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Effect of biomechanical load factors on the stress–strain state of teeth and underlying bone tissue

Emilia A. Olesova, Alexander A. Ilyin, Alexandra V. Em, Maxim S. Grishkov, Dmitriy V. Martynov

A.I. Burnazyan State Medical Research Center of the FMBA of Russia, Moscow, Russia

ABSTRACT

BACKGROUND: The biomechanical conditions under which teeth, implants, and bone tissue function clearly determine their resistance to overloading and subsequent destruction. However, mathematical modeling has not previously been used to compare functional stress in teeth across a wide range of sensitive biomechanical load conditions.

AIM: To compare the stress-strain state parameters of tooth and socket tissues under various biomechanical load conditions.

MATERIALS AND METHODS: A mathematical model was used to assess the stress-strain state parameters of dental tissue and sockets under vertical and oblique load (150N) with various modeling settings, compared to reference model parameters. The following parameters were assessed: enamel attrition, bone density reduction, bone resorption by 30% and 50%, supra-occlusion, tooth cavity, composite restoration, and ceramic inlay.

RESULTS: Enamel attrition significantly increases stress under vertical and oblique loads: 1.9 and 1.6 times for enamel, and 1.5 and 1.2 times for dentin, respectively. Tooth cavities increase stress by 1.2 and 1.8 times (enamel; vertical and oblique loads, respectively), and 1.3 times (dentin; vertical load). Increased functional load causes a proportional increase in stress in hard tooth tissues and adjacent bone tissues. Supra-occlusion causes a sharp increase in stress in the enamel, with a point stress concentration. When a tooth cavity is filled with a composite or ceramic material, the stress-strain state parameters are similar to those in intact teeth (however, the enamel still experiences a 1.5-fold increase in stress under vertical pressure).

CONCLUSION: 3D mathematical modeling revealed a significant difference in maximum stress in tooth and socket tissues compared to normal biomechanical conditions, as well as when comparing various sensitive load conditions. Stress in tooth and bone tissues increased in all cases of abnormal biomechanical conditions, especially when oblique load was applied.

Keywords: tooth; load; mathematical modeling; stress; biomechanical conditions.

Влияние биомеханических факторов нагрузки на напряжённо-деформированное состояние зуба и подлежащей костной ткани

Э.А. Олесова, А.А. Ильин, А.В. Эм, М.С. Гришков, Д.В. Мартынов

Государственный научный центр Российской Федерации — Федеральный медицинский биофизический центр имени А.И. Бурназяна Федерального медико-биологического агентства, Москва, Россия

АННОТАЦИЯ

Обоснование. Влияние биомеханических условий функционирования зубов, имплантатов, костной ткани на их сопротивляемость перегрузке и последующему разрушению очевидно. Однако с помощью математического моделирования сравнение функциональных напряжений в зубе в широком перечне уязвимых биомеханических условий нагрузки ранее не проводилось.

Цель исследования — сопоставление параметров напряжённо-деформированного состояния тканей зуба и альвеолярной лунки в разных биомеханических условиях нагрузки.

Материалы и методы. В математической модели изучены параметры напряжённо-деформированного состояния зуба и костной ткани при вертикальной и наклонной нагрузках 150Н в разных условиях моделирования в сравнении с параметрами в базовой модели: стирание эмали, снижение плотности костной ткани, резорбция костной ткани на 30 и 50%, окклюзионный супраконтакт, полость в зубе, композитная реставрация, керамическая вкладка.

Результаты. Стирание эмали значительно повышает напряжения при вертикальной и наклонной нагрузках — в 1,9 и 1,6 раза в эмали, 1,5 и 1,2 раза в дентине. Наличие полости в зубе увеличивает напряжения в 1,2 и 1,8 раза в эмали при вертикальной и наклонной нагрузках, в 1,3 раза в дентине при вертикальной нагрузке. Повышенная функциональная нагрузка пропорционально увеличивает напряжения в твёрдых тканях зуба и окружающих костных тканях. Окклюзионный супраконтакт резко повышает и точечно концентрирует напряжения в эмали. Замещение полости в зубе композитным или керамическим материалом приближает параметры напряжённо-деформированного состояния зуба к напряжениям в интактном зубе (превышение напряжений в 1,5 раза сохраняется в эмали при наклонной нагрузке).

Заключение. Трёхмерное математическое моделирование выявило существенную разницу в величинах максимальных напряжений в тканях зуба и альвеолярной лунки не только в сравнении с адекватными биомеханическими условиями, но и при сравнении разных уязвимых условий нагрузки зубов. Во всех случаях неадекватных биомеханических условий происходит увеличение напряжений в зубе и костной ткани, особенно при наклонной нагрузке.

Ключевые слова: зуб; нагрузка; математическое моделирование; напряжения; биомеханические условия.

BACKGROUND

The impact of biomechanical conditions under which teeth, implants, and bone tissue function on their resistance to overload and subsequent destruction is well-recognized. However, the scientific evidence supporting this postulate remains insufficient. Individual clinical scenarios involving significant violations of biomechanical loading conditions in teeth and implants have been relatively well-studied. Examples include cantilever restorations, short and narrow implants, and lateral loading of abnormally positioned teeth [1–3].

Currently, three-dimensional mathematical modeling is considered the most informative and evidence-based method for studying tissue overload [4–7]. However, this method has not previously been used to compare functional stress in teeth across a wide range of sensitive biomechanical loading conditions.

STUDY AIM: To compare the stress-strain state parameters of tooth and socket tissues under various biomechanical loading conditions.

MATERIALS AND METHODS

A three-dimensional mathematical model of a single-rooted mandibular tooth surrounded by the alveolar socket and a segment of the mandible was developed (Fig. 1).

The model included enamel, dentin, cortical bone, and cancellous bone tissues, maintaining their natural size proportions. The physical and mechanical properties of the analyzed tissues were obtained from the literature: the elastic modulus of cortical and cancellous bone was 20,500 MPa and 3,500 MPa, respectively, with Poisson's ratios of 0.32 and 0.34. For enamel, the elastic modulus was 81,700 MPa (Poisson's ratio 0.28), and for dentin, it was 23,300 MPa (Poisson's ratio 0.31) [5, 7]. To ensure accurate calculations of the stress-strain state, the model incorporated the mechanical properties of the periodontal ligament (elastic modulus 10 MPa, Poisson's ratio 0.3) and tooth cementum (elastic modulus 4,200 MPa, Poisson's ratio 0.3). To account for variability when modifying the reference model to simulate hard tissue defects, the properties of restorative materials were also included: ceramic (elastic modulus 200,000 MPa, Poisson's ratio 0.22) and composite (elastic modulus 58,840 MPa, Poisson's ratio 0.32).

This study analyzed the stress-strain state parameters of the tooth and bone tissues under vertical and oblique loads of 150 N with various modeling settings, compared to reference model parameters. Under vertical loading, the maximum stress values in enamel, dentin, cortical bone, and cancellous bone tissues were 44.204 MPa, 9.174 MPa, 5.066 MPa, and 1.382 MPa, respectively. With oblique loading, stress values increased by 1.5 to 5.5 times [7].
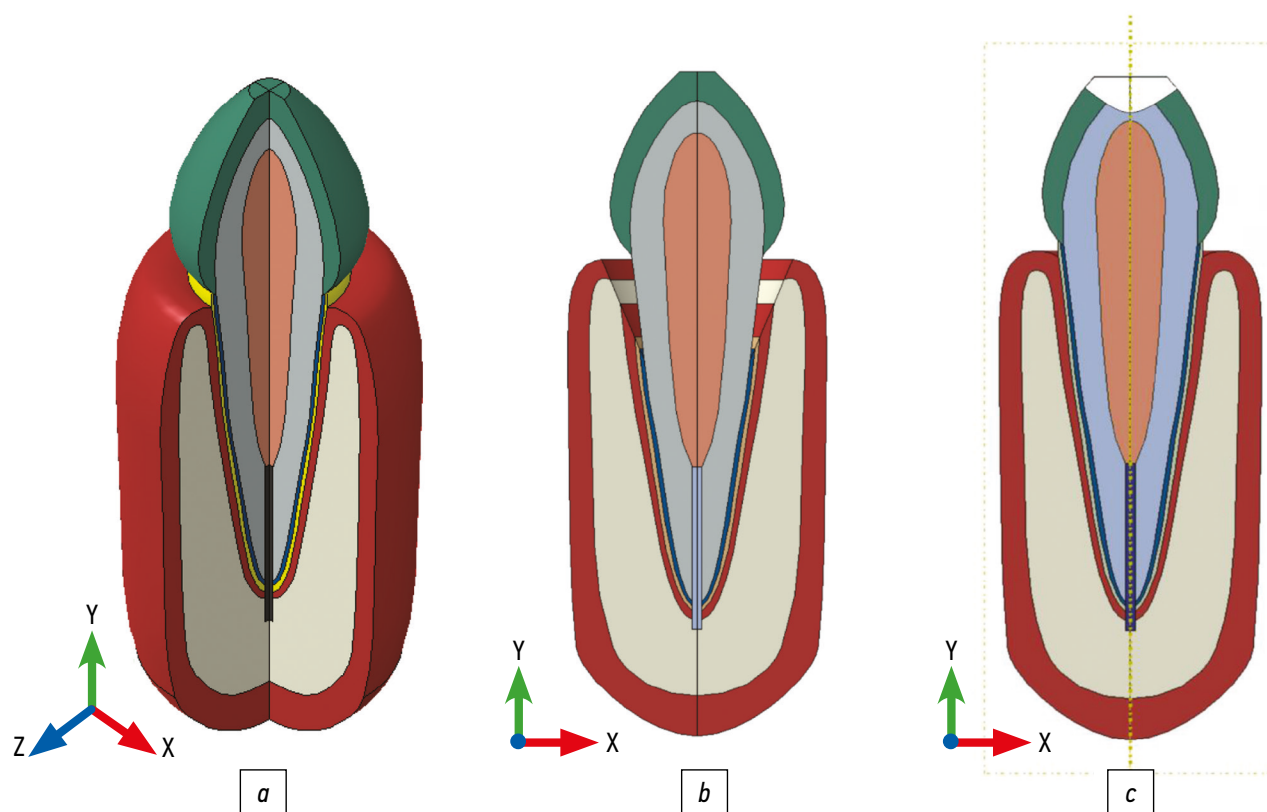

Fig. 1. Options of a three-dimensional mathematical model of a single-root mandibular tooth (premolar) under abnormal biomechanical conditions: a, intact tooth; b, bone resorption by 30%; c, tooth cavity.

Color mapping of the integral stress distribution in the analyzed tissues and materials was presented alongside a stress scale (Fig. 2). The biomechanical conditions analyzed included enamel attrition, bone density reduction, bone resorption by 30% and 50%, supra-occlusion, tooth cavity, composite restoration, and ceramic inlay.

RESULTS

The study revealed a significant impact of enamel attrition on the stress-strain state of the tooth (Table 1). A 30% reduction in enamel thickness led to notable stress increases. Maximum stress in enamel increased by 47.4 (83.973 MPa) under vertical loading and by 39.2% (108.003 MPa) under oblique loading. Stress in dentin rose by 31.6% and 18.6% (13.407 MPa and 57.056 MPa) under

vertical and oblique loading, respectively. In cortical bone tissue, stress slightly increased under oblique loading by 8.8% (30.595 MPa).

Mathematical modeling showed that variations in bone density had no significant effect on functional stress levels in tooth and bone tissues.

Bone resorption involving one-third of the tooth root length increased stress levels in dentin and bone tissue. Stress in dentin under vertical and oblique loading reached 11.546 MPa and 59.767 MPa, respectively, reflecting increases of 20.8% and 32.3% compared to the reference model. Stress in cortical bone tissue under vertical and oblique loading increased by 4.5% and 51.0% (5.304 MPa and 56.918 MPa), while cancellous bone tissue showed an increase by 19.6% and 29.9% (1.720 MPa and 6.240 MPa), respectively.
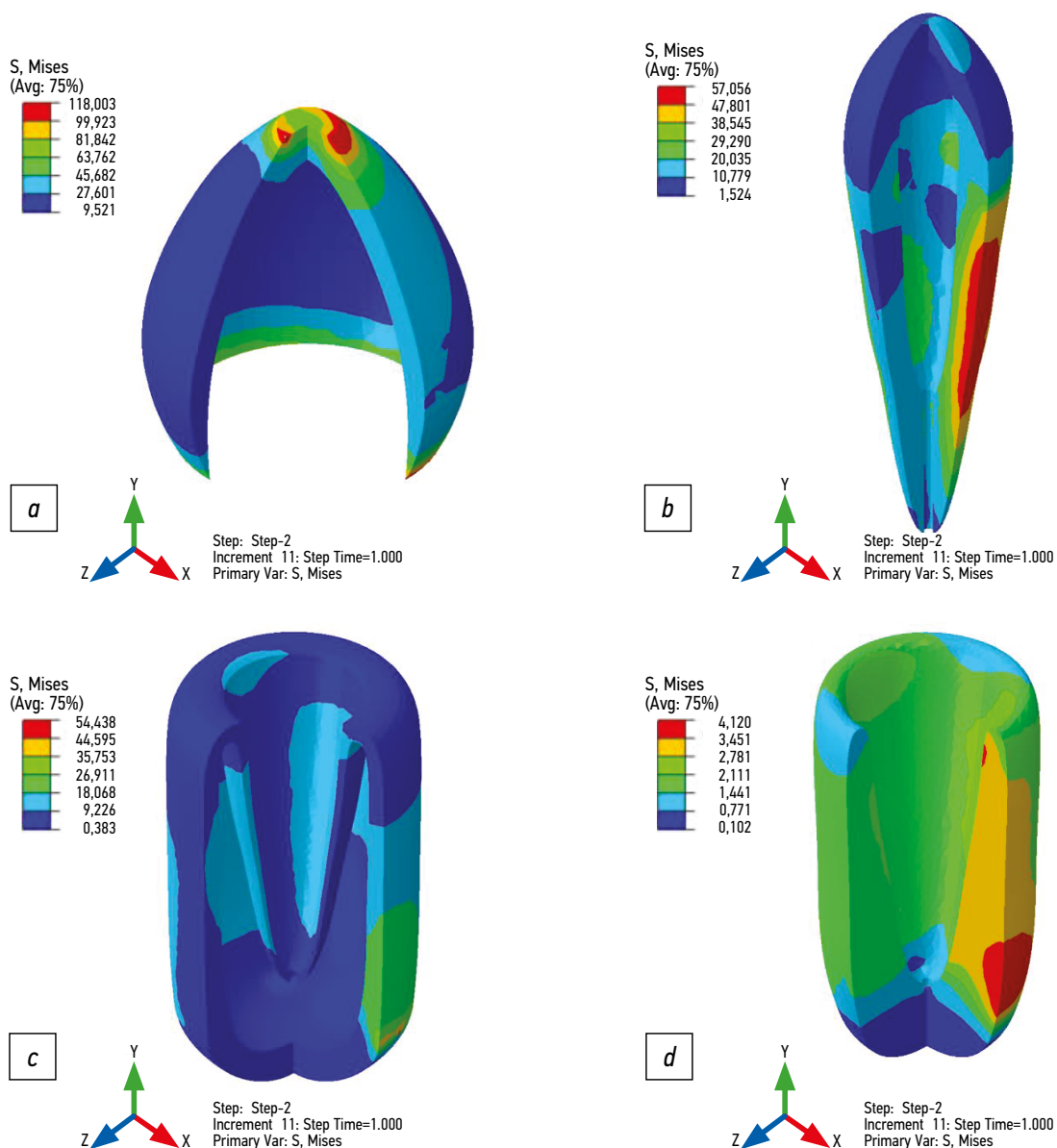

Fig. 2. Distribution of functional stress values in a tooth and bone tissue under oblique loading in unfavorable biomechanical conditions (increased enamel attrition): *a*, enamel; *b*, dentin; *c*, cortical bone tissue; *d*, cancellous bone tissue.

Table 1. Maximum stress values under functional loading of a tooth in unfavorable biomechanical conditions (MPa)

Test object	Enamel attrition	Bone density reduction	Bone resorption by 30%	Bone resorption by 50%	Increased load	Supra-occlusion	Tooth cavity	Composite restoration	Ceramic inlay
Enamel (v)	83.973	44.277	48.271	46.474	57.465	1231.636	54.531	42.192	43.486
Enamel (o)	108.003	67.610	64.250	72.762	85.417	1730.188	117.520	100.193	82.747
Dentin (v)	13.407	9.172	11.546	15.866	11.926	18.745	12.299	10.888	10.875
Dentin (o)	57.056	46.525	59.767	75.015	60.410	56.468	56.278	45.269	43.276
Cortical bone (v)	4.631	5.065	5.304	6.478	6.586	5.067	6.659	6.220	5.508
Cortical bone (o)	30.595	51.151	56.918	69.431	36.282	51.152	27.260	30.026	33.824
Cancellous bone (v)	1.274	1.390	1.720	2.298	1.797	1.382	1.985	1.399	1.179
Cancellous bone (o)	4.121	5.644	6.240	10.463	5.688	5.644	4.877	5.003	5.005

Note: (v), vertical load; (o), oblique load.

Greater resorption (up to half the root length) resulted in further stress elevation. When compared to intact teeth, stress in enamel increased by 4.9% under vertical loading (maximum stress 46.474 MPa) and by 9.7% under oblique loading (72.762 MPa). Stress in dentin increased by 42.2% and 38.1% (15.866 MPa and 75.015 MPa, respectively). Stress in cortical bone tissue increased to 6.478 MPa under vertical loading (21.8% higher) and to 69.431 MPa under oblique loading (59.8% higher). In cancellous bone tissue, stress increased to 2.298 MPa (39.9%) and 10.463 MPa (58.2%) under vertical and oblique loading, respectively.

A 30% increase in functional loading proportionally elevated stress across all analyzed layers of the model.

Supra-occlusion sharply concentrated stress, particularly in enamel, which reached 1,231.631 MPa under vertical loading and 1,730.188 MPa under oblique loading, exceeding stress levels in intact enamel by 96.4% and 96.2%, respectively. Stress in dentin increased by 51.1% under vertical loading (18.745 MPa) and by 17.7% under oblique loading (56.468 MPa). Stress in cortical bone tissue increased by 45.4% under oblique loading (51.152 MPa), while cancellous bone stress increased by 22.5% (5.644 MPa). Vertical loading caused no changes in bone stress, with levels consistent with the reference model (5.064 MPa in cortical bone and 1.382 MPa in cancellous bone).

A cavity on the occlusal surface, limited to enamel and dentin while preserving intact pulp, increased stress in all studied tissues. In enamel, stress increases to 54.531 MPa under vertical loading (19.0% higher than in an intact tooth) and to 117.520 MPa under oblique loading (44.1%

higher than in an intact tooth). In dentin, the presence of a cavity results in stress increases of 25.4% and 17.5% under vertical and oblique loading, respectively, reaching 12.299 MPa and 56.278 MPa. Cortical and cancellous bone stress levels increased by 24.0% and 30.4% (6.659 MPa and 1.985 MPa, respectively) under vertical loading. Under oblique loading, stress levels in cortical and cancellous bone changed minimally, increasing by 0% and 10.3% (27.260 MPa and 4.877 MPa, respectively).

Filling a cavity with composite material normalized enamel stress under vertical loading (42.192 MPa). However, under oblique loading, enamel stress increased by 34.5% (100.193 MPa) compared to intact enamel. Dentin stress approached normal levels (10.888 MPa under vertical loading, 15.7% higher than intact dentin; 45.269 MPa under oblique loading, which is comparable to intact dentin). Cortical bone stress levels increased by 18.6% and 7.1% under vertical and oblique loading (6.220 MPa and 30.026 MPa, respectively), while cancellous bone stress levels showed changes of 0% and 12.5% (1.399 MPa and 5.003 MPa, respectively).

Filling a cavity with a ceramic inlay caused minimal changes in tooth and bone tissues compared to composite fillings. Stress levels in enamel were 43.486 MPa under vertical loading and 100.747 MPa under oblique loading. In dentin, stress levels were 10.875 MPa and 45.276 MPa, respectively. Cortical bone stress levels were 5.808 MPa under vertical loading and 33.824 MPa under oblique loading, while cancellous bone stress levels were 1.179 MPa and 5.005 MPa, respectively.

In the composite restoration, stress levels reached 24.614 MPa under vertical loading and 29.085 MPa under

oblique loading. For the ceramic inlay, stress levels were 31.126 MPa and 38.419 MPa, respectively.

DISCUSSION

Three-dimensional mathematical modeling revealed significant differences in maximum stress in tooth and socket tissues compared to normal biomechanical conditions, as well as when comparing various sensitive load conditions. Stress in tooth and bone tissues increased in all cases of abnormal biomechanical conditions, especially when oblique load was applied.

CONCLUSION

Enamel attrition significantly increases stress under vertical and oblique loading, by 1.9 and 1.6 times in enamel, and by 1.5 and 1.2 times in dentin, respectively. A tooth cavity increases stress by 1.2 and 1.8 times in enamel under vertical and oblique loading, and by 1.3 times in dentin under vertical loading. Increased functional loading proportionally raises stress levels in both hard tooth tissues and the surrounding bone tissues. Supra-occlusion sharply increases and concentrates stress in enamel.

Filling cavities with composite or ceramic materials normalizes the stress-strain state of the tooth, bringing it closer to that of an intact tooth, though stress levels in enamel under oblique loading remain elevated by 1.5 times.

ADDITIONAL INFORMATION

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AUTHORS' INFO

* Emilia A. Olesova, MD;
address: 46 Zhivopisnaja street, 123098 Moscow, Russia;
ORCID: 0000-0003-4511-6317;
eLibrary SPIN: 5767-9158;
e-mail: emma.olesova@mail.ru

Alexander A. Ilyin, MD, Dr. Sci. (Medicine), Professor;
ORCID: 0000-0002-8021-4599;
eLibrary SPIN: 2615-2137;
e-mail: Alex2017ilyin@yandex.ru

Alexandra V. Em, MD, Cand. Sci. (Medicine), Associate Professor;
ORCID: 0000-0001-8590-5279;
eLibrary SPIN: 2057-2173;
e-mail: alexandra.em.work@gmail.com

Maxim S. Grishkov, MD, Cand. Sci. (Medicine), Associate Professor;
ORCID: 0000-0002-2617-8726;
eLibrary SPIN: 3167-9478;
e-mail: maxim335@yandex.ru

Dmitriy V. Martynov, MD, Cand. Sci. (Medicine), Associate Professor;
ORCID: 0000-0002-0136-5621;
eLibrary SPIN: 1956-9162;
e-mail: mdv.dent@gmail.com

* Corresponding author / Автор, ответственный за переписку

ОБ АВТОРАХ

* Олесова Эмилия Артёмовна;
адрес: Россия, 123098, Москва, ул. Живописная, д. 46;
ORCID: 0000-0003-4511-6317;
eLibrary SPIN: 5767-9158;
e-mail: emma.olesova@mail.ru

Ильин Александр Александрович, д-р мед. наук, профессор;
ORCID: 0000-0002-8021-4599;
eLibrary SPIN: 2615-2137;
e-mail: Alex2017ilyin@yandex.ru

Эм Александра Викторовна, канд. мед. наук, доцент;
ORCID: 0000-0001-8590-5279;
eLibrary SPIN: 2057-2173;
e-mail: alexandra.em.work@gmail.com

Гришков Максим Сергеевич, канд. мед. наук, доцент;
ORCID: 0000-0002-2617-8726;
eLibrary SPIN: 3167-9478;
e-mail: maxim335@yandex.ru

Мартынов Дмитрий Викторович, канд. мед. наук, доцент;
ORCID: 0000-0002-0136-5621;
eLibrary SPIN: 1956-9162;
e-mail: mdv.dent@gmail.com