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Machining Accuracy of Crowns by CAD/CAM System Using TCP/IP : Influence of Restorative Material and Scanning Condition

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The purpose of this study was to determine the optimal condition for fabricating accurate crowns efficiently using an internet-based CAD/CAM system. The influences of three different CAD/CAM restorative materials (titanium, porcelain, and composite resin) and three different step-over scanning distances (0.01 mm, 0.11 mm, and 0.21 mm) were evaluated, and their interactive effects were carefully examined.

Several points on the inner and outer surfaces of machined crowns — as well as height — were measured. These measurements were then compared with the original models, from which machining accuracy was obtained. At all measuring points, the inner surface of all crowns was machined larger than the die model, whereas the cervical area of porcelain crown was machined smaller than the crown model. Results of this study revealed that a step-over distance of 0.11 mm was an optimal scanning condition, taking into consideration the interactive effects of scanning time required, data volume, and machining accuracy.

Keywords: TCP/IP, CAD/CAM, Machining accuracy

INTRODUCTION

The introduction of dental CAD/CAM systems has brought about many benefits such as high-quality dental restorations[1,2], standardized machining accuracy[3-5], streamlined design and fabrication processes[6,7], and improved laboratory environments[8-11]. With the development of internet technology, internet-based CAD/CAM systems have gained much attention and attracted much interest lately. In this setup, a scanning unit and a computer loaded with CAD software are installed at the dental office and connected with a CAM processing center *via* internet.

For dental technicians working at the centralized processing centers, they could fabricate accurate dental prostheses only with digitized information transmitted from the dental offices. On this note, one factor that affects scanning accuracy is the step-over scanning distance, which defines the distance between neighboring scanning strips. Scanning accuracy increases with smaller step-over distance. However, this would mean greater data volume as well as longer data processing time. Thus, determination of the optimal scanning condition would entail the combination of different factors.

The aim of this research was to determine the effects of step-over and CAD/CAM restorative material on machining accuracy. Models were scanned with three different scanning conditions (*i.e.*, step-over distances of 0.01 mm, 0.11 mm, and 0.21 mm). Each of the three restorative materials — namely, titanium, porcelain, and composite resin crowns — were then machined with each scanning condition. Machining accuracy was obtained by measuring the deviation between a machined crown and the original model.

MATERIALS AND METHODS

Materials

Three kinds of CAD/CAM restorative materials, titanium blocks (Ti) (JIS II H4650; Advance Co. Ltd., Tokyo Japan), porcelain blocks (Po) (Cadim Porcelain; Advance Co. Ltd., Tokyo Japan), and resin blocks (HR) (GC composite resin; GC Corp., Tokyo Japan) were used for this test. Tables 1 and 2 show the compositions and mechanical properties of the CAD/CAM restorative materials used in this study, respectively.

Methods

To investigate the influences of different CAD/CAM restorative materials and scanning conditions on the machining accuracy of inner and outer surfaces of crowns, experiments were carried out with different experimental factors and combinations. Data obtained were then analyzed using two-way analysis of variance (ANOVA).

Three kinds of CAD/CAM restorative materials — Ti, Po, and HR — were prepared for factor A, and three step-over scanning distances of 0.01 mm, 0.11

mm, and 0.21 mm (St0.01, St0.11, St0.21) were prepared for factor B.

Shapes of the die and crown models were scanned. Captured and manipulated scanning data were transmitted to the processing center *via* internet, where crowns were fabricated. Machining processes with combinations of factor A and factor B were repeated three times, so that a total of 27 crowns were fabricated.

Specimen fabrication

1. The die model and crown model

Figure 1 shows a schematic illustration of the die and crown models (SUS-304), as well as their dimensions. Dimensions of the die model were as follows: base diameter (ϕ9.0 mm), occlusal surface (ϕ6.0 mm), height (6.0 mm), 8-degree taper, and a round form of 0.5 mm radius was prepared at both the cervical contour and axial-occlusal line angle.

Table 1 Compositions of CAD/CAM restorative materials

Code	Compositions
Ti :	Ti: Balance, O: 0.20%, Fe: 0.25%, N: 0.05%, H: 0.02%
Po :	SiO_2: 55～65%, Al_3O_3: 15～25%, Na_2O: 6～8%, K_2O: 6～8%
HR :	Fine particle of silica: 60%, Uretangemetacrirat: 40%

Dimensions of the corresponding crown model were as follows: base diameter (ϕ9.0 mm), occlusal surface (ϕ8.0 mm), height (7.0 mm), 8-degree taper, and a round form of 0.5 mm radius was prepared at the axial-occlusal line angle.

2. CAD/CAM system

Internet-based CAD (Dental Cadim 107D, Advance Co. Ltd., Tokyo Japan) was used in this study (Fig. 2). Cadim consisted of a scanning unit — whereby scanning was done with contact analog method, and a personal computer loaded with a CAD software (Tracecut 24, Renishaw Plc., UK). Table 3 gives the specifications of Cadim.

3. Scanning

After mounting the die model on Cadim Setting Plate using a dental stone (New Fujirock, GC Corp., Tokyo, Japan), it was installed on the scanning area of the unit (Fig. 3).

First, the cervical area of die model was scanned with 2D X-Y scanning, from which scanning range for 3D scanning was defined. Shape of the die model was scanned radially with a 3D contact scanning method based on the defined scanning range, thus

Table 2 Mechanical properties of CAD/CAM restorative materials

		Ti	Po	HR
Hardness	(HV)	110	552±27	388
Density	(g/cm^3)	4.51		1.62±0.01
Compressive strength	(MPa)		617	595±24
Bending strength	(MPa)		95	190±15
Proofstress	(MPa)	215		
Elongation	(%)	23		
Tensile strength	(MPa)	340～510		
Modulus of clasticity	(MPa)		4500	49±100
Filler particle content	(wt%)			60
Modulus of thermal expansion	(^{1}/K)		8.3～9.6×10.6	

used the manufacturer's official data

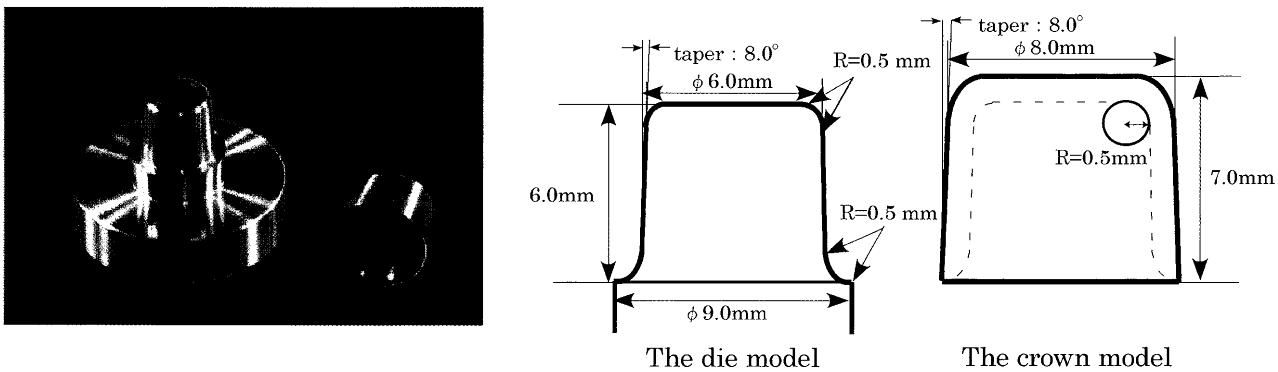


Fig. 1 Schematic illustration of the die and crown models and their dimensions.

Fig. 2 Dental Cadim 107D.

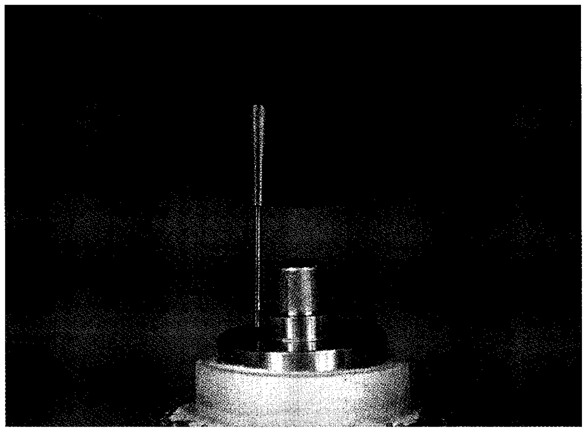


Fig. 3 Scanning of the die model.

Table 3 Specifications of Cadim

Scanning unit	
Range	$\phi 90 \times 45$ mm
Probe deflectoin	18～30 g
Probe resolution	1／1000 mm
Overall siza	W245×D315×H505 mm
Weight	13 Kg
PC	Desktop PC
	Windows 2000
Software	Tracecut 24

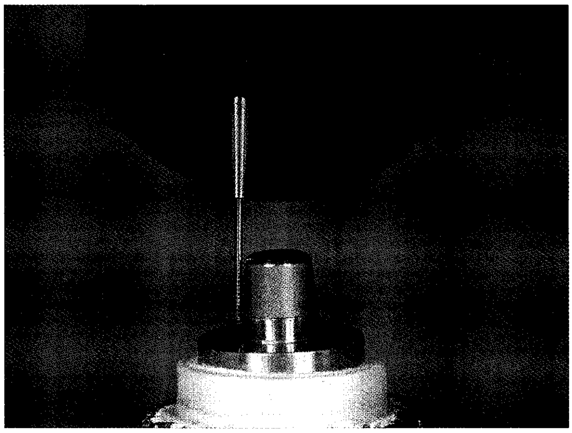


Fig. 4 Scanning of the crown model.

capturing 2D and 3D data. Shape of the crown model, having been mounted on the die, was scanned in the same manner as the die model (Fig. 4).

As for the scanning condition, three different step-over distances (0.01, 0.11, 0.21 mm) were used in this study. Tests were carried out for each scanning condition. With the exception of step-over, other scanning parameters were the same for all the tests as follows:

Scanning speed: 1000 mm/min;
Scanning pitch (die model): 0.05 mm;
Scanning pitch (crown model): 0.1 mm;
Probe deflection: 30 g;
Scanning direction: Two-way.

2D and 3D data were captured by positioning a stylus of ϕ1 mm and made of cylindrical tungsten carbide bur in contact with the models. Digitized crown shape was generated by combining captured 3D die data with captured 3D crown data on the screen. The photographs of Fig. 5 represent the captured scanning data of both die and crown models with each step-over distance. The time durations required for scanning the die and crown models with each scanning condition are shown in Table 4.

Table 4 Time durations required for scanning the die and crown models with each scanning condition

step-over	die model	crown model
0.01	175	183
0.11	18	35
0.21	9	10

step-over distance (mm) die and crown mode(min)

4. Data transmission

Digitized data was compressed into LZH format and transmitted to the processing center using Cadim Software (Advance Co. Ltd., Tokyo Japan). Data volumes required were 11.8 MB (St0.01), 957 KB (St0.11), and 500 KB (St0.21).

5. Machining process

At the processing center, NC cutter paths and CAD output files were generated based on the transmitted digitized data. Table 5 shows the machining parameters for Ti, while Table 6 shows the machining

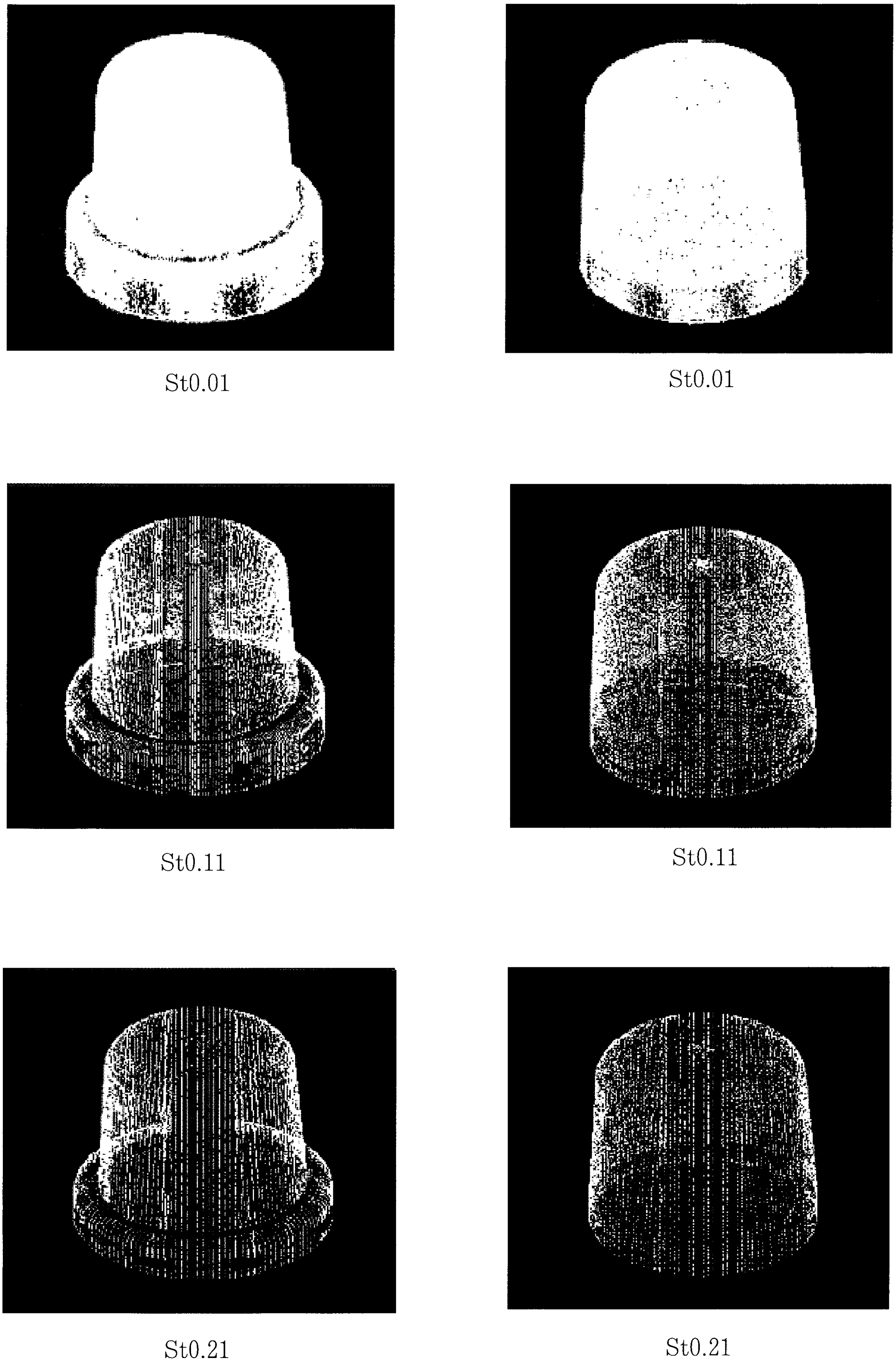


Fig. 5 Captured scanning date of the die and crown models scanned with St0.01, St0.11, St0.21.

Table 5 Machining parameters of Ti

	Inner surface			Outer surface	
	Coarse machining	Medium machining	Finishing	Coarse machining	Finishing
Tool diameter (mm)	2	2	1	2	1
Feedrate XY (mm/min)	1000	400	318	1000	250
Feedrate Z down (mm/min)	500	200	318	500	150
Feedrate Z up (mm/min)	1500	500	318	1500	200
Machining method	Terrace	Terrace	Redial	Terrace	Radial
Type of cut	Clear	Finish	Finish	Clear	Finish
Surface offset (mm)	0.1	0	0	0.1	0
Machining derection	Rectangular Spiral	Rectangular Spiral	One way	Rectangular Spiral	Two way

Table 6 Machining parameters of Po and HR

	Inner surface					Outer surface	
	Coarse machining	Medium machining	Finishing	Margin finishing1	Margin finishing2	Coarse machinig	Finishing
Tool diameter (mm)	2	2	2	1	1	2	2
Feedrate XY (mm/min)	300	300	300	300	300	300	300
Feedrate Z down (mm/min)	250	250	100	200	200	250	200
Feedrate Z up (mm/min)	1000	1000	200	300	300	1000	300
Machining method	Terrace	Terrace	Radial	Terrace	Radial	Terrace	Radial
Type of cut	Clear	Finish	Finish	Finish	Finish	Clear	Finish
Surface offset (mm)	0.05	0	0	0	0	0.05	0
Machining derection	Rectangular Spiral	Rectangular Spiral	Two way	Rectangular Spiral	Two way	Rectangular Spiral	Two way

parameters for Po and HR. As for cement space, a luting cement film thickness of 50 μm was set at 1 mm above the margin line, and it gradually decreased to 0 mm at margin line.

Measurement of CAD/CAM crown using 3D coordinate measuring machine

1. Measuring machine

Inner and outer surfaces of machined crowns were measured using a 3D coordinate measuring machine (E-DC-M400, Tokyo Seimitsu Co. Ltd. Japan), which consisted of three main components: the machine itself, a computer-controlled system (Type 2400-WBB S/N97-A0231, IBM), and a measurement software (40 series, all-purpose measuring program XYZAX).

Measurements were carried out using a probe (TP1, Renishaw Inc.) with a 1-mm-radius stylus. Measurement parameters were as follows: horizontal probe deflection (15 gf,), vertical probe deflection (25 gf). Thus, a measurement accuracy of less than $\pm$2.0 μm was obtained. Ambient operating temperature was 23.0$\pm$2.0℃, humidity was 50$\pm$5%.

2. Baseline setup

Setup of the baseline and measuring points were carried out in accordance with those of Konishi[12]. Inner occlusal was aligned with X-Y plane of the machine and defined as the baseline. Twelve random points on the circumference of the inner surface of CAD/CAM crown were measured 5.0 mm away from the baseline in Z-direction, and from which the central coordinates of the circle were computed.

Similarly, outer occlusal was defined as the baseline. As such, 12 random points on the circumference of the outer surface of CAD/CAM crown were measured 6.0 mm away from the baseline in Z-direction, and from which the central coordinates of the circle were also computed. Central axis was established as the line that crossed at right angle through the central coordinates. Each measured value was derived from the radius between a measuring point and the central axis.

3. Measuring points

For inner measuring points, they included the height

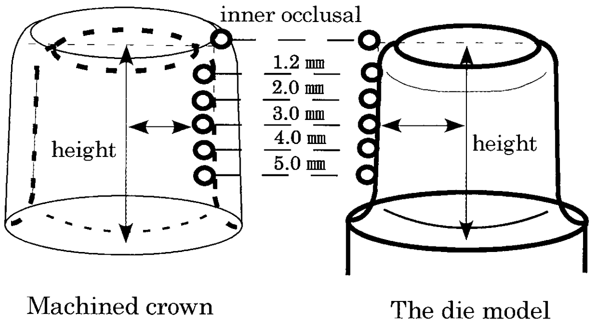


Fig. 6 Inner measuring points.

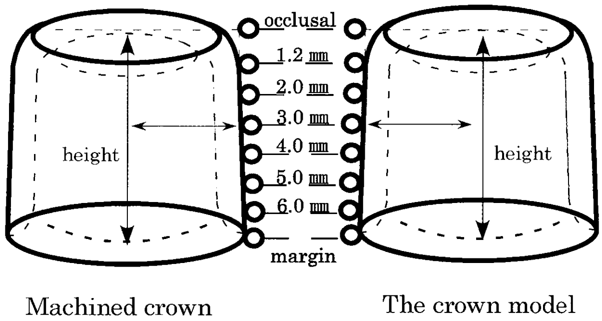


Fig. 7 Outer measuring points.

Table 7 Dimensions of die and crown models

	occulusal	1.2 mm	2.0 mm	3.0 mm	4.0 mm	5.0 mm	6.0 mm	margin	hight
Die model (Inner)	3.076	3.164	3.22	3.292	3.364	3.435			5.945
Crown model (Outer)	3.994	4.085	4.142	4.215	4.289	4.365	4.439	4.506	7.033

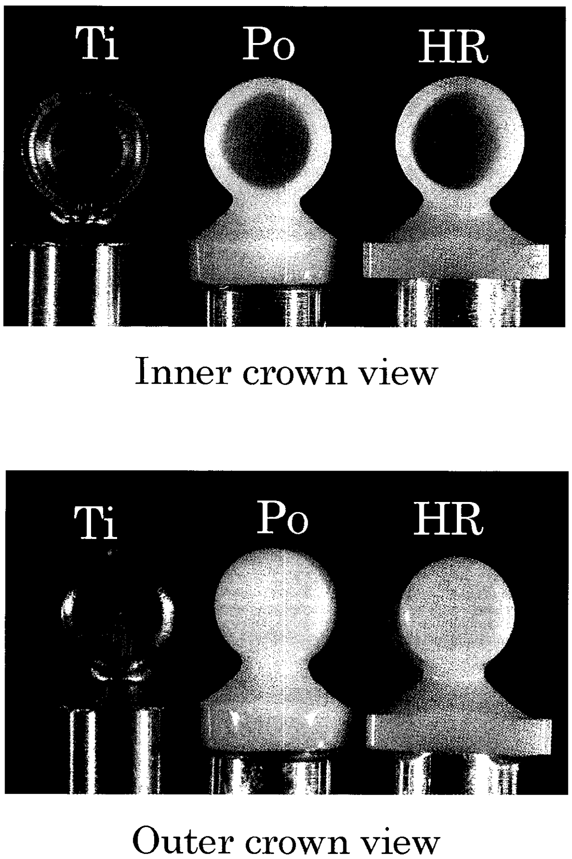


Fig. 8 Inner and outer surfaces of machined crowns.

(*i.e.*, the distance between inner occlusal and cervical area), the inner occlusal surface, and the following five points: 1.2, 2.0, 3.0, 4.0, and 5.0 mm away from the inner occlusal (Fig. 6).

For outer measuring points, they included the height, the radius of cervical area, the outer occlusal surface, and the following six points: 1.2, 2.0, 3.0, 4.0, 5.0, and 6.0 mm away from the outer occlusal (Fig.7). As the radius of the stylus tip was 1.0 mm, we set it at 1.2 mm so that it was possible for contact measurement.

4. Measured values of die and crown models

Table 7 shows the measured values of both die and crown models using contact 3D coordinate measuring machine. Figure 8 shows the inner and outer surfaces of machinedcrowns which were used for measurement. Each measuring point was measured five times and averaged to obtain a mean, measured value.

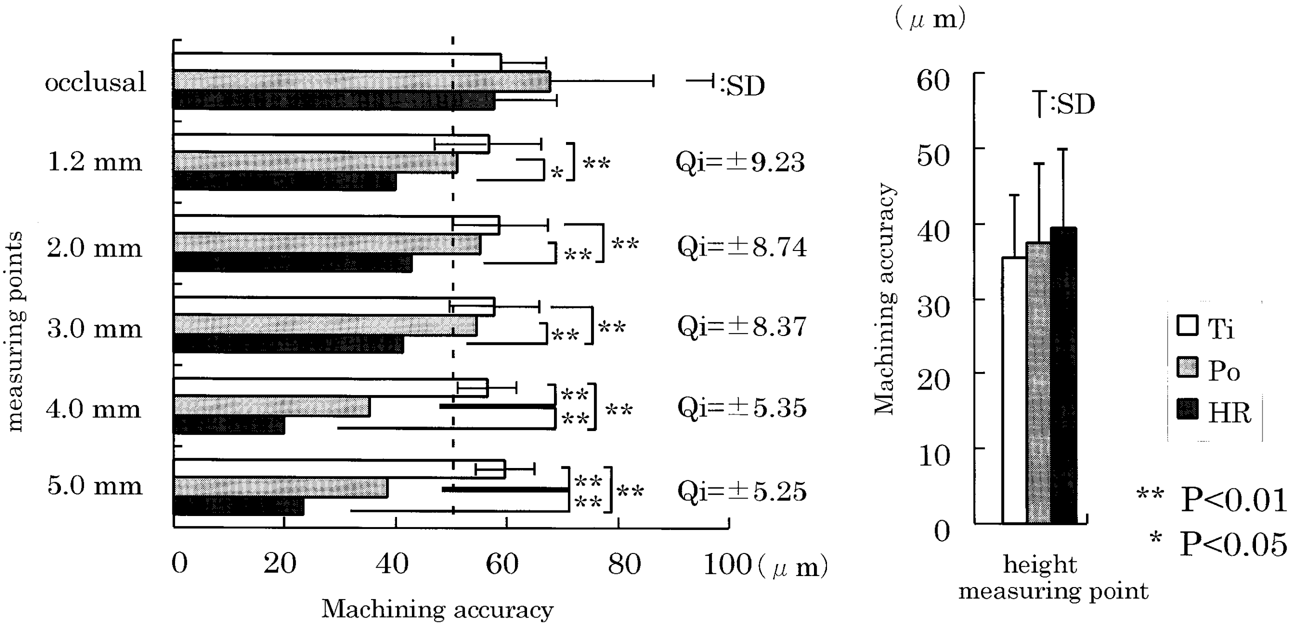
Machining accuracy of the inner surface of a crown was obtained from deviation between the machined inner surface of a crown and the die model. In the same way, machining accuracy of the outer surface of a crown was obtained from deviation between the machined outer surface of a crown and the crown model.

After confirming that machining accuracy was equally spread out at each measuring point, two-way analysis of variance (ANOVA) was performed on the data obtained. When significant differences were noted, Fisher's multiple contrast test was carried out. A plus sign (+) indicates that a crown was machined larger than the die or crown model, and *vice versa*.

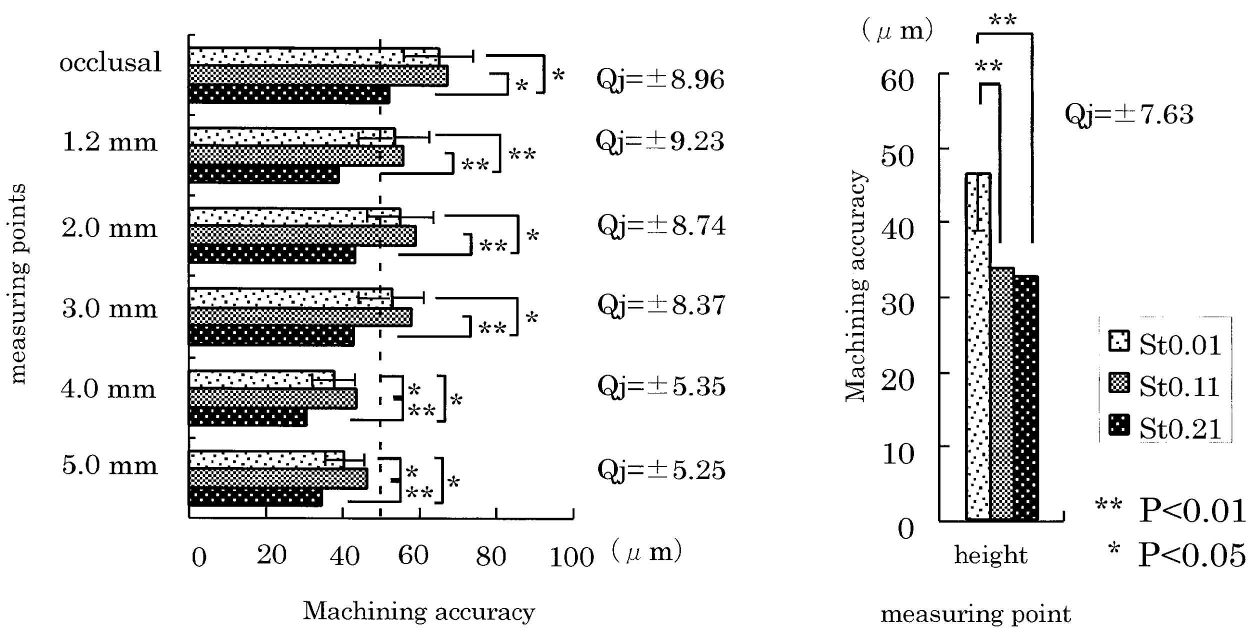
RESULTS

Deviation between inner surface of crown and the die model

Figure 9 shows the machining accuracy results of the inner surface of crowns and as analyzed by multiple



Machining accuracy affected by materials



Machining accuracy affected by step-over

Fig. 9 Inner machining accuracy and multiple contrast test.

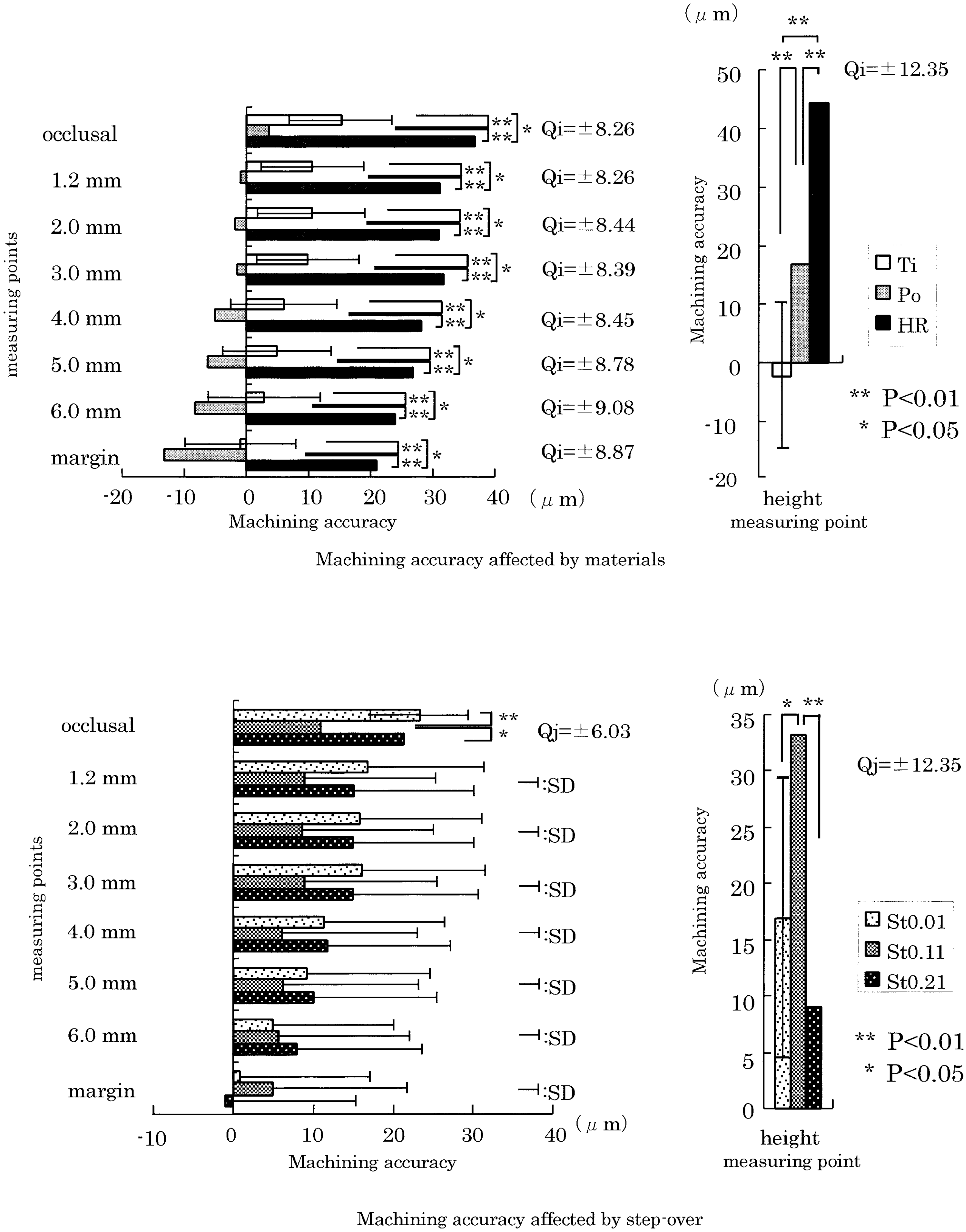


Fig. 10 Outer machining accuracy and multiple contrast test.

contrast test. When examining the influence of three different CAD/CAM restorative materials on inner machining accuracy, the following were noted:

(1) At inner occlusal surface, there were no significant differences;
(2) At 1.2 mm, significant differences were found in the descending order of Ti, Po, and HR;
(3) At 2.0 mm, 3.0 mm, 4.0 mm, and 5.0 mm, significant differences were also found in the descending order of Ti, Po and HR;
(4) With titanium, almost the same deviation of 60 μm was observed at all measuring points;
(5) With porcelain, the largest deviation of 68 μm was observed at occlusal surface, then gradually decreased to 38 μm at 5.0 mm of cervical area;
(6) With resin, the largest deviation of 58 μm was observed at occlusal surface, then gradually decreased to 23 μm at 5.0 mm of cervical area — thus showing a similar trend to porcelain;
(7) With all the three restorative materials, the inner surface was machined larger than the die model (*i.e.*, increased gap);
(8) As for the height, deviation was in the descending order of 40 μm (HR), 39 μm (Po), and 36 μm (Ti), with no significant differences.

When examining the influence of step-over on inner machining accuracy, the following were noted:

(1) At occlusal surface, 1.2 mm, 2.0 mm, and 3.0 mm, deviations of St0.01 and St0.11 were significantly larger than that of St0.21;
(2) At 4.0 mm and 5.0 mm, deviation was high in the descending order of St0.11, St0.01, and St0.21;
(3) As for the height, deviation of St0.01 was significantly larger than those of St0.21 and St0.11;
(4) St0.01 was the least spread out in deviation;
(5) In all step-over distance, deviation gradually decreased from occlusal surface to 5.0 mm, *i.e.*, from 65 μm (occlusal surface) to 40 μm (5.0 mm) when scanned with St0.01, from 67 μm (occlusal surface) to 47 μm (5.0 mm) when scanned with St0.11, and from 52 μm (occlusal surface) to 34 μm (5.0 mm) when scanned with St0.21.

Deviation between outer surface of crown and the crown model

Figure 10 shows the machining accuracy results of the outer surface of crowns and as analyzed by multiple contrast test. When examining the influence of three different CAD/CAM restorative materials on outer machining accuracy, the following were noted:

(1) Significant differences were noted at all measuring points in the descending order of HR, Ti, and Po;
(2) Deviation was largest at the occlusal surface, and gradually decreased toward the cervical area in all materials;
(3) With Ti, deviations ranged from 15 μm (occlusal surface) to -1 μm (margin);
(4) With Po, deviations ranged from 2 μm (occlusal surface) to -16 μm (margin);
(5) With HR, deviations ranged from 37 μm (occlusal surface) to 21 μm (margin).

When examining the influence of step-over on outer machining accuracy, the following were noted:

(1) At occlusal surface, deviation of St0.11 was significantly smaller than those of St0.01 and St0.21;
(2) As for the height, deviation of St0.11 was significantly larger than those of St0.01 and St0.21;
(3) In all step-over distance, deviation gradually decreased from occlusal surface to the margin, *i.e.*, from 23 μm (occlusal surface) to 1 μm (margin) when scanned with St0.01, from 11 μm (occlusal surface) to 5 μm (margin) when scan-

Table 8 Results of ANOVA (inner surface of crown)

Measuring points	occlusal	1.2 mm	2.0 mm	3.0 mm	4.0 mm	5.0 mm	height
A : Materials	non	**	**	**	**	**	non
B : St	*	**	**	**	**	**	**

**<0.01, *<0.05

Table 9 Results of ANOVA (outer surface of crown)

Measuring points	occlusal	1.2 mm	2.0 mm	3.0 mm	4.0 mm	5.0 mm	6.0 mm	margin	height
A : Materials	**	**	**	**	**	**	**	**	**
B : St	*	non	non	non	non	non	non	non	**

**<0.01, *<0.05

ned with St0.11, and from 20 μm (occlusal surface) to −1 μm (margin) when scanned with St0.21.

Results of ANOVA

Table 8 shows the two-way ANOVA results of the inner surface of crowns as well as the indication of significance for the different factors and interactions. Factor A (CAD/CAM restorative material) significantly affected all measuring points except for occlusal surface and height, while factor B (step-over) significantly affected all measuring points. No significant interactive effects were observed at all measuring points.

Table 9 shows the two-way ANOVA results of the outer surface of crowns as well as the indication of significance for the different factors and interactions. Factor A (CAD/CAM restorative material) significantly affected all measuring points. Factor B (step-over) significantly affected the occlusal surface and height, but not measuring points from 1.2 mm to the cervical area. No significant interactive effects were observed at all measuring points.

DISCUSSION

Internet-based CAD/CAM system

In an internet-based CAD/CAM system, CAD and CAM are independently installed and connected *via* internet. To put it correctly, shapes of dental models are scanned at the dental office, whereby the captured scanning data is manipulated with a CAD program. Digitized information is then sent to the processing center, where dental restorations are fabricated and finished restorations are delivered back to the dental office.

Based on the above system setup, initial investment cost — even if the cost of upgrade option were included — is much lower than that of stand alone CAD/CAM system, as only a scanning unit needs to be purchased.

In computerized fabrication processes, the time required for scanning and data manipulation does not vary with CAD/CAM systems. On the contrary, the time required for machining varies widely with CAD/CAM systems, and it is also the most time-consuming and costly process in computerized fabrication of restorations.

With a standalone CAD/CAM system, its indisputable advantage over an internet-based CAD/CAM system is that it can start machining immediately after the completion of scanning and data manipulation. However, its productivity per day may be limited by a longer machining time required. On the other hand, an internet-based CAD/CAM system requires time only for scanning and data manipulation.

Besides the tangible benefit of time-saving, the intangible benefit is that the personnel-at-work can obtain enough experience to become proficient because the milling of units is centralized at one place. In addition to these two advantages, high machining accuracy can be constantly achieved because system maintenance is done on a regular, scheduled basis.

Machining accuracy compared with standalone CAD/CAM system

Komatsu *et al.*[5] tested the machining accuracy of inner and outer surfaces (from occlusal surface to cervical area/margin) of Ti, Po, and HR crowns using a standalone CAD/CAM system. Inner and outer machining accuracy were reported as follows: 34∼31 μm and 9∼7 μm with Ti, 32∼37 μm and −29∼−1 μm with Po, and 37∼34 μm and −1∼−29 μm with HR.

This study was a similar experiment, except that an internet-based CAD/CAM system was used. Machining accuracy values of the inner and outer surfaces of Ti, Po, and HR crowns were as follows: 59∼60 μm and 15∼−1 μm with Ti, 68∼35 μm and 2∼−16 μm with Po, and 58∼20 μm and 37∼21 μm with HR. (occlusal/margin)

As for cement film thickness, 50 μm was offset in this study in the same way Komatsu *et al.*[5] did in their study.

Compared with a standalone CAD/CAM system, inner crown achieved a machining accuracy which was designated for cement film thickness. Outer crowns tended to be machined smaller than the crown model (*i.e.*, smaller crown), but their reduction rate was smaller than that of a standalone CAD/CAM system, showing higher machining accuracy.

Influence of step-over

At almost all measuring points on the inner crown surface, St0.01 and St0.11 significantly affected machining accuracy as compared with St0.21. As for the machining accuracy of the outer surface of crowns, no significant differences were found at almost all measuring points. In particular, St0.11 achieved the highest machining accuracy around the cervical area.

To meet the demand for high-precision machining, rigorous scanning accuracy is required. In the case of Cadim, CAD data was processed by connecting each digitized point with a straight line. Therefore, as shown in Fig. 11, when a large step-over distance was used, slightly more inward-oriented machining was done due to smaller data volume, thus fabricating significantly smaller crowns when compared with smaller step-over distances.

When comparing the inner and outer surfaces of

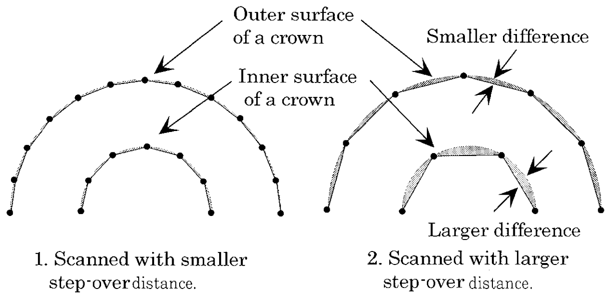


Fig. 11 Relation between data volume and machining accuracy.

a crown, inner surface with a smaller radius is more susceptible to be influenced by step-over. This was probably why significant differences were observed at the inner surface of crowns, but not so at the outer surface.

At the measuring points of 4.0 mm and 5.0 mm of inner crown, St0.11 achieved the most accurate machining despite high-precision scanning of St0.01. Scanning noise increases in proportion to measurement accuracy. When machining based on captured scanning data varies among scanning points, higher scanning points are automatically recognized to enable machining of a ϕ1 mm tool.

To eliminate over-machining, Cadim automatically recognizes digitized points, which allow minimum machining. This could be a key reason why the amount of machining was reduced.

Considering the interaction of machining accuracy, scanning time required, and data volume, the authors have come to a conclusion that St0.11 was an optimal scanning condition.

Clinical application

Nakamura *et al.*[13] reported that a cementing medium of even film thickness was critical to high bond strength. In the case of ceramometal crowns, Konishi *et al.*[12] advocated a 15-μm film thickness at cervical area and 20～50 μm for the remaining area. On the other hand, Yoshida[14] suggested a film thickness of 40～70 μm, but that it gradually decreased to a minimal film thickness at cervical area. In this study, mean machining accuracy of inner titanium crowns was approximately 60 μm at all measuring points, which was consistent with the recommendation by Yoshida[14]. With porcelain and resin, cement film thicknesses were approximately 38～68 μm and 20～58 μm, respectively.

Beschnidt and Strub[15] reported that the mean marginal adaptation of all ceramic crowns fabricated with porcelain-fused-to-metal method was 47～99 μm. In this study, the following mean machining accuracies at the cervical area were obtained: -1 μm (titanium), -13 μm (porcelain), and 21 μm (resin). Clinically acceptable marginal fit of a crown is reported to be 100～200 μm[16,17]. In light of this clinically acceptable range, the CAD/CAM crowns fabricated in this study were considered clinically safe and applicable[18-24].

CONCLUSIONS

To investigate if accurate crowns could be fabricated efficiently using an internet-based CAD/CAM system, this study was carried out with three different step-over scanning distances (0.01 mm, 0.11 mm, and 0.21 mm) and three different CAD/CAM restorative materials (Ti, Po, and HR). Results were then compared to determine the optimal scanning condition. Within the limitation of this study, the following conclusions were drawn:

(1) When examining the influence of three different CAD/CAM restorative materials on inner machining accuracy from occlusal surface to 5.0 mm, the following deviation values were obtained: 60 μm with Ti, range of 68 μm to 35 μm with Po, and range of 58 μm to 20 μm with HR.
As for outer machining accuracy from occlusal surface to margin, deviation ranged from 15 μm to -0.7 μm with Ti, from 2.3 μm to -15.7 μm with Po, and from 36.7 μm to 21 μm with HR.
Deviation of both inner and outer surfaces of crowns gradually decreased from occlusal surface to cervical area, except for the inner surface of Ti crown.

(2) When examining the influence of step-over on inner machining accuracy, deviations of St0.01 and St0.11 were significantly larger than that of St0.21 from occlusal surface to 3.0 mm. At 4.0 mm and 5.0 mm, deviation was high in the descending order of St0.11, St0.01, and St0.21.
As for outer machining accuracy, no significant differences were observed from 1.2 mm to cervical area.
In all step-over distances, deviation gradually decreased from occlusal surface to cervical area.

(3) Height was machined larger than the die or crown model in all conditions, except for titanium outer surface.

The present study revealed that the inner surface was machined larger than the die model, whereas the outer surface of porcelain crown was machined smaller than the crown model. Considering the interactions of machining accuracy, scanning time required, and data volume, the authors have come to a conclusion that St0.11 was an optimal scanning condition.

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