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Mechanical Characterization of Dental Materials

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Abstract

The tooth is the only mineralized organ that is located partially internal and partially external to the human body. From materials science point of view, a tooth is a composite material with mineralized matrix and organic reinforcements. Human teeth act as a mechanical device during masticatory processes such as cutting,tearing and grinding of food particles. Its mechanical properties are due to its mineral composition and structural arrangement. A calcium phosphate apatite is the basic constituent of the enamel, typically as hydroxyapatite forms. The enamel mineral matrix of teeth is usually named as enamel apatite (EAP) or carbonated hydroxyapatite. The mineral phase consists primarily of calcium phosphate in the form of large hexagonal hydroxyapatite crystals that are both carbonated and defective. Human tooth is composed of three basic structural parts, namely enamel, dentine and dentine-enamel junction (DEJ) which has been characterized in terms of microstructure, phase analysis and compositional gradient. It has been observed that microindentation hardness varies from enamel to dentine with the highest hardness observed for enamel at the outermost surface (around 3.5GPa). Hardness values monotonically decreases with depth to less than 1GPa, measured at the interior dentine. Such a variation depends partially upon the mineral concentration in enamel and dentine, with a possible dependence also on local microstructural features such as enamel rod orientation and dentinal tubule density. Furthermore, the measured hardness variation is found to have a noticeable correlation with the compositional variation.

Keywords: Enamel, Dentine, DEJ, Mineralization, Microstructure

Introduction

Dental enamel is the hardest and most mineralized human tissue. Its physical and mechanical properties are due to its mineral composition and structural arrangement. A calcium phosphate apatite is the basic constituent of the enamel, typically as hydroxyapatite forms [1].

Apatite crystals are arranged in prismatic structures densely packed and perpendicular to the surface, and this structural disposition gives the tooth considerable mechanical resistance. The small amounts of enamel organic matter (structural proteins, lipids and carbohydrates), placed in the interprismatic spaces, can play an important role in the plasticity of such a rigid structure. However, the enamel is also a dynamic tissue that takes part in the transport of ions and solutions from the saliva as well as in demineralization and remineralization processes. Such dynamics properties depend on the porosity as well as on

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the electrochemical characteristics of the enamel [membrane potential and fixed charge) [2, 3].

Studies of the interaction of laser irradiation with dental enamel [4, 5] indicate changes affecting some of the general properties of the enamel. The most outstanding aspect of such interactions is the increase of the demineralization resistance shown by the irradiated dental enamel, however, the explanation for this is still under debate and could relate to other unresolved issues such as the dental caries mechanism or the laser-matter interaction [6, 9].

Elastic modulus and hardness

Mechanical properties of teeth were reflected in elastic modulus and hardness of dentine near the DEJ [8].

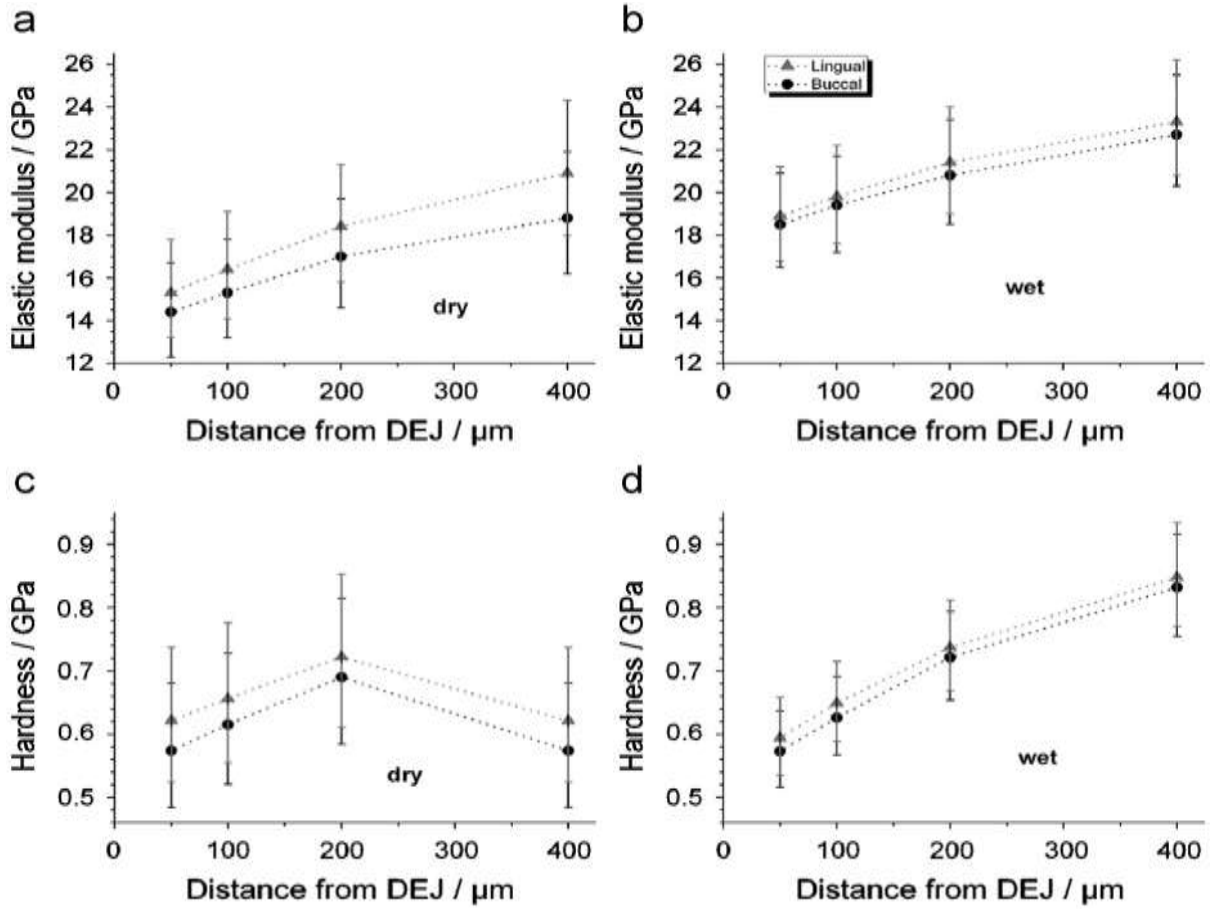

Fig. 1 Elastic modulus (top) and hardness (bottom) from nanoindentation experiments of both dry (left) and wet (right) crowns for buccal and lingual sides of teeth as a function of distance from the DEJ[8].

Hardness and elastic modulus values showed large variability. At each distance (50, 100, 200 and 400 mm) from the DEJ, elastic modulus and hardness from nanoindentation experiments on dry and wet coronal dentine are lower on the buccal than on the lingual side (Fig. 1); however, differences are not statistically significant. In addition, elastic modulus and hardness increased with distance from the DEJ but trends were not statistically significant (global LRT, $p > 0.05$).

Microhardness of dry coronal dentine (Fig. 2a) shows similar trends to those for nanohardness, results being lower on the buccal side and increasing with depth but trends are not statistically significant. Microhardness of dry root dentine (Fig. 2b), on the other hand, is higher on buccal sides than on lingual. In root as in crown dentine microhardness increases in deeper dentine; again, results are statistically not significant. On dry coronal dentine nanohardness (Fig. 1b) gives larger values than microhardness (Fig. 2a); this is particularly noticeable at 100–400 mm from the DEJ.

Dentine is known for its gradual transition in structure and properties [9,10,13,14,15,16] and this change in mechanical properties is reflected in the observed gradual increase in hardness and elastic modulus with increasing distance from the DEJ. Two main factors can account for this: dentine near the DEJ is known to be softer than bulk dentine, and the number of tubules per unit area, i.e. the fraction of harder and stiffer peritubular dentine, decreases. Due to the large microindenter size in relation to the dentine microstructure, microhardness results give a composite average of peritubular dentine, tubule orifices and intertubular dentine [12] while nanoindentation allows measurement of elastic modulus and hardness in small features, e.g. of peritubular dentine. Therefore nanohardness shows larger maxima due to measurements on peritubular dentine. Nanoindentation also yields larger average hardness than microindentation, particularly at increasing distances from the DEJ, due to microindentations including the empty space of the tubuleorifices, giving a smaller average value. This difference between nano-and microindentation measurements becomes more pronounced with increasing number of tubules per unit area at increasing distance from the DEJ. Recently it was reported that the mechanical properties of the dentine soft zone show a bucco-lingual asymmetry [18] with buccal dentine near the DEJ being less stiff than lingual. The author ssuggested that this asymmetry could be related to tooth function during mastication, as the enamel cap was shown to tilt towards the buccal side when loaded [19]. Asymmetry in strain and stiffness was reported repeatedly [15, 17, 18] and modelling suggested that ITD governed the elastic behaviour of dentine [11].

Our results show buccal coronal dentine to have consistently lower elastic modulus and hardness than lingual which suggests that the asymmetry found by Zaslansky et al. might at least partially be caused by differences in dentine materials properties with tooth side. Our finding that root dentine on the lingual side is less hard than buccal (opposite to crown dentine) suggests a compensatory effect, through which the root provides stability for the flexibility present in the crown. However, due to the small number of samples used in this study (n=3 for each method), the differences failed to reach statistical significance at the 0.05 level. It is worth noting that [18] Zaslansky et al.(2006a) noted the buccal/lingual asymmetry on maxillary premolars, while here also upper teeth were investigated. Considering that in maxillary and mandibular teeth opposite cusps are loaded during mastication, functional differences might be associated with opposing differences in buccal and lingual properties.

a **Crown**

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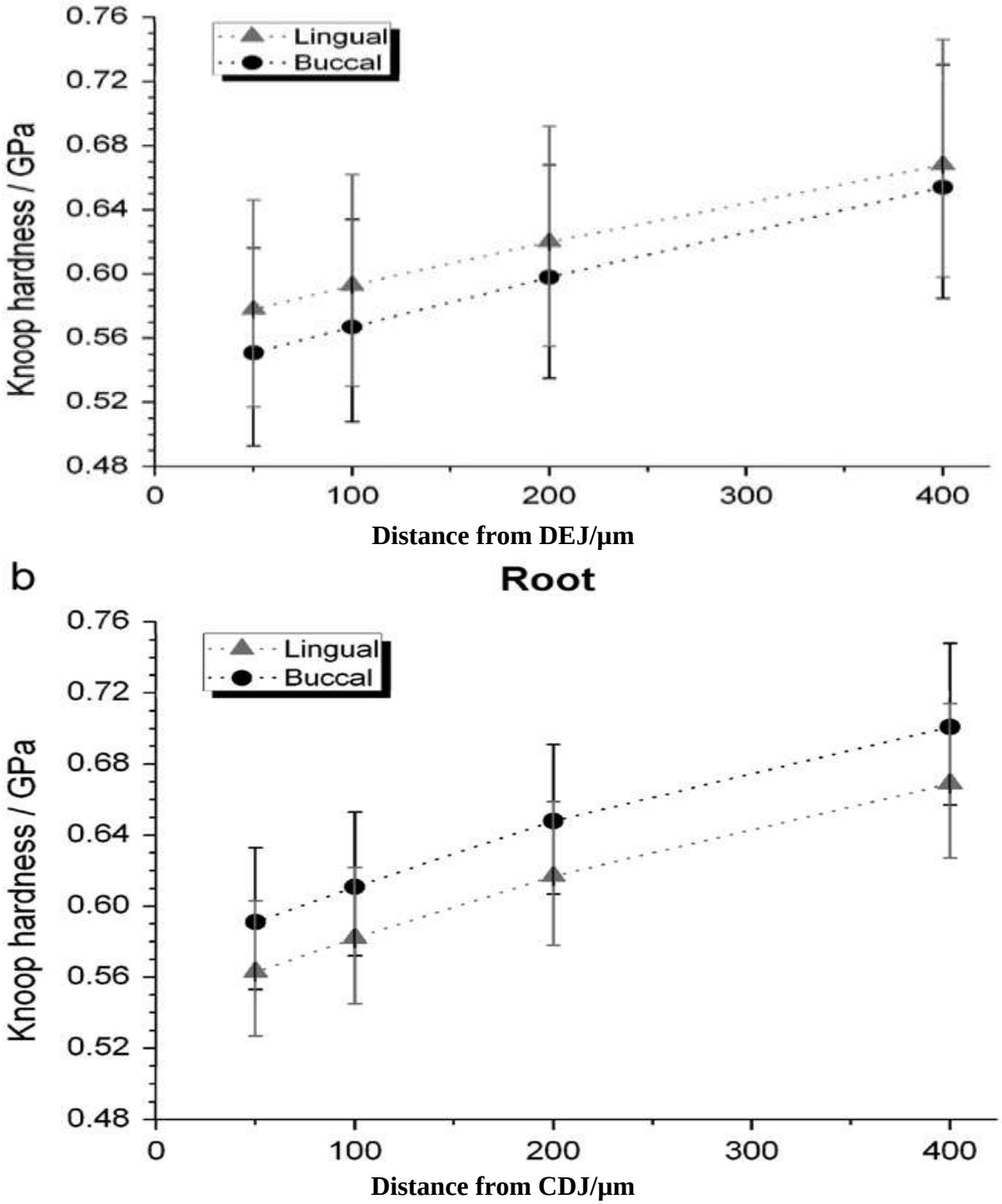

Fig. 2 Microhardness from microindentation experiments on dry (a) crowns and (b) roots for buccal and lingual sides of teeth as a function of distance from the DEJ (crowns) or CDJ (roots).Results are presented as mean ±95% confidence interval [8].

Despite the limitations of this study due to small sample numbers, our findings provide a potential explanation for the findings of Zaslanskyet al.:teeth resist impact forces

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through asymmetries in mechanical properties between the sides of the tooth, in opposite directions in crown and root dentine.

When the enamel membranes are treated with laser, the membrane potentials became more positive than those measured in natural membranes, indicating that the permselectivity of enamel membranes is modified by the laser irradiation.

The Knoop microhardness values obtained from nonlased sound dental enamel ranged from 340 to 388 and were in agreement with those previously published [25]. In all samples a Knoop hardness increase was observed when it was measured after laser application. Although these increases are not very large, they always happen and their values are connected with the initial hardness values of the correspondent untreated enamel. Figure 3 shows that larger initial hardness values correspond with smaller hardness increases and smaller initial hardness correspond with larger hardness increases.

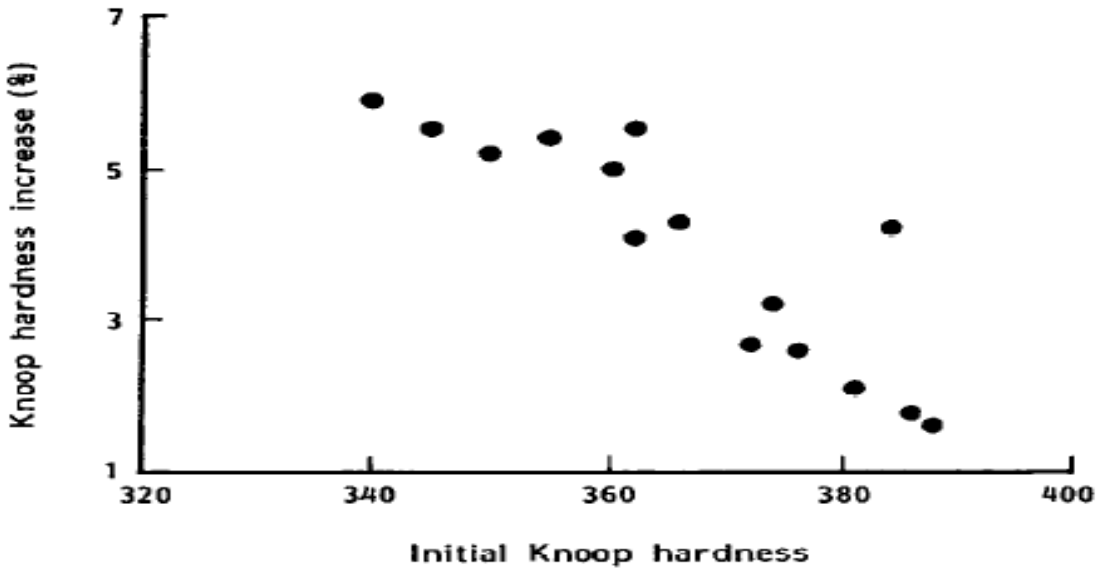

Fig. 3 Representation of the Knoop hardness number increases of lased enamel samples (%) with regard to their natural Knoop hardness number. Each point corresponds to a sample and is obtained from two collections of 20 indentations (before and after laser irradiation) [27].

In previously published works enamel hardness has been related to the mineral content in demineralization and remineralization phenomena [25,26]. If we accept this point of view it could be assumed that the laser application increases the mineralization, but only by decreasing the water and organic matter ratio with regard to the inorganic content and obviously not affecting the amount of this mineral content. This could explain the hardening of the enamel up to values characteristic of amore mineralized one, such that when its initial

hardness is high there are only little variations. However, other complementary or alternative explanations could be supposed, such as that hardness increases arise from the structural reorganization of the apatite crystals, or that the laser irradiation produces little molecular changes in the mineral composition affecting the structure of each crystal or the interactions between themselves. These last two possibilities could be due to the surface microfusion of the mineral matter and could make the enamel more resistant to the Knoop indentations. Figure 4 shows a SEM micrograph of non-lasered and lasered dental enamel. The most significant structural changes are demonstrated by the loss of the characteristic surface structure of the prisms due, possibly, to the enamel fusion.

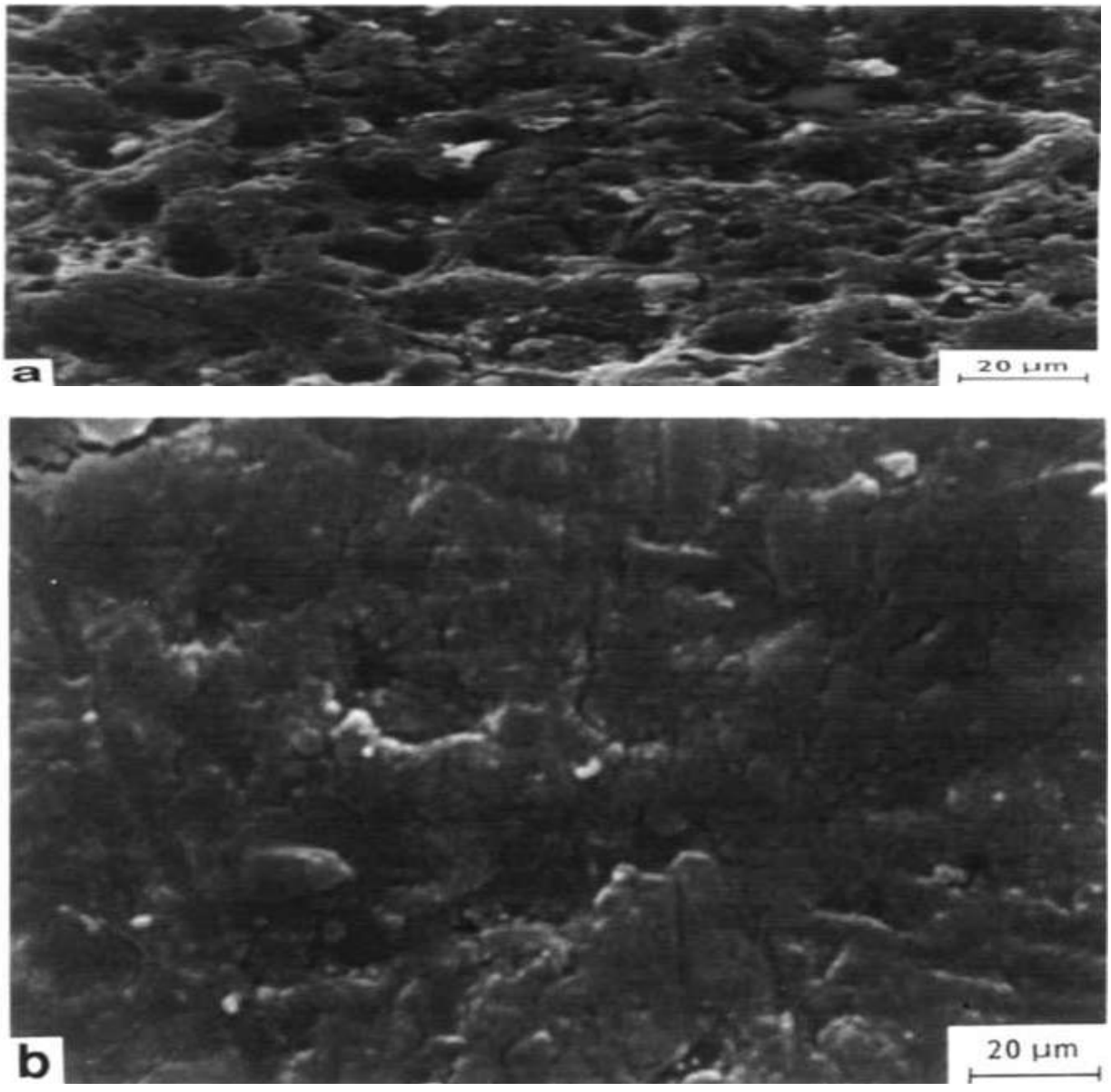

Fig. 4 (a) Scanning electron micrograph of an enamel surface showing the typical layout of the hydroxyapatite prisms.(**b)**SEM micrograph of a lasered enamel surface. Note the absence of the surface prismatic structure typically seen on the non-lasered enamel [28].

The observed modification in the permselectivity of lased enamel membranes could be explained in the same way. The possible changes produced by the surface fusion, as well as the loss of water, carbonate and organic substances could change the electrochemical properties of the enamel membrane and be responsible for the changes in the permeability.

Conclusion

The mechanical property measurements reveal variations in hardness of enamel and dentin. Enamel is found to hardest 3.5 GPa at the outermost surface, however dentin is softer less than 1 GPa. A progressively decreasing hardness with depth from the surface was measured. Such a variation depends partially upon the minerals concentration in enamel and dentin. It also depends on local morphology and microstructural features such as enamel rod orientation and dentinal tubule density.

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