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Fundamentals of biomechanical analysis of immediately loaded dental implants

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Success of immediately loaded dental implant can be achieved by selecting appropriate implant dimensions through establishing their correlation with interfacial strains which are responsible for bone healing and osseointegration process. This study aim was to correlate maximal bone strains induced by variable-sized implants with functional loads for the purpose of their comparing with mean experimental functional load. 3D models of 24 implant-bone assemblies were designed and finite element analysis was performed in ANSYS 15. Maximal first principal strains were analyzed. Current ultimate functional load values, corresponding to 3000 μstrain of pathological bone turnover, were determined and compared with 120.92 N mean experimental functional load to evaluate the success prognosis. Strains were found directly dependent on bone quality and implant dimensions. So, bone strains alone have an impact on immediate loading success. It is favorable for tested implants placed in type III bone, if functional load does not exceed 120.92 N. Type IV bone is completely unacceptable for immediate loading.
Keywords: dental implant; immediate loading; strain; finite element method

Introduction

Immediate loading is defined as “a restoration placed in occlusion with the opposing dentition within 48 hours of implant placement” [1] The success of immediate loading is predetermined by tolerable strain level in bone-implant interface because bone strains are usually regarded as the important phenomenological stimulus for bone healing process [2]. Frost theory [2] suggests that strain levels in bone surrounding dental implants should be kept within an acceptable range. Frost defined strain thresholds that have to be exceeded to induce different bone adaptation processes: minimum effective strain for remodeling (MESr), modeling (MESm) and pathological (MESp), and their values were proposed as following: 50–100, 1000–1500 and 3000 μstrain. For successful bone healing, in implant immediate loading, strain level should be above MESr, but below MESp. Furthermore, for increase of bone mass around implants, strains should be kept above the MESm. Therefore, biomechanical investigations may aid in establishing the interactions between the factors which influence bone strain magnitude: (a) quantity of bone and its quality described in terms of mechanical properties, such as modulus of elasticity and Poisson’s ratio; (b) implant dimensions; (c) parameters of bone-implant interaction [3-5]. It is only computer simulation of the bone-implant interaction that allows to interrelate functional loads and strains. By its means, the impact of implant dimensions and bone quality on stress-strain spectrum may be quantified. Since strains are to be limited by the abovementioned thresholds, it becomes possible to determine ultimate functional load for particular implant [6], beyond which bone healing under immediate loading is impossible. With such approach, comparing the ultimate functional load with its experimentally established mean value for the particular site [7], the implant success can be evaluated [8]. The aim of the study was to correlate maximum strains generated by different-sized implants under different bone quality conditions with functional loads to determine their ultimate values for the purpose of evaluating the prognosis of immediate loading.

Materials and methods

The 3D geometrical models of bone segment were generated considering micro-computed tomography (CT) images. They simulated Types III and IV mandibular bone according to Lekholm and Zarb classification [9] and consisted of two volumes: shell of cortical bone with 1.0 mm thickness and cancellous core (see Fig. 1). Bone tissues were assumed to be ideally connected. Gingival soft tissues were not modeled. Outer diameter and height of the model was set to 22 mm, so stress and strain fields were localized in vicinity of implants.

CAD models of implants spectrum, which represented Straumann® Bone Level implants, were designed: 3.3, 4.1 and 4.8 mm diameter and 8.0, 10.0, 12.0 and 14.0 mm length. Each implant model included an abutment with 4.5 mm height. Implant and abutment were considered as rigidly connected. Implants were assumed to be in friction contact (0.3 frictional coefficient) within cortical bone. This condition simulated zero osseointegration in healing period. The contact zone transferred pressure and also tangential forces. Within the limits of cancellous bone, implants were assumed to be rigidly fixed. FE analysis was performed in software ANSYS 15 with 20-node quadratic SOLID 185, SOLID 186 finite elements. For surface contact modeling, CONTA174 vs. TARGE170 elements of 0.1 mm minimum size were generated. The total number of FEs was up to 1,370,000. Mapped meshing was applied. Loading of the implants, with forces of 116.8 N and 31.4 N in axial and horizontal directions, respectively, simulated 120.92 N experimental mean maximal functional load [7] at a 75 degrees angle to occlusal plane (Fig. 1). Due to force and geometric symmetry of the models application FEs were refined.

For boundary conditions, nodes on cylindrical surface of bone models were restrained, i.e. the boundaries were absolutely fixed. These boundary conditions were selected after comparing the stress distributions at peri-implant region of the whole mandible model and 22 mm diameter and height bone segment model (convergence test). All materials were assumed to be linearly elastic and isotropic. Implants and abutments were assumed to be made of titanium with 114 GPa modulus of elasticity and 0.34 Poisson’s ratio [10]. Poisson’s ratio of bone tissue (both cortical and cancellous) was assumed to be 0.3 [11]. For both bone types, modulus of elasticity of cortical bone was 13.7 GPa [11]. For Type 3 bone, Modulus of elasticity of cancellous bone was 1.0 GPa and for Type 4 bone it was 0.2 GPa.

A concept of ultimate functional load [6] was applied to compare load-carrying capacity of tested implants and to correlate ultimate functional load magnitude for a specific implant with experimental functional load for the particular anatomical site. Maximal first principal strain in bone-implant interface was proposed as a criterion of bone failure risk/success and was calculated for each implant and bone quality type under 120.92 N mean experimental functional load. Ultimate functional loads, which corresponded to 3000 µstrain (MESp) were calculated assuming linear correlation between load and strain. Each UFL value was compared with 120.92 N mean experimental functional load [7] to estimate the perspective of immediate loading success for studied implants and bone types.

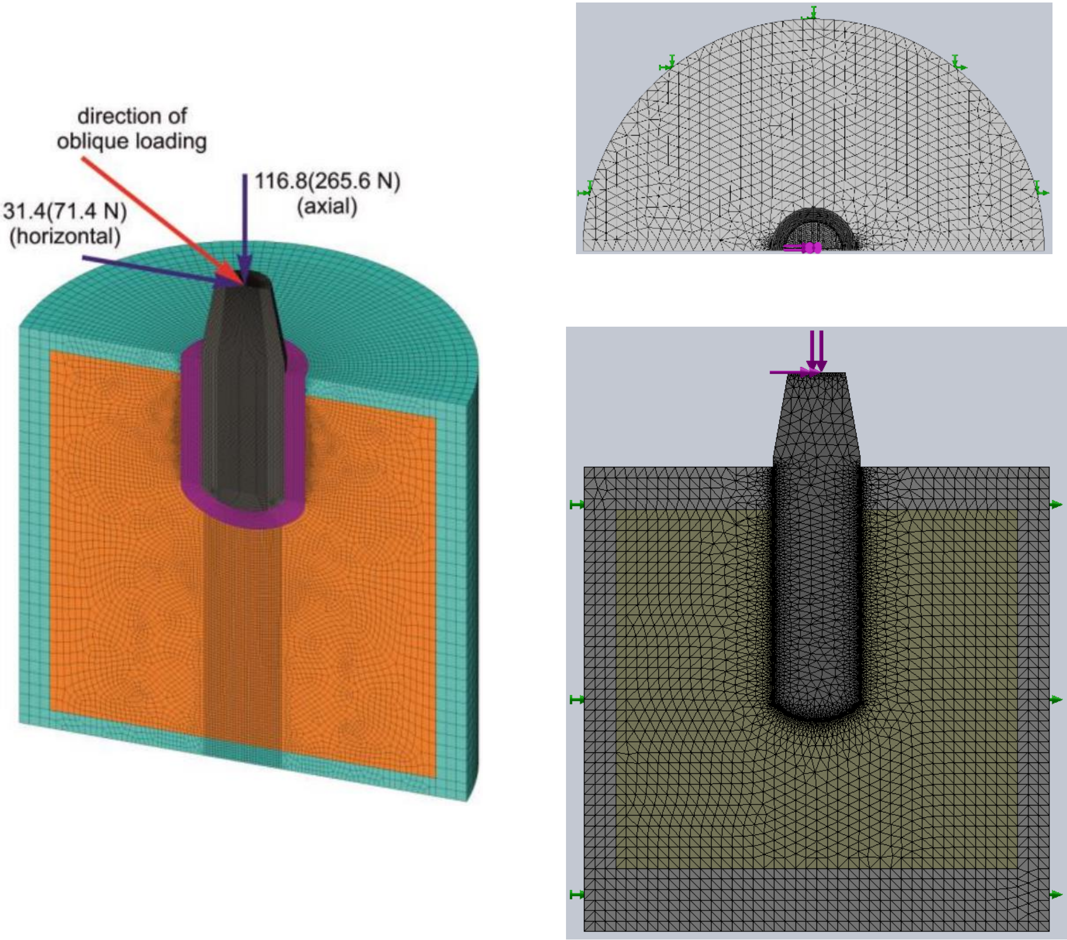

Fig. 1. 3D FE model of types III-IV bone segment with placed implant. Cylindrical surface of the model is restrained. Thin arrows represent components of 120.9 N oblique functional loading applied to the center of abutment upper surface at 4.5 mm distance from bone margin. Symmetry condition was used in the model design.

Results

First principal strain distributions along the critical bone-implant interface were analyzed to find areas of strain concentrations. It was found that maximal first principal strains were located in cortical-cancellous bone interface. These strains are illustrated on Fig. 2 for III-IV bone quality conditions. Ultimate functional load magnitudes, which generated 3000 μstrain of maximal first principal strain were calculated. They are shown on Fig. 3 for the spectrum of implants and III-IV bone quality types.

Effect of implant length on ultimate functional load magnitude was studied for different bone quality types. In Type III bone, length increase from 8 mm to 14 mm for narrow implants (3.3 mm diameter) caused ultimate functional load rise from 224 N to 365 N (63%), while for wide implants (4.8 mm diameter) it was from 305 N to 443 N (45%). 15 In Type IV bone, length increase from 8 mm to 14 mm for narrow implants (3.3 mm diameter) caused ultimate functional load rise from 68 N to 101 N (49%), while for wide implants (4.8 mm diameter) it was from 88 N to 127 N (44%).

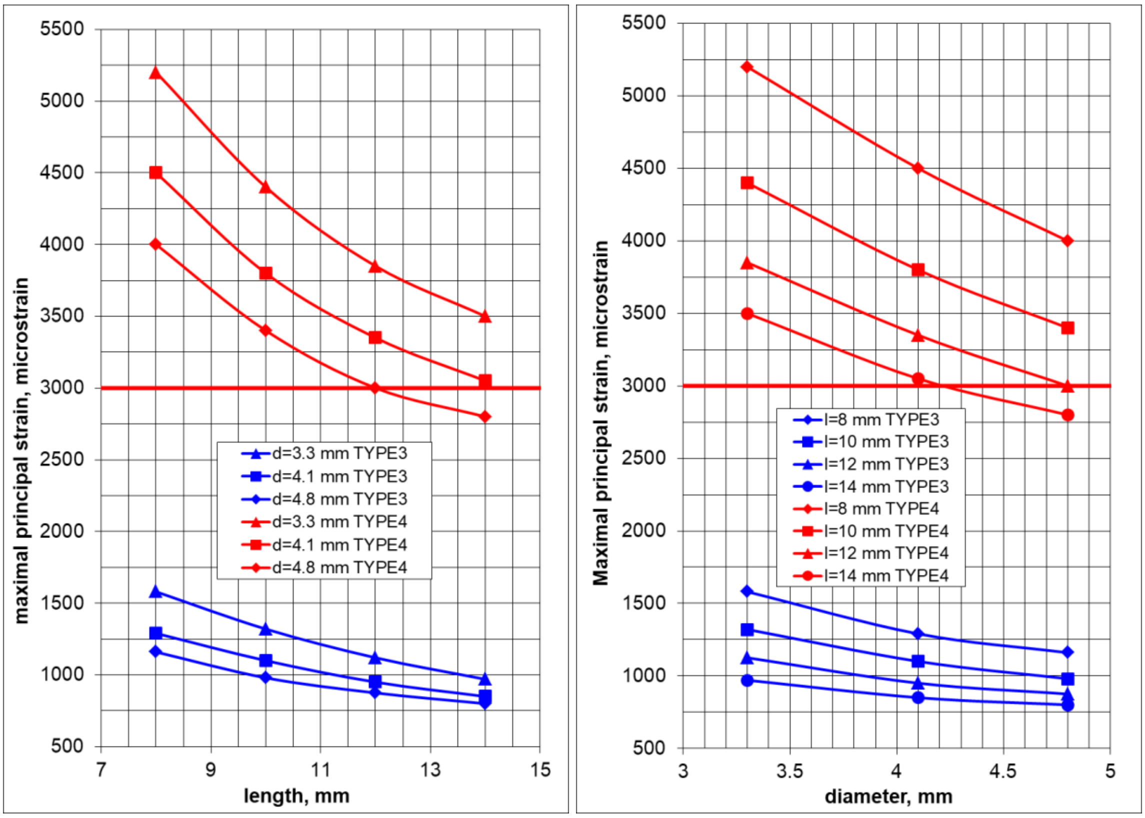

Fig. 2. Maximal first principal strain dependence on implant length (a) and diameter (b) for III-IV bone quality types.

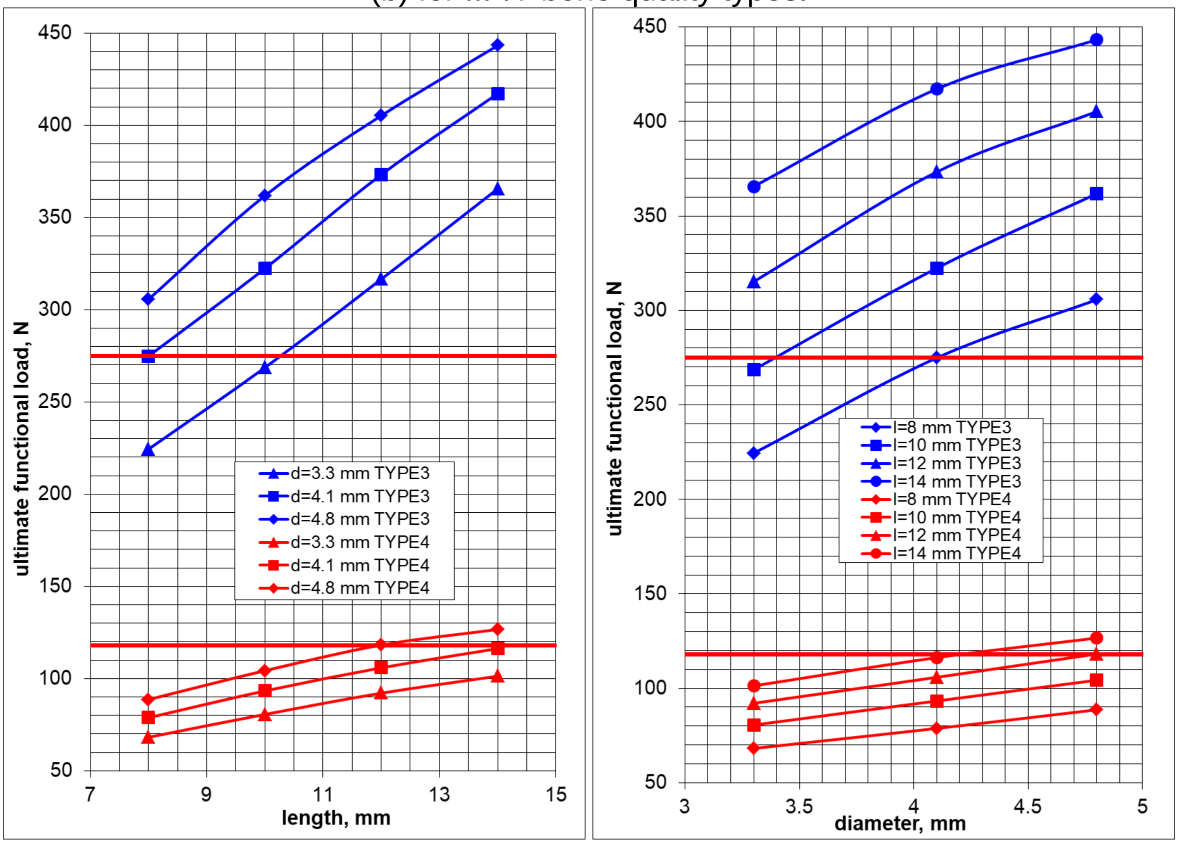

Fig. 3. Ultimate functional load dependence on implant length (a) and diameter (b) for III-IV bone quality types

Impact of implant diameter on ultimate functional load magnitude was also studied for considered bone quality types. In Type III bone, diameter increase from 3.3 mm to 4.8 mm for short implants (8 mm length) caused ultimate functional load rise from 224 N to 306 N (37%), while for long implants (14 mm length) it was from 365 N to 443 N (21%). In Type IV bone, diameter increase from 3.3 mm to 4.8 mm for short implants (8 mm length) caused ultimate functional load rise from 68 N to 89 N (34%), while for long implants (14 mm length) it was from 101 N to 126 N (25%).

Prognosis of successful immediate loading was evaluated under results of ultimate functional load magnitudes comparing with experimental functional loads. In the case of 120.92 N mean experimental functional load for mandibular first molar [7], the implants which corresponded to the symbols above the lower bold line on Fig. 3 were considered as successful.

Conclusions

In present study, numerical simulation of immediate loading was applied not only for analysis of strain distributions in bone-implant interface, but mainly for transformation of strain magnitudes into numerical parameters of implant success. Within the spectrum of implants and loading conditions, several conclusions seem to be important. (A) Bone strains are directly influenced by bone quality and implant dimensions. (B) Bone strains had a strong impact on immediate loading prognosis. The pattern of strain distribution was found identical for every diameter and length, with critical strain localization in cortical-cancellous bone interface. This finding allowed us to determine the essence of eventual bone failure due to overstrain. (C) It was found that ultimate functional loads and also, the implant load-carrying capacity, were significantly dependent on implant diameter and length in case of implant placement in types III and, especially, IV bone. (D) The results of present simulation have showed that implants with larger diameter help to reduce strains and thus may be a better choice in clinical situations for Type III bone quality conditions.

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Основи біомеханічного аналізу зубних імплантатів з миттєвим навантаженням

Успішність життєвого циклу дентального імпланта за миттєвого навантаження можна забезпечити шляхом вибору його розмірів за наслідками встановлення їх кореляції з деформаціями прилеглих тканин, від яких залежить відновлення кістки та процес остеоінтеграції. Метою цього дослідження було встановити зв’язки максимальних деформацій кісткових тканин, викликаних імплантами різних розмірів, з поточними функціональними навантаженнями з метою порівняння останніх із експериментальним функціональним навантаженням. Було розроблено 3D-моделі 24-х біомеханічних систем «імплант-кістковий сегмент» та виконано скінченно-елементний аналіз їх деформованого стану із використанням ANSYS 15. Було проаналізовано найбільші перші головні деформації за умов косого функціонального навантаження. Граничні функціональні навантаження, які відповідають 3000×10^{-6} граничній патологічній деформації кісткової тканини, були визначені та порівняні з 120,92 Н експериментальним функціональним навантаженням для визначення перспектив успішності. Було кількісно встановлено, що деформації та граничні функціональні навантаження суттєво залежать від якості кісткової тканини та розмірів імпланта. Таким чином, рівень деформацій визначає перспективу успішності миттєвого навантаження. Вона позитивна для вивчених імплантів, які вживлено у кісткову тканину III типу якості, якщо функціональне навантаження не перевищує 120,92 Н. Кісткова тканина IV типу якості абсолютно неприйнятна для миттєвого навантаження дослідженими імплантами.

Ключові слова: дентальний імплант; миттєве завантаження; деформація; метод скінченних елементів

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