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Silicone attachment for avoidance of bone tissue overloading in single implant-retained denture

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ABSTRACT

Purpose: The application of single implant-retained dentures (SIDs) is still rare. It seems that the reason of that is the fear of the overloading of a bone tissue around the implant that alone bears the occlusal loads. In this paper, stress level in the bone tissue around the single mini-implant that alone retained the lower denture was investigated. This stress level depends on the denture joint (the attachment) to the implant.

Design/methodology/approach: 3D finite element method (FEM) analysis was used in order to determine the transmission of occlusal loads between mucous membrane foundation and the bone tissue around small diameter (1.8 mm) implant. Standard rotationally and axially mobile denture attachments were compared with the laterally compliant silicone attachment. Oblique mastication loads were assumed for the purposes of a better simulation of realistic conditions.

Findings: Both types of standard attachments, rotationally and axially mobile, born remarkable values of oblique mastication force. This load results in a high stress in the bone tissue around a single mini-implant, in the area convergent with clinically observed "funnel-shaped" marginal bone loss around the implant neck. The silicone attachment reduced the loading to a level, which did not create any stress that would be dangerous for the bone tissue.

Research limitations/implications: In the FEM model a perfect denture adherence to mucous foundation was assumed and a perfect joint between the implant and bone tissue. Further simplification were the linear isotropic characteristics of used materials.

Practical implications: The use of single mini-implants requires the highest quality of the alloy and surface finishing due to the risk of fatigue cracks in case of a quickly progressing "funnel-shaped" bone loss. The silicone attachment provided better utilization of the mucous membrane support that significantly improves safety of implant and diminishes the requirements of bone foundation conditions for an implantological treatment.

Originality/value: Presented was a possibility to achieve a much more reliable SID by means of used silicone attachment.

Keywords: Denture attachment; Biocompatibility; Narrow implant; Load; Force

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

The complete edentolouism, which is a problem faced by numerous elderly people, constitutes an object of concern for both the dentists and people responsible for medical techniques. This problem afflicts, in a number of European countries, more than 70% of elderly people and 25-30% elderly people in North America [1]. Technological development makes available new generations of biomaterials, new equipment for their treatment and the clinical tools aiding planning and conducting of procedures, starting with obtaining impressions and finishing on dental implants. In the branch literature there are many cases of reporting an increased successfulness of the rehabilitation of edentolous oral cavity in case of the dentures equipped with implants. Nevertheless, there is still a lack of remarkable improvement that might bring benefits to a larger population of patients. The improvement is possible by defining and setting parameters for particular factors that influence functional characteristics of the system denture-oral cavity tissues. Due to the function that is played by the denture, as the most important should be treated all problems related to biostatics perceived as mutual relations between mastication (occlusal) forces and loads on denture supporting tissues. The occlusal forces, depending on various types of dentures are relatively well determined, as the measurement of active occlusal forces is available in clinical practice and can be used in individual cases. Evaluation of the support reactions forces in a larger scale is not feasible. Moreover, the loads of soft tissue foundation still belong to the least determined phenomenon, which is crucial in assessment of the clinical success.

The difficulties related to the search of relations between denture biostatics and natural tissue reactions cause that this area is still poorly recognized. Limited possibility of clinical experiment and the number of factors influencing loading studies in the natural oral cavity conditions makes it necessary to use modeling methods, including physical in vitro simulations, and especially numerical FEM analyses that make it possible to evaluate mechanical conditions of constructions that replace natural tissue and tissues loading [2]. Although, model studies do not reflect the real conditions to 100%, they make it possible to assess the influence of particular factors and meaning of system structures, which is necessary for a physical determination of the cause-result relations and to point the direction of activities.

The tissues reactions, depending on the manner, in which the denture is supported are loadings of the mucous membrane or bone tissue adjacent to implant or one and the other at the same time. In case of a typical, fixed implant-dentures the whole occlusal loading is transmitted by the implants onto the bone tissue. It is worth mentioning that the typical implant-dentures that give high sense of comfort are available for a relatively small population of wealthy patients. Economical barrier results from single implant price, as well as denture suprastructure costs. In case of the implant-denture, in order to ensure a safe level of bone tissue loadings around the implant it is necessary to increase the number of implants to 5 and often even to 6 or 8.

The search for less expensive dentures solutions and more available for a wider population of patients has lead to introduction of an edentolouism treatment standard, in which there are used 2 implants only. They are located in the front section of the alveolar process in order to improve the retaining and stabilization of the conventional lower acrylic denture. These solutions; the so-called “two implant-retained soft tissue-supported dentures” (TID), also called “two-implant overdentures”, belong to the safe, as far as the risk of implant loss is concerned unless the foundation conditions are insufficient. A method, in which the denture is attached to the implants, is crucial for the function of the implant-retained overdentures. The attachment has to it make possible to settle the denture and to use the mucous membrane supporting function. Together with the increased use of the natural support areas on mucous membrane there takes place a desired reduction of implants loads. Nevertheless, attachments solutions that are available on the market do not show required reliability. Very common are: excessive wear and failures of attachments, abutment failures and denture fractures close to implants [3]. “Funnel-shaped” marginal bone loss around implant neck are also quite common. These effects prove that implants bear excessive occlusal loads. In case of worse osseous conditions the risk of implants loss increases, especially if there is a large bone loss around the implant neck [4].

The effective methods of decreasing the overloading effects are the silicone attachments [5]. The silicone elastic attachments between the denture and implant that enables denture displacements according to the mucous membrane deformations, which take place during its loading. The commercial attachments enable only the denture rotation along the axis created by the two attachment points. Denture displacement restriction in directions along the oblique mastication forces results in remarkable lateral loads of the implants [6]. The term of “mechanically bio-compatible attachments” is more a marketing trick based on the phenomenon of a low risk of loss of implants that are correctly located in the front section of the mandibular bone. The silicone attachments are in fact mechanically biocompatible, as they enable the implants lateral loads monitoring depending on the attachments lateral compliance. Design of silicone attachments was presented in detail in paper [5]. Thanks to a well considered selection of the silicone material elasticity and the interference in relation to implant diameter there was achieved an increased attachment durability, as the frictional wear that accompanies mastication is decreased [7]. Lately, there were presented in paper [8] the possibilities of increasing silicone attachment resistance to fungal and bacterial colonization by means of a modification with nano-particles.

The TID solutions were accepted as a standard in the mandible edentolouism treatment based on numerous clinical experiments, mechanical studies and material conditions of their functioning. A reduction of costs resulting from the prosthetic treatment for overdentures is possible by reduction of the number of implants that retain the lower denture from two- to single-implant-retained dentures (SID). The results of clinical examinations of such a type of solutions are quite promising [9-11]. Nevertheless, in spite of a dozen of years that passed since the first clinical experiments with SID, the clinical material is still too poor to make a single implant-retained denture a standard in implantological treatment. Especially, the knowledge of the occlusal loads distribution, which should constitute the base of using new implantological solutions is still very weak. It can be assumed that the reason why these attempts were so rare is the fear of overloading the single implant. In previously presented biomechanics in vitro examinations [12] there was assumed a model scheme of denture loading with the vertical occlusal forces only. Due to that the achieved attachments and implant loading values might remarkably differ from the real ones.

The previous experiences with the silicone attachments show that there is a possibility to achieve a less loaded implant in case of the SID. In this paper there is presented a FEM estimation of the loads of the single implant that retains the lower denture. The hypothesis of the work was the statement that the implants loads that accompany mastication are remarkably higher in case of commercial attachments than in case of the silicone attachments.

2. Methods

2.1. FEM analysis of occlusal loads transfer onto the single implant

In the model analyses it is necessary to select the system characteristics that influence the examined phenomenon and to neglect the remaining characteristics that only make the model more complex [13]. The Conditions of a model FEM analysis of SID occlusal load transmission biomechanics is illustrated in Fig. 1. Here abandoned was the attempt of a precise representation of teeth shape, which was unnecessary for the purposes of the described studies and which would significantly increase the size of numerical analysis. There was selected for the analysis a case of an osseous foundation with strongly atrophied processes and flat slopes, where due to a small resistance plane there occur a higher implant load. There was assumed a similar shape of the edentolous processes and a constant system of layers as presented on the cross-section in Fig. 1.

In order to simplify the calculation procedures for all of the system structures, linearly elastic mechanical characteristics were assumed. The average mucous membrane thickness was assumed on the level of 2-3 mm. The influence of the mucous membrane compliance on the attachments loadings was investigated by means of the assumed extreme Young modulus values 5 or 1 MPa. The incompressibility was, to some extent, represented by the high Poisson ratio $\nu = 0.49$. For the cortical bone assumed was Young modulus $E = 17$ GPa; whereas for the spongy bone $E = 600$ MPa; at the Poisson ratio in both cases equal $\nu = 0.3$. The denture material characteristics were described with $E = 2000$ MPa and $\nu = 0.3$.

The central implant location was examined without the marginal asymmetric shift resulting from the anatomical reasons. In the paper authors proposed a different approach to the model boundary conditions that enables a determination of the implantological supports loads without the necessity to construct a complex system of the attachments together with the implantological construction. The directional constraints were introduced in the attachment location. They reduce the freedom of denture displacement in relation to the implant according to the principle of the attachment functioning. According to the FEM principles, the complicated task was divided into the two independent sub-tasks. The first task is based on the analysis of denture biomechanics and implants loadings depending on the type of attachments. The values of these loadings constitute the input data for realization of the second task. This second task was to analyze bone tissue loadings around the implant. It was realized separately on a distinct model. There were examined the most common types of the attachments, in which there is enabled a freedom of rotation around the fixing point (marked as „R”). Due to the construction and the used materials, these commercial attachments are characterized by a negligible lateral compliance. In the output calculations there was assumed a high stiffness value of 50,000 N/mm both for the directional constraints and for the joint support. Then, there was conducted series calculations, in which the possibility of implant bending was allowed by means of a gradual reduction of the constraints stiffness down to 1,000 N/mm.

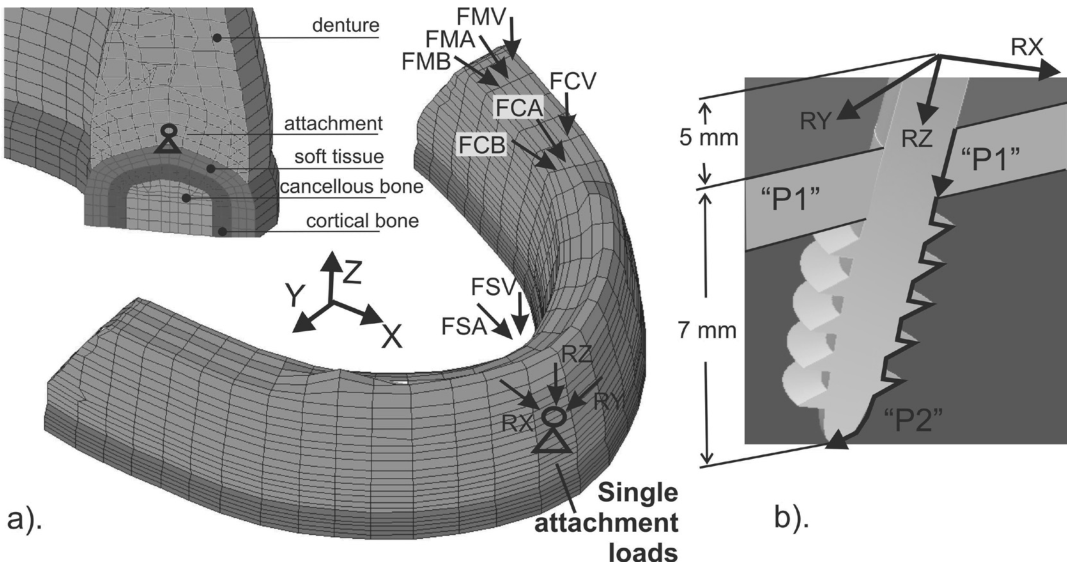

Fig. 1. FEM model analysis conditions (a) Small diameter and length of a mini-implant retained lower denture (b) A Scheme of reaction forces on implant calculated from the first step analysis of occlusal load distribution and the material groups

There was also examined an attachment that has a freedom of mobility along the implant axis (marked as „M"). The silicone attachment ("S") with a lateral stiffness of 40 N/mm and a vertical stiffness of 7 N/mm was compared to the standard commercial attachments. The attachment stiffness was determined for a ring-shaped model [5] with a typical prosthetic silicone material characterized by the Young's modulus equal 5 MPa and the Posisson ratio on the level of 0.49.

The entire model was fixed at the bottom of the mandibular bone segment. The ideal denture adherence to the surface of the mucous membrane was assumed. In this way it was assumed that the comparison of attachments loadings is conducted for the conditions of a stable denture-to-foundation pressure. Nevertheless, a special attention was paid to the realistic loading of the denture with an oblique forces that accompany mastication. In such a case, the denture is not only vertically pressed to the foundation, but also additionally settled by oblique forces, which results in an increase of the attachment load. The attachment load resulting from reactions in the assumed constraints were analyzed for a number of locations and directions of the occlusal forces of 100N. There was assumed an ccclusal force in the molar zone that is oriented buccally under the angle of 45 degree (FMB). In the second analyzed case there was assumed a force applied at the angle of 45 degree towards the front in the sagittal plane (FMA). The denture reaction in a case of a relocated occlusal force applied in the premolar zone (respectively FCB and FCA), as well as a case of loading on the incisors by the force applied at the angle of 45° towards the front plane (FS) was also analyzed. Additionally, there were determined the attachments loads with an assumption that the occlusal forces were directed only vertically: in the molars zone (FMV), premolars zone (FCV) and on the incisors (FSV).

2.2. A FEM analysis of stresses in the bone tissue around the implants

During the next stage there assessed the stresses, which take place in bone tissue around the implant. They result from transmission of loadings calculated in the previous section. In Fig. 1 there is presented a model cross-section that illustrates the analyzed geometrical characteristics of the implant. There was assumed the-implant geometry that is matched to a strong atrophy of alveolar processes. Hence, there is an extremely shallow anchorage in the bone on the length of 7 mm and a small diameter of 1.8 mm. In case of the commercial attachments the values of the lateral loadings that accompany mastication depending on foundation compliance and in case of the applied occlusal force they were close to 60 N (FCA). Such a force was transferred onto the implant in the distance of 5 mm above the bone surface. Although, in the case of a more compliant mucous membrane and the applied occlusal force FS there was measured maximum lateral load of 65.6 N. Such remarkable values of forces on the incisors for mucous membrane-supported dentures are, in practice achieved very rarely. Moreover, the loadings that accompany food biting off are remarkably less cyclical than the mastication. There were assumed the values reflecting the mastication forces for the purposes of calculation. Between the implant and the bone there was assumed a perfect adherence. The analyzed bone zone was reduced to the cylindrical shape around the anchoring. The model was fixed to the lateral and lower surface of the cylindrical bone segment.

According to the previously assumed bone tissue characteristics, the cortical bone thickness was assumed at the level of 2.0 mm; cortical bone Young modulus of 17,000 MPa, whereas for the cancalleous bone E = 600 MPa; at the Poisson's ratio in both cases equal ν = 0.3. For the implant there were assumed characteristics of titanium alloy E = 140 000 MPa and ν = 0.3.

3. Description of achieved results

The values of forces bore by single R-type attachments for the analyzed occlusal forces variants were presented on the diagram in Fig. 2 and Fig. 3, respectively for the cases of a more and a less compliant mucous membrane. The absolute resultant value of the lateral forces, i.e. transverse to the implant axis in horizontal „XY" plane were presented as the bars. The values of „Z" axial component were presented divided to negative values resulting in pressure on the bone and the positive values creating pulling upwards, i.e. striving to open the attachment in the moment, when the attachment retention limit value is reached.

Fig. 4 presents the influence of implant deflection for the analyzed range of the stiffness on the value of the bore lateral loads (in case of the less compliant mucous membrane). Fig. 5 shows the loading bore by the attachment characterized by an axial mobility „M" as compared to the laterally compliant silicone attachment „S". Fig. 6 presents values of stresses in the bone adjacent to the implant combined with "R" commrecial attachments or silicone attachment „S". The diagram in Fig. 6a shows the profile of an equivalent Huber-Mises stress along the "P1" path in the cortical bone tissue at the side compressed by the bent implant. The stresses in the cancalleous bone along the "P2" path were presented on the Fig. 6b. A graphic representation of stresses in the implant was omitted. The stresses in the implant in case of commercial attachments reached the yielding point at the level of 700-880 MPa for a cold-forged titanium alloys Ti6Al4V. The distribution of stresses in a mini-implant were similar to those occurring in TID solutions that were analyzed in paper [6]. The zone, in which the yielding stress was exceeded was very small at the edge of the implant introduction to the bone. Nevertheless, such a situation creates the need for high requirements regarding the quality of the implant. Especially, the defects in implant surface finishing contribute to a decrease of the fatigue strength [14]. In case of the silicone attachments the stress was lower proportionally to the decrease of the force bending the implant (Fig. 5).

The determination of SID biomechanics is limited to a single paper based on the calculations conducted on a physical model [12]. In these studies it was proven that solutions based on single implant does not varies from the standards set by the solutions based on two implants, as far as implantological foundation loadings are concerned. The comparisons were although carried out with assumed dominant role of the vertical occlusal forces. The Conditions, in which there are applied occlusal forces have basic importance, as far as the level of the implantological supports reaction is concerned. The risk determinant for a clinical failure is constituted by the forces creating implant bending, as pressing is perceived as much less dangerous [15,16].

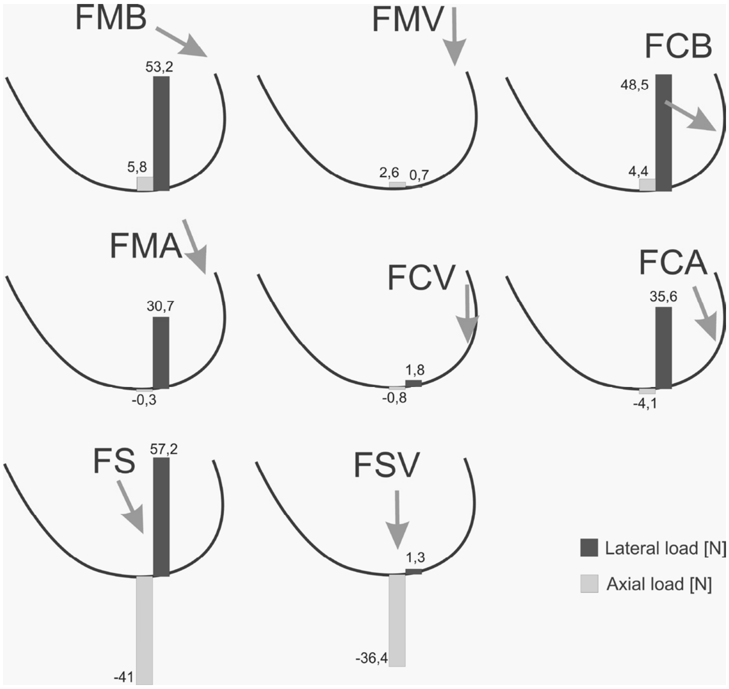

Fig. 2. Lateral and axial forces for „R" ball and stud rotational attachments under assumed occlusal loads Mucous membrane elasticity E = 5 MPa

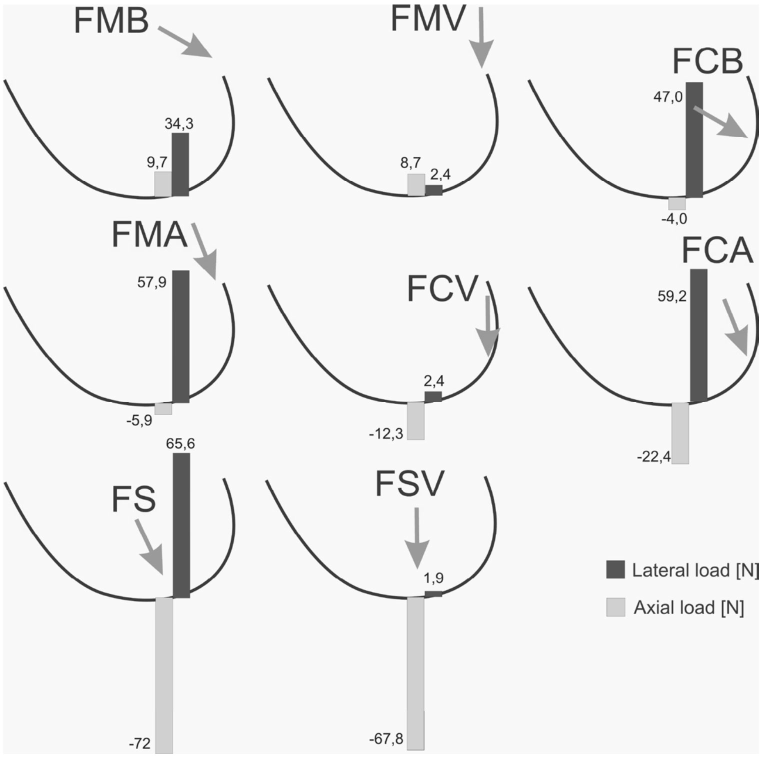

Fig. 3. Lateral and axial forces for „R" ball and stud rotational attachments under assumed occlusal loads. Mucous membrane elasticity E = 1 MPa

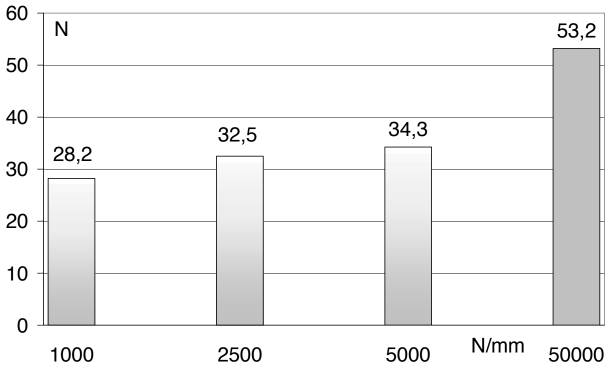

Fig. 4. Lateral load for "R" ball attachment under oblique mastication forces FMB for a different lateral stiffness of the single implantological support. Mucous membrane elasticity E = 5 MPa

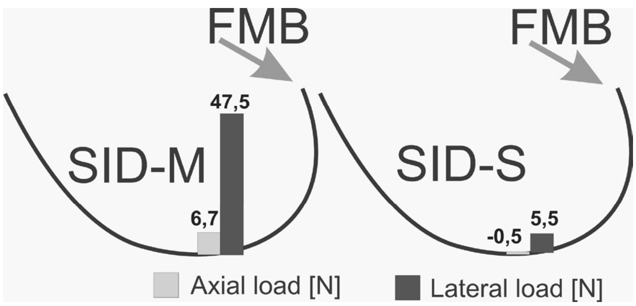

Fig. 5. Lateral and axial forces for the axially mobile attachment "M" and silicone resilient attachment „S" under oblique mastication force (FMB). Mucous membrane elasticity E = 5 MPa

A lot of studies confirm that loading the denture with vertical mastication forces results in a remarkable underestimation of lateral attachments and implants loadings [17-19]. As it was proven in the elasto-optical experiment conducted for TID in paper [20] there is a lot of variety among the loadings around implants, in case of applied vertical force and an oblique force. Oblique forces creates a much higher loading around the implant at the working side. In paper [21] a FEM analysis of the stress distribution around the implant shows that the force deviation from the vertical direction up to 60 degrees results in an increased stresses respectively from 3.5 MPa up to 25.3-28.1 MPa. The attachments analyzed in work [21] did not differ a lot as far as bone loading transmission is concerned. In spite of a remarkable constructional differences the stress design in the bone were only different by 2.8 MPa, i.e. by maximum 10%. In the paper [21] attachments were compared with the same implant and abutment construction. The reason for doing so was the attempt to ensure the same arm of the lateral forces that bend the implant. Nevertheless, the small differences between stresses in the bone might result from a different distribution of contact stresses in the attachment, which leads to a small differentiation of the resultant of lateral forces that bend the implant. Hence, the results of the studies [21] justify the assumed model simplification based on a replacement of the complex attachment design with the elastic constraints. It is worth mentioning here that if the attachments are compared for different implantological solutions, the achieved results vary depending on the different force arm and a different implant diameter. Such comparative studies taking into account the entire solutions but varying as far as their implant design do not make it possible to define the main influence of the attachment functioning principle on the loads that are bore by this attachments. Thanks to the directional constraints that replaces attachments in the model the presented analysis gains an universal character. Possible is an unequivocal evaluation of the loading bore by the attachment depending on the displacement of the whole denture, which are limited by the restraints defined by the type of the attachment.

a)

b)

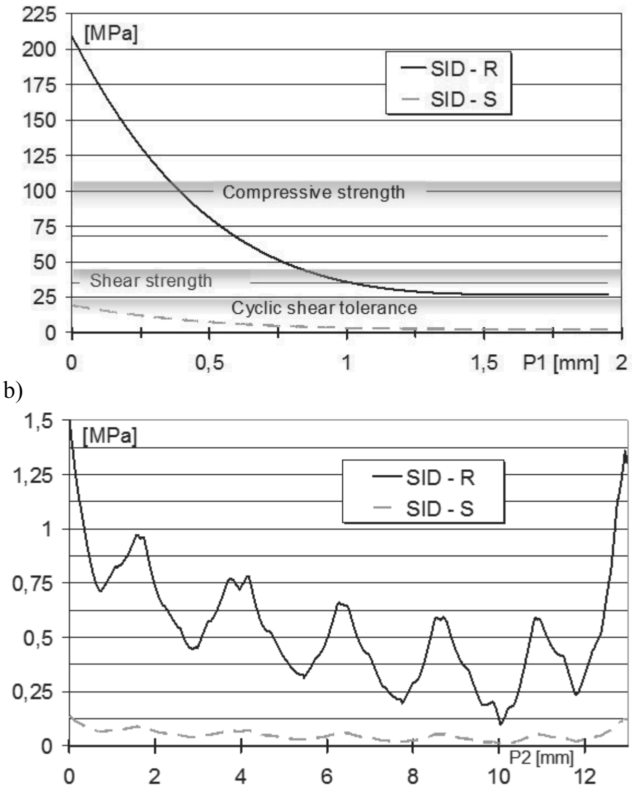

Fig. 6. The equivalent stress in the cortical bone (a) and in the cancellous bone (b) adjacent to a single mini-implant along the paths "P1" or "P2" for the R-type rotational attachments and for the laterally compliant silicone retained S-type attachment

In case of a single support the rotation in the attachment is not restricted, which results in a significant increase of the denture mobility. In such a situation, the lack of lateral mobility seems to be the advantage of the TID solution, which discredits the SID, as a significantly worse solution, as far as the stabilization is concerned. Based on the above, does the reduction of the number of implants to a single one has a different justification than economy only? Especially, when the conclusions resulting from the clinical experiments described in the paper [9], are mainly based on a subjective patients' evaluation. Comparison of subjective evaluations in a situation when the SIDs wearers do not have any reference to a more stable TID solution can be negated. The SID must constitute a remarkable quality improvement for patients that previously faced an insufficiency of the traditional dentures. Hence, in a general evaluation of wearing characteristics the SIDs might not be worse than TIDs. Although, mentioned should be at this point that pain sensations and mucous membrane injuries are main factors, which directly influence both on the objectively measured chewing ability and on the subjective patients satisfaction. In this aspect, clinical results show that SIDs are free from foundation soft tissue injuries [9], which very often accompany wearing of the TIDs. It seems to be a paradox: it is the SID where the loading is to a higher extent distributed onto the foundation soft tissue due to a lower load bore by the implant. This paradox however, explains the fact that in case of SID the foundation is used in a much more even way. The denture tilts towards the applied occlusal force, whereas in the TID irrespective of the occlusal forces direction, due to the forced hinge movement, always the same areas of foundation bear the loadings. Moreover, in case of TID, injuries are also caused by the lower tolerance to inaccuracies in the attachments positioning in relation to the implants. In SID, any deviations created during manufacturing can be to a larger extent compensated thanks to the complete rotation freedom in relation to a single point. In TID hinge-like restraint reduced the possibility of compensating pressures on the processes slopes.

The final clinical result and patient's evaluation is however based on several additional factors. The chewing ability depends on the denture behavior during the phase of a double-sided food mastication, i.e. the function of balancing contacts. Attention should be paid to the fact that chewing ability also depends on counteracting denture detachment and lifting the denture that is glued by the food during the opening phase. These effects were so far neglected during the comparative studies of the chewing ability.

The calculations showed significant values of the attachments lateral loads, which are in compliance with the common problems resulting from the cyclical implant bending. Such bending causes loosening and failures of abutments in case of the two-piece implants. The values are also in compliance with the effects of bone overloading around implants and the changes taking place in implants supporting conditions in the bone of the alveolar ridge [4,22]. The high values of loading bore by the commercial attachments resulted in remarkable stresses in the bone around single implant. These stresses significantly exceeded safety limit, which for a cyclic shear stress should not exceed 30-35 MPa [15]. The maximal equivalent stress reached higher value than those described in paper [21], which results in the used narrow implant. The overloading area is convergent with the "funnel-shaped" bone loss observed in practice around the implant neck. The loss of bone lower than 0.5 mm for the first year and further atrophic decrease of bone within the range of 0.1-0.2 mm/year is assumed as a clinical success. Together with the decreased quality of the bone, the overloading effects that lead to an excessive loss result in a gradual exposure of implant thread and the increased risk of a fatigue failure [4,14].

The possibility of relieving implants by means of application of the O-ring type of attachments or the axially mobile attachments are presented [23]. In the O-ring type of attachments, in spite of the used materials similar to the presented silicone attachments differ remarkably as far as their function is concerned. Design of the O-ring housings restrains freedom of deformation of the nearly incompressible rubber-like material. Finally, the attachment gets stiffen together with the increased load and works similarly to the typical joint-attachments that have an insignificant lateral susceptibility. In turn, measurements conducted for the axially mobile attachments loaded with vertical forces have a very weak reference to the reality. If a denture in the model conditions settles evenly, then the advantages of the telescope or axially susceptible attachments might be visible. In the real conditions a vertical denture settlement does not occur. The presented calculations showed that the axially mobile attachments loaded by an oblique occlusal force bear similar values of the lateral loadings to the ball-attachments. Vertical forces pressing the implant to the bone are much less dangerous than the lateral forces. Hence, their decrease is of a lower importance for the marginal bone loss around the implant neck.

The results of the calculations are in line with the results of the studies [24], in which there is emphasized a necessity of using in SIDs special construction of a larger attachment and implant foreseen for work under remarkably higher loads in order to reduce the number of failures. In the presented paper however, it was proven that the much more effective way of achieving the required SID reliability is the use of the silicone attachment for the purpose of reducing attachment loading. In case of the silicone attachments the stresses around the implant neck were remarkably lower than in case of commercial attachments. Further studies should definitely take into account the real conditions of denture destabilization and sliding on the surface of the mucous membrane. As it was recently proven, it is possible by means of a FEM large displacements analysis [25]. The values of attachments loadings might, in reality be higher for both of the examined types of attachments due to the assumed perfect adherence on the mucous membrane surface. Although this assumption was very helpful for the purposes of the conducted comparative analysis, at the same time, to some extent it reduces denture displacements and attachments loadings. Nevertheless, the zone of overloading around the implant working with the silicone attachment was remarkably smaller than the one in case of the TID retained on the mini-implants [6] that are successfully used in practice. Significant implant loading, which was achieved thanks to the lateral attachment compliance shows better possibilities of using one-piece and one-stage small implants. A larger attachment and a larger implant does not show such a perspective. On the contrary, requirements related to the bone foundation for SIDs remain on the same level as previously for the TIDs, and might be even higher. The diagram in Fig. 4 shows that an increase of implant stiffness results in an increase of the bore loadings. Although the implant and attachment construction in this case is more reliable, the loadings of the bone might increase.

There was presented a design of a biocompatible overdenture, which does not constitute an economical barrier for the common use. Moreover, it was proven that the silicone attachment enables control of implant loading depending on individual foundation conditions in a way that was earlier not available at all.

4. Conclusions

The implant load under realistic oblique occlusal mastication forces was remarkably higher in case of a commercial attachment than in case of a silicone attachment. The silicone attachment that is susceptible not only vertically but also laterally makes it possible to relieve the bone tissue significantly around the single implant. Conducted FEM analyses showed that the stress around the implant neck remained on a safer level than in case of the successfully used two-implant dentures retained by means of the rotational attachments. Hence, the silicone attachment creates a possibility to use mini-implants in order to retain lower denture in case of bone conditions, which are currently perceived as insufficient for the implantological treatment due to a risk of implant loss resulting from overloading of the bone tissue. Further studies are defined by the necessity to take into account the denture detaching and sliding on the mucous membrane interface, as well as the impact of the balancing contacts on the denture stability and the pressures beneath the denture in a large displacements range.

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