Original**Mineral Density of Coronal and Radicular Dentin**

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Abstract: Surprisingly little is known about how the structure and composition of tooth dentin varies between different areas of the tooth. This study was to investigate and compare the mineral density of coronal and radicular dentin using ten bovine incisor teeth. The mineral density of coronal and radicular dentin was quantified at two locations per tooth using micro-computed tomography (micro-CT). The coronal area was 15.0 mm coronal to the cemento-enamel junction on the buccal side of the tooth, while the radicular area was 5.0 mm apical to the cemento-enamel junction, also on the buccal side. Mean mineral density value was compared statistically by the paired Student's t-test. The mineral density of coronal dentin was $1,628.8 \pm 34.0$ mg/cm³, and that of radicular dentin was $1,406.1 \pm 38.7$ mg/cm³, suggesting that the dentin mineral density is higher in the crown than in the root. Micro-CT intensity data is a useful method for quantitating dentin mineral density.

Key words: dentin, crown, root, teeth, mineral density.

Accurate diagnoses in clinical dental science require clear information on the mechanical properties of teeth. Dentin is the most abundant mineralized tissue in the tooth, by both weight and volume, so a clear understanding of its characteristics is important when evaluating new types of dental material and in predicting the behavior of tissue at the tooth/restoration interface.

Dentin is present in both the tooth crown (coronal dentin) and its root (radicular dentin), and dentin fracture behavior is reported to differ between these sites, as indicated by strain concentration and impression-induced damage tests.¹⁾ Clinically, coronal and radicular dentin have different microtensile bond strengths.^{2,3)} Thus, it appears that the dentin is structurally and/or compositionally different between the tooth crown and root, making it important to consider differences in the structural properties of coronal and radicular dentin.

As a component of dentin, the mineral content or mineral density has a large influence on the structural

integrity of teeth⁴⁾. However, information on the mineral density of dentin is scant. The emergence of micro-computed tomography (micro-CT), a novel imaging technology, as an analysis technique has opened up new ways of measuring and visualizing the mineral density of dentin through quantitative analysis of micro-CT intensity data. Hence, we aimed in this study to quantitate mineral density in coronal and radicular dentin to illustrate the usefulness of micro-CT in analyzing the composition and structure of this dental hard tissue, and to provide insight into how dental tissues might behave physically.

Materials and Methods

Ten bovine lower central incisors were used for this study (Fig. 1A). The mineral density of coronal and radicular dentin was quantified using micro-CT at two locations per tooth. The coronal area was located in the buccal center of the dentin layer 15.0 mm coronal to the cemento-enamel junction (CEJ), while the radicular area

Fig. 1 A) Representation of bovine tooth. B) The vertical position of the coronal and apical regions of interest relative to the cemento-enamel junction (CEJ; dotted line). The coronal ROI was 15.0 mm coronal to the CEJ, whereas the radicular ROI was 5.0 mm apical to the CEJ. The pulp volume and position were also confirmed within the teeth. C, D) White circles in each image indicate the position of the ROI from which data were extracted to estimate average mineral density across the sample. Pseudo-color three-dimensional images of bovine lower central incisor teeth generated from micro-CT data. Images show colorized representations of mineral density in the coronal (C) and radicular (D) portions of the tooth. Bar indicates 10.0 mm.

Table 1 Experimental groups.

Group	Location
1	Coronal dentin
2	Radicular dentin

was in the buccal center of the dentin layer 5.0 mm apical to the CEJ (Fig. 1B).

An X-ray micro-CT system (SMX-90; Shimadzu, Kyoto, Japan) was used to evaluate the mineral density of specimens. Specimens and hydroxyapatite (HAP) samples were scanned with X-rays generated by a sealed micro-focus X-ray tube at 90 keV and 110 μ A. Specimens were rotated through 360° at rotation steps of 0.2°. An aluminum filter was placed in front of the detector to remove low-energy X-rays.

TRI/3D-BON software (Ratoc system engineering, Tokyo, Japan) was used for visualization and analysis of mineral density. Regions of interest (ROI) were selected in each specimen at 50 μ m $\times$ 50 μ m $\times$ 50 μ m, and mineral density calculated within each ROI. To convert CT intensity into mineral density, apatite phantoms of different densities were used as calibration standards with each scan. There was a linear correlation between CT intensity and mineral density using these apatite phantoms.^{5,6)} Thus, density values for dentin specimens were extrapolated from this standard profile. A calibration

Fig. 2 Mineral density values of the coronal and radicular portions of the teeth. Data (in mg/cm³) were extracted from the regions of interest shown in Fig. 1 and collated to give average data for the whole sample, shown here as mean $\pm$ standard deviation. * indicates presence of statistical difference between groups.

equation derived from the phantoms with each tooth was used for mineral density calibration. Mean mineral density value was statistically compared by the paired Student's t-test with a p-value of 0.05.

Results

The mineral density of each group is shown in Fig. 2. Data represent the mean $\pm$ standard deviation. The results indicate that the mineral density of coronal dentin within the ROI was 1,628.8 $\pm$ 34.0 mg/cm³, whereas that of radicular dentin within the ROI was 1,406.1 $\pm$ 38.7 mg/cm³. Thus, mineral density appears to be greater in

the coronal dentin than in the radicular dentin, suggesting that mineral concentration varies between different areas of the tooth.

Micro-CT cross-sectional images of 3D pseudo-color representations of mineral density are indicated in Fig. 1C (coronal dentin) and Fig. 1D (radicular dentin). Warmer colors (red, yellow) denote high mineral density, while cooler colors (blue, green) indicate low mineral density. It can be seen that mineral density is markedly higher in the coronal dentin (yellow; Fig. 1C) than in the radicular dentin (blue; Fig. 1D).

Discussion

We have shown here that the mineral density of coronal dentin is greater than that of radicular dentin, and thus that mineral concentration varies between different areas of the same tooth.

It has been reported that mineral volume is positively correlated with the mechanical properties of tissues such as bone^{7,8)} and teeth.^{9,10)} We have previously investigated the hardness and Young's modulus of coronal and radicular dentin.¹¹⁾ Hardness is the ability of a material to resist permanent indentation,^{12,13)} and was found to be 0.8 GPa in coronal dentin and only 0.6 GPa in radicular dentin. Similarly, the Young's modulus (a measure of material stiffness or elasticity¹⁴⁾) of coronal dentin (26.6 GPa) was higher than that of radicular dentin (20.9 GPa). These results showed that lower tissue mineral content, such as that in radicular dentin compared with coronal dentin, correlates with lower strength and hardness.

There are several methods for assessing mineral density. Electron probe micro analysis (EPMA) is used for elemental analysis at the ultra-structural level, using a principle based on energy emitted in the form of X-ray photons when electrons from external sources collide with atoms in a material, generating characteristic X-ray spectra of the element.¹⁵⁾ This technique has been used to investigate the calcium and phosphorous content of dental hard tissue in several studies,^{16,17)} as well as to delineate various other elements within dental hard tissues. Scanning electron microscopy (SEM)

and energy-dispersive spectrometry (EDS) have also been used to determine mineral levels in dentin.^{18,19)} However, the measurements made using SEM and EDS were not repeated at exactly the same point, so direct comparison of these techniques could not be achieved. Instead, the average mineral content of an area was recorded in each sample. Further complications with these techniques are the potential for secondary diffraction due to dentin porosity, meaning that the dentin surfaces must be polished perfectly prior to scanning. However, this polishing can produce a smear layer that can itself be responsible for differential element profiles at the dentin surface.²⁰⁾ While the X-ray micro-CT system does not require samples to be polished prior to reading, it is known to have inherent artefacts itself, such as a 'beam hardening effect', 'random noise' and a 'partial volume effect', that mandate careful handling. However, the most notable advantages of micro-CT are its non-destructiveness and its ability to measure and visualize mineral density in the same lesion repeatedly. Thus, in this study, X-ray micro-CT has been shown to be a valuable method for calibrated qualitative and quantitative analyses of dental hard tissues.

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