Original Article

Comparison of using different bridge prosthetic designs for partial defect restoration through mathematical modeling

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ABSTRACT

Objective: To analyze the stress–strain states of bone and abutment teeth during the use of different prosthetic designs of fixed partial dentures with the use of relevant mathematical modeling principles. **Materials and Methods:** The use of Comsol Multiphysics 3.5 (Comsol AB, Sweden) software during the mathematical modeling of stress–strain states provided numerical data for analytical interpretation in three different clinical scenarios with fixed dentures and different abutment teeth and demountable prosthetic denture with the saddle-shaped intermediate part. **Statistical Analysis Used:** Microsoft Excel Software (Microsoft Office 2017) helped to evaluate absolute mistakes of stress and strain parameters of each abutment tooth during three modeled scenarios and normal condition and to summarize data into the forms of tables. **Results:** In comparison with the fixed prosthetic denture supported by the canine, first premolar, and third molar, stresses at the same abutment teeth with the use of demountable denture with the saddle-shaped intermediate part decreased: at the mesial abutment tooth by 2.8 times, at distal crown by 6.1 times, and at the intermediate part by 11.1 times, respectively, the deformation level decreased by 3.1, 1.9, and 1.4 times at each area. **Conclusions:** The methods of mathematical modeling proved that complications during the use of fixed partial dentures based on the overload effect of the abutment teeth and caused by the deformation process inside the intermediate section of prosthetic construction.

Key words: Dental rehabilitation, mathematical modeling, prosthetic bridges design

INTRODUCTION

The prevalence of partial and full adentia among adults is one of the key problems of modern medicine. The WHO has even identified prerogative for the dental health development to ensure retention of at least 20 natural teeth among persons over 80 years old through the complex programs of dental prophylaxis and preventive measures provided on different levels of dental care system.[1] However, despite the key role of prevention, treatment of patients with already existing partial defects of dentition remains one of the most widespread manipulation in the prosthodontic practice.[2] Tan *et al.* found that the 10-year probability of survival for fixed partial dentures equals nearly 89.1% (being in rage of 81%–93.8%) while the probability of success was found to be 71.1% (being in range of 47.7%–85.2%).[3] Obviously, the prognosis of dental bridge constructions depends on the adequacy of functional load distribution between the abutment teeth and the intermediate part of the prosthesis.[4] Decisive role of such parameter, Lang

et al. and Brägger *et al.* described in their recent papers, where they marked the importance of load distribution among natural teeth and dental implants during different approaches of prosthetic rehabilitation.[5,6] The evaluation of elastically deformed states of bone near abutment teeth and implant infrastructure is one of the key aspects to provide effective prognosis of long-term prosthetic success rate. Although the implant-supported dentures remain common and predictable method of prosthetic rehabilitation during the partial adentia,[7] partial fixed prosthetic designs with the support of natural teeth are more financially acceptable treatment option for a significant number of patients. According to relevant research, dentists usually do not fully evaluate all of mucosa and bone support potential while using fixed partial dentures.[8-10] In some cases, the use of demountable design of bridge structure can provide an effective alternative for successful restoration of adentia defect.[4,11] Relevant mathematical modeling approaches provide opportunities to argument the use of different designs of dental prostheses based on practically oriented objectives of treatment in different clinical situation.[12-15] Such approaches also include evaluation of extent and topography of the defect, the state of supporting natural teeth, qualitative characteristics of bone, and features of interocclusal relation with antagonist's teeth. Therefore, the aim of this study was to analyze the stress–strain states of bone and abutment teeth during the use of different prosthetic designs of fixed partial dentures with the use of relevant mathematical modeling principles.

MATERIALS AND METHODS

The use of Comsol Multiphysics 3.5 (Comsol AB, Sweden) software during the mathematical modeling of stress–strain states provided numerical data for analytical interpretation in three different clinical scenarios. Initially three-dimensional mathematical model of normal condition included mandible with continuous tooth row, consists of teeth, periodontium, compact and spongy bone, and mucosa of the alveolar process. The dimensions of the teeth, the thickness and shape of the bone contours, deviation axis of the teeth, alveolar bone, and mucosal thickness imitated the average statistical data presented in the literature. To simulate included partial dentition defect with the absence of three teeth, we used only a lateral fragment of mandible. Such kind of defect was found to be the most prevalent (27.4%) among randomly selected 256 patients of Prosthetic Department at Lviv National Medical University Clinic, who had different forms of

partial adentia. We have analyzed next three scenario of possible prosthetic treatment of clinical situation with adentia of the second premolar, first and second molars on mandible:

- Restoration of partial adentia by the fixed prosthetic denture supported by the first premolar and third molar
- Restoration of partial adentia by the fixed prosthetic denture supported by the first canine, premolar, and third molar
- Restoration of partial adentia by the demountable prosthetic denture with the saddle-shaped intermediate part fixed on the canine, first premolar, and third molar with the use of rigid locking fasteners.

The total number of nodal points in the mathematical model for the first scenario was 216,734 and for the second and third 252,049. During the mathematical simulation of those clinical situations, we assumed that all components of dentition are isotropic and homogeneous. The use of tetrahedral volume elements helped to form three-dimensional mathematical models [Figure 1]. The main biochemical characteristics that were used during the modeling are present in Table 1.

Functional modeled load was applied tangentially to the occlusal surface of artificial teeth in the structure of partial fixed denture because the force that is acting at a distance from the abutment teeth has a more significant impact on the supporting teeth compare to their direct load. Total load was 400 N. Such occlusal load was chosen based on the results of previous analogical studies published in peer-reviewed journals.[16,17] Analysis of stresses and strains at the
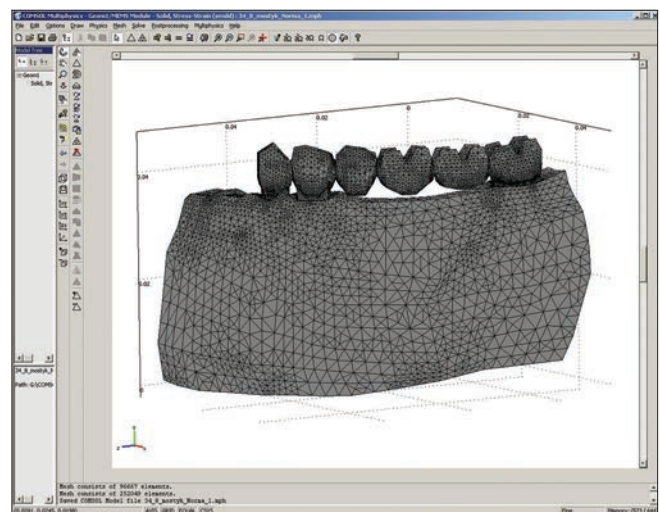

Figure 1: Tetrahedral volume elements used to build the model

different components of the model was carried out by colorful representation of stress distribution and the numerical data to provide objective comparison; the stress–strain state of dentition in the normal condition without any defect was determined. All the original data, such as the geometric structure of the model, properties of tissues, size, direction, and load location, were preserved for further comparison with all three mentioned above scenarios of possible prosthetic rehabilitation.[2,15,18]

To provide clinical evidences of effective use of demountable prosthetic denture with the saddle-shaped intermediate part fixed on the canine, first premolar, and third molar with the use of rigid locking fasteners, we approbate such scenario on 16 patients with partial adentia of the second premolar, first and second molar at mandible. These 16 patients represented study group. Other 16 patients with partial adentia of the second premolar, first and second molar were treated by fixed partial denture placed on the canine, first premolar, and third molar. Inclusion criteria for patients from study and control group were partial adentia of the second premolar, first and second molar at mandible without any somatic, periodontal, or other medical conditions that can influenced results of prosthetic treatment. Observation of bone resorption was provided using spot-film radiography method after 1 and 3 years of prosthetic treatment. Standardization of bone state analysis based on radiographical results was provided by superimposition method of saddle-shaped intermediate part of prosthetic construction, which was used as a reference line for bone reduction registration.

Microsoft Excel Software (Microsoft Office 2016, Developed by Microsoft) helped to evaluate absolute mistakes of stress and strain parameters of each abutment tooth during three modeled scenarios and normal condition and to summarize data into the forms of tables.

Table 1: Biochemical parameters used during the mathematical modeling

Element of the model	E (MPa)	v	σ_c (MPa)	σ_p (MPa)
Tooth	1.56×10^4	0.3	230-310	2-104
Mandible bone	4.9×10^3	0.3	26-160	10-20
Mucosa	75	0.4	-	-
Metal part of fixed partial denture	22×10^4	0.33	-	700-970
Saddle-shaped intermediate part of demountable prosthetic denture	5×10^3	0.3	-	-

RESULTS

During the first scenario of modeling fixed partial dentures supported by the first premolar and third molar, maximum stress occurred in the abutment crowns and places of their connection with the intermediate part of the denture. The greatest stresses were located at the area of distal tooth that reached 190.88 MPa, and the lowest of 29.94 MPa registered at the intermediate part of fixed prostheses, where the load was applied. Mesial abutment tooth reached stress of 122.98 MPa while strain of mesial and distal abutment tooth was nearly the same and stated for 85.36 and 84.39 μm, respectively. Deformation level of intermediate denture part reached 115.00 μm [Figure 2]. In the area of abutment teeth, maximum stress occurred in the cervical region and was gradually decreasing while going along vestibular side to half of the roots length and along oral side to
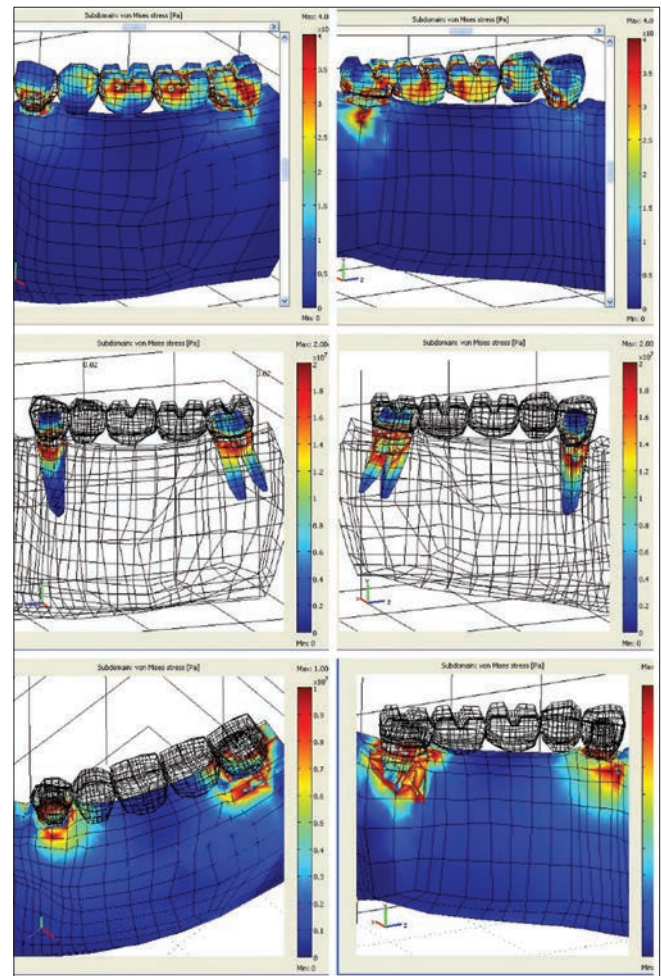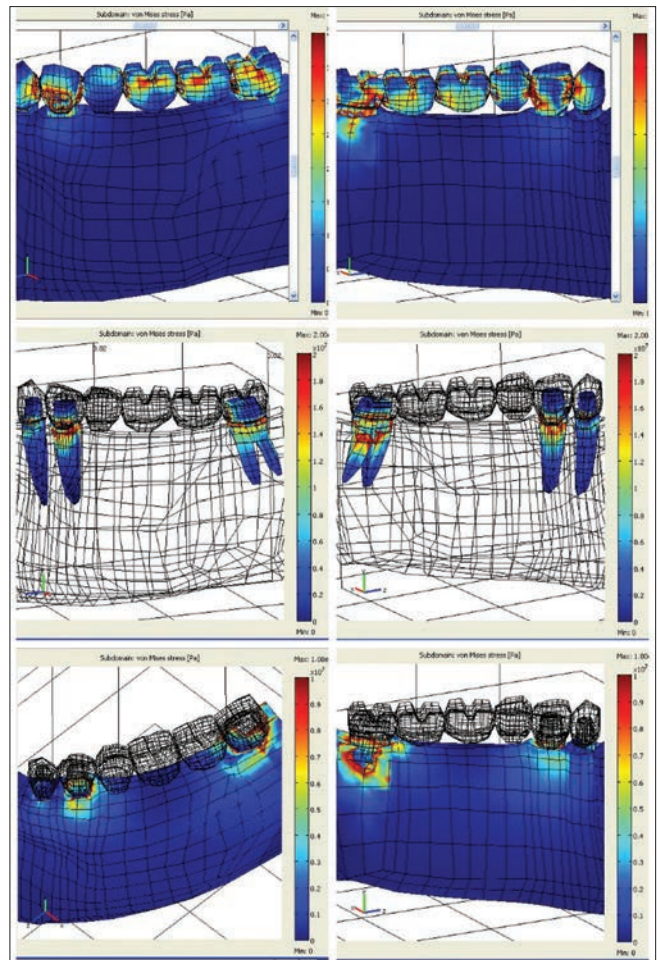

Figure 2: Representation of stress and strain states of denture elements, abutment teeth, and bone structure during the first scenario modeling with the use of fixed prosthetic denture on the first premolar and third molar

2/3 of roots length. The greatest stress was defined in the area of distal abutment tooth (44.97 MPa) and the greatest strain in contrast was registered at mesial abutment tooth (66.15 μm). Due to such scenario, stress that occurred in mesial abutment tooth was 8 times higher compare to normal condition of natural denture and 20 times higher in the area of distal abutment tooth. The deformation of abutment teeth was also increased at the first premolar by 23 times and for the third molar by 26 times compare to the normal condition. The stressed in the bone structure around the mesial tooth (29.48 MPa) was lower than at the distal abutment tooth (41.04 MPa). Comparative analysis of stress–strain state of bone around abutment teeth (first premolar and third molar) in condition of defect and during normal state of teeth row obtained that such parameter was 20 times higher in the area of premolar and 31 times higher in the area of molar, while strain parameters were also increased by 17 and 14 times, respectively, for each area of abutment teeth.

In the case of the second scenario, the use of canine as an additional abutment tooth was found that the greatest stresses were located in the area of distal tooth (113.21 MPa) and the smallest in the intermediate part of prosthetic denture (23.23 MPa). However, the value of the maximum stress was lower compare to the first modeling scenario: in the area of mesial supporting crowns just by 1.5 times higher, in the area of distal crown by 1.7 times higher, and in the intermediate part by 1.3 times higher. Deformation of prosthetic elements had inverse representation: the greatest deformation was observed in the intermediate part of denture (68.53 μm) and the smallest at the abutment crown fixed on the third molar (32.37 μm). The magnitude of the deformations was also lower compare to the first scenario, especially in the area of supporting crown by 2.6 times. Maximum stress in the area of abutment teeth occurred in the cervical region and gradually decreasing through the vestibular side to 1/3 the length of roots and from oral side to the two half of the roots length. The greatest stress was stated in the distal abutment tooth (26.55 MPa), and the smallest was observed near canine that served as additional abutment tooth (9.50 MPa) [Figure 3]. Compared with the first modeled scenario, the maximum stress in the first premolar decreased by 1.6 times and in the third molar by 1.7 times. However, these values were higher than the corresponding parameters at the natural integral state of dentition (by the 5 and 12 times, respectively). Loading of the intermediate part caused the greatest strain in the first premolar (35.57 μm) and the smallest in the canine area (17.05 μm). The

Figure 3: Representation of stress and strain states of denture elements, abutment teeth, and bone structure during the first scenario modeling with the use of fixed prosthetic denture on the canine, first premolar, and third molar

maximum stress in the bone tissue around the abutment teeth located at the cervical area of alveolus and was gradually decreasing toward the roots apices and toward the defect space. The stress level at the mesial abutment teeth (17.07 MPa) was lower than at the distal abutment teeth (23.83 MPa). The greatest bone deformation observed at the first premolar (14.03 μm) that was characterized by orally distal direction. Deformations occur near the third molar (12.61 μm), distributed in the mesial-oral direction, toward the defect space. The maximum stresses of bone tissue in the area of abutment teeth decreased by 1.7 and the strain decreases by 2 times compare to the first modeled scenario. However, such values were higher than at the areas of corresponding teeth with no partial defect [Figure 4].

During the third modeled scenario, the stresses of the mesial crowns (28.05 MPa) were noted to be higher than at distal abutments (15.74 MPa). The

lowest stress was registered in the saddle-shaped basis of demountable prosthesis construction (2.07 MPa). Deformation of structural denture elements had an inverse relationship to previous scenarios: the most deformed was saddle-shaped basis of prostheses (46.36 µm), and the least deformed was abutment mesial crown (14.58 µm). In comparison with fixed prosthetic denture supported by the canine, first premolar, and third molar, stresses at the abutment teeth in third modeled scenario were smaller: at the mesial abutment tooth by 2.8 times, at distal crown by 6.1 times, and at the intermediate part by at 11.1 times, respectively, the deformation levels decreased by 3.1, 1.9, and 1.4 times. Values of maximum stresses exceeded defined stress maximums of normal state by 2.2 times at the canine, by 2.9 times at the premolar, and by 3.1 times at the third molar. Because the canine served as additional abutment, its stress and strain were minimal compared with other supporting teeth. The maximum deformation of abutment teeth were higher than normal state by 3.5, 4.2, and 6.2 times, respectively. The use of demountable prosthesis at third clinical scenario helped to decrease the stresses in bone tissues around the mesial abutment teeth by 3.0 times, around distal abutment teeth by 3.4 time, and level of deformation – by 1.5 and 1.2 times, respectively [Figure 5 and Table 2].

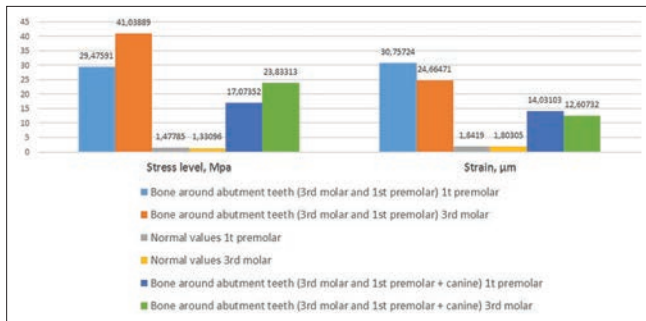To provide clinical evidences of effective use of such demountable prosthetic denture with the saddle-shaped intermediate part fixed on the canine, first premolar, and third molar with the use of rigid locking fasteners, we approbate such scenario on 16 patients with partial adentia of the second premolar, first and second molar. These 16 patients represented study group. Other 16 patients with partial adentia of the second premolar, first and second molar were treated by fixed partial denture placed on the canine, first premolar, and third molar (control group). After 1 year of functioning, the atrophy progress of the alveolar bone under saddle-base demountable prosthesis in study group was noticed to be uniform and amounted to 0.2 mm. After 3 years
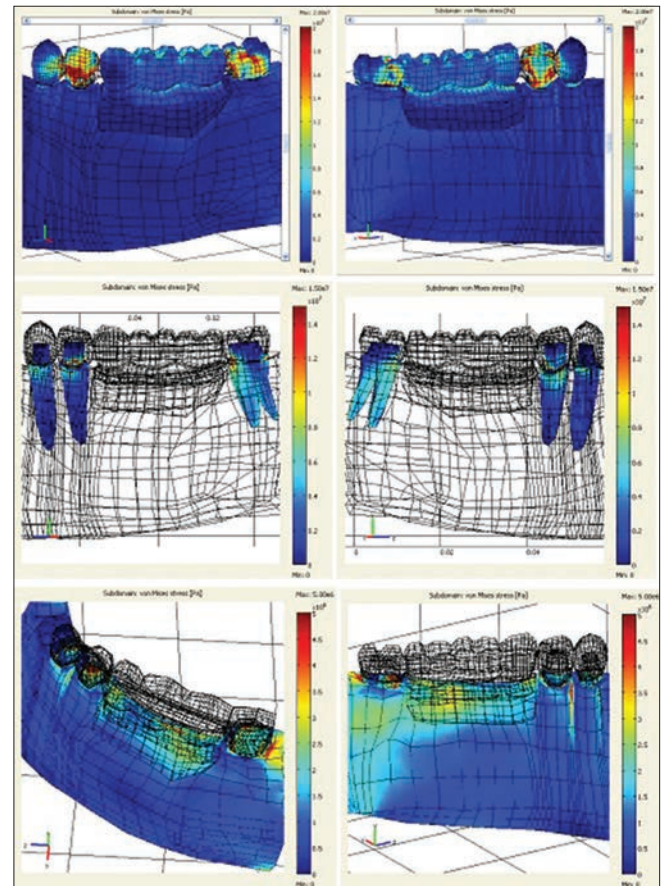

Figure 5: Representation of stress and strain states of denture elements, abutment teeth, and bone structure during the third scenario modeling with the use of demountable prosthetic denture with the saddle-shaped intermediate part

Figure 4: The comparison of stress and strains values during the first and second modeled scenarios and normal state of dentition

Table 2: Comparison of stress and strain parameters of each abutment tooth during three modeled scenarios and normal condition										
Parameters	Fixed partial denture (3 abutment teeth)			Normal parameters			Fixed partial denture (2 abutment teeth)		Demountable partial denture (3 abutment teeth)		
	Canine	First premolar	Third molar	Canine	First premolar	Third molar	First premolar	Third molar	Canine	First premolar	Third molar
Stress (Mpa)	9.5±0.8	20.0±1.1	26.5±1.2	1.9±0.2	3.8±0.3	2.2±0.1	31.7±1.4	44.9±1.6	4.1±0.3	8.9±0.2	7.2±0.4
Strain (µm)	17.0±1.2	35.5±1.5	26.0±1.1	1.9±0.2	2.8±0.2	2.1±0.2	66.1±1.8	56.7±1.4	6.9±0.4	12.2±0.4	15.0±0.3

of functioning, the reduction of the alveolar process reached just 0.35 mm. In the second control group, radiographical expansion of periodontal gap and signs of osteoporosis were detected in 7.7% ± 4.3% of cases at the defect area of teeth row. The level of bone resorption at defect area after 3 years of functioning reached the range of 1.2–1.8 mm. In 23.1% ± 6.8% of cases, periodontal complications such as localized periodontitis or chronic gum inflammation have been developed due to overload of abutment teeth.

DISCUSSIONS

Fixed prosthetic rehabilitation of the second premolar, first and second molar adentia seems to be challenging task for practical dentist due to the appearance of considerable stresses and strains in the supporting tissues that varies based on different prosthetic designs.[6,11,19,20] Within the possibility to provide restoration of adentia region with construction supported by dental implants, it can be stated that retention parameters are definitely influencing not only stability of supra constructions but also a changes at peri-implant bone.[21,22] Finite element model (FEM) analytical researches dedicated to the evaluation of masticatory load distribution due to the different form and shapes of dental implants found that not all modification of dental screws are argumented by the prognosed functional results; thus, the question of choosing adequate materials and methods for prosthetic treatment is a primary question of planning procedures.[23] Previous studies of different types of single-tooth crown prosthesis with the FEM and Von Mises analyses found that cemented retained prostheses offer a better and more homogeneous distribution of the load forces compared to screwed prostheses. Such point could be transferred on the prosthetic designs with natural teeth support, but different effects of strain and stress distribution[24] could also influence functional prognosis of abutment teeth. Such effects increase with the convergence of abutment teeth, which presented in such cases by the first premolar and third molar. Inadequate prosthetic can cause the periodontal tissues alteration in future, the problems with appropriate crown fixation, and fracture of abutment teeth.[5,25,26] Additional support of prosthetic constructions with the mesial tooth such as canine improves the effectiveness of prosthodontic treatment, reducing the horizontal component of stresses and strains, but not completely resolving the problem of abutment teeth overload. Hard and soft tissue of partial defects with the appropriate design of intermediate prosthetic construction can play an

important role of optimal support and adequate distribution of functional loading.[3,8] To reduce negative impacts of saddle base of prostheses in defect area, an elastic lining could be used as an additional layer between prosthetic inner surface and soft tissue interface. The use of demountable prosthetic appliances supported by three abutment teeth decreases the levels of stresses and strains compare to nonremovable prosthetic design. Consequently, the use of mountable prosthetic appliances with saddle base transmitted functional load to the abutment teeth in a greater manner that to the soft tissue in defect area due to the use of rigid locking fasteners. Less load on the toothless area reduces atrophic processes under the saddle base. On the other hand, the proposed design eliminates the overloading of abutment teeth that occurs during the use of classic nonremovable prosthetics, reducing their stress and strains. Analysis of stress–strain state components of the models showed that the use of prosthetic appliances supported by two or three teeth marked inverse relationship between stress values and strains: in the areas, the greatest stresses were found the minimal deformations values. During the second and third modeling scenarios, the horizontal component of stresses and strains was directed orally and toward the defect. In addition, the stress inside the bone near abutment teeth spreads in the opposite direction from the defect, except areas of mesial abutment teeth in the second modeled situation, which indicates about the splinting effect of additional abutment tooth. Due to the limitations of this study, we can conclude that the use of a demountable prosthetic denture with the saddle-shaped intermediate part fixed on the canine, first premolar, and third molar with the use of rigid locking fasteners appeared to be considerable due to the obtained stress and strains values.

CONCLUSIONS

The methods of mathematical modeling proved that the causes of complications during the use of fixed partial dentures based on overload effect of the abutment teeth and deformation process inside the intermediate section of prosthetic construction. Inclusion of the additional abutment tooth leads to a decrease of stress–strain values in all the component elements of the mathematical model and provides a splinting effect of construction. Design of demountable prosthetic construction eliminates the overload effect of abutment teeth under the functional loading and helps to decrease the degree of bone structure atrophy during the prolonged functioning of the prostheses.

The use of rigid locking fasteners can transfer the functional load on abutment teeth in a greater manner than into soft and hard tissue of defect are, which reduces atrophic processes under the saddle-like base of prosthetic construction.

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Conflicts of interest

There are no conflicts of interest.

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