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ORIGINAL ARTICLE / ОРИГИНАЛНИ РАД

Stress and strain distribution in the lower jaw with shortened dental arch – A Finite Element Method study

Aleksandra Milić-Lemić[1], Ivan Tanasić[2], Ljiljana Tihaček-Šojić[1]

[1]University of Belgrade, School of Dental Medicine, Department of Prosthodontics, Belgrade, Serbia;
[2]Medical Health Center Obrenovac, Belgrade, Serbia

SUMMARY

Introduction/Objective The absence of functional loading due to molar loss might cause changes to the microstructure of the bone. Therefore we investigated and visualized deformation and strain pattern distribution of the mandibule with full arch dentition (FDA) and shortened dental arches (SDA) during occlusion.
Methods A 3D model of an adult cadaveric dentate mandible, without pathological and traumatic damages, was developed based on CT scan images, set to 0.7 mm slice thickness. The scanned slices were imported into software where the bone and teeth were identified and modelled separately based on image density thresholding. Using the software and based on the grey-scale analysis of the slices initial meshes for the cortical, cancellous bone and teeth were generated.
Results Highest stress/strain values were registered in the structures adjacent to molars i.e. molar region of processus alveolaris assigned by blue color in FDA model. Similar to FDA, the SDA models exibited deformation with evident highest strain (9.33%) at the processus coronoideus and mandibular angle. The highest overall stress (5 MPa) and strain (6.67%) was found in the mandibular intercanine segment of the SDA model, considering the mandibular body.
Conclusion Finite element method can be employed as a powerfull tool for visualization of the stress and strain of the loaded mandible models with full and shortened dental arches. It was registered that molar support loss caused higher stress and strain in SDAs compared to FDA model.
Keywords: partially edentulous mandible; digital image correlation method; removable partial denture; bone strain

INTRODUCTION

The term ‘shortened dental arches’ (SDA) was first introduced in 1981 by Arnd Kayser, explaining a dentition functional status with posterior teeth loss [1]. Since then, the proposed concept is still considered controversial by many clinicians [2]. It was speculated that molar loss is associated with reduced masticatory performance and in some cases, it has been reported that it led to mandibular displacement and various changes [3, 4]. Also, it was suggested that SDA might be associated with an increased risk for changes in the temporomandibular joint (TMJ) [5, 6]. On the other hand, epidemiological studies on SDA subjects emphasized that SDA is not a risk factor for temporomandibular dysfunction [7, 8] confirmed with the *in vivo* and *in vitro* findings of Hattori et al. [9]. In spite of the extensive assessment of the effects of molar support loss on the migration of the remaining teeth, possible interactions with temporomandibular disorders, and chewing function alterations, the influence of molar loss on loading distribution to the remaining supporting tissues was not widely analyzed. Kondo and Wakabayashi speculated that increased strain is likely to occur in a certain proportion of patients with bilateral loss of molar support, representing a potential activator of bone degradation [10]. Furthermore, the absence of functional loading due to molar loss and occlusal loading center shifting anteriorly might alter the bite force distribution pattern with resultant strain (deformation) concentration that might cause changes to the microstructure of the bone. The objective of this study was to investigate and visualize stress and strain pattern distribution of the mandibula with full arch dentition (FDA) and shortened dental arches (SDA) during occlusion. We aimed to test the hypothesis that loss of molar support causes increased strain and alter the stress distribution pattern in the supporting mandible bone.

METHODS

In order to perform the study on a three-dimensional (3D) numerical model of a full dentate human mandible, named FDA model, was constructed, and the generated stress and strain were evaluated during clenching. The same

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Correspondence to:
Ivan TANASIĆ
Medical Health Center
Obrenovac, Belgrade, Serbia
doktorivan@hotmail.com

analysis was conducted on 3D models of the mandible with shortened dental arches, determined as the SDA models. Shortening of the dental arch was done up to premolar (SDA 1) and up to canine (SDA 2). So, SDA 1 was highlighted as a model with absence of molar teeth only, while SDA 2 had only anterior teeth left. Due to obvious practical reasons, as direct strain measurement in the functioning human mandible cannot be achieved, it was assumed that finite element modelling may be used instead to predict the real biomechanical responses in mandible models [11].

A 3D model of an adult cadaveric dentate mandible was developed based on CT scan images (Siemens, Somatom Sensation 16, Germany) and set to 0.7 mm slice thickness, after it was visually inspected and established to be without pathological and traumatic damages. The skeletal specimen was obtained from the Laboratory for Anthropology of the, Institute of Anatomy, at the Faculty of Medicine, University of Belgrade. According to data from the Laboratory archive, the mandible donor was a Serbian man in his late forties.

The scanned slices (total number of 248) were imported into a visualization software (Mimics 9.0; Materialise, Leuven, Belgium), where different hard tissues of the bone (cortical and cancellous) and teeth were identified and modelled separately based on image density thresholding. Using the software, and based on the grey-scale analysis of the slices initial meshes for the cortical, cancellous bone and teeth were generated. The periodontal ligament (PDL) was modelled as uniform, elastic layer of 0.3 mm around the teeth roots. Also, the mentioned materials that compose the structure under investigation were assigned different material properties within the next phase of finite element definition. Young's modulus and Poisson's ratio for all modelled materials are given in Table 1 and are imported from the literature data [11–15].

Table 1. Material properties assigned to the structure under investigation

Structure	Young's modulus (GPa)	Poisson's ratio
Compact bone	9.1	0.3
Cancellous bone	4.5	0.3
Hard dental tissues	20	0.3
PDL	7.5×10^{-3}	0.3

The digital models created in this way were imported into the Hyper Mesh software and total number of 3D tetrahedron was obtained. Due to geometry complexity of the investigated structures, it couldn't be possible to use hexahedron finite elements. Therefore, it was decided that tetrahedron was considered better for describing the dento-alveolar complex. The total number of nodes and elements composing the finite element mesh are presented in Table 2.

Table 2. Total number of nodes and elements representing each material of the structure under investigation

Material	Nodes	Elements
Mandible	86,072	130,910
Teeth	6,185	34,714

Processing and post-processing was performed in MSC Patran 2002, while MSC Nastran 2002 was used as solver.

Simulation of biting and clenching in the mandibles with full and shortened dental arches was done using static vertical loading parallel to the teeth long axis. The following points were established for loading protocols for models while the force intensity was accepted according to literature data [16, 17]:

1. Load was applied bilaterally symmetrical to the midline in the FDA model simultaneously along the dental arch with the following distribution of force intensity: anterior teeth 150N, premolars 200N and 300N.
2. Load was applied bilaterally symmetrical to the midline in the SDA models, simultaneously along the dental arch with the following distribution of force intensity: anterior teeth 150N, premolars 200N and 300N.

Furthermore, the mandible in all researched models were constrained at the occlusal surface of the biting teeth and at both TMJ. These restraints correspond to fixation of the mandible at the endosteal surfaces of temporal bones assuming that both condyles are centered in the glenoid fossas (Figure 1). Lines of masticatory muscles actions were imported from the literature [17, 18].

RESULTS

The results of this experimental study were represented using software images/figures and table. An interpretation of software images was done using the scales next to figures. The coloured scales graduated the intensities of stress and strain. The highest stress of 9.33 MPa was assigned by green colour of the mandible models. Overall, a large portion of strain and the highest stress/strain values were registered in the structures adjacent to molars i.e. molar region of processus alveolaris assigned by blue color in FDA model (Figure 2). Similar to FDA, the SDA models exibited deformation with evident highest strain (9.33%). The red colour was used to determine the highest strain at the processus coronoideus and mandibular angle (Figure 3). However, gradually reducing number of teeth led to overloading of the premolar region, the foramen mentale and the mandibular anterior region, respectivelly. Thus, the highest overall stress (5 MPa) and strain (6.67%) was found in the mandibular intercanine segment of the SDA model, considering the mandibular body.

Generally, regarding the mandibular body the highest stress/strain values were detected in the marginal periodontium of the teeth and retromolar region. A uniform overall strain was detected in both body and processus while overall stress was not evenly distributed along processus. The uniform strain was additionally seen on the lingual side of processus alveolaris and along the basal side of the corpus and assigned by different gradient of pink color (Figure 3). The posterior segments of mandible model including mandibular processus shown the highest strain and the lowest stress values, although the retromolar region revealed the highest stress and strain in all models (Figures 2, 3). The highest values of the average stress and strain

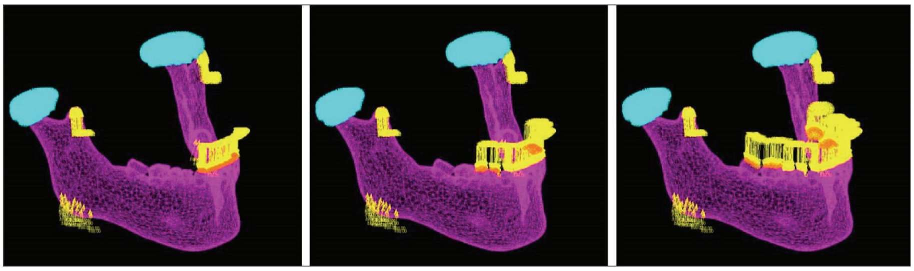

Figure 1. Investigated models (missing posterior teeth, missing molars and full dentate arch) were constrained at the occlusal surface of the biting teeth and at both TMJ

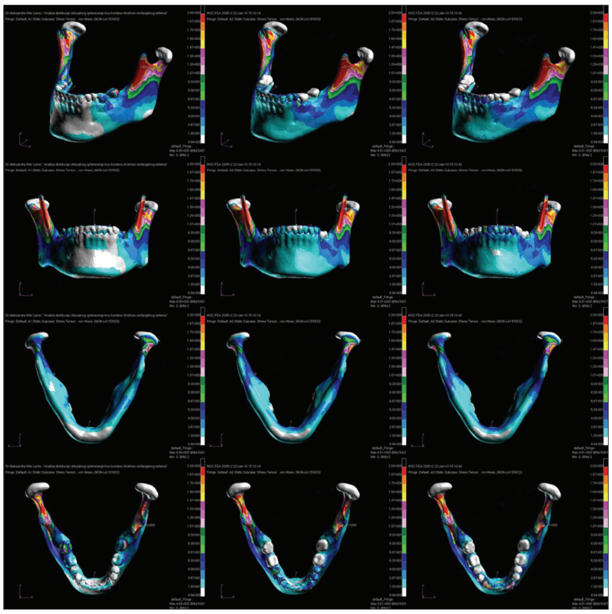

Figure 2. Collage of the mandible models exposed to stress viewed from frontal-lateral (first and second row), caudal-lingual aspect (third row) and occlusal (fourth row), respectively from up to down

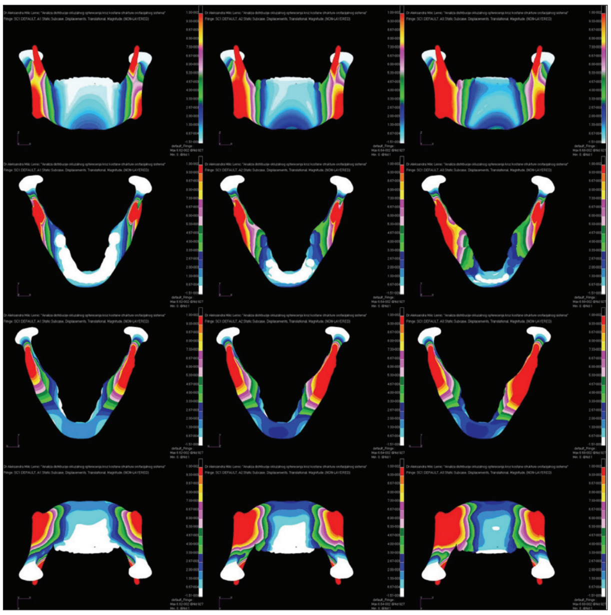

Figure 3. Collage of the strained mandible models imaged from the frontal-lateral (upper row), occlusal and lingual-caudal aspects (lower row), respectively from up to down

Table 3. Average stress and strain values obtained for three models: model with full dental arch, model determined by absence of molars and model with anterior teeth left

Stress and strain	average values		
	Full dentate (FDA)	Missing molars (SDA)	Missing posterior teeth (SDA)
Stress (MPa)	4.00	4.01	4.01
Strain (%)	6.62	6.64	6.68

FDA – full dental arch; SDA – shortened dental arch

were registered in mandible model with anterior teeth left (Table 3). The stress and strain were more concentrated in the anterior region of the SDA models compared to FDA model, that is supported with images, in frontal aspect (Figures 2, 3). The highest strain was also detected in the lingual side of alveolar bone and basal side of the corpus of SDA models (Figure 3).

DISCUSSION

So far, 3D finite element analysis (FEA) has been used many times in dentistry research field for various purposes [19, 20]. FEA has many advantages over other digital methods in simulating the complexity of clinical circumstances [10]. Still, the clinical studies were found to be more relevant for practice compared to the FEA evidence. In addition, FEA analyses can provide full visualization of stress and strain distribution without involving human subjects and thus excluding ethical dilemma [21].

This study is a simulation of an every-day clinical situation during biting and chewing of full dental and shortened dental arches. In the present study, FEA was used to examine the effects of the static loads on the stress/strain distribution in mandible models similar to previous study conducted using the digital image correlation method [22]. As a result of occlusal loading of the analyzed mandible models full stress/strain fields were observed [22]. The study revealed that shortening the dental arch partially changed the pattern of occlusal load distribution and increased stress and strain in the anterior mandibular segment which is supported by previous findings [7, 8, 9, 21, 22]. A location of the areas of higher stress was associated with the loading position and site [20, 22], but the action of masseter, medial pterygoid and temporalis contributed to the compressive stresses in the ramus and lingual side of alveolar processus and corpus observed during both simulated loading protocols [23]. Thus, the highest strain intensity at the coronoideus process was expected, because of the insertion of the masticatory muscles closest to force attack point and their function during closing. Strain of the lingual side is a consequence of mandible occlusal loading but also a result of masticatory muscles action. Therefore, results of this study may provide support for the idea that twisting and bending loads associated with condylar reaction and muscle forces must have a significant impact on states of stress and strain throughout both the basal and alveolar regions of the corpus [23].

The biomechanical behavior of FDA and SDA models under simulated load was observed and evaluated in relation to the stress–strain development. Whereas comparison between two investigated models in the study were done comparing principle strain where maximum strain is used to observe tensile strain and minimum for the compressive strain. Nevertheless, tensile stress and compressive strain showed significance during these courses due to their specifically allocation and accumulation. Tensile stress was observed at the lingual side of processus alveolaris and basal side of corpus mandibularis. On the other side compressive strain of 1.17–6.45% was observed at the loading point a few millimeters inside the bone. Furthermore, compressive strain was localized in the anterior region of processus alveolaris and basal corpus. The highest compressive strain was evident at the ramus and processus condylaris. Compressive strain values in SDA models were of lower intensity than the yield reported to cause deterioration effects [24]. However, from the biomechanical viewpoint compressive strain concentrated around the premolar and canine in SDA models may be of potential damage to alveolar bone at the site with the resultant resorption [22, 24]. The results of the study support the findings of previous studies when compressive stress and strain distribution is concerned in SDA [10, 22]. It is evident that the PDL and surrounding bone of premolars in SDAs with molar loss will be susceptible to higher compressive strain. Whether such teeth are prone to biomechanical stimuli, the weakening will primarily depend on individual patient characteristics and pathogenic bacterial accumulation [25]. Also, as stated, decreasing number in occlusal units may compromise dental stability in some patients with SDAs [22]. A similar tendency of tensile stress distribution along the lingual side of processus alveolaris and basal side of corpus was observed when SDA models were loaded. Just like in the previous model, highest compressive strain was observed at the loading point, in this case in the bone of the premolar region. Despite the fact that the loading was applied in the premolar teeth representing SDA, great intensity of compressive strain was noticed in the processus alveolaris adjacent the molar and in the ramus. The aforementioned is the confirmation that majority of strain in the mandible is a consequence of masticatory muscles activity. In addition, teeth displacement during occlusal loading amortizes functional and para-functional forces and thus avoids the overloading [25]. More importantly, the results have verified the initial statement that high stress is produced not only due to high load but also as a result of the morphology of the material or tissue that is susceptible to stress [9, 21, 24]. Perhaps the results presented in this paper are not real values of load in the mouth, but they indicate changes of stress and strain distribution to the implemented 3D models. Thus, the interpretation of obtained results make this method extremely important not only for preliminary and control investigation, but also as a method of choice when conducting in vitro studies [26, 27, 28].

CONCLUSION

Within the limitations, from and the biomechanical aspect of the study results, it may be concluded that: a) shortening the dental arch changes the pattern of occlusal load distribution; b) loss of posterior teeth support leads to increased stress and strain in mandible models; c) resultant compressive strain concentration caused by the dental arch shortening may be the source of the microstructre changes of the alveolar bone

Based on the study results the clinicians should not have the dilemma whether to restore SDA or not, at least not from the biomechanical perspective.

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Дистрибуција напона и деформација у доњој вилици са скраћеним зубним луком – студија методом коначних елемената

Александра Милић-Лемић[1], Иван Танасић[2], Љиљана Тихачек-Шојић[1]

[1]Универзитет у Београду, Стоматолошки факултет, Клиника за стоматолошку протетику, Београд, Србија;
[2]Дом здравља Обреновац, Београд, Србија

САЖЕТАК

Увод/Циљ Одсуство функционалног оптерећења услед губитка молара може изазвати промене у микроструктури кости.

Циљ овог истраживања је био да се испитају и визуелизују напони и деформације у мандибулама са интактним зубним луком (ИЗЛ) и скраћеним зубним луком (СЗЛ) у току оклузије.

Метод 3Д модел кадаверске доње вилице одрасле особе (процењена визуелним прегледом без патолошких и трауматских оштећења) развијен је на основу КТ слике, дебљине слоја од 0,7 *mm*. Скенирани пресеци су унети у софтвер где су идентификована и моделирана тврда ткива кости и зуби појединачно на основу сегментације слике. Почетне мреже за кортикалну кост, спонгиозну кост и зубе су произведене коришћењем софтвера и на основу анализе сиве скале пресека.

Резултати Највеће вредности напона и деформација су регистроване у структурама доње вилице непосредно уз моларе у тзв. моларном региону алвеоларног наставка, што је означено плавом бојом на ИЗЛ моделу. Слично ИЗЛ, и СЗЛ модели су показали највеће вредности деформација (9,33%) у короноидном наставку и мандибуларном углу. Највећи напон (5 *MPa*) и деформација (6,67%) пронађени су у интерканином региону СЗЛ модела, уколико се разматра тело доње вилице.

Закључак Методом коначних елемената су визуелизоване слике напона и деформација модела доње вилице са пуним и скраћеним зубним луковима. Уочено је да губитак моларне потпоре изазива јаче напоне и деформације у СЗЛ моделима у поређењу са ИЗЛ моделом.

Кључне речи: доња вилица; метод коначних елемената; скраћен зубни лук