Optimum Selection of the Dental Implants According to Length and Diameter Parameters by FE Method in the Anterior Position

Zeinab Arsalanloo, Reza Telchi, and Kambiz Ghaemi Osgouie

***Abstract*—Dental implants are used to retain and support fixed and removable dental prostheses. Over the past several decades, dental rehabilitation with implants has been widely accepted by dentists and patients because of its reliable functional and aesthetic results. In many clinical situations, local bone morphology requires dental implants that have a diameter that is significantly smaller than the typical implant diameters. In these cases, the fatigue life of the smaller diameter implants becomes a critical therapeutic parameter. According to particular situation of lateral incisor tooth, which has low space and also limited height due to the existence of the Sinus and Nerves in maxilla and mandible, respectively. Applications of various kinds of implants are being limited. This paper investigates the biomechanical behavior of a threaded dental implant/surrounding bone system under static and harmonic occlusal forces by using a three-dimensional finite element method for achieving the optimum diameter and length as the most effective parameters that are affected stress distribution in surrounding bones. The objective of this research was to select the optimum length and diameter for 26 different commercial dental implants by considering the variability in diameter and length and material of implants for missing upper/lower lateral incisor dental position by 3D finite element method. The influence of the length and diameter is considered after applying static, dynamic and fatigue loading for evaluation local/cycle failure probabilities in biodenta, CMI, DIO, implantium, and nobel implant systems. In this study, static dynamic and fatigue behaviors of the implants are investigated.**

***Index Terms*—Anterior mandible/maxilla, dental implant, finite element method, optimum diameter/length.**

I. Introduction

In general, the success of dental implants is being related to quality and quantity of local bones, implant designs, and surgical technique [1]. Some other factors are being influenced in implantation treatment, such as stress and strain characteristics, the material properties, implant surface definition, bone implant interface. Implant size also influences the area of possible retention in the bone; factors such as occlusion, masticatory force, the number of implants, and implant position within the prosthesis affect the forces acting on the bone adjacent to implants [2]. Therefore, implants diameter and length are accepted as key factors [3].

Manuscript received January 13, 2014; revised March 15, 2014.

Zeinab Arsalanloo is with the Mechanical Engineering Department Vali-e-Asr University of Rafsanjan, Iran (e-mail: pendar.soyleyin@yahoo.com).

Reza Telchi and Kambiz Ghaemi Osgouie are with the School of Engineering and Science, Sharif University of Technology, International Campus, Kish, Iran (e-mail: rezatelchi@gmail.com, osgouie@sharif.edu).

In some cases, anatomical considerations may exist that require either adjunctive treatment prior to implant placement or, the placement of irregular implants. Many attempts have been made to optimize the shape of dental implants. Most are focused on increasing the diameter and/or the length of the implant to increase the contact area between the bone and implant, and reducing the stress level in the bone. With appropriate selection, high success rates can be enjoyed for long, short, wide, and narrow implants, which were indicated.

Implant diameter is the dimension measured from the peak of the widest thread to the same point on the opposite side of the implant. It is considered more important than the implant length in the distribution of loads to the surrounding bone. At least 3.25 mm in diameter is required to ensure adequate implant strength and most implants are approximately 4 mm in diameter [4]. The increase in diameter will result in a higher percentage of bone contact by increasing the surface area of the implant. Implant diameters up to 7 mm are available but they are not so widely used since sufficient bone width is uncommonly encountered. Previous research, done by C. E. Misch *et al*. shows that increasing the diameter in a 3 mm implant by 1 mm increases the surface area by 35% over the same length in overall surface [5]. Another research, done by J. M. Mahon *et al*. shows that increasing the diameter of an implant results in a decrease in the abutment strain for a given load [6]. This means that an implant can obtain improved implant strength and resistance to fracture by appropriately increasing the diameter of implants. On the other hand, implant length is the dimension from the platform to the apex of implant. Most common lengths are between 8 and 13mm, which correspond quite closely to normal root length. It has been an axiom in the implant dentistry that longer implants guarantee better success rates even though there is no proven linear relationship between implant length and success rate of the implant [4]. Several mechanical analyses have supported the view that increasing the implant length may only increase success rate to a certain extent [7]. Short and long implants are now routinely placed with high success rate in institutional and private clinic settings. However, short implants offer a viable and successful alternative in patients who will otherwise require adjunctive treatment such as bone grafting prior to placement of a longer implant. This may also lead to greater case acceptance due to the treatment being less invasive, less expensive, and daunting for the patient. Nevertheless, normally, the use of short implants has not been recommended because it is believed that occlusal forces must be dissipated over a large implant surface area to prevent excessive stresses at the interface. In comparison between narrow and wide implants,

DOI: 10.7763/IJBBB.2014.V4.347

wider implants are being used when bone is scarce and the influence of diameter on bone-implant contact may not translate into a clinical advantage. From a biomechanical standpoint, the use of wider implants allows an engagement of a maximal amount of bone, and a theoretically improved distribution of stress in the surrounding bone. Nevertheless, the usefulness of small-diameter implants has to be discussed with an awareness of their potential limitations. Decreasing the diameter also means increasing the risk for implant fracture because of reduced mechanical stability and increasing the risk for overload [8]. As an example, lateral incisor is placed between central incisor and canine. Therefore has lake of space to replacing the implants. In this case, usually using narrow and long implant reduces the problem but due to the existence of alveolar nerve in the mandible and maxillary sinus in the maxilla, it cannot be available each time. Therefore, the wide and short implants provide the advantage of avoiding sinus and elevation lifting and extensive bone augmentation procedures in regions of limited bone height, potentially prevent the costs associated with bone grafting procedures. Therefore, the effects of implant diameter and length on stress distribution and implant stability in this region remain unclear. Thereby, by considering the advantages and disadvantages of short or long and wide or narrow implants, the ultimate goal of researches is being determined the optimum diameter and length parameters of implants. Usually for determination of the optimum parameters for implants, fatigue analysis by finite element method (FEM) is being used. The Finite Element Method (FEM) is an engineering numerical procedure used for analyzing structures, which allows investigate to assess stresses and strains within a solid body and investigating biomechanical interactions of different implant designs. This study has been directed to use the 3D Finite Element Method to analyze the stress distribution for the continuous variation of implant diameter and length to identify their optimal range in all quality bones from the perspective of biomechanics.

Chiapasco *et al*. proposed that it would be better to use implants more than 14 mm in length and more than 4 mm in diameter [9]. Researches by Himmlova *et al*., Plik ġolu *et al*. and Pierrisnard *et al*. [10]-[12] have all recognized the fact that the implant dimensions influence the magnitude and profile of stresses within the bone. It is commonly understood that increasing the implant length and/or diameter reduces the stresses within the bone. Furthermore, based on clinical experience practitioners appreciate the fact that if the bone is weak and then a wider implant is required. Larger implants were usually preferred as they may give better primary implant anchorage and final success. Pierrisnard *et al*. [12] found in their study that the stress to which implants were exposed increased as the length of the implant increased (range, 6 to 12 mm) while the maximum bone stress was found to be almost constant. Study of C. S. Petrie *et al*. [13] came to the conclusion that strain near crestal bone area reduces nearly by 300% due to increase in diameter as compared to the 165% reduction due to increase in length of implant. Therefore, comparatively larger diameter of implant design is preferred. Gerami *et al*. conducted a finite element analysis comparing displacement of a standard diameter and a wide diameter implant under an occlusal load applied at the disto-buccal cusp tip, and concluded that increasing the diameter of the implant will reduce both mesiodistal and buccolingual displacement of the implant system by approximately 50% [14]. Davarpanah *et al*. evaluated the resistance to fracture and depth of insertion of wide diameter implants versus standard diameter implants. They found that wider diameter implants demonstrate more resistance to fracture than standard implants because the supporting surface of the top area of implants with 5 mm diameter and 5 mm height is increased by 122% and 281% respectively, compared with standard implants. Consequently, implants with higher surface area distribute the occlusal forces more evenly [15].

According to above, in this study we want to investigate the effect of length and diameter of different implants by using CAD and FEM softwares. By considering the situation and condition of second tooth and due to exiting limitations in the anterior region, to achieve optimum diameter and length, and subsequently select the best implant system, we use finite element method analysis. Then, for more complete research process, the relations will be used to predict the fatigue life of the implant. To predict the fatigue life of 34 different commercial dental implants by considering the variability in diameter and length and material of implants and bone quality for missing upper/lower lateral incisor dental position by 3D finite element method.

II. Methods and Materials

The study was realized by using the three dimensional finite element techniques, for achieving the optimum conditions in lateral incisor position. In this paper, implant systems studied comprised two types of Nobel (Nobel Biocare Management AG Switzerland), one type of Neo CMI Implant (NeoBiotech, Seoul, Korea), a kind of Implantium system (Implantium, Dentium, UK Ltd.), and a Biodenta Endosteal implant (Biodenta Swiss AG, Berneck, Switzerland). DIO implant system (DIO, Haeundae-gu, Korea) also is being used with two types of DIO-ProTem Series that consisted of mini-implants series.

The 26 different implant designs of these seven implants categories, used in this study cover the diameter range from 2 to 3.5 mm that these series of diameters called Narrow Platform series and some other with diameters smaller than 3 are called mini-implants. On the other wise, among these different implants, length range varies from 8 to 16.0 mm for upper/lower lateral incisor situation. Mandible section geometries in lateral incisor tooth position are 88.461 mm height, 48.514 mm width, and 10 mm thickness. In this position, the geometries of maxilla are 99.258 mm height, 60.495 mm width, and 10 mm thickness. Mandible and maxilla are involve cortical and cancelious. The cortical bone is outer layer of jaw. According to CBCT scans reports the thickness of this layer varies among the jawbone that in lateral incisor teeth position, the most thickness in mandible is 22.39 mm and the less is 4.36mm. In this condition for maxilla the most thickness of cortical is 9.25 mm and the less is 1.085 mm. Nevertheless, the average thickness of this layer in maxilla and mandible respectively is 7.02 mm and 10.31mm.

After modeling implant-abutment complex and bone, we apply different kinds of loads. To simulate the average masticator force in a natural loading on the implant, forces of

17.1 N, 114.6 N, and 23.4 N were applied respectively in lingual, axial, and mesiodistal directions [16]. In general, torque was generated by using two equal forces in magnitude, opposite in direction, applied to two opposite points on the diameter of the implant head. Therefore, in this paper, due to masticator forces and loads that caused by foods moving and also bruxism and clenching para-functional habits, we assume four components of torques that were applied in teeth and implants. Values of torques components [17] are showed in Table I.

TABLE I: TORQUES IN DIFFERENT DIRECTIONS

Direction	Min Value	Ave Value	Max Value
Axial	50 N.cm	—	100 N.cm
Lingual	100 N.cm	—	200 N.cm
Distal	100 N.cm	200 N.cm	300 N.cm
Occulasal (Cronal)	200 N.cm	400 N.cm	600 N.cm

These loads were applied on the top middle node of each implant-abutment assembly in the studied models but in different directions. These estimations about forces and torques were based on the assumption that an individual has three episodes of chewing per day, each 15 min in duration at a chewing rate of 60 cycles per minute (1 Hz). This is equivalent to 2700 chewing cycles per day. Due to the foods and liquids, a thermal load is being applied to teeth and implants where its range is between 60 C as hot temperature and 15 C as cold temperature [16]. Another thermal load that has been applied to teeth and implants caused by drilling process. In this period must be careful that the bone temperature cannot exceed to 47 C because upper temperature of 47 C endamage to the living bone tissue. The pre-load that every time is imposed to jaw bone is cause by human skull that its approximate weight is 16N. In addition, the swallowing pressure is applied to implants and teeth in cyclic form which values are showed in Table II.

TABLE II: SWALLOWING PRESSURE CYCLIC LOADS

	Each swallowing	Per hour	Total Pres
16 hr-awaking	5 Pascal	25 time	2000 Pa
8 hr-sleeping		10 time	400 Pa

Other kinds of loads are relative to implants preparation and installation processes that involve drilling and tightening loads. These loads are defined according to different implants systems surgical catalogs. Following the modeling and loading, working steps in post processing consist of: 1) Analysis 2) Interpretation of results both numerically and by color-coding. In this paper, a nonlinear and complex static, dynamic, thermal and fatigue analysis was perfumed. The implant-abutment configurations were analyzed by using the Finite Element Method. After FE analysis, stress distribution in the FE model comes in numerical values and in color-coding.

Material property as an effective parameter in FEA, greatly influence the stress and strain distribution in a structure. In this research, we assume that materials are linear elastic isotropic for Titanium alloys and isotropic for Cobalt-Chrome alloys. The implant, abutment, and abutment screw were all designed to be Titanium, Titanium-Aluminum-Vanadium (Ti-6Al-4V) and/or cobalt-chrome alloy that are changed among the different implant systems. The segregated properties of different components are illustrated in Table III.

TABLE III: MATERIAL OF DIFFERENT COMPONENTS OF IMPLANTS SYSTEMS

	CMI	Implantium	Biodenta	Nobel	DIO
Fixture	Ti	Ti-6Al-4V	Ti Gr. 4	Ti Gr. 4	Ti-C
Abutment	Ti	Ti-6Al-4V	Ti-6Al-4V	Ti Gr. 4	Ti-C
Screw	Ti	Ti	Ti-6Al-4V	Ti Gr. 4	-

For bone because of the porous structure, we used nonlinear isotropic properties. Two types of bone density were modeled by varying the elastic modulus of compact bone and cancellous bone (with high and low densities) to account for the effect of the bone behavior on the implant accurately. The fragmental mechanical properties of materials that have been used in this study are listed in below Table IV.

TABLE IV: MECHANICAL PROPERTIES OF IMPLANTS AND BONE

Material	Elastic Modulus	Shear Modulus	Tensile Strength	Density	Poisson Ratio
	(MPa)			(kg/m^3)	N/A
Ti Gr. 4	105000	45000	550	4510	0.37
Ti Gr. 4	105800	41023	827.37	4428.78	0.31
Ti	105000	45000	440	4500	0.37
Co-Cr	190000		1200	8290	0.3
Cortical	14000		7.82	1720	0.3
Cancellous	1370				0.3

After material properties were applied, a mesh 3-D finite element model was constructed. For meshing, we used ANSYS version 14.0 and Solidworks version 2011. The element in meshing all three-dimensional models is eight nodes Brick element (SOLID45), which has three degrees of freedom (translations in the global directions). The interface between implant and bone was modeled as an immovable and rigidly junction, which simulated the condition of the optimal implant osseointegration. For this purpose, "Fixed Geometry" option in the software was chosen. The bone and implants simulated models, which were meshed tetrahedron elements. Another relevant parameter in meshing is mesh density. In this paper, a finer mesh was generated around the implant.

TABLE V: LENGTH OF CATEGORIES IN TERMS OF IMPLANTS

Length	8	10	11.5	12	13	14	16
Biodenta	■	■		■		■	
CMI		■	■		■		
IMPLANTIUM	■	■		■		■	
Nobel Speedy		■	■		■		
Nobel Replaced	■	■	■		■		
DIO-Ball		■		■		■	■
DIO-Post		■		■		■	

Next in our reasearch, we peruse different implants of five implants systems that are choised. In length and diameter comparing, we considered different cases. In one case, we considered the implants that have equal lengths. In this case among the 26 implant with variable length we choose somewhat have equal length and classify implants with identical conditions in special category. By this comparing, we have six categories with lengths 8, 10, 11.5, 12, 13 and 14. These categories include at least two different implants. From the Table V we have shown the available categories.

In second case, we assume that diameters are equals. It this case we have just one category with 3.5 mm diameter that included "Biodenta, CMI, Nobel Speedy, and Nobel Replaced". Other narrow platform implant that is not placed in this category is IMPLANTIUM that has 3.4 mm diameter. In our research in addition to narrow platform implants, we investigate the mini-implants. In according to small diameter of the mini-implants, in this study, we want to investigate differences of them with narrow platform implants in their performance. The mini implants normally have diameters smaller than 3mm, so in this study our selected mini implants have 2 and 2.5 mm diameter of DIO implant system. In this study, after analyzing implants, we interpret of results both numerically and by color-coding.

III. Results and Discussion

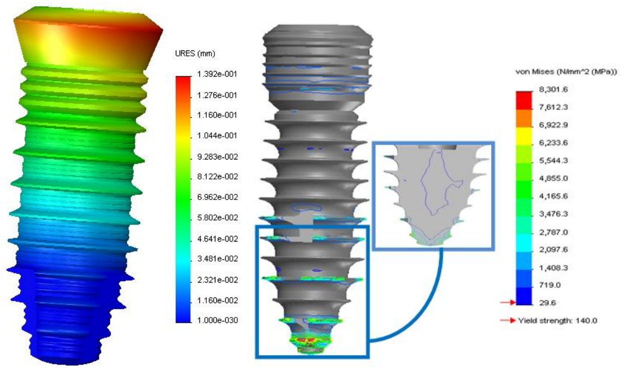

Fig. 1. Results of some implants simulations. a) Displacement with continuous fringe by URES criteria; b) Stress with line fringe show by von Mises criteria.

The success of dental implant depends on both endogenous and exogenous factors. Bone quality belongs to the endogenous factor, and implant design is among the exogenous factors. All these factors will significantly affect implant success rates [18]. In this study, the effect of implant diameter and length on the stress distribution in the lateral incisor position was investigated. In relation to this issue, it is noteworthy that due to placing the lateral incisor teeth between central incisor and canine teeth, there is always lake of space to replacing implants. In this case, usually using narrow and long implant reduces the problem but due to the existence of alveolar nerve in the mandible and maxillary sinus in the maxilla, it cannot be available each time. Therefore, the wide and short implants provide the advantage of avoiding sinus and elevation lifting and extensive bone augmentation procedures in regions of limited bone height, potentially prevent the costs associated with bone grafting procedures. Therefore, the effects of implant diameter and length on stress distribution and implant stability in this region remain unclear.

The purpose of this investigation was to provide an analysis among different geometric configurations of implants and to compare their biomechanical behaviors. Simulation results considered functioning implants, modeling crestal bone loss after a healing and loading period. These results have also highlighted the influence of implant length and diameter on load transfer mechanisms (Fig. 1). A comparison of the areas with maximum stress for implants of the same length but different diameters and also same diameters with different lengths showed distinct variances. The von Mises stress values for the models were compared with each other among 26 different models of five commercial implant systems to determine which length and diameter would best dissipate the stress caused by acting loads. In present study, according the color-coding, following points can be expressed according to Fig. 2.

Fig. 2. FEA Simulation result.

For small diameter implants, (narrow platform) increasing implants length can increase the stress in some points that are being exposed the most loads. In general, among the all models, three situations have more critical condition than others that are visible in above Fig. 2. The highest increased is related to self-tapping section that during implantation, due to the nature of cutting and forwarding of this section, it is predictable that increasing the length of implant also increases the amount of stress in this region. Another reason for highest stress values in self-tapping section can be stress concentration that is being created due to cuttings on fixture surface. In addition to self-tapping, the lowest thread on fixture is being exposed the highest loads. In some implants, the top of the fixture has a relatively high stress that it might because of the platform shapes and the type of connections between fixtures and abutments. In one-piece implants, the interfacial of threaded and non-treaded sections also has relatively high stresses. These following locations were identical for all implant lengths and diameters considered. Nevertheless, implants with larger diameters are more stable and others with smaller diameters can have better performance when increasing their length.

Except experimental articles that due to having enough time to passionately convey the planting process according to the physician faced with a variety of jaw bone of the patient and the physician in selecting the types of implants, in most conditions, theoretical papers have some restrictions that this issue cause to obtain various assumptions during FEA in various studies with quite different results. We tried to resolve these discrepancies. Therefore we have some innovations in this article. At first, it is noteworthy that checking out of lateral incisor issue of dental implants has been lacking in the debates so far. Our other innovations are:

1) Evaluation of the theoretical results is conformity with clinical studies.
2) Neglecting hundred percent osseointegration and imposed the micro-gap.
3) In most previous papers, just have been considered occlusal force, but in fact, other various loads are being affected on the implant that in this paper have been considered.
4) Because of the geometry complexities of the jaw in some papers, it is not being chosen the suitable elements for analysis. Nevertheless, in this paper, the number of elements and nodes is selected according to the optimum results.

and some others.

IV. Conclusions

Within the limitations of this study, numerical simulations showed that implant design, in terms of both implant diameter and length, crestal bone geometry and placement site affects the mechanisms of load transmission. Stress distribution pattern did not change from one implant to the other even with changing implant diameter or length in different implant systems, completely obvious. Based on the available data in this study, we can draw several conclusions:

1) In one-piece implants, interface of threaded and non-threaded portions are exposed high stresses.
2) In range of 3.4 and 3.5 diameters short implants have lower stresses, but with increasing the diameter.
3) In general, the strain rate is increased by increasing the diameter of the implant due to a higher stress on it.
4) On the other hand, increasing in implant diameter, are caused to decreasing the displacement.
5) The optimum length among the different lengths is ranged in 11.5-13 mm.
6) In used of diameters, the best results are achieved for 3.5mm diameter.
7) According to stresses and color-coding, shown that the Biodenta implant system has the best design. The others systems are IMPLANTIUM, Nobel Speedy, Nobel replaced, CMI, DIO Ball and DIO Post respectively.

Acknowledgment

The authors wish to express their deepest gratitude to Dr H. Mehdizade, Decedent Dr. H. Hamidi, Mr. D. Porafshar, Dr. Zeratiyan, Eng. Kazempour, Eng. Asakere, , Eng. Fathi and some others for their great helps and efforts.

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Z. Arsalanloo was born in Urmia of West Azerbayjan in 1988, and now she lives in Urmia. She studied agricultural machinery in Urmia University from 2007 to 2011. She earned her B.A. degree in agricultural machinery engineering (biotechnology engineering).

She is a MSc student of mechanical engineering (applied design) in the Faculty of Engineering, Vali-e-Asr University of Rafsanjan, Iran. She is working on dental implants. She has various papers that are accepted in several conferences and journals, such as ISME2013, ISBME, SJME, others. She also works in heat treatment and finite element analysis hence; she has a subscribed book with R. Telchi in title "Weld Molds Heat Treatment". Another book that she and R. Telchi are written is under the publishing with implants issue.

R. Telchi was born in Urmia of West Azerbayjan in 1988, and now he lives in Urmia. He studied agricultural machinery in Urmia University since 2005 to 2009. He earned his B.A. degree in agricultural machinery engineering (biotechnology engineering).

He is a M.Sc. student of mechanical engineering (applied design) at School of Engineering and Science, Sharif University of Technology, International Campus, Kish, Iran. He is working on dental implants. He has various papers that are accepted in several conferences and journals, such as ISME2013, ISBME, SJME, others. He also works in heat treatment and finite element analysis; hence, he has a subscribed book with Z. Arsalanloo in title "Weld Molds Heat Treatment". Another book that he and Z. Arsalanloo are written is under the publishing with implants issue.

K. G. Osgouie was born in Isfahan in 1977, and now he lives in Kish Island. He earned his B.A. M.Sc. and PhD degrees in mechanical engineering from Sharif University of Technology, Tehran, Iran.

He is the head of Mechatronics and Applied Design Groups, School of Engineering and Science, Sharif University of Technology International Campus, Kish Island, Iran, since 2009. He is an assistant professor of mechatronics and applied design mechanical engineering. He is working on various topics. Recently he works on dental implants too. He has various papers that accepted in various conferences and journals. He also works on robotics, artificial intelligence (genetic algorithms, neural networks, etc), advanced control, vibrations of continuous systems, optimal design in mechanical engineering, mechatronics, and composite materials.

Dr. Osgouie is are member of ASME, IEEE member. He is a reviewer of ASME/IEEE (USA), Robotica (Cambridge University Press, England), Scientia Iranica (Elsevier Science BV, Iran). He ranked 102 out of 210,000 students allover Iran in the National University Entrance Examination, 1995 and 21st out of over 3500 students allover Iran in the National Examination for Entrance in post graduate studies (M.Sc.), 1999.