Original Research

https://doi.org/10.36377/ET-0136

The ratio of the parameters of microhardness and elastic plastic deformation of natural teeth as a starting point for experimental studies on minimizing the weakening of the root structure during endodontic treatment

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Abstract

AIM. Evaluation of the parameters of microhardness and elastoplastic deformation of the dentine of the roots of untreated teeth for further use in experimental studies devoted to the search for protocols that minimally weaken the root structures during endodontic treatment.

MATERIALS AND METHODS**.** 14 premolars (9 upper and 5 lower) with a straight root, removed according to orthodontic indications, were selected for the study. The root of each tooth was divided into three parts (oral, middle, and apical), then the parameters of microhardness and elastic plastic deformation were determined for each of the parts. Measurements were carried out in three areas: at the channel, in the middle part of the sample and in the outer part of the sample.

RESULTS. Microhardness parameters: the middle segment has the highest microhardness values for all thirds of the root: in the mouth – 95.02 (91.97–99.31) HV, 1026.05 (993.03–1072.37) (MPa), average – 97.34 ± 12.45 HV, 1051.11 ± 134.47 (MPa) and apical- 100.08 ± 12.35 HV, 1080.69 ± 133.33 (MPa).

Parameters of elastoplastic deformation: the middle segment has the highest modulus of elasticity in all thirds of the root, the highest index is in the apical third of the root – 24.25 (24.01–25.30) (MPa), the lowest is in the middle third (21.87 ± 1.55 MPa); the highest relative work of elastic deformation is in the middle third of the root, the lowest is in the mouth a third. At the same time, it increases from the mouth to the middle third, and decreases from the middle third to the apical third. The greatest relative work of plastic deformation is in the estuarine third, the smallest is in the middle third, while it decreases from the estuarine to the middle third, and increases from the middle third to the apical third.

CONCLUSIONS. The apical third of the root is the hardest, while the middle third is the most elastic. When considering the wall in a cross-section, the middle is the hardest, while the segments at the channel and at the outer edge are less hard and more elastic.

Keywords: microhardness of the tooth root, modulus of elasticity, experimental study

Article info: received – 29.09.2025; revised – 01.11.2025; accepted – 07.11.2025

Conflict of interest: The authors report no conflict of interest.

Acknowledgements: There are no funding and individual acknowledgments to declare.

For citation: Taptun Yu.A., Makeeva M.K., Belov D.S., Byakova S.F., Voronov I.A., Omarova Kh.O., Babaeva L.K., Avetisian G.G., Babakhanov D.A., Starodubtseva E.E. The ratio of the parameters of microhardness and elastic plastic deformation of natural teeth as a starting point for experimental studies on minimizing the weakening of the root structure during endodontic treatment. *Endodontics Today.* 2025;23(4):603–614. https://doi.org/10.36377/ET-0136

Соотношение параметров микротвердости и упругопластической деформации натуральных зубов как отправная точка для экспериментальных исследований, посвященных минимизации ослабления структуры корня в ходе эндодонтического лечения

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Резюме

ЦЕЛЬ ИССЛЕДОВАНИЯ. Оценка параметров микротвердости и упругопластической деформации дентина корней необработанных зубов для дальнейшего использования в экспериментальных исследованиях, посвященных поиску протоколов, минимально ослабляющих структуры корня в ходе эндодонтического лечения.

МАТЕРИАЛЫ И МЕТОДЫ. Для исследования было отобрано 14 премоляров (9 верхних и 5 нижних) с прямым корнем, удаленных по ортодонтическим показаниям. Корень каждого зуба был разделен на три части (устьевую, среднюю, апикальную), далее у каждой из частей определялись параметры микротвердости и упругопластической деформации. Замеры проводили в трех областях: у канала, в средней части образца и в наружной части образца.

РЕЗУЛЬТАТЫ. Параметры микротвердости: сегмент середины имеет самые высокие показатели микротвердости по всем третям корня: в устьевой – 95,02 (91,97–99,31) HV, 1026,05 (993,03–1072,37) (МПа), средней – 97,34 ± 12,45 HV, 1051,11 ± 134,47 (МПа) и апикальной – 100,08 ± 12,35 HV, 1080,69 ± 133,33 (МПа). Параметры упругопластической деформации: сегмент середины имеет наибольший модуль упругости по всем третям корня, наибольший показатель – в апикальной трети корня – 24,25 (24,01–25,30) (ГПа), наименьший – в средней трети (21,87 ± 1,55 ГПа); наибольшая относительная работа упругой деформации – в средней трети корня, наименьшая – в устьевой трети. При этом от устьевой к средней трети увеличивается, а от средней трети к апикальной – уменьшается. Наибольшая относительная работа пластической деформации в устьевой трети, наименьшая – в средней трети, при этом от устьевой к средней трети уменьшается, а от средней трети к апикальной – увеличивается.

ВЫВОДЫ. Апикальная треть корня является наиболее твердой, тогда как средняя треть – наиболее эластичной. При рассмотрении стенки в поперечном срезе наиболее твердой является середина, тогда как сегменты у канала и у наружного края менее твердые и более эластичные.

Ключевые слова: микротвердость корня зуба, модуль упругости, экспериментальное исследование

Информация о статье: поступила – 29.09.2025; исправлена – 01.11.2025; принята – 07.11.2025

Конфликт интересов: Авторы сообщают об отсутствии конфликта интересов.

Благодарности: Финансирование и индивидуальные благодарности для декларирования отсутствуют.

Для цитирования: Таптун Ю.А., Макеева М.К., Белов Д.С., Бякова С.Ф., Воронов И.А., Омарова Х.О., Бабаева Л.К., Аветисян Г.Г., Бабаханов Д.А., Стародубцева Е.Е. Соотношение параметров микротвердости и упругопластической деформации натуральных зубов как отправная точка для экспериментальных исследований, посвященных минимизации ослабления структуры корня в ходе эндодонтического лечения. *Эндодонтия Today.* 2025;23(4):603–614. https://doi.org/10.36377/ET-0136

INTRODUCTION

The issue of reduced microhardness of root dentin during endodontic treatment has been extensively discussed in both Russian and international literature [1–4]. A significant decrease in this parameter under the influence of various factors may lead to vertical root fracture [5; 6]. Microhardness of root dentin can only be studied under experimental conditions, which creates certain challenges in applying the obtained results to clinical practice. To address this issue, researchers either compare their findings with previously published data or include a group of non-endodontically treated teeth in their own studies for comparison.

In several studies [7; 8], a direct comparison is made between the microhardness values of untreated teeth and those of the experimental groups. However, this approach has a limitation: direct comparison between treated and control teeth may not always be accurate, since root dentin microhardness can vary across different root regions, among different types of teeth, between young and elderly individuals, and even the presence of diabetes can affect dentin microhardness [9].

The most informative results to date are obtained using an approach that includes a group of untreated teeth, but instead of directly comparing the absolute values, the difference between them is analyzed [10; 11]. In this method, the root is divided into three thirds, and the microhardness difference between these thirds is measured. Then, the microhardness of the three thirds of the roots in the experimental group is measured and compared. If a statistically significant difference is observed, a conclusion is drawn regarding the change in microhardness under the influence of a specific root canal treatment. A certain limitation of this approach is that it compares mean microhardness values of the samples, while microhardness may vary within a single specimen.

Furthermore, considering that in vitro studies on the microhardness of root dentin are primarily aimed at preventing root weakening and fractures, it is essential to take into account not only microhardness but also elasticity parameters. It is known that one of the main functions of the tooth root is to transmit masticatory loads to the jawbone; therefore, the root can be regarded as a system subjected to multidirectional compressive and tensile stresses [12]. Stable functioning of such a system is possible only with a balanced ratio between hardness and elasticity.

Thus, to assess the effect of endodontic treatment on root strength, it is reasonable to measure not only microhardness but also parameters of elastoplastic deformation. In this context, the focus should be placed not so much on the absolute values of these parameters as on the ratios between them. The variation of these ratios allows researchers to evaluate the contribution of different endodontic canal treatment methods to the change in root strength.

Accordingly, the aim of the present study was to perform a comprehensive assessment of the parameters of microhardness and elastoplastic deformation of tooth roots, in order to identify key reference points for further experimental research aimed at developing treatment protocols that minimize structural weakening of the root during endodontic therapy.

MATERIALS AND METHODS

This experimental study is part of a research project approved by the Ethics Committee of the Peoples' Friendship University of Russia named after Patrice Lumumba (Protocol No. 7, dated April 21, 2022).

According to the literature, along with mandibular molars, premolars belong to the category of teeth with an increased risk of developing vertical root fractures. Therefore, in this study, both maxillary and mandibular premolars were evaluated.

Inclusion criteria: single-rooted premolars with straight roots (curvature not exceeding 5° according to the classification by Schneider [13]); root canal configuration type I according to Vertucci (i.e., a single root canal extending from the pulp chamber to the apex, ending with one apical foramen [14]); and no previous endodontic treatment.

The teeth were extracted for orthodontic reasons from male and female patients over 30 years of age who had no systemic or local conditions that could affect root dentin microhardness, such as hereditary disorders of dental hard tissues and mineral metabolism (imperfect dentinogenesis, imperfect amelogenesis, osteogenesis imperfecta, dentin dysplasia, etc.), diabetes mellitus [9], or periodontal pockets.

To ensure that the obtained sample more accurately reflected the studied parameters, taking into account possible individual variability among patients, only one tooth per jaw was taken from each patient (i.e., only one maxillary and/or one mandibular premolar).

Thus, based on the specified criteria, the study included 14 premolars (9 maxillary and 5 mandibular) extracted from 13 patients (5 males and 8 females) aged 35 to 43 years, with a mean age of 37.9 ± 2.7 years.

The crowns were removed using a separation disc so that the remaining root length was 15 mm (Fig. 1).

The root was divided into three sections: coronal, middle, and apical thirds (Fig. 2).

Each root section was assessed for microhardness parameters: H (Hit) (MPa) – microhardness, HV – Vickers hardness, hm (nm) – indenter penetration depth; and elastoplastic deformation parameters: E (Eit) (GPa) – elastic modulus (Young's modulus), We (%) – relative work of elastic deformation, and Wp (%) – relative work of plastic deformation using the microindentation method.

The laboratory stage of sample preparation for indentation included embedding in epoxy resin, polymerization, polishing, and treatment with isopropyl alcohol (GOST 9805-84). Measurements were performed using a Micro-indentation tester (CSM Instruments, Switzerland) (Fig. 3) with a Berkovich indenter (Fig. 4), at a maximum load of 50 mN and a dwell time of 10 seconds.

For a comprehensive assessment of the microhardness and elastoplastic deformation parameters of the tooth root, measurements in each root section (coronal, middle, apical) were performed in three segments: adjacent to the canal, in the middle of the specimen, and in the outer part of the specimen (Fig. 5).

Fig. 1. Marking and measurement of the premolar root

Рис. 1. Маркировка и измерение корня премоляра

Fig. 2. The root of the premolar after dividing into three parts

Рис. 2. Корень премоляра после разделения на три части

Statistical analysis was performed using StatTech v. 4.8.11 (LLC StatTech, Russia). Quantitative variables were assessed for normality using the Shapiro–Wilk test. Quantitative variables with a distribution consistent with normality were described using mean values and standard deviations (M ± SD). The 95% confidence interval was reported as a measure of representativeness for the mean values. In cases where the distribution deviated from normality, quantitative data were presented using the median and interquartile range (Me (Q1–Q3)).

RESULTS

The comparison of the obtained values for a comprehensive assessment of microhardness and elastoplastic deformation parameters was carried out as follows:

1. Comparison of the overall mean values of each third of the root.
2. Comparison of the overall mean values of each segment (e.g., the mean of the canal-adjacent segments across all three root thirds).

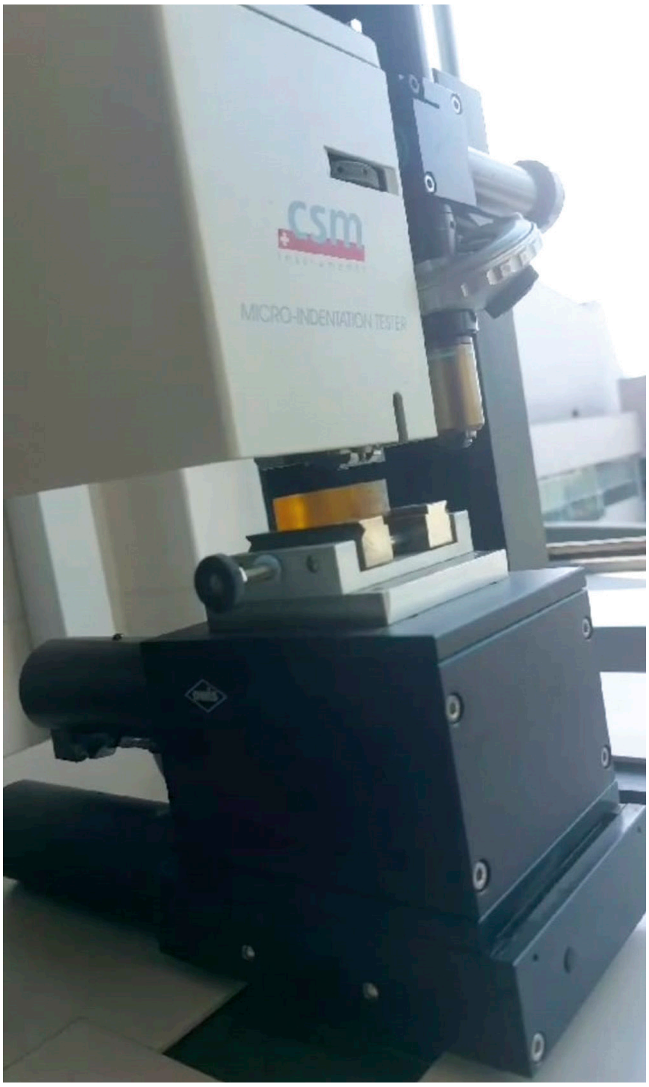


Fig. 3. Appearance of a microindentometer with a mounted sample

Рис. 3. Внешний вид микроиндентометра с установленным образцом

Fig. 4. Berkovich indenter (a truncated three-sided diamond pyramid) with a device for measuring microhardness

Рис. 4. Индентор Берковича (усеченная трехгранная алмазная пирамида) со снаской для измерения микротвердости

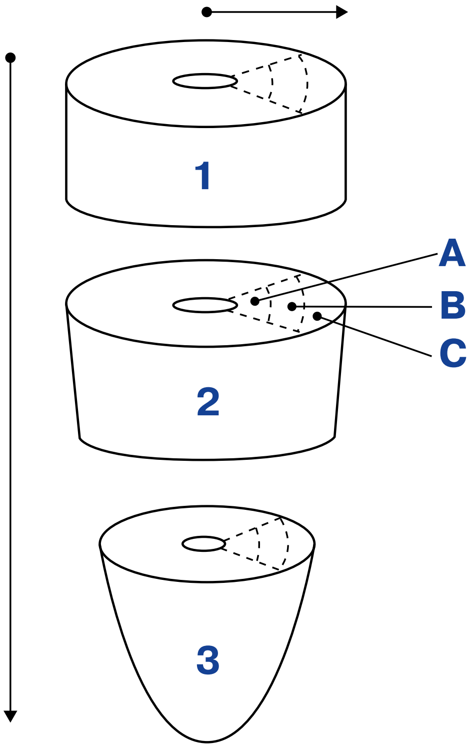


Fig. 5. The diagram of the root areas in which measurements were carried out: in each of the root parts (mouth (*1*), middle (*2*) and apical (*3*)), measurements were carried out in three segments (at the lumen of the root canal (*A*), in the middle of the sample (*B*) and at the outer edge (*C*)). When calculating the relative difference in parameters between different thirds of the root and segments, they moved vertically from the mouth to the apex, and horizontally from the channel to the outer edge (indicated by arrows)

Рис. 5. Схема областей корня, в которых проводили измерения: в каждой из частей корня (устьевой (*1*), средней (*2*) и апикальной (*3*)) проводили измерение в трех сегментах (у просвета корневого канала (*A*), в середине образца (*B*) и у наружного края (*C*)). При расчете относительной разницы параметров между различными третями корня и сегментами в вертикальном направлении двигались от устья к апексу, а в горизонтальном направлении – от канала к наружному краю (указано стрелками)

3. Comparison of the mean values of each segment within a single root third.

4. Comparison of the mean values of a specific segment across different root thirds.

5. Assessment of the relative difference between statistically significant mean values.

The comparison of the overall mean values of the studied parameters for each root third indicates that, in terms of microhardness, there was no statistically significant difference between the coronal, middle, and apical thirds of the root. Statistically significant differences were observed for the elastoplastic deformation parameters.

The highest elastic modulus was recorded in the apical third, and the lowest in the middle third (19.22 [17.93–23.93] GPa and 18.50 [15.91–20.45] GPa, respectively; $p = 0.032$). Calculation of the relative difference between mean values showed that the elastic modulus decreased by 1.5% from the coronal to the middle third and increased by 3.8% from the middle to the apical third.

The highest relative work of elastic deformation was observed in the middle third, and the lowest in the coronal third (27.25 ± 2.86% and 25.24 ± 2.67%, respectively; $p = 0.002$). The relative difference between mean values indicated an increase of 7.9% from the coronal to the middle third and a decrease of 0.4% from the middle to the apical third.

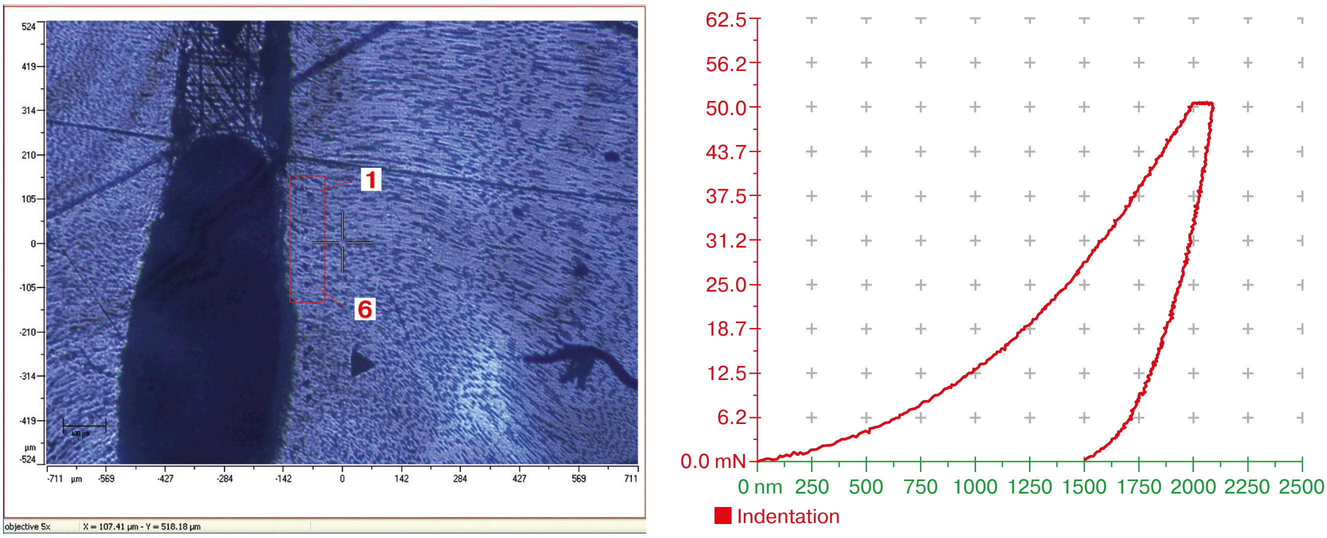
The highest relative work of plastic deformation was found in the coronal third and the lowest in the middle third (74.44 [73.05–76.49] % and 72.49 [71.11–74.53] %, respectively; $p = 0.007$). Calculation of the relative difference showed a decrease of 2.6% from the coronal to the middle third and an increase of 1.1% from the middle to the apical third.

When comparing the overall mean values of each segment, it was found that the middle segment had significantly higher microhardness and elastic modulus compared to the canal-adjacent segment and the outer-edge segment ($p < 0.001$).

Next, the mean values of each segment within a single root third were compared. In the coronal third, the middle segment exhibited the highest microhardness (95.02 [91.97–99.31] HV, 1026.05 [993.03–1072.37] MPa), whereas the canal-adjacent segment showed the lowest values (60.98 [51.76–85.06] HV, 658.43 [558.89–918.50] MPa), with the differences being statistically significant ($p < 0.001$).

Fig. 6 shows a microphotograph of the specimen at the canal-adjacent segment of the coronal third, along with the corresponding indentation curve for this measurement.

When calculating the relative differences between mean values, it was determined that microhardness increased by 55.8% from the canal-adjacent segment to the middle segment, then decreased by 23.4% toward the outer-edge segment.



A B

Fig. 6. Sample of the mouth of the root during the indentation of the segment at the canal: *A* – micrograph (the measuring points near the lumen of the root canal are highlighted in a red rectangle, points *1* and *6* are numbered); *B* – indentation curve at point 6 of this sample, the abscissa axis is the depth of penetration of the indenter, the ordinate axis is the load, the horizontal section (exposure) demonstrates the retention of the sample under a maximum load of 50 mN for 15 seconds, the depth of the indenter penetration (hm) for this point was 2087.69 nm

Рис. 6. Образец устьевой части корня в процессе индентирования сегмента у канала: *А* – микрофотография (точки замера около просвета корневого канала выделены красным прямоугольником и пронумерованы 1 и 6); *В* – кривая индентирования в точке 6, ось абсцисс – глубина проникновения индентора, ось ординат – нагрузка, горизонтальный участок (выдержка) демонстрирует удержание образца под максимальной нагрузкой 50 мН в течении 15 секунд, глубина проникновения индентора (hm) для данной точки составила 2087,69 нм

Regarding elastoplastic deformation parameters, the highest elastic modulus was found in the middle segment (23.41 [22.57–26.22] GPa) and the lowest in the canal-adjacent segment (16.17 [15.40–21.21] GPa), with a statistically significant difference ($p < 0.001$). The relative difference calculation showed an increase of 44.7% from the canal-adjacent segment to the middle segment and a decrease of 3.3% from the middle to the outer-edge segment.

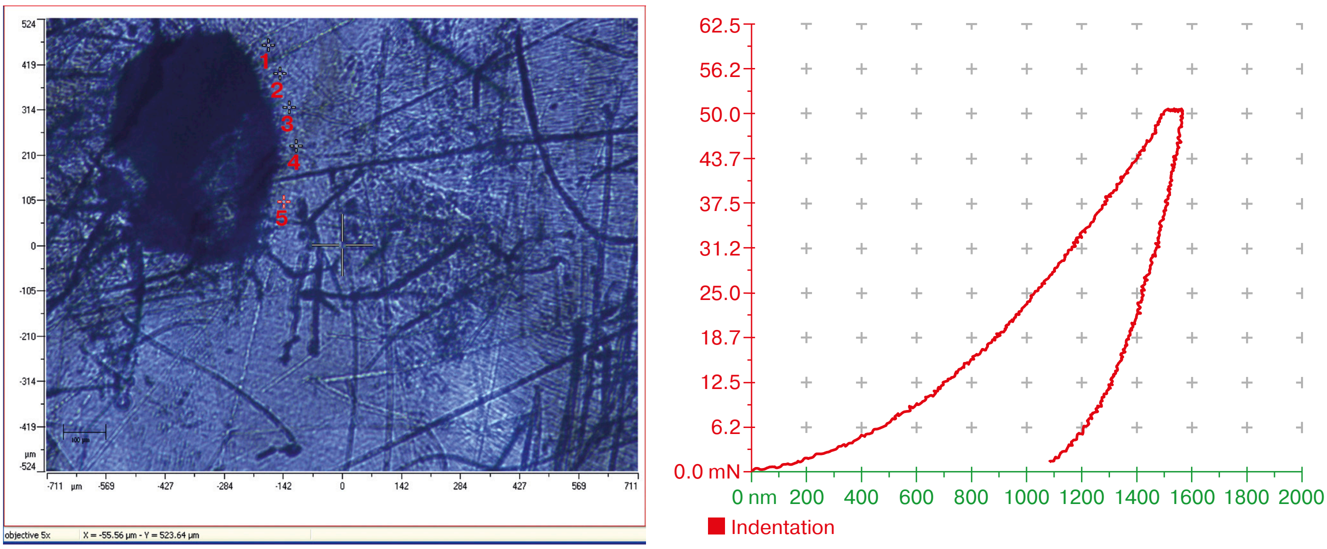
In the middle third of the root, the middle segment exhibited the highest microhardness (97.34 ± 6.45 HV, 1051.11 ± 75.47 MPa) and the outer-edge segment the lowest (72.22 ± 9.80 HV, 779.84 ± 50.83 MPa), with significant differences ($p < 0.001$). Relative difference calculations indicated an increase of 25.2% from the canal-adjacent segment to the middle segment, followed by a decrease of 25.8% toward the outer edge. For elastoplastic parameters, a significant difference was observed in the elastic modulus: the middle segment had the highest value (21.87 ± 1.55 GPa), and the outer-edge segment the lowest (17.09 ± 2.97 GPa) ($p < 0.001$). Relative difference analysis showed a 26% increase from the canal-adjacent segment to the middle segment and a 21.9% decrease from the middle to the outer-edge segment.

In the apical third, similar patterns were observed. The middle segment had the highest microhardness (100.08 ± 6.35 HV, 1080.69 ± 65.33 MPa) and the outer-edge segment the lowest (70.18 ± 5.01 HV, 757.83 ± 54.03 MPa), with significant differences ($p < 0.001$). Relative difference calculations showed an increase of 17.2% from the canal-adjacent segment to the middle segment and a decrease of 29.8% toward the outer edge. Regarding elastoplastic parameters, a significant difference was observed in the elastic modulus: the middle segment had the highest value (24.25 [24.01–25.30] GPa) and the outer-edge segment the lowest (18.10 [17.10–19.38] GPa) ($p < 0.001$). Relative difference analysis indicated a 26.8% increase from the canal-adjacent segment to the middle segment and a 25% decrease from the middle to the outer-edge segment.

Fig. 7 shows a microphotograph of the specimen at the canal-adjacent segment of the coronal third of the root, along with the corresponding indentation curve for this measurement.

Next, the mean values of each specific segment were compared across different thirds of the root.

When evaluating the *segment near the canal*, it was found that microhardness significantly increased from the coronal third toward the apical third of the root ($p = 0.045$). The relative difference analysis showed that the microhardness of the segment near the canal increased by 19.2% from the coronal to the middle third and by an additional 13.8% from the middle to the apical third.



A **B**

Fig. 7. Sample of the apical part of the root during the indentation of a segment at the canal: *A* – micrograph (the measuring points near the root canal lumen are numbered); *B* – indentation curve at point 5 (highlighted in red) of this sample, the abscissa axis is the indenter penetration depth, the ordinate axis is the load, the horizontal section (exposure) demonstrates the retention of the sample under a maximum load of 50 mN for 15 seconds, the indenter penetration depth (hm) for This point was 1570.85 nm

Рис. 7. Образец апикальной части корня в процессе индентирования сегмента у канала: *А* – микрофотография (точки замера около просвета корневого канала пронумерованы); *В* – кривая индентирования в точке 5 (выделена красным), ось абсцисс – глубина проникновения индентора, ось ординат – нагрузка, горизонтальный участок (выдержка) демонстрирует удержание образца под максимальной нагрузкой 50 мН в течении 15 секунд, глубина проникновения индентора (hm) для данной точки составила 1570,85 нм

Among the *elastoplastic deformation parameters*, statistically significant differences were observed in the relative work of elastic and plastic deformation. The *relative elastic work* significantly increased from the coronal to the apical third of the root (p = 0.024): from the coronal to the middle third, this parameter increased by 4.26%, and from the middle to the apical third – by 8.7%. Conversely, the *relative plastic work* significantly decreased from the coronal toward the apical third (p = 0.05): from the coronal to the middle third, it decreased by 1.8%, and from the middle to the apical third – by 4.8%.

When evaluating the *middle segment*, no statistically significant differences in microhardness were found between the coronal, middle, and apical thirds of the root. However, among the elastoplastic deformation parameters, a significant difference was detected for the *elastic modulus*, which was highest in the apical third (24.4 ± 1.07 GPa) (p = 0.002). The modulus decreased by 5.4% from the coronal to the middle third and increased by 10.8% from the middle to the apical third.

When analyzing the *outer edge segment*, no statistically significant differences in microhardness were observed. However, a significant difference was identified in the *relative elastic work*, which was highest in the middle third (27.52 ± 2.96%) (p = 0.046) and lowest in the coronal third (25.35 ± 1.94%). The parameter increased by 8.5% from the coronal to the middle third and decreased by 4.8% from the middle to the apical third.

Fig. 8 presents a schematic representation of the statistically significant relationships between the parameters; mean values are given without standard deviation or interquartile range.

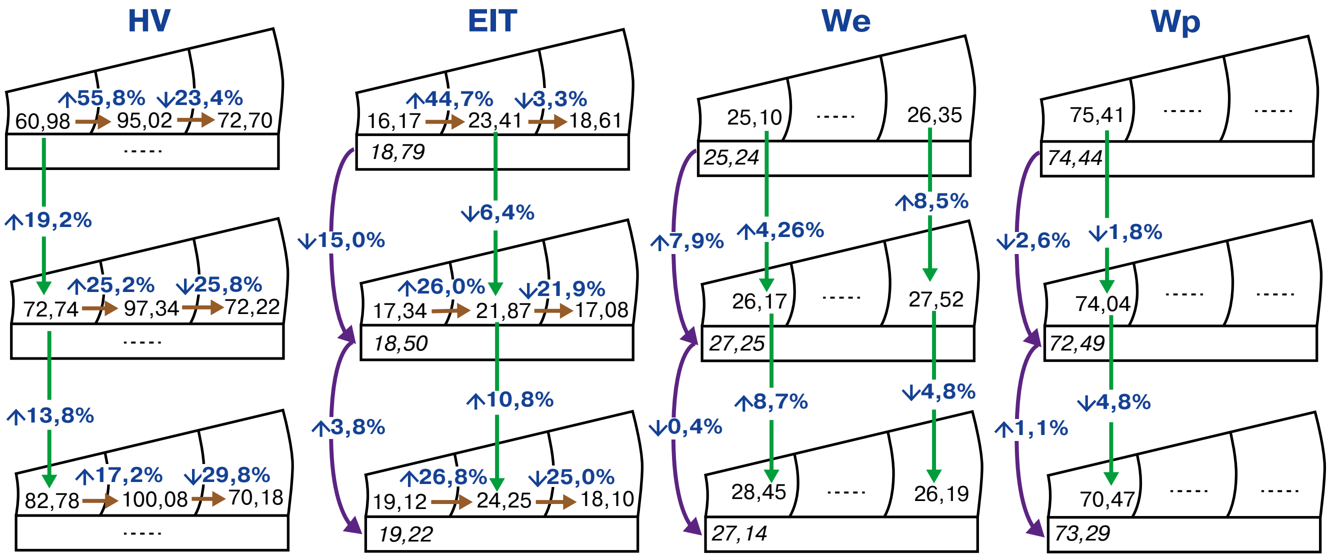


Fig. 8. Schematic representation of the mouth, middle and apical thirds (from top to bottom) teeth with significantly different parameters (HV is the Vickers microhardness, Eit is the modulus of elasticity, GPa, We(%) is the relative work of elastic deformation, Wp(%) is the relative work of plastic deformation).The black numbers in bold are the average values of the parameters in each of the segments (from left to right: the segment at the channel, the segment in the middle, the segment at the outer edge), the numbers in italics are the average values of the parameter for a third of the root as a whole.The arrows indicate the difference between significantly different values, the direction of the arrow indicates from which digit to which the difference is calculated: green arrows indicate the change in the parameter between equally spaced segments of different thirds of the root; brown arrows – between different segments of the same third of the root; purple arrows – the difference between the total average values of the parameter for a third of the root as a whole; The dotted line indicates that there are no significantly different values

Рис. 8. Схематичное изображение устьевой, средней и апикальной третей (сверху вниз) зуба с указанными достоверно различающимися параметрами (HV – микротвердость по Виккерсу, Eit – модуль упругости, ГПа, We (%) – относительная работа упругой деформации, Wp (%) – относительная работа пластического деформирования). Цифры черного цвета, выделенные жирным шрифтом – средние значения параметров в каждом из сегментов (слева направо: сегмент у канала, сегмент середины, сегмент у наружного края), цифры, выделенные курсивом – средние значения параметра для трети корня в целом. Стрелками указана разница между достоверно различающимися значениями, направление стрелки указывает от какой цифры к какой посчитана разница: зеленые стрелки указывают изменение параметра между одинаково расположенными сегментами различных третей корня; коричневые стрелки – между различными сегментами одной и той же трети корня; фиолетовые стрелки – разницу между суммарными средними значениями параметра для трети корня в целом; пунктирная линия указывает на отсутствие достоверно различающихся значений

DISCUSSION

Several studies have confirmed that determining microhardness is an appropriate method for the indirect assessment of changes in the mineral component of dental tissues [15–17]. The microhardness of root dentin is an important, though not the only, parameter responsible for the tooth's mechanical strength. Numerous investigations have been devoted to evaluating the microhardness of root dentin [18–20].

Considering the tooth as a system that perceives and transmits masticatory load, the elasticity of its constituent tissues should not be underestimated. Studies focusing on this property of root dentin are also presented in the literature [21], although they are less numerous compared to those dedicated to microhardness. This indicates a certain underestimation of the contribution of elasticity parameters to the fracture resistance of the root.

In the present study, the authors conducted a comprehensive assessment of both the microhardness and elastoplastic deformation characteristics of the same root dentin specimens. The obtained data may contribute to a deeper understanding of the role and interrelation of these two parameters within different regions of the root in ensuring overall tooth strength.

One of the challenges of experimental research lies in the applicability of findings to real clinical conditions and in the comparability of results across different studies. The use of various standards, reference samples, and baseline values enables such assessment. In this work, the authors aimed not only to investigate the changes in microhardness and elastoplastic deformation parameters across different thirds and segments of the tooth root, but also to determine the relative difference (in percentage terms) between statistically significant values. These data can be used for comparison with other studies, as they allow conclusions to be drawn regardless of the measurement units applied or the indentation load used.

In the literature, only a limited number of studies have been found that focus on mapping the mechanical properties of dental tissues [22; 23], analyzing the gradient of their strength characteristics [24], or modeling the fluctuation of specific parameters [21]. The results obtained by the authors of this study complement the data from these previous works and expand the current understanding of the distribution of strength and elastic properties throughout the root dentin.

In the studies analyzed during the literature review stage, dedicated to the investigation of microhardness, most authors evaluated the mean values for one-third of the tooth root (coronal, middle, and apical thirds) [10; 11]. In several studies, measurements were performed for the entire root [25], while one study assessed only the middle third [26]. The distinctive feature of the present research is that, in addition to evaluating the mean microhardness and other parameters of each root third, measurements were also conducted within three segments of each third (near the canal, in the middle, and near the outer surface). This approach allows assessment of parameter variations both in the vertical direction (from the cervical to the apical region, consistent with the direction of masticatory load transmission) and in the horizontal direction through the root wall (from the canal to the outer surface, corresponding to the direction of stress propagation in the presence of an intracanal post or inlay).

When comparing the results of the present study with other works, a generally similar trend can be observed. As in the authors' findings and in other studies [25], no statistically significant differences in microhardness were found among the mean values of the coronal, middle, and apical thirds of intact roots. No studies assessing microhardness across different segments within the same root third were identified during the literature search.

In the study by Jíra and Němeček [27], the elastic modulus of root dentin was evaluated using a design similar to that employed in the present study, with an identical indentation load of 50 mN. The distribution of elastic modulus values was assessed in both longitudinal and transverse directions; however, transverse measurements were performed only for the middle third of the root. According to their findings, on the cross-section of the middle third, the elastic modulus of root dentin was approximately 17 GPa at the cement-dentin interface, 23 GPa in the middle of the specimen, and 14 GPa near the root canal. In the present study, comparable values were obtained for the middle third of the root: 17.0 GPa near the outer surface, 21.87 GPa in the middle, and 17.34 GPa near the canal. The mean longitudinal elastic modulus reported by Jíra (~18 GPa) and in the present study (18.80 GPa) were also similar.

A limitation of Jíra's study compared with the present research was that the transverse elastic modulus was evaluated only in the middle third of the root. Conversely, its advantage was the assessment of two directions – mesiodistal and buccolingual – whereas in the present study, measurements were performed in a single direction. The statistical significance of differences between measurement points was not provided in Jíra's study, likely because the analysis was conducted on a single extracted premolar.

A major limitation of ex vivo studies evaluating the microhardness and elastoplastic properties of extracted teeth lies in the difficulty of forming a homogeneous sample group. This constraint was mentioned in all the cited sources and also applies to the present research. Several reviewed studies noted that one of the key factors influencing the mechanical properties of dental tissues is the patient's age. Additionally, the authors of the present study emphasize that the reason for tooth extraction also plays a crucial role. In most reviewed papers, teeth extracted for orthodontic reasons were used, although one study [26] included teeth extracted due to periodontal disease.

It is known from the literature that natural anatomical connections exist between the pulp and periodontal tissues [28]; therefore, chronic inflammatory processes in the periodontium can stimulate increased secondary dentin deposition. According to Surdina [29], in patients with periodontitis, the histological age of the pulp exceeds the chronological one. These variations must be considered when interpreting results from pooled tooth groups or should be addressed by separating such teeth into distinct study cohorts.

CONCLUSION

The presented study has a fundamental character, as it refines and complements existing data on the distribution of microhardness and elastoplastic deformation parameters in root dentin. The apical third of the root was found to be the least elastic, whereas the middle third demonstrated the highest elasticity. This relationship likely provides optimal resistance to vertical loads.

In cross-sectional analysis, the central zone of the root wall exhibited the greatest hardness, while the segments adjacent to the canal and the outer surface were less hard and more elastic. This distribution presumably facilitates the perception and transmission of horizontal stresses, during which different parts of the root wall alternately experience compression and tension.

Overall, this study contributes to the understanding of the mechanical properties of the tooth root and provides a more detailed characterization of their distribution compared to previously published works, owing to the segmental evaluation of each root third.

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Dmitry S. Belov – drafted the article or revised it critically for important intellectual content; approved the version to be published.

Svetlana F. Byakova – has made a substantial contribution to the concept or design of the article; the acquisition, analysis, and interpretation of data for the article.

Igor A. Voronov – drafted the article or revised it critically for important intellectual content; approved the version to be published.

Khadizhat O. Omarova – analysis, or interpretation of data for the article.

Louisa K. Babaeva – analysis, or interpretation of data for the article.

Gor G. Avetisian – analysis, or interpretation of data for the article.

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