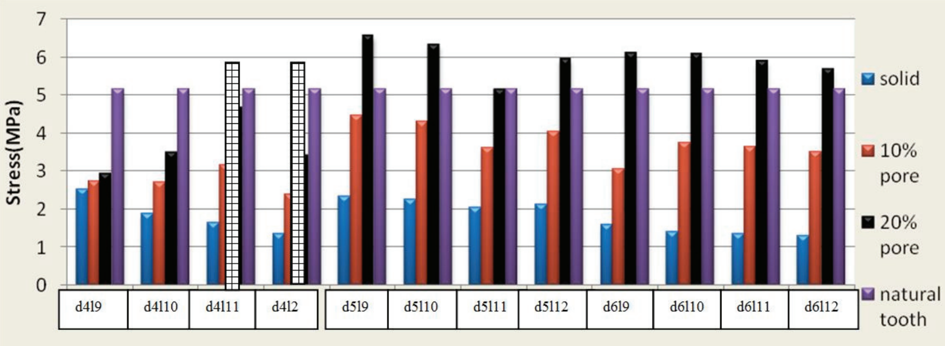


(a) Interface Stress

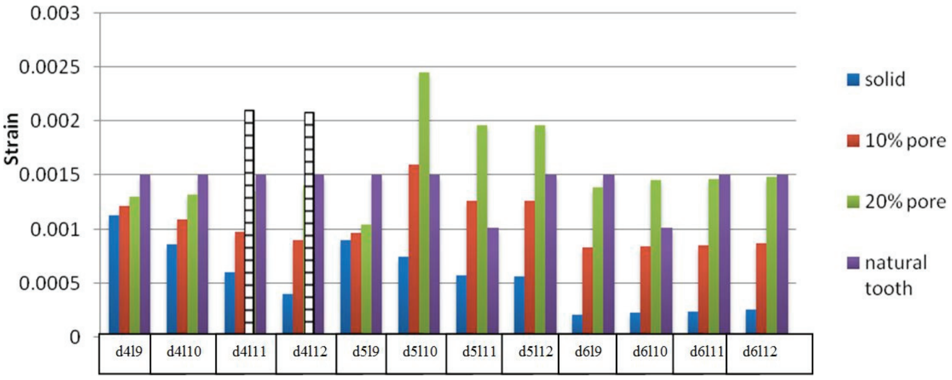


(b) Interface Strain

Fig. 4. Comparison of values of Interface Stress and Interface Strain of implants with different diameter and length for weak bone condition

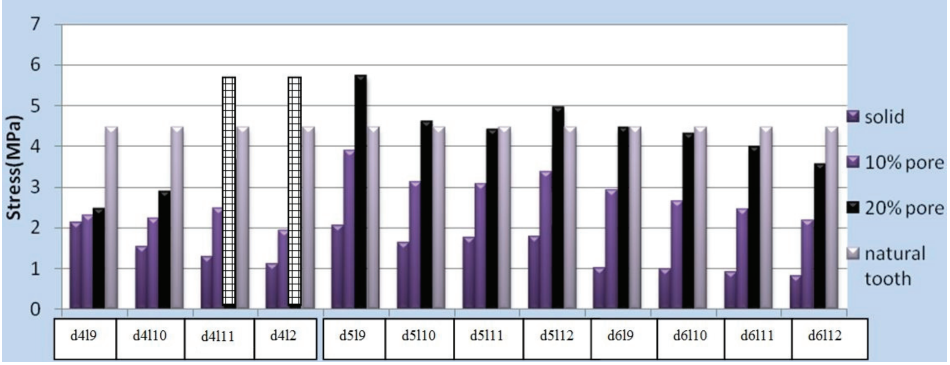


(a) Interface Stress

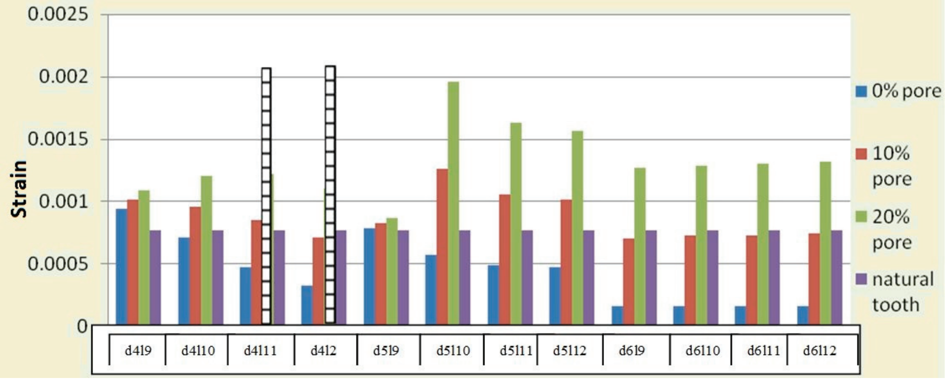


(b) Interface Strain

Fig. 5. Comparison of values of Interface Stress and Interface Strain of implants with different diameter and length for normal bone condition



(a) Interface Stress

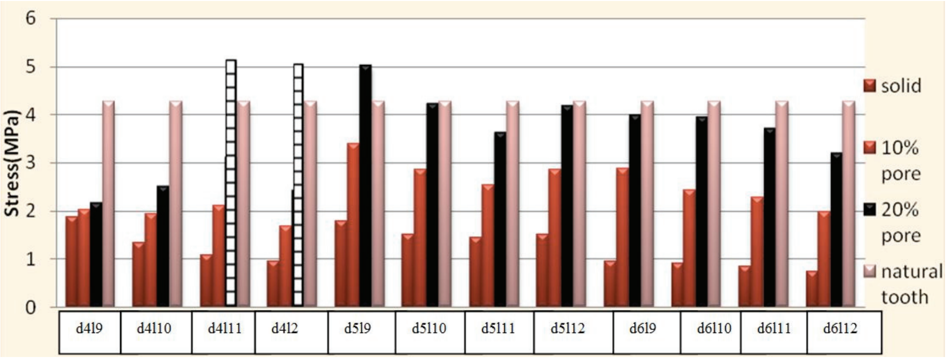


(b) Interface Strain

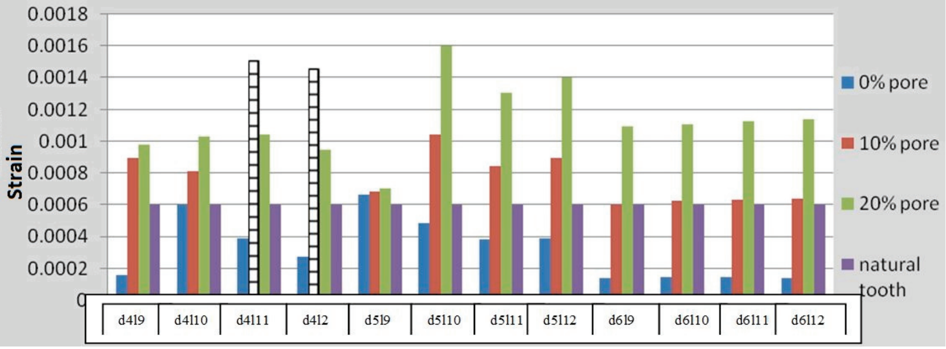
Fig. 6. Comparison of values of Interface Stress and Interface Strain of implants with different diameter and length for strong bone condition

The results, shown in Fig. 3a and 3b are obtained for very weak bone condition under 120 N vertical load. Maximum interface stress, developed in d6L9 (20% porous) implant was 11.28 MPa, whereas, in the case of natural molar tooth, it turned out to be 7.05 MPa. The d5L10 (20% porous) implant exhibits the highest interface strain of 3509 microstrain, compared to 1622 microstrain in the case of natural molar tooth.

Figure 4a and 4b represent the distribution of interface stress and strain under 120 N vertical load for weak bone condition. It is noticed that maximum Von Mises stress of 8.37 MPa is developed in d5L9 (20% porous) implant, while in natural molar tooth 5.875 MPa stress is generated. Maximum interface strain of 2938 microstrain is observed in d5L10 (20% porous) implant compared to 1289 microstrain in natural molar tooth.

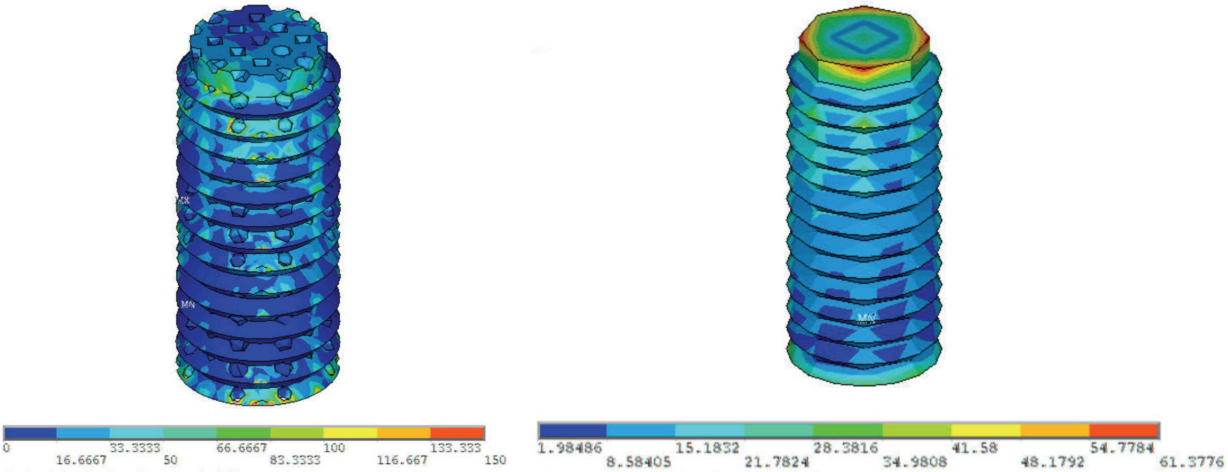


(a) Interface Stress



(b) Interface Strain

Fig. 7. Comparison of values of Interface Stress and Interface Strain of implants with different diameter and length for very strong bone condition



(a) Porous Model (b) Solid Model

Fig. 8. Von Mises stress contour for solid and 20% porous, d4L11 implant under 250N load

For normal bone condition, maximum stress is 6.58 MPa in d5L9 20% porous implant and maximum strain is found to be 2448 microstrain in d5L10 20% porous implant. Corresponding stress and strain in natural molar tooth are 5.17 MPa and 1458 microstrain, respectively (Fig. 5a and 5b).

d5L9 20% implant exhibits maximum stress of 5.74 MPa (Fig. 6a) and maximum 1958 microstrain (Fig. 6b) is developed in d5L10 20% implant for strong bone condition. For natural molar tooth maximum stress is equal s 4.465 MPa and microstrain to 767.

Finally, for very strong bone condition, the maximum stress of 5 MPa is observed in d5L9 20% implant and maximum 1599 microstrain is found in d5L10 20% implant (Fig. 7a and 7b). Von Mises stress and strain in natural molar tooth are 4.2 MPa and 604 microstrain, respectively.

## 4. Discussion

A common biting force of 120 N was applied to the numerical model and the stress and strain distribution in different dental implants were studied for bones of five different conditions for the prospect of better bone remodelling and osseointegration.

The stress and strain contour of bone adjacent to the osteointregated dental prosthesis were influenced by a number of biomechanical parameters which include implant screw geometry, materials properties of the prosthesis, type of loading , the quality of the surrounding bone and the condition of bone implant interface [2], [6], [19], [24].

For the design of dental implants, a number of simulations have been carried out considering different screw parameters, loading parameters, coating parameters, material parameters etc. [12], [21]. But little literature have been found where the bone conditions of the patients were considered as principal parameters.

Some studies have highlighted the importance of variety of conditions of the patients' bones for the patient specific design of dental implant. According to our literature review, the analyses considering the bone conditions as a basic parameter with proper thread geometry and pore parameters of implants have not been carried out so far.

In regard to stability, dental implant exhibiting lesser implant stress should be selected. As far as remodelling is concerned, when implant strain lies within 1500–3000 microstrain range [5] the damaged bone can be repaired by bone remodelling activity at a balanced rate. For very weak bone condition, d4L9 solid implant, d5L9 solid and 10% porous implants have lower stress and approximately 1500 microstrain. There are other options of dental implants with higher strain value (and within 3000 microstrain). If the bone condition is very weak, selection of those implants may results in failure of the mandibular bone. Similarly, for weak bone condition, d4L9, d4L10, d6L9, d6L10, d6L11, d6L12 with 20% porosity and d5L10, d5L11 and d5L12 with 10% porosity would be good selections. Implant having d5L10 with 20% porosity was rejected because of the mandibular bone failure concern. For normal bone condition, all solid implants and d5L10 with 10% porosity, d5L11 and d5L12 with 20% porosity are appropriate selections. For strong bone condition, d5L10, d5L11 and d5L12 implant with 10% and 20% porosity and for very strong bone condition, d6L9-L12 with 20% porosity and d5L10, d5L11, d5L12 with 20% porosity will be precise selections. Implants with higher strain values are selected for strong and very strong bone condition as they can withstand higher strain.

For even better bone remodelling, better tissue growth around the implant and improved degree of osseointegration, porous implants should be used instead of solid implants, like d5L10 with 10% porosity, d5L11 and d5L12 with 20% porosity, etc. Better osseointegration may be achieved in different ways, such as surface treatment using different coating materials, etc. However, this study has been focused on improving the osseointegration by varying the stiffness of implant corresponding to the patient's bone quality.

Since the bone quality of edentulous patients vary within a wide range, it is quite unlikely that it will be close to one of the five bone conditions that we have considered here. So, the selection of a dental implant for a patient having bone quality in between these five pre-assigned bone qualities can be performed in different ways, which is open for future work.

It is observed that the results obtained from our study (von Mises stress and strain) at implant bone and bone implant interfaces are very much close (within +/–20%) to the previous research work [4], [7], [9], [20], [21], [28], [32].

Our study is very similar to the study of Demenco [14] for solid implants cases but that study has not considered the thread part of the screw properly. All stress levels obtained in our study were higher than the former one by about 20% when the stress concentrates at the apex of the thread. This study has depicted that in the case of solid implant, increase in diameter of the implant has greater impact in stress reduction where the length has lesser for all type of bone qualities.

In the present study porous implants have been considered, which as opposed, to other researchers, so the results obtained can not be validated with previous studies but the expected outcome has been observed.

Bone quality should be considered as one of the most important factor such as planning and selection of dental implants. In most of the cases, implant longevity is more dependent on bone density that arc location [26]. Proposing the approach of modification of treatment plans and designing protocol of implants based on bone density was aimed in this study to help the clinician to achieve good success rate for all bone conditions. The correlation of bone density and implant dimension to the elastic module of bone tissue is taken into account by the algorithm to calculate ultimate occasional load. Though the calculation methods were previously developed for strong cortical bone and high dense travecular bone [14] an attempt is made in the present work to study the effect of bone density on the level of ultimate occasional load for a wide range implant dimension using the same algorithm.

Material properties have been assigned for the bone according to the Hounsfield unit value of pixels achieved from CT scan data so they vary for each and every finite element in the model. But the stress strain ratio of bone have been considered as linear elastic.

A bone is viscoelastic and highly non-linear after a certain limit. In near future non-linearity can be included [38] for designing an implant and to observe the mechanical response at bone implant interface, many simulations have been done.

# 5. Conclusions

From the results it can be observed that both interface stress and strain increase along with the increase in porosity percentage and this is valid for all types of bone conditions, but, in the case of natural molar tooth, the Von Mises stress and strain are always lower than the maximum stress and strain for each of the bone condition. Even though, stress is high for a few implants for a bone of particular condition, but all stress values are permissible for the mandible.

A list of suggestions of dental implants for specific mandibular bone quality from the mechanical response of the dental implants, simulated under common biting force (120 N) is shown in Table 2.

Table 2. Implants selected for different bone condition
(S implies solid, % implies percentage of porosity)

| Bone condition | Average Young's Modulus (GPa) | Selected implant |
|---|---|---|
| Very Weak | 1.872 | d4L9(S), d5L9 (20%) |
| Weak | 2.497 | d4L9, d4L10, d6L9, d6L10, d6L11, d6L9 (all 20%),<br>d5L10, d5L11, d5L12 (all 10%) |
| Normal | 3.121 | d5L10 (10%), d5L11 (20%), d5L12 (20%) |
| Strong | 3.745 | d5L10, d5L11, d5L12 (both 10% and 20%) |
| Very Strong | 4.369 | d5L10 (20%) |

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