

Biomechanical finite element analysis of **small diameter** and **short dental implant**

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Abstract

Short and mini dental implants have been widely used as treatment alternatives in certain selected clinical situations. However, a profound scientific analysis of the mechanical and biomechanical impact of the reduced length and diameter of these implant geometries has not been published until now. Using finite element analysis, a series of different experimentally designed short and mini implants have been analysed with regard to their load transfer to the alveolar bone and have been compared to respective standard commercial implants. Mini implants have been inserted in an idealised bone bed representing the anterior mandibular jaw region and loaded with a force of 150 N. An immediate loading condition was assumed and analysed using the contact analysis option of the FE package MSC.Marc/Mentat. Short implants were inserted in an idealised posterior bone segment and loaded in an osseointegrated state with forces of 300 N. Clearly increased bone loading was observed for the short

and mini dental implants compared with standard implants, clearly exceeding the physiological limit of 100 MPa. The determined biomechanical characteristics could explain the slightly increased failure rate of short and mini dental implants.

Introduction

The loss of crestal bone around dental implants has been reported to be influenced by many factors. These include surgical trauma, implant abutment microgap, bacterial infection of peri-implant tissues and biomechanical factors related to loading. Factors that affect the load transfer at the bone-implant interface include the type of loading, material properties of the implant and prosthesis, implant geometry, surface structure, quality and quantity of the surrounding bone, and nature of the bone-implant interface.⁹ There are many dental implant designs available on the market for specific clinical applications: standard implants, short implants with wide diameter and implants with small diameters. All are available in different geometries, thread configurations (if any) and thread depth (Fig. 1).

After tooth loss, however, severely atrophic residual alveolar ridges are fairly common, especially in patients who have been edentulous for a long period of time. Posterior areas of the maxilla and the mandible are areas where clinicians have greater anatomical limitations. Reduced alveolar bone height very often represents a contraindication to implant therapy, unless a procedure such as ridge augmentation or sinus floor elevation is performed. Although widely utilised, these techniques imply greater morbidity, longer treatment times and higher costs. The sinus cavity in the maxilla and alveolar nerve proximity in the mandible are clinical situations where short implants could be considered as an alternative treatment option. Numerous

Fig. 1 Overview of some available commercial short and mini implants.

Fig. 2 Loading direction of the numerical models. A mini implant (2.5 x 15 mm) inserted in an idealised bone block with a cortical thickness of 1.2 mm (left) and a short implant (5.5 x 7 mm) inserted in an idealised bone block with a cortical thickness of 0.5 mm (right).



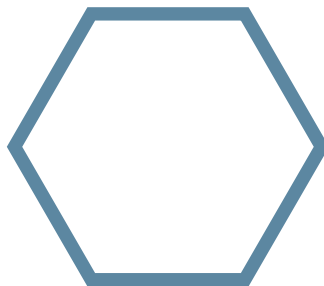
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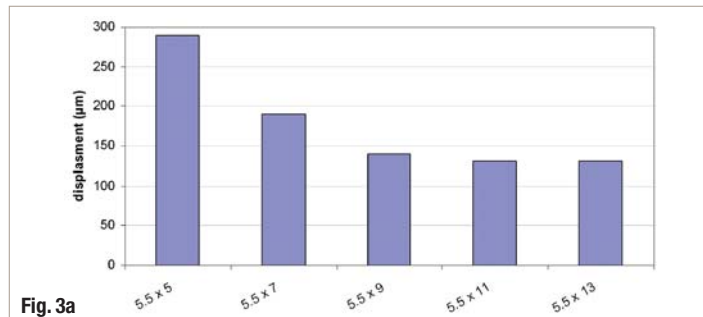


Fig. 3a

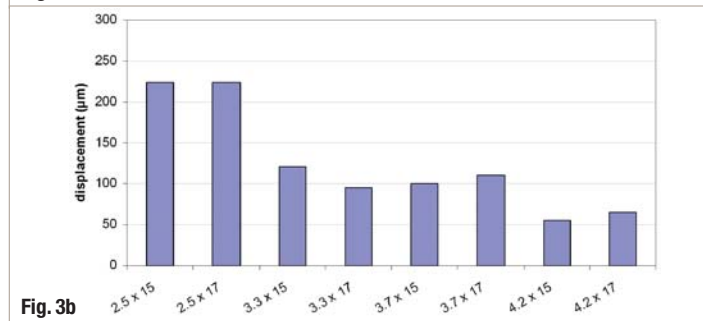


Fig. 3b

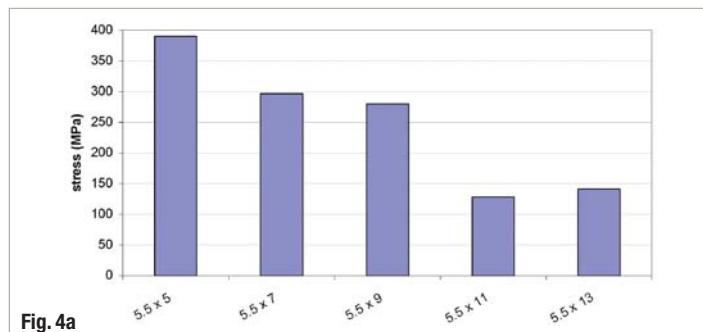


Fig. 4a

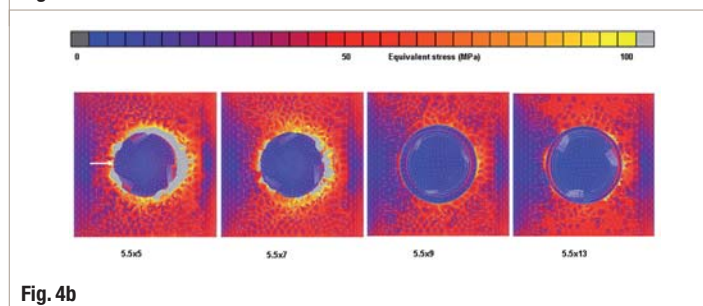


Fig. 4b

Fig. 3 Implant displacements obtained for (a) the short implants and the corresponding standard implants after loading of 300 N in 308 from the implant axis, (b) the MDIs and the corresponding standard implants after loading of 150 N in 308 from the implant axis.

Fig. 4 Total of equivalent stress obtained for the short implants and the corresponding standard implants. (a) Maximum values obtained at the cervical region of the alveolar bone, (b) occlusal view of the stress distribution. The arrow indicates the direction of the applied load.

short implants might have improved over the past few years.

In addition to standard and short implants, there are the implants of smaller diameters, which are called mini dental implants (MDIs). Those are generally 2.75 mm to 3.30 mm in diameter, and they are frequently used in cases of limited bone volume. Several MDIs exist with even smaller diameters, ranging from 1.8 mm to 2.4 mm.^{28,29} In the beginning, the main application of MDIs was to serve as the remedy and provisional instrument for insertion of provisional restorations during the osseointegration phase of conventional standard (larger diameter) endosseous implants.^{1,2,12} The assumption was that MDIs are unable to provide functional load of im-

plant supported prostheses.^{2,11} In the course of time, it was observed that those implants osseointegrated very well clinically.¹² It became clear that, in combination with a minimally invasive implant insertion protocol for the MDIs, they could provide a satisfactory prosthodontic rehabilitation effect.^{12,29}

The advantage in use of MDIs is the minimally invasive, single stage placement procedure^{2,11} in comparison to the procedure for conventional implants (diameter 3.5 and wider). The philosophy of MDI insertion is a minimally invasive technique of inserting the implant into the bone through a small opening of the soft tissue, but not a prepared bone site.^{2,11} Therefore, the bone damage and bone wound during implantation is minimised. Bleeding and postoperative discomfort are reduced¹² and healing time is shortened. It is recommended to load such implants immediately.² The purpose of the present study was to numerically analyse the biomechanical differences of short and narrow (mini) dental implants to the standard ones according to their clinical applications. This study tested some of the available geometries for the narrow as well as short implants. The magnitude of micromotion of implants was investigated, in addition to the magnitude and distribution of stresses and strains in the alveolar bone around the implants.

Materials and methods

A total of 13 three-dimensional finite element (FE) models were developed: two models for short implants, three for the corresponding standard implants, two for mini implants, and finally six models for the corresponding standard implants (Table I). The geometries of the implants were constructed from the CAD/CAM data that were generated and provided by a Dental Implant company and subsequently fed into the FE program MSC. Marc/Mentat 2008. According to several previous studies¹⁵, the tetrahedral element type (4-nodes) was selected for model generation and the bone in its two components (cortical and cancellous bone) was meshed using a coarsening factor of 1.5 mm to gradually enlarge the tetrahedral element size from the implant contact region (0.2 mm) to the external surface (0.5 mm). As in the previous studies, the non-linear incremental Full Newton-Raphson solver was used¹⁵ running on a small Dell server cluster (Power Edge 1950, 20 cores, 40 GB RAM).

Implant geometries of group 1 (short implants)

Two short implants were investigated with a diameter of 5.5 mm and a length of 5 mm and 7 mm, respectively. Three commercially available standard

implants served for comparison: 5.5x9 mm, 5.5x11 mm, and 5.5x13 mm. According to their clinical applications, full osseointegrated condition was considered for the numerical analysis of the above-mentioned models. Young's modulus of the different components was chosen to match the bone quality in the anatomical regions (mandibular and maxillary posterior bone) where the short implants are typically inserted: 110 GPa for the implants, 20 GPa for cortical bone, and 300 MPa for cancellous bone. Typically, short implants are inserted in the posterior jaw region, thus the cortical layer in the idealised bone model had a thickness of 0.5 mm.

Implant geometries of group 2 (mini implants)

Two mini implants were studied with a diameter of 2.5 mm and a length of 15 mm and 17 mm, respectively. Six commercially available standard implants were used as a reference: 3.3x15 mm, 3.7x15 mm, 4.2x15 mm, 3.3x17 mm, 3.7x17 mm, and 4.2x17 mm. According to their clinical applications, immediate loading condition was considered for the numerical analysis of the mini implant models. This has been done by considering a contact situation at the bone implant interface. A Coulomb friction model with a coefficient of friction of 0.5 was selected for the contact analysis.¹⁵

Young's modulus of the different structures was chosen to be 110 GPa for the implants, 20 GPa for cortical bone, and 1,000 MPa for the cancellous bone. Typically, mini implants are inserted into the anterior mandibular jaw region, thus the cortical layers had a thickness of 1.2 mm.

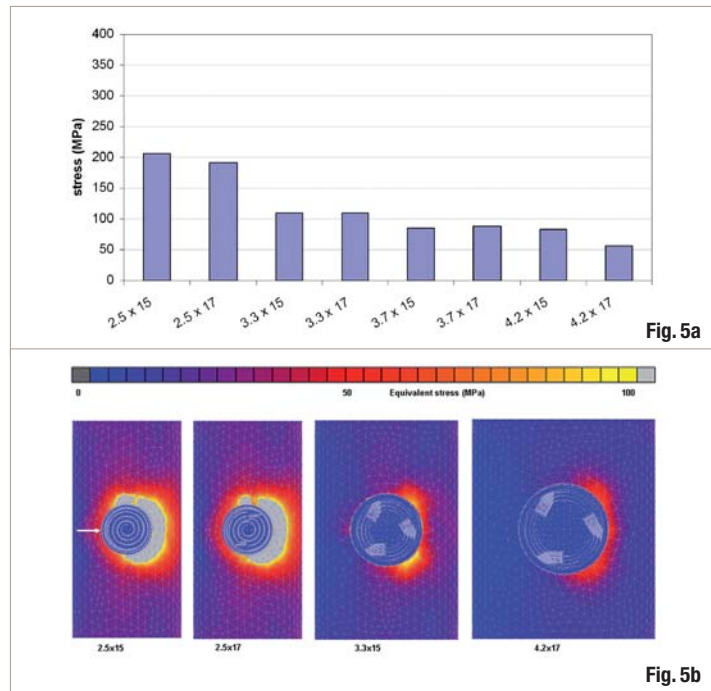


Figure 2 displays the idealised bone segments with the inserted implants. The mini implants were inserted into the bone segments (left) such that the screw threads did touch the cortical bone. Short implants were combined with an idealised bone segment that ensured sufficient distance to the basal cortical layer to simulate adequate distance to the nerve canal. For the whole 13 models, implants were subjected to a load at an angle of 30° from the implant axis. Loading direction was adjusted analogous to the ISO standard 14801:18. The magnitude of the applied force was 300 N for comparing group 1 and 150 N for comparing group 220. The end faces were constrained in all three degrees of freedom (Fig. 2).

Fig. 5 Total of equivalent stress obtained for the MDIs and the corresponding standard implants. (a) Maximum values obtained at the cervical region of the alveolar bone, (b) occlusal view of the stress distribution. The arrow indicates the direction of the applied load.

Model	Loading condition	No. of elements	No. of nodes
Comparing group 1			
Shorty 5.5 x 5 mm	Delayed loading	116,167	22,315
Shorty 5.5 x 7 mm	Delayed loading	127,367	24,176
tioLogic 5.5 x 9 mm	Delayed loading	146,890	27,990
tioLogic 5.5 x 11 mm	Delayed loading	152,218	28,764
tioLogic 5.5 x 13 mm	Delayed loading	162,185	30,377
Comparing group 2			
Mini 2.5 x 15 mm	Immediate loading	151,851	34,870
Mini 2.5 x 17 mm	Immediate loading	179,773	41,481
tioLogic 3.3 x 15 mm	Immediate loading	127,569	27,685
tioLogic 3.3 x 17 mm	Immediate loading	141,938	30,925
tioLogic 3.7 x 15 mm	Immediate loading	136,560	29,650
tioLogic 3.7 x 17 mm	Immediate loading	148,259	32,245
tioLogic 4.2 x 15 mm	Immediate loading	145,351	31,427
tioLogic 4.2 x 17 mm	Immediate loading	167,624	20,393

Table 1

Table 1 Description of the numerical models used in the study and their loading conditions.

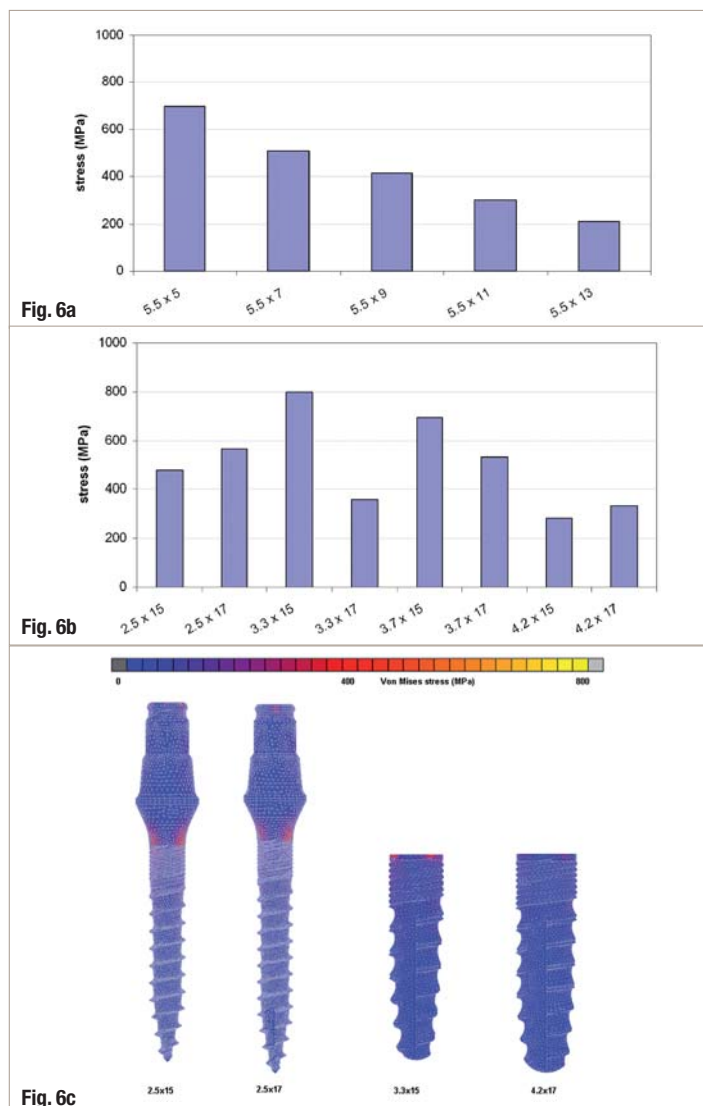


Fig. 6 Von Mises stress values obtained for (a) the short implants and the corresponding standard implants, (b) the MDIs and the corresponding standard implants, (c) stress distribution of the MDIs and standard implants.

tact artefacts. Correspondingly, maximum stresses in the implants were determined in the second inner implant element layer to omit artefacts due to the force application, and cancellous bone strains followed the same strategy as applied in cortical bone stress determination.

The highest displacement at the abutment was observed with the shortest implant (290 mm, implant: 5.5x5 mm). By increasing the length of the short implants, the displacement noticeably decreased (Fig. 3a). Regarding the MDIs, the displacement was higher with the small diameter (223 mm) than with the wide diameter implants (65–120 mm, Fig. 3b). Determined cortical bone stresses of the short implant FE models are displayed in Figure 4. The stress was higher with short implants than with the standard implants. Moreover, stress distribution was wider and covered more area of the cortical bone with the standard implants than with the short implants (Figs. 4a and b). Figure 5a and b display the cortical bone stresses determined with the mini im-

plant FE models. The stress was higher with the MDIs (206 MPa, Ø2.5 mm) than with the wider diameter implants (57–109 MPa, Ø3.3–4.2 mm). The magnitude of the stress decreased by increasing the diameter of the implant. Additionally, the distribution of the stress was wider with the MDIs than the standard wide diameter implants (Figs. 5a and b). Concerning the stress in the short implants, a decrease of the maximum stress was observed by increasing the length of the implants (700 MPa for 5.5x5 mm and 213 MPa for 5.5x13 mm, Fig. 6a). However, the maximum stress values obtained for the MDIs and standard implants showed a non-uniform behaviour (Fig. 6b) due to interplay of multiple factors, such as implant diameter, implant length, and screw configuration. Nevertheless, the stress distribution covers a wider region in the case of the MDIs than for the standard implants (Fig. 6c).

Highest strain values (22,000 and 16,000 μ strain) were determined with the short implants (5.5x5 mm and 5.5x7 mm) and decreased by increasing the length of the implants (8,000 μ strain, 5.5x13 mm). A more homogeneous strain distribution was observed by increasing the length of the implants (Figs. 7a and b). The strain was higher with the MDIs than with the wide diameter implants (3.3–4.2 mm) and the strain distribution was more homogeneous by increasing the diameter of the implants (Figs. 8a–b).

Discussion

In addition to conventional dental implants, there are so called short and mini implants for certain clinical applications. Even for these implants, there are numerous different commercial geometries available on the market. Based on this, the purpose of this study was to numerically analyse selected dimensions of short and mini implants and compare them to the conventional standard implants, to determine whether limit dimensions for the length and the diameter of a dental implant can be postulated. The analysis was based on the FE method and included stress and strain distributions in the bone around the implants, implant stresses, and implant micromotions.

One of the limitations of the present study was that the anatomical situation could of course not be reproduced perfectly. An idealised bone geometry as an implant bed was used and differentiation between the anterior and posterior jaw segments was accomplished by consideration of only the cortical layer thickness and the cancellous bone quality, i.e., the respective Young's modulus. Together with further typical limitations of an FE study, a predictability of 20% can be assumed for the presented results. Short implants offer several surgical advantages



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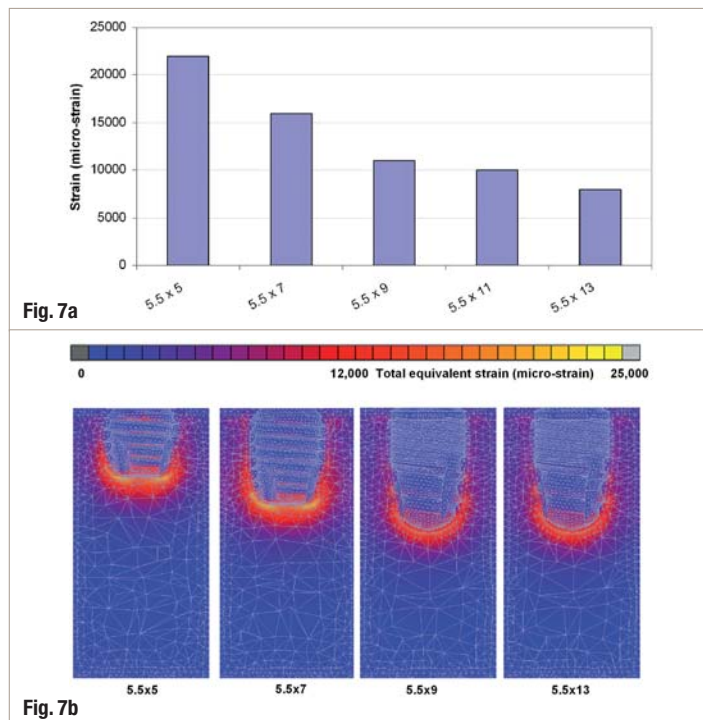


Fig. 7 Equivalent of total strain obtained for the short implants and the corresponding standard implants.

(a) Maximum values obtained,
(b) strain distribution.

compared to longer implants. The use of short implants in the posterior jaw region reduces the need for bone augmentation procedures prior to or in conjunction with implant placement in the maxilla and the mandible. Shorter implants reduce the surgical risk of sinus perforation or mandibular paresthesia, with an overall reduction in surgical complications. Owing to the decreased length of the drills and implants, the osteotomy preparation implies less risk of overheating the bone. Insertion of drills and implants are also easier in small intra arch spaces. In the case of apical root proximity short implants can be the only possible choice. From the patient's point of view, shorter implants reduce treatment time, discomfort, and overall costs related to graft procedures. All these factors make short implants a highly attractive restorative option. In a recent study, Hagi and coworkers¹⁴ concluded that dental implant surface geometry is a major determinant in how well the implants perform in short lengths, which were defined in that study as being shorter than 7 mm. Threaded implants showed higher failure rates in short vs. longer length, sintered porous surfaced implants performed well in short lengths. Moreover, various researchers using FE analysis have demonstrated that horizontal and vertical occlusal forces placed on implants were distributed primarily in the crestal bone, rather than along the entire implant-bone interface. These findings led the Lum group to conclude that short implants serve as favourable as longer implants.^{17, 21, 22} Implant diameter should also be considered as an important clinical variable. It has been suggested that increasing implant diameter could compensate for decrease of length. Himmlova

and colleagues showed that an increase in the implant diameter decreases the stress around the implant neck more than an increase in the implant length, as a result of a more favourable distribution of the simulated masticatory forces.¹⁶

Concerning the strain, the values obtained with the short implants were relatively high (above 10,000 μ strain) in comparison with long implants (up to 5,000 μ strain). The same behaviour was observed for implant displacements. Short implants have a displacement of approximately 290 μ m. This behaviour could be explained by discussing the material properties and cortical bone thickness that were used in this analysis which were based on the typical region for the clinical application of these implants (posterior region), where the bone quality is poor. The retention of the implants was mainly at the cortical layer which had a thin thickness of 0.5 mm, whereas the rest of the implant length was in the cancellous bone which had a low stiffness of 300 MPa, causing a high deformation range.

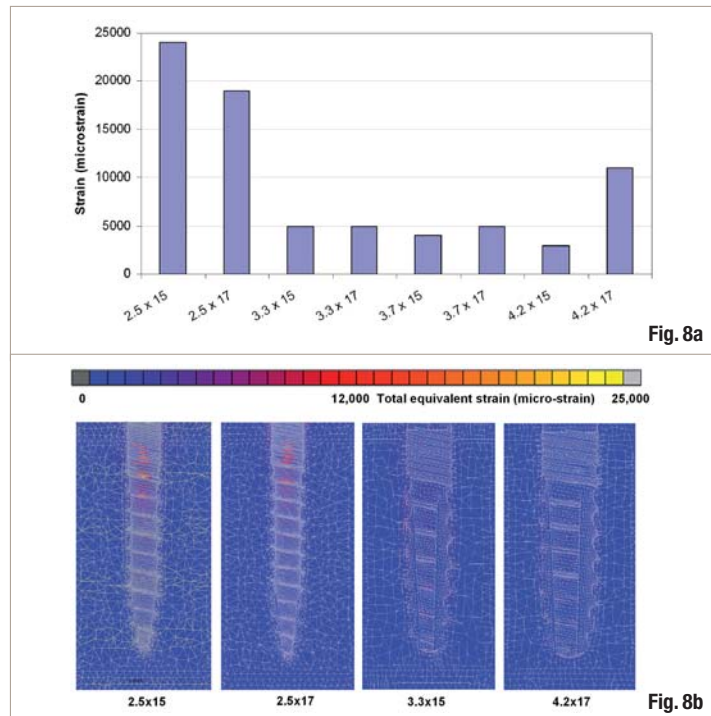
The present study confirms these results. Short implants showed higher stress values than long implants and less homogeneous distribution than long implants. However, the magnitude of stresses was clearly above the physiological ranges as suggested by Frost.⁸ Maximum physiological stresses and strains defined by Frost are in the regions of 100 MPa and 3,000 μ strain for cortical and cancellous bone, respectively. Consequently, the presented results indicate a high-risk of overloading the bone in certain selected cases. Nonetheless, although several studies in the literature have shown that short implants have risk factors and therefore higher failure rate compared to longer implants,^{19, 27, 36} several recent studies seem to prove the good long-term prognosis of short implants. It has also been shown that the crown/implant ratio does not seem to be a major risk factor in the case of favourable force orientation and load distribution. Tawil and coworkers in 2006 evaluated the bone loss around short implants (> 10 mm) and concluded that these implants are a long-term viable solution in sites with reduced bone height even when the prosthetic parameters exceed the normal values but under force parafunction control.³² Gentile et al.¹⁰ estimated the survival rate of short (5.7 mm in length) Bicon dental implants and compared it to Bicon implants of greater length (8 mm and longer). The authors reported no difference in the short implant survival rate when compared to implants of greater length. Essential condition for all implant uses, consequently mini implants as well, is successful osseointegration that can be confirmed only with the long-term studies of success and survival of MDIs under load in masticatory function. Shatkin et al.²⁹

in their retrospective analysis over 5 years of 2,514 MDIs which equally supported fixed and removable prostheses found the overall implant survival rate of 94.2 %. Initial stability is important for the successful osseointegration and high implant success rate. It is stipulated with bone quality, implant design, and surgical technique that is used.⁵ Some authors^{3,4} recommend bone drilling to the depth of only one-third of the length of the MDI. The obvious reason is the dense bone structure of the mandible of the treated patient, but such dense bone structure contributed to the good initial stability of the implanted MDIs. The study of Balkin *et al.*², in which they used a histological analysis, revealed that the quality of the osseointegration of MDIs could be compared with the quality of larger diameter implant osseointegration. Ertugrul and Pipko⁵ in their in vitro study revealed that implants of larger diameter are more stable under lateral forces than MDIs.

Implant displacements obtained in the present study are in agreement with these observations. MDIs showed a displacement of 223 mm, whereas the wider diameter implants of the same length had a displacement range of 55–120 mm. A similar observation was for the strain, MDIs had strains of 19,000–24,000 μ strain, whereas wider diameter implants had strains of 3,000–11,000 μ strain. Moreover, the stress within the implants was higher and widely distributed at the cervical one-third of the MDIs than for wide implants. In total, this could be one of the reasons to explain the failure case with small diameter implants²⁶ such as atypical implant location, extreme divergence of implant axes, infection, implant rejection, and poor prosthesis fit. Usually, dental implants are made of titanium Grade 4 or 5. The ultimate strength for these alloys is given to be around 550 MPa (Grade 4) and 900 MPa (Grade 5), fatigue limits of 425 MPa (Grade 4) and 510 MPa are listed. Consequently, the fatigue limit is exceeded in certain cases, indicating the risk of permanent loading fracture in the case of implants with a reduced diameter.

Conclusions

Short and mini implants have significant clinical advantages. However, from a biomechanical point of view it seems that the bone loading around short and mini implants is increased compared to standard implants. Additionally, the presented results show that there is an increased risk of overload and fracture for mini implants, especially when titanium Grade 4 is used. Consequently, considering an increased number of implants is recommended when short or mini implants shall be inserted. A detailed biomechanical analysis of various clinical sit-



uations will be performed to determine the necessary number of implants in these clinical situations.

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Fig. 8 Equivalent of total strain obtained for the MDIs and the corresponding standard implants. (a) Maximum values obtained, (b) strain distribution.

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implants

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