Three-dimensional finite element analysis of the effects of different attachments on molar distal displacement in invisible orthodontics

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Abstract: Objective: The aim of this study was to establish a three-dimensional finite element model and use finite element analysis to explore the effects of different attachments on the distal movement of molars. Methods: Using Mimics, Geomagic Wrap, Soildworks, and Ansys software, a three-dimensional finite element model of the mandible was established. According to the differences in the attachment attached to the second molar, the model was divided into four groups for experiment: A-Rectangular attachment(abbreviation:RA); B-Half water drop shaped attachment 1(abbreviation:HWDA1); C-Half water drop shaped attachment 2(abbreviation:HWDA2); D-Double half water drop shaped attachments set(abbreviation:DHWDAS). The distal movement of molar was analyzed by simulating the orthodontic process of invisible appliance with different loads.Results: The displacement patterns of all models were accompanied by different degrees of tilt. From the simulation results alone, the root control effect of half water drop attachment 2 was slightly better than that of half water drop attachment 1 and double half water drop attachments set, but both were better than rectangular attachments. In terms of volume, the volume of the double half water drop attachments set was significantly smaller than the other three groups, and the root control effect was also better. Conclusion: Comprehensively, when simulating the distal displacement of the second molar with clear aligner, the double half water drop attachments set has more advantages.

Key words: Clear aligner; Attachment; Molar distal movement; Finite element analysis

Introduction

Invisible orthodontic technology is a major high-tech technology in the field of international orthodontics. Compared with traditional fixed braces, invisible braces have the same fixed function as traditional orthodontics, but the aesthetic comfort, convenience, chewing function, and language satisfaction of invisible braces are better. The technology of invisible orthodontics without brackets can be traced back to 1945, when Dr. Kesling first proposed using vacuum thermoforming aligners to achieve small tooth movements . The first self-ligating invisible orthodontic system developed in China was created in 2002 by the Medical School of Capital University of Medical Sciences, the Laser Rapid Prototyping Center of Tsinghua University, and Time Angel Technology Co., Ltd., and began to be widely used after a series of experiments and obtaining national patents . Nowadays, as the material standard of living improves, people tend to choose the more aesthetically pleasing and comfortable invisible orthodontic appliances compared to brackets and arch wires . Currently, self-ligating invisible orthodontic systems are applied in the treatment of various malocclusions in clinical practice.

With the continuous development of self-ligating invisible orthodontic systems, scholars have recognized the limitations of this technology in treating difficult cases compared to fixed braces. Therefore, the application of attachments has been introduced into this orthodontic system in response to changes in this technology. Research conducted by Zhou Jiemin had shown that attaching attachments can significantly improve the efficiency of molar movement. Samoto et al. discovered that the torque generated by invisible braces themselves is insufficient to move the root of tooth, so applying vertical rectangular attachments generates equipollent forces that can counteract molars leaning toward the far medial side and facilitate overall molar movement.

In this study, a three-dimensional finite element model was established, and the finite element analysis method was used to explore the effects of different attachments on maxillary expansion.

1.Materials and Methods

1.1Establishment of the tooth-periodontal ligament-alveolar bone model

Firstly, a healthy volunteer was selected and Mimics software was used to extract the 3D stereo images of teeth and alveolar bone from CT images. Then, the teeth and alveolar bone were polished and smoothed using Geomagic Wrap software to form a smooth solid model. After that, the polished solid model was assembled in Solidworks, and the periodontal ligament was established and incorporated into the model accordingly. According to literature, periodontal ligament data was obtained by increasing the thickness of root data by 0.25mm. The process is shown in Figure 1.

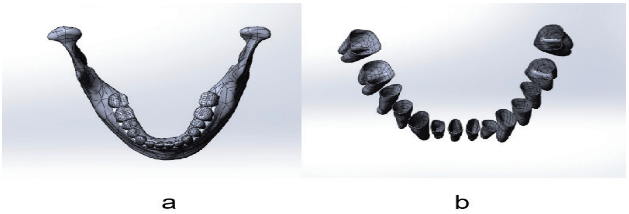

Figure 1 Solid models a:Solid models of teeth and alveolar; b: Solid model of Periodontal ligament

1.2 Establishment of the invisible orthodontic aligner model

Firstly, the established tooth-periodontal ligament-alveolar bone model was pasted with necessary accessories required for this experiment in Solidworks. Then, the teeth data and accessory data were imported into Geomagic Wrap software for the production of orthodontic aligners. In Geomagic Wrap, commands such as offsetting overall and cutting were used to increase the thickness of the teeth data and accessory data by 0.75mm and cut off the root data to form the required aligner model. After that, the model was solidified and imported into Solidworks for assembly.

1.3 Parameter setting, coordinate setting, and mesh division

The material parameters for teeth, alveolar bone, periodontal ligament, accessories, and aligners are shown in Table 1.

Table 1 Experimental material parameters

Material	Modulus of elasticity(Unit:Mpa)	Poisson ratio
tooth	$1.86*10^4$	0.31
pericementum	0.68	0.49
Alveolar bone	$1.37*10^4$	0.30
Invisible appliance	816.31	0.30
attachment	$1.86*10^4$	0.31

In ANSYS, a coordinate system was established with the centroid of the molars as the origin, cheeks-tongue direction as the X-axis, cheek direction as positive; proximal-distal direction as the Y-axis, distal direction as positive; and crown-root direction as the Z-axis, crown direction as positive. Then the mesh division was carried out using tetrahedral elements which are commonly used for medical models. The process is shown in Figure 2a.

According to the different attachments used for molars, the experiment was divided into four groups. Group A used rectangular attachment with a volume of 1.26 cubic millimeters; group B used half water drop shaped attachment with a volume of 2.23 cubic millimeters; group C also used half water drop shaped attachment, but with a volume of 1.37 cubic millimeters; and group D used double half water drop shaped attachments set with a volume of 0.94 cubic millimeters. The attachments are shown in Figure 2b-e.

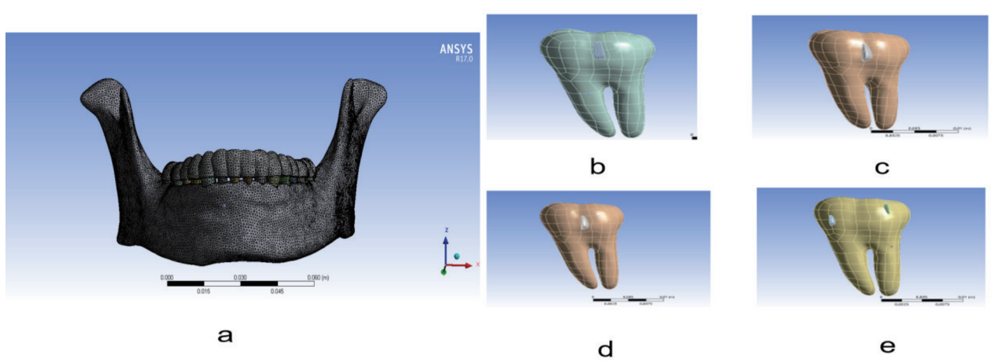

Figure 2 a:Grid division; b:Rectangular attachment; c:Half water drop shaped attachment; d:Half water drop shaped attachment; e:Double half water drop shaped attachments set

1.4 Contact and boundary conditions

The contact relationships between the alveolar bone and periodontal ligament, periodontal ligament and the root of tooth, and attachment and dental crown were set as bonding relationships (Bond); while the contact relationships between the dental crown and braces, and attachment and braces were set as frictional contact with a coefficient of friction of 0.2. The bottom of the alveolar bone was fixed in three-dimensional directions by fix support.

1.5 Mechanical loading conditions

For all groups, a displacement of 0.25mm in the mesiodistal direction was applied to the teeth. This was the only loading condition for group A. In addition to the displacement, groups B, C, and D were also subjected to a torque of 0.03N*m applied to the entire dental crown to simulate the angle at which the braces and dental crown are pre-rotated towards the mesial. The braces were tilted 5 degrees towards the mesial and this force system was applied on the optimized surface of the attachments.

2.Results

The displacement results for the second mandibular molar in the X, Y, and Z directions were calculated, and seven points including the mesial crown(MC) and distal crown(DC), lingual crown(LC) and buccal crown(BC), cervix, and mesial root(MR) and distal root(DR) were selected for observation.

The displacement nephogram in the buccolingual direction (X) are shown in Figure 3a-d and the displacement line chart is shown in Figure 3e.

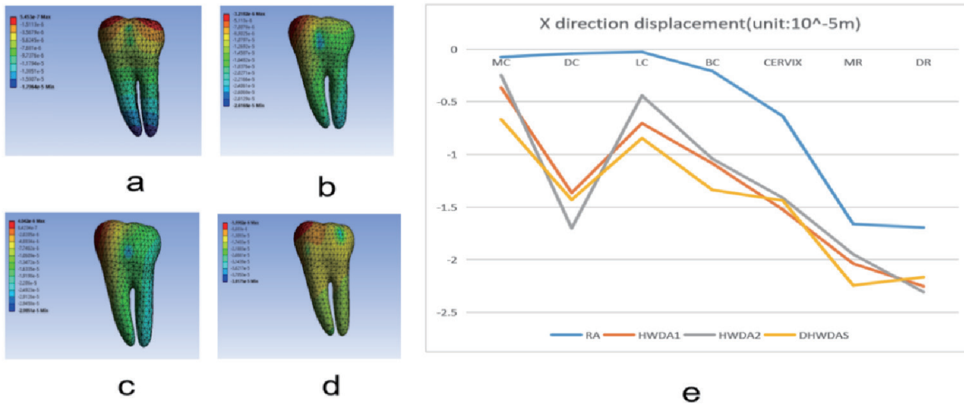

Figure 3 X-direction displacement a: Rectangular attachment X-direction displacement nephogram; b:Half water drop shaped attachment X-direction displacement nephogram; c:Half water drop shaped attachment X-direction displacement nephogram; d:Double half water drop shaped attachments set X-direction displacement nephogram; e:X-direction displacement line chart

From the plots, it can be observed that the rectangular attachment has a tendency to tilt towards the lingual side at the root (with the buccal side as positive). The three groups of half water drop shaped attachments have similar movement patterns with a tendency to move towards the lingual side. In all four groups, the displacement at the root is larger compared to the crown.

The displacement nephogram in the mesiodistal direction (Y) are shown in Figure 4a-d and the displacement line chart is shown in Figure 4e.

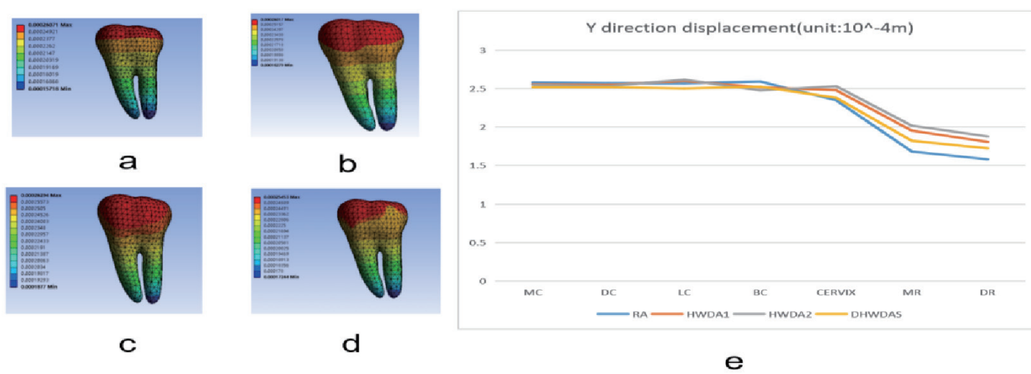

Figure 4 Y-direction displacement a: Rectangular attachment Y-direction displacement nephogram; b:Half water drop shaped attachment Y-direction displacement nephogram; c:Half water drop shaped attachment Y-direction displacement nephogram; d:Double half water drop shaped attachments set Y-direction displacement nephogram; e:Y-direction displacement line chart

From the plots, it can be observed that in all four groups, the tooth movement pattern is similar, with the displacement at the crown much larger than that at the root. Therefore, there is a noticeable tendency to tilt towards the distal direction, and from the result at the root, it can be seen that the optimized half water drop shaped attachments have a larger displacement at the root compared to the rectangular attachment, indicating that the control effect of all the half water drop shaped attachments on the roots is better than that of the rectangular attachment.

The displacement nephogram in the apical-coronal direction (Z) are shown in Figure 5a-d and the displacement line chart is shown in Figure 5e.

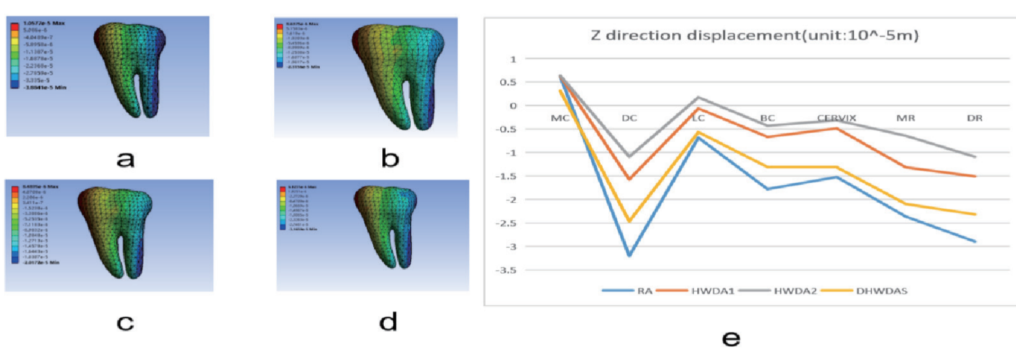

Figure 5 Z-direction displacement a:Rectangular attachment Z-direction displacement nephogram; b:Half water drop shaped attachment Z-direction displacement nephogram; c:Half water drop shaped attachment Z-direction displacement nephogram; d:Double half water drop shaped attachments set Z-direction displacement nephogram; e:Z-direction displacement line chart

From the plots, it can be observed that in all four groups, the tooth movement pattern in the apical-coronal direction is the same. The displacement at the near-mid crown is smaller than that at the far-mid crown, which indicates a tendency to tilt towards the distal direction during tooth movement. However, the overall displacement in the Z-axis direction is significantly smaller than that in the Y-axis direction, indicating that the tooth underwent only minor vertical changes.

3. Discussion and Conclusion

Invisible braces without brackets and wires are created by wrapping a high-quality polymer film around the dental crown. Compared to traditional fixed braces, invisible braces enable precise three-dimensional control of the molars as they completely envelop the dental crown, while traditional fixed braces only apply localized force through arch wires and brackets, resulting in inferior outcomes. Attachments serve as key auxiliary tools during the treatment process with invisible braces, serving two purposes: enhancing stability and boosting the braces' effectiveness in exerting force on the teeth.This paper established four sets of finite element models based on different attachments shapes, and analyzed the influence of different shaped attachments on the distal movement of molars. From the above results, it can be seen that all four groups of experimental attachments are capable of achieving distal movement of molars. Due to the different shapes of the attachments, the results of distal movement of molars also differ. Looking at only the amount of root movement towards the distal direction, the control root effect of the traditional rectangular attachment is not as good as the other three groups of experiments, but all four attachments have a tendency to lean towards the distal direction. Due to the clear contour and edges of the traditional rectangular attachment, there won't be too much deviation in the buccal-lingual direction, whereas the optimized half water drop shaped attachment has a relatively smooth shape and an irregular curved surface on the non-force-bearing side, making it more difficult to control and leading to greater deviation in the buccal-lingual direction compared to the rectangular attachment. However, the displacement in the buccal-lingual direction is much smaller than that in the distal direction, so these slight differences can be ignored in some cases. An important factor for people wearing invisible braces is their aesthetic appearance. If the design of the brace is too thick, it will affect its aesthetic appearance and comfort, so the brace should not be too thick. However, if the braces are not removed correctly or if the attachments make to remove the braces difficultly, it can lead to brace breakage. The sharp edges and corners of the traditional rectangular attachment result in strong holding power, making it a bit difficult to remove, which can easily cause brace breakage. Therefore, optimizing the attachments can achieve better results than the rectangular attachments. The optimized half water drop shaped attachment in this paper has a curved shape on the non-force-bearing side and is easy to remove. In the fourth group of experiments, the total volume of the optimized attachment composed of double half water drop shaped attachments set was much smaller than that of the rectangular attachment. It had better root control and greatly increased people's comfort levels during overall tooth movement. Therefore, in summary, the double half water drop shaped attachments set has advantages over the rectangular attachment in overall tooth movement.

There are still many shortcomings in this experiment. In the finite element analysis, we assumed that the periodontal tissue materials were isotropic linear elastic materials, while the materials in real situations are anisotropic nonlinear materials, which are difficult to simulate. This may affect the authenticity of experimental results. We hope that in future research, different material parameters can be tried to find the optimal material data. Additionally, due to the lateral displacement during the molar distal movement process of the optimized half water drop shaped attachment in this paper, it is hoped that these disadvantages can also be overcome in the future by adjusting the placement position or angle of the attachment and conducting multiple experiments to overcome tooth displacement.

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