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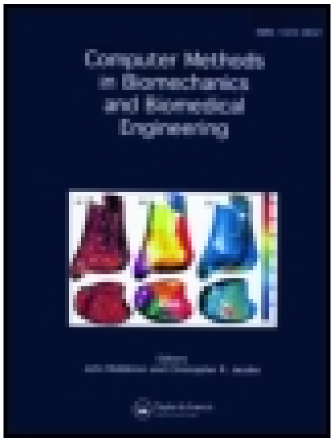

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Computer Methods in Biomechanics and Biomedical Engineering
Publication details, including instructions for authors and subscription information:
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Prognosis of implant longevity in terms of annual bone loss: a methodological finite element study

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Published online: 07 Apr 2015.

To cite this article: Vladyslav Demenko, Igor Linetskiy, Larysa Linetska, Vitalij Nesvit, Andrii Shevchenko, Oleg Yefremov & Hans-Werner Weisskircher (2015): Prognosis of implant longevity in terms of annual bone loss: a methodological finite element study, Computer Methods in Biomechanics and Biomedical Engineering, DOI: 10.1080/10255842.2015.1005079

To link to this article: http://dx.doi.org/10.1080/10255842.2015.1005079

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Computer Methods in Biomechanics and Biomedical Engineering, 2015
http://dx.doi.org/10.1080/10255842.2015.1005079

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(*Received 27 February 2014; accepted 5 January 2015*)

Dental implant failure is mainly the consequence of bone loss at peri-implant area. It usually begins in crestal bone. Due to this gradual loss, implants cannot withstand functional force without bone overload, which promotes complementary loss. As a result, implant lifetime is significantly decreased. To estimate implant success prognosis, taking into account 0.2 mm annual bone loss for successful implantation, ultimate occlusal forces for the range of commercial cylindrical implants were determined and changes of the force value for each implant due to gradual bone loss were studied. For this purpose, finite element method was applied and von Mises stresses in implant–bone interface under 118.2 N functional occlusal load were calculated. Geometrical models of mandible segment, which corresponded to Type II bone (Lekholm & Zarb classification), were generated from computed tomography images. The models were analyzed both for completely and partially osseointegrated implants (bone loss simulation). The ultimate value of occlusal load, which generated 100 MPa von Mises stresses in the critical point of adjacent bone, was calculated for each implant. To estimate longevity of implants, ultimate occlusal loads were correlated with an experimentally measured 275 N occlusal load (Mericske-Stern & Zarb). These findings generally provide prediction of dental implants success.

Keywords: bone loss; implant dentistry; osseointegration, finite element

1. Introduction

The use of dental implants for more than three decades showed their high efficiency in the treatment of partial and complete edentulism (Brånemark et al. 1977; Quirynen et al. 2002) and determined basic causes, which result their premature failure. Osseointegrated implants usually fail as a consequence of peri-implant bone loss (Isidor 1996; Fu et al. 2012; Klinge 2012). It usually begins in the first year of service with a value from 0.6 to 1.6 mm (Adell et al. 1981; Naert et al. 1992; Roos et al. 1997; Fransson et al. 2005). Annual bone loss from 0.05 to 0.33 mm was reported in the following period (Adell et al. 1981; Albrektsson et al. 1986; Naert et al. 1992; Van Steenberghe et al. 1999). Mean annual bone loss of less than 0.2 mm (Albrektsson et al. 1986) was recommended as a criterion for implant success.

Plaque-induced inflammation (peri-implantitis) in peri-implant tissues is one of two major factors of bone loss. It causes permanent loss of osseointegration from implant neck toward the apex (Esposito et al. 1998; Fu et al. 2012; Klinge 2012).

Mechanical overload (Laney 2007) may cause pathological stresses at the peri-implant region. It is considered as a second factor of bone loss (Esposito et al. 1998; Van Steenberghe et al. 1999; Heckmann et al. 2006). Combination of both factors may contribute to further bone loss (Quirynen et al. 2002; Klinge 2012). Due to these pathological conditions, extremely high stress concentrations may arise in bone–implant interface (Kitamura et al. 2005).

The finite element (FE) method was developed as a tool to simulate the mechanical behavior of dental systems under occlusal loading and to evaluate the effect of various parameters, i.e., implant geometry, prosthesis design, and load conditions on stress distribution in the peri-implant area (Siegele & Soltesz 1989; Geng et al. 2001, 2008; Faegh & Müftü 2010). It was shown that oblique loading is the most realistic type of occlusal loading which causes the highest localized stresses in cortical bone (Holmgren et al. 1998; Himmlová et al. 2004).

Stress fields around implant–bone contact area are affected by a number of biomechanical factors, including type of loading, mechanical properties of implants and bone tissue, implant geometry and size, surface structure, and quality and quantity of surrounding bone (Tada et al. 2003; Sevimay et al. 2005; Baggi et al. 2008, 2013; Tu et al. 2010). Inadequate implant dimensions are one of the most crucial causes of peri-implant bone overload and its further loss (Demenko et al. 2011, 2014a, 2014b).

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Attempts to minimize bone loss by increasing implant–bone interface area to reduce stresses at the cortical alveolar crest were focused on increasing implant diameter and/or length, or altering implant design (Holmgren et al. 1998; Bozkaya et al. 2004; Ding et al. 2009; Faegh & Müftü 2010; Demenko et al. 2014a). Finding optimal relations between implant design/dimensions and stress distribution at implant–bone interface is a significant problem because stresses around implant should be limited by bone tissue ultimate strength (Bozkaya et al. 2004) to prevent its loss due to overload and reveal risks of implant failure (Natali & Pavan 2002; Baggi et al. 2008, 2013).

Bone–implant interface condition greatly influences the mechanical state of adjacent bone. Van Oosterwyck et al. (1998) analyzed the effect of two extreme conditions (fixed bonded vs. frictionless free contact) using FE modeling. For both interface conditions, great differences in bone stress values were noticed. Besides, bone loss crucially distorts bonded bone–implant interface primarily due to a decrease in osseointegration area (Kitamura et al. 2005).

The evaluation of adjacent bone strength is based on comparing the calculated stresses and experimentally obtained strength value. The method based on correlation of implant dimensions with the neck area stresses was proposed to compare load-carrying ability of variable-sized implants (Demenko et al. 2011) and select a viable implant, i.e., the implant which generates stresses suitable for bone tissue. The method allows to (a) prevent bone loss by adequate implant selection; (b) evaluate decrease in specified implant load-carrying ability within its lifetime due to bone loss and determine its critical value; and (c) confirm the conditions of implant success.

Therefore bone loss analysis is an actual problem in implant dentistry. The aim of this study was to (a) correlate implant dimensions and ultimate occlusal load values for the range of commercial cylindrical implants in complete and partially osseointegration conditions (simulating bone loss from 0.1 to 1.9 mm); (b) evaluate and compare load-carrying abilities of the implants in gradual bone loss to help dental practitioners in adequate implant selection and to assess its long-term success.

2. Materials and methods

2.1 FE modeling

3D bone segment of molar area was modeled from computed tomography (CT) images of human mandible. Geometrical parameters of cortical and cancellous bone were analyzed using the Mimics 12.1 software (Materialise, Leuven, Belgium). The bone segment consisted of two volumes: an outer shell representing cortical bone with varying thickness from 1.5 to 2.3 mm, and an inner cancellous core assumed to be ideally connected with the cortical shell. The length of the segment in disto-mesial direction was set to 20 mm based on convergence test previously performed (Demenko et al. 2014b). The segment thickness in bucco-lingual direction was 12.5 mm and its vertical size was 22.5 mm. Bone tissue in the segment corresponded to Type II bone quality according to Lekholm and Zarb classification (1985).

Twelve CAD models of commercial cylindrical implants, 8.0, 10.0, 12.0, and 14.0 mm length and 3.3, 4.1, and 4.8 mm diameters were analyzed. Each implant model included conical abutment with 4.5 mm height. Implant and abutment were considered as a continuous unit. Occlusal load was applied to the center of abutment upper surface.

In the first part of the study, implants were assumed to be completely osseointegrated (fully bonded) and placed at the midspan of the bone segment. In the second part, 10 levels of cortical bone loss from 0.1 to 1.9 mm were simulated by establishing frictionless contact with nonpenetration constraints. Surrounding soft tissue in the area of osseointegration loss was considered a perfect lubricant. Under these conditions, contact zone transferred only pressure but not tangential and tension forces.

All 3D solid models (bone segment and implants) were designed in SolidWorks 2012 (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) software used for merging parts of a bone–implant model and for generating and solving discrete FE meshes (Figure 1).

FE meshes were constructed using four-node linear tetrahedral elements due to limitation of SolidWorks Simulation software (Dassault Systèmes SolidWorks Corp.). Von Mises stress was proposed as a measure of bone failure risk (Faegh & Müftü 2010; Almeida et al. 2015; Baggi et al. 2013). Nonhomogeneous meshing was used to increase the accuracy of the stress calculation (Figure 1(B)). Local downsizing of meshes in the vicinity of bone critical point was 0.04 mm. The level of mesh refinement was preliminary established based on convergence tests. The total number of nodes and FEs was up to 1,128,000 and 839,000, respectively.

Von Mises stress distributions in bone peri-implant area were evaluated to calculate maximum stress values for 12 implant–bone assemblies under complete and partial osseointegration conditions.

2.2 Loading and boundary conditions

Loading of the implants, in 3D, with forces of 114.6, 17.1, and 23.4 N in axial, lingual, and distomesial directions, respectively, simulated the resulting functional occlusal load of 118.2 N at an angle of approximately 75° to the occlusal plane (Himmlová et al. 2004; Figure 1). For

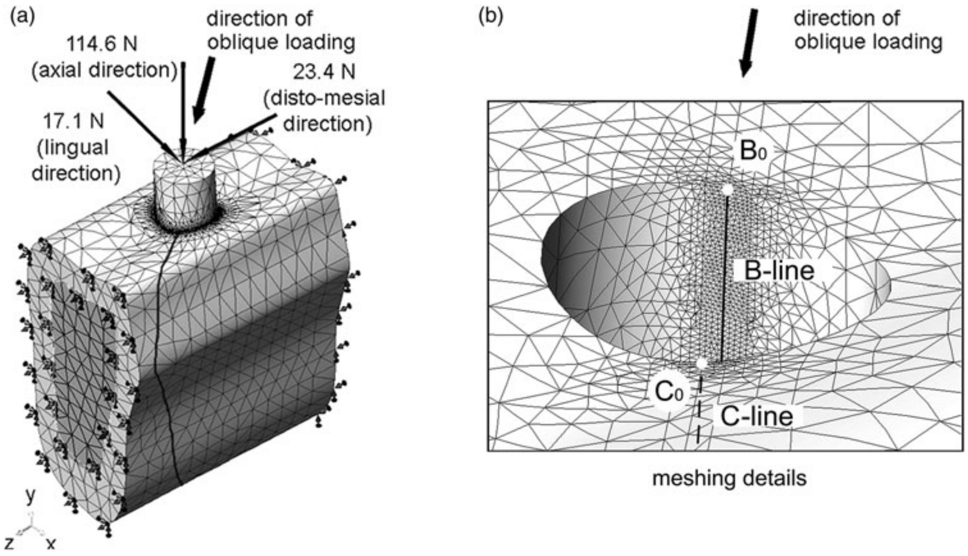

Figure 1. (A) A 3D FE model of a mandibular molar segment with cancellous bone core. Both ends are restrained. Thin arrows represent components of oblique occlusal force acting on the center of the abutment upper surface at a distance of 4.5 mm from the bone upper margin in a 3D nonaxisymmetric loading scheme. (B) Local downsizing of FE meshes along the B- and C-lines of implant–bone critical interface, where significant variation of the stress field was expected, with 0.04 mm FE size. The C_0 and B_0 points are the tracks of the B- and C-lines on the bone segment upper surface.

boundary conditions, nodes at both ends of the mandibular segment were restrained, i.e., the boundaries were absolutely fixed (Limbert et al. 2010).

2.3 *Material properties*

All materials were assumed to be linearly elastic and isotropic, and all material volumes were considered homogenous (Chou et al. 2008; Yu et al. 2009). Implants and abutments were assumed to be of titanium alloy with the modulus of elasticity and Poisson's ratio of 114 GPa and 0.34, respectively (Bozkaya et al. 2004). The Poisson's ratio of bone tissue (both cortical and cancellous) was assumed to be 0.3 (Baggi et al. 2008). As in other studies, cortical bone was considered to have 13.7 GPa modulus of elasticity (Himmlová et al. 2004; Motoyoshi et al. 2009; Hsu & Chang 2010; Mesnard et al. 2014). For cancellous bone, it was 1.0 GPa (Bozkaya et al. 2004). The ultimate tension strength for cortical bone was 100 MPa (Martin et al. 1998). The tension strength of cancellous bone was assumed to be 5 MPa (Martin et al. 1998).

3. Results

Areas of high stress concentrations were found in crestal cortical bone and also at the implant apex in cancellous bone. They were located in the vicinity of B- and C-lines of the oblique loading plane and implant surface intersection (Figure 1). C-line was found as the critical line of implant–bone interface. Because cortical and cancellous bone tissues have different ultimate strength, both areas were investigated to determine the actual critical point location. For that reason, von Mises stress distributions along C-line were studied. It was found that, for the range of implants, C_0 point was critical for complete osseointegration condition. The peak values of von Mises stress at C_0 point were correlated with the ultimate tension strength of cortical bone (100 MPa) according to the von Mises strength criterion. Using linear correlation factor, ultimate values of occlusal load which generated ultimate tension stress in cortical bone were calculated for each completely osseointegrated implant. These loads are summarized in the third column of Table 1.

The same approach was applied to find potentially critical points in both cortical and cancellous bone for 10 levels of crestal bone loss from 0.1 to 1.9 mm. It was discovered that the mobile critical point was located at the margin of remaining osseointegrated area of cortical bone (Figure 2). Actual ultimate occlusal load values for each implant at different stages of bone loss are summarized in Table 1 with corresponding percentages of implant load-carrying ability loss. They were calculated relative to ultimate load values for completely osseointegrated implants.

The longevity of partially osseointegrated implants was determined by correlation of calculated ultimate occlusal load values to experimentally obtained 275 N maximum occlusal load for molars (Mericske-Stern & Zarb 1996) (Figure 3). Theoretically calculated lifetime

Table 1. Ultimate occlusal loads for completely and partially osseointegrated commercial cylindrical implants.

Diameter (mm)	Length (mm)	Ultimate occlusal load for completely osseointegrated implants (N)	Ultimate occlusal load for partially osseointegrated implants and corresponding percentage of load-carrying ability decrease									
			Bone loss (mm)									
			0.1	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9
3.3	8.0	151.5	150.8	146.5	140.5	134.2	127.0	120.0	112.7	105.7	98.4	90.9
			−0.51	−3.35	−7.25	−11.46	−16.19	−20.81	−25.63	−30.25	−35.07	−40.00
	10.0	163.0	161.9	157.0	150.6	143.8	137.1	129.9	122.2	115.2	107.7	100.2
			−0.68	−3.72	−7.64	−11.80	−15.89	−20.33	−25.05	−29.34	−33.91	−38.56
	12.0	173.8	172.6	168.0	161.3	154.0	146.5	138.9	131.0	123.6	115.9	108.4
			−0.73	−3.37	−7.27	−11.47	−15.83	−20.21	−24.78	−29.06	−33.53	−37.83
	14.0	184.1	182.4	178.0	171.3	164.2	155.9	148.1	139.9	132.0	124.0	116.0
			−0.93	−3.32	−6.96	−10.83	−15.32	−19.55	−24.02	−28.30	−32.65	−36.99
4.1	8.0	218.9	217.7	211.1	201.0	189.1	177.5	165.2	153.0	140.8	129.0	118.0
			−0.55	−3.57	−8.16	−13.60	−18.92	−24.53	−30.10	−35.68	−41.07	−46.09
	10.0	235.0	234.1	228.0	216.9	205.6	193.5	181.0	168.5	156.0	144.0	132.0
			−0.40	−2.97	−7.71	−12.52	−17.66	−22.98	−28.29	−33.61	−38.72	−43.83
	12.0	248.8	248.3	242.7	233.6	221.8	209.8	196.5	184.0	170.5	157.5	145.0
			−0.21	−2.46	−6.13	−10.88	−15.68	−21.03	−26.06	−31.48	−36.71	−41.73
	14.0	263.8	262.1	257.0	248.8	237.3	224.5	212.0	198.0	184.1	171.0	157.6
			−0.67	−2.61	−5.68	−10.04	−14.91	−19.65	−24.95	−30.22	−35.19	−40.27
4.8	8.0	309.4	307.8	298.5	282.1	262.7	243.7	225.1	207.4	191.9	176.7	163.0
			−0.52	−3.54	−8.83	−15.11	−21.24	−27.24	−32.98	−37.99	−42.90	−47.31
	10.0	344.5	341.4	331.1	315.3	295.0	272.8	250.9	231.5	212.9	196.5	182.0
			−0.89	−3.88	−8.44	−14.31	−20.76	−27.08	−32.72	−38.10	−42.83	−47.04
	12.0	369.4	368.2	359.3	343.6	322.1	300.0	276.2	253.6	233.1	214.5	198.3
			−0.31	−2.74	−6.98	−12.81	−18.78	−25.23	−31.33	−36.88	−41.92	−46.31
	14.0	399.3	396.6	387.5	374.1	352.8	330.2	304.6	279.4	257.0	236.4	218.9
			−0.67	−2.95	−6.33	−11.64	−17.32	−23.71	−30.02	−35.65	−40.80	−45.19

for 4 acceptable implants out of 12 is shown by downwardly directed arrows for successful implantation, i.e., 0.2 mm annual bone loss.

4. Discussion

Estimating dental implant success is of utmost importance in implant dentistry. Osseointegrated implants often fail due to excessive loading as a result of selection of inadequate implant dimensions. Systemic reasons of failure phenomenon may be evaluated applying numerical tools for its simulation. Gradual bone loss is a result of different, often contradictory causes. However, it may be clinically evaluated, so it was chosen for the assessment of implant longevity. That is why acceptable value of bone loss was proposed as the criterion of implant success (Albrektsson et al. 1986; Roos et al. 1997).

Implantologists are fully responsible for adequate implant selection. Although nonsystemic factors and causes of bone overload (extreme bite forces, anatomical variations, insidious medical conditions, etc.) are usually invisible for the clinicians, knowledge of implant–bone interface biomechanics basics will aid them to deal with systemic causes of bone overload. That is why we developed a methodology of correlation of the load-carrying ability of particular implant, described by the term ‘ultimate masticatory load’ (Demenko et al. 2011) to experimentally acquired occlusal load. In this study, its value was taken from the measurement by Mericske-Stern and Zarb (1996) to assess longevity prognosis of implant inserted in the molar mandibular site for the case of 0.2 mm per year bone loss. The next step of this method advancement is its individualization for a particular patient using corresponding devices. Generally, this approach allows to describe implant load-carrying ability decrease up to the limiting value when the implant becomes incapable to withstand applied occlusal load without bone overload.

Nowadays, dental implant selection is more of a craftsmanship than science. Both patients and implantologists are primarily interested in esthetics. However, bone quality is a one of key determinants for treatment planning. Reduced implant lifetime is most often related to bone density than arch location. Herrmann et al. (2005) found that implant failures correlated with patient factors, including bone density, especially when coupled with pure bone volume (65% of these patients experienced failure). Therefore, ‘over the years, many independent clinical groups documented the indisputable influence of bone density on clinical success’ (Jemt et al. 1996; Herrmann et al. 2005).

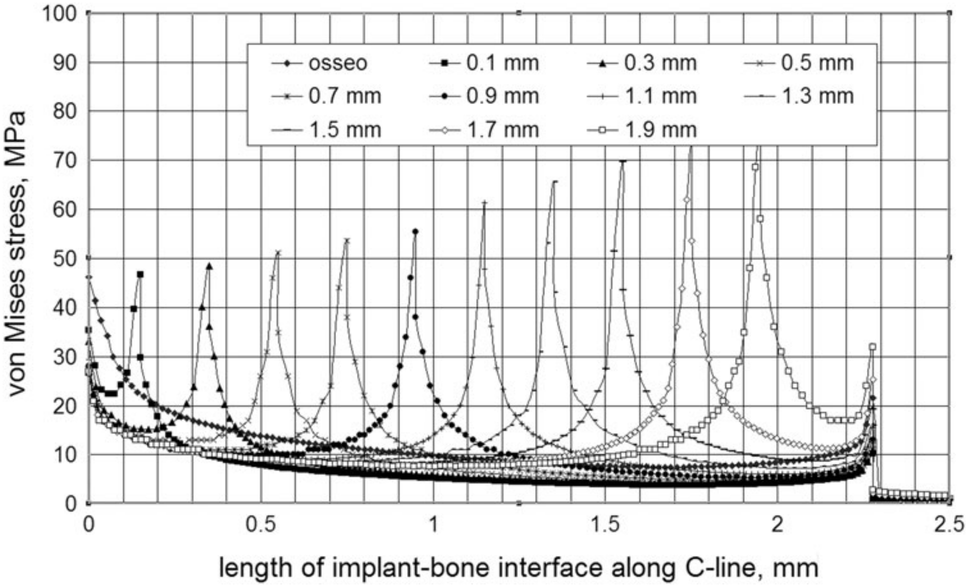

Figure 2. Distribution of von Mises stresses in crestal bone along the C-line length of implant–bone critical interface for a 4.1-mm diameter and 12.0-mm length implant at different levels of bone loss (from 0.1 to 1.9 mm). Rhombus symbol indicates complete osseointegration condition.

Bone density is evaluated on CT images analyzing the Hounsfield units. They are not interrelated directly with its elasticity modulus, which is a key factor in FE simulation. Unfortunately, accurate instrumental tools for determining bone elasticity parameters of living tissues are not yet available. Due to widest variation of bone elasticity moduli (Geng et al. 2001), we proposed the most critical conditions for defining viable implant dimensions and evaluating its longevity by considering the most unfavorable scenarios, i.e., analyzing the shortest lifetime of an implant. For this purpose, we used the largest experimentally measured 275 N occlusal load for the molar site according to Mericske-Stern and Zarb (1996). Bone elasticity moduli were selected assuming hard cortical ($E = 13.7$ GPa) and soft cancellous ($E = 1.0$ GPa) bone. This assumption manifested into the largest acting stresses and corresponding shortest longevity of implants. Exactly, these extreme data can aid specialists in safe treatment planning and evaluation of possible bone failure risk.

It was also proven that the critical point of implant–bone interface found in our previous studies (Demenko et al. 2011, 2013, 2014a, 2014b) was submerged apically due to gradual bone loss and extreme stress values in this point predetermined implant failure. It was found that von Mises stresses in cancellous bone were much lower than in cortical bone mainly reflecting the difference in elasticity moduli of these tissues. This fact concourses with findings of other studies. In contrast, in the present study, different tendencies of cortical and cancellous bone stress variations with bone loss propagation were discovered. They are generally predetermined by bone quality type and the level of bone loss. For the range of implants inserted in Type II bone and bone loss up to 1.9 mm, it was proven that von Mises stresses in the cortical bone predestine the load-carrying ability of the particular implant and its lifetime. However, the most dramatic scenario would be migration of the critical point into relatively soft cancellous bone (5 vs. 100 MPa ultimate strength for cortical bone).

It was concluded earlier (Himmlová et al. 2004) that optimum choice is an implant with the largest diameter based on bone quantity because increasing the implant diameter significantly decreases stresses and increases implant load-carrying ability. Interestingly, the results visualized in Figure 3 show that short implants (8 mm) with a sufficient diameter have a better survival rate than the longest ones with small diameters. The graph clearly shows that width is more advantageous than length considering the longevity of implants: at 180 N level the 3.3 × 14.0 implant reaches the critical point in 1 year, whereas the 4.8 × 8.0 implant in ca. 8.5 years. This remarkable result is important for implant planning and following prosthodontic treatment. That is why pre-implantation efforts should focus on keeping or establishing the width of alveolar bone rather than on its height.

It should be mentioned that according to Wolff's law, significant reduction of stresses in bone is also an important generator of noncontrolled bone loss (Lucas et al. 1999). The only way out is in stress level regulation by all available means including thread profile and neck

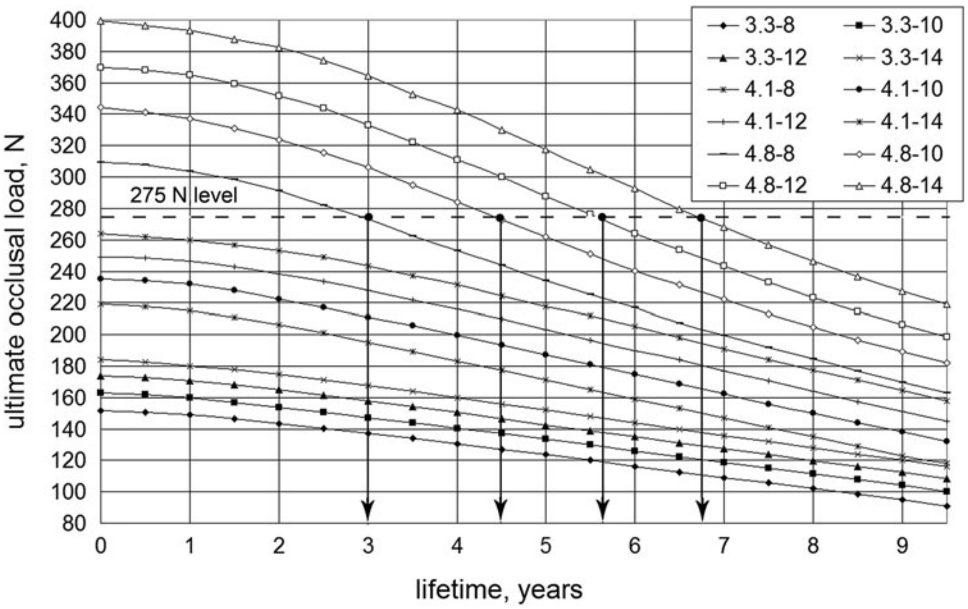

Figure 3. Decrease in the implant load-carrying ability due to bone loss in successful osseointegration conditions (0.2 mm per year bone loss). Based on 275-N ultimate occlusal load, 8 of 12 implants (below dotted line) were found inconsistent to the concept of successful implantation. The longevity of remaining four implants is shown in years.

shape improvement (Hansson 1999; Hansson & Werke 2003). These procedures are applicable nowadays together with numerical simulation advancing, which would allow to avoid both bone over- and underloading. Another problem originates due to destruction of periodontal neural feedback pathways after tooth extraction (Feine et al. 2006). Due to their partial compensation in patients with dental implants, nonpredictable and nonsystemic bone overload may take place resulting in bone loss. Unfortunately, numerical analysis cannot reflect this phenomenon.

For clinicians, the findings of this study could be an aid in choosing appropriate implant design and evaluating possible bone failure risk or advising patients in the prognosis of their implant.

Disclosure statement

The authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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