International Journal For Advanced Research In Science & Technology
A peer reviewed international journal www.ijarst.in
IJARST
ISSN: 2457-0362

The mechanical characteristics of human teeth: a literature review

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Abstract

Bronze teeth are a mechanical representation of actual teeth. Similar to the mechanical characteristics of a hard metal, these materials exhibit an internal gradient. Human teeth are able to effectively masticate because of these characteristics. The foundation for the creation of restorative materials is a deep familiarity with the mechanical characteristics of human teeth and dental materials. In order to get a better knowledge of the mechanical characteristics of human teeth, this research analysed the literature on the elastic properties, dynamic mechanical properties (visco-elasticity), and fracture mechanical properties of enamel and dentin.

Keywords:

Dentin, Enamel, Fracture Toughness, Fatigue Crack Growth, Mechanical Property.

INTRODUCTION

Bronze teeth are an approximation of the mechanical qualities of real teeth. A tooth's outside and inside have vastly different mechanical characteristics, with the former resembling those of a hard metal. These atri buttes are what give teeth their formidable biting power. To cut, lacerate, and grind food, natural teeth have the special mechanical qualities necessary for mastication. 2 There is no material that has been discovered that can fully replace human teeth in terms of their biological and mechanical qualities. The structure, mechanical characteristics, and biocompatibility of natural teeth outshine those of any dental restorative material now available, including composite resins, ceramics, and dental metals. Dental restoration materials research relies on a thorough understanding of the mechanical characteristics of natural teeth, which may be used as a benchmark against which novel dental materials can be judged. 3 This article reviews the mechanical properties of human teeth, including their elastic qualities, dynamic mechanical properties (viscos-elasticity), and fracture mechanical prop retires. The structure and content of teeth are what set their mechanical qualities. Enamel, dentin, cementum, and dental pulp are the four main components of a natural tooth. The first three of these make up the hard tissue, and each has its own distinct mechanical qualities. Table 1 shows the chemical make-up and morphology of teeth. The enamel rod, a 'keyhole' structure about 5 mm in diameter, runs perpendicular to the dentinal-enamel junk tion4, and is made up mostly of hexagonal prism hydroxyapatite crystals about 68 nm in length, 26 nm in diameter, and 2 nm in protein thick ness. 5 The hydroxyapatite crystals in the rod's core run perpendicular to the rod's axis, while the crystals on the rod's periphery make a 45° angle with the axis. 6

The rod sheath is formed when two crystals in the enamel meet at right angles, giving the enamel a 'fish-scale' or 'keyhole-like' look. The rod sheath, unlike the rest of the highly mineralized enamel, is hypo mineralized and contains more protein. As a result, the mechanical properties of enamel are anisotropic. Below the enamel is dentin, which protects the pulp chamber and root canals. Dentinal tubules are the microstructure of dentin and extend from the pulp to the cementum or enamel border of the tooth. Rich collagen fibers may be seen in both the peritubular and intratubular dentin. Peritubular dentin envelops the dentinal tubules. Dentinal tubules vary in size, number, and wall thickness from the periphery to the core of the tooth. 7 Cementum's cellular structure is very close to that of bone tissue, yet it's not as hard as dentin. Cementum is made up of collagen and noncollege proteins and apatite's, which are the major inorganic components and include callchum ion. There are two types of cementum, cellular and acellular. Cementum lamina forms the acellular cementum by adhering to the surface of the

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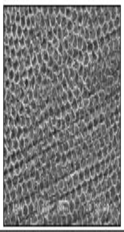
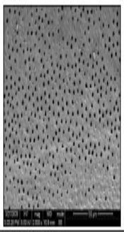
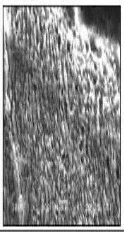
A peer reviewed international journal www.ijarst.in
ISSN: 2457-0362

Table 1 General information on the human tooth structure

Dental tissue	Enamel	Dentin	Cementum
Composition	96% inorganics, the rest are water and organics	65%–70% minerals, the rest are organics	45%–50% inorganics, 50%–55% water and organics
Microstructure	Enamel rods, enamel rod sheath	Dentinaltubule, peritubular dentin, intertubular dentin	Cellularcementum, acellularcementum
Microstructure chart			

Cementum that lies between the cervix and the apical third of the root is called the intermediate cementum, whereas the cellular cementum is found on the surface of the acellular cementum or alternatively with acelunar cementum at the apical third of the root. 8 The anisotropic mechanical characteristics of natural teeth are based on their distinctive gradient structure.

INDICATORS OF THE MECHANICAL PROPERTIES OF HUMAN TEETH

Teeth have mechanical qualities include elasticity, hardness, viscos elasticity, and fracture behaviour. Elasticity refers to the ability of a material to deform and then return to its original shape when an applied force is withdrawn. Natural teeth essentially have an elastic modulus (the ratio of normal stress to normal strain), a shear modulus (the ratio of shear stress to shear strain), and a Poisson's ratio (ratio of transverse contraction strain to longitudinal extension strain in the direction of the stretching force). By far the greatest research has been done on the elastic modulus. 9 Hardness is a measure of a substance's resistance to elastic deformation, plastic deformation, and destruction, and it also indicates how soft or hard a material is. 10 The introduction of new technologies has allowed for the precise assessment of hardness at various points along an enamel rod, marking a transition from macroscopic to micro scope measurements of the hardness of real teeth. 4 The term "viscos-elasticity" is used to describe materials that, when subjected to an external force, display both viscous and elastic behaviours. The composite modulus, which incorporates the storage modulus and the loss modulus, is the index used to describe the viscoelasticity of a material. 11 Research into the durability and crack development law of materials having crack-type flaws relies on a knowledge of their fracture mechanical characteristics. Characterizing the fracture toughness and fatigue crack development rate and defining the crack growth law have been the subject of 12 studies on the fracture mechanical characteristics of teeth. These mechanical property indices provide the basis for learning about and creating novel dental restorative materials, and they are used as criteria for assessing natural teeth.

ENAMEL AND DENTIN COMPARE IN ELASTICAL PROPERTIES AND HARDNESS

When measuring the elastic modulus and hardness of natural teeth, researchers often use the same testing protocol and utilize the same set of samples. The findings of the elastic modulus and hardness tests on enamel and dentin are summarized below.

Modulus of elasticity and hardness

The stiffness of a material is quantified by its elastic modulus, sometimes called Young's modulus. This number represents the ratio of stress to strain in an elastic condition. An individual's tooth's capacity to withstand elastic deformation is represented by the value of Young's modulus. 13 The resistance of a material's surface to compression deformation and fracture is often measured by its hardness. There is both static and dynamic tooth hardness. 14 Most often, scientists will perform a static indentation hardness test to determine a material's characteristics. 15 Many people refer to Vickers hardness, Knoop hardness, and nano-hardness when talking about static indentation hardness. Calculating the indentation force per unit area under bare testing conditions yields the Vickers hardness. The indenter has the shape of a diamond square pyramid with 1366-degree angles on opposing sides. In this case, the value is the fraction of the load over the indentation's surface area. 13 Knoop hardness indenters are likewise diamond square pyramids, but their base is made by two unequal opposed angles. The Knoop hardness is defined as the load divided by the projected contact area. 13 In the range of 10 millinewtons to 10 newtons, materials are said to have a microhardness of that range. 14 Measured on the micron or nanometre scale, nano-hardness describes the resistance of a material to indentation with a load of less than 700 MN. 16

Techniques for determining enamel and dentin's hardness and elastic modulus

The nano-indentation technique is the gold standard for measuring the hardness and elastic modulus of

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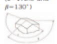
ISSN: 2457-0362

enamel and dentin, since it allows for the gathering of data in the nano-scale range with the use of a Perkovich indenter and a spherical indenter, or using atomic force microscopy (AFM). Two instruments, the conical Vickers hardness tester and the Knoop hardness indenter, are used to determine the material's hardness. The micro indentation system may be used to evaluate the hardness or elastic modulus of a material. Table 2 provides a comparison of these approaches.

Oral enamel's hardness and elastic modulus

Generally speaking, studies on the mechanical characteristics of teeth have focused on enamel hardness and elastic modulus. Traditional research methods treated enamel as if it were an isotropic material, meaning that its characteristics would be the same in whatever orientation. Anisotropic mechanical qualities were previously unknown;however, this has changed as researchers get a better grasp of tooth structure. 17–29 Science has uncovered some interesting findings about the axial

Table 2 Common methods of measuring and calculating hardness and elastic modulus[14–16]

Hardness test	Shape of indenter	Load/N	Depth of indentation/ μm	Measuring method	Calculation formula	Applied range	Advantages and disadvantages
Vickers hardness	Diamond square, pyramid formed by an opposite angle of 136° 	10–1 200, may be <0.25, <2 or <10, microhardness	1–100	Measure the diagonal length of indentation $D=(d_1+d_2)/2$	$H_V=1.854P/D^2$	Measure the macrohardness and microhardness of hard tissue of teeth	When load changes, the geometry of indentation remains similar; but on different scales, the indenter geometry cannot be similar
Knoops hardness	Diamond square, pyramid formed by two unequal opposite angles ($\alpha=172.5°$ and $\beta=130°$) 	2–40, <0.01, <2 or <10, microhardness	0.3–30	Measure the long diagonal length of indentation	$H_K=0.102\times14.23P/L^2$	Measure the macrohardness and microhardness of hard tissue of teeth	The sensitivity of measuring the variation of teeth microstructure is higher than Vickers hardness
Berkovi-chardness	Triangular pyramid forming an angle of 65.3° between centreline and conical surface	<0.5, <0.700 nanohardness	0.001–1	Real-time depth and load measurement of indentation	$H=\frac{P_{max}}{A}$ $\frac{1}{E_r}=\frac{1-V_i^2}{E_i}$ $E_r=\frac{S\sqrt{\pi}}{2\sqrt{A}}$ $S=\frac{dP}{dh}$	Measure the microhardness and nanohardness of hard tissue of teeth, as well as the elastic modulus	It can be real-time depth and load measurement of indentation; hardness and elastic modulus can be measured at the same time; on very small scales, the indenter geometry can be similar, and the results can be compared with Vickers hardness

A is the predicted contact area; D is the indentation's diagonal length in millimetres; d1 is the indentation's long diagonal; and d2 is the indentation's short diagonal. Elastic indenter modulus, abbreviated as Eid; lower elastic modulus; Sample elastic modulus, denoted by Es; Knoop hardness (HK), defined as the load-to-contact-area projection ratio; Vickers hardness, measured in kilograms per square millimetre squared (HV); Diagonal length, L; P = force per kilogram; Pmax = safe working load S, inertia under load; Poisson's indenter ratio (Vi) and sample ratio (Vs).

characteristics of the enamel of the second molar of the maxilla in cross section, in their study of enamel's mechanical qualities, Coy et al. 30 observed that the position, chemical composition, and arrangement patterns of the enamel rods all have a role. Enamel's highest hardness (3.5 GA) is found on its surface, and it diminishes progressively with increasing depth; nonetheless, enamel maintains a consistent hardness of 2-2.5 GA at a distance of 100-600 mm from the dentin enamel junction (DEJ). 31 Both nano-hardness and elastic modulus decrease progressively from the enamel surface to the dentin-enamel junction (DEJ), and are favourably linked with calcium concentration. 24,30,32–39 Furthermore, the orientation of the enamel rod array is connected to enamel's hardness and elastic modulus. The enamel's anisotropic mechanical characteristics are well-known. It has been shown that various locations along the same rod provide notably varied outcomes for the same mechanical properties. 17,23,28–29,40 Research by Jang et al. 17 on the nano-mechanical anisotropy of enamel rods revealed that their heads had a much higher hardness and elastic modulus than their tails and axial cross-sections.

Analysis at the microscopic level reveals a spatial correlation function for the enamel's mechanical characteristics. 17 From the tip to the base of the same enamel rod, its hardness and elastic modulus diminish mainly because of a shift in the crystal array directions inside the enamel and the organic components. 4,38,41 Values for the mechanical property index are known to differ from study to study (Table 3). External variables, such as the measurement equipment, the form of the indenter, the applied force, the nature of the samples, and the orientation of the enamel rod, may account for the discrepancy in the findings of tooth hardness and elastic modulus amongst research groups. While tooth hardness and elastic modulus were affected somewhat by environmental moisture levels and tooth location, neither factor had a significant impact on these properties. The most popular nano-indentation systems are the Stroboscope indenter system (Histrionic, Minneapolis, MN, USA), the Nano indenter XP (MTS Systems Corp, Minneapolis, MN, USA), and the CSM indentation tester (ultra-micro-indentation system (UMIS-2000; Commonwealth Scientific and Industrial Research Organisation, Campbell, Australia) with a Perkovichindenter) (CSM, Pseud, Switzerland). 42–52 The MTS provides the most accurate measurements of any of the current micro measuring devices (hardness of 6–7 GpA, elastic modulus of 120–130 GpA). With the UMIS, we may take readings of oral tissue in a hydrated setting that mimics the in vivo condition. 53 However, because measuring the hardness of a single crystal would need over a hundred indentation sites on each surface, this technology

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ISSN: 2457-0362

does not allow complete control over the exact location of indentation. 54 With the use of AFM, the Stroboscope indenter system can get exact measurements and photographs of the indentation point on the nanometre scale. 4 The effects of length on mechanical characteristics

Table 3 Results of enamel hardness and elastic modulus measurement

Author	Method and indenter	Site	Load	Hardness/GPa	Elastic modulus/GPa
E Mahoney (2000)	UIMS, Berkovich indenter	1st molar	50 mN 150 mN	4.88±0.41 4.87±0.29	80.94±6.65 79.77±8.86
S Habelitz (2001)	Nanoindentation, sharp cube shaped diamond indenter	3rd molar	1500 μN	Parallel to rod 3.9±0.3; Perpendicular to rod 3.3±0.3; Head 4.3±0.4; Middle 3.7±0.4; Tail 3.9±0.4	Parallel to rod 87.5±2.2; Perpendicular to rod 72.7±4.5; Head 88.0±8.6; Middle 88.0±8.6; Tail 86.4±11.7
SF Ang (2009, 2010)	Nanoindentation, spherical indenter	3rd molar	5–11 mN 0.4 mN	 5.7±0.3	123 86.4±11.7
B He (2010)	Knoop hardness indenter	3rd molar	50 g	Lingual 352.5±23.3; Buccal 351.7±42.1	
Y-R Jeng (2011)	Nanoindentation, Berkovich indenter	Premolar		Head 5.01±0.27; Tail 4.52±0.18; Cross-section 4.58±0.23	102.56±3.01; 97.30±3.96; 97.72±3.09
JL Cuy (2002)	Nanoindentation, Berkovich indenter	2nd, 3rd molar	400 or 800 nm in depth	Surface>6; Near DEJ<3	Surface>115; Near DEJ<70
ME Barbour (2003)	Nanoindentation, Berkovich indenter	3rd molar	3 000 μN 5 000 μN 7 000 μN	4.81±0.15 4.77±0.13 4.75±0.12	99.6±1.8 101.9±1.6 105.2±1.3
EK Mahoney (2004)	UIMS, Berkovich indenter	1st molar	20 mN	3.66±0.75	75.57±9.98
J Ge (2005)	Nanoindentation, Berkovich indenter	3rd molar	1 000 μN 300 μN	Rod 4.3±0.8 Sheath 1.1±0.3	Rod 83.4±7.1 Sheath 39.5±4.1
LH He (2006, 2009)	Nanoindentation, Berkovich indenter and spherical indenter	Premolar	450 mN 25 mN	Surface 5±0.45; Cross-section 4.5±0.45 Inner layer 3.05±0.41; Outer layer 3.98±0.19	Surface 60–100; Cross-section 40–80 Inner layer 56.80±5.39; Outer 82.67±1.80
B-B An (2012)	Nanoindentation, Berkovich indenter	Molar	3 mN		Surface 80; Middle layer 68; Inner layer 60
A Braly (2007)	Nanoindentation, Berkovich indenter	3rd molar		6–7	120–130
S Roy (2008)	Conical Vickers tester	3rd molar	160 g	Near surface 3. 5; Near DEJ 2–2.5	
S Park (2008)	Nanoindentation, Berkovich indenter and Vickers hardness tester	3rd molar		Young: inner 3.1; middle 3.5; outer 4.1 Aged: inner 3.0; middle 3.4; outer 4.0	75; 82; 87 79; 90; 100

The DEJ is the area where the upper and lower jaws meet; the UIMS is the ultra-micro-indentation system.

Because of its complex organization and anisotropy, enamel displays a wide variety of gradients.

28 The indenter's form has a role in the accuracy of the measurement. Unlike with the Perkovich indenter, where the hardness grows linearly with contact depth and tension, the hardness of a sphere indenter increases gradually. Consistent results at a given contact depth are not always produced using the same indenter. 29 Hardness and elastic modulus values decrease with increasing load because energy is lost as heat and light via fractures and brittle fracture, as measured by the same instrument. 50 Both the hardness and elastic modulus of old permanent dental enamel are greater than those of juvenile tooth enamel, as assessed by Park et al. 21,28,53-56. Over time, wear from the cusps causes enamel to thin and thinned areas to become more noticeable. Old permanent teeth have greater values of hardness and elastic modulus because their mineral content rises with age. Enamel rods' mechanical characteristics change in a variety of ways. The elastic modulus is (87.564.5) GpA and the hardness is (3.960.3) GpA when the indentation direction is parallel to the array direction of the rods. When the indentation direction is parallel to the rod array direction, these values are (72.764.5) and (3.860.4) GpA, respectively. 4 These findings demonstrate that increases in hardness and elastic modulus may be achieved along a perpendicular axis. The macroscopic and microscopic measurement findings give a global and local knowledge of the mechanical properties of enamel, which may be used as a basic mechanical reference in the production of artificial enamel by tissue engineering.

Dentin's hardness and elasticity

Studies of dentinal mechanical characteristics, like those of enamel, have concentrated on the benefits of the microstructures. Dentin, on the other hand, has a more intricate framework. Dentinal tubule location, density, and orientation, as well as collagen fibre orientation, and mineral phase average density, all play a role in determining dentinal mechanical qualities. 3 Studies have shown conflicting outcomes when examining the mechanical characteristics of dentin (Table 4). Micro-hardness of dentin was measured and shown to be low close to the DEJ, to grow fast to a peak, and to decline slowly towards the pulp cavity in a study by Wang et al. Changing hardness and elastic modulus have

Table 4 Mechanical properties of dentin

Author	Direction and Indenter	Tooth Position	Load	Hardness/GPa	Elastic modulus/GPa
E Mahoney (2000)	UIMS, Berkovich indenter	1st molar	50 mN 150 mN	0.95±0.11 0.90±0.09	20.55±2.00 19.22±1.84
M Balcooh (2001)	Nanoindentation, sharp cube shaped diamond indenter, dry environment	Root dentin	30 000 μN	Intertubular dentin 0.5–0.8; Peritubular dentin 2.2–2.6	Intertubular dentin: 24–25; Peritubular dentin: 40–45
L Angker (2003)	UIMS, Berkovich indenter, moist environment	1st molar, dentin of crown	25 mN	Dentin nearest the pulp wall 0.52±0.24; Dentin in the middle area 0.85±0.19; Dentin nearest dentinoenamle junction 0.91±0.15	Dentin nearest the pulp wall 11.59±3.95; Dentin in the middle area 17.06±3.09; Dentin nearest dentinoenamle junction 16.33±3.83
JH Kinney (2004)	Resonant ultrasound spectroscopy	3rd molar, dentin of crown	Vibration frequency: 0.5–1.4 MHz		Hydrated: 25.1 Dry: 28.1
SR Cohen (2008)	Nanoindentation, sharp cube shaped diamond indenter, dry environment	Molar		Lumen edge 4±0.5; Between lumen and mid-peritubular dentin 4.7±0.8; Between mid-peritubular dentin and intertubular dentin 1.8±0.4; Within intertubular dentin 1.2±0.2	
W Franzel (2009)	Nanoindentation	Molar		0.78±0.1	22.4±2.6
D Ziskind (2011)	Nanoindentation, Berkovich indenter	3rd molar, premolar, dry environment	200–300 μN	Peritubular dentin 1.34±0.5; Intertubular 0.60±0.2	Peritubular dentin 29.3±6.7; Intertubular dentin 17.4±3.5
YL Chan (2011)	Nanoindentation	Molar		1±0.1	19±2
LE Bertassoni (2012)	UIMS, Berkovich indenter	3rd molar	50 mN	Dry environment 1.43±0.12; Hydrated environment 0.88±0.11	
C-F Han (2012)	Nanoindentation, dry environment	Molar		10° to dentinal tubule: 0.588; 80° to dentinal tubule: 0.521	10° to dentinal tubule: 16.15; 80° to dentinal tubule: 13.28

Ultra-Indentation Microsystem (UIMS), or very small indenters.

regression to the mean; a linear relationship according to the data.

53 It is important for clinical tooth preparation that the middle dentin region has a greater hardness and elastic modulus than the peripheral dentin regions. Using atomic force microscopy (AFM), Cohen et al. 3 evaluated the microstructural mechanical characteristics of dentin by measuring the hardness and elastic modulus of the lumen edge, peritubular dentin, peritubular-intratubular junction (PIJ), and intratubular dentin. The findings demonstrated that mechanical microstructures differ throughout the dentin. Dentinal tubule cavity wall hardness

eventually lowers to intratubular dentin hardness as mineral content progressively diminishes. Dentin's mechanical qualities shift depending on its mineral composition. The Young's modulus of highly mineralized peritubular dentin is 40–42 GA, whereas that of weakly mineralized intratubular dentin is 17 GpA. 58 Peritubular dentin (PTD) hardness displays a clear gradient fluctuation with the difference in mineral concentration towards the pulp chamber. As far as we can tell, the DEJ shows no such variation.3 Anger et al. 59 examined the connection between carious dentin's mechanical characteristics and its mineral components, and they discovered that a drop in elastic modulus and hardness is strongly connected to, and has an exponential relationship with, mineral content. Dentin becomes more see-through and mineral-rich with age, while its crystals get finer. However, there is little to no variation in the elastic modulus. Because the organic content of dentin has diminished and mineral deposits have been formed in the dentinal tubules, microcracks have emerged in the dentin and are growing without any bending or giving. 60 Dentin's hardness and elastic modulus are remarkably stable throughout time. However, mineral deposition makes dentin more brittle, reducing its buffer capacity and increasing the likelihood of tooth fracture and cracking. More research is needed into the causes, risk factors, and remedies for dentin brittleness. Dentin's mechanical characteristics are heavily influenced by the tissue's internal structure and composition in addition to its external environment. A research indicated that in a hydrated setting, both the elastic modulus and hardness decreased by 35% and 30%, respectively. 61 Dentin is shown to be anisotropic in a wet environment, as verified by Kinney et al. 62.

Values of E are somewhat greater in the perpendicular to tubules direction, at 25.1 GpA, than in the parallel to tubules direction, at 24.7 GpA. However, in a dry environment, dentin acquires an isotropic E528.1 GPa. 62 Dentin's visco-elastic response is shown to be greater in dry settings, while its hardness and elastic modulus are found to be lower. 63 The results of these analyses suggest that environmental factors have a significant impact on the mechanical characteristics of dentin. Therefore, environmental issues need to be included in scientific investigations. Dentin's macro- and micromechanical characteristics change depending on its surrounding conditions. More study is needed to determine whether or not environmental factors affect a material's resistance to external pressures, fracture development, and growth. However, there is still need for development of recommendations on the use and refinement of clinical practices, particularly for teeth that have had root canal therapy. Following treatment, the mechanical characteristics of teeth are significantly impacted by the presence of water. Because of this, lubricating media may need to be included in future treatments.

DIFFERENTIAL MECHANICAL PROPERTIES OF ENAMEL AND DENTIN

Measurements of the storage and loss moduli, as well as the viscoelasticity of a material, may be obtained by an examination of its nano dynamic mechanical properties.

46 The storage modulus characterizes the elasticity of a material, whereas the loss modulus characterizes its viscosity. 46 The elastic part of deformation is represented by the storage modulus, which is a measure of the energy stored owing to elastic deformation throughout the deformation process. The viscous part is represented by the loss modulus, which quantifies the amount of energy lost as heat during deformation owing to viscosity. When the storage modulus is substantially larger than the loss modulus, materials mostly display elastic deformation in the solid state, whereas materials primarily exhibit viscous deformation in the liquid state. The material is in a gel like semisolid state when the storage modulus is equal to the loss modulus. The definitions of the storage modulus (E9) and the loss modulus (E0) are as follows:

$$E' = \frac{k_s\sqrt{\pi}}{2\sqrt{A}} \quad E'' = \frac{\omega c_s\sqrt{\pi}}{2\sqrt{A}} \quad \tan\delta = \frac{\omega c_s}{k_s}$$

where A represents the expected contact area, v represents the force frequency, C represents the damping factor, and k represents the stiffness of the system. By employing modulus mapping, Baloch et al. 64 (AFM + force-displacement sensor = 1/4 DEJ width) determined that the storage modulus of enamel at the DEJ was 51-74 GPa (average: 63 GPa). Nearly half as wide as the PTD is the peritubular-intratubular junction. There is more mineralization and a higher mean storage modulus in the PTD than in the ITD. Comparatively, the mean storage modulus of peritubular dentin (PTD) is 48 GPa, whereas that of intratubular dentin (ITD) is 21 GPa. Because of the large concentration of organic collagen fibers in dentin's ITD, this layer has a higher loss modulus and better capacity to dissipate energy than enamel and PTD. 62 If dental

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ISSN: 2457-0362

tissue has a high loss modulus, it is very viscous and difficult to break. The mean composite and storage moduli (19.6 and 19.2 GPa, respectively) are much lower than those of the PTD, according to research by Ryu et al. 46 on the dynamic mechanical characteristics of the PTD and ITD in a wet environment (31.1 and 30.3 GPa, respectively). The structure and content of dental tissues have the greatest impact on the storage modulus, which is a measure of the energy stored in the elastic deformation of dental tissue. The storage modulus is mostly unaffected by the loading frequency and quasistatic load. When the indentation load and loading frequency are both decreased, the loss modulus rises to indicate the energy dissipation coming from the viscous deformations of tooth tissue. 61 Dentin has been the primary focus of the little available research on the dynamic mechanical characteristics of hard dental tissue. There hasn't been any documented research on enamel yet. A lot of dental tissue is made of inorganic materials, and it has elastic characteristics and viscos-elasticity that are beyond the scope of this study. However, a highly developed measuring system is required for the measurement of viscos elasticity. This is because this property can only be determined by continuously monitoring the elastic and plastic deformation of nano dental structures and the detection of energy variation in real time. We anticipate that when new methods of measurement are developed, the dynamic mechanical characteristics of oral tissue will be better studied in a wide range of settings and under a wide range of loads. To further explain the process of oral tissue fracture, it is possible to combine evaluations of dynamic and fracture mechanical characteristics.

THE MECHANICAL PROPERTIES OF ENAMEL AND DENTIN AT FRACTURE

Indices of mechanical properties of fracture and techniques for measuring them Natural teeth have a high frac true toughness and a low frac true fatigue crack growth rate because to their mechanical features. The resistance of a substance to cracking is measured by its fracture toughness. Higher values for fracture toughness in dental tissue mean that the tissue is more resistant to cracking and can withstand a bigger force before cracking at a critical size. 12 When determining fracture toughness, it is common practice to apply a quasistatic load to a specimen, observe its response in terms of crack growth and fracture toughness, measure the crack length using the compliance method56, and then combine the load values with the relevant frac true mechanical property formulas. Dental tissue fracture resistance may be measured in three ways: flexural strength, fracture strength, and fracture energy. Because crack tips must occur in this state in order to determine KIC, the fracture toughness KIC is the critical value of the stress intensity factor KI for in-plane deformation and small-scale yielding. 12 Typically, notched bending specimens at three or four points and compact tension specimens are employed. When testing for three-point bending with a notch, the tester indenter presses down on the top center of the specimens to induce tensile stress, which causes fractures to form at the location of the lower notch. 65 The flexural strength, fracture strength, and fracture energy are all measured on four-point bending specimens. 66 Teeth are encased in resin for compact stress specimens, and their insertion location is determined using finite element analysis. 67–68 Tensile loads may be applied by inserting pins via predrilled holes in the square resin. Tensile tension creates a crack at the notch's location, and the crack widens as the stress increases. 69 Among the three stages that make up the fatigue process—crack initiation, steady crack extension, and fast crack propagation—the last is by far the most significant. 70–71 How well a fracture can extend itself without propagating farther without fail is a key factor in how long it will take for the whole tooth tissue to fatigue. The Paris formula is used to describe fatigue fracture development in tests with dental tissue.

$$\frac{da}{dN} = C(\Delta K)^m$$

The fatigue crack growth rate is then computed by taking the crack extension increment da, dividing it by the number of cycles den, and recording the result. The material constants C and m are connected to things like tooth tissue, the stress ratio, and the environment, whereas K is the stress intensity calculated from the crack size, specimen size, and load. Dental tissue fatigue crack growth is measured using the same specimen as fracture toughness. Tissue fractures at sites of notch growth as loads of increasing frequency and stress ratio are applied iteratively. 72 Optical microscopy and a compliance method are used to determine the crack's length. 63 Quantitative fracture topography is used to examine the fracture mechanism and fracture toughness. 73 Crack growth may also be measured using an indentation approach. 74

Linear elastic fracture mechanics (Kc) measurements may underestimate the

toughness of dentin, according to some studies, because of the presence of collagen fibers in the material.

67,75–76 Therefore, elastic-plastic fracture mechanics should be used to assess dentin's brittleness. 75

Crack Development Law of Enamel Most research on enamel's fracture mechanical characteristics, which are capped by enamel size, focuses on the crack growth law of enamel. First fractures form within the enamel at the hypocalcified EDJ and enamel tuft. 77 Using a micro-indentation method, Padmanabhan et al. 74 investigated the enamel fracture development law and discovered that crack resistance rises as crack length does. Unfortunately, the indentation approach could only yield fracture resistance and not crack toughness. Using a micron indentation method, we can see that the fractures are semi-circular in form and expand along the direction of the enamel rods from the perspective of microstructure. 69 Padmanabhan et al.74 used a fracture mechanics approach to demonstrate that enamel fractures spread along the rod sheath. In relation to the rods and hydroxyapatite crystals and protein shearing, the path of crack propagation makes an angle of a specific degree with the original fracture point. Using a fracture mechanical technique, researchers have calculated that the fracture toughness of both exterior and internal enamel is (0.6760.12) MPa? m0.5 and 1.13-3.93 MPa? m0.5, respectively. Incredibly high resistance to cracking is shown by the interior enamel. Resistance to fracture propagation rises from the surface inward, or from the outside to the inside. 78–79 Enamel and Hap are quite comparable in their crystallinity, chemical composition, and density, therefore Bajaj et al. 72 examined their fracture qualities. As these scientists suspected, fractures propagate around the rod's perimeter. Deflection, fracture bridging, and crack bifurcation are all phenomena that manifest themselves in decussated areas. These methods work together to make the material less prone to fracture formation, while Hap uses a different mechanism altogether.

Dentine's Fracture Resistance

When the crack development direction makes a sharp angle with the dentinal tubules, as was observed in the first research of fracture characteristics, dentin fracture is anisotropic.

80 The fracture property of dentin is linked to its complicated microstructure. Due to the absence of PTD, root dentin exhibits more fracture resisttrance than coronal dentin. Root dentin has a very anisotropic fracture behaviour, with the incremental lines being the weakest planes. Coronal dentin, on the other hand, breaks easily along the PTD and shows signs of being brittle. Fracture anisotropy is considerably reduced when highly mineralized PTD crosses with the incremental lines. 81 Crack extension increases dentin's resistance to fracture (rising R-curve behaviour). 54 For a fracture to widen, it must undergo an intricate process of internal and exterior toughening. Energy dissipation is principally characterized by the enormous number of microcracks near the crack tip, which is described by this internal toughening process. The crack's tip undergoes plastic deformation, which furthers the dissipation of energy. 76 Fracture bridging in intact dentinal ligaments leads to crack deflection and bifurcation, indicating the presence of an external toughening mechanism. These processes may reduce tension at the crack's tip and slow their expansion. 65

Dentinal fracture mechanical qualities are affected by a number of elements, including but not limited to moisture, age, indentation direction, and the dentin's complex microstructure.

82 Compared to dehydrated dentin, the average fatigue fracture development exponent of m513.361.1 is found in young permanent teeth's dentin (m518.862.8). Energy dissipation and resistance to fracture propagation are enhanced by crack bridging, crack deflection, and crack bifurcation in juvenile hydrated dentin. Less resistance to fatigue crack formation occurs in drier conditions. 56 Age has a substantial impact on dentinal crack formation; particularly, older dentin has lower initial toughness (Ko) and stable toughness (Kp) values compared with young dentin. 79 Dentinal tubules in developing dentin are virtually always unfilled with hydroxyapatite and seem open. Extreme fracture deflection caused by crack development in developing dentin lowers the severity of local stresses, preventing future crack formation. Simultaneously, microcracks form close to exposed dentinal tubules. The tips of the major cracks are not completely formed by the merging of the microcracks. Dentin ligaments that have not been ruptured lead to the development of crack bridges and halt the progression of cracks. There is no microcracking in the dentinal tubules that have closed. 81

CONCLUSIONS

Researchers have been looking at the microstructural mechanical characteristics of human teeth and the variables that affect such qualities. Despite the fact that no universal measurement conditions or methods have been established for this material, a few consistent characteristics have been noted. Both enamel hardness and elastic modulus show positive correlations with calcium concentration, and they decrease progressively from the enamel surface to the DEJ. The heads of the enamel rods have a much greater hardness and elastic modulus than the tails or axial cross section. In the perpendicular direction, the hardness and elastic modulus values are maximized. Dentin's hardness and elastic modulus gradually decrease as one moves closer to the pulp cavity. The Young's modulus of highly mineralized peritubular dentin is greater than that of less mineralized intratubular dentin. Dentin's mechanical properties are affected by its surrounding moisture level. Dentin study has made use of nano dynamic mechanical property analysis, which reveals the impacts of a moist environment rather clearly. The study of enamel requires further investigation. Crack resistance for enamel improves from the surface inward. Dentin's energy dissipation and fracture development resistance are aided by the processes of crack bridging, crack deflection, and crack bifurcation in young, hydrated dentin. The resistance to the formation of fatigue cracks is less under dry conditions. The Ko and Kp values of aged dentin are lower than those of young dentin. Dentinal tubule orientation is connected to fatigue crack development exponent.

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