# Load-carrying capacity of short implants in edentulous posterior maxilla: A finite element study

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## ARTICLE INFO

## ABSTRACT

Dental implant dimensions, and bone quality and quantity play a key role in early osseointegration and long-term prognosis in posterior edentulous maxilla. Treatment with short implants, preferably in a bi-cortical manner, is an accepted modality; however, short implants have limitations leading to increased stress concentrations in alveolar bone, potential overload and implant failure.

Implant models of 3.3, 4.1, 4.8 and 5.4 mm diameter and 4.5, 5.5, 6.5, 7.5 and 8.5 mm length were placed in posterior maxilla 3-D models with corresponding residual bone heights. Bone-implant assemblies were analyzed in finite element software ANSYS 15. All materials were assumed to be linearly elastic and isotropic. 118.2 N oblique loading was applied to investigate stress distributions in bone tissues. The concept of ultimate functional load (UFL) was selected as a criterion to compare load-carrying capacity of implants and to evaluate the influence of available bone height and implant dimensions on load-carrying capacity. For all implants, UFL was calculated by limiting von Mises stresses in cortical or cancellous bone with bone strength (100 MPa for cortical and 2 MPa for cancellous bone). Implant load-carrying capacity depends on diameter and available bone height. Wide implants have higher load-carrying capacity than narrow implants. Short implants with proper diameter and length avoid bone overstress, even in Type IV bone.

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## 1. Introduction

Dental implants effectively support prosthetic restorations in treatment of patients with edentulism [1,2]. Implantologists prefer to select the longest suitable implant; however, posterior maxilla usually offers insufficient bone height [3] and Type IV bone quality [4,5]. Furthermore, occlusal loads are significantly higher compared with those of the frontal area [6]. Surgical procedures to improve bone quality and quantity are a method of choice; however, they are associated with increased cost, additional surgical time, extra morbidity and healing time, and may increase the risk of complications [7].

In such challenging situations, placement of short implants provides a successful alternative [8]. There are several definitions of a short implant, including: "a device equal to or with less than 8 mm intrabony length" [9], "a device with a designed length of less than 10 mm" [10], and "6–7 mm length implants" [11]. Advantages of short implants include avoidance of additional surgery, easier

treatment planning, shorter treatment period, reduced chance of complications, and lower cost. [12,13]. However, short implants have smaller implant surface area, which reduces the contact area between bone and implant, and increases stresses and strains in alveolar bone.

Success rates of short implants have been intensively researched. Most of the older studies reported higher failure rates for short implants than for conventional implants. More recent reports indicated the overall success rate of short implants was similar to that of long implants, with rates up to 99.7% [14]. Such a discrepancy was likely caused by several factors, such as bone quality, implant primary stability, practitioner learning curve improvement, implant shape and surface advancement [9]. Unfortunately, there are only low levels of evidence in the literature, so relationships between bone quality, implant length and diameter, and survival rates are not determined. Therefore, biomechanical investigations may aid in establishing these interactions and indicate the conditions of short implant success.

Animal experiments [15] and clinical studies [16] have shown that in the absence of peri-implantitis, bone loss around implants was associated with unfavorable loading conditions. Mechanical overload [17] is considered a major factor of bone loss and implant

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failure. Overload can be activated by inadequate implant dimensions, bad occlusion, incorrect implant use, improper surgical placement and poor implant design [18,19]. Extremely high stress concentrations may therefore arise at the bone-implant interface [20,21]. The related strain fields would cause microdamage and bone failure [22]. These factors, including inadequate bone volume and quality [23], complicate the in vivo investigation of biomechanical factors related to implant failure.

Finite element (FE) analysis is a well-recognized method in simulating stress and strain fields around the bone-implant interface. Applying this method has shown that stresses and strains are affected by several biomechanical factors: type of loading, implant and bone mechanical properties, implant dimensions, bone quality and quantity, and the nature of the bone-implant interface [20,24,25]. Stress distributions in the bone-implant interface in posterior maxilla have been extensively studied [21,26–33]. These stresses were directly dependent on the height of the maxillary bone, bone quality and implant diameter.

Efforts to minimize crestal bone loss by increasing the area of bone-implant contact, and thus reducing stresses in the alveolar crest, focused on increasing the diameter and/or length of the implant [23,24]. Finding the optimal relationship between implant dimensions and stress distribution at the bone-implant interface is a challenge [19,29]. Stresses around successful implants should be limited by the ultimate strength of the bone [34], thus preventing bone overload, risk of bone loss and implant failure [18].

Implant success is predicted by correlating calculated stresses in bone under functional loading with experimentally determined bone ultimate strength. The methodology interrelating functional load, implant dimensions and adjacent bone stresses was proposed to compare load-carrying capacity of different-sized implants and predict their success [20,35]. Applying this approach to short implants in posterior maxilla with Type IV bone, where implant diameter, bone height and quality are essential factors influencing implant longevity, enables correlation of ultimate functional load (UFL) for particular implant with experimentally determined values [36] to evaluate load-carrying capacity and failure prognosis.

Finally, bone stress analysis at the bone-implant interface and implant longevity prognosis are of utmost importance in short implant research. The aim of this study was to evaluate the influence of available bone height and implant dimensions on load-carrying capacity of dental implants placed in edentulous posterior maxilla with poor bone quality to aid practitioners in implant selection.

## 2. Materials and methods

It was assumed that a short implant from the range of 3.3, 4.1, 4.8, 5.4 mm diameter and 4.5, 5.5, 6.5, 7.5, 8.5 mm length was placed bicortically in the maxillary first molar area. As a reference, 14.5 mm conventional implants with the same diameters were selected. Six posterior edentulous maxilla 3D models with Type IV bone quality were developed with corresponding residual bone height. Models height, mesiodistal length and buccolingual width were adjusted to 15, 30 and 10 mm, respectively. Cortical bone
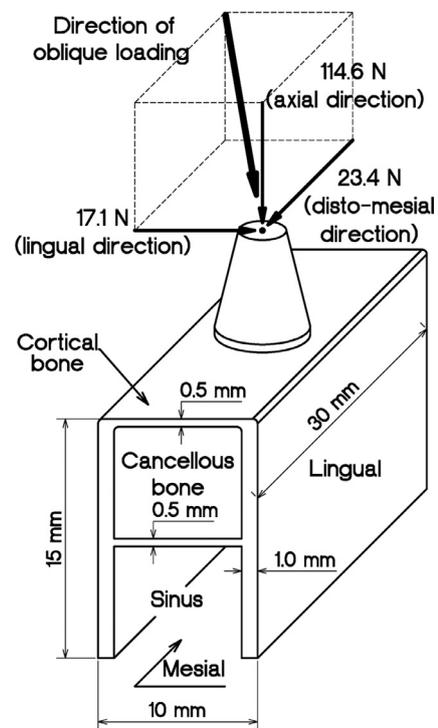


**Fig. 1.** Maxillary bone segment with cancellous bone of different thickness under oblique loading applied to the center of implant abutment upper surface at a distance of 4.5 mm from the bone margin.

thickness of alveolar crest and sinus floor was 0.5 mm. Buccal and lingual cortical bone walls were 1 mm wide. Cancellous bone thickness was 3.5, 4.5, 5.5, 6.5, 7.5 and 13.5 mm (Fig. 1).

3-D models were analyzed in FE software ANSYS 15 (ANSYS, Inc., Canonsburg, PA, USA). 20-node SOLID186 FE that exhibits quadratic displacement behavior was selected for this study. SOLID186 is a higher order 3-D 20-node solid element, which is defined by 20 nodes having three degrees of freedom per node: translations in the nodal *x, y*, and *z* cartesian directions. FEs were generated with their total number up to 2,920,000, and mapped meshing was applied in the bone-implant interface (Figs. 2, 3). Minimal mesh size was set to 0.05 mm. It was selected under the results of the convergence test and the convergence criterion was set to be less than 5% changes of the highest von Mises stress of bone between the FE sizes. The polynomial extrapolation procedure was applied to increase the accuracy of von Mises stresses calculation at the bone-implant interface.

All materials were assumed to be linearly elastic and isotropic and all material volumes were considered homogenous. Implants and abutments were assumed to be of titanium alloy with 114 GPa elasticity modulus and 0.34 Poisson's ratio [34]. Poisson's ratio of bone tissues was 0.3. Cortical bone was considered to have 13.7 GPa elasticity modulus [18] while cancellous bone had only
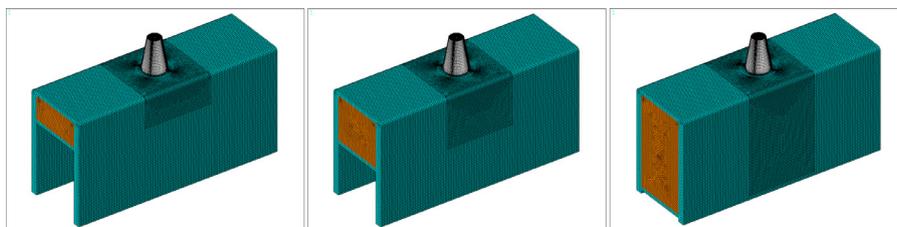


**Fig. 2.** 3D FE models of maxillary bone segments with 4.5 (left), 7.5 (middle) and 14.5 mm (right) bone height and 3.3 mm diameter implants. Total number of FEs was up to 2,920,000.
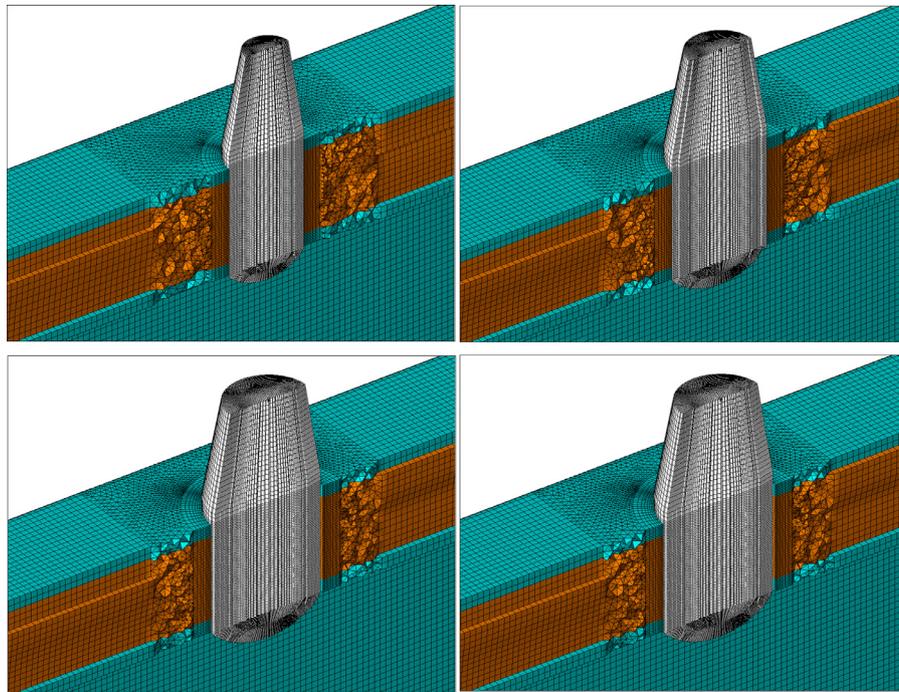
**Fig. 3.** 3D FE models of maxillary bone segments with 4.5 mm bone height and 3.3 (top left), 4.1 (top right), 4.8 (bottom left) and 5.4 (bottom right) mm diameter implants. Minimal value of FE size is 0.05 mm.

0.69 GPa [23]. The ultimate tension strength of cortical and cancellous bone was 100 MPa and 2 MPa, respectively.

Mesial and distal faces of each model were restrained. Loading of implants at the center of 4.5 mm abutment, in 3D, with 17.1, 114.6 and 23.4 N forces in lingual, axial and mesiodistal directions, respectively, simulated 118.2 N functional loading in oblique direction [37].

Critical von Mises stress distributions in peri-implant bone were evaluated to calculate maximal stress magnitudes for six bone-implant assemblies. UFL methodology was developed taking into account the linear relationship between functional loading and peak values of von Mises stress [20]. UFL magnitudes were computed for each implant and used to assess the influence of bone height and implant dimensions on implant load-carrying capacity.

## 3. Results

Areas of high stress concentrations were found in cortical and cancellous bone for each bone-implant assembly. Fig. 4 shows six bone-implant assemblies with 3.3 and 5.4 mm implant diameter and 3.5, 7.5 and 13.5 mm cancellous bone thickness. Von Mises stress distributions were studied in the plane of critical bone-implant contact (Fig. 4, right). They are illustrated in Fig. 5 for tested 4.5 mm length implants. It was determined that the neck area was critical for crestal cortical bone. Also, the midsection of the cancellous layer was found to be potentially critical because of significantly lower cancellous bone strength. Therefore, maximal von Mises stresses were calculated in both tissues. UFL for each implant was calculated by proportional correlation of maximal von Mises stresses in cortical and cancellous bone under 118.2 N functional loading with 100 MPa and 2 MPa tension strength of cortical and cancellous bone under UFL. Load-carrying capacity of the spectrum of implants was shown to be limited by cancellous bone because of its poor density and low strength.

The results showed that implant load-carrying capacity was dependent on its diameter and available bone thickness. The UFL increase for the largest implant (5.4 × 8.5 mm) was 2.5-fold greater than that for the smallest implant (3.3 × 4.5 mm). UFL dependence on cancellous bone thickness may be assumed to be linear for all short implants (Fig. 6). A two-fold increase in cancellous bone thickness corresponded to a 40% increase in UFL for a 3.3 mm diameter implant, and 35%, 34% and 32% for 4.1, 4.8 and 5.4 mm diameter implants, respectively.

The dependence of UFL on implant diameter is illustrated in Fig. 7. An increase in implant diameter from 3.3 to 5.4 mm caused UFL to change from 83% for a 4.5 mm length implant to 73% for an 8.5 mm length implant.

To evaluate short implants load-carrying capacity relative to conventional implants, UFL reduction was studied. For 4.5, 5.5, 6.5, 7.5 and 8.5 mm implants, it was within the range 53–54, 48–50, 43–46, 38–42 and 32–37%, respectively.

Under 275 N experimental maximum functional load on the molars [36], only a 5.4 × 8.5 mm implant can withstand such a load without cancellous bone overstress. However, under 120.9 N experimental mean maximal functional load, all implants from the spectrum, excluding the smallest, would be acceptable.

Load-carrying capacity of short implants is significantly dependent on cancellous bone strength (density). Assuming a hypothetical 2.5-fold increase of cancellous bone strength (from 2 to 5 MPa), UFL would increase by 75% for all implant diameter and bone thickness values (Fig. 8).

## 4. Discussion

Mathematical modeling is often applied to study the function of living tissues and predict their lifetime. Unfortunately, analytical methods are powerless to evaluate the mechanical state of such complex objects with unique shape and heterogeneous structure. As a result, only a few biomechanical problems have been solved.

The era of numerical solutions in the biomechanics of dental structures started more than 40 years ago. FE analysis has become a widespread method in biomechanics because of the complexity of in vivo investigation of living hard tissues behavior under functional loading. As posterior maxilla remains the most challenging
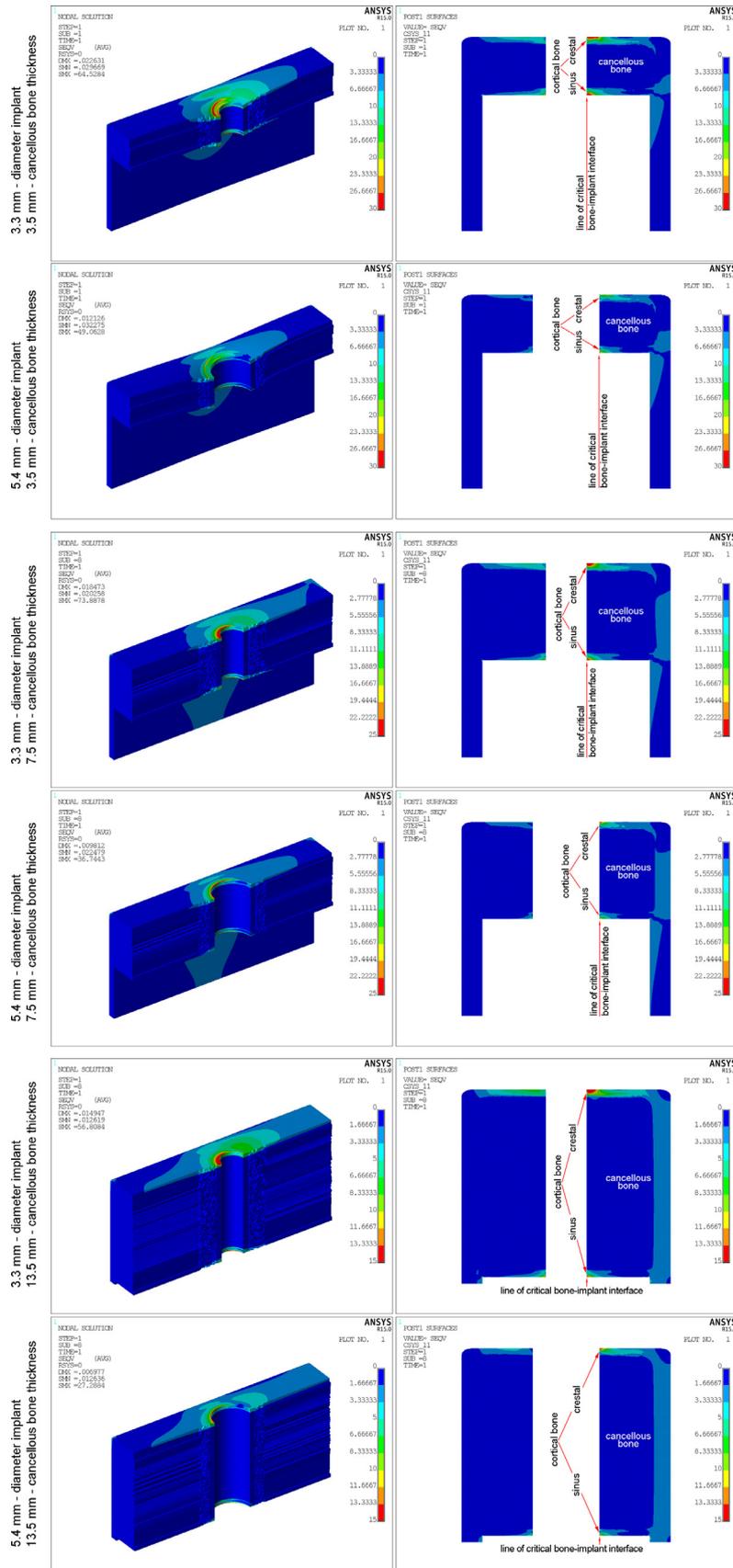
**Fig. 4.** Areas of von Mises stress concentrations in cortical bone for four bone-implant assemblies with 3.3 and 5.4 mm implant diameter and 3.5, 7.5 and 13.5 mm cancellous bone thickness in longitudinal (left) and oblique (right) cross sections.
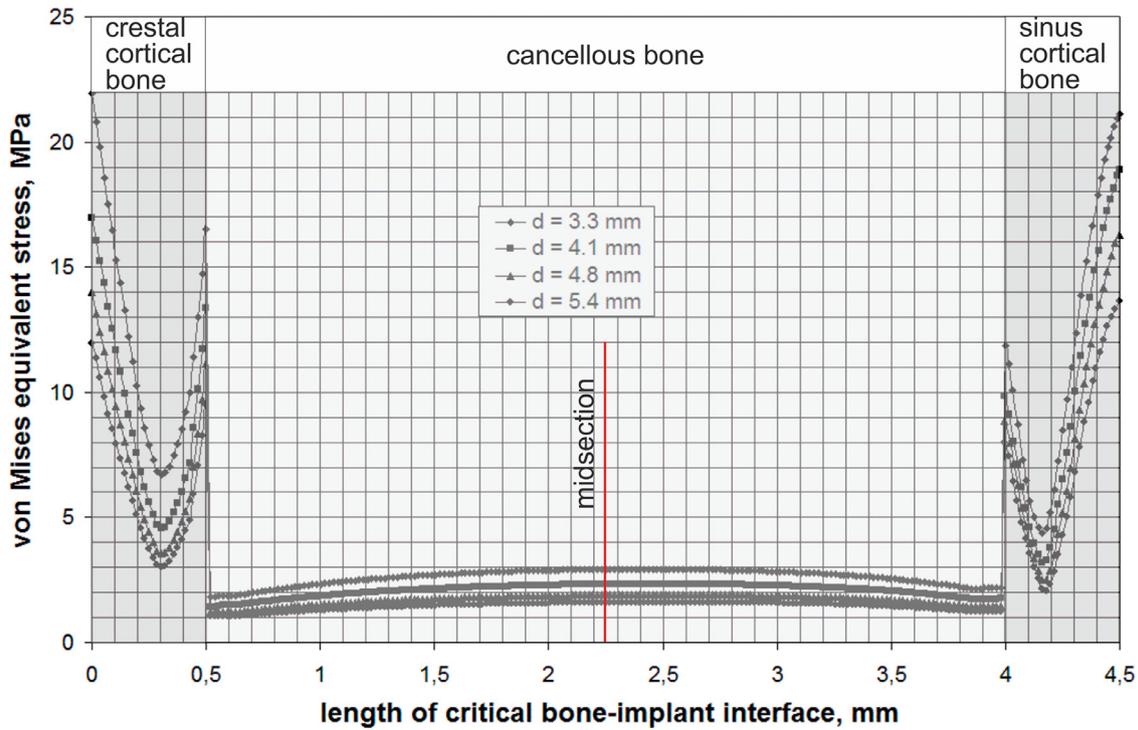
**Fig. 5.** Von Mises stress distributions in the plane of critical bone-implant interface for 4.5 mm length implants.
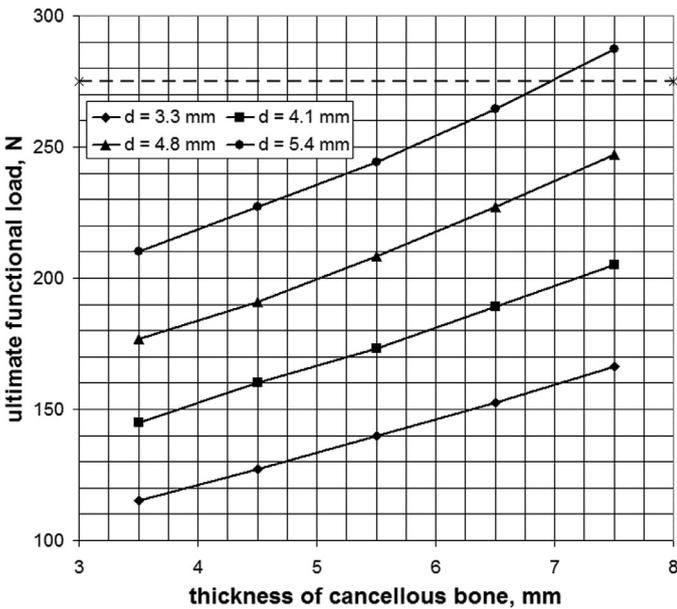


**Fig. 6.** Ultimate functional load (UFL) dependence on cancellous bone thickness within the range 3.5–7.5 mm for tested implants.
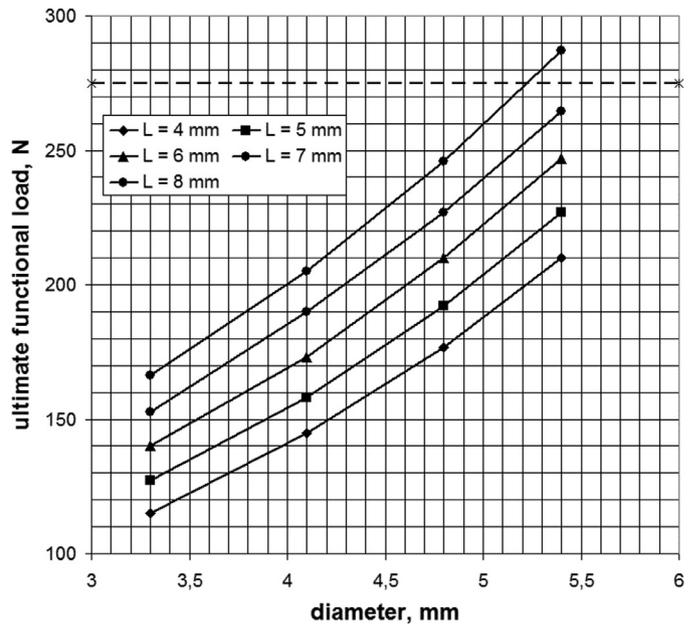


**Fig. 7.** Ultimate functional load (UFL) dependence on implant diameter within the range 3.3–5.4 mm for tested implants.

site for dental implant placement, it was selected for biomechanical analysis of bone-implant system functioning.

Adequate residual bone volume has been repeatedly suggested to be an important prerequisite for achieving long-term service of implant-supported restoration [38], which is often unfulfilled in the posterior maxilla. Implant dimensions are among the most critical factors for attaining high success rate [19,39–42].

Increased implant diameter has been shown in many studies to significantly reduce stresses in cortical and cancellous bone [24,27,32]. Furthermore, short implant diameter has been shown to be more important than length in influencing survival rate

[30,31,43]. This is supported by our study where maximum von Mises stresses in cortical bone were reduced by 47–49% with wide compared with narrow short implants. In addition, maximum von Mises stresses in cancellous bone were reduced by 42–45%. These results show that wide short implants utilize available bone thickness more effectively than narrow implants because of a more favorable distribution of stresses.

The present study supports the concept of "optimal range of parameters for wide short implants" for moderately atrophic maxilla with Type III bone [30], where the optimal diameter for a 7.0 mm length implant was ≥ 5.0 mm. For such implants, maximum von
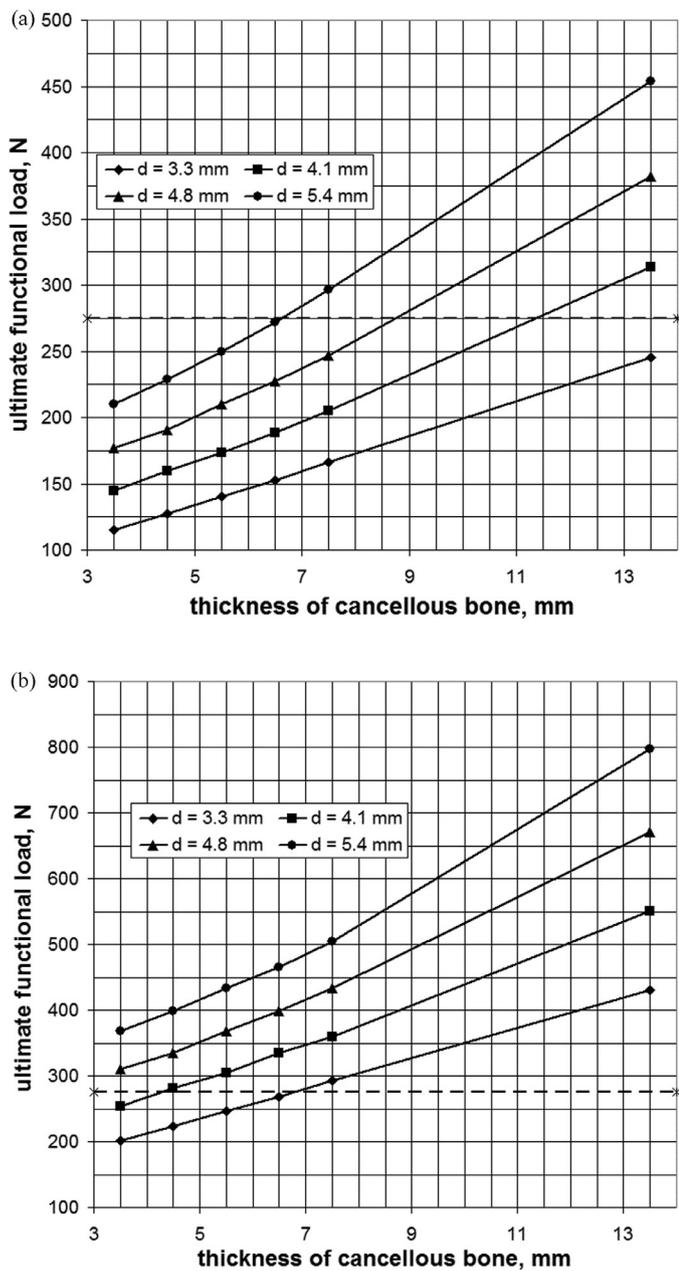
(a)

(b)

**Fig. 8.** (a) Ultimate functional load (UFL) dependence on cancellous bone thickness within the range 3.5–13.5 mm for tested implants and (b) 75% ultimate functional load rise for all implant diameters and lengths due to hypothetical 2.5-fold increase of cancellous bone strength (from 2 to 5 MPa).



**Fig. 9.** Dependence of maximum von Mises stress on thickness of cancellous bone. Tested implants are represented by continuous lines. Interrupted line represents hypothetical 5.0 mm diameter implants and describes upper boundary of wide implants range.

Mises stresses in the maxilla were lower than those for a conventional $4.1 \times 10$ mm implant. The same optimal diameter range was found in our study for Type IV moderately atrophic maxilla: von Mises stress magnitudes for $5.0 \times 7.0$ mm and $4.1 \times 10$ mm implants were similar (10.5 and 11.4 MPa) (Fig. 9).

To compare the impact of bone-implant anchorage (bicortical vs. monocortical) on bone stresses and implant load-carrying capacity, our findings were correlated with results for monocortical anchorage [26,44], where von Mises stress levels produced by short implants in cancellous and cortical bone were, respectively, 2- and 3-times larger than those for conventional implants. The present study showed the following stress levels: for $3.3 \times 6.5$ mm short implant, von Mises stress rise in cancellous and cortical bone relative to $3.3 \times 14.5$ mm implant wedas 75.2% and 69.6%, and for $5.4 \times 6.5$ mm short implant was 83.8% and 78.6%. Such findings
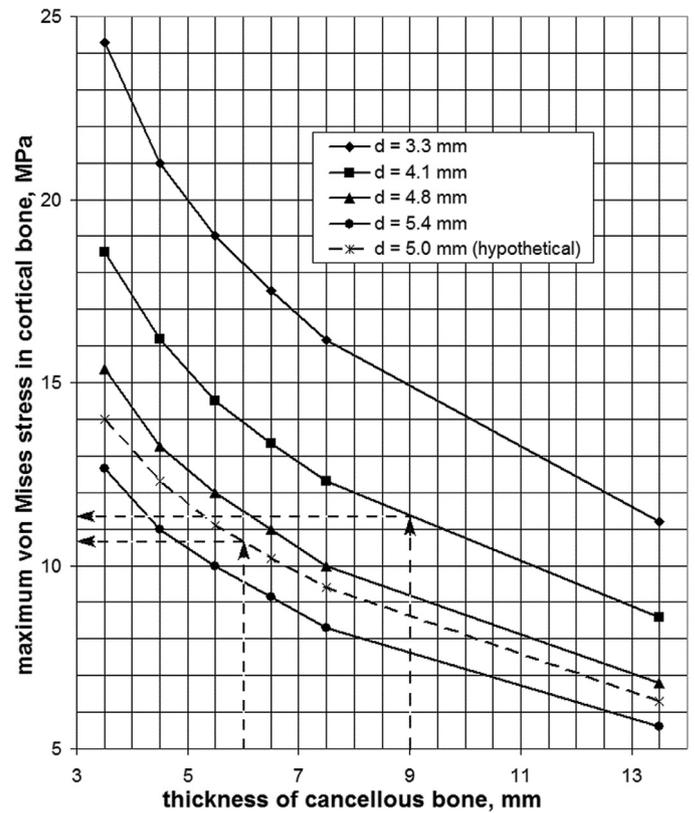
support the conclusion that bicortical anchorage is preferable to monocortical.

The FE analysis cannot be validated by comparing with in vivo experiments; therefore, special procedures supported by convergence test were applied to select adequate FE type and size in the area of the critical bone-implant interface and extreme stress gradients. Also, FEs were manually refined in the vicinity of the critical bone-implant contact within the volume of special geometric model subassemblies. To increase the FE modeling precision using fewer FEs, SOLID186 higher order 3-D 20-node element was chosen because it is advantageous compared with the linear 8-node element.

Several assumptions made in this study could impact the results. Primarily, von Mises stress was selected to describe bone stress state, as in other studies [26,31,32,41]. Also, ultimate stress state was analyzed in both bone tissues applying von Mises strength theory, which is applicable to ductile, homogeneous and isotropic materials. In fact, bone tissue properties are directionally dependent [45,46], so bone structure modeling is extremely difficult. Furthermore, bone properties are not supported by reliable experimental data. According to O'Mahony et al. [47], elasticity modulus values for cancellous bone were: (A) in mesiodistal direction, mean 907, SD±849, range 52–2283 MPa, (B) in bucco-lingual direction, mean 511, SD±565, range 71–1464 MPa and (C) in infero-superior direction, mean 114, SD±78, range 47–262 MPa. Thus, we modeled bone tissues as homogeneous isotropic materials.

Posterior maxilla is usually represented by bone Type IV [5]. Lekholm and Zarb classification [4] does not contain any numerical data on bone mechanical properties. The spectra of elasticity modulus for cancellous and cortical bone are 0.056-2.0 GPa and

1.37-20.0 GPa [48]. In such moduli variation, we selected widely used values in FE simulation of Type IV bone [23].

As previously indicated [28,49], the bone-implant interface has a strong impact on stress pattern and level in surrounding bone. Most FE studies, including the present study, assumed 100% bone-implant contact in osseointegration simulation. However, osseointegration inhomogeneity and bone porous structure mean implants could never be perfectly bonded to bone [49]. For these reasons, our results have certain inaccuracy and more clinically relevant FE models should be developed for more reliable data.

Despite the limitations of this study, the proposed approach can be considered an essential tool for evaluating load-carrying capacity of different-sized implants and bone failure prevention. Bone stresses may be effectively reduced by selecting a proper diameter and length of short implants placed in atrophic posterior maxilla. In terms of UFL, load-carrying capacity of short implants is greatly dependent on their diameter and length.

In conclusion, this study provides important insights to clinicians about perspective of short implants in atrophic maxilla.

## Conflict of Interest

All authors of this paper disclose no conflict of interest with any institutions.

## Funding sources

## Ethical approval

Not required.

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