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RESULTS OF STRESS-STRAIN STATES STUDY IN PROSTHETICS OF DIFFERENT TYPES OF ATROPHY OF EDENTULOUS MANDIBLE

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Ключові слова: *повна адентія, нижня щелепа, зубне протезування, дентальна імплантація, кінцево-елементний аналіз*
Ключевые слова: *полная адентия, нижняя челюсть, зубное протезирование, дентальная имплантация, конечно-элементный анализ*

Abstract. Results of stress-strain states study in prosthetics of different types of atrophy of edentulous mandible. Fastovets O.O., Sapalov S.O., Shtepa V.O. *Complete dentures remain still popular due to the economic component of such prosthetic treatment. However, additional fixation on intraosseous implants provides a greater clinical and functional effectiveness and a greater level of satisfaction with the results of prosthetics in edentulous patients. At the moment, the biomechanical aspects of prosthetics of edentulous jaws with complete dentures and prosthetics with fixation on implants, taking into account the degree of atrophy of the edentulous jaws, are not completely understood. Such studies make it possible to develop recommendations on the choice of prosthetic tactics for edentulous patients. The aim of the research was to study the distribution of stress-strain states in prosthetics of the edentulous mandible with complete dentures and with designs supported on intraosseous implants, taking into account the type of atrophy. It was carried out computer simulation of 8 virtual finite element models of mandible with different types of atrophy according to Keller: 4 models - with the system of biomechanical simulation "complete denture – mandible" and 4 ones – "denture – intraosseous implants – mandible". In each of the models, a chewing load of 100 N was simulated (symmetrically and asymmetrically). The ANSIS 12.1 finite element analysis was used to calculate the stress-strain states in the described calculation systems. Distribution of Mises-equivalent stresses in cortical bone and displacements of the prosthetics construction was estimated. In prosthetics with complete dentures, the maximum stresses in the bone tissue of the prosthetic bed were observed in the third type of mandible atrophy with all types of power load, the minimal ones – in the fourth type. Additional fixation of removable dentures in simulation models of biomechanical systems "denture – intraosseous implants – mandible" leads to a significant increase in stresses in the alveolar bone. The maximum stresses were observed in the area of the marginal bone, while their greatest values were in the well-expressed alveolar part of the mandible in the first and third types according to Keller. The displacements of bases of complete dentures were insignificant and fluctuated within hundredths of a millimeter in all types of atrophy. The use of intraosseous implants for fixation of dentures caused increase in movements by several times. Besides, displacement fields were characteristic: they were uniform in complete dentures but in the use of implants – not. The expressed alveolar process in the first and third types of atrophy of the edentulous mandible caused an increase in the displacements of the distal sections of the dentures on both sides with a symmetric force load and on one side – with an asymmetric one. It can be assumed that such a distribution of stress-strain states accelerates atrophy of prosthetic bed tissues. As a result of prosthetics of edentulous mandible, both with traditional complete dentures and with additional support on implants, different distribution of stress-strain states occurs in different phases of the chewing act in the bone of the prosthetic bed, the character of which is determined by the shape of the alveolar part described by Keller's classification. The results allow us to develop an algorithm for determining the type of prosthetics for edentulous patients, depending on the type of mandible atrophy.*

Резюме. Результаты исследования напряженно-деформированных состояний при протезировании разных типов атрофии нижней беззубой челюсти. Фастовец Е.А., Сапалёв С.А., Штепа В.А. *Полные съемные протезы остаются по-прежнему востребованными благодаря экономической составляющей такого лечения. Однако дополнительная фиксация на внутрикостные имплантаты обеспечивает большую клинико-функциональную эффективность и больший уровень удовлетворенности результатами протезирования у пациентов с полным отсутствием зубов. На данный момент не до конца изучены биомеханические аспекты зубного протезирования беззубых челюстей полными съёмными конструкциями и протезами с опорой на имплантатах, с учетом степени атрофии альвеолярных отростков. Подобные исследования позволят составить рекомендации по выбору тактики ортопедического лечения больных с полным отсутствием зубов. Цель исследования – изучить распределение напряженно-деформированных состояний (НДС) при протезировании беззубой нижней челюсти полными съёмными протезами, а также конструкциями с опорой на внутрикостные имплантаты, с учетом типа её атрофии. Проведено компьютерное моделирование 8 виртуальных конечно-элементных моделей нижних челюстей с разными типами атрофии по Келлеру: 4 – с имитацией биомеханической системы «полный съемный протез – нижняя челюсть» и 4 – «съемный протез – внутрикостные имплантаты – нижняя челюсть». В каждой из моделей имитировали жевательную нагрузку силой 100 Н (симметрично и асимметрично). Для определения НДС в описанных расчетных системах использовали конечно-элементный анализ ANSIS 12.1. Изучали распределение эквивалентных по Мизесу напряжений в кортикальной кости протезного ложа, а также перемещения конструкции протеза. При протезировании полными съемными протезами максимальные величины напряжений в костной ткани протезного ложа наблюдались при третьем типе атрофии нижней челюсти при всех вариантах силовой нагрузки, наименьшие – при четвертом. Дополнительная фиксация съемных протезов в имитационных моделях биомеханических систем «съемный протез – внутрикостный имплантат – нижняя челюсть» привела к существенному росту напряжений в альвеолярной кости. Максимальные напряжения наблюдались в области маргинальных участков, при этом наибольшие значения были получены для хорошо выраженной альвеолярной части нижней челюсти (первый и третий типы по Келлеру). Установлены незначительные перемещения базисов полных съемных протезов, колеблющиеся в пределах сотых долей миллиметра при всех типах атрофии. Применение внутрикостных имплантатов для фиксации протезов приводит к многократному увеличению перемещений. При этом характерны поля перемещений: при полном съемном протезировании они* *равномерные, а при применении имплантатов – нет. Выраженный альвеолярный отросток при первом и третьем типах атрофии нижней беззубой челюсти явился причиной увеличения перемещений дистальных участков покровных протезов с обеих сторон при симметричной силовой нагрузке и с одной стороны – при асимметричной. Можно предположить, что такое распределение НДС способствует ускорению атрофии тканей протезного ложа. При протезировании полных дефектов зубного ряда нижней челюсти, как традиционными конструкциями, так и с дополнительной опорой на имплантаты, в разные фазы жевательного акта в костной основе протезного ложа происходит различное распределение НДС, характер которого определяется формой альвеолярной части, описываемой классификацией Келлера. Полученные результаты позволят разработать алгоритм выбора вида протезирования больных с полным отсутствием зубов на нижней челюсти в зависимости от типа ее атрофии.*

In the orthopedic treatment of patients with complete absence of teeth, the functional efficiency (fixation, stabilization and balance) of removable structures is largely related to the anatomical and topographic features of the prosthetic bed. The nature of atrophy of edentulous jaws is taken into account when choosing the patient's prosthetics, in particular when determining the method of fixing a removable denture – by functional suction in "classic" designs of complete dentures or by additional mechanical fixation on implants [4, 9]. In this case, the right decision causes a long-term favorable outcome of prosthetics, while otherwise the undesirable uneven distribution of masticatory pressure in the tissues of the prosthetic bed can lead to progression of atrophy processes and impaired fixation of the structure, as well as significantly complicate the conditions of re-prosthetics [17].

It should be noted that traditional complete dentures remain very common due to the economic component of such treatment [20]. At the same time, additional fixation on intraosseous implants provides greater clinical and functional efficiency and a greater level of satisfaction with the results of prosthetics in patients with complete absence of teeth [1, 14]. It should also be taken into account that the result of edentulous jaw prosthetics is influenced by the number of implants, their diameter, as well as the type of fixation and design of the superstructure [2, 8, 13, 19]. On the other hand, the use of implants does not prevent the progression of atrophy of the tissues of the prosthetic bed, even, on the contrary, leads to its progression in the distal parts of the mandible [6].

At the same time, according to computed tomography and occlusiography (T-Scan), it was found that the rate of resorption of alveolar bone is lower in implants use than in complete dentures, but its nature is different in different parts of the alveolar process and depends on the individual distribution of occlusion loading [7].

In turn, to search for the most effective ways to restore the functionality of the dental apparatus, in particular in the complete absence of teeth, simulation modeling of stress-strain states (SSS) in the tissues of the prosthetic bed is used. This method allows determining the nature of the distribution of SSS in biomechanical systems (BMS) "prosthesis – prosthetic bed" in their interaction due to functional (chewing) load [5].

Given that biomechanical factors associated with occlusion loading, the use of finite element method which takes into account the distribution of masticatory forces, interdental ratios and the nature of adhesion of bases to the prosthetic bed impact the success of prosthetics using complete dentures, makes it possible to improve the design features of complete dentures [20].

It should be noted that in the complete absence of teeth, simulation using the finite element method enables to determine the effectiveness of different prosthetic options based on implants [10]; describe the distribution of masticatory load under the base of the prosthesis, which causes pain in patients [21]; to substantiate the expediency of using soft liners in two-layer bases of complete dentures [18].

At the same time, despite the research conducted in this direction, the issues of SSS distribution arising during prosthetics with complete dentures and prostheses with fixation on implants, taking into account the degree of atrophy of alveolar processes, remain unexplored. In our opinion, such studies will have a practical solution in making recommendations on the choice of prosthetics for patients with complete absence of teeth.

In this regard, the purpose of the present work is to study the distribution of SSS in prosthetic of edentulous mandible with removable dentures, as well as constructions based on implants, taking into account the type of atrophy of its alveolar part.

MATERIALS AND METHODS OF RESEARCH

To create computer models of the mandible with different types of atrophy, the averaged data of digital scanning of diagnostic models and computed tomography were used (Fig. 1). As the main tool for studying the biomechanics of the BMS "prosthesis – mandible", virtual finite element models were used, on which the conditions of connection of the jaw with the prosthesis were studied. Thus, four models of BMS "complete denture – mandible" (CD) were created, which corresponded to four types of atrophy of edentulous jaws according to Keller.

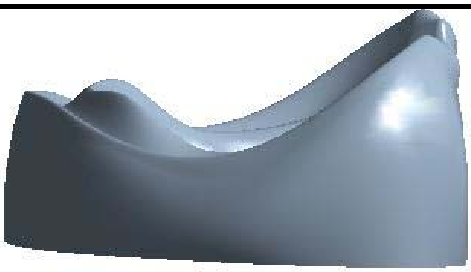
Type of edentulous mandible according to Keller	Side view	Anterior view
I		
II		
III		
IV		

Fig. 1. Graphic representation of 3D models of edentulous mandible in the environment of the geometric modeling system Autodesk Inventor 11.0

By analogy, simulation computer modeling of four more BMS models "removable denture – intraosseous implants – mandible" (RDI) was performed. The calculation was performed for two intraosseous titanium screw cylindrical implants with a diameter of 3.75 mm and a length of 11.5 mm, fixed in the projection of the canines.

In each of the eight models, the BMS simulated a masticatory load of 100 N according to the three variants shown in Figure 2 (symmetric in the area of molars and premolars on both sides and two asymmetric in the area of molars and canines on different sides and in the area of molars and premolars on the one side). Thus, SSS was calculated for 24 developed BMS models (12 CD and 12 RDI).

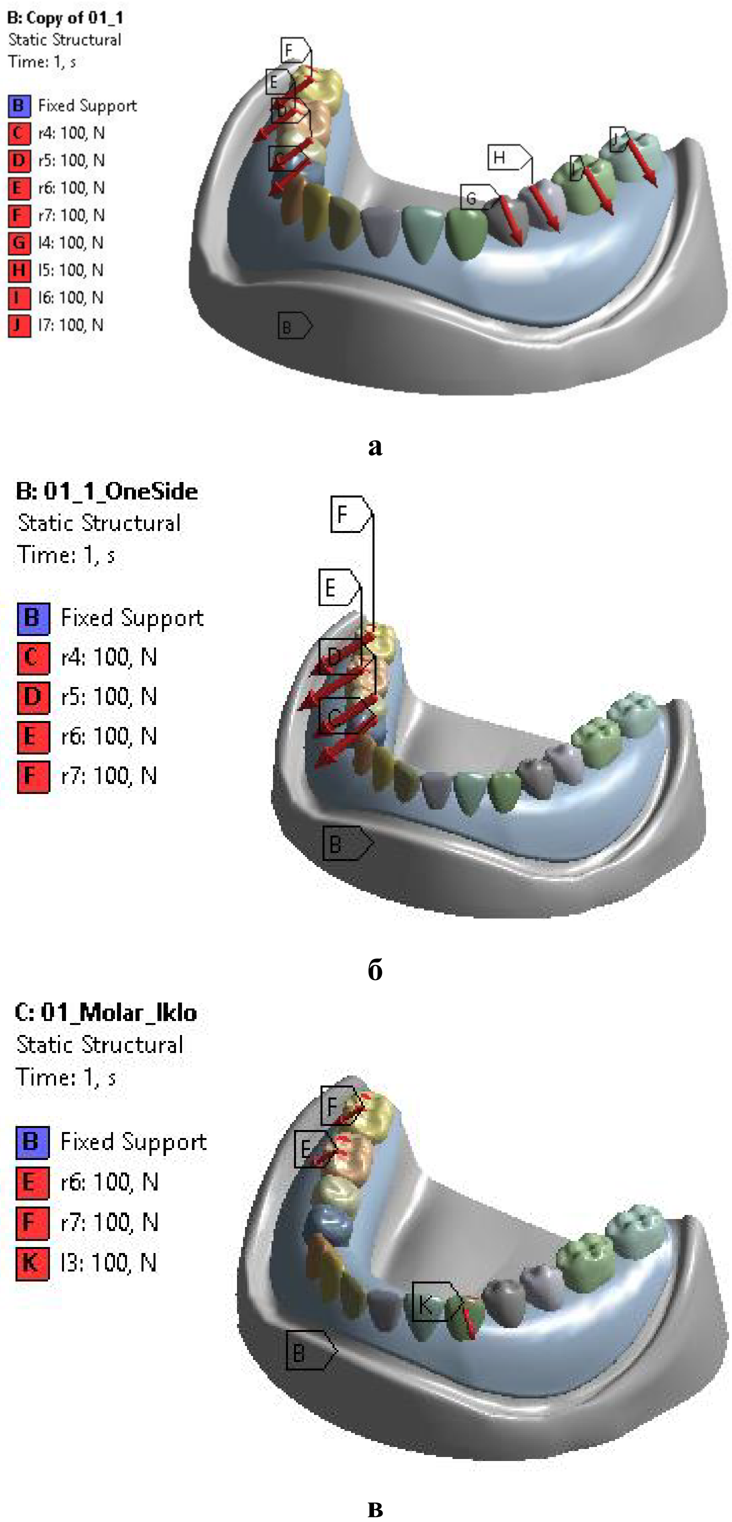


Fig. 2. Power load in BMS simulation models: symmetric in the molars and premolars area (a), asymmetric in the molars and premolars area (b), asymmetric in the molars and canines area (c)

The ANSIS 12.1 finite element analysis system was used to calculate SSS in simulation models. The distribution of Mises-equivalent stresses in the cortical bone of the prosthetic bed was evaluated. The displacement of the prosthesis design was also determined for all developed BMS models.

In the calculations it was assumed that the bone tissue of the mandible is continuous, homogeneous, so the physical and mechanical properties were given in the form of an isotropic material with elastic averaged characteristics. For the mandible, a Young's module of 0.1x105 MPa, Poisson's ratio of 0.25, and an allowable stress for particles of its material of 100,0 MPa were used, which corresponds to experimental data of values for the elastic limit of the cortical bone [3].

RESULTS AND DISCUSSION

As a result of the calculations, shown in Table 1 it was found that the maximum values of Mises-equivalent stresses in the bone tissue of the prosthetic bed are observed in the third type of mandibular atrophy at all types of loadings. The largest values for this model are calculated for asymmetric loading in the area of molars and canines; they were 9.2 MPa. The maximum stresses are set in the area of the preserved alveolar part in the anterior area (Fig. 3).

Table 1

Maximum values of voltages of Mises equivalent in the bone tissue of the prosthetic bed (MPa)

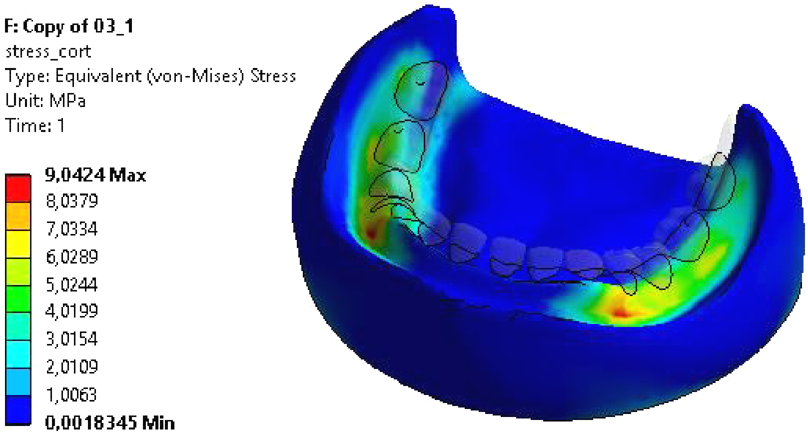
Type of load	Type of atrophy of edentulous mandible according to Keller							
	I		II		III		IV	
	CD	RDI	CD	RDI	CD	RDI	CD	RDI
Symmetric	7.6	93.0	7.0	53.0	9.0	68.5	7.1	31.4
Asymmetric	7.3	76.9	5.6	56.8	9.0	68.3	7.1	30.3
(molars and premolars)	8.0	47.1	5.1	56.8	9.2	60.1	7.0	18.7

Notes. CD – BMS model "complete denture - mandible"; RDI – BMS model "removable denture - intraosseous implants mandible".

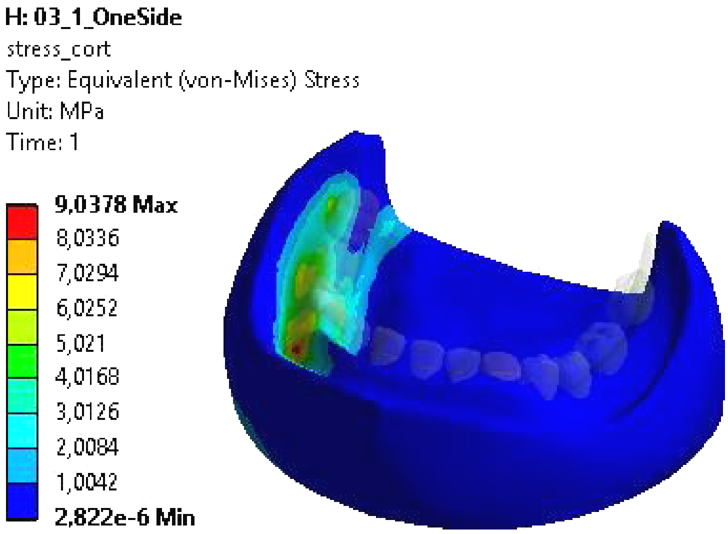
The lowest stresses were on models that simulated the second type of edentulows jaw according to Keller. Accordingly, the lowest result of Mises-equivalent stresses in the bone tissue of the prosthetic bed is calculated for the same asymmetric load in the area of molars and canines; it was 5.1 MPa.

Most favorable for prosthetics, the first type of edentulous mandible was characterized by significant differences in the distribution of maximum values of Mises-equivalent stresses in the cortical bone of the prosthetic bed. Thus, in symmetric load this indicator was equal to 7.6 MPa, for asymmetric (molars and premolars) – 7.3 MPa, for asymmetric (molars and canines) – 8.0 MPa. Whereas in the model of the fourth type of atrophy, the results were equivalent for all variants of load, being equal to 7.0-7.1 MPa.

Additional fixation of removable dentures in simulation models of BMS "removable denture – intraosseous implants – mandible" led to a significant increase in stress in the alveolar bone (Table 1). The obtained data completely coincide with the results of the work which indicates a significant exaggeration of stresses and strains in the simulation model of the mandible in the manufacture of overdentures based on implants, which, according to the authors, leads to accelerated bone resorption [16].



a



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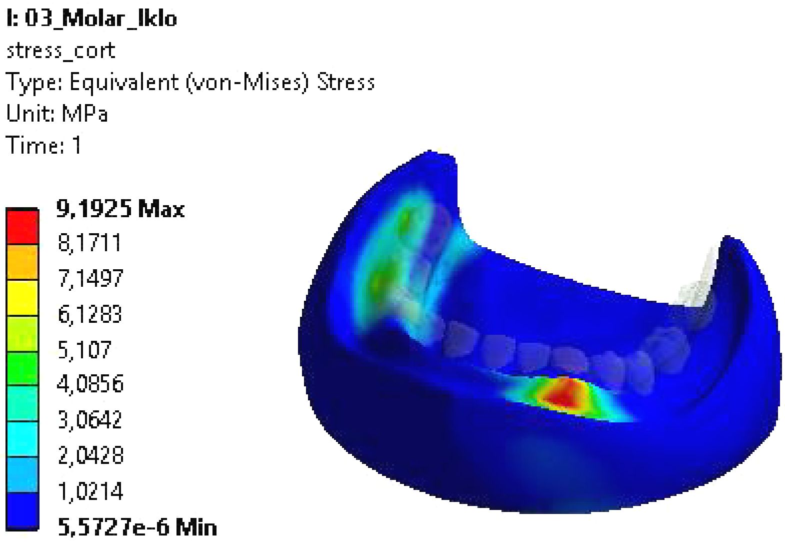

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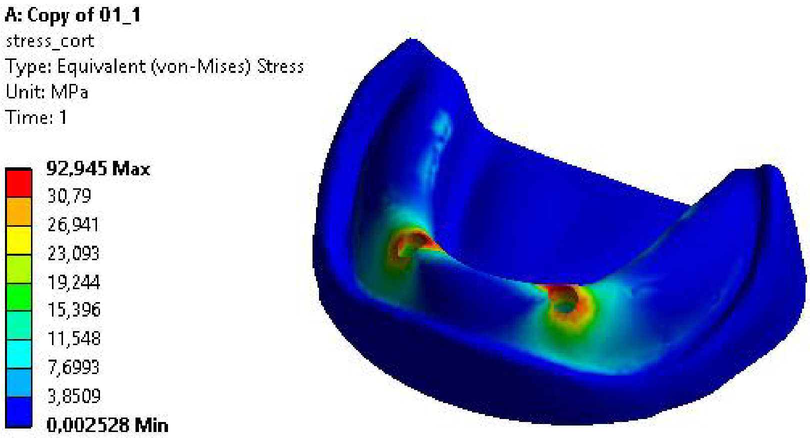
Fig. 3. Stress distribution in the simulation model of BMS "complete denture – mandible type III" in symmetric force load of molars and premolars (a), in asymmetric – in the area of molars and premolars (b), in asymmetric – in the area of molars and canines (c)

As shown in Figure 4a, the maximal values of Mises-equivalent stresses in the bone tissue of the prosthetic bed were observed in a well-defined alveolar part in edentulous mandible type I and symmetric loading (93.0 MPa). In general, higher stresses were registered in expressed alveolar process (types I and III of edentulous mandibles), while in significant atrophy (types II and IV) the minimal stress states were registered.

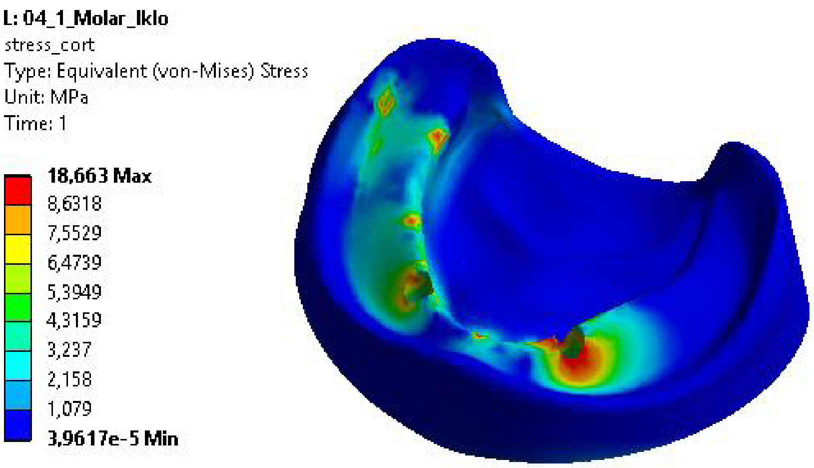
The distribution of stresses was also influenced by the nature of the force load: the smallest values were calculated for the asymmetric load in the area of the canines and molars, the largest – for symmetric loading.

Thus, the minimal values of Mises-equivalent stresses (18.7 MPa) were established for type IV atrophy of the mandible under asymmetric load in the area of artificial canines and molars on different sides (Fig. 4 b).

At the same time, according to all simulation models of BMS "removable denture – intraosseous implants – mandible", the maximal stresses are observed in the area of the marginal bone, which coincides with the results of previous studies [11]. According to [15], the maximal stresses occur around one implant, regardless of the type of bone tissue according to Mish, but decrease in increasing number of implants to two.



а



б

Fig. 4. Stress distribution in the simulation model of BMS "removable denture - intraosseous implants - mandible":
a - the maximal values in symmetric force load of molars and premolars in type I atrophy of the edentulous mandible,
b - the minimal values in asymmetric one in the area of molars and canines on different sides in type IV atrophy

The maximum displacements of structures under different types of load for BMS "complete denture - mandible" are given in Table 2. As can be seen, the displacements of the bases of complete dentures are insignificant and fluctuate within hundredths part of a millimeter for all types of atrophy. The smallest displacements were registered at a considerable and uniform atrophy of the alveolar process (type II of edentulous mandible according to Keller).

Table 2

Maximum displacements of structures in different types of load (mm)

Type of load	Type of atrophy of the lower edentulous jaw according to Keller							
	I		II		III		IV	
	CD	RDI	CD	RDI	CD	RDI	CD	RDI
Symmetric	0,07	3,4	0,02	2,0	0,05	4,9	0,07	2,0
Asymmetric	0,07	3,2	0,01	2,0	0,05	4,9	0,07	1,7
(molars and premolars)	0,08	2,5	0,01	1,5	0,03	3,9	0,06	1,2

Notes. CD – BMS model "complete denture – mandible"; RDI – BMS model "removable denture - intraosseous implants - lower jaw".

At the same time, the use of intraosseous implants for dentures fixation led to a significant increase in displacement (Table 2). At the same time, the fields of displacement are characteristic: in complete denture they are uniform, while in the use of implants they are not (Fig. 5-7).

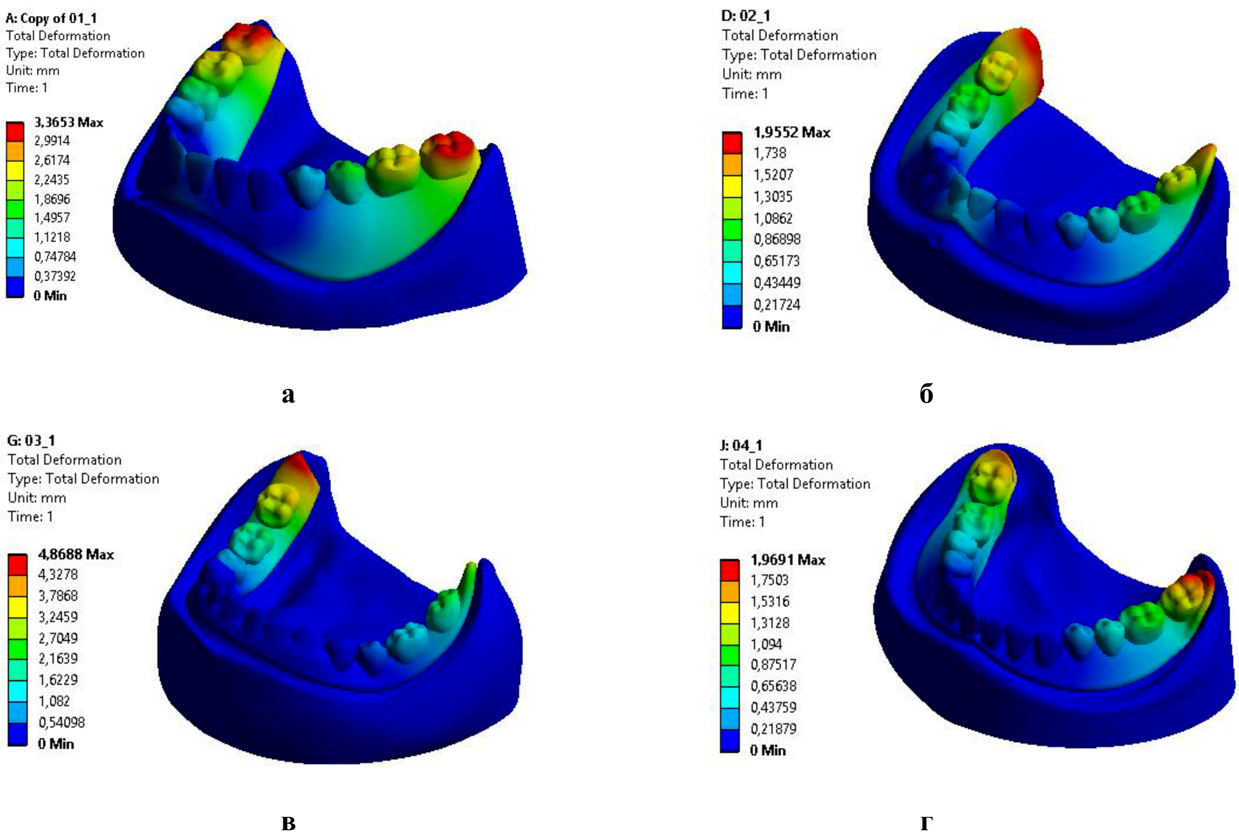


Fig. 5. Fields of denture displacement in the simulation model of BMS "removable denture - intraosseous implants - mandible" with symmetric force load in the area of molars and premolars with different types of atrophy of the mandible: a - I; b - II; c - III; d - IV

In symmetric load in BMS "removable prosthesis – intraosseous implants – mandible" there is a considerable mobility of a denture only in distal areas on both sides (Fig. 5), whereas in asymmetric – in distal area only on the side of load (Fig. 6-7). The most mobile was the denture base in type I of mandibular atrophy: displacements were observed throughout both distal areas. Whereas in other types of atrophy of the mandible, displacements were localized mainly in the most distal areas of the base (Fig. 5-7).

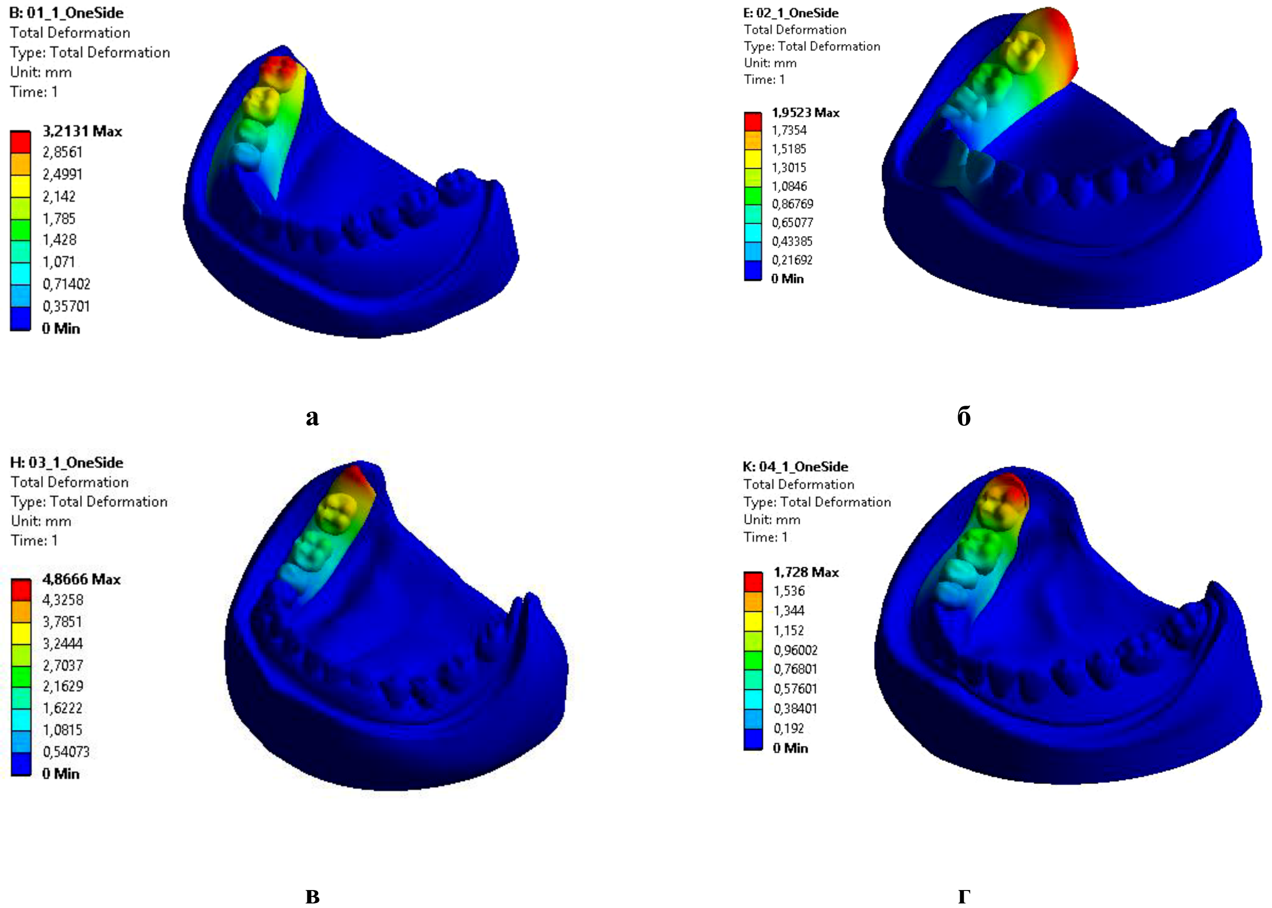


Fig. 6. Fields of denture displacement in the simulation model of BMS "removable denture – intraosseous implants – mandible" with asymmetric force load in the area of the molars and premolars in different types of atrophy of the edentulous mandible: a - I; b - II; c - III; d - IV

Summing up, it is advisable to agree that the increase in stresses and strains with the use of support implants causes greater masticatory efficiency, and thus leads to an increase in the masticatory load on the edentulous alveolar process [12]. In our opinion, in this situation we can assume the effect of plastic bases of removable prosthesis on the distal parts of the mandible by the principle of the console. Thus, the hydrostatic pressure in the mucous membrane exceeds the critical values that causes the development of bone atrophy.

Our new data on the peculiarities of the distribution of SSS depending on the type of atrophy of the mandible allow us to differentiate the tactics of prosthetics. Thus, according to the calculations, the use of complete dentures without additional support on implants is most indicated in type I of edentulous mandible. This type of prosthodontic treatment will allow to avoid transient atrophy of the distal areas of the alveolar part of the mandible. In type II a significant uniform atrophy of the alveolar part of the mandible is an indication for dental implantation. From the standpoint of biomechanics in III and IV types of mandibular atrophy, it is better to place implants in areas of low or absent alveolar process. In general, in order to prevent atrophy of the distal parts of the alveolar bone in all types of edentulous jaws, it is advisable to consider the possibility of increasing the number of support implants.

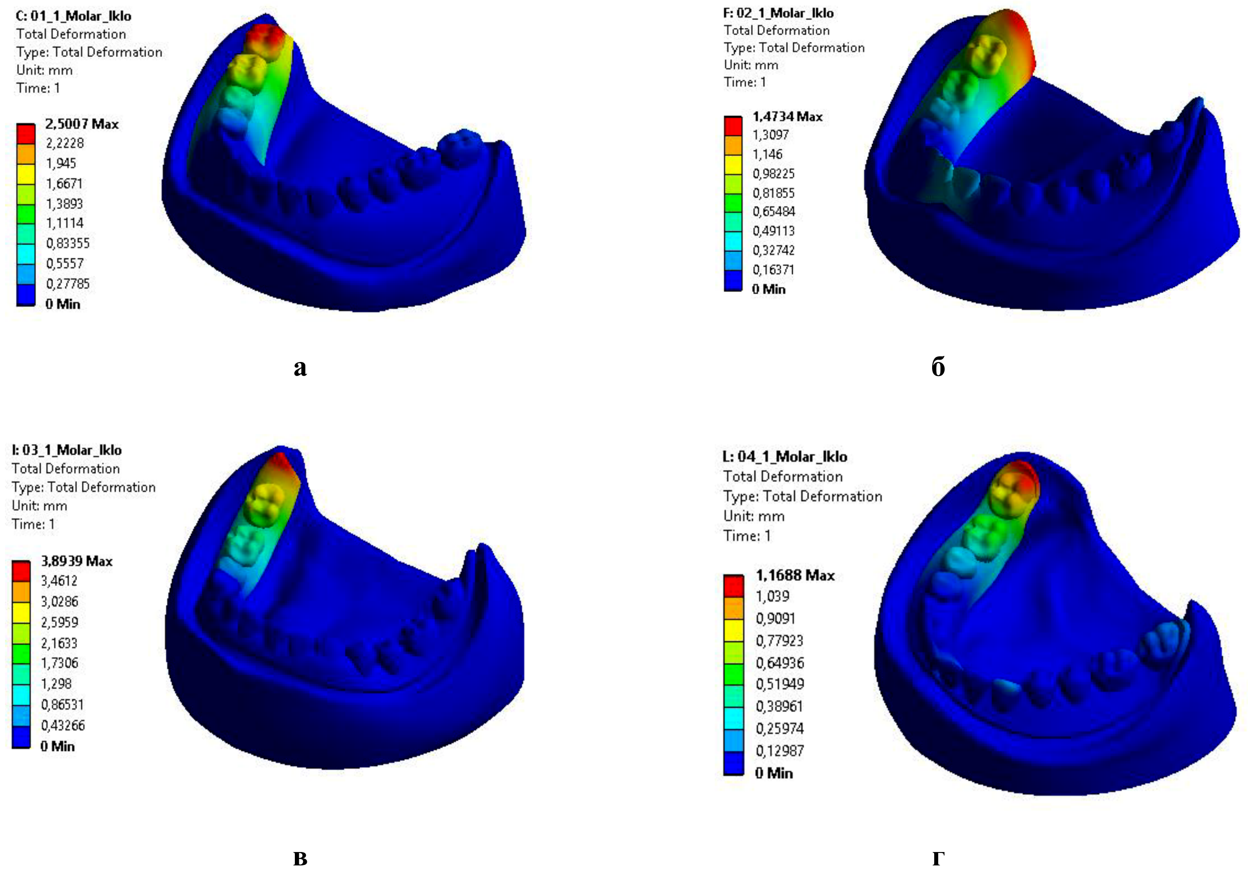


Fig. 7. Fields of displacement of denture in the simulation model of BMS "removable denture – intraosseous implants – mandible" with asymmetric force load in the molar and canine area in different types of atrophy of the edentulous mandible a - I; b - II; c - III; d - IV

CONCLUSIONS

1. In prosthetics of edentulous mandible both with "classic" removable constructions and with additional support on implants, in different phases of the masticatory act in the osseous base of the prosthetic bed different distribution of SSS occurs, this is determined by the shape of the alveolar part described by Keller classification.
2. The worst fixation of a complete denture on the mandible in type II is characterized by the lowest stresses in the tissues of the prosthetic bed. On the contrary, the best conditions for denture fixation are in type I of edentulous mandible, which provide the highest functional efficiency, lead to an increase in masticatory pressure on the bone tissue under the base of the denture and increase in SSS.
3. Fixation of a removable denture on the mandible on intraosseous implants which increases the functional efficiency at the same time leads to an increase in the masticatory load on the alveolar part, thus causing a significant increase in SSS.
4. The maximum stresses during dental implantation are local in nature and are observed in the areas of the marginal bone where the implants are fixed. The pronounced alveolar process in types I and III of the edentulous mandible causes an increase in displacements of the distal parts of the over-dentures on both sides in symmetric force load and on the one side – in asymmetric. It is expected that such a distribution of SSS in fixing dentures on implants will accelerate the atrophy of the tissues of the prosthetic bed.
5. The obtained results allow us to develop an algorithm for determining the indications for different types of prosthetics of edentulous mandible depending on the type of atrophy.

Conflict of interest. The authors declare no conflict of interest.

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