INTRODUCTION
Fracture toughness is often used as a performance metric in characterizing dental materials. It is also used in examining properties of dentin and enamel. The fracture toughness of enamel has been estimated almost exclusively from indentation measurements [1-3]. There are recognized limitations to this approach, particularly when applied to materials that undergo toughening with crack extension [4]. The primary objective of this investigation was to estimate the fracture toughness of enamel using an incremental crack growth approach, and compare that with measures obtained by indentations.

MATERIALS AND METHODS
Inset compact tension (CT) specimens (N=5) were prepared by embedding small pieces of cuspal enamel in a mixture of resin composite (Fig. 1). Incremental crack growth was achieved using a universal testing system and the crack growth resistance was quantified as a function of distance from the occlusal surface. The stress intensity at the crack tip (Kc) for an opening mode load (P) was modeled using Eqn. 1 [5] with B, B* and W defined in Fig 1(b), and

\[ K_c = \frac{P}{B^{\frac{1}{2}}} \left[ \frac{W}{B^2} + \frac{1}{11} \right] \left( 0.69 - 0.801a + 12.5a^2 \right) \]  

(1)

In addition, indentation cracks were created in polished surfaces of enamel (N=10) at selected distances from the occlusal surface (Fig. 1(c)). There were two criterion used in estimating the indentation fracture toughness. In Criterion I the crack length was estimated from the average of all four cracks emanating from the diagonals (Fig. 2(a)). In Criterion II, only the longest crack was selected among all cracks generated from an indentation. The indentation fracture resistance (Kic) can be estimated for each indentation according to Eqs. 2 [6] with P and HV defined as the elastic modulus and the transition point hardness, respectively, and P, L and e are the indentation load (kg), average diagonal length (m) and crack length (m), respectively.

\[ K_{IC} = 0.0084 \frac{E^{0.5}}{H_{IV}^{0.5}} \frac{P}{L^2} \cdot \frac{1}{1.4} \]  

(2)

Results obtained from both indentation and crack growth measurements were normalized by dividing the distance of the measured indent (or the crack tip position from the occlusal surface) by the total thickness of enamel from the occlusal surface to the DEJ.

RESULTS AND DISCUSSION
Typical cracks resulting from indentation of the enamel specimens are shown in Fig. 2. There was a notable variation in the nature of cracks that developed and extended from the indentation diagonals. Several indentations exhibited four distinct cracks with one from each corner as shown for an indent in the outer enamel in Fig. 2(a). Many of the indents promoted complicated crack patterns or microcracking (e.g. Fig. 2(b) and 2(c)).

The average toughness estimated from indentations was 0.92 MPa m\(^{0.5}\) (Criterion I) and 0.77 MPa m\(^{0.5}\) (Criterion II). Though the toughness estimates from the two different measurement criterion (p<0.05), there was no dependence on distance from the occlusal surface (Fig. 3). The average toughness obtained from the indentation-based measurements (considering both criterion) was 0.84 MPa m\(^{0.5}\).

CONCLUSION
Enamel exhibes a rise in resistance to crack growth with extension from the outer enamel towards the DEJ. Based on the incremental approach the fracture toughness of enamel exceeds 2 MPa m\(^{0.5}\). The indentation technique did not identify the extent of toughening resisting the growth of surface contact cracks in enamel.

REFERENCES

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What is the Real Fracture Toughness of Human Enamel?
D. Bajaj1, S. Park1, G.D. Quinn1,2,3 and D. Arola1,2,3
1Department of Mechanical Engineering, University of Maryland Baltimore County, Baltimore, MD
2Department of Endodontics, Prosthodontics and Operative Dentistry, University of Maryland, Baltimore, MD
3Paffenbarger Research Center, American Dental Association Foundation, Gaithersburg, MD

Figure 1. Schematic diagram of specimen configurations. (a) A typical indentation and crack pattern with well-defined cracks at each of the indentation corners. This indent was obtained in the outer enamel. (b) A complex crack network observed for an indent placed near the intersection of the outer and inner enamel. (c) Indents near the DEJ resulting in microcracks but no distinct cracks from the indentation corners. Note that the indentation patterns in (b) and (c) were not included in estimating the Kc.

Figure 2. Crack morphology about selected Vickers indents in the enamel specimens. (a) A typical indentation and crack pattern with well-defined cracks at each of the indentation corners. This indent was obtained in the outer enamel. (b) A complex crack network observed for an indent placed near the intersection of the outer and inner enamel. (c) Indents near the DEJ resulting in microcracks but no distinct cracks from the indentation corners. Note that the indentation patterns in (b) and (c) were not included in estimating the Kc.

Figure 3. The indentation fracture toughness (Kic) distribution as function of normalized distance. Note that 0 is closest to the outer enamel and 1 is closest to the DEJ. Results measured using (a) the average crack length (Criterion I) and (b) the maximum crack length of the four diagonals (Criterion II) exhibited a significant difference in the toughness as a function of distance from the occlusal surface.

Figure 4. Incremental crack extension in the outer enamel occurred along a straight path followed by growth in the inner enamel that occurred over a tortuous path. Crack growth in the inner enamel was accompanied by a number of mechanisms including crack bridging, crack bifurcation and crack deflection. Arrow indicates the direction of crack growth.

Figure 5. Incremental crack growth responses exhibited a rising R-curve behavior with a distinct rise in toughness occurring with crack growth in the inner half of the enamel. Dashed area represents data obtained from the indentation experiments.