Experimental Study on Deformability of Polymeric Dental Aligner by Digital Image Correlation Method

by

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Polymeric dental aligners manufactured by thermoforming are recently used in clinical treatment of misaligned teeth. In this study, a polyester sheet with 0.75 mm thickness was used and the deformability of thermoformed aligner is discussed experimentally with the help of digital image correlation method. The experimental apparatus to apply prescribed displacement to aligners mounted on a teeth model was developed focusing on the situation of treatment for misaligned left canine. The deformation mode was discussed through measured displacement field and maximum principal strain distribution. It was found that mechanical behavior of aligner was influenced more significantly by the shape of teeth, movement vector of left canine and crooked shape of aligner especially at inter-teeth borders than the thickness distribution of thermoformed aligner. The role of deformable edge part of the aligner was also revealed.

Key words:
Dental aligner; Polyester; Deformability; Digital image correlation method; Strain concentration

1 Introduction

Polymeric dental aligners are an innovative solution to teeth misalignment and present numerous advantages with respect to the commonly used metal brackets. Polymeric aligners are less invasive, more esthetic because of the transparency and are easily removable as well. Among many possible polymeric materials for dental applications, polyester was used in this study. It is one of the thermoplastic materials suited for thermoforming of complicated shape, and is now used for dental treatment of patients with misaligned teeth array. The motivation of this study lies in the fact that unexpected movement of teeth is observed sometimes. It is very important to understand the dental mechanics in the use of polymeric aligners, in the same way with other dental treatments including implant.

One of the authors used 3-dimensional finite element analysis of two teeth model fixed in plaster, and this simple numerical model was experimentally examined to validate the numerical simulation. The contact areas between tooth and aligner and displacment of the tooth root part were analyzed. Many other researchers also utilized finite element method to analyze stress distribution and/or displacement distribution. Since the setup of realistic boundary condition in numerical analysis is difficult, the validation of simulation by comparison with experimental measurement remains unsolved. The use of digital image correlation method in the measurement of displacement field can be an effective approach to resolve this open problem.

Many experimental studies have been also reported that measured the resultant force and moment by moving one tooth. However, a straight 3 teeth array model and enlarged model to embed sensors were used in one of the authors' work. In ref., realistic teeth model was used and central incisor was moved for comparison between two aligners with and without edge part, but the detailed mechanism was not discussed because only resultant force and moment were measured at the tooth root point. The evaluation of deformation is more important in the dental mechanics for polymeric aligner system. The force given to teeth from aligner comes from the elastic property of deformed aligner, and therefore the measurement of deformation of aligner is highly needed. In other studies that measured force and moment also couldn’t measure the deformation of polymeric aligner. Another drawback of these works lies in the lack of discussion of force or pressure distribution on the teeth surface in addition to the resultant force and moment at the root point. To obtain the force or pressure distribution on the teeth surface, finite element simulation may become a useful tool, but the given boundary condition is hardly determined.

Therefore, this study focuses on the measurement of displacement field and strain field for thermoformed polymeric aligner with the help of digital image correlation (DIC) method as well as the measurement of resultant force.
Two types of experimental apparatus were specially designed to give directly displacement to the aligner set on a tooth array model, and to give displacement by the movement of a tooth in order to simulate the real dental treatment. To this end, the deformability was discussed considering the strain concentration, thickness distribution of pressure formed aligner and the shape of each tooth.

2 Fabrication of Polymeric Dental Aligner

The aligner was thermoformed by a dental pressure forming apparatus named Biostar (JM Ortho, Tokyo) shown in Fig. 1, using a polyester sheet with 0.75 mm thickness and 125 mm diameter named Duran + 3430 (JM Ortho, Tokyo). This apparatus is certificated for dental clinical use. It is well known that the formed product has non-uniform thickness, but, as far as the authors know, no paper is found that discussed the thickness distribution after thermoforming. Hence, micro-CT imaging was used to measure the thickness distribution in this study.

Figure 2 shows the formed aligners without and with edge part. The edge part was removed in the former one. Gao and WIchellaus37 discussed the influence of edge length on the resultant force and concluded that shorter edge is better. In this study, the influence of presence of edge on the deformation of aligner is discussed through displacement field. Note that aligned teeth model was used to form the aligners in Fig. 2, and the left canine is supposed to have misalignment in later experiment and discussion. The inter-teeth border (vertical line) is named as A as shown in Fig. 2 and, in the same way, borders B, C, D are defined later.

In the experiment using DIC method19) that tracks the movement of specific random pattern with stereo-vision system to calculate displacement and strain based on continuum mechanics, transparent aligner surface was first turned to white color by spray and then texture was given by black spray.

3 Development of Experimental Apparatus

In order to address the deformability of polymeric aligner, two types of experimental apparatus were developed. The first one gives direct point loading to the aligner at the left canine position as shown in Fig. 3. Note that the aligner is mounted on a plaster model without misalignment.

A bar was attached to a micrometer to give prescribed displacement through the hole in the center of left canine of the plaster model. The same hole exists also in the lingual side of the aligner. Then, the buccal side of the aligner is pushed by a bar. The displacements given by the micrometer were 100, 200, 250 μm, because approximately 200 μm movement is considered in one step of the practical clinical treatment. The developed apparatus allows us to give load not only to left canine but also to some other teeth by changing the position and angle of the holder in Fig. 3, but this paper only describes the result for left canine.

The second experimental setup aims to reproduce a surface loading condition that is more suitable to simulate the real phenomenon. As shown in Fig. 4, left canine moves from normal position to buccal side. The canine part is connected to the micrometer. The aligner is designed for normal position of teeth and mounted on the model without misalignment, where no deformation occurs in the aligner and strain is zero at this moment. The movement direction followed the actual one from clinical viewpoint.

When canine moves, the aligner is deformed, then displacement and strain are measured by DIC method. In clinical use, the role of aligner is to move a tooth from misaligned position to normal position. This apparatus provides us with the displacement and strain in aligner at the start point of the clinical treatment. During the movement, the separated left canine part of teeth model never make contact with other parts. Whereas, the aligner is not separated. This experimental test is called in this paper as surface load case. A load cell is implemented in this case as shown in Fig. 4(c) to measure the resultant force in the movement direction. In later experimental work, the displacement and strain were measured under 3 to 5 N loading conditions. It was confirmed

Fig. 1 Thermoforming apparatus certificated for clinical use.

Fig. 2 Thermoformed polyester aligner.

Fig. 3 Experimental apparatus (point load case).
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4 Experimental Results

4.1 Point Load Case

Using the apparatus shown in Fig. 3, the aligner was pushed at the center position of buccal side of left canine. Figures 5 and 6 show the measured displacement field on the surface of aligner when 250 μm displacement was given. Figure 5 shows the incisor side view. Another test was carried out to have the view from premolar part as shown in Fig. 6. As is clear from these figures, differences were found between two aligners with and without edge parts. It should be noted that large displacement was observed in edge part.

When 100 μm to 250 μm displacements were given, the surface displacements of aligner on a horizontal line at the center of teeth were plotted in Fig. 7 for incisor side view and Fig. 8 for premolar side view. When edge was removed, the maximum displacements of the aligner were almost the same with the given displacements by a bar. With edge part, the displacements were much smaller than those without edge. In Fig. 8 from premolar side view, in all cases, the displacements in canine area became flat near border C. The sudden drop of displacements were seen at border C. The maximum principal strain distribution is shown in Fig. 9. Near the pushed position at the center part and at both borders of canine, large strain was observed regardless of the presence of edge part. Also large strain was observed in the edge part in Fig. 9(b).

4.2 Surface Load Case

This section describes the results of the aligner without edge only, when 3 N, 4 N and 5 N resultant forces were applied using the apparatus in Fig. 4. Figure 10 shows the displacement field.

The displacements along horizontal line at the center

Fig. 5 Displacement field from incisor side view in point load case.

Fig. 6 Displacement field from premolar side view in point load case.

Fig. 7 Displacement on horizontal line at center part of teeth in incisor side view obtained in point load case.
part are plotted in Fig. 11. It should be noted that the displacement under 4 N and that under 5 N are almost the same, and the maximum value is approximately 280 μm. It means that no more deformation is allowed for the aligner.

The maximum principal strain contour is shown together with the strain vector display in Fig. 12. The strain concentration was observed only one border in lateral incisor side. At this border, the direction of maximum principal strain was in the horizontal direction.

5 Discussion
5.1 Presence of Edge
Gao and Wichelhaus(17) concluded from the viewpoint of resultant force that shorter edge is preferable. This study compared the displacement mainly between aligners without and with edge in order to discuss how the load from canine was transmitted to neighboring tooth from clinical viewpoint.

Although the same energy was given to the aligners without and with edge, the energy was partially used to cause deformation of the edge part for the one with edge. The deformation mode is deeply discussed. Therefore, in the following section, the deformation mode is sketched because its surface is more flat than canine and 1st premolar worked as a stiffener. On the other hand, shallower wrinkle-like cropped shape at the border between 1st premolar and canine1st premolar except the edge part. The thickness was almost constant.

0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0
Position on vertical line at center of canine (mm)

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in Fig. 7(b) with edge than that in Fig. 7(a) without edge. Except the area of lateral incisor, displacement was larger in the case without edge. This implies the difficulty for dentists in the design of applied load to teeth via aligner if edge part is not removed, because unexpected deformation mode occurs. In other words, the deformation mode is dominated by the edge part where large strain energy appears. Newly obtained experimental results focusing on the deformability of the edge part suggests to remove the edge part, which agrees with the conclusion of Gao and Wichelhaus [17].

### 5.2 Influence of Thickness Distribution on Strain Field

As introduced in chapter 2, thickness distribution of the thermoformed aligner will play a significant role in the deformation. The normalized thickness distributions on vertical lines were plotted in Fig. 13. The position in those figures in the horizontal axes was measured from top part of the tooth to the root position. Therefore, the top part of the tooth had the largest thickness. It is reasonable because the top part had first contact with cold plaster model in the thermoforming. That is, the top part is stuck by cold model and no more stretch is allowed in the forming process. The thickness was distributed in border area. The minimum was affected by the shape of the teeth. The thickness in thinnest region was only 30% of that at top position. Whilst, in the center part, the thickness was almost constant.

Figure 14 shows the maximum principal strain distribution under 5 N loading condition to compare with thickness distribution in Fig. 13. At border B, very high strain was observed in most of the area, but strain was very small at border C and in the center part of canine except the edge part. However, no significant correlation with thickness was found. Therefore, in the following section, the deformation mode is deeply discussed.

### 5.3 Strain Concentration and Deformation Mode

A surprising aspect that emerged from our results is the presence of strain concentration at the borders of shifted canine. In the point load case in Fig. 9, strain concentration was observed at both borders regardless of the presence of edge part. On the other hand, in the surface load case without edge in Fig. 12, strain concentration was seen only at the border between lateral incisor. The thickness was almost the same at both borders. Hence, the strain distribution in Fig. 12 couldn’t be explained by the thickness of aligner.

Figure 15(a) illustrated three teeth and aligner at the start point of the experiment. The lateral incisor is abstractly sketched because its surface is more flat than canine and 1st premolar. To this end, it was supposed that the thermoformed aligner had different angles at two borders as illustrated. The wrinkle-like cropped shape at the border between 1st premolar worked as a stiffener. On the other hand, shallower angle at border between lateral incisor allowed larger displacement, also affected by the movement direction of canine. This illustration can also explain the maximum principal strain vector as shown in Fig. 12.

This implies that the shape of teeth may be more influential on the deformation and strain than thickness distribution. Also, the direction of the movement vector is an important factor. In the clinical treatment so far, only the movement vector was taken into account, but the shape of teeth should be also considered because both give influence on the deformation of polymeric aligner. To verify this idea, more experimental studies are requested for examples with different teeth shape and array. The mechanical properties of
thermoformed polyester should be also investigated, because the non-uniformity of the mechanical properties may lead to such local deformation. Note also that the deformation mode in Fig. 15 may be able to explain the bad load transmission to neighboring teeth in the point load experiment, which was observed in the sudden drop of displacement at border C in Fig. 8.

The strain concentration determines the force caused by elastic recovery of the material in dental treatment, which is applied to teeth for their movement. This study revealed the strain distribution experimentally for the first time and gave informative results to clinicians. Especially, the elastic recovery of polymeric material was found to be important, which arises from the given deformation by mounting the dental aligner on misaligned teeth array. Since the measured strain was very large locally, the reversibility and geometrical nonlinearity should be deeply investigated in the near future.

The final goal of this study is to understand the pressure distribution given to teeth by the elastic recovery of deformed aligner. It is very difficult to measure the pressure distribution in contact area, but the measured displacement field can be used as the Dirichlet boundary condition in the finite element analysis in the future. The measurement of material properties of thermoformed polyester is difficult, but is important not only for finite element analysis but also to know whether the material behaves elastically or not in limited region with very high strain value. The contact condition between aligner and teeth should be considered deeply in both experimental and numerical analyses.

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