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THREE-DIMENSIONAL DIGITIZATION: METHOD FOR EVALUATING MORPHOLOGICAL DIFFERENCES BETWEEN TEETH

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ABSTRACT

A new comparative method has been developed for evaluating morphological differences between a pair of teeth. This method consists of five steps: 1) digitization of the surface morphology of the teeth, 2) standardization to enable comparison of the teeth on a common axis, 3) reversal of data on one tooth to enable comparison with the opposite tooth, 4) qualitative evaluation by computer graphic superimposition and 5) quantitative evaluation by the set operation.

To illustrate its effectiveness, this method was applied to a pair of extracted premolars. Application to the dental crown on a clinical plaster cast was also discussed.

Key words: Tooth morphology, 3-D morphological comparison, Graphic image, Set operation, Morphometry

INTRODUCTION

The occlusion of upper and lower teeth is influenced by variations in the tooth morphology, such as the cusp number, the position of the ridge, the size of the tuberculum, the occlusal groove and so on (Hellman [1]). Therefore, examining the tooth morphology precisely is an important theme in dentistry.

Previous studies have provided many findings by utilizing parameters like classification of the grade of dental trait (Dahlberg [2]) and measurement of tooth width, thickness, height and so on (Fujita [3]). However, these methods can not provide researchers with an accurate and detailed comparison of the morphologies of two teeth, because they can not show the three-dimensional property of a tooth, being in the first case, classified by a nonmetric categorical scale and in the second, measured only one-dimensionally.

To fill this need, we developed a new comparative method for providing a detailed morphological information on differences between two teeth. Our method uses three-dimensional digitization to show the qualitative and quantitative differences in the tooth morphology.

PROCEDURE FOR THIS METHOD (Fig. 1)

I. Digitization of tooth's surface morphology

Measuring points were plotted on the tooth's surface, as many as possible, reflecting the morphological characteristics in detail and also including the anatomical landmarks such as occlusal pit, tip of the cusp and so on. The maximum distance between the nearest points was 3mm on the flat, smooth-surfaced portion of the

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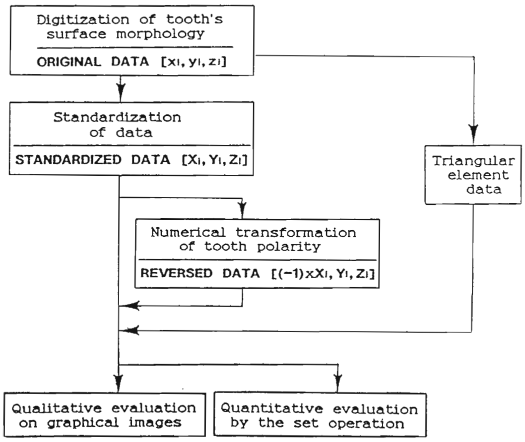


Fig. 1. Flow Diagram of the Method

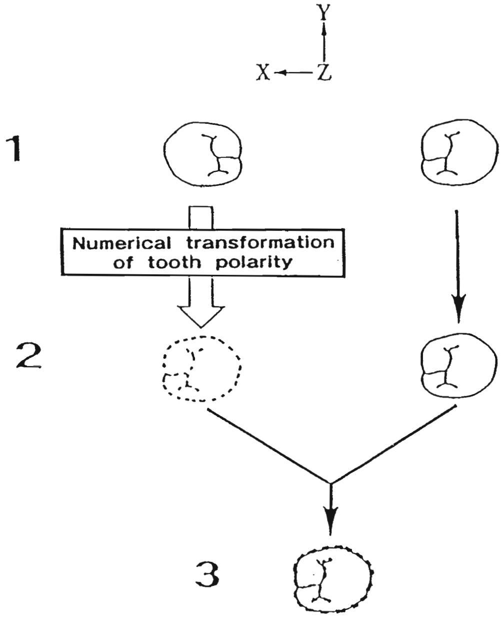


Fig. 2. Schematic Expression of the Numerical Transformation of Tooth Polarity
Comparing the same kind of left and right hand tooth becomes possible by transforming the standardized data of one side to the reversed data.

1. The standardized data of a pair of teeth have symmetric tooth polarities and are not comparable as they are.
2. X coordinates are reversed by the symmetric transformation on the Y-Z plane.
3. Comparison by superimposition is enabled.

tooth, such as the middle region of the dental root. The spatial location of these points were digitized by a three-dimensional input device (Micro Cord D1, Mitutoyo Co., Ltd.). There digitized data were stored in the computer as a set of $[x_i, y_i, z_i]$ coordinates, comprising the raw data. The triangular element data expressing the geographical relationships among the points were also stored (Christiansen and Sederberg [4]).

II. Standardization of data

This step makes it possible to compare a pair of teeth on the common axes. These axes correspond to the new standardized orthogonal axes used in the method of principal component analysis (Rao [5]) and coincide with directions of maximum variation in the data provided by the tooth.

A set of new standardized data [Xi, Yi, Zi] scattered surrounding these axes was computed by using the following formula (Akasaka [6]).

$[Xi, Yi, Zi]=[x_i, y_i, z_i]\times U \quad V=U\times\lambda$

where V, U, λ mean the symmetric matrix of variance and covariance, eigenvector matrix and diagonal matrix of eigenvalues, respectively.

III. Numerical transformation of tooth polarity for comparing opposing teeth

This additional step is required to compare a left tooth with the corresponding right tooth. Tooth polarity is numerically transformed, like a reflection in the mirror, by converting the standardized data to the reversed data by the symmetric transformation on the Y-Z plane (Fig. 2).

IV. Comparison by superimposition

A. Qualitative evaluation

Qualitative differences in the tooth morphology between a pair of teeth were expressed by superimposing images generated from the technology of computer graphics.

This process for graphing was as follows:

Using the above-mentioned standardized and the reversed data along with the triangular element data, the hidden surface removal procedure and smooth shading procedure were done in the computer to make a surface model on the CRT of the two teeth (tooth A and tooth B) to be compared. The software utilized for this was MOVIE BYU (Christiansen and Stephenson [7]), developed by Brigham Young University in the U.S.A..

The two images were then overlapped on the CRT, producing a superimposed image. These images could be viewed from any angle by three-dimensional rotation on the CRT. The three-dimensional differences between teeth A and B were differentiated as the unoverlapped parts on the superimposed image of images A and B.

B. Quantitative evaluation

Quantitative differences in tooth morphology between a pair of teeth were calculated by using the set operation for solid model (Nakashima et al. [8]); The set operation, also called the Boolean operation, is a method which deals with the volume of union or intersection of a pair of solid models.

In this study, the solid models derived from tooth A and B were considered as the assemblage of the primitives of a triangular pyramid (Yamaguchi and Tokieda [9]). The software named CADKEY SOLIDS (Kubota Co., Ltd.) was used in the procedures of the solid modeling and the set operation.

The three-dimensional difference between solid models A and B was then evaluated as a ratio of the unoverlapped parts (mentioned in the above paragraph) to the union of the solid models ($A \cup B$). The volume of the unoverlapped part is derived by subtracting the intersection of solid models A and B ($A \cap B$) from the union.

If we call the union "solid model C", then the volumes of solid models A, B and C can be denoted by Va, Vb and Vc, respectively. The above ratio is then difined as follows:

$(D1+D2) / Vc$

where $D1=Vc-Va$, $D2=Vc-Vb$

This formula gives the rate of the total morphological difference (RTMD).

RESULT OF THIS METHOD'S APPLICATION

A pair of right and left lower first premolars from the same individual was used as an example to make this method concrete and to show its effectiveness.

The original data of $[x_i, y_i, z_i]$ and the triangular element data were made by using such as the mesial and distal occlusal pits, the occlusal groove, the mesial and distal marginal ridges, the cervical line and the root apex. The number of measuring points was 214 on the right tooth and 209 on the left one, and that of the triangular elements was 425 and 415, respectively.

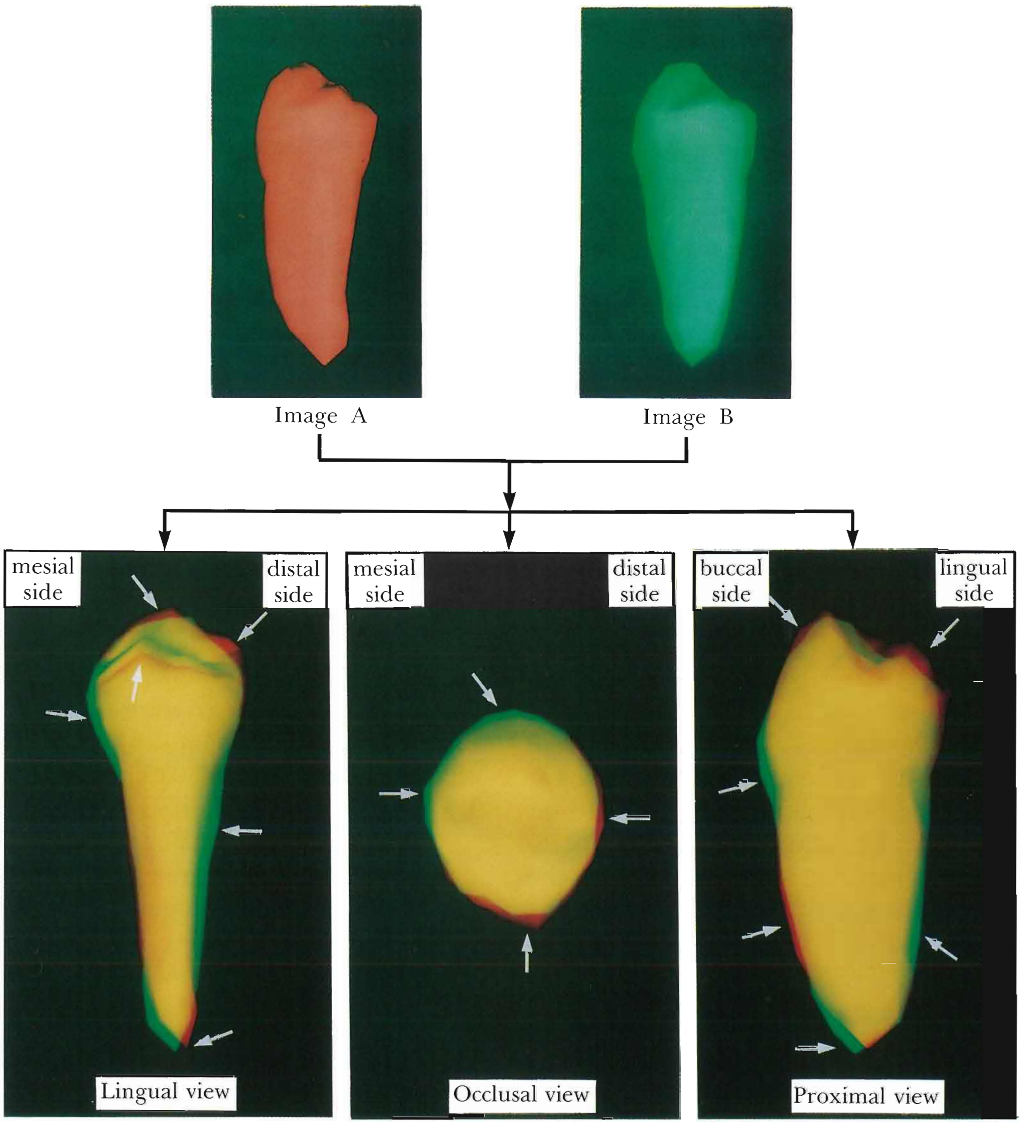
I. Standardization of data

The standardized data and the reversed data were also calculated by using the eigenvectors and the eigenvalues in the new standardized planes. The calculated eigenvalues and proportions of the total variance are shown in Table 1. The proportions of the total variance of the first

Table 1. Calculated Eigenvalues (λ) and Proportions of Total Variance (**P**)

	Right premolar (**4**|)	Left premolar (|**4**)
λ_X	4.500	4.331
λ_Y	6.791	7.202
λ_Z	46.355	46.968
$\mathbf{P}_X$	0.078	0.074
$\mathbf{P}_Y$	0.118	0.123
$\mathbf{P}_Z$	0.804	0.803

X, Y, Z; Component of X, Y, Z axis on the standardized coordinates system



Superimposition of Image A and Image B

Fig. 3. Qualitative Evaluation Using Graphical Superimposition

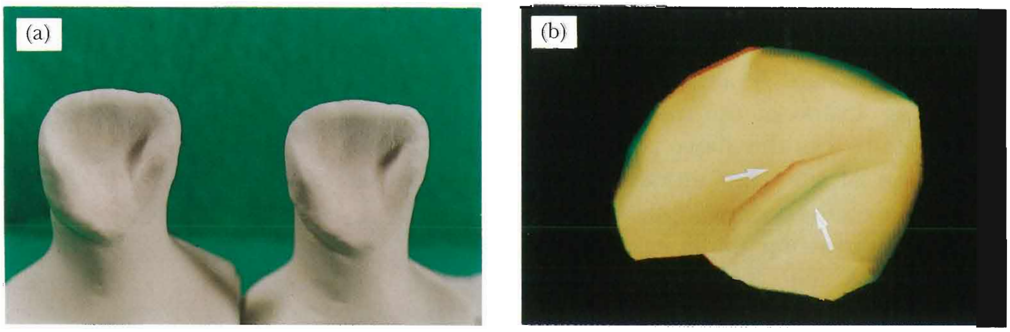


Fig. 5 Example Showing This Method's Effectiveness

principal component (Pz) are 0.80 in both teeth. Each value demonstrates that the measuring points are mostly distributed along the axis of Pz. This confirms that the axis has a high reproducibility as a standard in comparing a pair of teeth.

II. Comparison by superimposing

A. Qualitative evaluation

Using red and green to represent the right and left teeth respectively, the images of the teeth were superimposed graphically (Fig. 3). The morphological differences were recognized by their own color and the morphological similarities were represented in yellow where the two colors coincided on the CRT. The lingual, occlusal and proximal views of the superimpositions are also shown in Figure 3. The three-dimensional morphological differences can be seen in the distal marginal ridge, the buccal cusp, the lingual cusp and the root apex.

B. Quantitative evaluation

The results of the example presented above are shown in Table 2. The volumes of Va, Vb, Vc are 702.6mm^3, 600.5mm^3 and 722.8mm^3, respectively. By using these values, the volumes of the unoverlapped parts (D1 and D2) take the quantities of 20.2mm^3 and 122.3mm^3. Finally, the rate of the total morphological difference (RTMD) is expressed by 0.179 as a definite numerical value.

Table 2. Quantitative Evaluation Using Rate of Total Morphological difference (RTMD)

D1=Vc−Va= 20.2	(mm^3)
D2=Vc−Vb=122.3	
Va=702.6	
Vb=600.5	
Vc=722.8	
RTMD=(D1+D2)/Vc=0.197	

(D1+D2): Volume of unoverlapped parts between models A and B Va, Vb, Vc: Volume of models A, B and C

Discussion

I. Approach to the clinical application for this method

Above we have described how to apply this method to the extracted teeth, having a dental crown and also a dental root. In this paragraph, we would like to discuss how to apply this method clinically, having only a dental crown.

In this case, in order to orient properly the two subjects to be compared, another data processing step must be taken prior to the standardizing process. Whereas the points for the dental crown and root on the extracted tooth are distributed directionally along its long axis, the measurig points for the dental crown on the clinical plaster model are spatially scattered haphazardly and undirectionally, making orientation difficult.

To overcome this difficulty, then, we weighted the measuring points having the important anatomical characteristics on the dental crown to emphasize its spatial direction. We continued adding data to the original data file in proportion to the weight of the area, thus forming a cumulative weighted data file.

Figure 4 shows an example of this process of weighting the points on an upper central incisor. Weighting was increased stepwise from the middle part of

Fig. 3.
Three-dimensional morphological differences can be seen as differences in color (arrow) in the distal marginal ridge, the buccal cusp, the lingual cusp and the root apex.

Fig. 5.
Graphical superimposition enables the evaluation of the minute morphological differences between a pair of teeth having much similarity shown in Figure (a). Figure (b) shows the positional difference and the size difference in the area of the mesial marginal ridge (arrow) from the lingual oblique view.

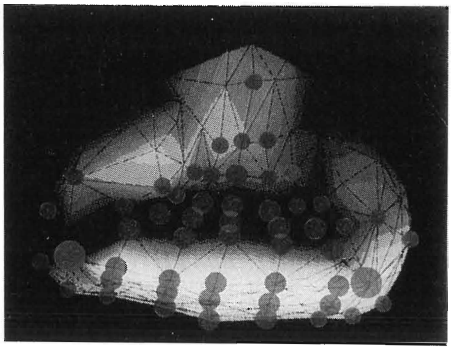


Fig. 4. Process of Weighting the Points
An example on the upper central incisor (1|). The stepwise weighting was conducted on the middle part of the tooth crown, incisal edge and mesio-distal incisal angle in increasing order by adding their data of points to the original data. The diameter of the dots on the tooth represents the degree of the weight.

Table 3. Comparison Before and After Weighting Process of Eigenvalues (λ) and Proportions of Total Variance (**P**)
Values after the weighting process were increased compared with those before the weighting process in the component of the principal axis (Z); This changing of the values means that the weighting process gave a spatial direction to a dental crown.
Upper Central Incisor (**1**|) Weighting process

	After	Before
λ_X	5.494	9.270
λ_Y	3.748	3.579
λ_Z	35.580	5.785
$\mathbf{P}_X$	0.127	0.498
$\mathbf{P}_Y$	0.084	0.192
$\mathbf{P}_Z$	0.794	0.310

X, Y, Z; Component of X, Y, Z axis on the standardized coordinates system

the tooth crown, the incisal edge and the mesio-distal incisal angle in increasing order.

As a result, the proportion of the total variance of the Z axis (Table 3) increases from 0.31 to 0.79 which is similar to that of the extracted tooth shown in Table 1. The similarity of these values means that this weighting process is reasonable and available for use clinically with plaster models of the dental crown.

II. Characteristics of this method

In this parapraph, characteristics of this method are compared to previous evaluation methods of the tooth morphology (Dahlberg [2]; Fujita [3]; Ozaki et al. [10]).

The most important characteristic of this method is the ability to superimpose two tooth morphologies by digitizing their morphology and computer graphics. This enables 1) detailed quantitative and qualitative evaluation of the three-dimensional differences between whole teeth or partial teeth and 2) the calculation of the differences in their morphology by using the set operation between their data matrix.

Using measurements such as tooth width, thickness, height, contour and the grade of dental trait in previous studies has not been enough to reflect properly the morphological information of the teeth which consist of complex curved planes and show undefined forms. It has been especially hard to distinguish the differences in a pair of teeth having a great deal of similarity.

However, this new method is effective on a highly similar pair of teeth. The superimposed display of Figure 5 is an example of two upper central incisors, which are highly similar, and their morphological details were difficult to express by the previous methods. The morphological differences are seen in the position and the grade of the mesial marginal ridge from the lingual oblique view.

Another characteristic of this method is the ability to compare qualitatively and quantitatively by reflecting a pair of right and left hand teeth in the same dimensional orientation by means of the numerical transformation of the tooth polarity.

Furthermore, this method provides a

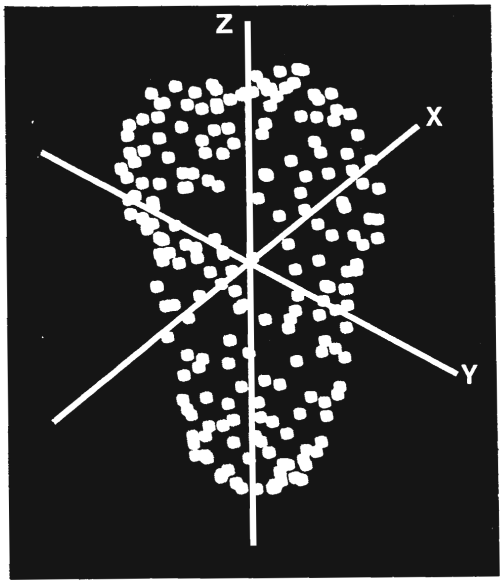


Fig. 6. Distribution of Points on Standardized Coordinates System
It is recognized that these points are scattered in an isometric and unbiased view.

new objective standardized system of coordinates to compare undefined tooth forms. The reliability for the new system was confirmed in Table 1 showing that the proportion of the total variance of the Z axis is 0.8 in a high ratio, and also in Figure 6 showing that the measuring points scatter in an isometric and unbiased view surrounding the orientated standard axis.

In addition, this Z axis was nearly matched to the long axis which was defined conceptually as a straight line that runs through the central part of the tooth. From this point of view, it would be suggested that this calculated axis would substitute as a kind of quantitative definition for the so-called dental axis (Dempster et al. [11]) used in the field of dentistry.

Finally, in the digitization of the tooth morphology, we used a mechanical type of input device with a contacting probe. To determine the degree of methodological error produced by differences of the location of measuring points using this device,

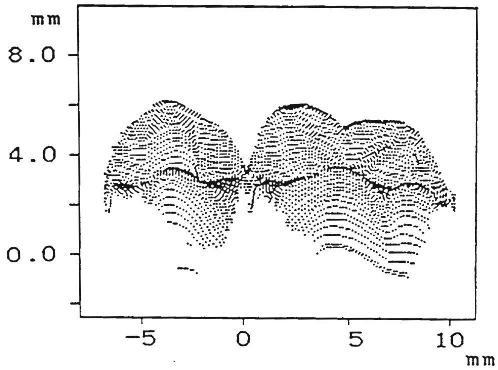


Fig. 7. Example of Data Input With High Accuracy Inputting Device

the points were plotted and digitized three times independently on the same extracted premolar used in the previous chapter. Calculating each volume by the set operation, the methodological error determined by the ratio of differences among the three volumes was within 2%. If we would use an optical type of input device with a laser beam (Fig. 7), the measurement reproducibility would be advanced.

Summary

We developed a comparative method for tooth morphology for either entire or partial aspects by digitizing a pair of three-dimensional subjects through a system of coordinates and have summarized its effectiveness as follows:

1. Qualitative differences in tooth morphologies can be evaluated by the three-dimensional superimposed images via computer graphics from any desired view.
2. Quantitative differences in tooth morphologies can be evaluated with the measurement of their volume calculated from the set operation.
3. Numerical transformation of tooth polarity enables comparison both qualitatively and quantitatively of opposing teeth.
4. Standardization of data enables orientation of the numerical dental axis objectively.

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