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Fracture Resistance and Toughening Mechanisms in Human Dentin: A Biomechanical Perspective

Petro Mazur, Natalia Markova, Iryna Khodzinska, Anatolii Savychuk

Department of Pediatric Dentistry, Shupyk National Healthcare University of Ukraine,
Kyiv, Ukraine

Address for correspondence:

Anatolii Savychuk

E-mail: anatolii.savychuk@gmail.com

Abstract: *fracture resistance in dentin is crucial for maintaining the structural integrity of a vital or endodontically treated tooth, particularly as aging and restorative interventions exacerbate mechanical vulnerabilities. This article explores the biomechanical properties of dentin, focusing on intrinsic toughening mechanisms such as crack deflection, bridging, and microcracking, which act to diminish crack propagation. The composite-like structure of dentin, comprising mineralized collagen fibrils within a heterogeneous matrix, facilitates a balance between stiffness and flexibility, resisting multiple cyclic loads under complex intraoral environments. The impact of dentin dehydration, age-related changes, and the formation of sclerotic dentin on fracture resistance in dentine is discussed. A thorough understanding of toughening mechanisms in dentin is essential for optimizing clinical approaches aiming to ensure the durable success of dental treatment.*

Keywords: Dentin; Biomechanical Phenomena; Physiology; Etiology; Treatment.

Introduction

Human dentin cannot regenerate but undergoes multiple structural changes over decades of functioning and aging, even when clinically intact. Modern restorative procedures, being highly predictable (Seltzer, 1999), from simple fillings to complex interventions like endodontic therapy and post-and-core or crown placement, can initiate microscopic flaws and microcracks in dentin (Arola et al., 2017; Reeh, 1989; Dietschi, 2007, 2008). Over time, these defects can develop and lead to catastrophic failures in tooth structure (Tonami & Takahashi, 1997; Carter, 1983; Kerekes & Tronstad, 1979).

With the rising elderly population and an increasing number of dentated aged individuals seeking reliable dental services (United Nations, 2003), understanding crack propagation and toughening mechanisms in dentin is crucial for preventing irreversible mechanical failures and selecting or developing the most predictable solutions for reconstruction (Pietrokovski & Lantzman, 1973). Dentin is a composite-like material made of mineralized collagen fibrils embedded in a three-dimensional matrix, organized into inter- and peritubular dentin. Its heterogeneous structure at both nano- and microscopic levels contributes to its toughness by allowing different regions to respond differently to stress during function (Berkovitz, 2002). The interactions between the collagen matrix and hydroxyapatite mineral crystals play a critical role (Kishen, 2006). The collagen matrix provides flexibility, while the minerals provide stiffness and strength, aiding energy dissipation and fracture resistance. This allows the dentin to undergo plastic deformation, absorbing energy and preventing fractures from extensive growth. Additionally, dentin tubules running from the pulp to the outer layers can act as crack arrestors and deflectors, increasing the energy required for crack propagation and contributing to the anisotropy of dentin's mechanical properties (Kinney, 1999).

Aim

This review aims to bring more light on the mechanical properties of dentin, specifically on its toughening mechanisms and their changes with age.

Results

Types of Toughening Mechanisms in Dentin

Clinically, the risk factors for tooth fracture can be classified as iatrogenic and non-iatrogenic. Non-iatrogenic factors are primary (due to the anatomical position of a tooth or prehistory of recurrent disease) and secondary (due to dentin aging) (Kishen, 2006). From a biomechanical perspective, fracture formation and propagation are a complex process that depends on the structure and properties of the body and involves the formation, nucleation, and spreading of micro- and macro-cracks (Kinney, 2002). Microscopic cracks can accumulate and grow over time, eventually leading to critical fracture and structure collapse with time or given number of repeated mechanical load cycles (Bajaj, 2006).

Several factors must be present simultaneously for a fracture to occur: (1) stress concentrators, such as a crack or a geometric notch (e.g., sharp corner, thread, hole), and (2) tensile stress of sufficient magnitude to cause microscopic plastic deformation at the stress concentration tip (Kishen, 2006). Tensile stress may not be applied externally but could be a normal residual stress within the structure due to compressive loads. Most known material properties, such as yield strength and tensile strength, do not influence the vulnerability of a material to crack extension and fracture (Kishen, 2006). However, an increase in tensile stresses and stress concentrations renders the remaining tooth structure prone to fracture. It is important to note that the tensile strength of dentin is much lower than its compressive strength - compressive and shear strengths are about 250 MPa, while tensile strength is around 50 MPa (Gupta et al., 2006). Fracture resistance can change and even increase with crack extension, particularly when involving different toughening mechanisms in dentin (Koester, 2008).

Two main principles of toughening mechanisms in dentin have been suggested: (1) intrinsic, where mechanisms operate ahead of the crack tip to enhance the material’s inherent resistance to microstructural damage and cracking, and (2) extrinsic, where mechanisms operate primarily behind the crack tip by promoting crack-tip shielding, reducing the concentration of local stress intensities at the crack tip (Kishen, 2007). Toughness in dentin increases through mechanisms that raise the energy required for fracture or methods that prevent strain energy from reaching the crack tip. In normal hydrated dentin, both factors are well-presented, which is not the case for dehydrated or aged dentin (Kinney et al., 2005). It is suggested that the viscous effects in within hydrated dentin can slow down the rate of energy delivery to the crack tip, allowing the crack to be shielded and propagated slowly.

Three major toughening mechanisms are known to be present in dentin: (1) crack deflection, (2) crack bridging, and (3) microcracking (Kruzic et al., 2003). Crack deflection occurs when cracks deviate from the plane of maximum driving force or tensile stress, reducing the stress intensity at the crack tip, and thereby providing toughening. Crack deflection is promoted by features in the microstructure that deviate from the crack path. For dentin with tubules in a parallel orientation, there is practically no out-of-plane deflection, implying minimal contribution to toughening in this orientation. The same is true macroscopically for the perpendicular orientation. However, small local deflections (up to 20 µm) may occur along the tubule axis.

In crack bridging, as the crack opens, fibers or filaments extend across it, dissipating energy through their own deformation or by friction as they pull out from the bulk material (Bajaj, 2006). Crack bridging is the most common form of crack-tip shielding, especially in fiber composites where intact fibers tend to bridge the crack and oppose its opening. Crack-path observations indicate possible bridging by collagen fibers. Another type of bridging occurs when the dominant crack links with smaller cracks ahead of the tip to form uncracked ligaments. These mechanisms are only observed in the parallel orientation in dentin (Nalla & Kinney, 2003).

Microcracking causes dilation and increases the compliance of the region surrounding the crack. The sharpness of the crack tip focuses strain energy onto the next susceptible bond, a critical factor in fracture propagation. Micro-cracks ahead of the main crack initiate from the stress concentration associated with dentin tubules and form in the more highly mineralized peri-tubular region. This mechanism is not represented in dehydrated dentine.

In aged dentin, tubules accumulate minerals inside their lumens, decreasing microcracking formation in intertubular dentin and lowering the toughening ability of aged dentin (Kinney et al., 2005). The orientation of dentin tubules has been proposed as another toughening mechanism (Nalla & Kinney, 2003). They showed that dentin fracture resistance is anisotropic. Elephant dentin was used due to limitations in human sample preparation. They emphasized that, except for the root, human dentin tubules do not run straight from the enamel to the pulp; instead, they have a complex, S-shaped curvature from the cervical margin through the crown. Their research showed that cracking perpendicular to the tubules occurs with the lowest toughness while cracking parallel to the tubules occurs with the highest. The anti-plane and in-plane parallel orientations are, respectively, 55% and 65% tougher than the perpendicular orientation. Clinically, tuber fractures can contribute to this due to the structure of mantle dentin and the low density of dentin tubules in the peripheral layers of crown dentin (Bajaj, 2006). While these mechanisms are well documented, the role of mineral-collagen interactions, dentin hydration, and water content, especially in aged dentin, are not well-defined and require further investigation.

Impact of Dehydration

The presence of water in dentin affects its mechanical properties. Water acts as a plasticizer, increasing the dentin's ability to deform plastically and absorb energy. Hydrated dentin is generally tougher than dry (Kishen & Vedantam, 2007). A study demonstrated significantly higher fracture values for hydrated dentin compared to dehydrated dentin, and rehydration substantially restored these values (Kahler, 2003). During loading, a region of hydrostatic tension and superimposed shear stresses develop around the crack tip. In hydrated and porous dentin, these stresses can induce dilation around the crack tip, with energy consumed by fluid inflow and egress in this region. The collagen within this area also extends when moist, accommodating such dilation and shear strains. In the absence of fluid, dilation must be solely accommodated by shear or cavitation of the existing fluid (Kishen & Vedantam, 2007).

There are still many questions regarding the role of dehydration in changes in collagen and mineralized collagen fibers, as well as in mineral content in dental tissue due to dehydration (Kinney et al., 2004; Weber, 1974). The highly mineralized peritubular dentin, along with the less permeable enamel and cementum on the outer aspect of bulk dentin, creates a confined environment for free water in dentinal tubules and pulp space. The mechanism of dentin dehydration, considering that pulpless teeth remain in a water-based environment (saliva in the mouth and blood/tissue fluid surrounding the root), has not been fully explained (Van der Graaf & Ten Bosch, 1990). While cementum is permeable without tubules and there is considerable evidence of enamel permeability, the full extent of dehydration's effects on dentin needs more investigation (Kinney et al., 2004).

The extracellular matrix proteins of the pulp have high water-holding properties, with the total water content of the pulp exceeding 90%. Physiological intrapulpal pressure of 10–28 mm Hg constantly drives pulpal fluid outward along the dentinal tubules (Pathways of the Pulp, 2005). The loss of water-rich pulp tissues and free water from dentin surface porosities and dentinal tubules can contribute to a reduction in the mechanical integrity of endodontically treated teeth (Hayashi et al., 2008). The water content of normal dentin is believed to vary with location. Tubules contain 75% of the moisture in dentin, with the rest being associated with the mineralized matrix (Angker et al., 2004).

Types of Dentin Fluids

There are two main types of fluids in dentin. Type one, or ‘bounded’ water, is associated with the apatite crystal of the inorganic phase and collagenous and non-collagenous matrix proteins of the organic phase. The second type is the free or ‘unbound’ water that fills the dentinal tubules and other porosities in the dentin matrix. Free water is associated with inorganic ions such as calcium and phosphate, aiding in their transport within the dentin matrix (Kishen, 2006). When dentin is compressed, the water-filled dentinal tubules are compressed, and the water is squeezed out in the direction of the dentinal tubules. This water movement within the material is a possible mechanism for toughening dentin (Kishen & Asundi, 2001). Water has a viscosity, requiring additional energy to carry it through the dentinal tubules, leading to dual effects in hydrated dentin: (a) an inherent plasticity effect and (b) distinct strain responses in directions parallel and perpendicular to the dentinal tubules. Loss of water from the dentinal tubules and pulp space diminishes these water-induced effects, increasing dentin stiffness and reducing plasticity. Fully hydrated dentin demonstrates significantly higher crack-initiation toughness and crack-growth toughness compared to dehydrated dentin (Kinney et al., 2003).

Collagen Hydration and Mechanical Properties of the Tooth

Collagen microstructure and hydration are critical factors contributing to the fracture toughness of dentin. Moisture content profoundly impacts collagen's properties, with dry collagen being brittle and stiff, exhibiting an elastic modulus of about 6 GPa. Rehydration progressively softens the collagen (Kinney et al., 2004). Studies have shown that during rehydration, a monolayer of water molecules adsorbs to the surface of hydroxyapatite via hydrogen bonds, with additional water held by weak van der Waals forces and laws of intermolecular attraction and repulsion (Kinney et al., 2003).

In normal dentin, the interacting water molecule is an integral part of the collagen structure. When water content exceeds two molecules per tripeptide, the molecule starts to swell. At this level of hydration, water acts as a plasticizer, keeping the matrix soft and flexible. The collagen fibrils in the dentin are made up of smaller microfibrils separated by spaces filled with water (Kishen & Asundi, 2001). The surface tension forces of water and other molecular forces like interpeptide hydrogen bonds and van der Waals forces allow the collagen fibers to slide along each other and deform plastically under load. After the end of the masticatory force, these forces pull the collagen fibers back, restoring the spatial shape of the dentin and ensuring tooth elasticity (Huang, 1992).

Dehydration leads to the loss of these interfibrillar spaces and shrinkage of the overall fibril diameter. Collagen fiber chains contact each other, forming molecular associations that cannot be formed in an aqueous environment. These interpeptide forces stabilize the structure of dried collagen and increase its stiffness. It has been shown that the loss of free water compromises the viscoelastic behavior of dentin (Bajaj, 2006). Kinney et al. (2004) used nanoindentation-based experiments showing that dry dentin exhibited an elastic modulus of 23.9 GPa, while wet dentin exhibited an elastic modulus of 20 GPa. Kishen and Asundi (2001) concluded that the presence of water in hydrated dentin resulted in a stress-strain response characteristic of tough material, while the loss of free water resulted in stiffening and brittle material response. A significant increase in stiffness and a decrease in toughness were also reported after dehydration at 20°C for seven days (Huang, 1992).

Dentin Aging and Sclerotic Dentin

Dentin aging and the formation of sclerotic dentin also influence dentin's mechanical properties and toughening mechanisms (Kinney et al., 2005; Weber, 1974). A comparative study of normal, dehydrated, and sclerotic dentin showed no significant differences in elastic parameters between normal and sclerotic dentin, though the level of hydration in both groups was similar. Sclerotic dentin showed no plasticity and significantly higher brittleness, with a 20% reduction in fracture toughness (Kinney et al., 2005). This could be partially explained by mineral changes in dentin followed by the occlusion of dentin tubule lumens. Filling the tubules reduces stress concentration in intertubular dentin, lowering the tendency for microcrack nucleation, which in turn reduces dentin's fracture toughness.

Conclusion

Human dentin is a dynamic, complex composite-like structure. Its multiple elements at the nano and microscopic levels provide unique mechanical behavior in response to occlusal loads. Hydration of dentin is one of the critical factors affecting its mechanical parameters. Changes in its structure due to aging or clinical intervention have serious impacts on dentin's mechanical behavior. The elastic properties of dentin do not fully explain its response to cyclic loading. Further research on toughening mechanisms present in dentin are important for better understanding on how dentin withstands various loading conditions and remains stable over decades of functioning.

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ORCID ID and authors contribution

0009-0005-5012-5228 (B,C,D) Petro Mazur

0000-0003-3410-3043 (B,C,D) Iryna Khodzinska

0000-0002-1367-9580 (B,C,D) Natalia Markova

0000-0002-0424-3590 (A,B,C,D,F) Anatolii Savychuk

A – Work concept and design, B – Data collection and analysis, C – Responsibility for statistical analysis, D – Writing the article, E – Critical review, F – Final approval of the article.

REFERENCES

Angker, L., Watson, P., Watson, J., Haake, S., & Miller, C. (2004). Correlating the mechanical properties to the mineral content of carious dentine—A comparative study using an ultra-micro indentation system (UMIS) and SEM-BSE signals. Archives of Oral Biology, 49(6), 369-378.

Arola, D., Gao, S., Zhang, H., & Masri, R. (2017). The tooth: Its structure and properties. Dental Clinics of North America, 61(4), 651-668. https://doi.org/10.1016/j.cden.2017.06.001

Bajaj, D. (2006). Age, dehydration, and fatigue crack growth in dentin. Biomaterials, 27(14), 2507-2517.

Berkovitz, B. K. B. (2002). Oral Anatomy, Histology, and Embryology (3rd ed.). Mosby.

Carter, J. M. (1983). Punch shear testing of extracted vital and endodontically treated teeth. Journal of Biomechanics, 16(10), 841-848.

Dietschi, D. (2007). Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of literature – Part 1. Quintessence International, 38(9), 735-747.

Dietschi, D. (2008). Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of literature – Part 2. Quintessence International, 39(2), 93-112.

Gao, H., Ji, B., Jager, I. L., Arzt, E., & Fratzl, P. (2003). Materials become insensitive to flaws at nanoscale: Lessons from nature. Proceedings of the National Academy of Sciences, 100(11), 5597-5600.

Gupta, H. S., Seto, J., Wagermaier, W., Zaslansky, P., Boesecke, P., & Fratzl, P. (2006). Cooperative deformation of mineral and collagen in bone at the nanoscale. Proceedings of the National Academy of Sciences, 103(47), 17741-17746. https://doi.org/10.1073/pnas.0604237103

Hayashi, M., Harada, A., & Tanaka, M. (2008). Static and fatigue fracture resistances of pulpless teeth restored with post–cores. Dental Materials, 24(12), 1178-1186.

Huang, T.-J. (1992). Effects of moisture content and endodontic treatment on some mechanical properties of human dentin. Journal of Endodontics, 18(5), 209-215.

Kahler, B. (2003). Fracture-toughening mechanisms responsible for differences in work to fracture of hydrated and dehydrated dentine. Journal of Biomechanics, 36(6), 229-237.

Kerekes, K., & Tronstad, L. (1979). Long-term results of endodontic treatment performed with a standard technique. Journal of Endodontics, 5(3), 83-86.

Kinney, J. H., Hauptfuehrer, J., Breunig, T. M., & Ritchie, R. O. (2004). Resonant ultrasound spectroscopy measurements of the elastic constants of human dentin. Journal of Biomechanics, 37(3), 437-441.

Kinney, J. H., Nalla, R. K., Pople, J. A., Breunig, T. M., & Ritchie, R. O. (2005). Age-related transparent root dentin: Mineral concentration, crystallite size, and mechanical properties. Biomaterials, 26(16), 3363-3376. https://doi.org/10.1016/j.biomaterials.2004.09.010

Kishen, A. (2006). Mechanisms and risk factors for fracture predilection in endodontically treated teeth. Endodontic Topics, 13, 57-83.

Kishen, A., & Asundi, A. (2001). Analysis on the nature of thermally induced deformation in human dentine by electronic speckle pattern interferometry (ESPI). Journal of Dentistry, 29(8), 531-537.

Kishen, A., & Vedantam, S. (2007). Hydromechanics in dentine: Role of dentinal tubules and hydrostatic pressure on mechanical stress–strain distribution. Dental Materials, 23(12), 1296-1306.

Koester, K. J. (2008). The effect of aging on crack-growth resistance and toughening mechanisms in human dentin. Biomaterials, 29(7), 1318-1328.

Kruzic, J. J., Nalla, R. K., Kinney, J. H., & Ritchie, R. O. (2003). Crack blunting, crack bridging and resistance-curve fracture mechanics in dentin: Effect of hydration. Biomaterials, 24(26), 5209-5221.

Nalla, R. K., & Kinney, J. H. (2003). Effect of orientation on the in vitro fracture toughness of dentin: The role of toughening mechanisms. Biomaterials, 24(24), 3955-3968.

Pathways of the Pulp. (2005). Mosby.

Pietrokovski, J., & Lantzman, E. (1973). Complicated crown fractures in adults. Journal of Prosthetic Dentistry, 30(4), 801-807.

Reeh, E. S. (1989). Reduction in tooth stiffness as a result of endodontic and restorative procedures. Journal of Endodontics, 15(11), 512-516.

Seltzer, S. (1999). Long-term radiographic and histological observations of endodontically treated teeth. Journal of Endodontics, 25(12), 820-828.

Tonami, K., & Takahashi, H. (1997). Effects of aging on tensile fatigue strength of bovine dentin. Dental Materials Journal, 16(2), 156-169.

United Nations. (2003). World population prospects: The 2002 revision. Volume II: Sex and age distribution of populations. New York: United Nations.

Van der Graaf, E. R., & Ten Bosch, J. J. (1990). The uptake of water by freeze-dried human dentine sections. Archives of Oral Biology, 35(9), 731-739.

Weber, D. F. (1974). Human dentine sclerosis: A microradiographic survey. Archives of Oral Biology, 19(2), 163-169.

Опір тріщинам і механізми зміцнення в людському дентині: погляд з позицій біомеханіки

Петро Мазур, Наталя Маркова, Ірина Ходзінська, Анатолій Савичук

Кафедра стоматології дитячого віку НУОЗ України імені П.Л. Шупика, Київ, Україна

Address for correspondence:

Savychuk Anatolii

E-mail: anatolii.savychuk@gmail.com

Анотіція: *опір утворенню тріщин у дентині є вагомим механізмом для підтримання структурної цілісності вітального або ендодонтично лікованого зуба, особливо в умовах, коли старіння і реставраційні втручання підвищують його механічну вразливість. У цій статті досліджуються біомеханічні властивості дентину, зосереджуючи увагу на внутрішніх механізмах зміцнення, таких як відхилення тріщин, мостування та мікророзтріскування, які сприяють зменшенню поширення тріщин. Композитоподібна структура дентину, що складається з мінералізованих колагенових фібрил у гетерогенній матриці, забезпечує баланс між жорсткістю та гнучкістю, чинячи опір багатократним циклічним навантаженням в умовах специфічного середовища у ротовій порожнині. Обговорюється вплив дегідрації дентину, вікових змін і утворення склеротичного дентину на його опір утворенню тріщи. Ґрунтовне розуміння механізмів зміцнення дентину є важливим для оптимізації клінічних підходів, спрямованих на забезпечення тривалого успіху стоматологічного лікування.*

Ключові слова: дентин, біомеханіка, фізіологія, етіологія, лікування