INTRODUCTION

Ceramic materials have seen significant improvements in their esthetic and mechanical properties. All-ceramic prostheses have also seen significant improvements in their precision of fit because of newly developed fabrication techniques. Together, these improvements have endeared all-ceramic prostheses to both dentists and patients alike. However, the fracture of all-ceramic prostheses has still clinically occurred. Once a single fracture of all-ceramic prostheses occurs clinically, removing the failed all-ceramic prostheses, especially when removing zirconia-core-based prostheses, becomes a serious trouble for both dentists and their patients.

Dental ceramics are inherently brittle and susceptible to failure, especially when subjected to repeated contact loading in moist environments. In the oral environment, bending forces induce tensile stresses and the maximum tensile stress occurs at the contact surface area of a prosthesis. Flaws and pores are inherently present in ceramic materials, and brittle fractures occur because of stress concentration at these sites.

With an inevitable presence of microscopic flaws and pores in ceramic materials, an assessment of their ability to withstand tensile stresses seemed to be a meaningful approach to estimate or predict the service life of all-ceramic prostheses. Numerous reports have shown that when all-ceramic prostheses were subjected to loading, the presence of pores heightened the stress concentration and reduced their fracture resistance. Thompson et al. further pointed out that the fracture initiation sites of dental ceramics were controlled primarily by the location and size of the critical flaw. Their study of clinically failed all-ceramic crowns by fractographic analysis revealed that failure initiation sites were located at large internal pores or at the veneer-core interface. Fractographic analysis studies by Kelly et al. also showed that the source of fracture in all-ceramic prostheses was typically located at the veneer-core interface.

Fractography is a method routinely used on fractured specimens to determine the original sites and root causes of failure. In this study, we proposed using micro X-ray CT as a nondestructive inspection tool to reveal the internal morphology of experimentally fabricated all-ceramic prostheses before seating, by revealing the locations and sizes of pores as well as measuring veneer and core thicknesses. Clinically failed all-ceramic prostheses were examined with scanning electron microscopy (SEM) and micro X-ray CT to investigate the relation between the presence of pores and crack propagation.

MATERIALS AND METHODS

Fabrication of experimental all-ceramic crowns

Ceramic copings (n=4) made from glass-infiltrated Vita In-Ceram Zirconia (Vita Zahnfabrik, Bad Säckingen, Germany; In-ZI) were fabricated using the Wol-Ceram system (Wolz Dental-Technik, Ludwigsafen, Germany). Infiltration of borosilicate glass on zirconia was performed at 1,100°C (Esthemat Slim, Shofu, Kyoto, Japan). Excess glass was removed using a coarse-grit diamond bur. After airborne-particle abrasion with aluminum oxide (Al₂O₃) at 4-bar compressed air, all copings were veneered with a feldspathic porcelain (VM7, Vita Zahnfabrik, Bad Säckingen, Germany).

Internal morphology inspection before crown seating

Micro X-ray CT (TDM, Yamato, Tokyo, Japan) was used to nondestructively inspect the internal morphologies of the experimentally fabricated all-ceramic crowns to reveal pore locations and pore sizes. A series of 500...
images were taken in each axis, amounting to a total of 1,500 images for each experimental all-ceramic crown. To investigate pore size distribution, 21 images of each axis were selected as follows. First, the middle piece was selected. Then, 10 pieces were selected from the middle one toward both ends at 25-piece intervals. In every image, the number of pores at each of these three sites was counted: veneer, veneer-core interface, and core.

Fracture site observation using SEM and micro X-ray CT
The fracture sites of four clinically failed, all-ceramic prostheses were observed using a scanning electron microscope (Miniscope TM-1000, Hitachi, Tokyo, Japan). As with the experimentally fabricated all-ceramic crowns, they were manufactured using the Wol-Ceram system; their veneer and core ceramic materials were VM7 and In-ZI respectively. Backscattered electron microscope images of their fracture sites were acquired under 15 kV accelerating voltage. The internal morphologies of the clinically failed all-ceramic prostheses were also nondestructively observed by micro X-ray CT under 75 kV X-ray tube voltage and 0.010 mA tube current.

RESULTS
Internal morphology of all-ceramic crowns
Micro X-ray CT analysis revealed that multiple pores existed within the veneer and core of experimentally fabricated all-ceramic crowns (Figs. 1a and 1b). As given in Table 1, pores ranging from φ50 to φ300 µm existed within the veneer, veneer-core interface, and core. The prevalent pore sizes were φ50–100 µm, with scanty large ones of φ250–300 µm located in the core and veneer-core interface.

In Fig. 1c, both veneer and core had the same thickness, and thus their contours were parallel to each other. In Fig. 1d however, the veneer had an irregular
thickness. Either end of the veneer had a greater thickness than the center, and that the core had inadequate thickness to match or support the greater veneer thickness at both ends.

In both Figs. 1c and 1d, large pores were observed at the veneer-core interface. Pore size was φ230 µm in Fig. 1c, but φ330 µm in Fig. 1d.

**SEM fractographic analysis**

Figure 2 is a series of characteristic SEM images of the fracture sites of clinically failed all-ceramic prostheses. Figure 2a shows a fracture site which appeared like a three-dimensional terraced landscape. Several crater-like pores (white arrows) existed on or adjacent to the linearly stretched edge. These pores (dashed arrows) were also present at the junction of fractured site. Figure 2b shows a fracture site with two pores near the veneer-core interface. In Fig. 2c, a long linear crack at the veneer-core interface ran through a pore of about φ18 µm. Micro X-ray CT analysis revealed pores/flaws in the veneer and cracks in the core (white and black arrows).

### Table 1 Pore size distributions within the veneer, veneer-core interface, and core

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average pore amount</th>
<th>Veneer</th>
<th>Interface</th>
<th>Core</th>
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</thead>
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<tr>
<td></td>
<td>-φ100 µm</td>
<td>φ100–200 µm</td>
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<td>-φ100 µm</td>
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<tr>
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<td>0</td>
<td>5</td>
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</table>

**Fig. 2** SEM and micro X-ray CT images of clinically failed all-ceramic prostheses. (a) Several crater-like pores existed on or adjacent to the linearly stretched edge (white arrows). Several pores were also present at the junction of fractured site (dashed arrows); (b) Two pores of about φ20 µm existed near the veneer-core interface; (c) A crack parallel to the veneer-core interface ran through a pore of about φ18 µm; (d) Micro X-ray CT analysis revealed pores/flaws in the veneer and cracks in the core (white and black arrows).
DISCUSSION

During the process of ceramic manufacturing which entails the build-up and sintering stages, pores are inevitably formed within ceramics\(^\text{15,11}\). Volume changes with temperature during ceramic manufacturing is another contributing factor to pore formation\(^\text{12}\). In this study, micro X-ray CT clearly and nondestructively revealed the distribution patterns of pores within the veneer, veneer-core interface, and core. The average amounts of pores shown in Table 1 were based on only 21 pieces of 500 images in each axis. This meant that many more pores existed within the all-ceramic prostheses.

Pores can scatter light, decreasing translucency, and act as crack initiators with high stress concentration, lowering strength in tension and shear\(^\text{19}\). In this study, pores existed on the crack, at the edge of fractured surface, or at the junction of several fracture sites (Fig. 2a). These images indicated a strong relationship between the existence of pores and crack propagation.

The veneer-core interface is a highly vulnerable source for failure because of poor adhesion between the veneer and core ceramics, which are sintered together\(^\text{9}\). The existence of pores at the interface renders an all-ceramic prosthesis even more vulnerable to failure. Our SEM images of the clinically failed all-ceramic prostheses showed a crack running through a few pores along the veneer-core interface (Figs. 2a and 2c). Micro X-ray CT analysis of the experimentally fabricated all-ceramic crowns showed that pores could exist within any part of all-ceramic prostheses, including the veneer-core interface (Table 1). In view of the detrimental effect of porosity, a continuous pore pattern extended along the veneer-core interface would well increase the risk of delamination.

In the present study, copings were made from glass-infiltrated In-Ceram Zirconia. It was reported that the fracture resistance of In-Ceram Zirconia (Dentsply Ceramco) was greater than those of In-Ceram Alumina and IPS Empress 2\(^\text{16}\). While zirconia cores are very fracture-resistant, the fracture toughness of veneer ceramics still poses a problem\(^\text{15}\). Veneer ceramics have an aesthetic advantage, but are lower in flexural strength and fracture toughness compared to core ceramics.

Apart from the mechanical properties of veneer and core ceramics, veneer and core thicknesses also play a critical role in reducing chipping or fracture risks. In Fig. 1c, both veneer and core had an even or regular thickness, and thus the veneer contour was parallel to that of the core. Such a core design with matching veneer and core thicknesses is resistant to stress loading. On the other hand, in a mismatched core design, the veneer had greater thickness at both ends without a matching core thickness to support it (Fig. 1d). In the latter case, there is a greater risk of chipping or fracture when an occlusal force (dashed arrow) is applied. In the present study, crown copings were fabricated by electroforming method using the Wol-Ceram system. With electroforming systems, some parts of the veneer might have a greater thickness. Therefore, electroformed all-ceramic prostheses might have a lower fracture toughness and higher chipping/fracture risk.

With heightened awareness about metal allergies and increasing aesthetic demands, all-ceramic prostheses are well poised to be a popular treatment choice among dentists and patients in the future. However, all-ceramic prostheses are prone to brittle fractures and the need for removal in the event of a fracture can be a daunting prospect for both the dentist and patient. Consequently, these fears and concerns may thwart the use and development progress of all-ceramic prostheses. Therefore, it is important to be able to nondestructively inspect all-ceramic prostheses for flaws and defects before seating, and reproduce them if there is a risk of failure. In this study, micro X-ray CT proved to be a useful tool for nondestructive inspection of the internal morphology of all-ceramic prostheses: location and size of flaws/pores inside, core and veneer thicknesses, and crack initiation and propagation. It is thus highly recommended to be used for the pre-seating inspection of all-ceramic prostheses to reduce the rate of clinical failure.

CONCLUSION

Results of this study showed that micro X-ray CT could be used to determine pore location and pore size within both core and veneer, as well as reveal core and veneer contours. With a view to preventing clinical failures of all-ceramic prostheses, we recommend using micro X-ray CT as a nondestructive inspection tool to screen these prostheses for critical defects before seating.

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REFERENCES

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