Machining Accuracy of CAD/CAM Ceramic Crowns Fabricated with Repeated Machining Using the Same Diamond Bur

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The purpose of this study was to investigate the effect of repeated machining up to 51 times using the same diamond bur on machining accuracy of inner and outer surfaces of CAD/CAM (computer-aided designing and computer-aided manufacturing) machined ceramic crowns. The surface topography of machined crowns was examined using photographs. It was found that machining accuracy was not affected by the number of machining times. In all measuring points, the inner surface was machined to a dimension larger than the die model (i.e., increased gap), whereas the outer surface was machined to a dimension smaller than the crown model (i.e., smaller crown). Photo observation showed that cervical contour was machined in a clear, rounded form from 1st to 11th crowns.

Key words: CAD/CAM, Ceramic crowns, Machining accuracy, Diamond bur, Repeated machining

INTRODUCTION

Clinically acceptable CAD/CAM machined dental restorations have been fabricated these days, largely owing to the high quality of dental prostheses, streamlined working process, and improvement of laboratory environment1-7). On top of these reasons, cost reduction is another indisputable factor that encourages clinicians and dental technicians to use commercially available CAD/CAM system in their daily practice. If high-quality ceramic crowns can be fabricated with repeated machining using the same diamond bur without replacing a new one, production cost will be significantly reduced. Therefore, in this study, the authors aimed to investigate the machining accuracy of ceramic crowns fabricated with repeated machining, i.e., how many crowns can be machined using the same diamond bur, as well as determine the extent of surface degradation of the diamond bur used.

Machining accuracy of inner and outer surfaces of CAD/CAM machined ceramic crowns fabricated with repeated machining were evaluated using a three-dimensional coordinate measuring machine. In addition, durability of the diamond bur and surface topography of machined crowns were observed using SEM (scanning electron microscope).

MATERIALS AND METHODS

Materials

CAD/CAM restorative material (Bioceramics, ADVANCE Co. Ltd.) and machining tool (diamond ED (electro deposition) bur, CRESTECH Co. Ltd.) were used for this test. Bioceramics consisted of 60-65 wt% SiO2, 20-25 wt% Al2O3, 8 wt% K2O, 7 wt% Na2O, and 0.3 wt% CaO. In terms of mechanical properties, their values were as such: hardness was 552 HV, intensity was 2.4 g/cm², compression stress was 757 MPa, bending stress was 154 MPa, and thermal expansion was 8.8×10^-6/°C.

Methods

To evaluate machining accuracy of inner and outer surfaces of CAD/CAM machined ceramic crowns fabricated with repeated machining, the experiments were carried out with the experimental factors and standards shown in Table 1. The data were analyzed by one-way ANOVA. Fifty-one CAD/CAM ceramic crowns were fabricated using the same diamond bur.

Table 1 Experimental factors and standards

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<td>A: Crowns measured</td>
<td>1st</td>
<td>11th</td>
<td>21st</td>
<td>31st</td>
<td>41st</td>
<td>51st</td>
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This working process was repeated three times, where a total of 153 CAD/CAM ceramic crowns were fabricated.

**Specimens fabrication**

1. Die model and crown model
   Fig. 1 shows the die model (18-8 stainless steel, SUS304) and crown model (18-8 stainless steel, SUS304) used for this test. Table 2 shows their dimensions. A round form of 0.5 mm radius was prepared at both cervical contour and occlusal/axial line angle.

2. CAD/CAM System
   The CAD/CAM System (Dental Cadim, ADVANCE Co. Ltd., Japan) consisted of the working area where contact scanning and machining were done, complete with a built-in PC computer and software (Tracecut, Renishaw Plc.) (Fig. 2).

3. Scanning
   Shape of the die model and crown model was scanned using contact analog scanning method where the tip of a 1 mm cylindrical ruby probe contacted the die or crown model.
   
   Scanning parameters were as follows:
   - Scanning direction: two-way;
   - Scanning method: radial;
   - Scanning pitch: 0.05 mm;
   - Step-over distance: 0.05 mm;
   - Scanning speed: 100 mm/min;
   - Probe deflection: 70 g.

4. Data capture
   Shape of the die and crown was scanned in the scanning area of the CAD/CAM system unit. First, cervical contour of the die was scanned with 2D scanning. Margin line was defined using captured 2D X-Y data. The shape of the die was scanned radially with a 3D contact scanning method based on the captured 2D data. The shape of the crown, having been mounted on the die, was scanned in the same manner as the die.

5. Tool paths generation
   NC cutter paths and CAD output files were generated based on the captured data. The machining process was done in accordance with machining parameters shown in Table 3. A 2.0 mm diamond bur was used in the whole machining process, which comprised coarse, medium, and finishing machining.

6. Machining
   A diamond bur and a ceramic block were installed in the designated position in the CAD/CAM system unit. The inner and outer surfaces of a crown were machined according to generated tool paths data. When inner surface had been machined, the workpiece was turned 180° for machining on the outer surface. It took 50 minutes to machine the inner surface of a crown and another 25 minutes to machine the outer surface, totaling 75 minutes to

| Table 2 Dimensions of the die model and the crown model (mm, radius) Inner & Outer occlusal |
|---------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                                  | occlusal | 1.2 mm   | 2.0 mm   | 3.0 mm   | 4.0 mm   | 5.0 mm   | 6.0 mm   | margin   | height   |
| Die model (Inner)                | 3.087    | 3.175    | 3.230    | 3.303    | 3.376    | 3.447    | 5.945    |          |          |
fabricate a crown.

**Measurement**

1. Measuring machine

Inner and outer surfaces of machined crowns were measured using a 3D coordinate measuring machine (E-DC-M400, 3A ACCRETECH-TOKYO SEIMITSU Co. Ltd.) which consisted of both hardware (Type 2400-WBB S/N97-A0231, IBM) and software (40 series, all-purpose measuring program XYANA). Measurements were done using a probe (TPI, Renishaw) and a 1.0 mm stylus (radius). Measurement parameters were as follows: horizontal probe deflection (15 gf,), vertical probe deflection (25 gf). Ambient operating temperature was 21.0±2.0°C. The inner and outer surfaces of 1st, 11th, 21st, 31st, 41st, and 51st machined ceramic crowns were measured three times, such that a total of 18 crowns were measured using 3D coordinate measuring machine. After confirming that X-R control limit was equally spaced out, factor A (the number of machining times) was statistically analyzed by one-way ANOVA with significance level at 5%. If a significant difference was established, then Tukey test was used.

2. Baseline set-up

Set-up of the baseline and measurement were carried out in accordance with those of Konishi. Inner occlusal was aligned with the X-Y plane of machine and defined as the baseline. Twelve points on the circumference of the inner surface of CAD/CAM crown were measured 6.5 mm away in Z-direction from the baseline. From which, central coordinate of the circle was computed. Likewise, outer occlusal was defined as the baseline. As such, twelve points on the circumference of the outer surface of CAD/CAM crown were measured 5.5 mm away in Z-direction from the baseline. From which, central coordinate of the circle was also computed. Central axis was established as the line that crossed at right angle through central coordinate. Measured values were derived from the radius of measuring point on central axis.

3. Inner and outer measuring points

The following 16 points were measured with 3D coordinate measuring machine. Fig. 3 shows the inner measuring points and Fig. 4 the outer measuring points.

(1) Radii of inner and outer occlusal surfaces of a crown (hereinafter called inner occlusal and outer occlusal).

(2) Radii of the point 1.2 mm away from inner and outer occlusal (hereinafter called 1.2 mm).

(3) Radii of the point 2 mm away from inner and outer occlusal (hereinafter called 2 mm).

(4) Radii of the point 3 mm away from inner and outer occlusal (hereinafter called 3 mm).

(5) Radii of the point 4 mm away from inner and outer occlusal (hereinafter called 4 mm).

(6) Radii of the point 5 mm away from inner and outer occlusal (hereinafter called 4 mm).

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<th>Table 3 Machining parameters</th>
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<td>Tool diameter (mm)</td>
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<td>Surface Offset (mm)</td>
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<td>Machining Direction</td>
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outer occlusal (hereinafter called 5 mm).

(7) Radius of the point 6 mm away from outer occlusal (hereinafter called 6 mm).

(8) Radii of cervical contour.

(9) Height from inner and outer occlusal to cervical contour (hereinafter called height).

Each measuring point was measured five times and averaged to obtain measured value or mean value. Machining accuracy of inner surface of crown was obtained from the deviation between the machined inner surface of a crown and the die model. In the same way, machining accuracy of outer surface of crown was obtained from the deviation between the machined outer surface of a crown and the crown model.

SEM observation
After use of 1st, 11th, 21st, 31st, 41st, and 51st machining, the tip of the diamond bur was examined under SEM (S-400, HITACHI Co. Ltd.) to evaluate the extent of surface degradation of the bur at ×50 and ×200 magnification and at 5 kV accelerating voltage.

Photo observation
Inner surface and cervical contour of 1st, 11th, 21st, 31st, 41st, and 51st crowns fabricated with repeated machining were photographed at ×2 magnification (F5 Nikon Corp.).

RESULTS
Machining accuracy of ceramic crown
Machining accuracy of inner and outer surfaces of a ceramic crown is presented in Figs. 5 and 6. A plus sign (+) indicated that a crown was machined larger than the die model, and vice versa. Machining accuracy was not significantly affected by repeated machining and no significant differences were found in the number of machining times. In all measuring parts, inner surface was machined to be larger than the die model (i.e., increased gap), whereas outer surface was machined to be smaller than the crown model (i.e., smaller crown). Means and standard deviation (SD) of machining accuracy of inner surface were as follows: inner occlusal (78(6.6) μm), 1.2 mm (76(3.2) μm), 2.0 mm (42(2.2) μm), 3.0 mm (31(2.5) μm), 4.0 mm (32(2.4) μm), 5.0 mm (36(2.5) μm), and height (49(9.1) μm). Deviation gradually decreased from inner occlusal to 3.0 mm, then almost the same deviation was observed at 5.0 mm. The following were means and SD of outer surface: outer occlusal (-14(1.4) μm), 1.2 mm (-18(1.8) μm), 2.0 mm (-19(1.8) μm), 3.0 mm (-18(1.6) μm), 4.0 mm (-17(1.7) μm), 5.0 mm (-18(1.8) μm), 6.0 mm (-21(3.3) μm), cervical contour (-11(6.4) μm), and height (-45(23.8) μm). Almost the same deviation was observed from outer occlusal to 6.0 mm, then slightly increased at cervical contour, showing striking contrast between inner and outer surfaces.

SEM observation
Figs. 7 to 8 show SEM photomicrographs of the diamond bur (×50 magnification) and its tip (×200 magnification) respectively. Sharp abrasive particles were densely attached on the surface of the first diamond bur, but after 11 to 21 times of machining, abrasive particles were gradually lost (bur wear) as the number of machining times increased, showing a wider binder.

Photo observation
Fig. 9 shows the photographs of inner surface and cervical contour. These areas were machined circularly at inner cervix from 1st to 11th crowns. Tiny chip marks, however, were found at cervical contour from 21st to 51st crowns.

DISCUSSION
The purpose of this study was to investigate the inner and outer machining accuracy of ceramic crowns fabricated with repeated machining using the same diamond bur.

No significant differences in accuracy of ceramic crowns were found after 51 times of machining. Therefore, repeated machining did not significantly affect machining accuracy. The following mean values were obtained from each measuring point: inner occlusal (78 μm), 5.0 mm (36 μm), height (49 μm), outer occlusal (-14 μm), cervical contour (-11 μm), and height (-45 μm). Komatsu et al.9 reported inner machining accuracy of titanium ceramic crowns using one diamond bur. The following mean values were obtained from each measuring point: inner occlusal (38 μm), 5.0 mm (35 μm), height (53 μm), outer occlusal (-1 μm), cervical contour (-30 μm), and height (53 μm). Machining accuracy of repeated machining was shown to be the same as that of one ceramic crown using one diamond bur. Takeuchi et al.9 reported inner machining accuracy of titanium crowns fabricated with repeated machining using the same tungsten carbide bur, and showed the following machining accuracy: inner occlusal (53 μm), 5.0 mm (21.5 μm), and height (41 μm). Our results in this study indicated that repeated machining accuracy of ceramic crowns with one diamond bur was almost equal to that of one tungsten carbide bur9,10.

SEM observation of the diamond bur indicated that loss of abrasive particles from the diamond bur gradually increased from 11th to 21st machining. However, at 31st machining, the surface became similar to that of 1st machining, showing densely attached abrasive particles. This phenomenon might be explained by the replacement of outer worn out particles with inner new ones. Particle loss was mostly observed at the rounded tip of the diamond bur.
Fig. 5 The machining accuracy, average, and standard deviation of crown's inner data after repeated machining.
Fig. 6 The machining accuracy, average, and standard deviation of crown's outer data after repeated machining.
Fig. 7 SEM photomicrographs of the representative diamond bur (Cadim machining bur with a diameter of 2.0 mm).
Fig. 8 SEM photomicrographs of the representative diamond bur (Cadim: machining bur with a diameter of 2.0 mm).
Fig. 9 Marginal view after repeated machining.
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(within a radius of 1 mm). Since surface deterioration of the bur hardly affected machining accuracy, crowns of almost-the-same accuracy were fabricated from 1st to 51st machining. As shown in Fig. 9, inner surface of the crown and cervical contour were machined circularly with a clear, distinct rounded form at inner cervix, but chip marks were observed at cervical contour from 21st to 51st crowns. This might be because machined surface roughness increased with increasing abrasive particle loss and decreased grinding area also caused machining inefficiency\(^{11-16}\).

Clinical evaluation
Esthetics is a prime concern in dental practice today\(^{17-21}\). Whenever esthetics is a priority, metal-free ceramic restorations including CAD/CAM dental restorations will be chosen. To optimize cost effectiveness, many CAD/CAM ceramic crowns must be machined — while maintaining quality — using the same diamond bur. No significant differences in inner and outer machining accuracy was found from 1st to 51st machining and without fracture of the diamond bur. The results indicated that a diamond bur was usable for machining up to 51 ceramic crowns in clinical practice. The 41st and 51st crowns had a tendency to be machined slightly smaller in inner surface (less gap) and slightly larger in outer surface compared with the 1st crown. This might be due to increased abrasive particle loss, making the diameter of the diamond bur smaller. In this study, inner machining accuracy of 30 to 80\(\mu\)m was obtained — a result almost consistent with that of Yoshida\(^{12}\) (he reported gaps of approximately 40 to 70\(\mu\)m). However, the values he used were larger than JIS-proposed value of 30\(\mu\)m and ADAS-proposed cement film thickness of 25\(\mu\)m. Outer machining accuracy at cervical contour was \(-11\) to \(-21\(\mu\)m, having the tendency to be machined smaller than the crown model. Optimizing the surface offset will solve this problem. Marginal discrepancy, due to tiny chip marks at margin, is considered to be one of the leading causes of plaque accumulation, recurrent caries, and poor esthetics. This problem may be related to the computer program, and could be improved by optimizing machining parameters such as machining pressure, machining volume, and machining speed.

CONCLUSIONS
To explore the possibility of applying CAD/CAM machined ceramic crowns in clinical practice, machining accuracy with repeated machining until 51 times using the same diamond bur was evaluated.

Repeated machining did not significantly affect machining accuracy. In all measuring points, inner surface was machined to be larger than the die model (increased gap), whereas outer surface was machined to be smaller than the crown model (smaller crown). Inner surface discrepancy was within the level of clinical acceptance. Outer surface discrepancy can be solved by optimizing the surface offset during CAD process. Same diamond burs could be used repeatedly until 51 times without affecting the accuracy of machined crowns, even when deterioration of surface texture was observed in SEM pictures. These results indicated that CAD/CAM machined ceramic crowns have the potential to be applied in clinical practice.

REFERENCES
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