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THE INFLUENCE OF MOLAR EXTRACTION IN MANDIBLE ON THE BONE REMODELING PROCESS UNDER DIFFERENT CHEWING CONDITIONS

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Abstract: The aim of this study is to analyze the process of remodeling the mandibular bone in the context of functional adaptation after tooth extraction. The mandible, as a bone structure, undergoes continuous remodeling, allowing it to adapt to changing mechanical conditions. After tooth loss, significant changes occur in the distribution of loading, which can lead to bone resorption in areas with reduced mechanical stimulation and to excessive loading of the remaining teeth. The study utilizes a geometric model of the mandible, taking into account different chewing conditions before and after tooth extraction, as well as numerical simulations to assess changes in bone density. The results show significant changes in stress and bone density in the region of the extracted tooth, including an increase in the density of cortical and cancellous bone, confirming hypotheses regarding adaptive mechanisms. Understanding these processes is crucial for dental practice, enabling doctors to better plan therapy after tooth extractions and to avoid complications associated with tooth loss.

Key words: tooth extraction, mandible, bone remodeling simulation, finite-element-analysis

1. INTRODUCTION

The mandible undergoes a process of functional adaptation of bone. As a bone structure, it combines the properties of living tissue with the strength necessary to withstand large loads resulting from muscle contractions during chewing. It undergoes continuous remodeling of its structure, allowing for the ongoing exchange of old bone material for new(1). In addition to systematic renewal, a process of functional adaptation may occur, allowing the bone structure to adjust to changes in the mechanical environment(2). This corresponds with the 19th-century theory known as Wolff's law(3). Its further development has been contributed to by researchers such as Cowin(4, 5), Carter and Beaupre(6), Huiskes(7, 8), and Frost, who formulated the "mechanostat" hypothesis(9). According to all these studies, the value of the so-called mechanical stimulus beyond a threshold level (the "lazy zone") can disrupt the equilibrium state of bone, leading to "functional adaptation": a value of the stimulus below the threshold level can cause resorption, while a value above the threshold level leads to additional bone formation. This mechanistic approach is very straightforward and is often applied in bioengineering analyses.

The process of functional adaptation of the mandible can be disrupted in the event of the loss of one or more teeth. The mandible adapts to new working conditions, for instance, when a tooth or teeth are extracted. As a result, changes occur in the transfer of loads through the mandible. After tooth loss, the distribution of loading changes, which can lead to excessive loading on the remaining teeth and areas of bone. This situation is the opposite of the case when a full dentition is present, where the chewing forces are evenly distributed across all teeth, providing optimal stimulation of the bone(10). After tooth loss, the mandible may respond through the process of resorption in areas where there is a lack of mechanical stimulus, which can lead to a decrease in its volume and a loss of bone density(11).

Unfortunately, tooth removal, also known as tooth extraction, is one of the most commonly performed dental procedures in clinical practice. Tooth extraction is a common dental procedure in adult populations, often performed due to caries or periodontal disease [12]. The most common reasons for this dental procedure include dental caries, misalignment of teeth, teeth damaged by trauma, or the need to prepare teeth for orthodontic treatment. Furthermore, the teeth most frequently subjected to this procedure are molars [13].

Understanding the processes of bone remodeling and functional adaptation is crucial for dental practice, enabling dentists to properly plan and conduct therapy after tooth extraction, which is essential for maintaining the integrity and health of the stomatognathic system(12). Additionally, the research context suggests that a better understanding of these processes is necessary to improve the effectiveness of therapy and to avoid complications after tooth extraction. The study conducted in this article aims to investigate the state of bone strain before and after tooth removal under various chewing conditions. By utilizing numerical simulations and current scientific knowledge, we can understand the impact of tooth extraction on the biomechanics of the stomatognathic system and identify potential risk factors for the state of the mandible.

2. METHODS

2.1. Geometrical and material model

The mandible model was developed based on imaging data from computed tomography and processed using the 3D Slicer Image Computing Platform. Both the trabecular bone and the surrounding cortical bone were modeled, reflecting the structure of the

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mandible visible in the tomographic data. Two geometric models were prepared: 1) a basic anatomical model, which included all the teeth, such as incisors, premolars, and molars; and 2) an anatomical model following the extraction of a right-side molar from the mandible (Fig. 1)

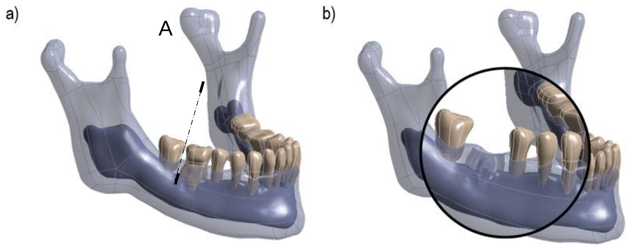

Fig. 1. Geometric models prepared for the study: a) basic anatomical model before extraction; b) anatomical model after tooth extraction

In the studies, it was assumed that the Young's modulus for cancellous bone is 1.37 GPa, for cortical bone 13.7 GPa, for dental enamel 80 GPa and for dentine 20 GPa, (Fig. 2). The initial density for cancellous bone is 0.71 g/cm3 and for cortical bone is 1.37 g/cm3. The Poisson ratio was assumed to be 0.3 for all materials.(13-15).

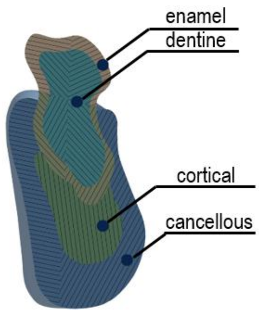

Fig. 2. The cross-section A-A of the molar tooth and the mandibular bone

The discretization of the model was carried out using the ANSYS system preprocessor, utilizing 10-node tetrahedral elements (Solid187). A quality mesh test was conducted to evaluate the maximum Huber-Mises-Hencky (HMH) stresses. Given the complex anatomy of the mandible, the mesh was optimized globally and locally. A Jacobian test was also performed, where it was determined that the coefficient was 0.4, which is consistent with literature data(16). The optimized mesh comprised approximately 56,000 elements, distributed over about 80,000 nodes.

2.2. Boundary conditions

During the modeling of boundary conditions, the conditions prevailing in the temporomandibular joint during chewing were assumed. To this end, a cylindrical coordinate system was introduced along the main axis of the joint, which was used to define the boundary conditions, allowing rotation around the Z-axis while blocking the other two degrees of freedom, namely displacement along the X-axis and displacement along the Z-axis. The study was conducted for four support variants, considering the conditions present when during chewing the following occurs:

- incisors resting on the maxillary teeth (Fig. 3a),
- symmetric lower and upper molars (Fig. 3b),
- lower and upper molars on the side of the deficiency (Fig. 3c),
- lower and upper molars on the opposite side of the deficiency (Fig. 3d).

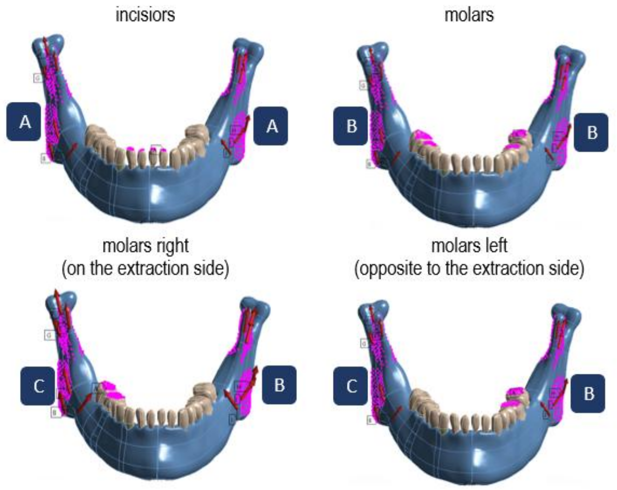

Fig. 3. Representation of the force vectors exerted by the main muscles acting on the mandible. The vectors are labeled (e.g. RM: Right Masseter, LT: Left Temporalis) to correspond with the muscle names listed in Table 1. The directions and magnitudes of the vectors were determined based on the values provided in Tab. 1

Analyzing the anatomy of the musculoskeletal system, the locations of the forces exerted by the main muscles acting on the mandible were identified (Fig. 3), namely: right masseter, left masseter, right temporalis, left temporalis, right lateral pterygoid, and left lateral pterygoid. It was taken into account that changes in contact between the teeth also vary the values of the muscle forces. Therefore, for four different chewing conditions, appropriate muscle force actions were designed, indicated in Figure 3 by the letters A-A, B-B, B-C, and C-B. The corresponding muscle forces were assigned to the letter designations in Table 1.

Tab. 1. Values exerted by the muscles(17)

Muscles description	A	B	C
Middle temporalis [N]	5.7	64.0	63.0
Deep masseter [N]	21.2	48.9	17.1
Superficial masseter [N]	76.1	114.2	137.0
Anterior temporalis [N]	1.6	91.6	115.4
Medial pterygoid [N]	136.4	104.9	146.9

2.3. Bone remodelling

Research on bone regeneration utilizes Huiskes' algorithm(7), developed by Weinans(8). The model integrates bone density ρ with strain energy density U, which is called as mechanical stimulus and described by the equation:

$$S = \frac{U}{\rho} \tag{1}$$

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The bone remodeling algorithm takes into account the process of bone resorption, the dead zone, where the processes of resorption and bone formation are in equilibrium, and the process of bone formation:

$$\frac{d\rho}{dt} = \begin{cases} B\frac{U}{\rho} - (1-S)k, & \frac{U}{\rho} < (1-S)k \\ 0, & (1-s)k \leq \frac{U}{\rho} \leq (1+S)k \\ B\frac{U}{\rho} - (1+S)k, & \frac{U}{\rho} > (1+S)k \end{cases} \quad (2)$$

The constant values used in the algorithm were as follows: s = 0.1, B = 10, and k = 0.002. Initial material values for the bone and the implant were assumed, which are described in the "Geometrical and Material Model" section. The material model of the bone underwent remodeling:
for cortical bone according to the relationship(18):

$$E = 0.014\rho^3 - 6.142 \quad (3)$$

gdzie: C – constans = 3790, ρ - bone density at the given step, for cancellous bone according to the relationship(19):

$$E = 1.02\rho^{1.22}\,. \quad (4)$$

The bone remodeling algorithm was implemented in ANSYS APDL language. Numerical calculations were performed using the finite element method in ANSYS v. 24R1 (Ansys Inc., Canonsburg, Pennsylvania, United States).

3. RESULTS

The results are presented as maps of HMH stress for cancellous bone (Fig. 4a) and cortical bone (Fig. 4b) in the region surrounding the root of molar tooth number 6. The bone remodeling process was modeled based on Equations (1) and (2).The change in material properties of cortical and cancellous bone was conducted according to equations 3 and 4, respectively.

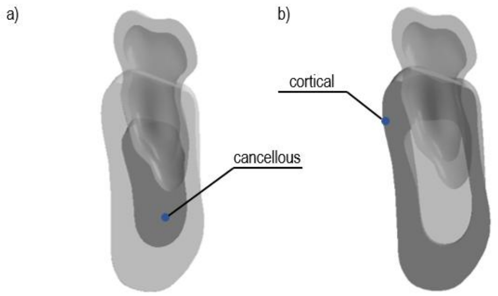

Fig. 4. Cross-section of the tooth and mandibular bone highlighting the zone: a) for cancellous bone; b) for cortical bone

Below are the results for trabecular bone in the presence of a tooth (Fig. 5), trabecular bone after the extraction of the molar (Fig. 6), cortical bone in the presence of the molar (Fig. 7), and cortical bone after the extraction of the molar (Fig. 8), during different chewing conditions, namely for:

– incisors – when contact occurs between the incisors of the mandible and the incisors of the maxilla,
– molars – when contact occurs between the molars of the mandible and the molars of the maxilla,
– left molars – when contact occurs on the left side between the molars of the mandible and the molars of the maxilla,
– right molars – when contact occurs on the right side between the molars of the mandible and the molars of the maxilla.

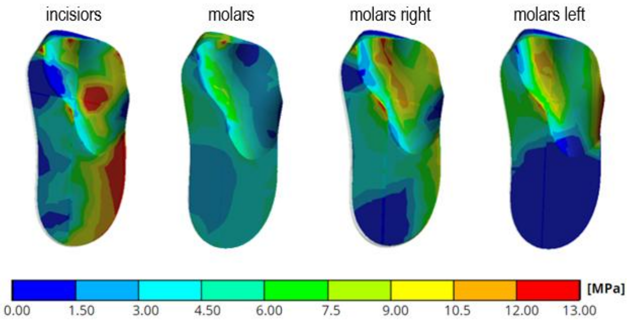

Fig. 5. Distribution of HMH stress [MPa] in cancellous bone before tooth extraction

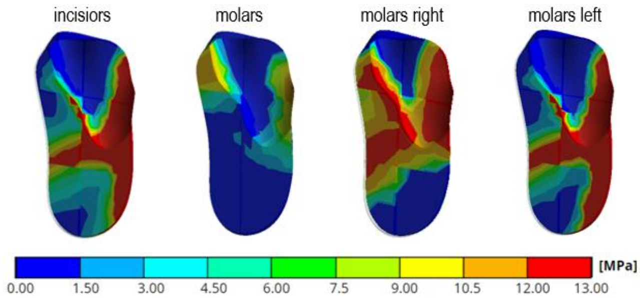

Fig. 6. Distribution of HMH stress [MPa] in cancellous bone after tooth extraction

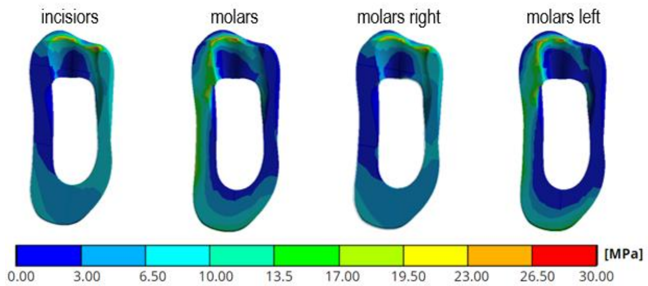

Fig. 7. Distribution of HMH stress [MPa] in cortical bone before tooth extraction

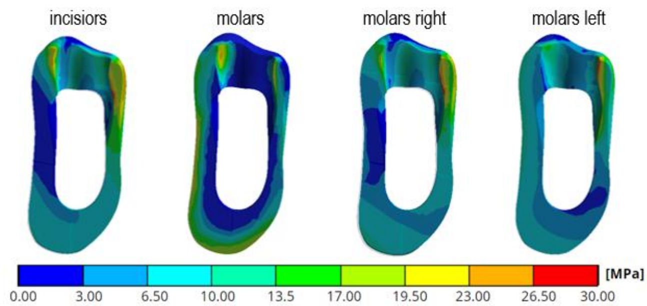

Fig. 8. Distribution of HMH stress [MPa] in cortical bone after tooth extraction

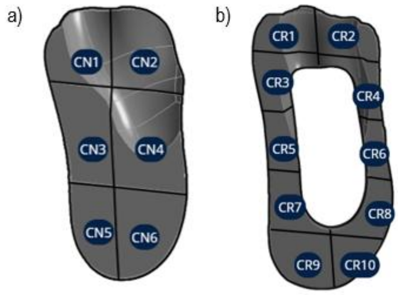

Fig. 9. Division into areas for: a) cancellous bone; b) cortical bone

Tab. 2. Change in cancellous bone density in the analyzed areas [g/cm3] for the model after tooth extraction compared to the model before tooth extraction

Region	Incisiors	Molars	Molars right	Molars left
CN1 [%]	938	-72	505	27
CN2 [%]	82	-56	103	725
CN3 [%]	80	0	59	483
CN4 [%]	-24	-18	28	1415
CN5 [%]	37	0	189	49
CN6 [%]	68	0	2059	0

Tab. 3. Change in cortical bone density [g/cm3] in the analyzed areas for the model after tooth extraction compared to the model before tooth extraction

Region	Incisiors	Molars	Molars right	Molars left
CR1 [%]	0	102	-9	-12
CR2 [%]	-12	27	-9	-2
CR3 [%]	285	28	52	2
CR4 [%]	-7	49	-5	3
CR5 [%]	323	-4	127	0
CR6 [%]	-72	181	0	0
CR7 [%]	-10	-4	9	0
CR8 [%]	0	48	0	-17
CR9 [%]	0	3	0	0
CR10 [%]	0	8	0	0

4. DISCUSSION

The results of the analysis of the area around the molar tooth (Fig. 5) indicate significantly higher stresses in the trabecular bone at the moment of contact between the incisors, reaching values from 4.50 to 13.00 MPa. The maximum HMH stress are located at the end of the root, where a phenomenon of stress shielding is observed. Slightly lower stress values are noted in the case of contact with molars, especially the left molars, where the maximum values reach up to 10.50 MPa. After tooth extraction, the distribution of H-M-H stress changes in each of the four chewing conditions, wherein for aliquots as well as for molars on the left and right sides, stress shielding is noted in the area around the extraction site (Fig. 6). Stresses accumulate on the posterior wall of the socket where the root of the molar tooth was supported. There is also a decrease in H-M-H stresses on the lateral wall of the tooth deficiency.

In the cortical bone, a concentration of stresses was observed around the upper boundary between the bone and the molar tooth. In the analyzed area, the maximum HMH stress reach approximately 30 MPa across the four different chewing conditions. The distribution of stresses changes after tooth extraction. In the case of incisors, stresses increase to 26.5 MPa from both the anterior and posterior sides of the tooth (Figs. 7, 8). A similar phenomenon occurs with contact between the right and left molars, with the maximum HMH stress being localized at the anterior side within the cortical bone and the socket. Around the socket, in the area of support between the molars, a minimum of H HMH stress was noted.

The results of the analysis of cortical and trabecular bone density after tooth extraction confirm the mechanisms of functional adaptation of the bone, consistent with Wolff's law. The mandible undergoes intense remodeling after tooth removal, evidenced by changes in bone density in the analyzed areas. In the cortical bone, particularly around the socket (CR1–CR4), significant increases in density were recorded, especially in CR3 (+285%) and CR5 (+323%) (Tab. 3). This increase can be explained by the increased mechanical stimulation of the remaining areas that must take on additional loads after extraction. In contrast, the decreases in density in areas such as CR6 (-72%) may indicate diminished loads, leading to bone resorption in line with Frost's "mechanostat" hypothesis (Tab. 3). This indicates that a lack of adequate mechanical stimulus leads to a decrease in bone density. Similar phenomena occur in the trabecular bone, where the most significant changes were observed in the alveoli (CN1, CN2, CN4) and surrounding areas. An extreme increase in density in CN1 (+938% for incisors, +505% on the right side) and CN6 (+2059% on the right side of the molars) indicates intense remodeling of these regions, acting as an adaptive response to the altered loading conditions (Tab. 2). In contrast, areas such as CN4 (-24% for incisors, -18% for molars) experienced a decrease in density, suggesting reduced mechanical stimulation and associated resorption.

These results clearly show that in regions where force transmission increases after extraction, bone density rises, consistent with Wolff's law. Conversely, in areas with reduced loading, such as CR6 and CN4, resorption occurs due to the lack of mechanical stimulation. This phenomenon illustrates how crucial the balance between loading and bone remodeling is. From a clinical perspective, these findings highlight the importance of understanding the processes involved in the functional adaptation of bone following tooth extraction. Proper planning of therapy and rehabilitation, including appropriate mechanical stimulation, can support bone regeneration and prevent excessive resorption in areas with reduced loading. This is vital for maintaining the health and integrity of the mandible after tooth removal, which has significant implications for the long-term health of the patient.

5. CONCLUSION

Both cortical and trabecular bone undergo intensive remodeling processes after tooth extraction. In areas of increased loading, there is a rise in bone density, whereas in places with reduced stimulation, resorption is observed.

After tooth extraction, bone density increases in the areas surrounding the socket, particularly in regions that take on greater loads. This phenomenon was especially noted in CR3, CR5, as well as in CN1 and CN6.

In some areas, such as CR6 and CN4, there was a decrease in bone density, suggesting that the lack of an adequate mechanical stimulus leads to bone resorption.

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The results of the study confirm the crucial role of mechanical stimulation in maintaining the health and density of the mandible. Proper rehabilitation after tooth extraction should include a bone stimulation strategy to prevent resorption and promote regeneration.

The findings are significant for planning dental treatment after tooth extractions. Understanding the adaptive mechanisms of bone can aid in developing effective therapies that minimize the loss of bone density and support the regeneration process.

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