Relationship between the Load-Displacement Curve and Deformation Distribution in Porcine Mandibular Periodontium*

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Abstract

A porcine mandible was separated to prepare thin periodontium specimens, consisting of a molar, periodontal ligament (PDL), and alveolar bone. Occlusion was simulated by applying a forced compressive displacement, using a table-top material tester. We photographed images of the displacing periodontium specimen and simultaneously obtained the load-displacement curve during the test. The displacement and deformation distributions were examined using digital image correlation analysis. Then, we correlated the distribution with the load-displacement curve, which was characterized by biphasic behavior, as noted in many previous studies. We found that the displacement and deformation distributions of actual periodontium correlated with the load-displacement curve during dental occlusion. Regarding the biphasic characteristics of the load-displacement curve, we showed experimentally that the first phase indicated deformation of the PDL and the second indicated deformation of the alveolar bone and tooth.

Key words: Dental Occlusion, Load-Displacement Curve, Deformation Distribution, Digital Image Correlation, Whole-Field Measurement, Periodontium, PDL, Alveolar Bone, Porcine Mandible, Biphasic Characteristics

1. Introduction

Dental occlusal analysis is an important research theme in dentistry, from the perspective of investigating problems, such as occlusion, orthodontics, and periodontal disease. Studies on the displacement and deformation behaviors of periodontium have used two primary approaches in dental occlusion analysis. One is the investigation of the displacement or strain distribution, using conventional optical interferometric techniques, such as the photo-elastic method⁽¹⁾⁽²⁾, laser speckle interferometry⁽³⁾⁻⁽⁵⁾, holography⁽⁶⁾⁻⁽⁸⁾, and moiré interferometry⁽⁹⁾⁽¹⁰⁾, under simulated dental occlusion, where phantom biomaterials, such as photo-elastic materials, are used as the periodontium specimen. The other is the evaluation of actual tooth mobility under dental occlusion, attaching laser displacement sensors⁽¹¹⁾⁻⁽¹³⁾ or strain gauges⁽¹⁴⁾⁻⁽¹⁶⁾ on the tooth of the person being tested. It is often pointed out that the former investigations may differ from the behavior of actual

periodontium, although it is possible to obtain the distributions of displacements or strains in two or three dimensions. Due to the limitations of the measuring devices, including the available space for measurement, the latter technique typically allows only single-point measurements of local displacement or strain, although it has the great advantage that it enables measurement of the displacement and deformation behavior of actual periodontium. Therefore, using the advantages of both approaches, we studied the whole-field displacement and deformation distribution using a digital image correlation method with the freshest possible porcine periodontium, from an animal slaughtered a few days earlier for human consumption⁽¹⁷⁾⁽¹⁸⁾.

Dental occlusal analysis from the load-displacement curve of the periodontium is also an important measurement in dental occlusion. Many researchers have studied the load-displacement curve of the periodontium under dental occlusion⁽¹⁹⁾⁻⁽²⁵⁾, including Parfitt, who revealed the characteristics of the load-displacement behavior of the periodontium under dental occlusion⁽²⁶⁾. These studies concluded that the load-displacement curve was non-linear with biphasic characteristics, in which the increase in the rate of the load was relatively small in the initial period of dental occlusion, the first phase, and relatively large in the middle and final periods of dental occlusion, the second phase. Regarding this behavior, it has been suggested that the first phase indicates the deformation of the periodontal ligament (PDL), and the second phase indicates the deformation of the alveolar bone and teeth. However, this has not been visualized directly, because it is quite difficult to measure the displacement and deformation distributions of actual periodontium, as mentioned above.

Therefore, we examined the correlation of the load-displacement curve with the displacement and deformation distributions of actual periodontium under simulated dental occlusion. Porcine skulls, obtained from animals slaughtered a few days earlier for human consumption, were used to simulate the actual periodontium as closely as possible. The mandible was separated from the skull and specimens that including a molar, PDL, and alveolar bone were prepared. The specimens were displaced forcibly in a table top material tester. Then, the periodontium specimens were photographed during the occlusion test to obtain the load-displacement curves. Finally, the displacement and deformation distributions obtained from these images were analyzed using a digital image correlation method⁽²⁷⁾⁽²⁸⁾, and we correlated the distributions with the load-displacement curves. To our knowledge, no such research using actual periodontium has been reported. This study clarified the displacement and deformation distributions of the periodontium under dental occlusion. In addition, it suggests the ideal displacement distribution in dental implants, where titanium alloy osseointegrates into alveolar bone directly, without using the PDL as a buffer.

2. Experimental methods

2.1. Digital image correlation method

The digital image correlation method uses patterns unique to an object's surface, or intentionally spray-coated random patterns. Patterns and brightness distributions on the object to be measured are photographed using a charge-coupled device (CCD) camera or similar device before and after displacement. In this way, the amount and direction of displacement on the surface of the object can be measured simultaneously.

More specifically, a small region of $N \times N$ pixels centered on an arbitrary position in an image before deformation acts as a reference subset. The position showing the greatest correlation with this reference subset in the image after deformation is then identified, so that the amount and direction of displacement can be determined. To correlate the subsets, a rough search is conducted, in which the displacement is measured to an accuracy of one pixel. Then, a fine search is conducted in which the displacement is obtained with a

measurement accuracy finer than one pixel. In the rough search, the correlation function C_R is determined using the minimum residual method (Eq. 1).

$$C_R(X+u, Y+v) = \sum_{i=-M}^M \sum_{j=-M}^M |I_a(X+u+i, Y+v+j) - I_b(X+i, Y+j)| \quad (1)$$

where $I_b(X, Y)$ and $I_a(X+u, Y+v)$ are the light intensities before and after deformation, respectively; X and Y are the center coordinates of a subset; u and v are displacements in the x - and y -directions, respectively; and $N = 2M + 1$. When C_R reaches a minimum, the subset containing this position is considered to be the pixel nearest the center of displacement.

Since the actual displacements do not equal integral multiples of the pixel values, it is necessary to obtain displacements with an accuracy finer than one pixel. This is generally accomplished by one of two methods. In the first, the discrete light intensity distribution of pixels is directly interpolated numerically to obtain the position of the pixel with the highest correlation coefficient⁽²⁹⁾⁽³⁰⁾. In the second method, the correlation coefficients of the pixel with the highest correlation coefficient and the pixels immediately surrounding it are subjected to interpolation using an approximate curve. The peak value position is then identified by the displacement of the reference subset after deformation⁽³¹⁾⁽³²⁾. We used the former method for the analysis. The correlation function C_F was used for the fine search (Eq. 2). Using this equation, deformation can be measured with a measurement resolution finer than one pixel:

$$C_F(X+u, Y+v) = \frac{\sum_{i=-M}^M \sum_{j=-M}^M \{I_a(X+u+i, Y+v+j)\} \cdot \{I_b(X+i, Y+j)\}}{\sqrt{\sum_{i=-M}^M \sum_{j=-M}^M \{I_a(X+u+i, Y+v+j)\}^2 \cdot \sum_{i=-M}^M \sum_{j=-M}^M \{I_b(X+i, Y+j)\}^2}} \quad (2)$$

Indeed, the sensitivity of this technique was about 0.05 pixels. Validation studies of this algorithm have been reported in Refs. (33) and (34).

2.2. Preparation of specimens

The specimens for the experimental analysis were taken from the mandible of fresh cadavers of adult pigs, in which secondary teeth eruption was finished. Using a metal saw, the mandibles were dissected free into segments containing first and second complete molars with the surrounding PDL and alveolar bone (between dotted lines I and I' in Fig. 1(a)), and then the adhering soft tissues were removed. The segments were cut into 2.0-mm-thick slices, parallel to the longitudinal axis of the tooth using a low-speed bone saw (Isomet, Buehler, IL, USA). A counterbalance weight on the saw was used to lighten the load on the specimen. The mandible and saw blade were cooled in physiological saline

Fig. 1 A specimen used in this study. (a) A mandible from the fresh cadaver of an adult pig. (b) Periodontium structure.

Fig. 2 Load-displacement curve of the periodontium during simulated dental occlusion.

to avoid denaturing the tissues⁽³⁵⁾. Sliced samples containing tooth, PDL, and bone naturally have different geometries, depending on the cutting position of the saw blade. Additionally, in some samples, several- μm out-of-plane displacements were observed in the tooth region due to the thinness of the sample during the simulated dental occlusion. In total, we acquired and processed 17 samples. The precise displacement distribution was not same since the geometry of the root of the tooth, in particular, is quite variable. Nevertheless, the results obtained were qualitatively similar in each cross-section. The specimens were kept in physiological saline until mechanical testing to prevent them from drying.

2.3. Experimental set-up

In the experiment, the test specimen was taken out of the physiological saline and random patterns were created on its surface by spraying it with a synthetic resin, pigment, and organic solvent (S05032, Dai Nippon Toryo). The mandibular bone of the specimen around the medullary cavity was fixed in a vice (dotted line II, Fig. 1(b)) and was placed in a table-top materials tester (EZ Test, Shimadzu), with a load resolution of 0.01 N and a displacement resolution of 10 μm . A compression load, parallel to the tooth axis, was applied to the top of the tooth (point III in Fig. 1(b)) at a crosshead speed of 500 $\mu\text{m}/\text{min}$, by increasing the displacement continuously, until a compressive displacement of $-200 \mu\text{m}$ was reached. Load and displacement data were recorded throughout the loading period. Digital images of the specimen surface were taken every $-20 \mu\text{m}$ of displacement during the continuous loading. Although the occlusal load on a single human molar has been reported⁽³⁶⁾⁽³⁷⁾, the occlusal load on a single pig molar, as prepared in this study, has not been reported. Therefore, a forced compressive displacement to $-200 \mu\text{m}$ was adopted. Intrusion of $-200 \mu\text{m}$ was considered to be appropriate, because it is equal to the actual amount of displacement in dental occlusion⁽¹¹⁾⁽¹²⁾⁽²⁵⁾⁽³⁸⁾.

3. Experimental results and discussion

Figure 2 shows an example of a load-displacement curve obtained in the simulated occlusion test. The horizontal and vertical axes represent the displacement of the crosshead of the material tester, and the load obtained by the load cell, respectively. The rate of increase in the load was low from 0 to $-80 \mu\text{m}$ and then relatively large after $-80 \mu\text{m}$, indicating the biphasic characteristics. This indicates the reasonableness of the simulated occlusion test, as it showed the same non-linear behavior (biphasic characteristics) of the load-displacement curve during simulated dental occlusion in previous studies⁽¹⁹⁾⁻⁽²⁶⁾.

Figure 3 shows actual images of the periodontium during a simulated occlusion test. Images (a) to (f) in Fig. 3 correspond to the states *a-f* in Fig. 2, respectively. Each image

Fig. 3 Images of a fresh periodontium specimen under simulated dental occlusion. (a) to (f) correspond to the image at points *a* to *f* in Fig. 2 ($\delta = -20, -40, -80, -120, -160$, and $-200 \mu\text{m}$, respectively).

measured 1300×1700 pixels, and one pixel was equivalent an area of $20 \times 20 \mu\text{m}^2$. The black dots on the specimen surface are part of the random pattern intentionally created for application of the digital image correlation technique. The displacement magnitude was so small that little change or difference is observed in the images.

Figures 4 and 5 present the resulting horizontal (*u*) and vertical (*v*) displacement calculations, respectively, based on the digital image correlation method. The analysis conditions included a subset size of 41×41 pixels. The calculations were performed in three-pixel steps for the 1300×1700 pixels. To reduce salt-and-pepper noise in the images, 3×3 pixel median filtering was used. Images (a)-(f) in Figs. 4 and 5 correspond to states *a-f* in Fig. 2, respectively. Contour lines of the displacement are also shown in Figs. 4 and 5 to clarify the displacement distributions. The sensitivity of the contour lines is 20 and $10 \mu\text{m}/\text{line}$ in Figs. 4 and 5, respectively.

States *a* and *b* in Fig. 2 correspond to the first phase of the biphasic curve, representing the initial period of dental occlusion. Figs. 4 and 5 (a), (b) show the displacement

Fig. 4 Horizontal (*u*) displacement distributions with contour lines of a fresh periodontium specimen under simulated dental occlusion. (a) to (f) correspond to the distributions at points *a* to *f* in Fig. 2 ($\delta = -20, -40, -80, -120, -160$, and $-200 \mu\text{m}$, respectively).

Fig. 5 Vertical (v) displacement distributions with contour lines of a fresh periodontium specimen under simulated dental occlusion. (a) to (f) correspond to the distributions at points a to f in Fig. 2 ($\delta = -20, -40, -80, -120, -160$, and $-200 \mu\text{m}$, respectively).

distributions in these states. The simulated occlusion test was conducted properly, meaning that the compression load parallel to the tooth axis (y -axis) was applied in the correct way, without tooth rotation, because no contour lines of displacement appeared in the tooth area (see Figs. 4 and 5 (a), (b)). The contour lines of the displacement appeared only in the PDL for the v -displacement distributions. This suggests that rigid body movement occurred only in the molar and deformation was seen only in the PDL as the force intrusion increased. Next, states c - f correspond to the second phase in the biphasic curve, representing the middle and final periods of dental occlusion. At state c in Fig. 2, the deformation of the PDL increased (Figs. 4, 5 (c)). There, deformation occurred only in the alveolar bone and the root of the tooth, because a contour line of the displacement was seen. Therefore, the load increase around state c in Fig. 2 can be attributed primarily to the deformation of alveolar bone. Moreover, the rate of increase of the load increased around state d of the load-displacement curve (Fig. 2). The displacement distribution in Figs. 4 and 5 (d) shows that the gradient of the displacement changed in the molar, representing deformation of the molar, with increasing PDL and alveolar bone deformation. That is, the drastic rise in the load after state d in Fig. 2 was due to deformation of the molar. Finally, the displacement distributions at states e and f in Fig. 2, shown in Figs. 4 and 5 (e), (f) represent increased deformation of all components: PDL, alveolar bone, and molar. In summary, the first phase of the load-displacement curve of the periodontium shown in Fig. 2 indicated that the rate of increase of the load was relatively small, showing prominent deformation of the PDL, which consists of fibrous connective tissue. In large part, this is due to an appropriate amount of sway in the tooth. This was clarified by visualizing the displacement distributions experimentally, which showed that during the second phase, when the rate of increase of the load was relatively large, there was deformation of the alveolar bone first, and then, finally, deformation of the tooth.

4. Summary

The experimental specimens consisted of sliced periodontium, composed of a molar, PDL, and alveolar bone, separated from the porcine skull. Each specimen was set in a table-top material tester, and a compressive test simulating dental occlusion was then conducted. The images of the deformed periodontium were photographed to obtain the load-displacement curve, and the displacement and deformation distributions were obtained using digital image correlation analysis. The results support the following conclusions:

- (1) This study is the first to show that the displacement and deformation distributions of actual periodontium are correlated with the load-displacement curve during dental occlusion.
- (2) Regarding the biphasic nature of the load-displacement curve, we demonstrated that the first phase indicates deformation of the PDL and the second indicates deformation of the alveolar bone and tooth.

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