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Comparative mechanical behavior of dentin enamel and dentin ceramic junctions assessed by speckle interferometry (SI)

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ABSTRACT

Objective. The dentin–enamel junction (DEJ) plays a crucial role in dental biomechanics; however, little is known about its structure and mechanical behavior. Nevertheless, natural teeth are a necessary model for prosthetic crowns. The mechanical behavior of the natural DEJ and the dentin ceramic junction (DCJ) manufactured with a CAD-CAM system are compared.
Methods. The reference samples undergo no modification, while the experimental samples were drilled to receive a cemented feldspathic ceramic crown. Longitudinally cut samples were used to achieve a planar object observation and to look "inside" the tooth. A complete apparatus enabling the study of the compressive mechanical behavior of the involved tooth by a non-contact laser speckle interferometry (SI) was developed to allow nanometric displacements to be tracked during the compression test.
Results. It is observed that the DEJ acted as a critical zone accommodating the movement between dentin and enamel. A smooth transition occurs between dentin and enamel. In the modeled prosthetic, the same kind of accommodation effects also occurs, but with a steeper transition slope between dentin and ceramic.
Significance. On the natural tooth, the stress accommodation arises from a differential behavior between enamel and dentin from the DEJ. In the ceramic crown, the cemented dentin–ceramic junction should play this role. This study demonstrates the possible realization of prosthetic crown reconstructions approaching biomechanical behaviors.

1. Introduction

The dentin–enamel junction (DEJ) in teeth is the zone between two distinct calcified tissues with very different biomechanical properties: enamel and dentin [1]. Enamel is hard and brittle and envelops the softer dentin. The enamel and dentin work together during the many load cycles experienced by the tooth over its lifetime. Generally, interfaces between materials with dissimilar elastic and mechanical properties represent "weak links" in a structure; however, the DEJ acts to successfully transfer applied loads (e.g., masticatory or impact) from the enamel to the dentin and inhibits enamel cracks from propagating into the dentin and causing tooth fracture [2,3].

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The DEJ appears as a discrete line when visualized microscopically and is thought to represent the original position of the basement membrane of the ameloblasts and odontoblasts where they coincide in the embryological tooth bud [4]. In human enamel and dentin, fatigue damage is the end result of extreme loads and is frequently associated with pathology or extensive wear. The fracture-resistant properties of the DEJ are believed to originate from a gradual change in microstructure and in the properties of dentin and enamel rather than from the abrupt transition between the two dissimilar materials [5,6]. Wang and Weiner suggested that the DEJ is one of the working sites of the tooth during mastication [7]. Imbeni et al. [1] believe that collagen fibrils perpendicular to the interface constitute the key reinforcing mechanism at the DEJ, thus explaining why so few cracking events cause delamination when they impinge on the DEJ. Zaslansky et al. [8,9] highlighted the importance of the DEJ as the binding interface between enamel and dentin. They have shown that adjacent to the DEJ is a 200–300 mm-thick zone of dentin of a much lower stiffness (compression elastic modulus) than the bulk of the dentin in the tooth.

Restorations that are all ceramic require proper adhesive bonding on the dentin to achieve their required life expectancy. All-ceramic restorations are made with feldspathic or zirconia ceramics. The strongest ceramics have a fracture toughness of at least 3.0 MPa m$^{1/2}$ [10], which is relatively close to the enamel fracture toughness of 1.3 MPa m$^{1/2}$, in a direction perpendicular to the enamel rods [8]. Nevertheless, fractures of the ceramic part of all-ceramic crowns are difficult to prevent, and crack growth is a significant problem [11]. This phenomenon can be explained by the absence of a stress accommodation zone. The natural stress accommodation zone of 200–300 μm-thick dentin has a much lower stiffness than the bulk of the dentin core [8].

Bonding agents must be selected very carefully because they determine not only the adhesion but also the ultimate strength of full-ceramic crowns [12–14]; therefore, it is important to compare the mechanical behavior of natural teeth and of the all-ceramic crown cemented on dentin. Instead of "cement joint", we will use the term "dentin–ceramic junction" (DCJ).

We applied compressive forces representative of those occurring in the oral cavity on natural teeth and all-ceramic crowns, and we determine the relative movement of enamel and dentin, or ceramic crown and dentin, respectively.

2. Materials and methods

2.1. *Natural teeth*

Intact lower first premolars free of caries were stored in physiological serum after having been extracted as part of the routine orthodontic treatment of young healthy adolescent patients (aged < 18). Five sets of two samples each (one natural tooth and one prosthetic tooth) were amassed. Right and left premolars from the same patient were used. One was kept intact, and the other was prepared to receive the prosthetic crown.

2.2. *Prosthetic crowns*

We employed the Cerec 3D® (Sirona Dental System®, Bensheim, Germany) CAD/CAM (computer aided design/computer aided manufacturing) unit to manufacture each prosthetic crown as a clone of the opposite tooth using the reproduction capability of the Cerec® software V2.80. This CAD/CAM system is composed of two distinct units: the optical imprint recording also allowing the CAD, and the milling unit using the CAD data to manufacture the sample out of a ceramic block. The software was set to give a dento-prosthetic spacing of 100 μm and a peripheral joint of 40 μm for a total thickness of 800 μm. Optical imprints, of the prepared tooth and of the opposite tooth, were recorded, and the Cerec MC® machine milled the prosthetic crowns [15]. The whole cloning process is presented in Fig. 1.

The Vita MarkII® (Vita Zahnfabrik, Bad Säckingen, Switzerland) ceramic blocks of albite-enriched feldspathic ceramic were used. Their abrasion coefficient is close to that of natural dental enamel. After milling, the extrados were glazed (Azkent®, Vita Zahnfabrik, Bad Säckingen, Switzerland).

The crowns were cemented onto the prepared teeth using Relyx Unicem® adhesive cement (3MESPE Dental Division, St. Paul, MN, USA) following the standard clinical protocol of illumination of each side of the crown for 4 s at 3000 mW/cm^2 with a Swissmaster Light® lamp (E.M.S., Nyons, Switzerland).

2.3. *Specimen preparation*

After extraction, the teeth were disinfected and stored in physiological serum with traces of chloroform. The teeth were longitudinally cut in the vestibular–lingual orientation, and one of the two resulting parts was removed with a diamond disc. Longitudinal cuts have been used to allow planar observation and to appreciate the different behaviors inside the tooth of the natural DEJ and of the DCJ interfaces. The tooth was then glued into the sample holder with a layer of Araldite® (Hunstman Advanced Materials, The Woodlands, Texas, USA). The sample holders have been cast in chromium cobalt using the imprint of a root. The mechanical stability of the specimen holders was validated by a speckle interferometry (SI) experiment.

2.4. *Loading system*

The compression test device fulfills the high sensitivity of speckle interferometry and copes with the rigid body motions of the whole system. The sample tooth cemented in the sample holder was placed under the force transducer (Model 31, Honeywell International, Morriston, NJ, USA). This mid-range precision miniature load cell is slowly translated vertically by the motor (M-235®, PI. Karlsruhe, Germany). The system can generate a force-driven displacement (C-862 Mercury PI, Karlsruhe, Germany) or simply a user's displacement. The compression apparatus communicates with the computer through a NI USB-6251 port (National Instruments, Austin, TX, USA) and is interfaced with an in-house LabView program. The entire mechanical system was bolted onto the holographic table top (Newport, Irvine, CA, USA). Very small displacement steps, as small as 1.6 nm, can theoretically be achieved. The