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Elastic silicone matrices as a tool for load relief in overdenture implants

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The objective of this study was to analyze how the elasticity of matrices attaching to an overdenture affects implants and how the location of implants affects their loading. The attachments proposed made from elastic matrix increase the denture stability and simultaneously preserve the mechanisms of occlusion load transfer in compliance with principles usually applied in the denture used in the case of edentulous maxilla or mandible.

It was revealed that denture dislodgement caused by occlusion forces did not result in the force being greater than the attachment retention force determined empirically. Our analysis also demonstrates that in the case where the implants are inserted in such a way that they are shifted too much to the back area of the tooth arc, an increase in the implant bending occurs, with the supporting capacities of alveolar processes not being fully utilized. This fact suggests the necessity to increase the susceptibility of attachments in a posterior location.

Key words: *implant, denture, attachment, FEM, mechanics, force, load*

1. Introduction

One of the essential tasks of dental engineering is to invent implant dentures that would be optimal both in terms of biomaterial characteristics and in natural denture-supporting areas. The problems connected with stomatological bridges evenly fixed onto implants and onto a patients's own teeth have been well-documented [1]–[3]. The differences in the existing mobility of both supporting areas inevitably lead to an overload of the stiffer support. Similar phenomena appear with overdentures, where implants, along with mucous membrane in oral cavity, create the supporting areas. In this case, the solution is to enable a denture rotation about the axis created, for example, by two ball joints or a cylindrical joint [4], [5], [6], resulting in a decrease of bending loads generated in the implants. In the natural state, however, this does not prevent the occurrence of unfavourable changes of the bone stresses and leads both to the overloading of cortical bone tissues directly surrounding the implant and a decrease in bone load in the areas between the implants. Taking into account the role of a mechanical stimulator in the processes of bone re-modelling, both mentioned phenomena intensify atrophic processes [7]–[13], often leading to a loss of a implant. Especially for the jaw, approximately 30% of the failures observed [14]–[17] were caused by bone-related changes. In some cases, mechanical destruction of the implants themselves takes place as well [7], [13], [17], [18]. Therefore, an optimal remedy would be a denture operating in conditions allowing the implant to transmit only the part of the occlusive load into the bone. The rest of the load should be distributed onto the bone surface underneath the denture saddles, thereby evenly spreading it over the entire surface [19]–[21], and not only towards back areas, as it is in the case of the best-known solutions. Force distribution should be selected in such a way as to minimize

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unfavourable changes in the bone. This problem is known and numerous attempts have been made to modify the attachments' structure [22]–[37], thereby enabling prosthesis movement alongside the implant's axis in accordance with the natural resilience of the mucous membrane. The damper's role is played by elastic inserts with various retentive forces, embedded in a matrix. However, the problem of the correlation between their deformability and mucous membrane resilience has not been discussed. Meanwhile, only a precisely chosen flexibility – not only the axial one, but also the lateral one, assures control over bone load transmission, particularly the one originating from implant bending. The limited effectiveness of the heretofore proposed solutions also results from the fact that they do not allow the denture to follow the alveolar atrophy of the foundation, which is particularly intensive in the initial period of toothlessness [38]–[39].

According to the authors, this problem can be solved by an implant-retained tissue-supported denture, where the matrix enables both resilient movements corresponding to the mucous membrane's resilience and a shift of the denture, where the foundation atrophy is considerable. It is assumed that an overdenture should be supported by implants due to friction forces. If the pressure forces generated during chewing are not greater than the friction forces, such a joint functions as a membranous spring, without changing the position vis-à-vis the implant. An increase in deflection caused by atrophy of the bone foundation and by the thinning of the mucous membrane will result in exceeding the friction force and the denture's following the atrophic foundation. A new resting position of the attachment is determined on the implant, and lasts until the friction force is exceeded. For a correct functioning of the attachment of this type, it is important to appropriately define its rigidity, as well as to have appropriate implant arrangement ensuring the best possible denture stability.

Just prior to the development of prototypes for laboratory studies, we should undertake the research based on numerical models, allowing us to specify the requirements, which must be fulfilled by products to be used in practice, at a low cost. The aim of this study was to find how the quantity and distribution method of overdenture implants and the appropriate rigidity of elastic attachments affect the reactions counteracting the movements generated by occlusive forces. Based on a FEM modelling, the effects and purposefulness of making matrices of relining silicones have been evaluated.

2. Methodology

The principle ensuring a successful model research is an appropriate selection of factors that crucially affect the phenomenon analyzed as well as the selection of appropriate evaluation criteria. In order to solve the problem, the researchers adapted a procedural method, which allowed them to specify the biostatic conditions of the implant denture retention, such as the implant reactions and denture mobility. Therefore, the following procedural sequence was adapted:

- A numerical spatial model of a tissue-supported denture was built, founded on an alveolar process in an edentulous jaw (figure 1). An ideal shape of prosthetic foundation with unfavourable retention conditions comparable to those of atrophied alveolar processes was adapted [40].

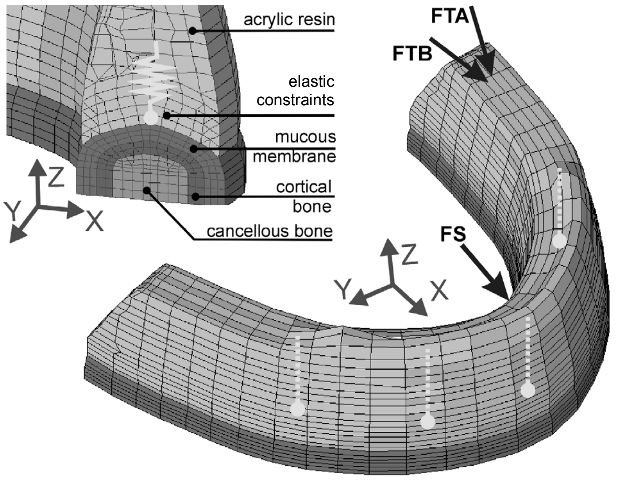

Fig. 1. View of spatial model of denture–foundation system together with scheme of loading forces and localization of elastic constraints on model

- The elastic constraints characterized by the rigidity corresponding to the attachment variant selected, with a soft or rigid matrix, were placed on the anchoring locations of appointed implants, distributed according to the scheme in figure 2. The elastic constraints were applied alongside the directions clearly indicated by front, sagittal and vertical axes. Model names were associated with implants' location. Location in the front area: anterior (A); medial (M), medium-strongly shifted backwards; and posterior (P), strongly shifted backwards. The distance between the implants shifted backwards, measured from the central point on the top of the alveolar ridge, is marked in the drawing. It is worth mentioning that this distance is different in variants 2A and 3A. Because in variant

3M, the line of back implants is shifted, it differs from variants 2M and 4M. In variants with 4 implants, these distances are equal. In the model with 4 implants (4P), the front implants AL and AR are also shifted. The implants are marked according to locations occupied by them: anterior (A), posterior (P), left (L), and right (R). The right side (R) has always been the working one.

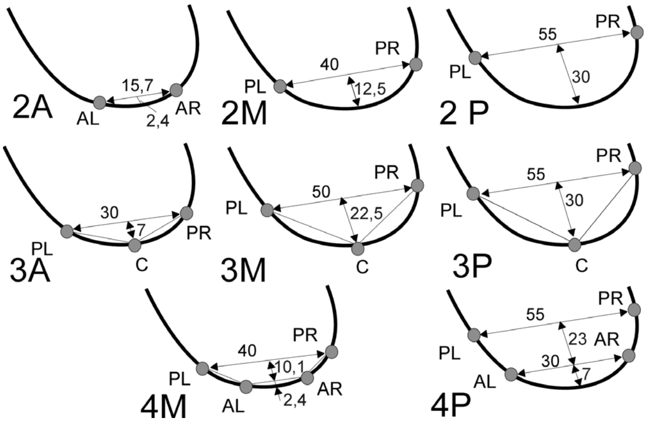

Fig. 2. Scheme for marking location variants of silicone attachments and implants: anterior (A), medial (M), posterior (P)

- The rigidity of matrices was determined for a ring-shaped model with the diameter *d* = 6 mm, the height *h* = 2 mm, and the internal diameter *i* = 2.2 mm by making calculations for materials with Young's modulus equal to 5 MPa, which covers the range of material properties that are characteristic of prosthetic silicones used for denture relining. Next, the material with Young's modulus equal to 10 MPa was chosen, corresponding to more rigid materials that could be used for attachments having an increased retention. The rigidity values determined for "soft" materials were as follows: 7 N/mm vertically (SH), 40 N/mm laterally (ST), and those for "hard" materials were 34 N/mm and 70 N/mm. The values for lateral rigidity (ST "40" and "70") influencing implant-bending reactions were used to mark and identify the results in graphs. We can assume that the total rigidity of the constraint is influenced only by the matrix rigidity, provided that the junction between the implant pillar and the bone is strong.
- The models of implant-retained dentures were loaded with the force of 100 N in the areas of molar or incisor teeth. During mastication, the resultant occlusive forces can change its direction, which clearly influences denture movement and induces reactions of the implants. For this reason, the obliquely-acting forces that negatively influence denture stability have been taken into consideration. The force acting on incisors was applied with its constituent directed forward in a sagittal plane (FS). The forces applied to molars were studied in two cases: with a constituent directed towards cheek in a front plane (FMB) and a constituent directed forward in a sagittal plane (FMA). A 45° inclination angle of the force applied was deliberately large in order to simulate extremely unfavourable conditions of implant loading [41]. Assuming a full contact between denture saddles and the foundation, the conditions are created for adhering denture to foundation surface due to the loading forces.

In order to simplify all calculations, a linearly-elastic isotropic mechanical characteristic was adapted for all model structures. Young's modulus $E = 17$ GPa was assumed for the cortical bone; $E = 600$ MPa was adapted for the spongy bone, with the Poisson coefficient $\nu = 0.3$ in both cases. The material characteristics of the denture are described by $E = 2000$ MPa and $\nu = 0.3$, with an average value of mucous membrane resilience, elasticity modulus $E = 3$ MPa, and $\nu = 0.49$.

3. Results

As a result of numerical calculations we obtain the constituents *X*–*Y*–*Z* of reactions affecting individual implants. The values of the vertical reactions (*Z*-constituents) should be related to the desirable retaining force. Initial static laboratory research of the analyzed types of attachments reveals that the value of retention force until the beginning of matrix shifting on the implant falls within 4–5 N. Based on the calculations made it can be inferred that in the least favourable case, the vertical reaction produces the force of 2.3 N, which ensures the attachment's stability. Therefore, the level of implant-bending lateral forces was chosen as a rate of the solution evaluation. These loads cause most of the mechanical damages to implants as well as heavy bone overloads in the area of the implant grafted into the cortical bone.

The values of the lateral forces acting on particular implants are presented in figures 3–5, with the absolute values given for the resultant of *X*-constituents (bending in sagittal plane) and *Y*-constituents (bending in front plane). Depending on the attachment rigidity, the models are hereinafter marked with "40" or "70". As an example, the mark 2A40 refers to the model fixed by a "soft" matrix on two implants situated forward, while the mark 2A70 refers to the same kind of the constraints' location, with the application of a "rigid" matrix.

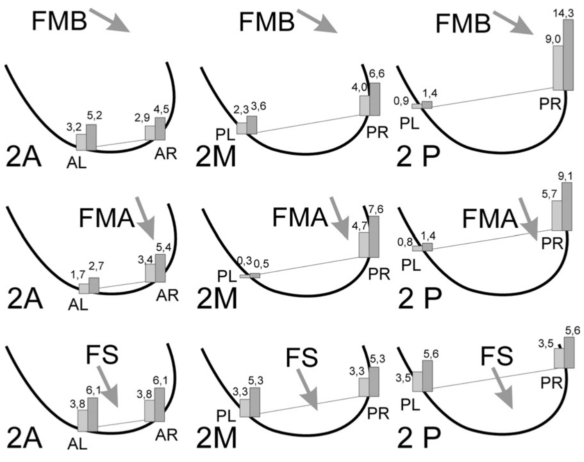

Fig. 3. Absolute values of lateral forces acting on implants.
Variants with two implants
of low “▢ 40” and high “▨70” attachment rigidity

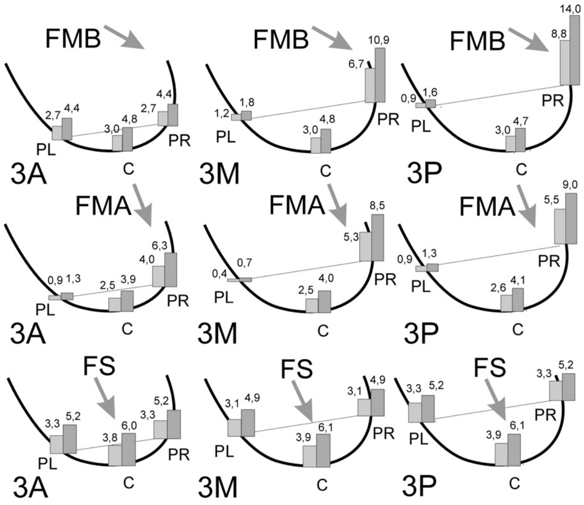

Fig. 4. Absolute values of lateral forces acting on implants.
Variants with three implants
of low “▢ 40” and high “▨70” attachment rigidity

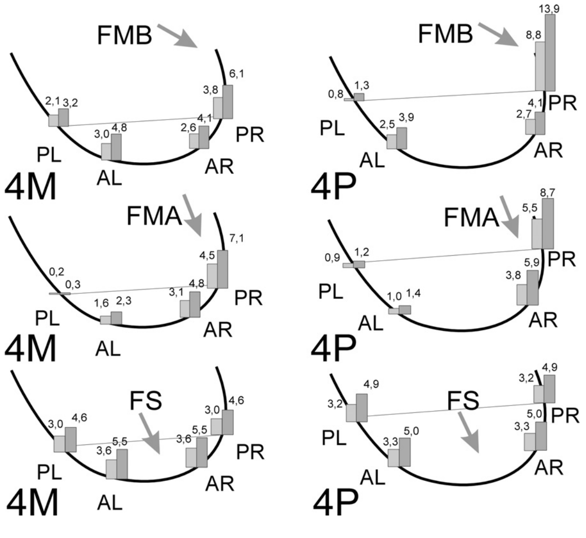

Fig. 5. Absolute values of lateral forces acting on implants.
Variants with four implants
of low “▢ 40” and high “▨70” attachment rigidity

Figure 6 shows the dependence of the forces acting on the implant's working side on the backward shift of implants' line.

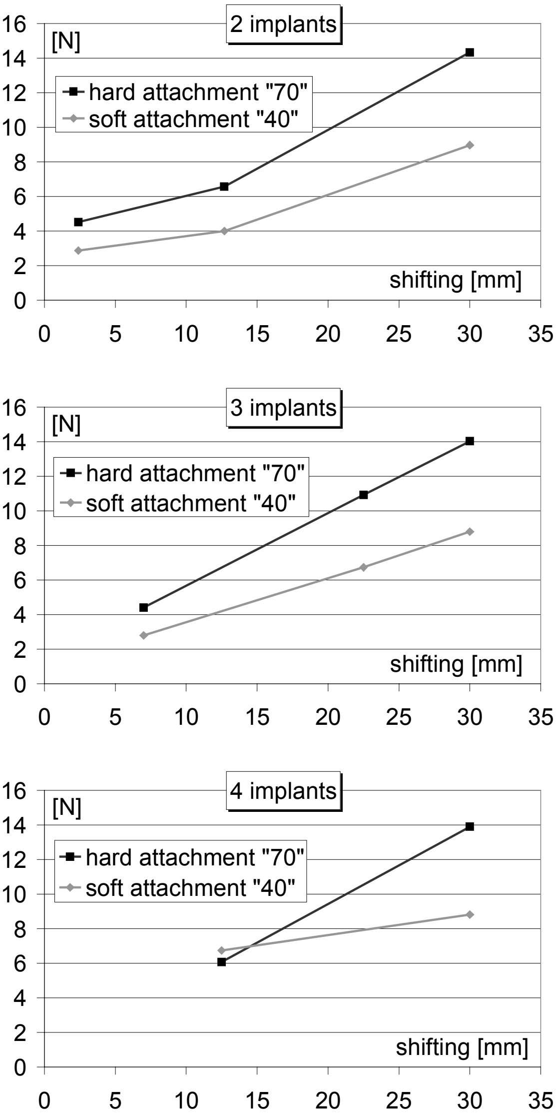

Fig. 6. Lateral loads vs. posterior shifting of implants

4. Discussion

A model research has the advantage of making the testing conditions comparable [3], [42], which is impossible while dealing with changeable occlusion conditions, as in the case of in vivo research [35], [47]. Supporting reactions obviously depend on the loading method and support conditions. Although a clinical significance of model research results is questionable [43], mainly due to the influence of neuro-muscular reactions on the occlusive loads induced, the evaluation and selection of constructional solutions conducive to a clinical success would be impossible without the model research results. However, when evaluating the results, we have to be aware of the limitations introduced by the model assumptions adopted. In the present study, it was neither possible nor reasonable to analyze all cases of occlusive forces or individual support conditions varying, depending on the foundation topography and changeable mucous membrane resilience. The adapted hypothetical unfavourable loading conditions that contribute to denture dislodgement off the foundation enable a comparative analysis of lateral loads, to which the implants may be exposed.

Assuming a full contact between the saddle surfaces and the foundation during mastication we are able to ascertain the extent which allows the foundation to decrease an implant loading. The correctness of such an assumption is confirmed by clinical observations showing that during the loss of adherence, patient reflexively decreases occlusive forces, attempting to counteract a denture dislodgement [44]. Thus, the analysis does not take into account the incidental effects connected with the further loading of a denture, which has lost its mucous support; however, it serves as a comparative evaluation in stable loading conditions.

Calculations were performed for the medium resilience of a mucous foundation. A supposition can be made that an increase in resilience will result in an increase in the implant loading [45], which can be the subject of further analyses.

The forces acting on implants in the case of using the attachments available on the market [20], [36], [46]–[48] can reach the values as high as 240 N, where the vertical constituent belongs to the dominating elements, and the constituent causing an anterior–posterior bending reaches the level of 50 N. In the case of using attachments [36] that enable the denture movements consistent with the mucous membrane resilience, it has been ascertained that the implant loading force ranges from 78 to 88% of the denture loading force. This minor decrease in the value of force acting on implants demonstrates that these attachments do not possess an appropriate resilience. The results obtained in this study indicate that higher compliance of matrices leads to a reduction of vertical forces on an implant, if compared to lateral forces (similar effect during mastication was also observed by MERICSKE-STERN [49], although less significant, i.e., 100–300%).

The location and quantity of implants as well as the varying rigidity of attachments influence, to a different extent, the values of force components acting on implants in the horizontal plane *XY*. Matrix rigidity has a significant influence on the reactions taking place on implants [36], [49]–[51]. This is corroborated by the research on the “soft” matrix model (“40”), whose application in each case led to a decrease of forces by approximately 40% while compared with the “hard” matrix (“70”). Application of an attachment with “hard” matrix is responsible for a higher risk to the implants’ durability and their anchoring zone. For the variant with two implants, their shifting backwards (“2P 70”, figure 5), when the denture is loaded on a molar tooth by lateral force FMB forwards, creates an increase in lateral reaction on implant PR from 4.5 to 14.3 N. In the case of frontal molar loading forwards (FMA), the lateral reaction in the implant increases from 5.4 to 9.1 N. The values of lateral forces on implants for incisor loading (FS) are similar in both variants.

Similar effects can be observed in variants with three or four implants. In general, the retraction of the line of implants into the molar area causes, in the case of occlusive loads in the area of molars (FMB and FMA), an increased weighting of the most retracted implant on the working side [51]. This is an understandable process, as the implants situated backwards better stabilize the denture, while unnecessarily taking over the part of the load that could be equally well transferred to the contact surfaces. The analysis of the variants with four implants reveals that an increase in the number of implants causes a more uniform distribution of loads on individual implants; however, the advantages due to this increase are insignificant in terms of strength. This means that in the case where a satisfactory retention force is exerted on two or three implants [52], [53], an increase in their number is inevitably unjustifiable.

Implant-bending forces belong to very unfavourable forces [54]–[56]. The excessive weighting of the bone, by causing overload being responsible for bone tissue atrophy, increases the risk of implant exposure and even of pillar fatigue-related fracture at threads uncovered on the bone, forming stress concentrators.

In the already known solutions that need implant relief, as the resilient attachment elements, we mainly use “O-ring” type seals or dentures fixed to beams or to implants attached by resilient elastomer–metal attachments.

Many solutions have the disadvantage that the attachments wear which, leads to the loss of retention characteristics [28], [57], [58] or the attachments are damaged [8], [13], [14], [59]. The damage to attachments also poses a real risk of inhalting its small pieces, which is a serious hazard to patient’s health.

The development of implant-retained overdentures should proceed in such a way as to allow an effective denture retention on the foundation with a simultaneous elimination of the structure overloads. Assuming that a prosthodontist has no influence on occlusive loads being an individual characteristic, the only way is to ensure the optimal selection of denture support conditions. Further, the cost reduction should be found in an efficient implant loading and an appropriate utilization of the natural supports. The authors' idea was to assess the mechanical conditions of functioning of a system where implants constitute one-piece implants cooperating with matrices polymerized directly in a denture made of silicone materials used for denture relining. The silicone matrix with properly selected properties of a membranous spring will allow denture movements vis-à-vis the implant, corresponding to the mucous membrane resilience. The friction forces that damage the matrix are generated very rarely, in fact only if a denture is being inserted or removed.

The results obtained show the possibility of limiting reactions on implants due to their appropriate location and adjustment of the matrix rigidity to individual properties of the foundation. Based on the results given for direct rigidities of the matrices, it is possible to forecast the loads to be imposed on the implants. By controlling the compliance, it is possible to obtain implant-loading conditions being favourable even for patients with strong alveolar atrophy. Until now, in such cases clinicians have been avoiding standard implant treatment due to the risk of overload-related bone atrophy around the implants [7]. The results of this study can also be useful in the context of consecutive phases of curing where single-phase implants are applied, [60]–[61] and in the procedure of a gradual loading in standard treatment employing implants.

Our model methodology of evaluating the loads imposed on resilient attachments can serve in biomechanics of implant-retained and tissue-supported dentures as a useful starting point for the strength analysis of attachments, implants and tissue in the area of their anchorage in the bone.

5. Conclusions

The model research carried out allows the following conclusions to be drawn:

(1) The application of silicone materials to the fabrication of matrices having the properties of a membranous spring enables the reduction of implant loading and transmission of the part of occlusive loads onto the mucous membrane foundation.

(2) The shifting of the implant anchorage points towards posterior molar areas causes their increased loading, whereas the load bearing capacity of a mucous membrane is not fully utilized.

(3) In the case of implant-retained dentures, a decrease in the reaction forces through an increased number of implants cannot be inevitably justified.

(4) One of the safe and economical solutions is the variant with two implants in the front area or with a medium posterior shifting (2A or 2M), since, with a reduced number of implants, the load per implant is the lowest for every variant of occlusive forces, and the mucous membrane undergoes deformation within its natural resilience limits.

(5) The present method of evaluation of implant loading can be used as a starting point for the analysis of gradual implant loading within an individual implant treatment procedure, adapted to consecutive phases of osseointegration.

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