ORIGINAL

Construction method of a tooth crown model using data generated by micro-focus CT

― Voxel models of anterior and premolar teeth ―

Yasuo Ueda, Yuya Kobayashi, Osamu Takamichi and Noboru Ohata

ABSTRACT : Currently, a number of dental CAD/CAM systems are in operation in Japan. Many of them adopt a non-contact optical system using a CCD camera and light patterns to measure the model teeth. One disadvantage of this method is that it is difficult to measure the parts in the shade. However, this problem can be solved if we can carry out measurements using 3D CT. In this study we have examined how to construct a 3D model of a tooth crown shape using micro-CT data.

An R_mCT2 micro-CT manufactured by Rigaku Corporation was used under maging conditions of FOV10 (ϕ 10 mm×H10 mm), 90 kV tube voltage and 160 μA tube current. Basic study models manufactured by KaVo Dental GmbH were used in the imaging, which was carried out in two phases, as the size of the artificial teeth was greater than that of the FOV. The image data was output in 512 slices in the form of DICOM files, and transferred to a personal computer. We examined the CT values of all the voxels of all images using software we developed ourselves. Based on the results, we determined the threshold by comparing the distribution of the CT values of the artificial teeth area with those of the remaining area in each image, and extracted the shape of the artificial tooth by binarizing the image. The separate image data was aligned by detecting the location of the closest number of pixels to the binarized image. Artifacts included in the images were removed manually and the completed voxel data output in DICOM format. Shape was confirmed using free DICOM viewer software (OsiriX).

As a result, the margin of error for superimposing the contour shape of the split image data is approximately one voxel (± 20 μm). Artifacts were seen in 20 to 50 slices of the binarized images but because they were minor, we were able to process the images quickly and easily. In this study we were able to construct a high-resolution model of artificial teeth with relative ease. In future, if we can success in realizing low-cost, higher performance dental cone-beam CT, we will be able to use it to measure abutment teeth.

Key Words : Voxel Model, CAD/CAM, Micro-CT, Shape Measurement

Introduction

In recent years, many dental computer-aided design and computer-aided manufacturing systems (CAD/CAM systems) have been introduced in Japan, and are in operation at a practical level[1-5]. In addition, the measuring devices of CAD/CAM systems are expected to act as tools for homogenous evaluation and enhancement of understanding in student education[6-8]. Many of these employ contact-less optical systems for shape measurement, made up of lasers or pattern projection and CCD sensors[9-14]. The disadvantage of these methods is that it is difficult to measure the undercut area of the parts. Therefore, it is necessary to combine the data of measurements taken in multiple directions. In addition, in the case of optical impressions using intraoral scanners, which have recently been introduced in Japan, although the burden on the patients had decreased significantly as

Division of Oral Rehabilitation, Department of Oral Functional Science, Hokkaido University Graduate School of Dental Medicine (Chief : Prof. Noboru Ohata) Kita 13 Nishi 7, Kita-ku, Sapporo 060-8586, Japan.

impression materials are unnecessary, it is still necessary to perform gingival retraction using displacement cord around the abutment tooth, and if the margins are not done directly, the scanners will not be able to scan sufficient data. However, if three-dimensional computed tomography (3D-CT) data can be utilized, this problem can be overcome[15-18].

In this study of shape measurement of artificial teeth, we had the opportunity to use micro focus computed tomography (micro-CT) for laboratory animals, and considered a method of constructing three-dimensional models (3D-model) of tooth crown forms taken with this micro-CT, using the data from artificial teeth used for practical educational purposes[19-24].

Methods

We used an R_mCT2 micro focus X-ray CT for laboratory animals manufactured by Rigaku Corporation. As with dental CT, this device operates using a cone-beam method. At the time of this study, imaging conditions were FOV10 (ϕ10 mm × H10 mm) − the maximum attainable with this apparatus; a tube voltage of 90kV; and a tube current of 160 μA. The artificial teeth used in the imaging were basic study models manufactured by KaVo Dental GmbH, used by students at the university (Fig.1), and each tooth was imaged individually.

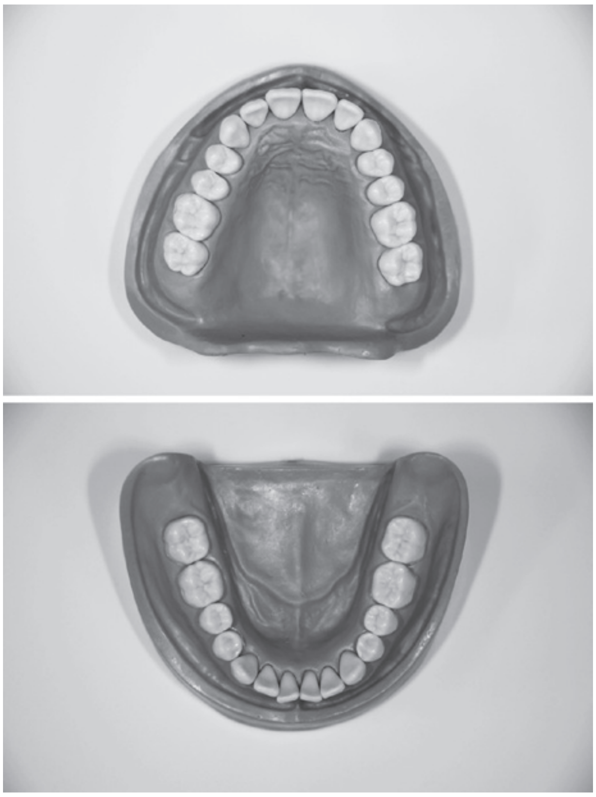

Fig.1 Artificial teeth and basic study models manufactured by KaVo Dental GmbH, used in the imaging
The artificial anterior teeth in this model were taken out individually and measured

With the above-mentioned Field of View (FOV), the size of the artificial tooth would not fit inside the imaging area. Therefore we measured it twice while the imaging platform was stationary in the direction of the XY axis, and was controlled to move in parallel only in the direction of the Z axis.

The recorded data was output in the form of a DICOM file made up of 512 slices of 512 × 512 pixels, and transferred to a personal computer. The CT values of all the voxels of the entire image data were checked using our own original software (Fig.2). Generally, the value of the output of helical CT used for medical purposes on patients is represented in Hounsfield units (HU), in which 0 is water and −1000 is air. On the other hand, if a device such as a micro-CT or dental CT is employed and the cone-beam method is used, the CT values (voxel values) are not represented as HU and are not fixed values according to the substance. The CT values will vary depending on the size of the scanning area (FOV). Therefore, it is often thought that there is a problem with the accuracy of CT values in cone-beam CT. However, in cases where we want to extract shapes from such data, the resolution (voxel size) is important, not just the CT value as an absolute value. We believe that the CT value changes dynamically depending on the subject conditions and the conditions at the time the images were taken. We believe that the problems

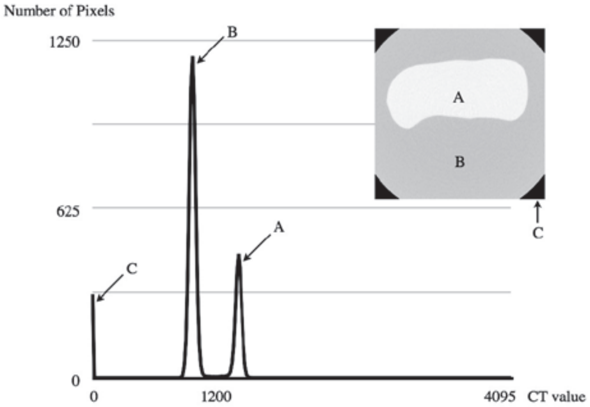

Fig.2 Distribution of CT values within one slice image
Top right: Example of an analyzed image (256th slice of the first image of the maxillary left-side central incisor)
A: artificial tooth area B: surrounding space
C: region outside the scope of imaging

regarding the accuracy of the CT values can be solved if we can set the threshold dynamically for shape extraction. Based on this idea, we examined the CT values of all the voxels of all the scanned images. Based on the results, the local minimum value was determined by comparing the distribution of the CT values of the artificial teeth with those of the remaining area in each image. The images were binarized by the threshold of the local minimum value, and the data of the shape of the artificial tooth was extracted by binarizing the image. The local minimum value used as the threshold was determined as the local minimum value of the cubic approximation curve (Fig.3). Images were binarized in advance and the divided scanned image data was aligned by calculating the location (slice) closest to the pixel number of the digitized image in the Z axis direction (Fig.4). The direction of the XY axis had been fixed at the time the images were taken, but just to be sure, each image was superimposed to check whether or not misalignment had occurred with each volume (Fig.5). Slight artifacts included in the digitized images were manually removed using general-purpose image processing software (Adobe Photoshop CS3) (Fig.6). Once this processing was complete, the combined data was once again output in DICOM format, and free

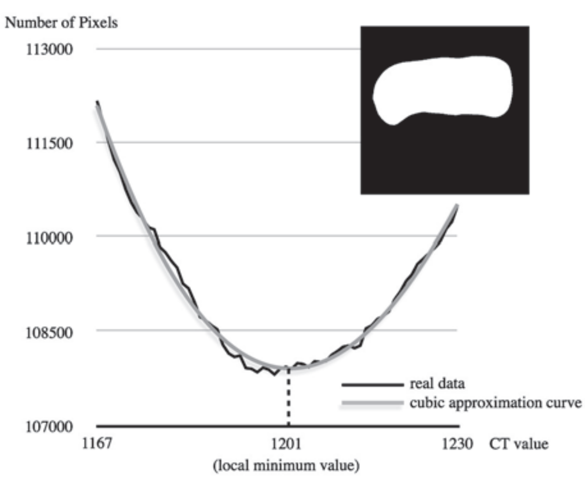

Fig.3 The shape was extracted from the image by the threshold calculated from the local minimum value

With regard to the distribution of CT values shown in Fig.3, all of the pixels were calculated for 512 slice images of the one-path scanning, only for the part where the CT values were shown to be in the region of 1200. Subsequently, a cubic approximation curve was calculated with regard to that data and the threshold value established from of the graph's local minimum value to binarize the image. The top right is the binarized image according to the calculated threshold.

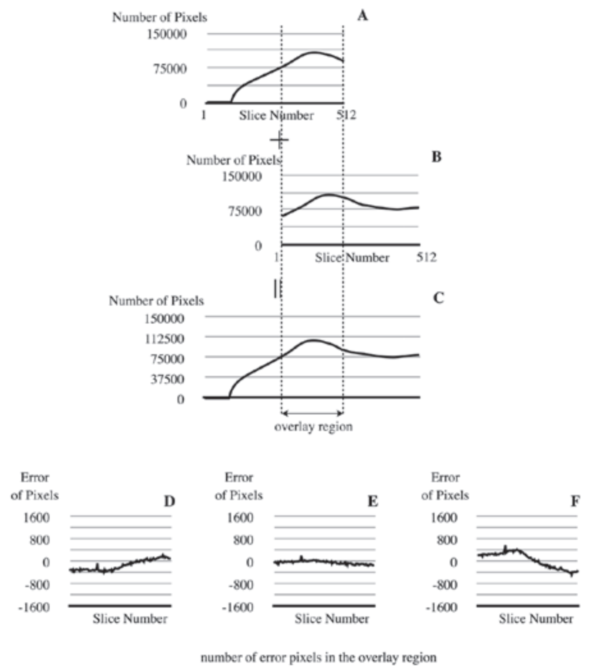

Fig.4 Alignment of voxel data from the divided image volume

The number of artificial tooth pixels for each of the 512 slices extracted in Fig.4 was used to create graphs (A and B).

The positions that were the most similar in alignment were considered (C).

B was moved one slice to the left (D)

Most appropriately aligned locations (E),

B was moved one slice to the right (F)

Calculation of the number of error pixels in the overlay region was verified using graphs.

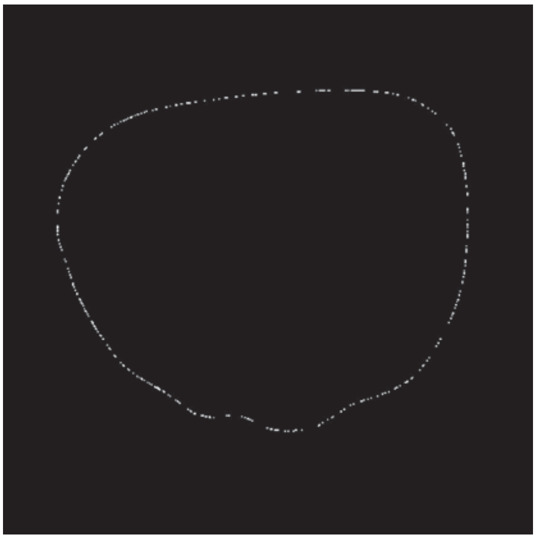

Fig.5 Verification of horizontal misalignment

The absolute values of the differences in the same slice images in the aligned regions were calculated and pixels causing errors were confirmed visually. The misalignment along the contour was approximately 1 pixel.

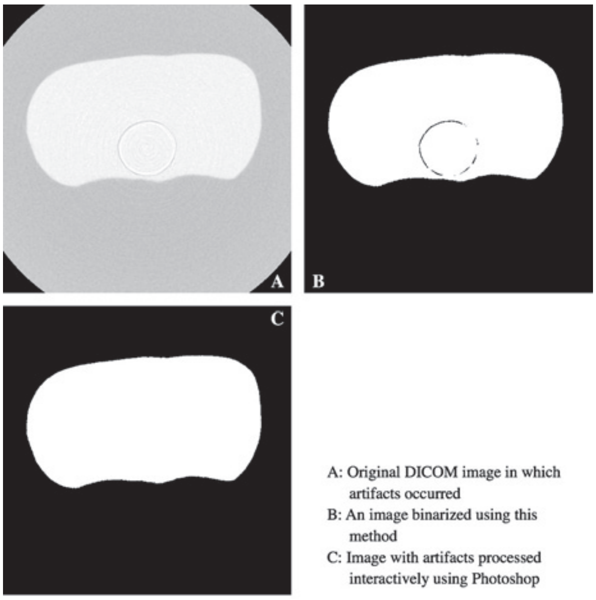

Fig.6 Artifacts occurring in binarized images

Table List of threshold values

Tooth number	Data file	Threshold	Tooth number	Data file	Threshold
11	1	1203	31	1	1201
	2	1205		2	1198
12	1	1204	32	1	1201
	2	1197		2	1199
13	1	1209	33	1	1205
	2	1205		2	1202
14	1	1203	34	1	1205
	2	1202		2	1200
15	1	1204	35	1	1207
	2	1199		2	1204
21	1	1201	41	1	1186
	2	1211		2	1192
22	1	1206	42	1	1196
	2	1208		2	1195
23	1	1200	43	1	1199
	2	1201		2	1198
24	1	1201	44	1	1198
	2	1204		2	1196
25	1	1208	45	1	1205
	2	1207		2	1202

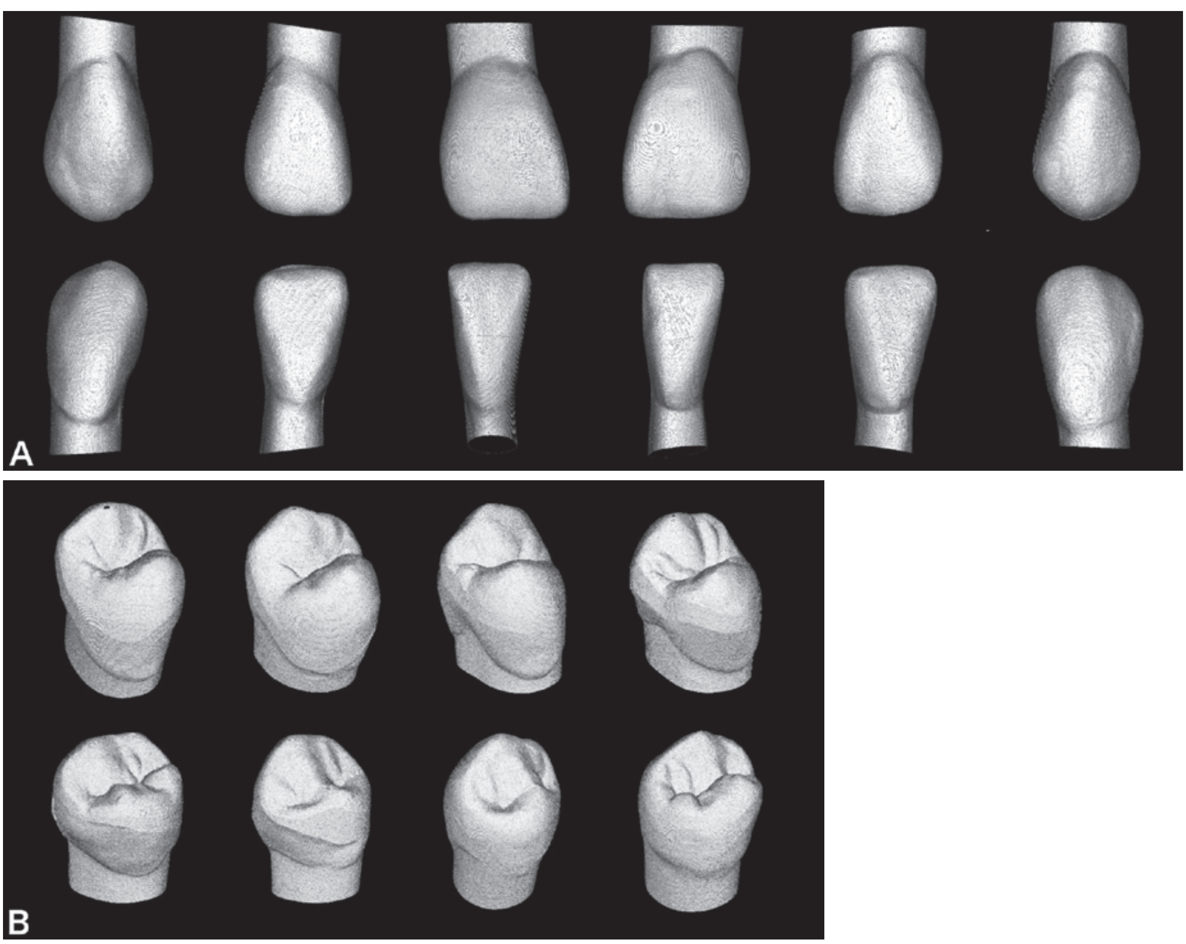

Fig.7 Voxel models of anterior and premolar teeth
A: Anterior models B: Premolar models

DICOM viewer software OsiriX was used to carry out volume rendering and confirm the shape.

Results

With regard to the distribution of CT values shown in Fig.2, we only examined the CT values indicated in the region of 1200. The total number of pixels in the target area of all 512 slices from one scanning was accumulated (Fig.3). Then we calculated the three-dimensional approximation curve for the data and set the local minimum value of the curve to the threshold value for binarizing the images. The graph in Fig.3 is the result of an upper-left central incisor (21). The local minimum value was calculated as 1201. The image in the upper right-hand corner of Fig.3 is the result of binarization calculated by this threshold.

Similarly, the table shows a list of threshold values for the two sets of measurement data of the anterior and premolar teeth. The threshold values determined based on the local minimum values in the anterior teeth averaged 1201, with most of the values around that number, although the minimum value was 1186 and the maximum value 1211. In the premolar teeth, the average value was 1203; the minimum was 1196, and maximum was 1208. In the same manner as in Fig.3, an example of an upper-left central incisor (21) was binarized by the method in Fig.3, and the graphs created by aggregating the number of pixels in the area of the artificial teeth of each of the 512 slices are shown as Fig.4A and Fig.4B. The positions that matched are shown in Fig.4C. In order to verify how many errors occurred at that time, we subtracted the number of pixels from the superimposed area of the data of Fig.4B from that of Fig.4A and the results are shown in Fig.4D to 4F. Fig.4E shows the most appropriately aligned locations; in the case where B was moved one slice to the left (Fig.4D) and B was moved one slice to the right (Fig.4F), it was confirmed that the changes in values were between -800 and 400 without convergence in the vicinity of the zero value of the graph. This verifies that the area in Fig.4E is the most appropriately aligned.

Furthermore, in order to visually verify the status of the data superimposed in this way, in the middle of the superimposed area we calculated the absolute value of the differences in the same slice and displayed only the error pixels with white points, while all the others were displayed in black, as shown in Fig.5.

As a result, the scope of error of the contour shape when the divided image data was being superimposed was, generally speaking, around 1 voxel ($\pm 20\ \mu$m) along the contour of the area (Fig.5/example of the upper-left central incisor (21)). Misalignment in the XY axis direction was seen in 5 of the 12 anterior teeth models, but all could be aligned with 1- to 3-pixel correction. In the premolar teeth models, misalignment was not seen. In both the anterior and premolar teeth models, ring-shaped artifacts were seen in 20 to 50 slices of the binarized images in volume (Fig.6A). These artifacts became more vivid when the image was binarized using the processing methods in this study (Fig.6B). These were removed manually but most of them were minor – measuring no more than a few dozen pixels – and could be disposed of easily in a short space of time. Fig.6c is an example of the image after processing was complete (example of the upper-left central incisor (21)). After all the above processes had been completed, the Voxel model output in DICOM format could be loaded into OsiriX DICOM viewer software, easily. The voxel models of the anterior teeth produced in this experiment are shown in Fig.7A, and the voxel models of the premolar teeth are shown in Fig.7B.

Discussion

In digital image processing by computers, various methods have been developed for a long time[25]. Our method used in this study, binarization process is performed using a density histogram from the grayscale image. This method belongs to the mode-method that is one of the techniques to extract the region of interest. There are similar techniques such as the P-tile method and the discriminant analysis method. In the case of high-contrast image as this experiment, we believe that mode-method is a useful way to process easily and faster. However, we should not pursue the automation of the process too. In order to generate the high quality and high accuracy data as far as possible, we considered it was important to finely tune the parameters.

Studies to utilize CT for shape measurement are being carried out by Sohmura et al.[15-18], and on a commercial base, the Invisalign system provided by Align Technology, Inc. is known to directly scan silicone impressions using industrial-use CT, but it has yet to be applied to measurement in standard dental CAD/CAM systems. In this experiment we discovered that the highest resolution attainable from imaging using currently available micro CT modes is approximately 20 μm. However, because of the limited FOV, one artificial tooth cannot be imaged all at once. It can be considered that, with student training, the acquired shape can be utilized sufficiently in morphological evaluation. On the other hand, it can be considered that in order to design and produce the tooth crown efficiently in clinical cases, the imaging area needs to be 2 to 4 times the size to enable the entire shape to be captured in one measurement.

Sato et al described in detail the suitable accuracy of the margin of the crown required for clinical purposes[26]. In addition, Shiozawa et al described the fitting accuracy of crowns fabricated using the conventional method[27]. As a guideline, these are within approximately 100 μm. Also, with regard to practices of Hokkaido University School of Dentistry, when students make crowns and bridges, they have been taught for many years that the standard accuracy of crown fitting is within a 100 μm margin.

In general, the measured numerical data contains the error in the last digit of the significant digits. For this reason, it is considered that the necessary resolution is 10 times the required accuracy. Therefore, if the clinically required margin of accuracy of the crown is within 100 μm, to increase it by one more digit, the resolution of the measurement system is required to be within 10 μm. This is twice the resolution than at the time of the study of this device. However, at the time of writing, performance has been already been achieved by means of manufacturer's improvements. On the other hand, the fact that the area of the FOV is halved currently remains a problem. In order to achieve the goals of this research, the performance of the device needs to be improved, with sufficient settings of both FOV and resolution in only one measurement.

Conclusion

As high-resolution voxel models of anterior and premolar artificial teeth can be constructed relatively simply using currently available micro-CT, it can be considered that future improvements in high-performance, low-cost cone beam CT can be used in evaluation of student training and clinical measurement of abutment teeth.

Acknowledgements

Thanks to Rigaku Corporation for supplying the micro-CT for test use. This study was presented at the 121st Scientific Meeting of Japan Prosthodontic Society (May 2012, Yokohama).

References

1) Uchiyama Y : The CAD/CAM System Is Absolutely for Dental Medicine. The Progress of Development, the Present Condition, and the Outlook in the Future. J Jpn Prosthod Soc 45 : 381–396, 2001.
2) Yamaguchi H, Ino S, Katumata Y, Hamano N, Watanabe T, Houjyou S, Toyoda M : The Manufacturing Characterization of Zirconia Core Corpings of CAD/CAM Systems. Annals of Japan Prosthodontic Society, Special Issue 1 : 140, 2010.
3) Miyazaki T, Hotta Y : Current status and future perspective of dental CAD/CAM. J J Dent Mater 30 : 219–222, 2011.
4) Ebihara Y : Current status of CAD/CAM system. J J Dent Mater 30 : 223–226, 2011.
5) Maeda Y, Sugata F : CAD/CAM System and Process for Dental Ceramic Restorations. Panasonic Technical Journal 57 : 35–37, 2011.
6) Hirata K, Nakashima M, Imura S, Yamamoto K, Sekine I, Moriwaki Y, Yoshida S : Application of Non-contact High Speed 3-D Shape Measuring System to Restorative Dentistry Part 1. Accuracy in Measuring Width and Depth of Standard Cavity. Jpn J Conserv Dent. 40 : 287–293, 1997.
7) Hikita K, Yorimoto T, Aita H, Ueda Y, Ohata N : An application of dental CAD/CAM system to dental education : (Part2) – An evaluation of abutment tooth form in clinical education–. J J Dent Mater 17 (Special Issue 32), 169, 1998.
8) Nishiyama Y, Abe M, Hosoi T, Kikuchi S, Otsuka K, Komatsubara R : An Objective Evaluation Method for Tooth Carving by 3D Measurement. JJDEA 20, 92–96, 2004.
9) Sohmura T, Takahashi J. : CAD/CAM fabrication of dental prostheses (Part 9) : On the shape measurement of teeth by means of high speed measurement system and others. J J Dent Mater, Special issue 15 : 42–43, 1996.
10) Hikita K : A Study on Three-Dimensional Measurement and Restoration of Tooth Crown-Form (by CAD/CAM). J Jpn Prosthod Soc 41 : 804–813, 1997.
11) Nagao M, Sohmura T, Kojima T, Wakabayashi K, Nakamura T, Takashima F, Takahashi J, Maruyama T : High speed 3D shape measurement of teeth model and face (Part 5) Accuracy and application of integrated 3D shape data of dental arch and face. J J

Dent Mater 19 : 117, 2000.
12) Nagao M, Sohmura T, Ojima T, Wakabayashi K, Nakamura T, Takashima F, Takashi J : High-speed 3D shape measurement of dental arch and face (Part 6) Accuracy of integrated 3D shape data of dental arch and face examined by using simple model. J J Dent Mater 19 : 103, 2000.
13) Okuyama Y, Kasahara S, Muramoto M, Kimura K : Study on the Accuracy of Non-contact 3D Measuring System of Prepared Tooth. J Jpn Prosthod Soc, Special Issue 46 : 167, 2002.
14) Murao H, Yamada S, Takeuchi M, Kamata M, Shimakura M : Influence of Measuring Method of CAD/CAM System on Fitting Accuracy of Crown. J J Dent Mater, Special issue 52 : 173, 2008.
15) Wakabayashi K, Sohmura T, Matsumura K, Oku H, Nakamura T, Takahashi J : Three-dimensional measurement of dental model using X-ray CT. J J Dent Mater 22 : 167, 2003.
16) Taiji S, Kazumichi W, Rungnapa L, Hirokazu H, Naoki K, Hiroshi O, Tetsuya K : 3D Shape Measurement of Dental Casts Using Medical X-ray CT. Dental Materials Journal 23 : 121-128, 2004.
17) Kamegawa M, Nakamura M, Tsutsumi S : 3D Morphological Measurements of Dental Casts with Occlusal Relationship using Microfocus X-ray CT. Dental Materials Journal, 27 (4) : 549-554, 2008.
18) Mikami I, Kuroe T, Taniyama T, Sohmura T : Evaluation of Pixel Value of Dental Cone Beam CT. Journal of Japanese Society of Oral Implantology 24 : 405-413, 2011.
19) Ueda Y. : A Study of Computer Aided Design System for Tooth Crown Form. J Jpn Prosthod Soc 40 : 993-1003, 1996.
20) Aita H. : A study on creating the tooth crown basic models used for CAD in crown fabrication. Hokkaido J Dent Sci 17 : 203-220, 1996.
21) Aita H, Ueda Y, Yorimoto T, Hikita K, Uchiyama Y : A Study on Creating the Tooth Crown Basic Models Used in CAD System for Crown Restorations - The Creation of the Tooth Crown Basic Models of Molar Teeth -. J Jpn Prosthod Soc 41 : 787-795, 1997.
22) Aita H, Ueda Y, Yorimoto T, Hikita K, Ohata N, Uchiyama Y : A Study on Creating the Tooth Crown Basic Models Used in CAD System for Crown Restorations : Part 2 The Creation of the Tooth Crown Basic Models of Anterior Teeth. J Jpn Prosthod Soc 42 : 832-838, 1998.
23) Kimura H, Kawanaka M, Watanabe Takasi, Takahasi J, Omura K, An H : An Approach to the Dental CAD/CAM (Part 3) : The CAD Data Base. J J Dent Mater 7 : 924-929, 1988.
24) Nagasawa S, Obata A, Arai Y, Yoshida T, Ito M, Kuroiwa A : The three dimensional teeth models : Voxel model. J J Dent Mater 24 : 404, 2005.
25) Kenneth R. Castleman : Digital Image Processing. 452-459, Prentice-Hall, New Jersey, 1995.
26) Sato T, Miura H and Hasegawa S : Clinical Evaluation of the All-Porcelain Labial Margin for Collarless Metal Ceramic Restoration. Jpn Prosthodont Soc 40 : 141-146, 1996.
27) Shiozawa I, Sato T, Daidohji Y, Funayama N, Gorohmaru T, Ogonuki A, Okada D, Kuriyama M and Hasegawa S : A Clinical Investigation on the Fit of Full Cast Crowns Made by Various Impression Materials and Investment Techniques. J Jpn Prosthodont Soc 43 : 80-89, 1999.