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A novel polymer infiltrated ceramic for dental simulation

Li-Hong He · David Purton · Michael Swain

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Abstract Simulation of tooth preparation using rotary cutting instruments is viewed as beneficial and essential in dental training. Various types of materials have been used for simulation systems in dental preclinical training. However, the phantom tooth materials used for simulation have not changed significantly for decades and they are acknowledged to be different from natural teeth. This study investigated the mechanical properties and microstructure of a widely used phantom tooth material and compared them with a novel, polymer infiltrated, ceramic. It was concluded that the polymer infiltrated ceramic has mechanical properties more similar to natural teeth than current phantom tooth materials, suggesting that it might be a good candidate material for phantom teeth for trainees to acquire initial tactile sense for tooth preparation.

1 Introduction

Simulation systems and related technology have significant benefits and have become prominent in health care educational institutions. Simulators are valuable in duplicating irreversible clinical situations and operations. For patients' safety, it is better for trainees to practice on a simulator than a patient.

Dentistry has also benefitted from the advent of modern simulators, especially in the area of undergraduate preclinical training [1, 2]. Simulators have become the safe and economic choice in assisting students to improve hand skills and practice their application of textbook and didactic knowledge. Appropriate simulation on phantom teeth, under the guidance of tutors, provides a smoother transition for students into clinics and reduces the burden on students, patients and supervisors in clinics.

Various types of simulation systems are available, which genuinely mimic different clinical situations. However, the core part of the dental simulator, phantom teeth, has not improved to better reflect the clinical behavior of natural teeth. Dental educators know that plastic phantom teeth are very soft. Unfortunately, few reports mention the exact mechanical properties of the phantom teeth material and its ability to mimic the behavior of natural teeth, which is important to give the trainees initial senses of tactile sensation associated with tooth preparation.

The aim of this study was to measure and compare the mechanical properties of currently used phantom teeth with a novel polymer infiltrated ceramic material. Comparison with enamel and dentine was also discussed.

2 Materials and methods

2.1 Sample preparation

Materials tested in this study were a prototype, polymer infiltrated, ceramic (VITA Zahnfabrik, Bad Säckingen, Germany) and plastic phantom teeth (model A5A-500, Nissin Dental Products Inc., Kyoto, Japan) for student simulation use.

Flat surfaces were polished (TegraPol-21, Struers, Copenhagen, Denmark) to 1 μm with diamond polishing paste for nanoindentation tests. Five beams per material were cut from ceramic blocks and plastic molar teeth for fracture toughness testing. Cutting of the specimens was

L.-H. He (✉) · D. Purton · M. Swain
Department of Oral Rehabilitation, Sir John Walsh Research Institute, School of Dentistry, University of Otago, P.O. Box 647, Dunedin 9054, New Zealand
e-mail: lihong.he@otago.ac.nz

done with a high speed cutting machine (Accutom-50, Struers, Denmark) with a diamond cut-off wheel (331CA, Struers) at a spindle speed of 3000 rpm and feeding speed of 0.05 mm/sec under water irrigation. The beams were polished to $2400^{\#}$ SiC paper (Struers) to the final dimension of 20 × 3 × 4 mm^3.

The beams for fracture toughness test were pre-notched with the high speed cutting machine (Accutom-50, Struers) to a depth of ~1.9 mm through the width of 4 mm. Then, a purpose built compressed air-driven cyclic movement machine, with a fixed razor blade and 3 µm diamond paste, was employed to sharpen the notch and extend it an additional 100–200 µm. The final length of the notch was measured with an optical microscope (YS2-H, Nikon, Japan) equipped with an objective micrometer (Olympus, Japan) to an accuracy of 1 µm. To minimise the notch blunting effect, the tip of every notch was double checked to ensure the radius of the notch tip was less than 10 µm.

2.2 Nanoindentation tests

The indentation experiments were performed using a nano-based indentation system (Ultra Micro-Indentation System, UMIS-2000, CSIRO, Australia). The polished specimens were mounted on metal bases that contained a strong magnet to ensure adequate contact was obtained with the test base in the UMIS. All the tests were performed under standard laboratory conditions.

The elastic modulus and hardness of the specimens were measured with a calibrated Berkovich indenter. The force applied during the experiments was fixed at 300 mN. Sixteen indents were made in a 4 × 4 array with the interval of 50 µm between indents at each load value. The maximum load was held for 30 s to minimize the effect of creep on the unloading curve. The Oliver-Pharr analysis method [3] was used by the UMIS software to calculate the elastic modulus (E) and hardness (H).

2.3 Fracture toughness test

Standard single-edge-notched beam (SENB) method was used to measure the fracture toughness (K_{1c}) [4]. The prepared samples were loaded in a three-point bending format with the support span of 16 mm at a cross-head speed of 0.5 mm/min until failure in a universal test machine (Model 3369, Instron, Norwood, MA, USA). The following equation was used to calculate the K_{1c},

$$K_{1c} = \frac{FL}{BW^{3/2}} f\left(\frac{a}{W}\right), \tag{1}$$

in which F is the fracture load, L is the lower supporting span, B is the breadth of the beam, W is the width of the beam, and a is the length of the notch. Geometrical factor $f(a/W)$ can be calculated by Eq. (2),

$$f\left(\frac{a}{W}\right) = 2.9\left(\frac{a}{W}\right)^{1/2} - 4.6\left(\frac{a}{W}\right)^{3/2} + 21.8\left(\frac{a}{W}\right)^{5/2} - 37.6\left(\frac{a}{W}\right)^{7/2} + 38.7\left(\frac{a}{W}\right)^{9/2}. \tag{2}$$

Five samples were prepared and tested for each material and the data were analysed statistically with Microsoft Excel 2007.

2.4 SEM observation

Representative fractured samples were gold coated for scanning electron microscope (SEM) investigation (S360, Cambridge Instruments, Cambridge, UK) with a secondary electron detector was employed to observe both polished and fractured surfaces of the samples.

3 Results

A phantom tooth has a nanoindentation determined E and H of 9.62 ± 1.79 and 0.63 ± 0.07 GPa, respectively, while polymer infiltrated ceramic has E and H of 30.14 ± 2.96 and 2.36 ± 0.57 GPa, respectively, which are approximately three times higher. However, the fracture toughness value of the phantom tooth material, which is 1.9 ± 0.07 MPa $\text{m}^{1/2}$, is slightly higher than that of polymer infiltrated ceramic which is 1.72 ± 0.09 MPa $\text{m}^{1/2}$.

Unlike a natural tooth which is a laminate of enamel and dentine, the phantom tooth was a homogeneous solid made using a fiber reinforced resin. Fig. 1a illustrates clusters of reinforcement fibers embedded in the resin matrix. Cracks generated during high speed cutting went through the fiber-rich region. Fig. 1b shows the presence of fibers inside a crack and Fig. 1c shows the broken ends of fibers at the center of the image. For polymer infiltrated ceramic, the images shown in Figs. 1d–f do not show any obvious pores or voids, which indicates that the polymer infiltration was complete. Fig. 1e illustrates a crack propagated within the polymer phase of the network with an occasional fracture of the interconnected brittle ceramic phase.

4 Discussion

Several manufacturers provide dental simulation systems and phantom teeth. During the preliminary test period, three phantom systems, including Nissin (model A5A-500, Nissin Dental Products Inc., Kyoto, Japan), Dentoform (T-860 Ivorine® teeth, Columbia Dentoform Corp., NY,

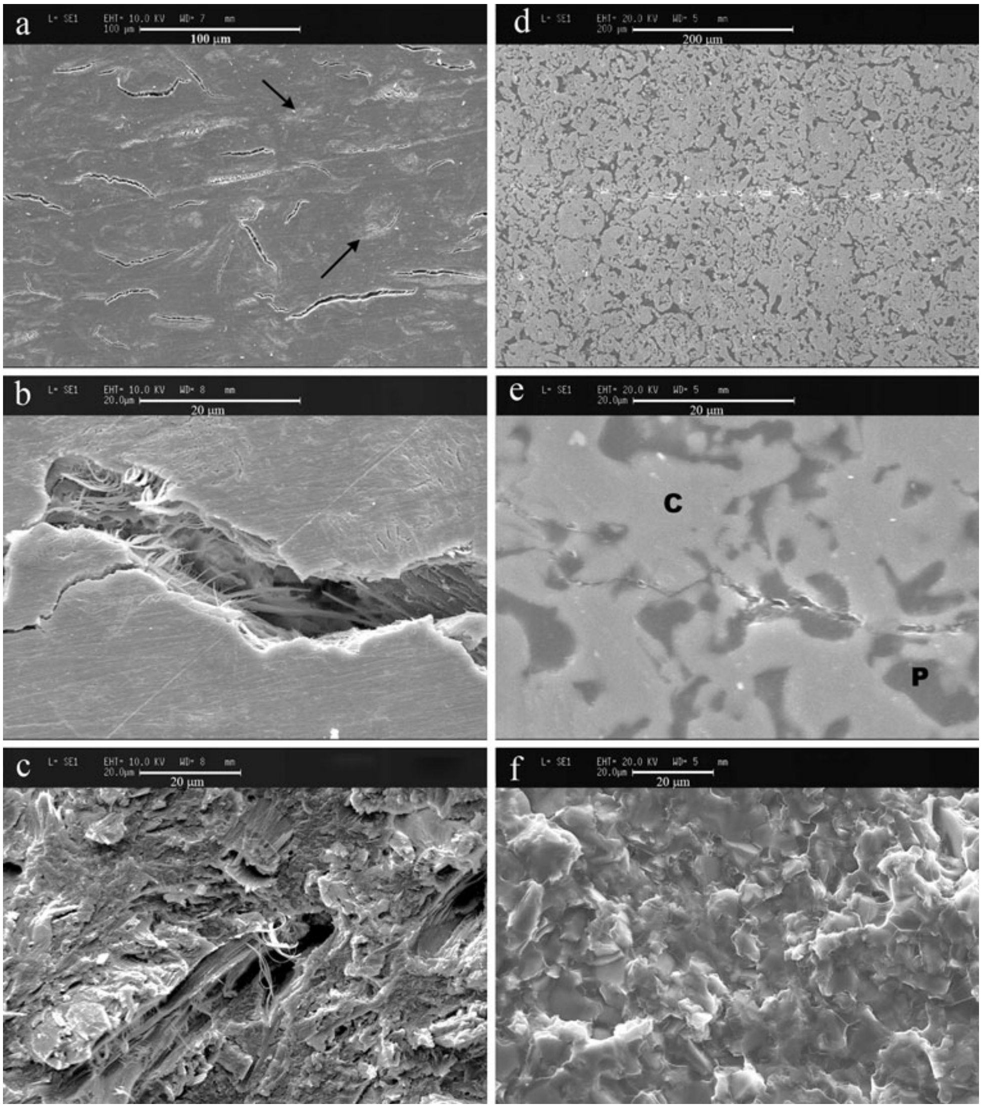

Fig. 1 SEM comparison of a phantom plastic tooth sample (**a**, **b**, **c**) and polymer infiltrated ceramic (**d**, **e**, **f**). **a** and **d** polished surfaces; **b** and **e** cracks on the polished surfaces; **c** and **f** fractured surfaces after fracture toughness tests. *Arrows* in figure (**a**) indicate clusters of fibers. "C" and "P" in figure (**e**) indicate ceramic and polymer phases, respectively

USA) and Frasaco (model AG-3, Frasaco GmbH, Tettnang, Germany) were investigated. Nanoindentation tests and SEM observation (results are not listed) indicated that they are all very similar materials, namely fiber reinforced plastic. Therefore, only Nissin teeth were used in the current study to compare with the novel polymer infiltrated ceramic.

Elastic modulus and hardness are two basic mechanical indices used to describe and compare materials. Elastic modulus quantifies the stiffness of a material while hardness is a reflection of a material's ability to resist permanent deformation. Fracture toughness reflects the crack and chipping susceptibility of a material, which is related to simulated dental cutting and drilling. To determine the similarity of the tested materials to natural teeth, their mechanical properties were compared (Fig. 2). Phantom teeth have E and H values similar to those of carious dentine, that is, one-sixth to one-tenth of the values for sound enamel. In contrast the polymer infiltrated ceramic has higher E and H than sound dentine. Regarding the fracture toughness, both synthetic materials have similar values to enamel and a lower value than dentine. Relatively low fracture toughness means chipping of the margin might occur during cavity preparation, especially with hand instruments such as hatchets. Furthermore, from the data for hardness and fracture toughness, the brittleness index [5] can be calculated by: $B = H/K_{1c}$, which is an indication of the machinability of the material [6]. Usually, the lower the B value, the more easily the material can be cut. Phantom teeth and polymer infiltrated ceramic have the

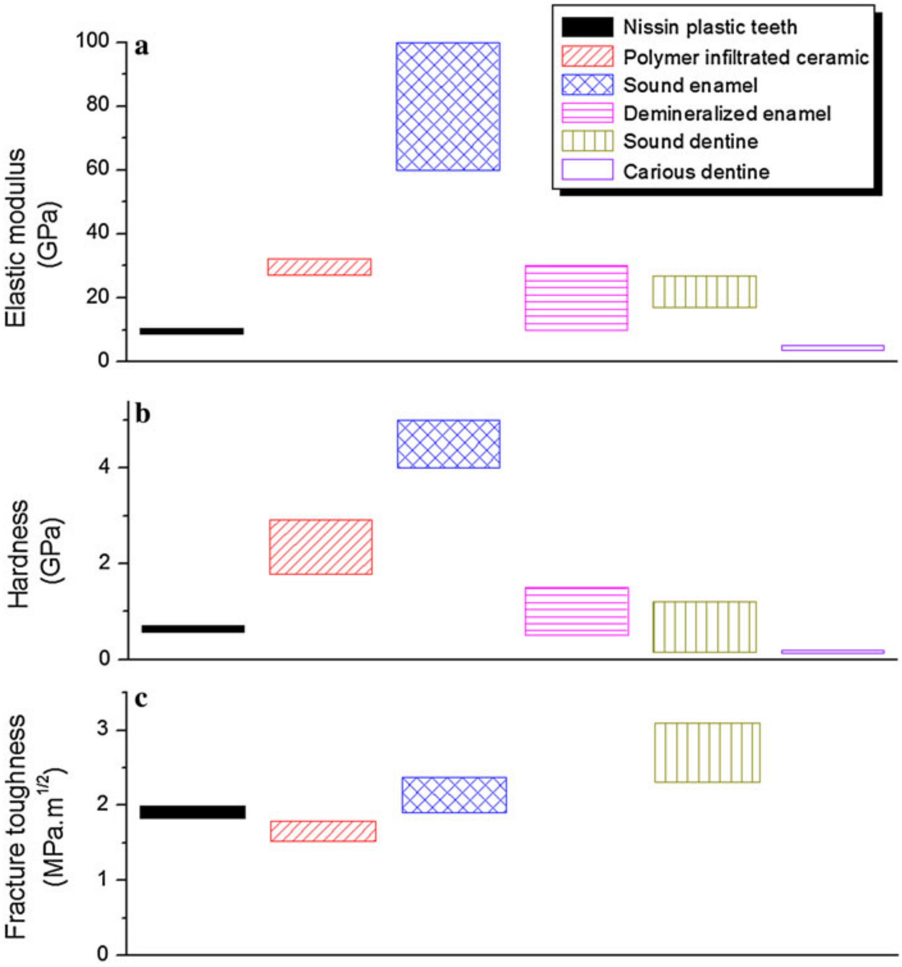

Fig. 2 Comparison of nanoindentation **a** elastic modulus, **b** hardness, and **c** fracture toughness between phantom teeth, polymer infiltrated ceramic and natural teeth. (*E* and *H* of sound enamel were extracted from He et al.[7]; *E* and *H* of demineralized enamel were extracted from Dickinson, Wolf et al.[8]; *E* and *H* of sound dentine were extracted from Angker and Swain [9]; *E* and *H* of the carious dentine were extracted from Shibata et al. [10]; fracture toughness of sound enamel was extracted from Bajaj and Arola [11]; fracture toughness of sound dentine was extracted from Yan et al. [12] and Mowafy and Watts [13].)

brittle indices of 0.33 and 1.37 $\mu m^{1/2}$. Therefore, phantom teeth would cut more easily than polymer infiltrated ceramic and natural teeth, using clinical burs. Starting simulation with the soft phantom teeth may give students unreal tactile sensations of cavity and crown preparations.

On the analysis of microstructure and fractography of phantom teeth, from a theoretical perspective, it is supposed that the fibers have the function of reinforcing the polymeric material. However, high speed sectioning generated many cracks, primarily parallel to the fiber bundles, within the fiber-rich region (Fig. 1a). Moreover, inside the propagated cracks, fibers detaching from the matrix were very common (Fig. 1b). This may be a consequence of the lack of adhesive bonding between fibers and matrix. The fractured surfaces were very irregular (Fig. 1c), indicating that cracks were somewhat deflected by the long fibers and could only propagate along the long axis, or near the ends of the fibers. Therefore, only a few broken fibers were observed on the fractured surface. Only a small number of detached or pulled out fibers could be found (Fig. 1c). Further observation illustrated that these detached fibers were relatively short (Fig. 1c), which implies they were ends of the whole fibers. This finding indicates that fibers reinforced the system by crack deflection and crack tip blunting mechanisms. The finding explains the high fracture toughness value of the material.

On another hand, SEM observations of the microstructure of the polymer infiltrated ceramic indicated that the porous pre-sintered block was successfully infiltrated but the volume of polymer phase is relatively small (Fig. 1e). High volume fraction of ceramic particles made the material harder and produced properties closer to sound enamel and dentine. Due to the crack deflection effects of tough ceramic particles (Fig. 1f), the fracture toughness of the material is comparable to plastic phantom tooth.

5 Conclusion

Current phantom teeth are a cheap option for simulation but are not very well suited to simulating the clinical sensation of preparing natural teeth. Due to their low hardness, stiffness and brittle index, students may easily cut too quickly and too deeply into the phantom teeth. As a result, it is not surprising to see poor quality cavity and crown preparations on phantom teeth in simulation clinics. Moreover, it can be a challenge for inexperienced students, lacking hand skills, to start with soft materials. Repeated poor quality cavity and crown preparations may limit the confidence and pre-clinical progress of the students. In contrast, incorporation of a high concentration of hard ceramic network makes the polymer infiltrated ceramic harder and stiffer than current phantom teeth, which should provide students a more valid simulation of the cutting resistance during cavity and crown preparation. Similar mechanical properties to enamel and dentine make the material a highly appropriate choice for simulation in dental education.

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