

Original Study Article

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Assessment of tooth devitalization as a risk factor for enamel and dentin functional overload using mathematical modeling

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ABSTRACT

BACKGROUND: Cracks and fractures of devitalized teeth caused by functional overload are common in dental practice, necessitating an assessment of the stress-strain state of intact and devitalized tooth tissues under similar loading conditions.

AIM: An experimental comparison of the stress-strain state of intact and devitalized hard tooth tissues and the surrounding bone tissue using mathematical modeling.

METHODS: A 3D mathematical modeling of the stress-strain state of a mandibular segment with an intact and devitalized tooth was performed. A vertical and oblique (45°) load of 150 N was applied; the maximum stress and its location in the enamel, dentin, cortical bone, and cancellous bone were analyzed by comparing them to the respective strength limits.

RESULTS: Devitalized hard tissues are subjected to a higher stress than intact teeth, especially when an oblique load is applied, by 49.3, 11.0, and 13.1% (86.186, 31.371, and 5.037 MPa) for the enamel, cortical bone, and cancellous bone, respectively. When a vertical load is applied, tooth devitalization increases the stress in the enamel and cancellous bone of the socket by 33.1 and 29.2% (51.147 and 1.953 MPa), respectively. Devitalized dentin shows almost no changes in stress under a vertical load due to the deterioration of physical properties (and, thus, a decrease in the strength limit), whereas an oblique load results in a decrease of 28.1%. Functional load in a devitalized tooth results in stress values close to the strength limit in the enamel (under a vertical and oblique load) and dentin (under an oblique load). Periapical resorption and root apex resection further increase the stress.

CONCLUSION: Tooth devitalization increases the stress in the enamel and bone tissues, especially under an oblique load. Despite the reduced stress in devitalized dentin caused by a decrease in its mechanical strength, stress values under an oblique load are close to the dentin strength limit in the tooth neck area. Due to tooth devitalization, the stress in the enamel exceeds its strength limit under both oblique and vertical loads (in the tooth neck area and along the occlusal surface, respectively). Periapical resorption and root apex resection cause a similar increase in the stress in the enamel compared to a devitalized tooth under both loads, as well as in the cortical bone under an oblique load.

Keywords: functional stress; mathematical model; tooth; bone tissue.

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Оригинальное исследование

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Оценка девитализации зуба как фактора риска функциональной перегрузки эмали и дентина с помощью математического моделирования

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АННОТАЦИЯ

Обоснование. В клинической практике нередки случаи трещин и переломов девитализированных зубов при их функциональной нагрузке, что делает актуальным анализ напряжённо-деформированного состояния тканей интактного и девитализированного зуба в идентичных условиях нагрузки.

Цель. Экспериментальное сравнение напряжённо-деформированного состояния твёрдых тканей интактного и девитализированного зуба и окружающей костной ткани с помощью математического моделирования.

Методы. Проведено трёхмерное математическое моделирование напряжённо-деформированного состояния тканей сегмента нижней челюсти с интактным и девитализированным зубом. Применяли нагрузку 150 Н в вертикальном и наклонном (45°) направлениях, анализировали максимальные напряжения и их локализацию в эмали, дентине, кортикальной и губчатой костных тканях в сопоставлении с их пределами прочности.

Результаты. Ткани девитализированного зуба испытывают большие напряжения по сравнению с интактным зубом, особенно при наклонной нагрузке: эмаль, кортикальная и губчатая костные ткани соответственно на 49,3; 11,0; 13,1% (86,186; 31,371; 5,037 МПа). При вертикальной нагрузке девитализация зуба увеличивает напряжения в эмали и губчатой кости лунки соответственно на 33,1 и 29,2% (51,147 и 1,953 МПа). В девитализированном дентине ввиду ухудшения его физических свойств (и, следовательно, снижения предела прочности) напряжение при вертикальной нагрузке практически не меняется, а при наклонной — снижается на 28,1%. Функциональная нагрузка девитализированного зуба приближает к пределу прочности напряжения в эмали (при вертикальной и наклонной нагрузках), а также в дентине (при наклонной нагрузке). Периапикальная резорбция и резекция верхушки корня усугубляет повышение напряжений.

Заключение. Девитализация зубов повышает напряжения в эмали и костных тканях, особенно при наклонной нагрузке. Несмотря на уменьшение напряжений в дентине девитализированного зуба из-за снижения его механической прочности, напряжения при наклонной нагрузке приближаются к пределу прочности дентина в области шейки зуба. Вследствие девитализации зуба напряжения в эмали превышают пределы её прочности как при наклонной, так и при вертикальной нагрузках (соответственно в области шейки и по окклюзионной поверхности). Периапикальная резорбция и резекция верхушки корня в близкой степени увеличивают напряжения в эмали в сравнении с девитализированным зубом при обоих видах нагрузки, а также в кортикальной костной ткани при наклонной нагрузке.

Ключевые слова: функциональные напряжения; математическая модель; зуб; костная ткань.

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BACKGROUND

Over the long term after root canal treatment, root cracks and fractures are frequently observed under normal masticatory function, indicating reduced dentin strength resulting from changes in its physical and mechanical properties [1–3]. In some cases, this complication can be managed with post-retained restorations. However, restoration of the crown’s integrity does not eliminate the risk of recurrent root fracture.

Therefore, the magnitude and distribution of functional stresses and their relationship to dentin strength in devitalized (nonvital) teeth under functional loading, compared with intact teeth, remain a subject of considerable scientific interest.

Three-dimensional mathematical modeling provides a highly detailed assessment of the stress–strain behavior of dental hard tissues [4–7]. It is essential that such models account for the actual ultimate strength values of dentin and restorative materials. Although the available data on the physical and

mechanical properties of dental hard tissues remain limited and sometimes inconsistent, several studies have demonstrated a significant reduction in dentin ultimate strength in devitalized teeth compared with intact teeth, which is critical for accurate interpretation of mathematical modeling outcomes [8, 9].

AIM

This work aimed to experimentally compare the stress–strain behavior of dental hard tissues in intact and devitalized teeth, as well as in the surrounding alveolar bone, using mathematical modeling.

METHODS

A baseline three-dimensional mathematical model of a mandibular premolar was constructed, including enamel, dentin, and the surrounding cortical and cancellous bone, preserving their natural anatomical proportions. The model variants included an intact tooth, a devitalized tooth, a tooth with periapical bone

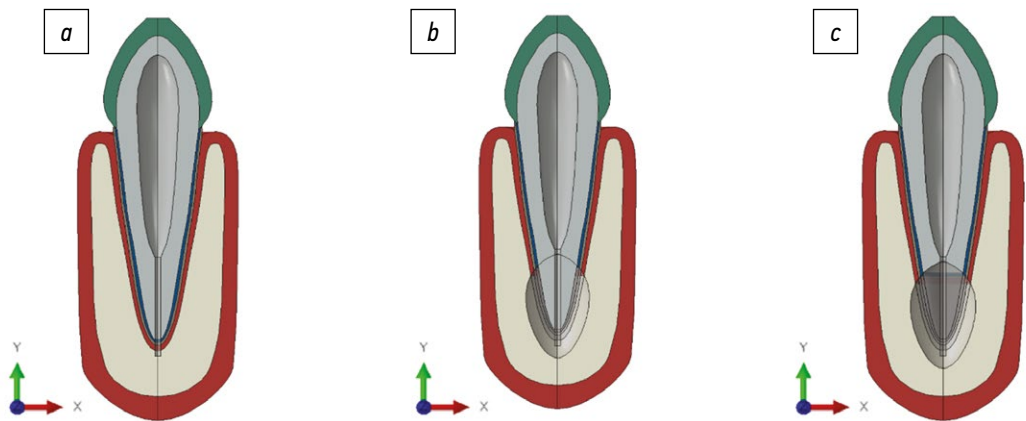


Fig. 1. Three-dimensional mathematical model of a single-rooted mandibular tooth (premolar) under unfavorable biomechanical conditions: *a*, intact tooth; *b*, tooth with periapical bone resorption; *c*, tooth after apicoectomy.

Table 1. Mechanical properties of dental hard tissues

Tissue / material	Elastic modulus (E), MPa	Poisson’s ratio	Ultimate tensile strength, MPa
Enamel	81 700	0.28	42.1
Dentin	23 300	0.31	104
Devitalized dentin	2600	0.31	30
Cortical bone	20 500	0.32	150
Cancellous bone	3500	0.34	15

resorption, and a tooth after apicoectomy (see Fig. 1).

The mechanical properties of the analyzed tissues and restorative materials were based on published data regarding their elastic modulus, Poisson's ratio, and ultimate tensile strength, which are lower than the corresponding compressive strength values (see Table 1). For modeling purposes, the ultimate strength of dentin was set at 104 MPa for intact and 30 MPa for devitalized teeth.

Stress distribution and the magnitude of stresses in the modeled tissues and restorative materials were analyzed under vertical and oblique loading of 150 N using color-coded stress maps and quantitative stress scales in SolidWorks (Dassault Systèmes, France) (see Figs. 2 and 3).

Comparative analysis of stress values across the different modeling variants was performed in Excel 2019 (Microsoft, USA) using Student's t-test; differences were considered statistically significant at $p < 0.05$.

RESULTS

Under vertical loading, the highest stresses in the intact tooth and its surrounding alveolar socket were observed in the enamel, reaching 34.204 MPa along the occlusal surface (see Table 2). In dentin, stresses up to 9.174 MPa were recorded above the pulp chamber, beneath the enamel layer of the occlusal surface. In cortical bone, the maximum stresses were distributed along the lower third of the tooth socket and its projection on the mandibular cortical plate (5.066 MPa), whereas in cancellous bone, stresses concentrated near the tooth apex (1.382 MPa).

Oblique loading substantially increased stresses in all hard tissues of the tooth: up to 43.705 MPa in enamel, 56.469 MPa in dentin, 27.909 MPa in cortical bone, and 4.375 MPa in cancellous bone. The areas of maximum stress shifted as follows: along the cervical region in enamel; in the middle third of the root in dentin; in the transition zone between the vertical and basal surfaces of

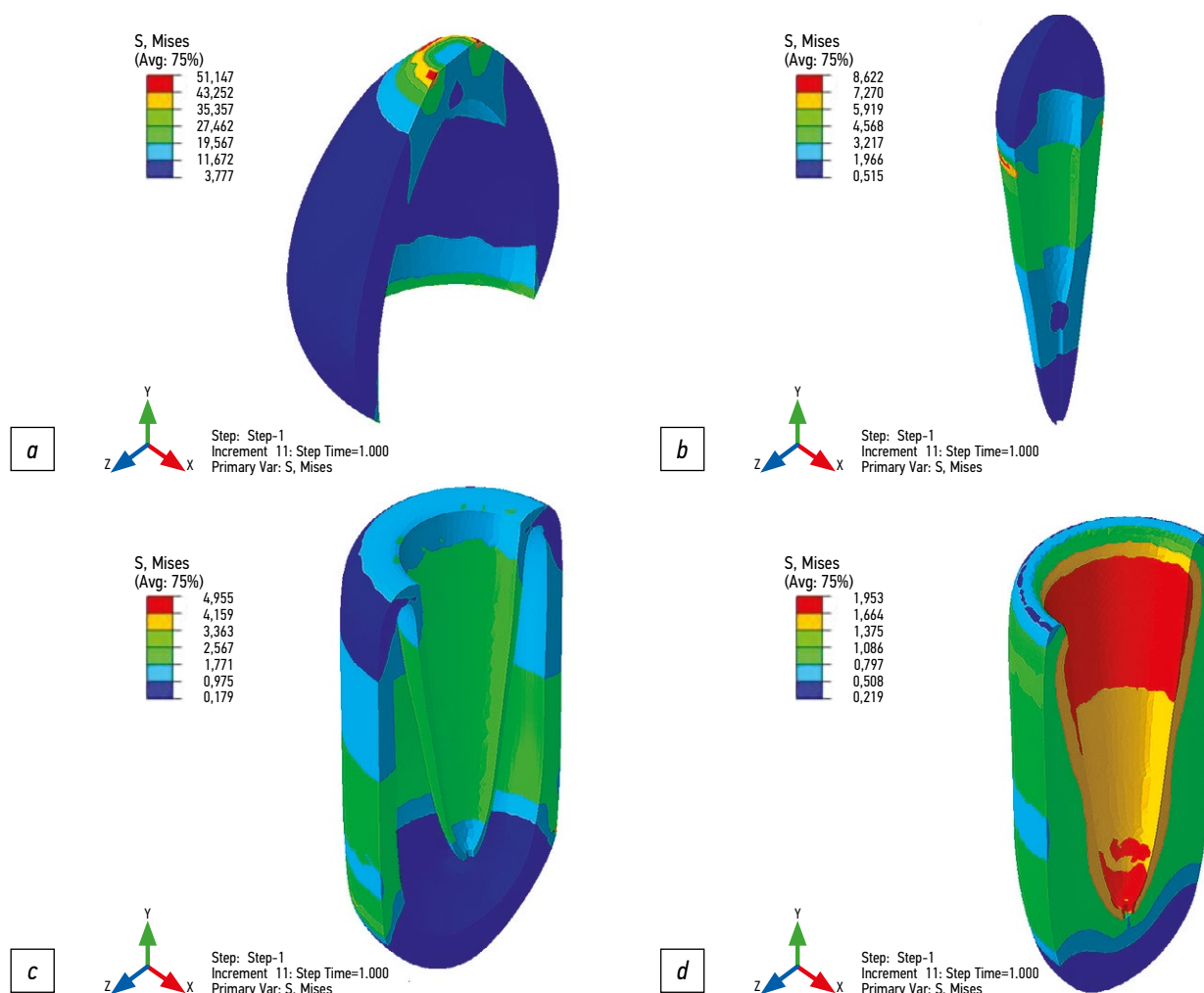


Fig. 2. Functional stress distribution in the tooth and surrounding bone tissue under vertical loading in unfavorable biomechanical conditions (devitalized tooth): *a*, enamel; *b*, dentin; *c*, cortical bone; *d*, cancellous bone.

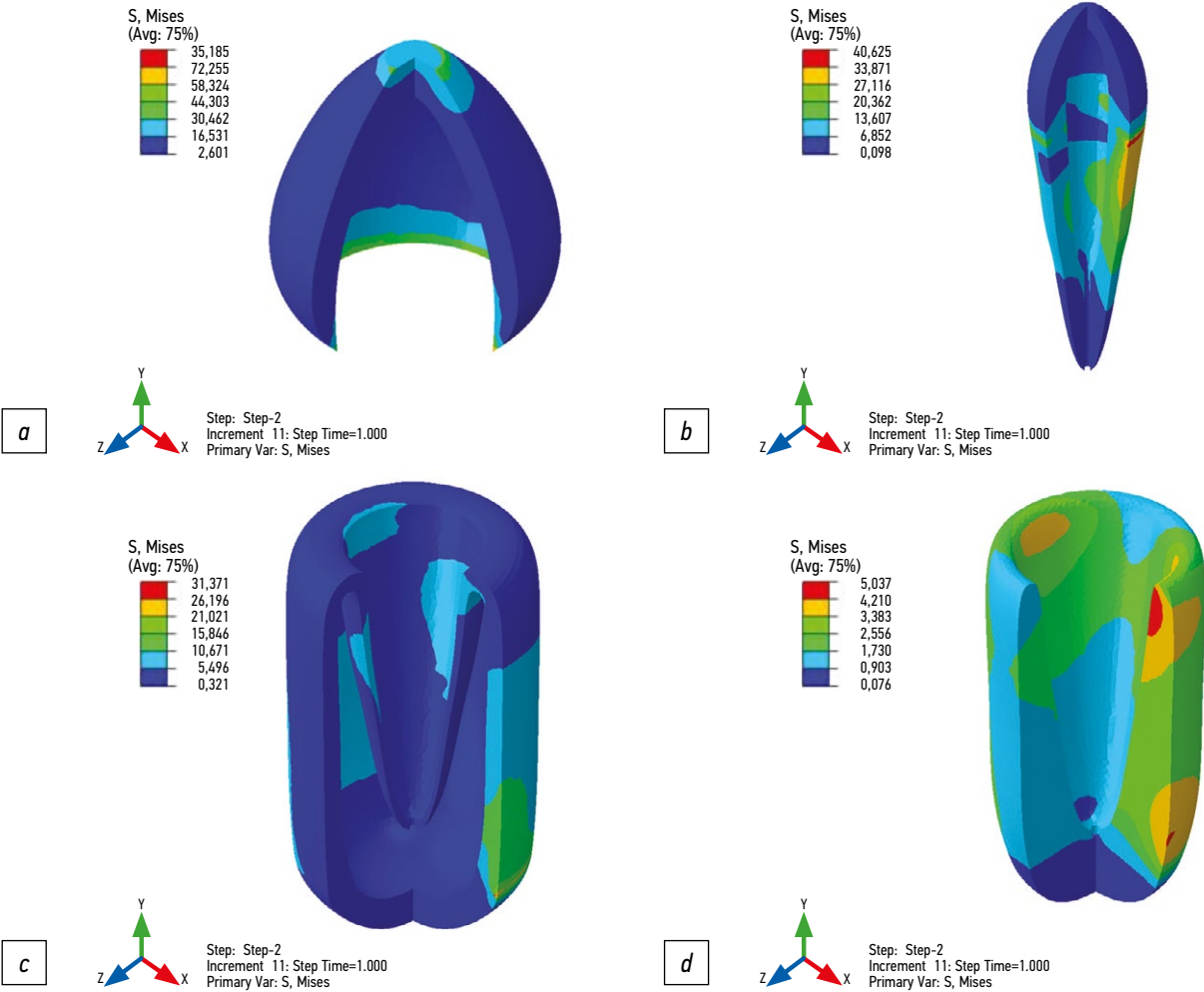


Fig. 3. Functional stress distribution in the tooth and surrounding bone tissue under oblique loading in unfavorable biomechanical conditions (devitalized tooth): *a*, enamel; *b*, dentin; *c*, cortical bone; *d*, cancellous bone.

Table 2. Maximum stress values under functional loading of a devitalized tooth (MPa)

Test object	Intact tooth	Devitalized tooth	Periapical bone resorption	Apicoectomy
Enamel (v)	34.204	51.147	57.360	57.360
Enamel (o)	43.705	86.186	110.489	110.505
Dentin (v)	9.174	8.622	7.971	7.971
Dentin (o)	56.469	40.625	36.792	36.790
Cortical bone (v)	5.066	4.955	5.418	5.419
Cortical bone (o)	27.909	31.371	47.968	47.969
Cancellous bone (v)	1.382	1.953	1.871	1.872
Cancellous bone (o)	4.375	5.037	5.107	5.111

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

the mandible in cortical bone; and in the cervical portions of the interalveolar septa in cancellous bone.

The hard tissues of the devitalized tooth were exposed to greater stresses than those of the intact tooth, particularly under oblique loading: by 49.3%, 11.0%, and 13.1% (86.186, 31.371, and 5.037 MPa) in the enamel, cortical bone, and cancellous bone, respectively. Under vertical loading, tooth devitalization increased stresses in enamel and cancellous bone by 33.1% and 29.2% (51.147 and 1.953 MPa, respectively). In devitalized dentin, due to the deterioration of its physical properties and consequent reduction of ultimate strength, stresses remained nearly unchanged under vertical loading and decreased by 28.1% under oblique loading.

A clinically common condition, periapical bone resorption, compared with a devitalized tooth without resorption, resulted in increased enamel stress—by 10.8% under vertical and 22.0% under oblique loading (57.360 and 110.489 MPa, respectively)—and in cortical bone under oblique loading by 34.6% (47.968 MPa). Under vertical loading with periapical resorption, stress values in enamel, dentin, cortical bone, and cancellous bone were 57.360, 7.971, 5.418, and 1.871 MPa, respectively. Under oblique loading, the corresponding stresses increased to 110.489, 36.792, 47.968, and 5.107 MPa, respectively.

The mathematical model of a devitalized tooth after apicoectomy showed no significant differences in stress magnitudes in tooth and bone tissues compared with the model featuring periapical resorption. Under vertical loading, maximum stresses in enamel, dentin, cortical bone, and cancellous bone were 57.360, 7.971, 5.419, and 1.872 MPa, respectively; under oblique loading, they were 110.505, 36.790, 47.969, and 5.111 MPa, respectively.

The stress distribution pattern in the devitalized tooth differed from that in the intact tooth only within dentin under vertical loading: stresses persisted in the cervical area but disappeared beneath the enamel layer of the occlusal surface.

Compared with a devitalized tooth, periapical bone resorption altered the stress distribution only in cancellous bone under vertical loading, where stresses were concentrated along the upper boundary of the periapical cavity.

The stress distribution patterns across all analyzed tissues were nearly identical in the models with periapical bone resorption and apicoectomy.

DISCUSSION

Analysis of stress values across the modeled teeth showed that functional loading of a devitalized tooth resulted in enamel stress levels approaching its ultimate strength under both vertical and oblique loading, and in

dentin under oblique loading. Periapical bone resorption further increased stress levels. Oblique loading was particularly detrimental to the stress–strain behavior of the tooth and surrounding alveolar bone.

The patterns revealed through mathematical modeling are consistent with clinical observations, confirming the applicability of this method for individualized prediction of the biomechanical consequences of dental interventions affecting the hard tissues of the tooth.

CONCLUSION

From a biomechanical perspective, tooth devitalization negatively affects the strength of hard dental tissues. Devitalization increases stresses in enamel and bone tissue, particularly under oblique loading. Despite a reduction in dentin stress caused by a decrease in its mechanical strength, the stress values in a devitalized tooth under oblique loading approach the dentin ultimate strength in the cervical region. As a result of tooth devitalization, enamel stresses exceed its ultimate strength under both oblique and vertical loads—at the cervical area and along the occlusal surface, respectively. Periapical bone resorption and apicoectomy similarly increase enamel stress compared with a devitalized tooth under both loading conditions and also raise cortical bone stress under oblique loading.

ADDITIONAL INFORMATION

Author contributions: E.A. Olesova: methodology, formal analysis; S.D. Arutyunov: conceptualization, writing—review & editing; E.A. Nekrasova: writing—original draft; M.R. Bersanova: validation, data curation; E.E. Olesov: investigation. All the authors approved the version of the manuscript to be published and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Generative AI: No generative artificial intelligence technologies were used to prepare this article.

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