Original Article

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Characterization of internal structural integrity of all-ceramic crowns using micro-computed tomography

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Different material and fabrication technique might affect the flaw distribution in a dental restoration. The objectives of this study were to quantify the percentage volume of the existing flaws in an all-ceramic posterior restoration fabricated by heat-pressing and computer-aided design and computer-aided manufacturing (CAD-CAM) techniques.

Materials and methods: Three lithia-disilicate-based dental ceramics were used in this study (VINTAGE LD Press, IPS e.max Press and IPS e.max CAD). Ten upper first molar crowns were made for VINTAGE LD Press and IPS e.max Press as monolithic crowns using a heat-pressing technique. Ten posterior crowns were made for IPS e.max CAD using a CAD-CAM technique. Ten upper first molar substructures were also made using IPS e.max CAD and veneered with IPS e.max Ceram using a conventional condensation and sintering technique, as a control group. Micro-computed tomography (micro-CT) was used to analyze internal defects within each ceramic crown using image pixel size of 9.16 micron and a power voltage of 80 kV. The statistically significant differences between the mean percentages of closed pore for all experimental groups were analyzed using Kruskal-Wallis nonparametric test at a significance level of .05.

Results: The quantity of existing pores in an all-ceramic posterior crown was ranged between 0.0018 to 0.0482 % and Vintage LD Press and IPS e.max® CAD veneered with IPS e.max® Ceram had the highest numbers of pore compared with other monolithic restorations. All the internal pores were randomly distributed with the sizes of 36.6-256 μm.

Conclusion: The results from this study indicated that processing technique and manufacturer had an effect on the quantity and size of internal pores observed in all-ceramic restorations.

Key words: all-ceramic crown, CAD-CAM, heat-pressing, internal porosity, micro-CT, 3D images

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Introduction

Micro- computed tomography (micro-CT) is a 3-dimensional imaging of an object. It is a nondestructive evaluation of an internal structure that can be related to physical, biological or mechanical properties of that object. Micro-CT has been widely used in structural analyses of soft and hard living tissues, both in medical and dental researches [1-3]. This technique has some advantages such as good resolution obtained from small and complex shaped materials, no specimen preparation, and noninvasive technique. There are also some limited conditions that micro-CT is not a suitable tool such as analyses of metal or material with high atomic number which can scatter the x-ray beam and compromise the resolution of obtained 3-D image [4].

In dentistry, micro-CT is used to characterize bone and implant interfaces, internal tooth structures and restorations [3,5-7]. Internal structures or interfaces can be effectively investigated using

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micro-CT when compared with observation from sliced specimens or detection from conventional instruments. Defects or voids within dental restorative materials can also be detected using this technique [6]. Internal and surface pores or defects are usually generated during fabrication process or during usage. For fixed partial dentures, conventional lost wax casting or pressing techniques, condensation and sintering of wet ceramic powder are common fabrication techniques used in a dental laboratory. Recently, computer-assisted design and computer-assisted manufacturing systems (CAD-CAM) has become a routine fabrication process and a variety of dental ceramic blocks can be used with these CAD-CAM systems. These dental ceramic blocks are presintered or fully sintered and their quality should be assured by the manufacturers.

Porosity or defects within dental materials could be commonly observed when processed by conventional casting or powder sintering techniques [8,9]. These defects could lower their fracture resistance and should be controlled to the minimal amount. It has been shown that clinically failed dental restoration would occur from surface damage or internal flaw with approximate size of 100-900 μm [10]. Therefore, defects or flaws are detrimental to ceramic materials both internally and superficially. Nevertheless, there is limited information regarding the size, shape, and distribution of flaws existing in all-ceramic prostheses after processing into a tooth-shape structure. Different material and fabrication technique may affect the flaw distribution in a dental restoration. The objectives of this study were to quantify the percentage volume of the existing flaws in an all-ceramic posterior crown fabricated by heat-pressing, conventional condensation and sintering and CAD-CAM techniques and characterize these flaws in terms of size and shape, including their location in that restoration.

Materials and methods

Materials used in this study were Vintage LD Press ,IPS e.max®Press, IPS e.max® CAD and IPS e.max®CAD veneered with IPS e.max® Ceram as shown in Table 1. Three lithia-disilicate-based dental ceramics were used in this study. Ten upper first molar crowns were made for each dental ceramics as monolithic crowns using either heat-pressing or CAD-CAM techniques. Ten upper first molar substructures were also made using IPS e.max® CAD and veneered with IPS e.max Ceram using a conventional condensation and sintering technique and used as a control group.

Table 1. Details of materials used in this study

Materials	Manufacturers	Compositions
VINTAGE LD PRESS	SHOFU INC. Address: 11 Kamitakamatsu-cho, Fukuine, Higashiyama-ku, Kyoto 605-0983, JAPAN	Lithium-disilicate-based glass ceramic for heat-pressed technique
IPS e.max® Press	Ivoclar Vivadent AG Bendererstrasse 2 9494 Schaan Liechtenstein	Lithium-disilicate-based glass ceramic for heat-pressed technique
IPS e.max® CAD	Ivoclar Vivadent AG Bendererstrasse 2 9494 Schaan Liechtenstein	Lithium-disilicate-based glass ceramic for CAD-CAM technique
IPS e.max® Ceram	Ivoclar Vivadent AG Bendererstrasse 2 9494 Schaan Liechtenstein	Nano-fluorapatite glass ceramic veneering material

1. Crown preparation

For heat-pressed lithia-disilicate-based dental ceramics, a wax-up of upper first molar crown was made. A die plaster model and a wax-up were scanned using a laboratory scanner (inEos Blue, Sirona dental systems GmbH, Bensheim, Germany) to attain 3-dimensional images and used to construct a 3-D full-contour crown model. Twenty crowns were milled from a milling machine (inLab MC XL, Sirona dental systems GmbH, Bensheim, Germany) using investable acrylate polymer blocks (IPS AcrylCAD blocks, Ivoclar Vivadent AG, Schaan Liechtenstein). After investing of twenty acrylate crowns and pressing according to the manufacturers'instruction, two ceramic crowns were fabricated, ten crowns for VINTAGE LD Press and ten crowns for IPS e.max® Press crowns. These ceramic crowns were cleaned, finished and glazed with glazing material to obtain the final restorations.

For posterior single crown fabricated from a CAD-CAM technique, ten crowns were milled from a 3-D full-contour crown model, identical to that used for pressing technique, using IPS e.max® CAD blocks. After crystallization in a furnace, all ceramic crowns were glazed with a glazing material to obtain the final restorations. Another ten crowns were milled from a cut-back crown model using IPS e.max® CAD blocks to obtain ceramic substructure for veneering. After crystallization, these substructures were veneered with IPS e.max Ceram veneering material using a silicone index in order to obtain all-ceramic crowns that were closely resemble to the monolithic crowns. These veneered crowns were glazed to obtain the final restorations.

2. Micro-computed tomography (micro-CT)

All ceramic crowns were scanned using a micro-CT (Skyscan 1173, Bruker, Kontich, Belgium) with image pixel size of 9.16 micron, a power voltage of 80 kV and tube current of 100 μA, a 1.0 mm Al filter with rotation step of 0.4 degree and scan for 180 degree parameters were used to analyze pore size and distribution in all-ceramic crowns. CT analyzer software (CTAn 1.16: Skyscan, Kontich , Belgium) was used to analyze the micro-CT 3-D images including pore size and distribution, percent porosity and connectivity. CT volume software (CT Vol: Skyscan, Kontich, Belgium) was used for 3-D image visualization.

For an x-ray analysis, the sample was fixed on a specimen holder with the diameter of 4 mm which rotated between the fixed x-ray source and a detector. The sample was positioned then the polychromatic spectrum was generated over a crown specimen. The polychromatic x-ray was attenuated when passing through the sample. The intensity of the attenuated x-ray was measured by a detector, and gray-level images representing the attenuation degree were reconstructed to represent the minimum and maximum intensity. The two-dimensional tomographic images which gray-level ranged (threshold) from 46 to 225 was constructed. The digital geometry processing was used to generate a three-dimensional image of a sample from a large series of two-dimensional radiographic images taken around a single axis of rotation. A specialized software (CTAn version 1.16) was used to analyze the micro-CT 3-D images including pore size and distribution, and percent porosity.

The amount of closed pore (percent porosity) in each all-ceramic crown was used for a statistical analysis. The statistically significant differences between the mean percentages of closed pore for all experimental groups were analyzed using Kruskal-Wallis nonparametric test at a significance level of .05.

Results

The pore characteristics of all-ceramic crowns are presented in Table 2. The mean percentages of closed pore were significantly different for all experiment groups except those of Vintage LD Press and IPS e.max® CAD veneered with IPS e.max® Ceram as shown in Table 2. The mode pore sizes of Vintage LD Press, IPS e.max® Press, and IPS e.max® CAD were similar (36.6 µm for >99%). Pores with the diameter of 73.25 and 109.88 µm were observed in Vintage LD Press but the quantity was very minute (0.1-0.5%). For IPS e.max® CAD, only one monolithic crown had pore with the diameter of 73.25 µm for 8%. These results indicated the excellent uniformity of ceramic ingots and blocks. For IPS e.max® CAD veneered with IPS e.max® Ceram, the mode pore size was also 36.6 µm but the amount were 57-97% depending on the volume of pores in the veneering layer. Two ceramic crowns made from IPS e.max® Press were excluded from the analysis because they had atypical large flaws having a diameter of 300-400 µm (Figure 2.) that might be created during the pressing process or exist within the ceramic ingots.

The representative 3-D images generated by CTAn Software of all-ceramic crowns are shown in Figure 1. Internal pores could be observed in each crown, and were generally distributed in the crown structure.

Discussion

The conventional processing techniques for dental ceramics are heat-pressing, slip-casting and condensation and sintering techniques, etc. These techniques are used to fabricate fixed partial dentures and the products made from these techniques are acceptable in terms of function, longevity and esthetics. Presently, the computer-aided design and manufacturing (CAD-CAM) technique has become a regular procedure in dental practice and several dental restorative materials can be used to fabricate dental prostheses using this CAD-CAM technique. Many machinable ceramic blocks are commercially available and they are different in compositions and properties depending on the manufacturer's expertise. Dental prostheses fabricated from these ceramic blocks are expected to have fewer defects and better mechanical and physical properties compared with those fabricated from a conventional casting and sintering procedures. However, there is very limited information regarding the internal structural reliability of these ceramic blocks.

For dental ceramic materials, there are not only existing flaws from a processing process. During masticatory function, repeated loading can create microcracks or propagate the existing flaws and failure of dental restorations would occur [10]. For an existing flaw that is large, it could also act as a failure origin for a sudden catastrophic fracture that happens unexpectedly. It also has been shown that porosity at or beneath the surface might associate with some surface cracks and microcracking and it could initiate the onset of surface wear process [11]. If the flaw population and distribution in dental ceramic prosthesis could be defined, an estimation of the

Table 2. The pore characteristics of all-ceramic crowns investigated in this study

Crown types	Mean closed pore (%)	Pore size distribution (µm)	Mode pore size (µm)
Vintage LD Press	0.0376 ± 0.0149 [A]	36.6-109.88	36.6
IPS e.max® Press	0.0124 ± 0.0101 [B]	36.6	36.6
IPS e.max® CAD	0.0018 ± 0.0014 [C]	36.6-73.25	36.6
IPS e.max® CAD veneered with IPS e.max® Ceram	0.0482 ± 0.0316 [A]	36.6-256	36.6

Different superscript letters indicates statistically significant differences between groups.

probability of survival of this dental prosthesis could be effectively evaluated. This process can prevent atypical fracture cause from undesirable defects or flaws produced during processing or handling. However, it is difficult to identify defects within dental prostheses whether they exist. Only visual observation is used to identify large surface or subsurface flaws. Recently, micro-CT has been widely used in structural analyses of soft and hard living tissues in medical and dental researches. In this study, micro-CT was used in an attempt to evaluate internal flaws in a dental ceramic restoration. The size and location of these defects could be precisely determined from these x-ray generated 3-D imaging.

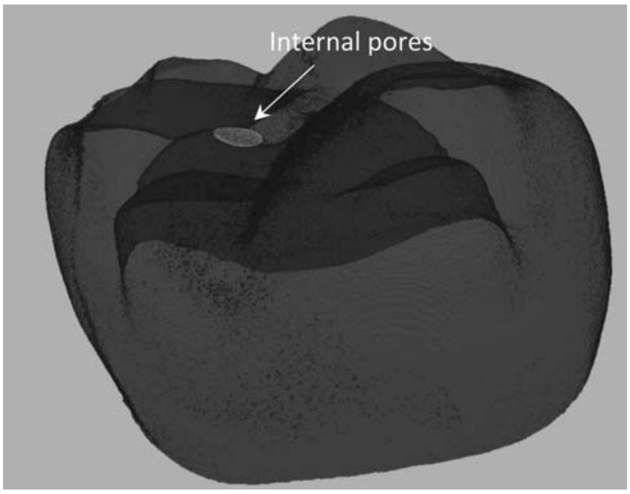
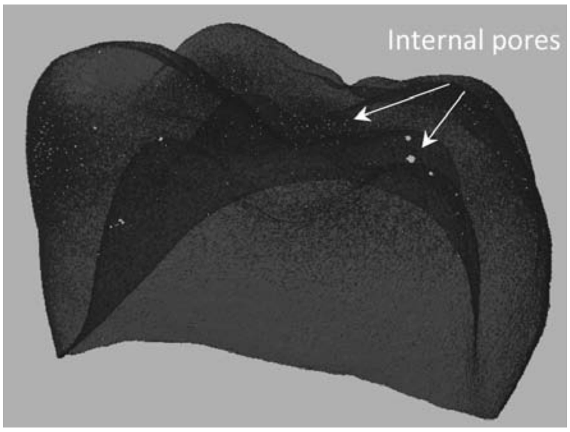
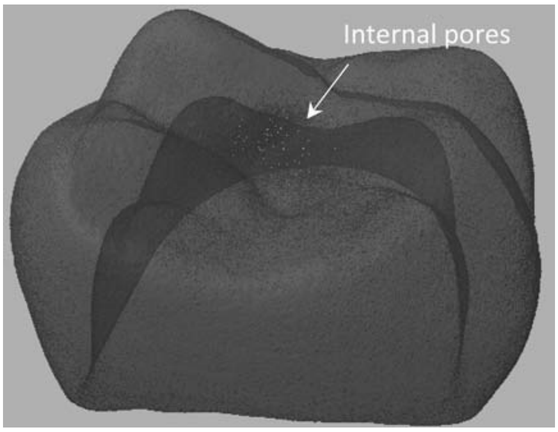


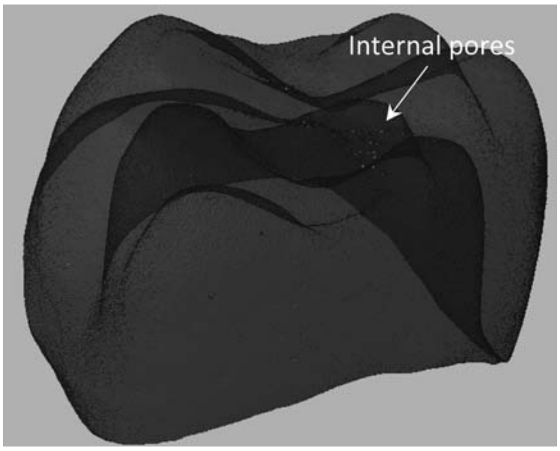
Figure 2. Atypical large pore in IPS e.max Press crown



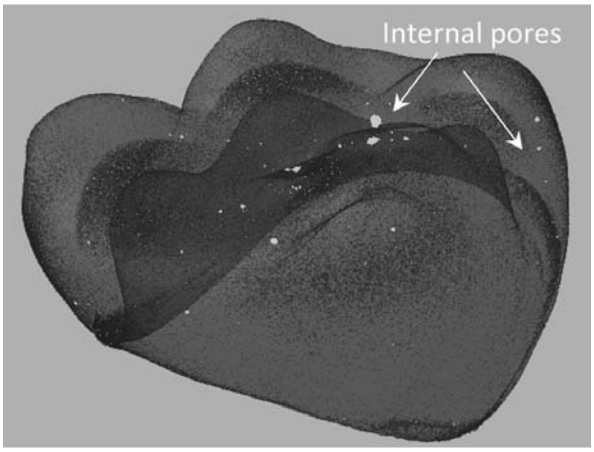
(a) Vintage LD Press



(b) IPS e.max Press



(c) IPS e.max CAD



(d) IPS e.max CAD veneered with IPS e.max Ceram

Figure 1. Three dimensional images of all-ceramic crowns with different size of internal pores

The results from 3-D image analysis in this study showed the distribution of very small pores within the ceramic material for all groups. The quantity of pores within IPS e.max® CAD was significantly fewer than those of IPS e.max® Press and Vintage LD Press. Because IPS e.max® CAD blocks were only milled the manufacturer-fabricated blocks and fired to obtain the final restorations, this might be the reason for less defects within the restoration. For IPS e.max® Press and Vintage LD Press, investing, pressing and divesting of ceramic restorations were performed and these processing steps could produce more surface and internal defects even these ceramic ingots were also prepared from the manufacturers. Two ceramic crowns made from IPS e.max® Press were excluded from the analysis because they had atypical large flaws having a diameter of 300 -400 μm (Figure 2.) that might be created during the pressing process or exist within the ceramic ingots. These a typical large flaws indicated the possibility of sudden failure as mentioned earlier if they were placed under functional loading conditions. Because ceramic ingots or blocks used in this study were produced from the manufacturers, it should be remarked that sizes of internal pores were incredibly discrete to be 36.63 and 73.25 μm for most of the pores and some was 109.88 μm (as observed in Vintage LD Press). These results suggested that different manufacturers had an effect on the quantity and sizes of internal pores.

For IPS e.max® CAD veneered with IPS e.max® Ceram, The number of pores was significantly higher than those of monolithic restorations. Veneering is the process of mixing powder with liquid and coat manually onto the substructure surface layer by layer. This process is well-known that it can produce enormous number of pore with various sizes [12]. In this study, the number of pore was increased significantly after IPS e.max® CAD was veneered with veneering materials. The pore sizes were varied in this group but they were obviously larger than those created by the manufacturing process.

As previously mentioned that clinically failed dental restoration would occur from surface damage or internal flaw with approximate size of 100-900 μm [10], it appears that internal pore sizes observed in this study were in the range that could cause failure of dental restorations, especially IPS e.max® CAD veneered with IPS e.max® Ceram. However, there are other factors that can affect the failure such as the location and orientation plane related to the masticatory loads [13]. Some internal flaws would become surface flaws after grinding and polishing. Or some near-surface flaws could help to propagate surface cracks created during chewing (repeated loading). The critical large flaw could definitely be the origin of failure by itself. Therefore, the quantity of flaws or defects should be kept minimal during processing or handling in order to reduce the susceptibility to failure of dental prostheses. For ceramic blocks and ingots used for CAD-CAM and heat-pressing techniques in this study, the numbers of internal flaws were minimal as shown in Figure1., except for Vintage LD Press and IPS e.max® CAD veneered with IPS e.max® Ceram. Because there is limited information regarding an acceptable limit number of pores, pore sizes and their distribution, careful selection of ceramic blocks or ingots should be addressed. The veneering procedure is also critical and it should not add more critical defects into dental restorations. Experienced dental technicians and careful handling at each step are required during working. Future works for internal characterization of other all-ceramic materials are necessitated to ensure the quality control and to evaluate the internal structural reliability of these dental ceramic materials.

Conclusions

1. The quantity of existing pores in an all-ceramic posterior crown was ranged between 0.0018 to 0.0482 % and IPS e.max® CAD veneered with IPS e.max® Ceram had the highest numbers of pore compared with other monolithic restorations.

2. All the internal pores were randomly distributed and the smallest size of pore was 36.6 μm and the largest flaw was 256 μm.

3. The results from this study implied that processing technique and manufacturer could have an effect on the quantity and size of internal pores observed in all-ceramic restorations.

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Competing interests: None declared
Ethical approval: None

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