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Mathematical Simulation of Maxilla Biomechanics Restored with Fixed Implant-Supported Denture

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Abstract

The aim of the present work was to research the stress-strain state of bone tissue and maxillary full-arch fixed implant-retained denture. The load of 150N and 250N, respectively, was applied to the anterior and posterior parts of the denture supported by 6 or 4 implants, including zygomatic ones and placed by on-all-4 treatment concept. The stress values in bone tissue, implants and denture were obtained showing a large strength margin of structural materials. At the same time, the bone strength values were small, especially of the bone around the zygomatic and distal implants of all-on-4-implants-supported dentures when the posterior part of the denture was under load.

Keywords: maxilla, edentulism, implants, biomechanics.

INTRODUCTION

The biomechanics of fixed implant-retained dentures in the edentulous mandibula has been studied to a much greater extent than that in the maxilla [1, 2, 3, 4]. Analysis of the stress-strain state of bone tissue, implants and fixed implant-supported denture in patients with maxillary edentulism is minimally represented in the special literature, which is associated with the maxilla complex configuration and difficulties in mathematical simulation. Meanwhile, a body of acquired practical experience of maxillary rehabilitation with fixed implant-supported dentures is gradually being accumulated [5, 6, 7, 8, 9]. The lesser density of the maxillary alveolar ridge in comparison with the mandible and the shortened dental arch of fixed implant-retained denture make such restorative solutions vulnerable from the perspective of long-term effectiveness. The relevance of biomechanical research of implants placed in the edentulous maxilla is also associated with the discussion of the advisability of the maxillary arch rehabilitation with fixed implant-supported denture with the use of all-on-4 treatment concept and zygomatic implants.

The purpose of the research was to study the stress-strain state of bone tissue and maxillary fixed implant-supported denture.

MATERIALS AND METHODS

The stress-strain state (SSS) of cortical and cancellous bone, titanium implants and ceramic denture teeth upon distributed vertical load of 150N and 250N applied to the anterior and posterior parts, respectively, of the denture was studied on the maxillary mathematical simulation model identical in size, structure and physico-mechanical properties to the real maxilla (Fig. 1, Table 1). The magnitude of the load was smaller than the maximum endurance limit of periimplant tissues defined taking into account the gnathodynamometric data of Lebedenko I.Yu. et al. on the magnitude of the masticatory pressures in young people not exceeding 35 kg. The standard recommendations for fully edentulous patients treated with fixed dentures with the limited number of supporting implants on taking in food of low viscosity and smooth consistency had also been considered [10, 11]. The SSS was assessed by finite element analysis using Solidworks 2016 and MSC Patran 2012 computer programs [1, 2, 3, 4, 12, 13, 14]. The stress was studied in 4 variants: 6 implants, 4 implants (including zygomatic and distal angled implants placed according to the all-on-4 protocol). Implants placed parallel to each other were of different lengths: 15.0 mm, 12.5 mm, and 8.0 mm (diameter 3.9 mm); in the variant with 4 parallel 12.5 mm-length implants, their diameters were different: 3.5 mm, 4.3 mm, and 5.0 mm. The implants were inserted at the sites of missing frontal and premolar teeth: when simulating the placement of 6 implants, the distance between the implants equaled to 6.0 mm, when simulating the placement of 4 implants – to 13.0 mm; the most distal implants (including zygomatic ones and placed by all-on-4 concept) were placed within the second premolars' projection; zygomatic implants were positioned only distally, and the implants inserted in the frontal area were root-type ones (Fig. 2-4). Regardless of the number of implants, fixed denture was modelled with the shortened dental arch (for 12 teeth replacement) and distal cantilevers. The load was distributed among incisors and first and second premolars when exerted on the anterior and posterior parts, respectively, of the implant-supported denture.

Table 1. Physical and mechanical properties of the mathematical simulation model materials.

Name	Young's modulus, E, MPa	Poisson's ratio, ν
cortical bone	18,000	0.30
cancellous bone	3,500	0.34
titanium	120,000	0.30
ceramics	200,000	0.30

RESULTS AND DISCUSSION

Under the load exerted upon the anterior and posterior parts of the maxillary fixed implant-supported denture, the maximum stress values in the bone tissue were localized around the implant neck spreading to the distant areas - the bottom of the nasal cavity, the walls of the maxillary sinus (Fig. 2-4). With the anterior part of the denture being loaded and the retention upon 6 implants with the lengths of 15.0 mm, 12.5 mm and 8.0 mm (diameter 3.9 mm), the stress values in the cortical bone were equal to 6.62 MPa, 6.61 MPa and 8.06 MPa, respectively; when the number of implants was reduced to 4, the stress values increased to 8.12 MPa, 9.28 MPa and 10.10 MPa, respectively (Table 2). The stress value in the area of the distal implants placed by all-on-4 concept (length 12.5mm, diameter 3.9mm) was 12.37 MPa. By placing zygomatic implants, the highest stress values of 12.25 MPa were observed in the alveolar crest around the implant neck, i.e. when the anterior part of the denture was loaded, zygomatic implants did not have any impact on the stress values compared to the all-on-4 treatment concept. The lesser the implant diameter was, the higher the stress values in the bone tissue were: with the implants of 12.5 mm in length and of 5.0 mm, 4.3 mm, 3.5 mm in diameter (the number of implants amounted to 4), the stress values in the maxillary cortical bone equaled to 5.75 MPa, 7.20 MPa, and 10.11 MPa.

The load exerted on the posterior part of the denture significantly increased the stress in the periimplant cortical bone. With the denture supported by 6 implants of 15.0 mm, 12.5 mm and 8.0 mm in length, the stress values resulting from the lateral load increased to 48.47 MPa, 49.71 MPa and 61.00 MPa, respectively, i.e. were by 86.3 – 86.8% higher compared to the load exerted on the anterior region ($p < 0.01$). When the denture was supported by 4 implants of the same size, the lateral load caused stresses equal to 51.57 MPa, 53.62 MPa, 67.66 MPa in the cortical bone, which was by 82.7-85.1% higher compared to the load exerted on the anterior part of the denture ($p < 0.01$). The change in the diameter of the implants from 3.9 mm to 4.3 mm and 5.0 mm reduces the stress values, and the reduction in diameter to 3.5 mm causes their increase. As in the case of implants of 12.5 mm in length, the load applied to the posterior part of the denture supported by implants with the diameter of 5.0 mm, 4.3 mm and 3.0 mm resulted in bone stress values equal to 38.44 MPa, 46.38 MPa and 54.46 MPa, respectively, which exceeded the anterior region stress values by 81.4 - 85.0% ($p < 0.01$). The stress values around the distal implants placed at an angle by the all-on-4 technique (151.32 MPa) were by 91.8% higher compared to the load exerted on the anterior part of the fixed denture ($p < 0.01$). In this situation - with the posterior part of the denture being under load - the zygomatic implants reduced the stresses in the bone tissue (104.09 MPa) by 30.7% ($p < 0.01$) in comparison with the all-on-4 treatment concept but increased the bone stress values by 88.2% ($p < 0.01$) compared to the load exerted on the anterior part of the denture. Concerning the average cortical bone strength (150 MPa), it should be mentioned that the bone tissue in the area of distal implants has no safety margin in case of the posterior part of the all-on-4 fixed denture being under load, whereas the bone safety margin around the zygomatic implants constitutes 30.6% [11].

Table 2. The results of three-dimensional simulation modeling of cortical bone tissue SSS with the fixed denture being under load depending on the features of intrabone implants placed in the fully edentulous maxilla (MPa).

Simulation model	Anterior	Posterior
h 15.0 mm; n=6	6.62	48.47
h 12.5 mm; n=6	6.61	49.71
h 8.0 mm; n=6	8.06	61.00
h 15.0 mm; n=4	8.12	51.57
h 12.5 mm; n=4	9.28	53.62
h 8.0 mm; n=4	10.10	67.66
h 12.5 mm; n=4 all-on-4 concept	12.37	151.32
zygomatic implants	12.25	104.09
h 12.5 mm; n=4, Ø 5.0 mm	5.75	38.44
h 12.5 mm; n=4, Ø 4.3 mm	7.20	46.38
h 12.5 mm; n=4, Ø 3.5 mm	10.11	54.46

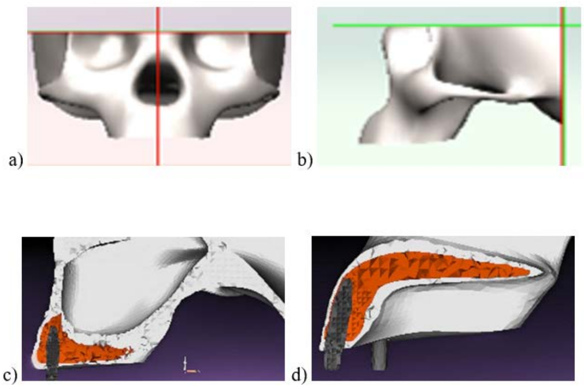

Fig. 1. Views of the three-dimensional mathematical simulation model of maxilla restored with fixed implant-retained denture (through the example of denture supported by 4 implants): a) frontal view, b) lateral view, c) cross-section at the level of distal implant; d) cross-section at the level of central incisor implant.

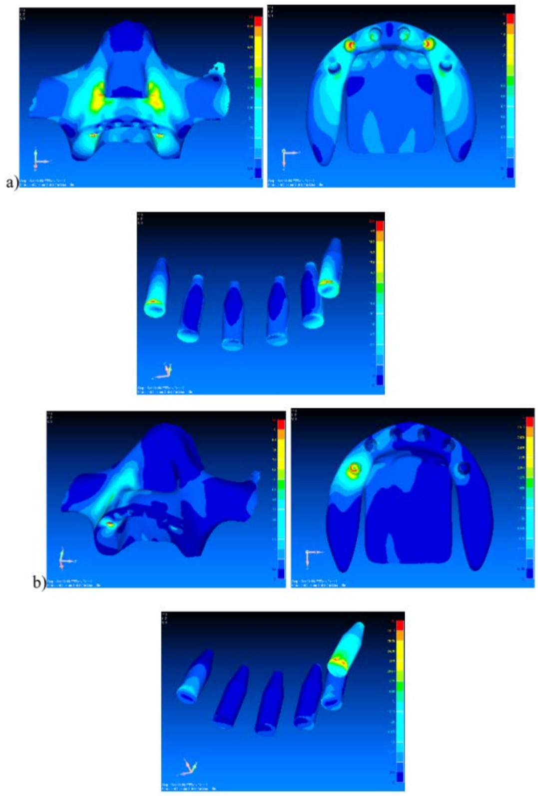

Fig. 2. Views of stress distribution at functional load exerted on maxillary fixed denture supported by 6 implants of 12.5 mm in length: a) frontal load - cortical bone, cancellous bone, implants; b) lateral load - cortical bone, cancellous bone, implants.

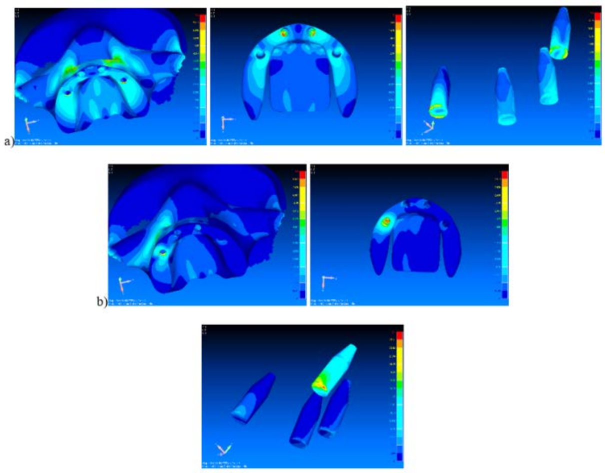

Fig. 3. Views of stress distribution at functional load exerted on maxillary fixed denture supported by 4 implants of 12.5 mm in length: a) frontal load - cortical bone, cancellous bone, implants; b) lateral load - cortical bone, cancellous bone, implants.

Upon mathematical simulation, the lowest stress values were found in the maxillary cancellous bone with the fixed implant-supported denture being under load, as well as in the implant materials and denture itself (being far from the strength values of metal alloys and ceramics), and therefore the results of the most unfavorable variant for biomechanics – with the load exerted on the posterior part of the maxillary fixed implant-retained denture – had been presented (Table 3). When the denture was supported by 6 implants of 15.0 mm, 12.5 mm and 8.0 mm in length (diameter 3.9 mm), the stress values for the cancellous bone reached 5.4 MPa, 5.6 MPa and 6.3 MPa, respectively. With the decrease in the number of implants up to 4 and with the length of implants being 15.0 mm, 12.5 mm and 8 mm, the stress values for the implants of smaller length slightly increased: at the above-mentioned sizes they equaled to 5.0 MPa, 6.1 MPa, 6.8 MPa, respectively. Upon placement of distal implants at an angle by the all-on-4 concept, the stress in the periimplant bone increased to 10.4 MPa. The use of zygomatic implants, on the contrary, reduced stresses in periimplant bone compared to the all-on-4 concept to 7.5 MPa. The reduction of implant diameters from 5.0 mm to 4.3 mm and 3.5 mm (with the equal length of 12.5 mm) increased the stress values to 4,4 MPa, 4,9 MPa and 6,0 MPa, respectively. Thus, in the cancellous bone, regularities are observed in the dependence of stress values on the size and the placement technique of implants; the greatest stresses are characteristic for implants place by the all-on-4 treatment concept and zygomatic implants with the length equal to 8.0mm; taking into account the strength limits of the cancellous bone, it should be pointed out that in these situations the stress values in periimplant bone approach to the critical ones.

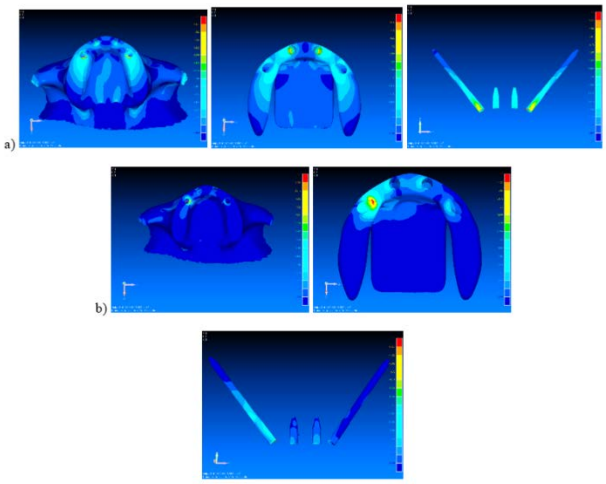

Fig. 4. Views of stress distribution at functional load exerted on maxillary fixed denture supported by a combination of zygomatic and root-type implants: a) frontal load - cortical bone, cancellous bone, implants; b) lateral load - cortical bone, cancellous bone, implants.

Table 3. The results of three-dimensional simulation modeling of cancellous bone tissue SSS with the posterior part of fixed denture being under load depending on the features of intrabone implants placed in the fully edentulous maxilla (MPa).

Simulation model	Stress values (MPa)
h 15.0 mm; n=6	5.4
h 12.5 mm; n=6	5.6
h 8.0 mm; n=6	6.3
h 15.0 mm; n=4	5.0
h 12.5 mm; n=4	6.1
h 8.0 mm; n=4	6.8
h 12.5 mm; n=4 all-on-4 concept	10.4
zygomatic implants	7.5
h 12.5 mm; n=4, Ø 5.0 mm	4.4
h 12.5 mm; n=4, Ø 4.3 mm	4.9
h 12.5 mm; n=4, Ø 3.5 mm	6.0

Stress values in implants and implant-retained dentures upon lateral load are far from the critical ones for titanium and ceramics (Table 4). So, in implants, the stress values ranged from 37.4 MPa to 68.0 MPa. More significant stress values were characteristic for zygomatic implants (91.8 MPa) and those placed by the all-on-4 concept (in distal implants the stress values reached 161.5 MPa). For the implant-retained denture, the typical stress values were equal to 24.0 MPa-49.3 MPa. Considering the large safety margin of titanium and ceramics compared to the stress values obtained in this study, the regularities of the dependence of stress values in implants and dentures on the size and the number of implants appear to be insignificant.

Table 4. The results of three-dimensional simulation modeling of SSS of titanium implants and fixed implant-supported denture being under lateral load depending on the features of intrabone implants placed in the fully edentulous maxilla (MPa).

Simulation model	Implant	Denture
h 15.0 mm; n=6	44.03	23.97
h 12.5 mm; n=6	52.02	25.50
h 8.0 mm; n=6	60.18	28.73
h 15.0 mm; n=4	49.30	26.01
h 12.5 mm; n=4	47.26	24.82
h 8.0 mm; n=4	51.00	27.54
h 12.5 mm; n=4 all-on-4 concept	161.50	49.3
zygomatic implants	91.80	40.8
h 12.5 mm; n=4, Ø 5.0 mm	39.10	26.52
h 12.5 mm; n=4, Ø 4.3 mm	37.40	27.37
h 12.5 mm; n=4, Ø 3.5 mm	68.00	35.36

CONCLUSIONS

Thus, according to the data of three-dimensional mathematical simulation, the functional load exerted upon the maxillary fixed implant-supported dentures didn't cause critical stress values in the implants and dentures. However, the bone tissue around the zygomatic implants and the distal ones placed by the all-on-4 concept being under lateral load was subject to high stresses and had no significant safety margin. Stresses in the bone tissue are localized in the area around the implant neck, extending to the bottom of the nasal cavity and the medial walls of the maxillary sinuses; the stress values decrease with the increase in the number, length and diameter of implants.

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