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Original Paper

3D Morphological Measurements of Dental Casts with Occlusal Relationship using Microfocus X-ray CT

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In the diagnosis of dental occlusion, it is necessary to quantitatively measure interocclusal contacts and transfer them to a computer model. In this aspect, three-dimensional computer models of upper and lower dental casts play a significant role. In this study, we proposed a new method to measure occlusal interaction by using a microfocus X-ray CT technique. Measurement accuracy was determined as ±0.03 mm in comparison with a coordinate measuring machine. A superimposition procedure for two sets of three-dimensional dental cast models was also established. Using the same dental cast, the standard deviation between the two sets of models was ±0.015 mm — which was defined as measurement precision. Between an optical laser scanner and the microfocus X-ray CT system, the standard deviation measured between the two models was ±0.05 mm. Data were acquired when upper and lower dental casts mounted on the bite impression were scanned, and then occlusal interaction, contacts, and distance distribution between the casts were visualized by a colored map on the cast models. Within the limitations of the current study, it was successfully demonstrated that microfocus X-ray CT was well poised for quantitative measurement of occlusal interaction.

Key words: Dental cast, Occlusion, Microfocus X-ray CT

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INTRODUCTION

Quantitative measurement of occlusal interaction is important in the diagnosis and treatment of occlusion. It is necessary to measure the interocclusal contacts of a patient and transfer this information to a computer model as the positional relationship between the upper and lower casts. In this aspect, three-dimensional (3D) computer models of upper and lower dental casts play a significant role. Moreover, in orthodontics and prosthodontics, storage area for dental casts of each treatment stage has become a serious issue — further driving the impetus for the development of 3D computer models.

Optical scanners that generate 3D computer models of dental casts have been proven to provide sufficient system accuracy for clinical application[1-3]. Therefore, optical scanners were used alongside computer-aided design and manufacturing (CAD/CAM) systems to produce dental restorations[4]. In particular in the scanning of single teeth, the accuracy is satisfactory for practical use[5].

However, dental casts have a complex shape with an undercut, and the optical scanner is required to measure from a number of directions to minimize blind areas that need to be synthesized. Nevertheless, this technique does not provide adequate accuracy for pits and fossae, especially around the cervical margins of teeth. This deficiency becomes more acute when measuring complete dental arches *versus* individual, separate teeth. To overcome this problem, a medical X-ray CT system was employed to obtain 3D models of dental casts[6]. Nevertheless, even with the latest model of medical CT, the slice thickness is not small enough to construct the fine details of dental casts.

To the best of our knowledge, no reports have been published on the quantitative evaluation method of occlusion, such as distance distribution measurement for complete dental arches. A microfocus X-ray CT has been developed for industrial use[7] and has been investigated for dental application[8,9]. However, most of these investigations and applications were limited to single tooth analysis.

In previous reports on occlusion diagnosis, bite impressions of patients were measured using optical scanners[10-12]. In those reports[10-12], it was necessary to scan multiple times and the measurement procedure was complicated with the possibility of error accumulation. As for the microfocus X-ray CT scanner, it has the advantage of capturing the precise 3D shapes of upper and lower dental casts together with the interocclusal record. The aim of this study, therefore, was to evaluate the accuracy and precision of microfocus X-ray CT technique and to examine its applicability for measuring occlusal interaction.

MATERIALS AND METHODS

Microfocus X-ray CT system

A microfocus X-ray CT system (SMX-225CT-SV, Shimadzu Corp., Japan) was used to construct 3D slice images. The maximum X-ray source output voltage, current, and minimum focus size were 225 kV, 1 mA, and 0.004 mm respectively. A 9-inch image intensifier with an aluminum window was used as the X-ray detector to convert X-ray fluoroscopic images into optical images, which were produced by a 1-mega-pixel CCD camera. A sample was mounted on the rotating table of which the axis was perpendicular to the X-ray beam line. While the sample was being rotated, multiple two-dimensional (2D) fluoroscopic images were acquired and sent to the computer to reconstruct the 3D images. The CT parameters were set and tuned to maximize the image quality to produce a good polygonal model. The X-ray tube voltage and current used in this study were 170 kV and 0.09 mA respectively. A total of 1200 fluoroscopic images were acquired with a total exposure time of 800 seconds. The reconstructed image size on the XY plane was 73.086 mm with a 512×512 matrix. Therefore, each pixel size was 0.143 mm.

Beam hardening correction

The X-ray beam used in this experiment consisted not of a monoenergetic X-ray, but a spectrum of photons of different energy levels. Lower-energy photons were more susceptible to attenuation by material than the higher-energy photons. Non-uniform attenuation of different energies resulted in beam hardening, which appeared as cupping, or a reduction of the reconstructed attenuation coefficient toward the center of a large object. To correct the beam hardening effect in this experiment, a copper plate (0.5 mm thick) was placed in front of the detector to reduce lower-energy X-rays. In addition, standard flat bars of varied thicknesses made from the same material (hard gypsum) were prepared, whereby prior to the CT scan, fluoroscopic images of these standard samples were taken and the attenuation coefficient of the material corrected.

Superimposition of dental casts

Upper and lower dental casts made from a hard gypsum (San-Esu Gypsum Co. Ltd., Hyogo, Japan) were replicated from a dental study model (Nissin Dental Products Inc., Japan).

To compare the 3D computer models, the STL (stereolithography) binary format was used. STL file format is a polygon mesh and is a list of triangular surfaces that describe a computer-generated solid model. This file format is widely used in manufacturing and is a standard input for most rapid prototyping machines. CT images, which were piled-up, multiple-sliced, cross-sectional images of 16-bit TIFF (Tagged Image File Format) format were converted into a STL 3D polygonal model using Mimics software (Materialise, Belgium). To determine the relative density of the threshold which separated the internal and external regions, the relative densities of air and cast portions were measured and their mean adopted as the threshold value. In addition, the region growing tool eliminated noise and separated structures that were not connected. Then, polygon mesh triangles in extraneous areas such as the base surface of the dental cast were deleted.

To develop an accurate and quantitative measurement of two sets of computer models, superimposition was carried out using Point Master software (Knotenpunkt GmbH, Germany). There were two steps in the alignment procedure to minimize the distance criterion. For coarse alignment, the tips of both second molar teeth and of both first bicuspid teeth were selected as reference points. For fine alignment, 100 points were selected on the tooth surfaces. Superimposition of the two sets of computer models was then carried out by software to minimize the average distances between each pair of shells.

Effect of CT threshold value

An engineering plastic, Acetal Copolymer (Polyplastics Co. Ltd., Japan), was shaped into two different forms for standard gages to evaluate the accuracy of microfocus X-ray CT technique. Gage A was a disk plate of 60 mm diameter and had 6-mm diameter-holes with 8-mm pitch (Fig. 1(a)). Gage B comprised flat bars of three different sizes (4×8 mm, 12×16 mm, 20×24 mm in XY plane and 8 mm in height) mounted on a plate (Fig. 1(b)).

To investigate the effect of threshold value, both kinds of gages were used. The threshold value would not affect the hole pitch but could affect the bar width. Prior to the CT scan, the hole pitch of Gage A and the width of Gage B were measured by a coordinate measuring machine, CMM (Crysta-Apex C9107, Mitsutoyo, Japan), and used as references. The gages were placed on the CT table, and images of XY plane cross-sections were taken. On the cross-section image of Gage A, distances between the five holes (8, 16, 24, 32 mm) were measured. On the cross-section image of Gage B, widths of the three flat bars (4, 8, 12, 16, 20, 24 mm) were measured. Using a grayscale line profile crossing the sample edge, the actual edge was determined with an accuracy smaller than the CT image matrix size.

Comparison of the measuring systems

The precision of the measuring system was defined as the standard deviation between two sets of 3D computer models of dental casts measured in series in the same condition — except for sample orientation — to make the superimposition process meaningful (CT-CT). Then, the microfocus CT system was compared against a conventional optical scanner by measuring the deviation between CT and optical scanner (CT-VIVID). A commercially available, non-contact, 3D optical scanner (VIVID 9i, Konica Minolta Sensing Inc., Japan) was used for comparison in this experiment. VIVID 9i had a point accuracy of ±0.050 mm and a resolution (point-to-point distance) of 0.174 mm per plane for X and Y. Scanned volume was 111 mm in X, 83 mm in Y, and 40 mm in Z (parallel to the line-of-sight of the instrument) with telescopic lenses at 600 mm distance from the object. The object was scanned from different views, such that when combined they defined a 3D surface. VIVID 9i had a feature to convert point group data into STL data. Models created by microfocus CT had approximately 120,000 shells, while models created by the optical scanner had approximately 137,000 shells. The same method as described above was used to compare the two sets of 3D computer models.

Occlusal interaction measurement

Upper and lower dental casts with interocclusal record were scanned by a microfocus CT scanner. Two kinds of impression materials, vinyl polysiloxane (Dent Silicone-V, Shofu Inc., Japan) and paraffin wax (GC Corp., Japan) were used as interocclusal recording materials.

Two cases were tested with paraffin wax. In the first "loose bite" case, the upper cast was not pressed strongly enough to touch the lower cast surface. During the STL conversion process with Mimics software by choosing an appropriate threshold value, the impression material was eliminated and the upper and lower cast models were segmented.

In the second "tight bite" case, compression was strong enough for the casts to touch each other and segmentation and separation of the two casts was not successful. To solve this problem, six aluminum blocks were used as reference makers by gluing them to the upper cast's side with wax. The scanning and alignment procedure was described as follows. (1) Lower cast was fixed on the CT turntable with adhesive. (2) Only the lower cast was scanned. (3) Impression record and upper cast were mounted on the lower cast. (4) Upper and lower casts were scanned together. (5) Lower cast and impression record were removed from the CT table and upper cast was scanned separately. (6) Markers were extracted from the model of Step (4) and upper and lower cast models were deleted. (7) Lower cast model of Step (2) was loaded. (8) Upper cast model of Step (5) was loaded and aligned with upper cast model of Step (6) with markers as references. The reason why the lower cast did not have markers was because Steps (2) and (4) shared the same coordination system. The distance between upper and lower cast models was measured, and the distribution was visualized with contour mapping.

RESULTS

Effect of CT threshold value

Figure 1(c) shows the comparison between CT and CMM measurements using standard gages. Hole center distances on Gage A, which were not affected by the threshold value, had an error within ±0.01 mm. Bar width had an error within ±0.03 mm, which was approximately one-fifth of the pixel size at 0.143 mm. Measurement accuracy was evaluated as ±0.03 mm.

Comparison of the measuring systems

Figure 2 shows the superimposition of two sets of computer models (CT-CT) and the distance distribution profile. This error value encompassed

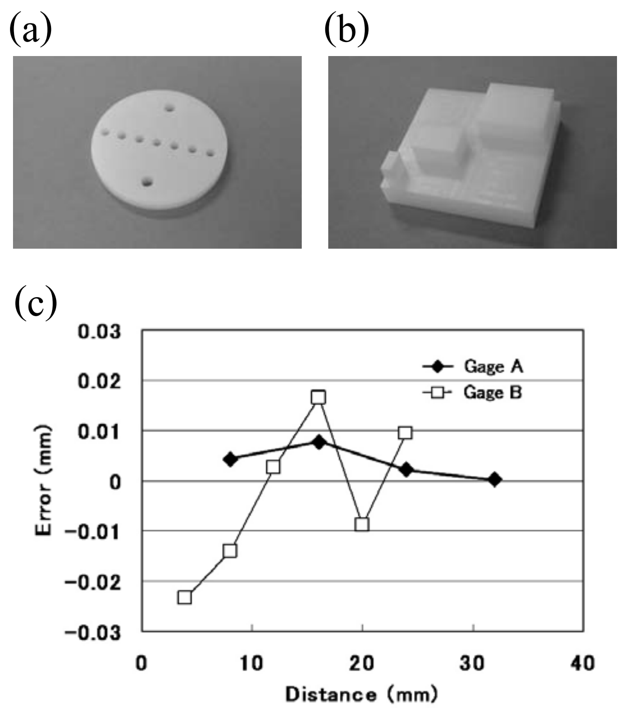

Fig. 1 Accuracy evaluation of microfocus CT in comparison with CMM measurement. (a) Gage A: disk plate with holes; (b) Gage B: flat bars of three different sizes mounted on a plate; (c) Relative error from CMM measurement.

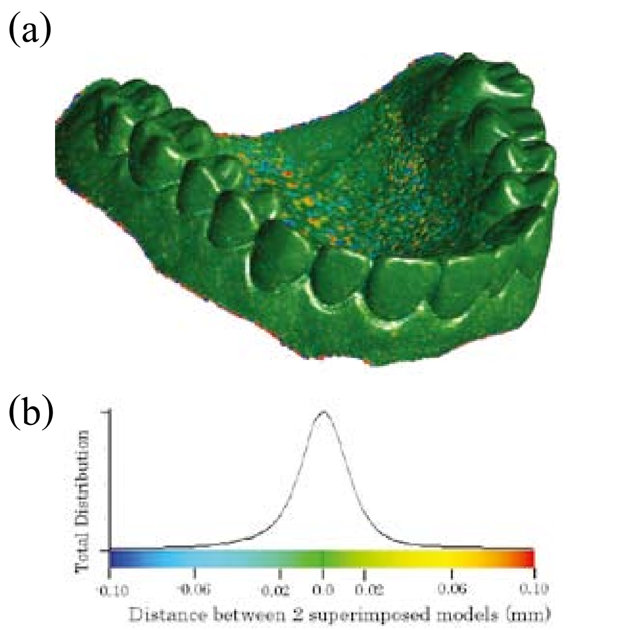

Fig. 2 Accuracy evaluation by repeating measurement: CT-CT Superimposition. (a) Superimposition of two computer models measured in series in the same condition by microfocus X-ray CT; (b) Color bar and distribution plot depend on the distance.

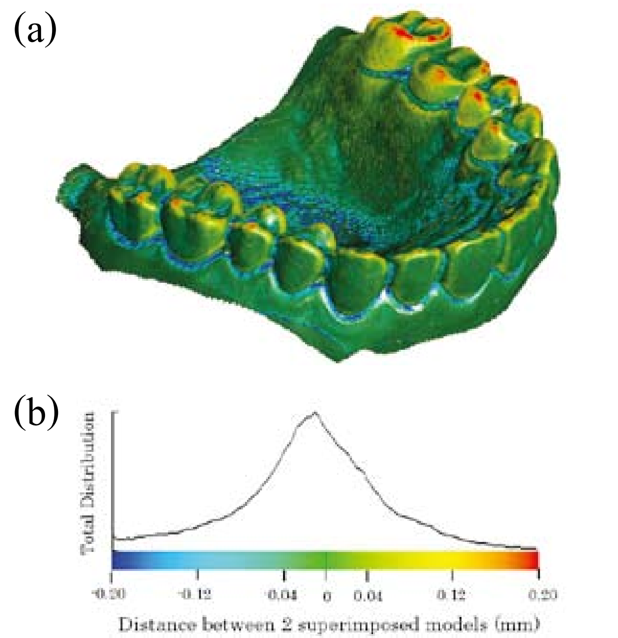

Fig. 3 Comparison of the measuring systems: CT-VIVID Superimposition. (a) Contour map of 3D CT model in comparison to optical scanner model; (b) Color bar and distribution plot depend on the distance.

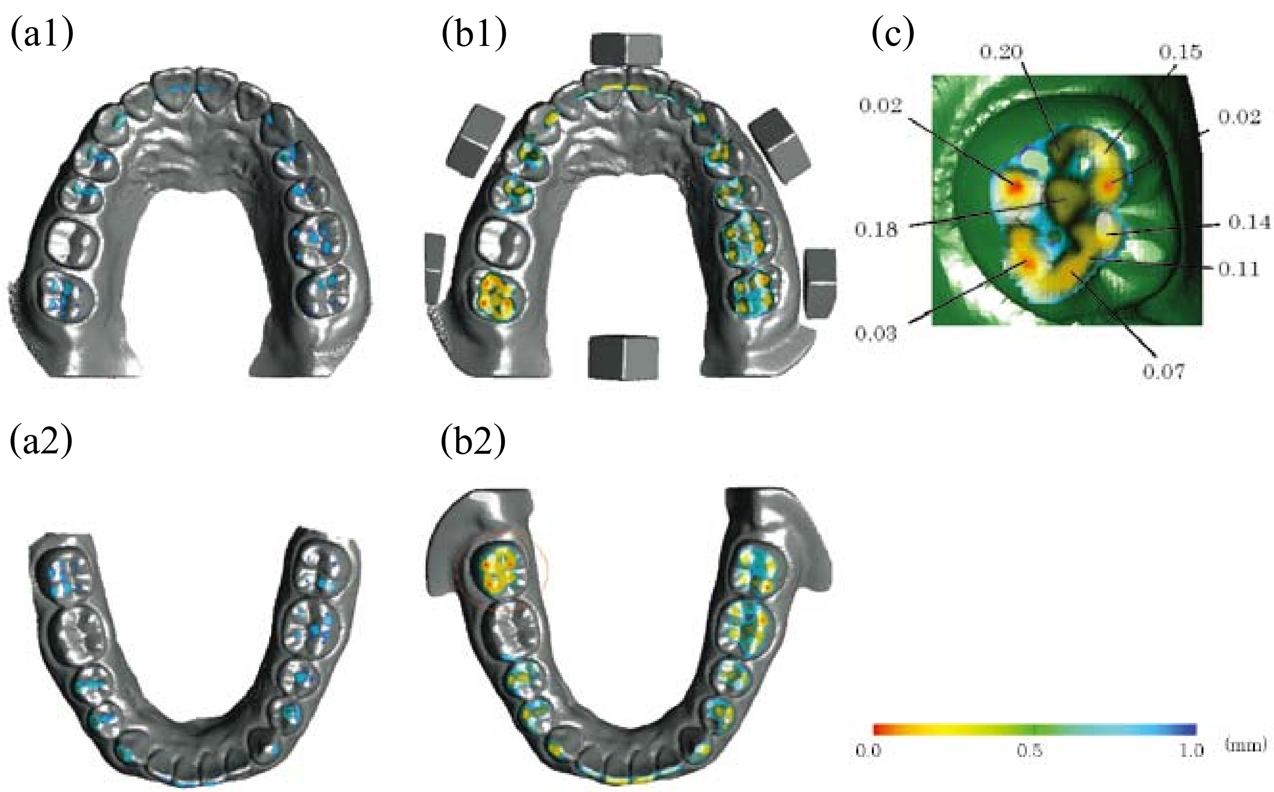

Fig. 4 Measuring occlusal interaction: contour map of distance distribution (less than 1 mm) between upper and lower cast models. (a1, a2) Loose contact with gap between casts; (a1) Distance distribution overlaid on upper cast model; (a2) Distance distribution overlaid on lower cast model; (b1, b1) Tight contact between casts; (b1) Distance distribution overlaid on upper cast model; (b2) Distance distribution overlaid on lower cast model; (c) Magnified image of second molar of (b2) surrounded by a red circle. Inserted labels were distance in mm.

two aspects: microfocus CT system reproducibility and superimposition accuracy. Full width at half the maximum of the distribution was 0.026 mm, which was one-sixth of the pixel size. Standard deviation was less than 0.015 mm and measurement precision was evaluated as ±0.015 mm.

Figure 3(a) shows the superimposition of two sets of computer models (CT-VIVID). A color difference map highlights the characteristic deviations. The target model was that of the CT scan, and the reference model was that of the optical scan. The red portion shows areas where CT data conveyed a convex surface, and the blue portion shows areas where the CT data conveyed a reentrant surface. Full width at half the maximum of this distribution was 0.096 mm, as shown in Fig. 3(b). Standard deviation of 100 selected points was 0.046 mm, which was less than 0.05 mm.

Occlusal interaction measurement

Material density and X-ray absorption coefficient of vinyl polysiloxane were close to those of hard gypsum. Therefore, the dental model could not be segmented from vinyl polysiloxane. However, paraffin wax had a lower X-ray absorption coefficient and segmentation was successful. Figures 4(a1) and (a2) show the first "loose bite" case, where the upper cast did not make contact with the lower cast. Minimum distance was 0.41 mm. Figures 4(b1) and (b2) show the second "tight bite" case. Minimum distance was zero. The results were precise enough to represent the distance distribution. Distances of several selected points on a second molar tooth were labeled and shown in a magnified image, Fig. 4(c).

DISCUSSION

Precision and accuracy, as shown in Figs. 1 and 2, were smaller than the CT pixel size. The latter was determined by the field of view size and reconstruction matrix. This result was attributed to the characteristics of the CT scanner. Output data from an optical scanner or probe scanner were in the form of a 3D point cloud. To improve the accuracy of the optical scanner, the number of sampling points needed to be increased. On the other hand, the CT scanner produced grayscale slice images. Therefore, it was important to maximize not only the spatial resolution, but also the signal-to-noise ratio (SN) of images. Using a grayscale line profile crossing the sample edge, it was possible to attain accuracy smaller than the pixel size.

At this juncture, it is noteworthy that creating a 3D computer model from grayscale data was a process that converted grayscale values into spatial information, which was different from simple spatial interpolation of point group data. Both spatial resolution and SN are factors that affect system accuracy. Spatial resolution was determined by the pixel size of the detector, view (fluoroscopic image) number, and CT reconstruction matrix. SN was determined by the total exposure time, X-ray dose, and X-ray voltage. A longer exposure time and a higher X-ray dose would provide a better SN. Depending on the sample size and material (hard gypsum in this case), an optimum X-ray voltage could be achieved.

Distances between the upper and lower cast models depended on the CT threshold value. Gap distance became larger with a higher threshold value. However, this effect occurred uniformly and the relative difference and distribution of gap distances consequently did not depend on the threshold value.

In comparison with the optical scanner, it was noticeable from Fig. 3 that most regions of the cervical margin were colored blue. This suggested that the CT model contained more reentrant areas than the optical data. The optical scanner had an indigenous problem which failed to capture delicate dimples and fossae. When scanning a single tooth, the accuracy is sufficient for practical application because the target is free from proximal teeth. Therefore, the optical scanner has been successfully used in the CAD/CAM field to produce dental restorations. However, the optical scanner was not suitable for scanning complete dental casts as the region around the cervical margins is important.

A significant difference between a medical CT scanner and a microfocus X-ray CT system is that the latter's magnification can be adjusted. Without cutting a dental cast into individual teeth, the CT image can be magnified by adjusting the distance between the CT table and X-ray source[9]. This technique is useful in increasing system spatial resolution.

Most of all, a prominent feature of the CT scanner is that it has no blind areas as long as X-rays can transit the sample. Therefore, it was possible to digitize the upper and lower casts together with their occlusal relationship with a single scan. If only the occlusal morphology were required, it was also possible to scan merely the bite impression without using the dental cast.

Where casts are mounted on an articulator, the entire assembly can still be scanned. However, it is recommended that plastic or aluminum be used to avoid artifacts from the hinge part of the articulator where the X-rays need to transit. Further, when combined with jaw motion measurements, it is possible to apply this technique for four-dimensional diagnosis. This may thus enable a digital articulator to be realized.

Another possible application lies in the quantitative and objective evaluation of wax patterns. A microfocus X-ray CT system not only can measure the gap between the abutment surface and the inside of the wax pattern[9], the 3D distance distribution between the wax pattern and the antagonistic teeth can also be visualized.

Findings of this study revealed that microfocus X-ray CT technique offered a practical way for complete 3D computer models to be generated for occlusal diagnosis, treatment planning, and outcome assessment. For this technique to be applied to monitoring treatment progress, further studies are required to measure clinical dental casts before and after treatment.

CONCLUSION

In summary, we successfully demonstrated the applicability of microfocus X-ray CT for occlusion diagnosis. Upper and lower casts with impression materials were scanned, and distance distributions were measured and visualized. Results showed that microfocus X-ray CT provided sufficient accuracy for its application in dental occlusion diagnosis.

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