ARTICLE IN PRESS

Journal of Dentistry xxx (xxxx) xxxx

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Influence of bone quality on the mechanical interaction between implant and bone: A finite element analysis

Francisco Azcarate-Velázquez[a], Raquel Castillo-Oyagüe[b,*], Luis-Guillermo Oliveros-López[a], Daniel Torres-Lagares[a], Álvaro-José Martínez-González[c], Andrea Pérez-Velasco[c], Christopher D. Lynch[d], José-Luis Gutiérrez-Pérez[a,*], María-Ángeles Serrera-Figallo[a]

[a] *Faculty of Dentistry, University of Seville, U.S., Calle Avicena s/n, 41009, Seville, Spain*
[b] *Faculty of Dentistry, Complutense University of Madrid, U.C.M., Pza. Ramón y Cajal s/n, 28040, Madrid, Spain*
[c] *ICEMM S.L.U., 8. Oficina 0-08. Edificio Antares, Calle las Fábricas, 28923, Alcorcón, Madrid, Spain*
[d] *University Dental School & Hospital/ University College Cork, T12 E8YV, Wilton, Cork, Ireland*

ARTICLE INFO

Keywords:
Dental implants
Bone quality
Finite element analysis

ABSTRACT

Objectives: To evaluate the influence of bone type in terms of bone density and cortical bone thickness, on the stresses induced by two implants under compressive and oblique loads.
Methods: A numerical simulation technique based on the finite element method was applied. Two implant types (M-12 and Astra Tech) were introduced in a model matrix whose geometry was extracted from a real CBCT radiograph of the posterior mandibular region. The Young's module and Poisson's coefficient of the bone qualities described by Misch were calculated. Loads with amplitude of 400 N were exerted in two directions: compressive and 15° oblique to 5 mm above the uppermost part of the implant.
Results: The von Misses variant was analysed. Both implant types presented greater tension in the cortical bone area than in the trabecular bone region under compressive loading. For the oblique load condition, the stresses obtained in the cortical zone were significantly higher than those registered as a consequence of compressive loads in both implant types.
Conclusions: Regardless of bone type, the M-12 implants presented lower tensions in the cortical bone than did the Astra implants. The tensions recorded for D3 and D4 bone types in the trabecular zone surrounding the M-12 implants were greater than those recorded for the Astra implants.
Clinical significance: For both compressive and oblique loads, good mechanical behaviour was observed. The decrease in bone quality determines a worse stress distribution, and the cortical bone is overloaded. An efficient distribution of the forces may increase the implants' longevity.

1. Introduction

The use of implants has become a common practice in dentistry. Various types of implants have been designed, tested, and marketed to provide prosthetic, anatomical, aesthetic, and functional solutions for partially or totally edentulous patients. Despite the high success rate of dental implants, several factors may lead to complications [1,2]. Clinically, some of the main causes of implant failure are incomplete osseointegration [2], complications with the surrounding soft tissues [2], biomechanical problems [1,2], poor maxillary bone quality [2], non-axial loading of the implant [2], and parafunctional habits [3]. Of these, bruxism should be highlighted, as it has been associated with bone and implant loss.

Osseointegration is the first concept to consider. This key factor is significantly conditioned by the biomechanical stimulus [3], which may directly affect the bone–implant contact (BIC) [4]. Hence, only the area of the implant which has been integrated in the alveolar bone (BIC) can distribute the stress through it. Partial osseointegration of a dental implant may lead to a poor stress distribution, thus compromising the implant longevity [3].

The alveolar bone is a living tissue that undergoes a continuous remodelling process after tooth loss. Hence, the study of biomechanical

* Corresponding authors at: Raquel Castillo-Oyagüe & José-Luis Gutiérrez-Pérez, Calle Avicena, s/n, 41009, Seville, Spain.
E-mail addresses: fco_azc_vel@hotmail.com (F. Azcarate-Velázquez), rcastill@ucm.es (R. Castillo-Oyagüe), lg_kn7@hotmail.com (L.-G. Oliveros-López), danieltl@us.es (D. Torres-Lagares), alvaro.martinez@icemm.es (Á.-J. Martínez-González), andrea.perez@icemm.es (A. Pérez-Velasco), chris.lynch@ucc.ie (C.D. Lynch), jlgp@us.es (J.-L. Gutiérrez-Pérez), maserrera@us.es (M.-Á. Serrera-Figallo).

https://doi.org/10.1016/j.jdent.2019.06.008
Received 19 April 2019; Received in revised form 19 June 2019; Accepted 26 June 2019
0300-5712/

variables, such as the forces exerted on the alveolar ridge, is of vital importance. To understand and, therefore, be able to avoid implant failure when osseointegration occurs correctly, we must take into account the distribution of the chewing forces along the implant, as they are absorbed by the surrounding bone and distributed without overloads. The loads generated and their dissipation along the implant depend on the forces generated with respect to the longitudinal axis of the implant; the quality, type, and geometry of bone surrounding the implant; and the quality of the implant interface. In summary, the following elements must be assessed when evaluating the distribution of loads [5]: the implant, the alveolar bone, the bone–implant union or degree of osseointegration, the bone geometry, the bone type or density, the type of forces generated, the connection type, and the implant abutment.

In addition, we must know the behaviour of the abovementioned factors when they act together. Even more, implant design plays a fundamental role. In this way, there are tapered or parallel-wall implants, implants with threads of greater or lesser size, implants with micro-threads at the neck, and implants with external or internal connections (such as Morse cones).

The aim of this study is to use numerical simulation techniques based on the FEA (finite element analysis) method to evaluate the influence of various bone types' densities and cortical zone thicknesses (according to the Misch's classification) [6] on the stresses induced by two implants under compressive and oblique loads.

The null hypothesis tested was that the forces' distribution is not affected by the bone quality regardless of using implants with different morphologies.

2. Methods

2.1. Dental implants

Two implants with 4 mm diameters and 13 mm lengths, and the following characteristics were used:

- M-12 (Oxtein, Madrid, Spain): Tapered implant of grade IV titanium with double internal hexagons and a surface treated with argon. It has coronal micro-threads, double U-spins in the middle third, and microthreads in the valleys, which increases the contact surface with the bone (Fig. 1). Model 1 (M-12) has a neck length of 3 mm incorporating six coarse microthreads, which have a pitch of 0.3 mm and a depth of 0.15 mm.
- Astra Tech 4013 (Dentsply Sirona, York, USA): Straight implant of grade IV titanium with double internal hexagons and a surface blasted with titanium dioxide and modified with fluorine (Fig. 2). Model 2 (Astra) has a neck length of 3.7 mm and fine microthreads along the entire neck, which have a pitch of 0.2 mm and a depth of 0.1 mm. The mechanical characteristics of the implants used in the numerical models are: Young's module of 110 GPa and Poisson coefficient of 0.3.

The main reason why these two implants were to be studied are the following: 1) to compare the effect of the number and size of microthreads in the distribution of the load in different bone qualities; 2) to analyse the influence of the type of thread; 3) to analyse the size of the neck in the transmission of stress; and 4) to check the distribution of the forces on tapered and parallel wall implants when they are fully osseointegrated.

2.2. Bone types

Following the bone density scheme defined by Misch [6], four bone types can be considered in jaws depending on the density and thickness of the cortical area.

For the comparative study between the M-12 and Astra implants, the influence of the four bone types defined in Table 1 was studied. Table 2 shows the densities and cortical zone thicknesses.

Basic bone geometry was extracted from a real radiograph of the posterior mandibular region. This facilitated the definition of the bone dimensions to be modelled. The depth was set at 10 mm, and the upper area was cut to leave a free surface 6.5 mm wide to properly house the implant.

2.3. Applied loads

The implants were submitted to compressive load and oblique load with 15° of inclination (Fig.3) with an amplitude of 400 N [6,7]:

2.4. FEA model

All analyses were carried out by applying the FEA method using the

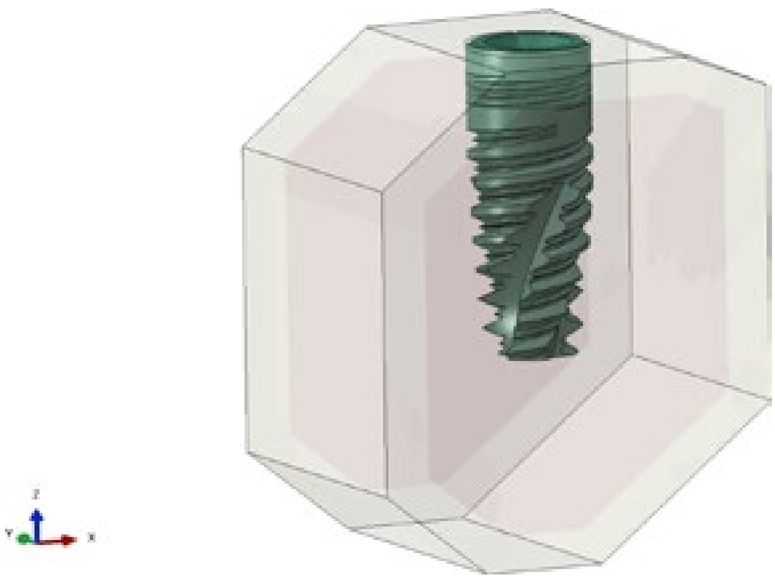

Fig. 1. General vision of the model for the M12 implant.

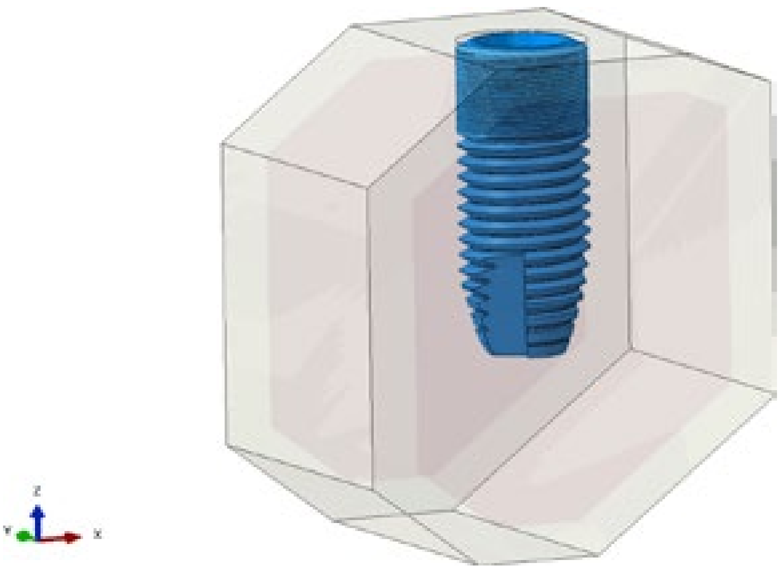

Fig. 2. General vision of the model for the Astra Tech implant.

Table 1
Misch's bone density classification [5].

Bone density	Description	Anatomical location
D1	Dense corticae	Mandibular anterior area
D2	Porous corticae and thick trabecular	Mandibular anterior area Mandibular posterior area Maxilla anterior area
D3	Porous corticae and thin trabecular	Maxilla anterior area Maxilla posterior area Mandibular posterior area
D4	Thin trabecular	Maxilla posterior area

Table 2
Mechanic and geometric properties depending on the bone type.

	Corticae Bone			Trabecular Bone	
Bone type	Thickness (mm)	Young's module (GPa)	Poisson coefficient	Young's Module (GPa)*	Poisson coefficient
D1	2.5	13.7	0.3	9.5	0.3
D2	2.0	13.7	0.3	5.5	0.3
D3	1.5	13.7	0.3	1.6	0.3
D4	1.0	13.7	0.3	0.69	0.3

* Simulated Young's module.

statistical package software Abaqus Standard 6.14.2 (Abaqus, Johnston, USA) The two materials were meshed using C3 D4 elements, first order tetrahedrals, and an average mesh size of 0.05 mm. Simultaneously, embedment contour conditions were imposed on the base, and Y movement was restricted in the lateral sections (Fig. 4). Perfect adhesion between bone and implant was modelled considering the FEA of the implant and bone at the interaction surface share nodes.

The loading point was placed 5 mm from the upper surface of the cortical bone. Such loads were distributed using a rigid interpolation element to impose restrictions on the degrees of freedom of a set of nodes and the movement of a rigid body defined by a reference node.

Mesh models were configured with 330.492 nodes and 1973.646 elements (4-node linear tetrahedron) for the M-12 implant. For the Astra Tech implant, 432.276 nodes and 2.567.561 elements (4-node linear tetrahedron) were used.

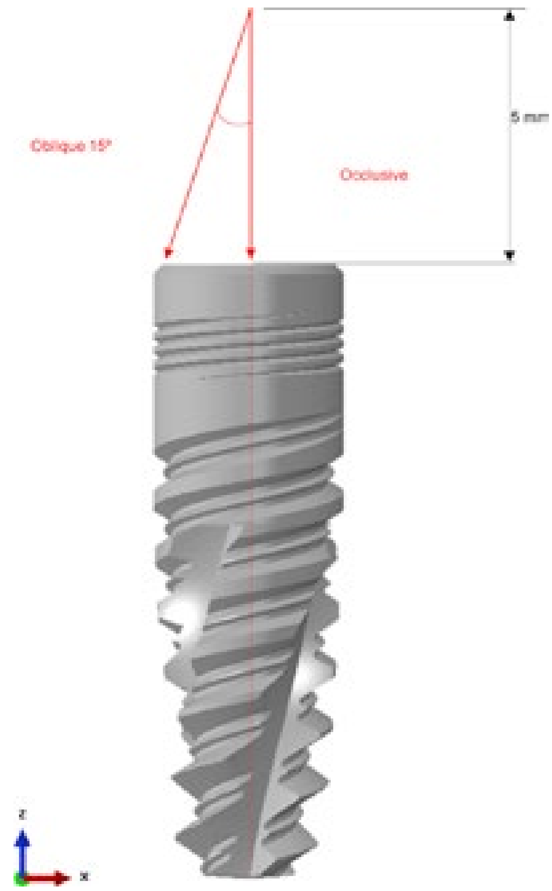

Fig. 3. Types of loads analysed.

The constitutive model used to characterise implant and bone was linear isotropic elastic [8]. Young's modules were defined according to the density of the bone type in each case [6] (Table 2).

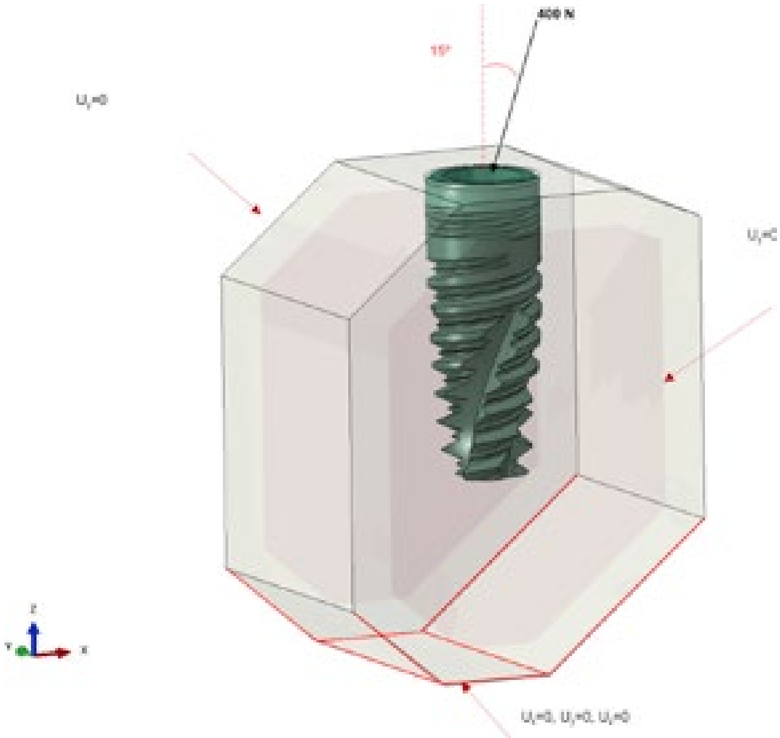

Fig. 4. Contour conditions and load status for the M-12 implant model.

3. Results

After the analysis of the four bone configurations for the two proposed load conditions, maximum stress values were obtained in the cortical bone zone and in the trabecular bone area [9].

With regard to *the compressive load*, both implants presented greater tension in the cortical bone area than in the trabecular bone region (Figs. 5A and B). This effect increased as bone quality decreased, and, consequently, as the difference in stiffness between cortical and trabecular regions increased. The M-12 implant presented less mechanical support in the cortical bone area than did the Astra implant. This outcome translated into lower tensions in the cortical zone and, in contrast, into higher tensions in the trabecular bone area (Figs. 5C-5E). This effect increased as bone quality decreased. Dental prostheses received comparable tensions in the trabecular bone area for D1 and D2 bones. However, for D3 and D4 types, a greater stress increase was observed for the M-12 implant when compared with the Astra implant (Fig. 5F).

Concerning the *oblique load (*15°*),* the stresses obtained in the cortical zone of both implants were significantly higher than those registered for compressive loads, being 200% higher for the M-12 implant and 275% higher for the Astra implant for the D4 bone type. This behaviour is derived from the bending and shear produced by the load's lateral component in the first zone of the implant support. Such an effect, together with the higher rigidity of the cortical zone with respect to the area of trabecular bone, leads to much higher stresses. Even though a lower impact was recorded, the previous phenomenon also affected the trabecular bone area. For the D4 bone type, an increase of 33% was observed for the M-12 implant and an increase of 28% was registered for the Astra implant. The performance of the two implants followed a trend similar to that shown for compressive loads (Figs. 6A and 6B), with a better behaviour of the M-12 implant in the cortical zone and higher tensions in the trabecular bone area, mainly for D3 and D4 bone types. The greater size of the threads in the apical part of the M-12 implant led to higher stress peaks in the base of the thread in this area of the trabecular bone (Fig. 6C-6 F).

4. Discussion

In this study, the mechanical behaviour of two commercial dental implants subjected to a maximum masticatory force of 400 N [6,7] was presented for various types of bone quality as defined according to Misch's bone density classification [6].

When two tapered implant designs were analysed no significant differences were registered in the FEA between cortical and trabecular bone.

The presence of threads is necessary for an efficient load distribution. The presence of threads avoids overload at the cortical bone level, reducing this load by 36% [10,11]. Additionally, as in our study, such a load was concentrated at the neck and the apex of the implant.

The decrease in thread pitch helps the stability of the implant and that increasing thread depth favours stability in patients with poor bone quality [12]. The microthreads at the implant neck increase the BIC and seem to preserve the marginal bone. Conversely, our study shows that the presence of microthreads at the neck of the Astra implant results in the reception of higher loads and a more deficient force distribution throughout the implant. The exact load that determines the resorption of crestal bone is unknown. In addition to this conclusion, the effect of microthreads on the coronal portion of the fixture on the marginal bone level around immediate dental implants in human subjects [13]. It was concluded that the microthread implant collar could not have a positive effect on the maintenance of the marginal bone level around implants placed in fresh extraction sockets in the anterior maxilla.

The behaviour of the bone and its interaction with the implant for compressive and oblique loads with a maximum angle of inclination of 15° has been assessed by evaluating the tensions in the cortical and trabecular bone areas.

Numerical modelling has been carried out considering bone as a linear isotropic material [8]. This concept is of direct application to the

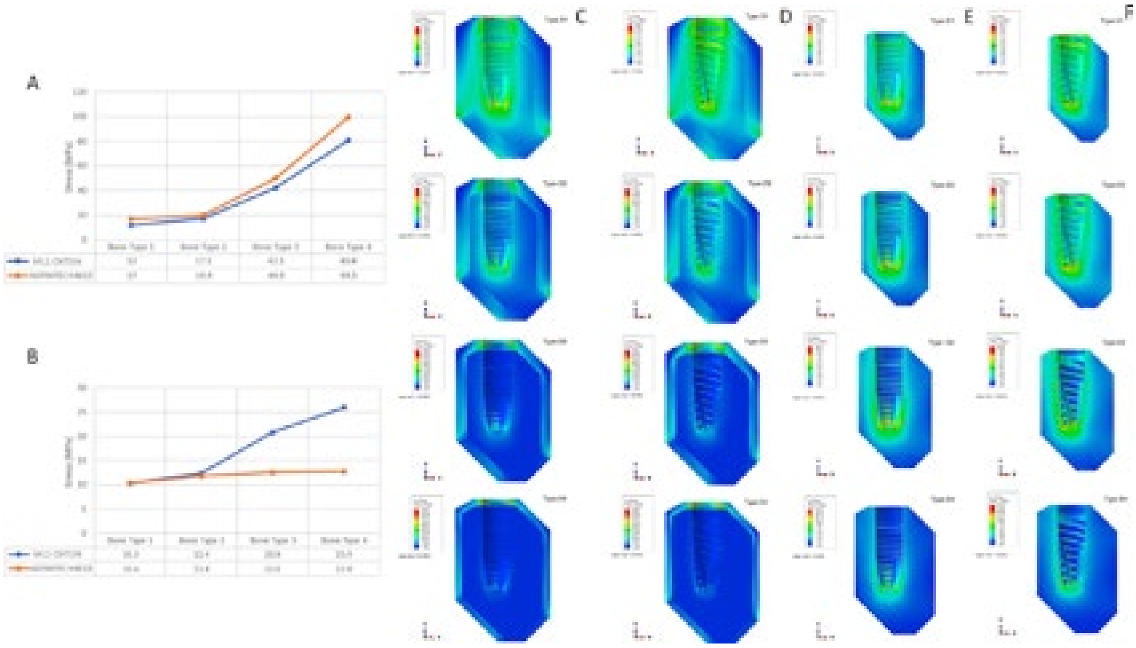

Fig. 5. A: Maximum tension in cortical bone for compressive load depending on the bone type. **B:** Maximum tension in trabecular bone for compressive load depending on the bone type. **C:** Tension state (von Mises) for the Astra implant under compressive load (MPa). **D:** Tension state (von Mises) for the M-12 implant under compressive load (MPa). **E:** Tension state (von Mises) for the Astra implant under compressive load. Trabecular bone area (MPa). **F:** Tension state (von Mises) for the M-12 implant under compressive load. Trabecular bone area (MPa).

cortical bone due to its low porosity and the elastic behaviour of the bone at the macroscopic level for the evaluated load state. The application of this constitutive model of material for trabecular bone depends on the definition of an apparent Young's module that adequately represents the macroscopic behaviour of the trabecular bone, taking into consideration the percentage of porosity and the dimensions of the cavities that make up bone. Consequently, the tensions obtained in the trabecular bone are also apparent tensions, which do not consider the stress concentrations derived from the percentage of porosity and the dimensions of the trabecular bone cavities, which are lower than the

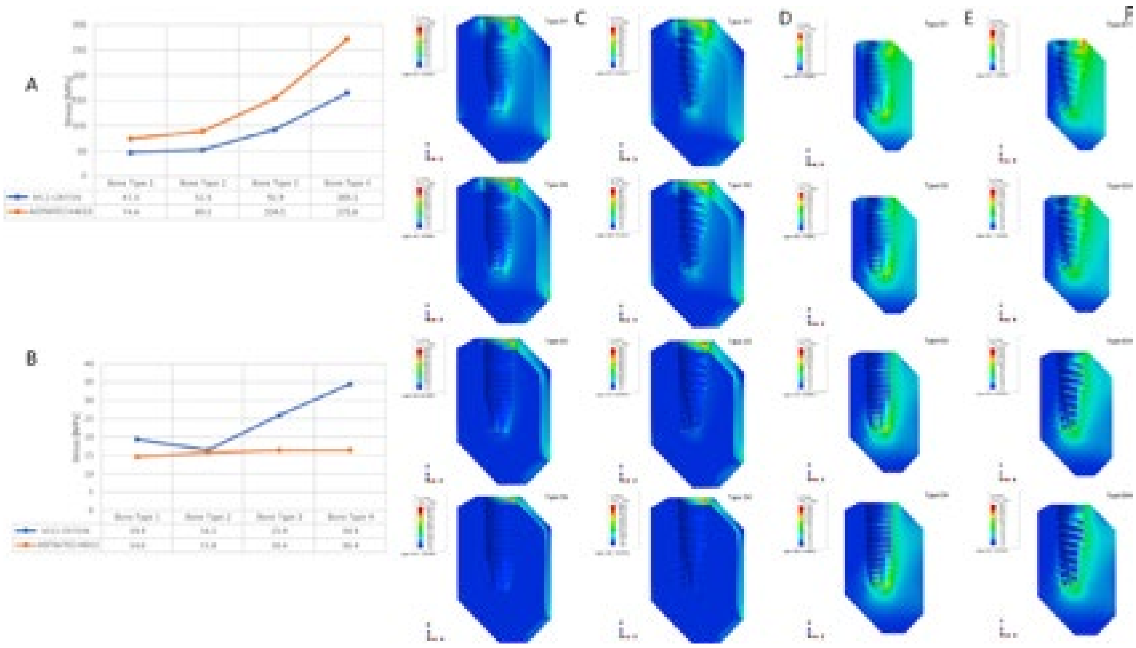

Fig. 6. A: Maximum tension in cortical bone for oblique load (15°) depending on the bone type. **B:** Maximum tension in trabecular bone for oblique load (15°) depending on the bone type. **C:** Tension state (von Mises) for the Astra implant under oblique load (15°) (MPa). **D:** Tension state (von Mises) for the M-12 implant under oblique load (15°) (MPa). **E:** Tension state (von Mises) for the Astra implant under compressive load. Trabecular bone area (MPa). **F:** Tension state (von Mises) for the M-12 implant under compressive load. Trabecular bone area (MPa).

actual stresses in the bone trabeculae.

The evaluation of the BIC for D4 type bone quality has been presented informatively, given that the specific stresses are above the resistance capacity of the bone and will cause the trabecular bone to break.

From the study of the curves of compressive and oblique loads (Figs. 5 and 6), it may be concluded that there is a direct relationship between increased stresses at the cortical bone and decreased bone quality. This effect cannot be extended to the trabecular area because the Astra implant does not present significant tension increases in the trabecular bone, and the M-12 implant is only affected in D3 and D4 bone qualities. Furthermore, such increases may be derived from the thread design in the trabecular zone.

The comparison between three implants according to their macrogeometry using a FEA model reached the conclusion that a tapered implant with microthreads in the upper area and V-shaped threads in the rest of the body has the most uniform and desirable stress distribution in the surrounding cortical bone [1].

Our research was performed with a BIC rate of 100%. Some authors estimate that real BIC is situated between 40% and 70% [14,15]. One technique, the ultraviolet functionalization of titanium on integration with bone, allows up to 98% BIC [16,17], making osseointegration faster [18]. This higher BIC can lead to a reduction in peri-implant stress [19], thus improving the distribution and diffusion of peri-implant stress more effectively than by using longer implants. Implant design is a key factor in the primary stability of implants and stress distribution. In some situations, such as when D4 bone or osteoporotic bone is present, expandable implants and neck tapered implants show better stress distribution. Moreover, tapered implants demonstrate better stability [20]. Longer screw-type implants could be a better choice in a jaw with cancellous low-density bone [21]. Finally, it should be noted that areas of higher stress concentration are susceptible to loss of bone material. This may also increase the probability of implant failure [1], especially in the case of implants placed in the cortical area, due to the greater rigidity of this bone compared to trabecular bone and, consequently, to the greater participation of such bone types in implant stability.

5. Conclusions

Within the limitations of this study, the following conclusions may be drawn:

1 Both implants show a good distribution of forces for compressive and oblique loads without concentrating forces at any particular region of the bone/implant interface. In both cases the load distribution may be compatible with the resistance of the maxillary bone and similar mean tension stimuli.
2 Decrease in bone quality negatively affects the stresses produced by the implants, mainly in cortical bone area.
3 When compared with the Astra implant, the M-12 implant presents lower tensions in the cortical bone region regardless of the bone type. In contrast, the tensions obtained in the trabecular bone area are greater for D3 and D4 bone types for the M-12 implant than for the Astra implant.
4 Given the magnitude of the maximum stresses obtained in the cortical bone area, both implants may be implicated in the loss of bone material under cyclic mechanical loads, this loss being more pronounced in the Astra implant due to the higher maximum stresses obtained.
5 The higher tensions registered in the trabecular bone region for the M-12 implant for D3 and D4 bone types are a consequence of the thread design defined for that area, in which a larger tooth size allows a greater load transfer that results in tension concentrations at the base of the thread.

References

[1] M. Geramizadeh, H. Katoozian, R. Amid, M. Kadkhodazadeh, Comparison of finite element results with photoelastic stress analysis around dental implants with different threads, Dent Med Probl. 55 (2018) 17–22, https://doi.org/10.17219/dmp/85077.

[2] H.E. Khorshid, H.A. Hamed, E.A. Aziz, Complications, risk factors, and failures of immediate functional loading of implants placed in the completely edentulous maxillae: a report of 3 consecutive cases, Implant Dent. 23 (2014) 125–131, https://doi.org/10.1097/ID.0000000000000027.

[3] P. Marcián, T. Zikmund, J. Kaiser, L. Borák, J. Wolff, L. Horáčková, Micro finite element analysis of dental implants under different loading conditions, Comput. Biol. Med. 96 (2018) 157–165, https://doi.org/10.1016/j.compbiomed.2018.03.012.

[4] P. Marcián, L. Borák, J. Valášek, J. Kaiser, Z. Florian, J. Wolff, Finite element analysis of dental implant loading on atrophic and non-atrophic cancellous and cortical mandibular bone - a feasibility study, J. Biomech. 47 (2014) 3830–3836, https://doi.org/10.1016/j.jbiomech.2014.10.019.

[5] J. Reis, L. Reis, A.M. Deus, P. Bicudo, M.F. Vaz, Mechanical behaviour of dental implants, Procedia Struct Integr. 1 (2016) 26–33, https://doi.org/10.1016/j.prostr.2016.02.005.

[6] C.E. Misch, Contemporary Implantology, third ed., Mosby-Elsevier, St Louis, 2009.

[7] M. Cicciù, G. Cervino, E. Bramanti, F. Lauritano, G. Lo Gudice, L. Scappaticci, et al., FEM analysis of mandibular prosthetic overdenture supported by dental implants: evaluation of different retention methods, Comput. Math. Methods Med. 2015 (2015) 943839, , https://doi.org/10.1155/2015/943839.

[8] J.P. Geng, K.B. Tan, G.R. Liu, Application of finite element analysis in implant dentistry: a review of the literature, J. Prosthet. Dent. 85 (2001) 585–598, https://doi.org/10.1067/mpr.2001.115251.

[9] A. Hannigan, C.D. Lynch, Statistical methodology in oral and dental research: pitfalls and recommendations, J. Dent. 41 (2013) 385–392, https://doi.org/10.1016/j.jdent.2013.02.013.

[10] E.B. Las Casas, P.C. Ferreira, C.A. Cimini, E.M. Toledo, L.P. da S. Barra, M. Cruz, Comparative 3D finite element stress analysis of straight and angled wedge-shaped implant designs, Int. J. Oral Maxillofac. Implants 23 (2008) 215–225.

[11] W.G. Assunção, E.A. Gomes, V.A.R. Barão, E.A.C. de Sousa, Stress analysis in simulation models with or without implant threads representation, Int. J. Oral Maxillofac. Implants 24 (2009) 1040–1044.

[12] A. Al-Thobity, A. Kutkut, K. Almas, Microthreaded implants and crestal bone loss : a systematic review, J. Oral Implantol. 43 (2017) 157–166, https://doi.org/10.1563/aaid-joi-D-16-00170.

[13] A. Khorsand, A.A. Rasouli-Ghahroudi, N. Naddafpour, Y.S. Shayesteh, A. Khojasteh, Effect of microthread design on marginal bone level around dental implants placed in fresh extraction sockets, Implant Dent. 25 (2016) 90–96, https://doi.org/10.1097/ID.0000000000000350.

[14] M.A. de Maeztu, I. Braceras, J.I. Alava, C. Gay-Escoda, Improvement of osseointegration of titanium dental implant surfaces modified with CO ions: a comparative histomorphometric study in beagle dogs, Int. J. Oral Maxillofac. Surg. 37 (2008) 441–447, https://doi.org/10.1016/j.ijom.2008.01.010.

[15] T. Ogawa, I. Nishimura, Different bone integration profiles of turned and acid-etched implants associated with modulated expression of extracellular matrix genes, Int. J. Oral Maxillofac. Implants 18 (2003) 200–210.

[16] A. Yadav, R. Yadav, A. Gupta, A. Baranwal, A. Bhatnagar, V. Singh, Effect of ultraviolet irradiation on the osseointegration of a titanium alloy with bone, Contemp. Clin. Dent. 8 (2017) 571–578, https://doi.org/10.4103/ccd.ccd_576_17.

[17] H. Aita, N. Hori, M. Takeuchi, T. Suzuki, M. Yamada, M. Anpo, et al., The effect of ultraviolet functionalization of titanium on integration with bone, Biomaterials 30 (2009) 1015–1025, https://doi.org/10.1016/j.biomaterials.2008.11.004.

[18] A. Funato, M. Yamada, T. Ogawa, Success rate, healing time, and implant stability of photofunctionalized dental implants, Int. J. Oral Maxillofac. Implants 28 (2013) 1261–1271, https://doi.org/10.11607/jomi.3263.

[19] T. Ohyama, T. Uchida, N. Shibuya, S. Nakabayashi, T. Ishigami, T. Ogawa, High bone-implant contact achieved by photofunctionalization to reduce periimplant stress: a three-dimensional finite element analysis, Implant Dent. 22 (2013) 102–108, https://doi.org/10.1097/ID.0b013e31827b9415.

[20] J.-R. Xiao, Y.-F. Li, S.-M. Guan, L. Song, L.-X. Xu, L. Kong, The biomechanical analysis of simulating implants in function under osteoporotic jawbone by comparing cylindrical, apical tapered, neck tapered, and expandable type implants: a 3-dimensional finite element analysis, J. Oral Maxillofac. Surg. 69 (2011) e273–e281, https://doi.org/10.1016/j.joms.2010.12.006.

[21] S. Tada, R. Stegaroiu, E. Kitamura, O. Miyakawa, H. Kusakari, Influence of implant design and bone quality on stress/strain distribution in bone around implants: a 3-dimensional finite element analysis, Int. J. Oral Maxillofac. Implants 18 (2003) 357–368.