Dental high-speed cutting of porous-machinable-ceramic/resin composites and bovine enamel

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New ceramic/resin composites were prepared by filling the intercrystal spaces of a porous-CaO·SiO_2-based machinable ceramic with [methyl methacrylate (MMA) + triethylene glycol dimethacrylate (TEGDMA) + Bis-phenol A glycidyl dimethacrylate (Bis-GMA)] copolymers. The composites exhibited a hardness, smaller and analogous to that of bovine enamel. Weight-load cutting tests were performed on the composites and bovine enamel, employing diamond points driven by an air-turbine handpiece. While the applied load was increased stepwise, we measured the rotational cutting speed and the cutting volume. With the addition of the applied load, the rotational cutting speed decreased and the cutting volume increased. With incrementing applied load, the degrees of the decrease in the rotational cutting speed and the increase in the cutting volume for bovine enamel were well simulated by those for the composites. It was therefore speculated that the porous-ceramic/resin composites are suitable for typodont teeth in the dental preclinical cutting exercise, and that another potential use of the composites might be in the production of future machined dental prostheses.

1. Introduction

In preclinical courses, dental students practice cavity and crown preparations on extracted human teeth and artificial typodont teeth. Because extracted human teeth are becoming difficult to obtain, there has been a widespread tendency towards increased use of artificial typodont teeth [1].

Melamine or epoxy resin typodont teeth have often been used in the preclinical classes [2, 3]. The soft and sticky nature of the resin, however, does not allow the student to employ fully a high-speed air-turbine handpiece, partly because of the excessive wear of rotary cutting instruments [4]. Thus, it is strongly expected that new typodont teeth will be developed so that cutting of natural teeth can be simulated better and the student would be provided with a much more realistic preclinical programme.

We have already reported that machinable ceramics are excellent candidates for typodont teeth [5–7]. The machinability of such ceramics results from a chip-forming process in which the cut is restricted to the vicinity of the cutting tool by a crack-deflecting mechanism. The machinability of a β-wollastonite (CaO·SiO_2)-based machinable ceramic depends on the pre-existing cracks (i.e. intercrystal porosity), which prevent the growth of cracks associated with machining and facilitate the formation of powdered chips during machining [8]. The porous-CaO·SiO_2-based ceramic also has the potential to be toughened and strengthened by filling the interconnected pores in the ceramic body with various resins. These composites may bring about new materials with behaviour upon cutting adjustable to that of natural tooth.

The purposes of this study were therefore, first, to prepare porous-CaO·SiO_2-based ceramic/(MMA + TEGDMA + Bis-GMA) copolymer composites, and to examine their physical and mechanical properties, and secondly, to evaluate their cutting behaviour with dental diamond points driven by a dental air-turbine handpiece under weight-load cutting test conditions, and to compare their behaviour with that of bovine enamel. The relationships between the applied load and the rotational cutting speed and between the applied load and the cutting volume were analysed.

2. Materials and methods

2.1. Materials

According to the manufacturer, the porous-CaO·SiO_2-based machinable ceramic (Machinax low-density type; INAX Co., Aichi, Japan) employed had the following material characteristics: density 1.98 $g\,cm^{-3}$, porosity 36 vol %, mean porosity radius 1.8 μm, compressive strength 98 MPa, Vickers hardness 180 H_v and coefficient of thermal expansion 7.0×10^{-6} °C^{-1} [8]. The monomer mixtures that infiltrated into the porous ceramic consisted of commercially pure MMA and TEGDMA (both from Wako Chemical Co., Osaka, Japan), and Bis-GMA

TABLE I Compositions and codes of the porous-ceramic and three porous-ceramic/resin composites investigated

Ceramic	Mixing weight ratio of the monomer mixtures			Code
	MMA	TEGDMA	Bis-GMA	
Porous-CaO·SiO_2-based ceramic[a]				ML
Porous-CaO·SiO_2-based ceramic	1	1	1	ML+R1
Porous-CaO·SiO_2-based ceramic	1	2	1	ML+R2
Porous-CaO·SiO_2-based ceramic	1	1	2	ML+R3

[a] Chemical composition 55.4 wt % SiO_2, 41.7 wt % CaO and 2.9 wt % MgO, identified by electron-probe microanalysis.

(Shin-Nakamura Co., Wakayama, Japan). The weight mixing ratios of MMA, TEGDMA and Bis-GMA were predetermined to be 1:1:1, 1:2:1 and 1:1:2, respectively. The sample preparation for the porous-ceramic/resin composite is outlined below. First, the mixed monomers were stored in glass bottles at room temperature for 2 weeks. Secondly, the porous-ceramic specimens, 3 mm × 4 mm × 36 mm for physical and mechanical testing and 5 mm × 5 mm × 10 mm for cutting experiments, were immersed in the monomer mixtures at 37 °C for 7 days, followed by adding 0.5 wt % benzoyl peroxide (Wako Chemical Co., Osaka, Japan) to each monomer mixture, and storing at 37 °C for an additional day. Finally, the monomer mixtures covering and intruding the porous-ceramic blocks were heat-cured at 75 °C for 30 min and, subsequently, at 100 °C for 60 min in a constant-temperature oven (DN-41; Yamato Co., Tokyo, Japan). The porous-ceramic/resin composites were then removed by means of a low-speed diamond saw (Isomet; Buhler Co., Illinois, USA), followed by metallographical polishing sequentially from coarse 240-grit to fine 800-grit sandpaper. Table I shows the compositions and codes of the porous-ceramic and three porous-ceramic/resin composites examined.

Freshly extracted 3-year-old bovine lower anterior teeth were mounted in cold-cured polyester resin (Rigolac; Showa Kobunshi Co., Tokyo, Japan) blocks. Before the cutting tests the teeth were sectioned into two equal pieces along the tooth axis, using a low-speed diamond saw. The enamel on the labial side of the dissected bovine incisor, perpendicular to the cut plane, was then exposed to the atmosphere.

2.2. Density, hardness and flexure strength measurements

The density was measured by a pycnometric method, employing a Hubbard-type specific gravity bottle (Shibata Co., Tokyo, Japan). The hardness was measured, using a D-type Shore hardness tester (Shimadzu Co., Kyoto, Japan).

Three-point bending tests were carried out in a universal testing machine (Autograph; Shimadzu Co., Kyoto, Japan) at a crosshead speed of 0.5 mm min^{-1}. The equation that was used to find the flexure strength (σ_{3b}) was

$$\sigma_{3b} = 3Pl/2wt^2$$

where P is the maximum load recorded at failure of the specimen (N), l is the span length (30 mm), w is the width of the specimen (4.0 mm) and t is the thickness of the specimen (3.0 mm).

The ruptured surfaces of the three-point bending specimens were sputtered with gold and observed by scanning electron microscopy (SEM, JSM-T330A; Jeol Co., Tokyo, Japan).

2.3. Weight-load cutting tests

The workpiece was bonded on a round stage mounted on one end of the lever arm of a high-reliability cutting test machine (J. Morita Co., Kyoto, Japan) as its cutting test site indicated in Fig. 1. On the other end of the arm, a weight was placed in such a manner that a constant upwards force was applied to the workpiece. The water-spraying (40 ml min^{-1}), air-bearing, air-turbine handpiece (Astron; J. Morita Co., Kyoto, Japan)

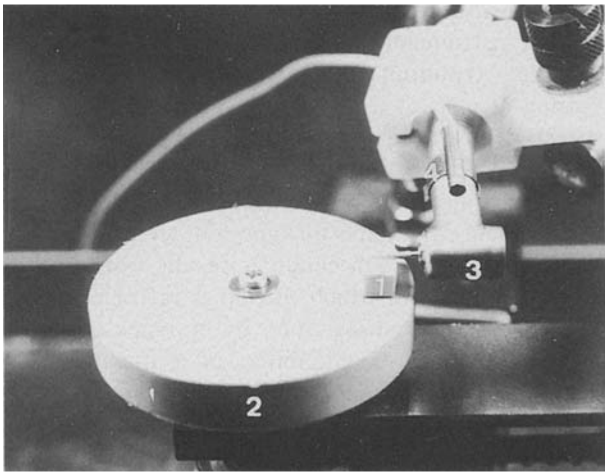

Figure 1 Photograph of the workpiece bonded on the round stage of the high-reliability cutting test machine: 1, workpiece; 2, round workpiece stage; 3, air-turbine handpiece; and 4, magnetic sensor for tachometer.

was held by a chuck and set in a fixed position so that the 4.0 mm long longitudinal tip of the rotating taper-cylinder fine-grit diamond point (mean diamond powder size 53 μm, B1f; GC Co., Tokyo, Japan) was in horizontal contact with the workpiece during the test cut. The air pressure was maintained at 3.5 kg cm^{-2}, as recommended by the manufacturer for the maximum cutting capability.

Cutting tests were performed in the following ways. While the applied load was varied from 20 to 40, 60 and 80 g, successively, with each test duration of 5 s, we measured two properties, namely the handpiece speed during cutting and the cutting volume. Throughout the test cut the speed of the handpiece was monitored consecutively at 0.1 s intervals by a magnetic sensor that detected the rotation of the magnetized point shank in the pick-up. The sensor was connected to an electric counter with a digital memory, which constituted a magnetic tachometer (Rammaster 1000; Ogura Jewel Co., Tokyo, Japan). The cutting volume of each test cut was determined by the mass of the heavy-bodied silicon impression material (Flexicon; GC Co., Tokyo, Japan) replicating the cut area divided by the density. The impression was weighed on an electric balance (Libror AEL-2000; Shimadzu Co., Kyoto, Japan) with a precision of 0.1 mg. For each workpiece a new diamond point was used, and cutting tests were repeated three times.

3. Results

Table II shows the density of the porous-ceramic and porous-ceramic/resin composites as well as of the three resins employed. It was confirmed that the density of the porous-ceramic (ML) was increased by infiltration of the monomer mixtures into the interconnected porosity of the ceramic and their subsequent heat-curing. For the three composites it was observed that ML+R3 composite had the highest density, followed by ML+R2 composite, and ML+R1 composite had the lowest density.

Table III indicates the mean Shore hardness and flexure strength values of the porous-ceramic and porous-ceramic/resin composites. It became evident that the three composites (ML+R1, ML+R2 and ML+R3) were harder and stronger than the porous-ceramic itself (ML). Of the three composites, ML+R3 possessed the highest two mechanical properties, followed by ML+R2, and ML+R1 had the lowest.

TABLE II Density of the three resins (copolymers) used, the porous $CaO \cdot SiO_2$-based ceramic and the three porous-ceramic/resin composites examined

Sample code	Density[a] (g cm^{-3})
R1 copolymer	1.21 ± 0.05
R2 copolymer	1.24 ± 0.02
R3 copolymer	1.30 ± 0.06
ML	1.98 ± 0.10
ML+R1	2.20 ± 0.10
ML+R2	2.30 ± 0.16
ML+R3	2.37 ± 0.40

[a] Means ± SD for three measurements.

TABLE III Shore hardness and flexural strength of the porous-$CaO \cdot SiO_2$-based ceramic and the three porous-ceramic/resin composites. Values are means ± SD for five measurements

	Sample code			
	ML	ML+R1	ML+R2	ML+R3
Shore hardness, H_S	32 ± 1	40 ± 3	63 ± 3	67 ± 1
Flexural strength (MPa)	56 ± 14	62 ± 8	76 ± 4	82 ± 3

Fig. 2a and b shows SEM micrographs of the porous-ceramic itself (ML) and the ML+R1 porous-ceramic/resin composite, respectively. As can be seen, the original porous-ceramic (ML) consisted of aggregates of acicular crystals and intercrystal spaces. In the ML+R1 composite the acicular crystals were found to be coated with the resin, but intercrystal spaces still remained.

Fig. 3a and b shows the experimental data for the handpiece speed changes when cutting bovine enamel and ML+R1 composite, respectively, with a maximum applied load of 80 g. During cutting enamel, following an initial gradual decrease, the handpiece speed became quasi-constant for about 1 s and then increased slightly. On the other hand, during cutting the composite, following an initial gradual decline, the

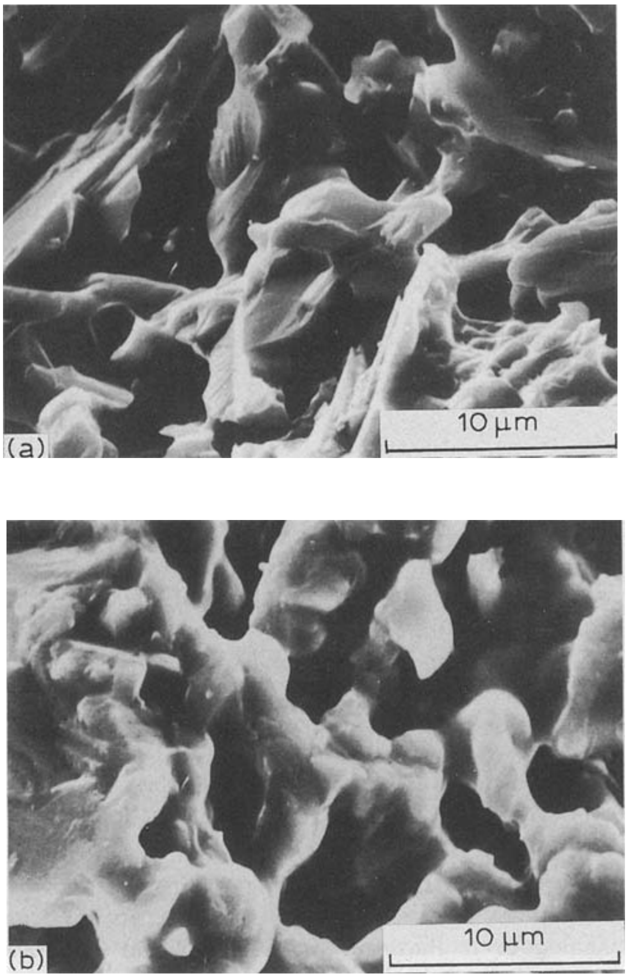

Figure 2 SEM micrographs of the ruptured surfaces of (a) the porous-ceramic (ML) and (b) the ML+R1 porous-ceramic/resin composite.

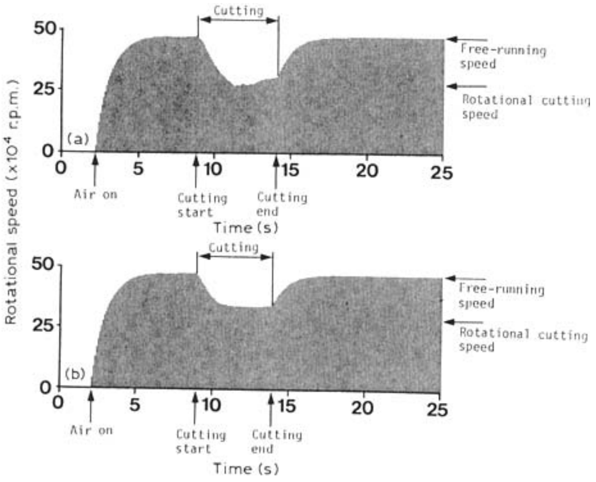

Figure 3 Handpiece speed changes when cutting (a) bovine enamel and (b) the ML + R1 porous-ceramic/resin composite with an applied load of 80 g.

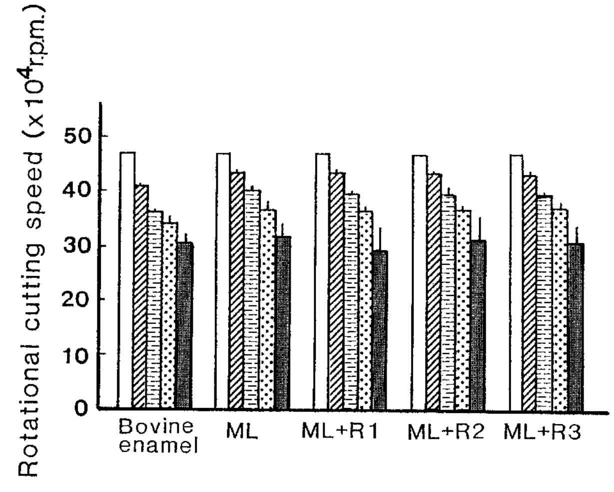

Figure 4 Effects of the applied load on the rotational cutting speed for the porous-ceramic and three porous-ceramic/resin composites. Note that each datum expresses the mean value of three measurements and the bar shows its SD. (□) 0, (▨) 20, (▤) 40, (▦) 60 and (■) 80 g load.

handpiece speed became almost constant for approximately 3 s. Although such variation existed, the minimum or steady-state rotational speed of the handpiece during the test cut was here referred to as the rotational cutting speed. Fig. 4 shows the effects of the applied load on the rotational cutting speed for all workpieces. It became apparent that increasing the applied load caused a decrease in the rotational cutting speed. The degree of this drop did not vary significantly between five workpieces. Fig. 5 shows the effects of the applied load on the cutting volume for all workpieces. It was found that increasing the applied load produced an increase in the cutting volume. The magnitude of this tendency for bovine enamel was analogous to those for the ML + R2 and ML + R3 composites, and exceeded those for the other two workpieces (ML and ML + R1). Over the whole load level examined, the cutting volume of bovine enamel was similar to those of ML + R2 and ML + R3 composites, and surpassed those of the other two workpieces (ML and ML + R1).

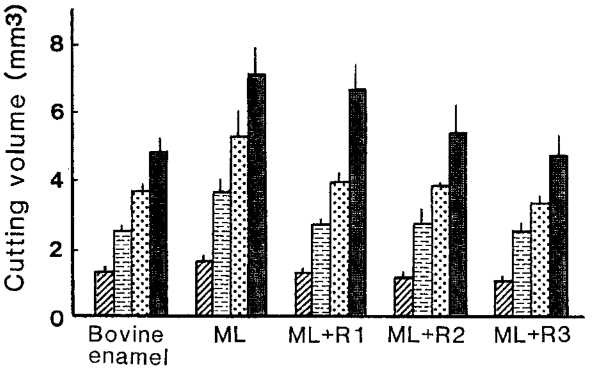

Figure 5 Effects of the applied load on the cutting volume for the porous-ceramic and three porous-ceramic/resin composites. Note that each datum expresses the mean value of three measurements and the bar shows its SD. (▨) 20, (▤) 40, (▦) 60 and (■) 80 g load.

4. Discussion

Because there is no standard to evaluate the dental high-speed cutting behaviour of typodont teeth, we adopted the weight-load cutting tests, as reported elsewhere [9, 10]. Although the cutting experiments conducted here were technically narrow, they seemed to provide valuable information. In the next phase of this study, however, some subjective evaluation by teachers and students will be needed.

It was demonstrated from the results obtained that partially filling the intercrystal porosity with resins (copolymers) gave the porous-$CaO \cdot SiO_2$-based machinable ceramic a higher density and improved its mechanical properties. The composition of the monomer mixtures significantly affected the density, hardness and flexure strength of the hardened porous-ceramic/resin composites. The greater the amount of high-molecular weight (MW) monomers (MW of MMA, TEGDMA and Bis-GMA 100, 286 and 512, respectively) in the monomer mixture, the higher the density, hardness and flexure strength of the set composite (Tables I–III). The increase in the high-MW monomer content in the monomer mixture, however, causes the monomer mixture to be more viscous, rendering monomer infiltration into the porous-ceramic difficult. Thus, caution is needed when choosing the mixing ratio of the three monomer liquids. It was speculated from the density measurements (Table II) that the degree to which the three monomer mixtures infiltrated into the porous ceramic was very high. However, it should be remarked that the monomers that entered into the porous-ceramic through interconnected spaces usually shrank when heat-cured, thereby leaving intercrystal spaces present after heat-curing, as shown in Fig. 2b.

Interestingly, there seems to be a correlation between the two strength values and the cutting volume. The stronger the porous-ceramic/resin composite is, the lower the cutting volume (Table III and Fig. 5). In this study ML + R3 composite had a hardness and cutting volume similar to those of the bovine enamel used (the Shore hardness value of the bovine enamel employed was about 70 H_S).

However, it should be noted here that natural enamel is heterogeneous. The density of enamel varies between the proximal edge and centre, as do the directions of the enamel rods [11]. The age, site and storage conditions considerably affect the properties of natural tooth enamel. Such heterogeneity might induce a variation in the handpiece speed during cutting enamel, in contrast to the steady-state handpiece speed during cutting the homogeneous porous-ceramic/resin composite (Fig. 3). Because the target is variable, it is desirable to prepare typodont teeth with various mechanical properties and behaviour upon cutting. The porous-ceramic/resin composites examined met this requirement. The advantage of the composite typodont tooth is that it allows preclinical simulational experience in classes of students and can provide identical anatomical shapes and homogeneous materials, thus reducing instructional variation. Furthermore, it was advantageous that during the first, second and third test cuts the cutting effectiveness of the diamond point on the prepared composites (i.e. the cutting volumes) remained almost constant. The rotational cutting speeds of three composites were close to that of bovine enamel (Fig. 4). This is also beneficial if the tactile sense during cutting is related to the speed-drop of the handpiece during cutting (Fig. 3). Porous-ceramic/resin composites may be most useful for the cutting exercise of the crown preparation, in which enamel reduction is the major part of the cutting. In the near future, however, it is expected that a dentine layer will be added to the composite typodont tooth so that the cutting exercise of the cavity preparation will be more practical.

Another potential use of the porous-ceramic/resin composite examined is a workpiece employed for crowns and inlays milled by computer-aided design and computer-aided manufacturing [12–14]. Research in this field is also expected.

5. Conclusions

To overcome the problem of the shortage of extracted human teeth available for preclinical cutting exercise, we prepared porous $CaO \cdot SiO_2$-based machinable ceramic/(MMA + TEGDMA + Bis-GMA) copolymer composites, and evaluated their physical and mechanical properties and behaviour upon cutting. The following observations were made.

1. The density, hardness and flexural strength of the composite were increased when the copolymer in the composite contained more-viscous monomers.
2. It became more difficult to cut the composite when the copolymer in the composite contained more-viscous monomers.
3. Dental high-speed cutting of the strongest composite obtained simulated that of bovine enamel well.

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References

1. E. R. AMBROSE, M. N. HALHOUL and J. M. GOURLEY, *J. Dent. Educ.* **49** (1985) 352.
2. A. R. SILVESTRI, JR, S. N. COHEN and I. SINGH, *ibid.* **43** (1979) 641.
3. A. Y. WONG, J. F. WATSON and R. P. THYE, *ibid.* **43** (1979) 637.
4. S. F. ROSENSTIEL, A. G. GEGAUFF, R. F. BLEINHOLDER, R. McCAFFERTY and J. MARTELLO, *J. Dent. Res.* **68** (Spec. Issue) (1989) 269 (Abstr. 704).
5. M. TAIRA, K. WAKASA, M. YAMAKI and A. MATSUI, *J. Dent. Educ.* **54** (1990) 244.
6. *Idem, J. Oral Rehabil.* **17** (1990) 461.
7. N. TANAKA, M. TAIRA, K. WAKASA, H. SHINTANI and M. YAMAKI, *Dent. Mater.* **7** (1991) 247.
8. Y. GOTOU, H. ISHIDA and T. FUJISAWA, *Fine Ceram.* **10** (1989) 27 (in Japanese).
9. W. B. EAMES and J. L. NALE, *J. Amer. Dent. Assoc.* **86** (1973) 412.
10. R. GRAJOWER, A. ZEITCHICK and J. RAJSTEIN, *J. Prosthet. Dent.* **42** (1979) 422.
11. J. W. OSBORN, *J. Dent. Res.* **47** (1968) 395.
12. D. REKOW, *J. Prosthet. Dent.* **58** (1987) 512.
13. F. DURET, J.-L. BLOUIN and B. DURET, *J. Amer. Dent. Assoc.* **117** (1988) 715.
14. W. H. MÖRMANN, M. BRANDESTINI, F. LUTZ and F. BARBAKOW, *Quintessence Int.* **20** (1989) 329.

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