Development of the Computerized Dental Cast Form Analyzing System—Three Dimensional Diagnosis of Dental Arch Form and the Investigation of Measuring Condition—

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To analyze the functional and morphological harmonies of the tooth and dental arch, a computerized system to measure a dental cast and to detect the apex of dental cusps and angle points of incisors was developed. Detailed morphology in the measured dental cast could be displayed distinctively by computer graphics (CG) with a surface model.

Accuracy in determining the position of the apex of the dental cusp was examined by increasing the measuring pitch from 50μm to 400μm, the error increased gradually with increased measuring pitch. Taking the measuring error, the time for measurement and the memory size for analysis into account, a measuring pitch of 200μm was determined to be reasonable.

Three-dimensional data measurements from the apex of the dental cusp in molar, and the mesial and distal angles in canine and incisor were fitted to a polynomial formula. In the present measured model, the 4th order polynomial formula was used for the dental arch, and the 2nd order polynomial formula was used for the anteroposterior and lateral occlusal curves. These formulae could be simultaneously superimposed on the surface model of the dental cast, and displayed using CG.

Key words: Measuring method, Quantitative analysis, Computer graphics

INTRODUCTION

Malocclusion has been thought to be a significant cause of temporomandibular disorders. The origin of malocclusion is believed to be malmorphology of the dental arch and occlusal curve. Occlusal reconstruction has been attempted as a prosthodontic and orthodontic treatment for malocclusion. The shape of the dental arch is often reconstructed using functionally and morphologically harmonious teeth as a reference.

However, at present, occlusal reconstruction is still treated empirically and not based on any theoretical criteria. If the morphological characteristics of harmonious teeth and the dental arch curve can be analyzed quantitatively, they will provide a useful and reliable index for dentists.

In former studies to obtain the morphological information on the teeth and
dental arch form, manual tools such as calipers or a touch probe with a computer have been used, and numerical formulae for the dental arch and occlusal curve have been estimated1–5).

In the present study, we used a noncontact three-dimensional shape measurement system with a point laser, and measured not only the apex of the dental cusp but also the whole dental cast automatically.

In order to analyze the measured data, software to search for the apex of the dental cusp and characteristic points in the tooth was written. The fitting of the obtained data points with numerical formulae was also attempted.

In this system, however, a three-dimensional measurement system which obtained intermittent measuring data was utilized. Since the shape of the tooth is complicated, the measuring pitch had a considerable effect on the accuracy of position determination in the apex of the dental cusp and so on. In the present study, we also examined the influence of the measuring pitch on the accuracy of three dimensional data acquisition for the apex of the dental cusp.

**MATERIAL AND METHOD**

*Measuring system*

A computer-controlled automatic measuring system developed by the authors was utilized to measure the dental casts6–8). This system is shown in Fig. 1 and is composed of a laser displacement meter with double sensors (MD1211-40, Mitsubishi Electric Co., Ltd., Tokyo, Japan) to measure the height of the dental cast, a computer controlled scanning machine (CAMM-3, Roland D.G. Co., Ltd., Hamamatsu, Japan) to scan the dental cast, and a personal computer (PC9801 RA, NEC Corp., Tokyo, Japan) to control the system. The software was written in the C++ language.
The wavelength of the laser displacement meter was 780 nm, the mean diameter of beam spot was 100 μm, and the available measuring depth was 10 mm.

Dental cast
A maxillary dental cast with harmonious dental arch and morphology was selected to measure the whole dental cast (Fig. 2). The cast was colored gray to minimize errors originating from second order reflection by the cast. In order to examine the effect of the measuring pitch on the accuracy of three-dimensional data acquisition for the apex of the dental cusp, a further five casts of maxillary right first molars were prepared.

Measuring method
As shown in Fig. 3, the dental cast was set on the X-Y table of the scanning machine so that the temporary occlusal plane, constructed by the center of the mesial angle of right and left incisors as shown I in the figure, and the right and left distobuccal cusps as shown R and L were in the horizontal plane.

The dental cast was scanned in the X (buccal-lingual) direction, and then stepped in the Y (distal-mesial) direction by the system mentioned above.

Experiment 1: Computer graphics (CG) of the measured dental cast and determination of the apex of the dental cusp.
The present measuring system acquires three-dimensional data using the same measuring pitch in the X and Y directions. It is then impossible to examine the morphology of the tooth or dental arch in the Z direction using wire frame model CG representation. In order to make such an examination in the third dimension, software to draw CG with a surface model was written. The angles between adjacent data were calculated, and the surface patches were filled with gradated colors depending on their angle.

This software was also equipped with algorithm to determine the three-dimensional data in the apexes of dental cusps in molar, and the tips and angles in the canine and angles in incisor in the CG.

Experiment 2: The effects of the measuring pitch on the accuracy of three-dimensional data acquisition for the apex of the dental cusp.
The present measuring system uses a point laser, and the X and Y coordinates of the acquired data points are intermittent. The accuracy in the position determination of the apex of the dental cusp seems to be affected by the measuring pitch. With the smaller measuring pitch shown in Fig. 4a), point B could be recognized as the apex of dental cusp, while with a larger measuring pitch as in Fig. 4b) the true apex was passed and point A would be recognized as the apex. In the present study, the effect of the measuring pitch on the accuracy of three-dimensional acquisition for the apex of the dental cusp was discussed.
The width measuring pitch was changed from 50 μm to 400 μm in increments of 50 μm, and five maxillary right first molars were measured. Three-dimensional data of the mesiobuccal, distobuccal, mesiolingual, distolingual apexes of the dental cusp were determined. They were compared with the data for the apex obtained using a pitch of 50 μm, which were assumed to be the true values as this pitch was the smallest possible with the present system.

Experiment 3: Data fitting of the dental arch and occlusal curve to numerical formulae. After acquiring the three-dimensional data for the apexes of dental cusps in the molar, tips and angles in the canine, and angles in incisor using the software described in experiment 1, numerical curve-fitting of these data was attempted to obtain the proper formula for dental arch and anteroposterior and lateral occlusal curves using the least squares fitting method.

The resultant numerical formulae were superimposed on the CG surface model of the dental arch.

RESULTS

Experiment 1: Computer graphics (CG) of the measured dental cast and determination of the apex of the dental cusp.

The CG surface model of the measured dental cast is shown in the left half in Fig. 5. Comparing this with the cast shown in Fig. 2, the complicated morphology of teeth, dental cusp, and dental arch are reproduced distinctively in the horizontal view.

The procedure to determine the three-dimensional position of the apex of the dental cusp or the mesial and distal angles is as follows. On selecting the objective molar for the apex search in the left CG display of the total dentition, a magnified picture
of the area was drawn in the right half of the display. A point around the apex was selected in this magnified molar image, and the data to be searched within the region of 1.6 mm square around that point were displayed as shown by green dots in Fig. 5. The data with the highest Z value and a 10 μm lower Z value were selected automatically, and marked with red and blue points in the magnified figure. These points were also transferred to the left hand CG model of the total dentition. By the repetition of these operations, the apexes in the dental cusps could be easily determined. In the case of the incisor, the mesial and distal angle points are significant. By selecting the angle points in the magnified CG display, three-dimensional data of the teeth were easily obtained. In the CG of total dentition in Fig. 5, all of the determined apexes and angle points are shown by red points.

Experiment 2: The effects of the measuring pitch on the accuracy of three-dimensional data acquisition for the apex of the dental cusp.

The width in the measuring pitch was changed from 50 μm to 400 μm in increments of 50 μm, and five maxillary right first molars with four cusps were measured. The CG models of one molar measured at 50 μm, 100 μm, 200 μm, and 400 μm pitch are shown in Fig. 6 a)–d). With increasing measuring pitch, the morphology of molar became indistinct. In each cusp of this molar, the data point with the highest Z value (considered to be the apex) was marked with a red dot in the display. Further, considering that the accuracy in the Z direction of the present laser displacement meter is 10 μm on a flat surface, the data points with a Z value 10 μm lower that the highest Z value were also candidates for the apex, and were marked with blue dots. In the case of a) with 50 μm pitch, these points are shown by arrows as the red dots were almost hidden among the blue dots. From the CG model shown in Fig. 6, the precise effect of data pitch on the accuracy of position determination of apex is indistinct. The average of the three-dimensional positions of these red and blue points among the five maxillary right first molars were calculated against eight steps of measuring pitch. The absolute differences from those of pitch of 50 μm were regarded as errors from the true position of the apex, and are shown in Table 1 with four cusps. Since the density of the measurement with pitch of 50 μm is thought to be high enough to determine the apex correctly, its coordinate is assumed to be the true value without error.

<table>
<thead>
<tr>
<th>Measuring pitch</th>
<th>Mesiobuccal dental cusp</th>
<th>Distobuccal dental cusp</th>
<th>Mesiolingual dental cusp</th>
<th>Distolingual dental cusp</th>
</tr>
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<tbody>
<tr>
<td>100 μm</td>
<td>24(13) 27(27) 12(13)</td>
<td>32(17) 33(30) 5(4)</td>
<td>50(41) 32(27) 12(10)</td>
<td>41(27) 26(20) 7(4)</td>
</tr>
<tr>
<td>150 μm</td>
<td>28(14) 64(51) 9(9)</td>
<td>40(47) 13(6) 15(8)</td>
<td>61(48) 31(37) 12(10)</td>
<td>18(17) 30(32) 7(4)</td>
</tr>
<tr>
<td>200 μm</td>
<td>42(16) 61(44) 14(11)</td>
<td>61(45) 40(33) 14(13)</td>
<td>72(46) 38(42) 14(8)</td>
<td>40(22) 35(46) 11(4)</td>
</tr>
<tr>
<td>250 μm</td>
<td>50(31) 127(74) 25(21)</td>
<td>98(106) 41(33) 20(15)</td>
<td>38(30) 51(31) 20(13)</td>
<td>91(35) 80(52) 13(8)</td>
</tr>
<tr>
<td>300 μm</td>
<td>86(38) 90(117) 19(13)</td>
<td>42(26) 82(42) 25(17)</td>
<td>72(64) 69(63) 28(8)</td>
<td>54(53) 45(66) 16(15)</td>
</tr>
<tr>
<td>350 μm</td>
<td>79(39) 98(31) 36(31)</td>
<td>114(65) 44(30) 18(13)</td>
<td>53(91) 45(38) 30(21)</td>
<td>74(23) 60(52) 24(12)</td>
</tr>
<tr>
<td>400 μm</td>
<td>60(46) 97(52) 26(24)</td>
<td>108(90) 34(30) 38(14)</td>
<td>83(62) 116(29) 27(11)</td>
<td>84(64) 107(102) 25(12)</td>
</tr>
</tbody>
</table>
Fig. 5  CG of dental cast measured. Left CG is the surface model with determined apexes on the cusp and angle points, and right CG is the magnified surface model under determination of the apex of the dental cusp.

Fig. 6  Distribution of the measuring point with the highest Z value around the apex of the dental cusp with different measuring pitches. Red dots represent the highest Z values, and blue are 10μm lower. a) 50μm, b) 100μm, c) 200μm, d) 400μm

Fig. 8  CG of dental cast superimposed together with the polynomial formula fitted. a) dental arch, b) lateral occlusal curve, c) right side anteroposterior occlusal curve, d) left side anteroposterior occlusal curve
The results for the mesiobuccal and mesiolingual dental cusp are shown in Fig. 7 a) and b) against the measuring pitch. In the case of the mesiobuccal dental cusp shown in a), the error in X increased gradually with increasing measuring pitch. The largest error in X of 86 $\mu$m was observed with the 300 $\mu$m pitch, and that in Y was 127 $\mu$m with the 250 $\mu$m pitch. These errors were observed among data with a large standard deviation between five casts. The error in Z also increased gradually with increasing measuring pitch, but was comparatively small and less than 36 $\mu$m at all times. In the case of the mesiolingual dental cusp shown in b), exception of the small error at 350 $\mu$m for X and Y, the error increased gradually with increasing measuring pitch.
Experiment 3: Data fitting of the dental arch and occlusal curve to numerical formulae.

Numerical curve fitting of the dental arch was attempted. The X and Y coordinates in the data of the buccal apexes of the dental cusps in molars and canines, and the mesial and distal angle points in incisors were selected and fitted with polynomial formula by the least squares method. Polynomial formulae the orders from 2nd \((y=ax^2)\), 4th \((y=ax^4+bx^2)\), 6th \((y=ax^6+bx^4+cx^2)\), 8th \((y=ax^8+bx^6+cx^4+dx^2)\) were examined, and their coefficient of determination \((R^2)\) values were calculated. With increasing order, \(R^2\) increased to 0.92636, 0.98754, 0.99022, and 0.99052, respectively. A sharp increase in \(R^2\) was observed at the 4th order, above which the value was almost saturated. For the present maxillary dental arch, in consideration of the relative simplicity of the formula, a 4th order polynomial was adopted as the function \((y=0.0000412x^4+0.0137x^2)\). The fitting formula thus obtained is shown in Fig. 8 a) superimposed on the CG dentition model.

In the case of the anteroposterior occlusal curve, the least squares fittings of Y and Z coordinates in the buccal apexes of the dental cusps in molars and premolars was attempted. A second order polynomial formula was the most suitable function in this case. The results are shown in Fig. 8 c) and d) in the right and left maxillary arches, respectively.

\[
\text{(right: } y=0.00222x^2-0.10743x \text{ left: } y=0.00338x^2-0.116x)\]

For the lateral occlusal curve, least squares fittings of X and Z coordinates in the buccal and lingual apexes of the first molars were attempted. In this case also, a 2nd order polynomial was adopted since only four apexes were applied for fitting. The result is shown in Fig. 8 b) together with the distal CG view.

\[
\text{(distal cusp of first molar: } y=0.00132x^2-1.03)\]

These results are useful for numerical and morphological recognition of the dental arch form.

DISCUSSION

In former studies to acquire three-dimensional data of characteristic points such as the apex of the dental cusp, manual operation by touch probe has often been used. Using this method, however, the coordinates of the detected apex will include experimental errors since the dental cusp is rounded, and is difficult to correctly determine the apex with the naked eye.

In the present study (Experiment 1), a computerized system measured the dental cast by noncontact laser and analyzed the data, providing a three-dimensional CG model of the whole dental cast. Furthermore, the apexes of dental cusp were detected automatically by searching for the position in each dental cusp with the highest Z coordinate. In Experiment 2 on the effect of the measuring pitch on three-dimensional data acquisition for the apex of the dental cusp, it is obvious that a smaller measuring pitch would minimize the error. However as shown in Fig. 6 with smaller measuring pitch, the number of the data points with the highest Z value, which are regarded
as the apex, increases on the plateau of the apex in the cusp. In the case of the mesiobuccal dental cusp, for instance, the 50 µm measuring pitch yielded 56 points, but a more manageable 24 points at 100 µm, and only 5 points at 200 µm were returned. It is thought that measuring pitch of 50 µm is unnecessarily small for effective detection of the apex. However, a large measuring pitch will miss the true apex point of the dental cusp, and as seen in Fig. 7, the error increases gradually with increasing measuring pitch. The same data point (such as 200 µm in the X direction for the mesiobuccal cusp and 350 µm in the X and Y directions for the mesiolingual cusp) deviated from linear interpolation, and it is thought that shape of the apex of the dental cusp sometimes becomes flat, resulting in a rather large deviation of the cusp determination. A measurement pitch of up to 200 µm gave errors of less than 72 µm, which are insignificant.

Furthermore, from the practical point of view, the computer memory required for the data of a full dental cast at a measuring pitch of 200 µm was 2MB, with 10,500 data points. Decreasing measuring pitch to 100 µm or 50 µm, the memory requirements increase drastically, to 8MB and 32MB respectively. It is impractical to deal such a large data on a personal computer. Increasing pitch also requires a far longer measuring time; in the present measuring system with a point laser, it took 6 hours for measurement at a pitch of 200 µm, and 24 hours for a pitch of 100 µm.

Considering the factors mentioned, it seems that a measuring pitch of 200 µm is the most appropriate to find the coordinate of the apex of the dental cusp in the present study.

In Experiment 3, using the coordinates of the apexes and characteristic angle points detected by the software in Experiment 1, numerical formulae fitting the dental arch and occlusal curve were determined. In other studies to produce numerical formula for the dental arch, several mathematical functions such as the catenary function by Scott9) and Burdi et al.10), the parabolic function by Mills et al.11), and the polynomial formula by Hayashi12) and Kawata13) have been proposed.

For the present dental arch, polynomial formulae up to the 8th order were examined with least squares method, and the largest coefficient of determination was obtained with the 6th order. However, according to the nature of the polynomial formula, while an increase in the order will yield a higher coefficient, but also makes the formula more complicated to treat. As mentioned in the results above, a sharp increase in R² was observed at the 4th order, after which the value was almost saturated. Accordingly, a 4th order polynomial function is sufficient in this case, as proposed by Miyamori14) and Iwabayashi14). In the present study, the results were limited to one cast, since the purpose of this paper is to introduce a newly-method developed. A statistical analysis of many dental casts will be reported in the near future.

In the case of the anteroposterior occlusal curve, Ito15) and Yasuda16) reported that a sufficient fitting was obtained using a 2nd order polynomial formula. In the present dental cast a 2nd order polynomial was also used. For the lateral occlusal curve, the fitting was done using only the 4 points of the right and left buccal dental cusps and lingual dental cusps, again with a 2nd order polynomial.
Previously, many studies have reported on the dental arch form and occlusal curves, however, these were reported separately and in two dimensions. In the present study, since we have obtained three dimensional shape data of whole dental cast, the dental arch form and occlusal curves could be displayed at the same time from three different view angles by CG models superimposed with a surface model of the dentition, as shown in Fig. 8. This method will be useful for recognition of the individual characteristics of each dentition, and their comparison with others.

CONCLUSION

The functional and morphological harmonies of the tooth and dental arch are a powerful source of reference for reconstruction of the occlusion in prosthodontic and orthodontic treatment. To analyze this dental arch form, a computerized system to measure the dental cast, and to detect the apex of the dental cusp and obtain the angle points was developed. The following conclusions have been down:

1. Measured data of a dental cast were displayed by CG with surface model, in sufficient detail for recognition of the detailed morphology of the cast.
2. Determination of three-dimensional data in the apex of dental cusp in molar, mesial and distal angles in canine, and incisor was possible using the software developed.
3. The effect of the measuring pitch on the accuracy of position detection in the apex of the dental cusp was examined. The pitch was changed from 50 µm to 400 µm in increments of 50 µm, measuring five right first maxillary molars. The error in the position determination up to a measuring pitch of 200 µm was within 70 µm, and thus insignificant. Measurement with a pitch of 200 µm is also reasonable since smaller pitches requires longer measurement times and larger computer memory for analysis.
4. The data were fitted to polynomial formula by the least squares method. In the present cast, a 4th order polynomial formula was used for dental arch, and a 2nd order polynomial formula for anteroposterior and lateral occlusal curves.
5. These equations could be superimposed with the dental arch and displayed by computer graphics.

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REFERENCES


クエン酸緩衝液中における従来型および光重合型グラスアイオノマーセメントの侵食過程

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本研究の目的は従来型および光重合型グラスアイオノマーセメントの侵食過程を明らかにすることである。1種類の光重合型および2種類の従来型グラスアイオノマーセメントをpH 4とpH 6のクエン酸緩衝液に浸せきした。フッ素の溶出はpHに無関係に両タイプのセメントでは同程度であった。他のイオン（Al, Sr, SiおよびP₂O₅）の溶出量はpH 4においては、従来型よりも光重合型のセメントの方が少なかった。しかし、pH 6においては光重合型セメントと従来型セメントの溶出量は同程度であった。pH 4においては、光重合型セメントの溶解はセメントマトリックス中における溶出イオンの拡散によって律連された。一方、従来型では拡散および表面での溶解の分離が同時に行われた。侵食後のセメント表面は上記の溶解過程に良く対応していた。pH 6では、いずれのセメントも拡散が溶解を律連していた。

歯列模様解析システムの開発
—歯列形態の3次元的診断および計測条件の検討—

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機能的かつ形態的に調和のとれた歯や歯列弓を解析するためには、歯列模様の計測、咬頭頂のサーチおよび隅角部における3次元座標の取得を行うシステムの開発を行った。計測された歯列模様の詳細な形態は、サーフェスモデルを用いたCGにより明確に表示された。

臼歯では咬頭頂の、犬歯では近遠心隅角部と尖突頂の、前歯では近遠心隅角部の3次元データを取得した後、歯列弓では4次関数を、前後のおよび側方の咬合変曲では2次関数をあてはめた。そしてCGにより、これらの関数を歯列模様のサーフェスモデルと同時表示した。

一方、咬頭頂の位置の誤差について、50μmから400μmまで計測ピッチを変えて検討した。計測ピッチをあけていくにつれ、誤差も大きくなった。計測誤差、計測時間およびデータ量を考慮すると、計測ピッチは200μmが最も効率的であることがわかった。