Design of class Ⅲ intermaxillary traction titanium plate for bone-anchorage based on finite element analysis

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Abstract: The purpose of this article is to investigate the effect of different bending angles and traction directions of the traction arm on the stability of the titanium plate for bone-anchored maxillary protraction (BAMP).The titanium plate models with different bending angles of the upper and lower jaws were modelled in three dimensions, where the bending angles were 90°, 120°, 135°, 150°, 180° and recorded as U1-U5 and L1-L5 respectively.Finite element analysis was performed on the titanium plates with different structural parameters to complete the structural design selection study of the titanium plates. The displacement limit was defined and different angular tensile forces were applied to record the equivalent stress and displacement of the titanium plates under each working condition. A total of 120 sets of orthogonal simulation tests were designed, which showed that the stress values at U2, U3 and U4 are smaller at traction angles of 135° (66.152 MPa), 155° (59.015 MPa) and 175° (55.589 MPa) respectively. The displacement is correspondingly smaller at tensile angles of 135° (0.0073 mm), 150° (0.0056 mm) and 160° (0.0058 mm). L2 has the smallest stress value (50.491 MPa) and displacement (0.0062 mm) at a tension angle of 120°. Therefore, it is recommended to design a titanium plate with a mandibular traction arm bending angle of 120° for BAMP, and the traction arm bending angle of the maxillary titanium plate can be flexibly designed according to the clinical traction direction.

1. Introduction

Bone-anchored maxillary protraction (BAMP) is an orthodontic treatment for skeletal Class III malocclusions in adolescents, in which titanium plates are implanted between the maxillary zygomatic alveolar ridge and the roots of the mandibular lateral incisors and canines, and elastic traction is applied between the plates to promote anterior maxillary bone development and inhibit mandibular bone overgrowth[1]. It has been shown that the stability of titanium plates is influenced by the density and thickness of the patient's own bone, surgical trauma, oral hygiene and plaque, and is closely related to the morphology and implantation position of the titanium plate, the position of the exposed traction hook and the method of force application. [2].

Currently, most of the titanium plates used in BAMP are I-shaped or L-shaped [3,4], or are bent intraoperatively using modified forms of surgical splints [5], which have a single shape and a simple and limited direction of force transmission. With this in mind, Fakharian et al [6] used a modified Y-shaped maxillary and T-shaped mandibular titanium plate to reduce soft tissue stimulation and facilitate traction. Kim et al [2] also designed and fabricated a bone-supported intermaxillary retraction device with a Y-shaped four-hole plate against the bone surface in the maxilla and a retention device wrapped under the roots in the mandible in the area of the mandibular symphysis. The traction hook was extended at the gingival junction 5 mm above the margin.

However, when the position of the titanium plate's traction hook shifted, the direction of the traction force also changed, which affected bone remodelling [7] (Figure 1). In addition, there are differences in the stability of titanium plates with different structural forms when subjected to various directions of traction. Therefore, it is significantly meaningful for clinical applications to design titanium plates that take into account both functional and mechanical properties through structural selection studies.

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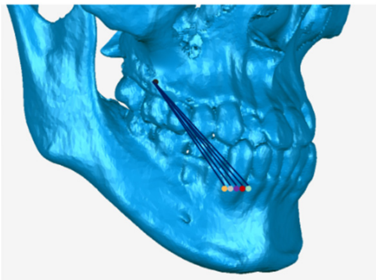


Figure1. Examples of changing traction points and traction angles on the jaws.

2. Material and method

2.1 Design of titanium plates for different bending angles of traction arms

The titanium plate was drawn in Soildworks 2020 (Dassault Systemes, France) (Figure 2). The titanium traction plate is divided into fixation plate, traction arm and traction hook parts, the maxillary fixation plate is a round triangle with three holes, the mandibular fixation plate is a long rectangle with three holes, the diameter of the fixation holes is 1. 5mm, the centre distance of the holes is 3mm, the traction arm is divided into fixed arm and free arm, the length of the fixed arm is 4mm, the length of the free arm mapped to the fixed part is 3mm, the inner diameter of the traction hook is 1.5mm, the outer diameter is 3mm. The maxillary titanium plate was designed with five bending angles of the traction arm, 90°, 120°, 135°, 150° and 180°. Each traction hook was placed in the same horizontal plane. The mandibular titanium plate was designed in the same way. The thickness of the titanium plate is 0.9 mm.

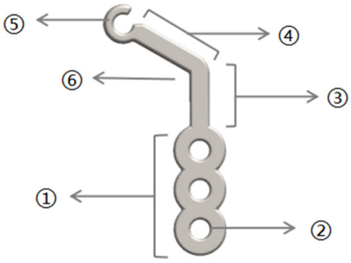


Figure2. Traction titanium plate structure.
① Retaining plate, ② Retention hole, ③Retention end traction arm,④ Free end traction arm, ⑤Traction hook, ⑥ Traction arm bending angle.

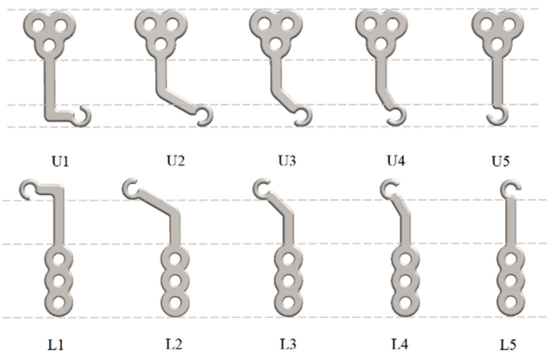


Figure3. Design of traction titanium plate.

2.2 Finite element analysis

The 3D model of the titanium plate with various structural parameters was exported in X_T file format and imported into ANSYS Workbench 2020R2 for static finite element analysis.

2.2.1Definition of material parameters

Select TC4 titanium alloy (Ti-6Al-4V), its Young's modulus is 1.034 × 105MPa, Poisson's ratio is 0.35, density is 4.5g/cm^3, thermal conductivity is 15.24 W/(m-K), yield strength is 828MPa, elongation is 25%, sectional shrinkage rate is 25%.

2.2.2Mesh division

After the mesh irrelevance test, the final mesh density of 0.1 mm is determined in each titanium plate model.

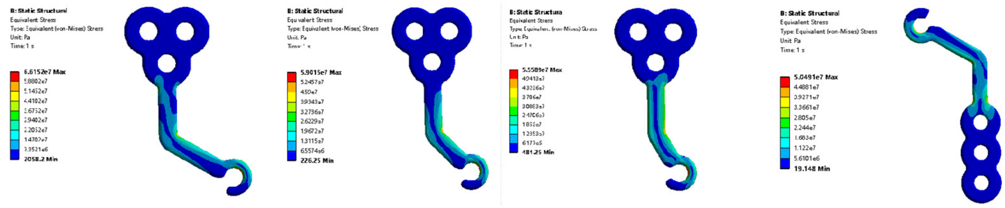
2.2.3Setting of force values and load boundary conditions

After applying a fixed constraint to the inner wall of the fixation hole of the titanium plate, a force of 500g was applied to the traction hook. The angular range of the traction line of the maxillary titanium plate and the fixed end traction arm is 90°-180°, with each 5° as a gradient, and 19 traction angles are obtained for each titanium plate, for a total of 95 angles. For the mandibular titanium plate, the angle of the traction line with the fixed end traction arm was 115° to 135°, with a gradient of every 5°, and 5 traction angles were obtained for each titanium plate, for a total of 25 simulations (Figure 4).

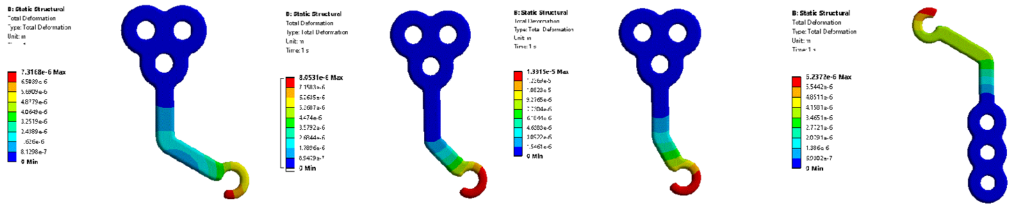
A total of 120 working conditions were tested in the simulation. The Mises equivalent stress and displacement of the titanium plate under different angular traction were recorded.

(a) Range of traction angle of maxillary titanium plate. (b) Range of traction angle of mandibular titanium plate.
Figure4. Titanium plate traction angle range.

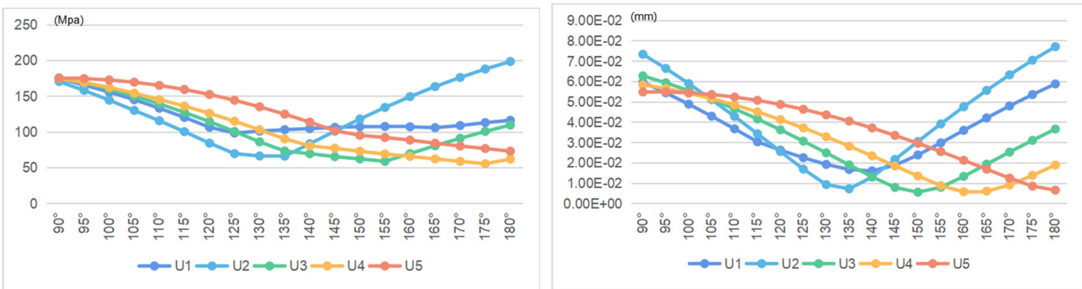
3. Results



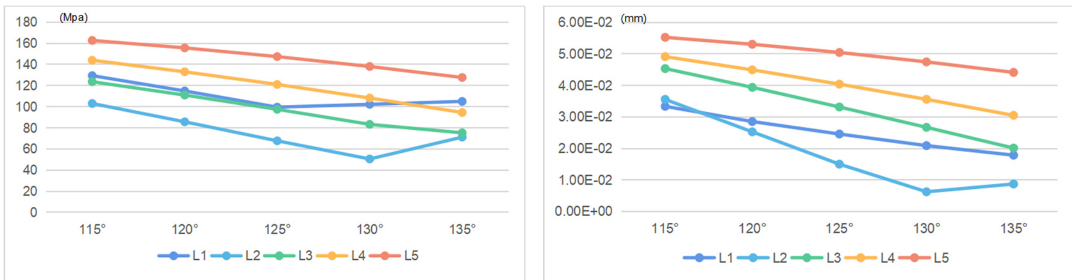
(a) Stress of U2. (b) Stress of U3. (c) Stress of U4. (d) Stress of L2.



(e) Displacement of U2. (f) Displacement of U3. (g) Displacement of U4. (h) Displacement of L2.
Figure5. Finite element analysis nephogram of some titanium plates.



(a) Relationship between Von-mises stress and traction angle of maxillary titanium plates. (b)Relationship between traction angle and displacement of maxillary titanium plates.



(c)Relationship between Von-mises stress (d)Relationship between traction angle and traction angle of mandibular titanium
plates. and displacement of mandibular titanium plates.

Figure6. Relationship between traction angle and stress/displacement of maxillary and mandibular titanium plates.

3.1 Data analysis

To ensure the accuracy of the simulation experiment, in the design we make sure that the fixed end of the titanium plate of each model and the towing hook structure are exactly the same size and protrude in the same plane, i.e. the finite element model is exactly the same as the three-dimensional physics. In addition, a single-variable comparative analysis method was used for each type of titanium plate. The direction of the control force was a single variable, and a total of 120 orthogonal simulation experiments were designed by analogous analysis between different groups to obtain stress and displacement results as shown in Figures 5 and 6.

3.2 Maxillary titanium plate

Von Mises stress results show that U1 traction angle from 90°to 180°, there is a tendency for the stress to decrease and then increase, when the traction angle was 125°, the stress was smaller (98.645 MPa). The stress on U3 was 59.015 MPa at a tensile angle of 155°, and the stress on U4 decreased gradually from 90° to 175°, and the stress on U4 was 55.589 MPa at a tensile angle of 175°. The minimum stress value was 73.213 MPa at 180°tensile angle. The displacement of the maxillary titanium plate also showed a similar trend to the stress, and the displacement of U1-U4 showed a trend of decreasing and then increasing with the increase of the traction angle, and the minimum values of the displacement were 0.0161 mm, 0.0073 mm, 0.0056 mm, and 0.0058 mm at the traction angles of 140°, 135°, 150°, and 160°, respectively. The

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displacement of U5 gradually decreased with increasing traction angle, and the minimum value of displacement was 0.0066 mm at the traction angle of 180°.

3.3 Mandibular titanium plate

The Von Mises stress results showed that the stresses of L1 and L2 decreased and then increased with the increase of the tensile angle from 115° to 135°, and the stresses of L1 were smaller at the tensile angle of 125°（99.53 MPa）, and the stresses of L2 were smallest at the tensile angle of 130°（50.491 MPa）. The stresses of L3, L4 and L5 decreased with the increase of the traction angle, and the stresses of the three types of titanium plates were 75.247 MPa, 94.458 MPa and 127.58 MPa at the traction angle of 135°, respectively.

The displacement of L2 showed a decreasing trend from 115° to 130° and an increasing trend from 130° to 135°, with the smallest deformation of 0.0062 mm at the traction angle of 130°. The deformation of the other titanium plates showed a decreasing trend with the increase of the traction angle. The minimum displacements of L1, L3, L4 and L5 occurred at the traction angle of 135°, and the values were 0.0179 mm, 0.0201 mm, 0.0305 mm and 0.0441 mm, respectively.

4. Discussion

Titanium and titanium alloy metal powders are widely used in bone-related medical research because of their ease of forming, high specific strength, low elastic modulus, corrosion resistance and excellent biocompatibility. In the field of orthodontics, a study have shown that changing the traction direction in traction treatment has an effect on the stress and displacement tendency on both the bones and the sutures, thus affecting the treatment outcome [7].

In this article, based on the finite element method, we aim to investigate the effect of different bending angles of the traction arm on the stability of the titanium plate itself under the action of traction forces in different directions, so as to find a design solution for the titanium plate that is suitable for most patients who receive intermaxillary traction treatment with skeletal support.

The morphological structure of the traction plate currently used in clinical practice has the following shortcomings: (1) The I-shaped morphological characteristics of the fixation end of the maxillary titanium plate lead to greater trauma caused by intraoperative flaps. (2) The traction arms are all straight, and it is difficult to change the traction direction. (3) The length of the traction arm of some titanium plates is much longer than the length of the fixation plate, and the traction force applied will lead to a larger moment on the fixation plate and the bone tissue in the area, which is not conducive to the fixation and stability of the titanium plate. Therefore, in this experiment, the design of the titanium plate was optimized: the maxillary plate was designed as a three-hole round triangle, which has a smaller surgical incision compared with the long rectangular plate previously reported [3,4], the mandibular plate was a three-hole long rectangle to avoid damage to the roots of adjacent teeth during implantation.

The results of this article show that there are smaller stress and displacement cases in a certain angular range for each type of titanium plate respectively (Figure 6). The yield strength of Ti-6Al-4V is 828 MPa, and the peak stresses are much lower than the yield strengths under all working conditions, indicating that the above-mentioned types of titanium plates do not fracture under intermaxillary traction. Among them, the Von-mises stress and displacement of U2 were smaller when the traction angle was 135°, suggesting that the titanium plate was more stable when traction was performed at this angle, while increasing or decreasing the traction angle increased the stress and displacement. The equivalent stresses and displacements of U3 were smaller in the traction angle range of 150° to 155°. U4 showed the smallest equivalent stresses for the maxillary titanium plate at a traction angle of 175°, and smaller stresses and displacements at traction angles of 160° to 175°. The displacement and equivalent stresses of L2 were smaller than those of the other mandibular titanium plates at all traction angles, especially at a traction angle of 130°.

The optimal traction angle of the upper and lower jaw titanium plate is close to the bending angle of the free end of its traction arm, and almost all of them are in the direction of passing through its center of mass, so it is inferred that when the direction of the force line passes through the center of mass of the upper and lower jaw titanium plate at the same time, the stress distribution of the titanium plate is more uniform and the tendency of rotation is smaller. The displacement of each type of titanium plate is the largest in the traction hook part, and the displacement decreases to the fixation plate. The areas with higher stresses were mostly found at the turning point of the traction arm and at the connection between the fixation plate and the traction arm, suggesting that the rounding process should be done in these areas (Figure 5). After the above analysis, it can be concluded that L2 had the best mechanical properties among the types of mandibular titanium plates designed in this paper, and the best performance was achieved at a traction direction of 130°. U2, U3, and U4 showed better mechanical properties at traction angles of 135°, 150°-155°, and 160°-175°, respectively.

Therefore, this paper proposes a selection scheme for titanium plates for intermaxillary traction therapy for skeletal branching resistance: after determining the bending angle of the mandibular titanium plate traction arm, the bending angle and placement of the traction arm of the matching maxillary titanium plate is flexibly designed according to the specific traction angle required by the clinical patient. This is due to the fact that different patients have different mandibular plane angles and require different traction directions. In contrast, the fixed end of the mandibular titanium plate for skeletal branching intermaxillary traction is influenced by the root position and is placed at a single angle, approximately parallel to the root, whereas the maxillary titanium plate is fixed to the zygomatic alveolar ridge, which is a bony dense area near the zygomatic process of the maxilla, without root obstruction, and the angle of fixation plate placement is more flexible [8].

In this experiment, the bending angle of the traction arm was used as an entry point, and titanium plates with bending angles of 90, 120°, 135°, 150° and 180° were designed. The opening direction of the titanium plate traction hook was determined according to the wearing direction of the clinical elastic collar. For the design of the traction force size and direction according to the clinical practice, the clinical implementation of the skeletal support III intermaxillary traction, the force size range is mostly between 75g-250g, and the traction force is gradually increased according to the length of time after implantation [9], or 500g continuous traction force is used to ensure the skeletal effect [10]. In this study, we designed a force value of 500g. In designing the traction angle, we mainly considered the actual clinical traction direction, so that the traction force of the mandibular titanium plate was designed to be in the range of 115°-135° with the fixed end traction arm, which also met the need for different directions of traction force due to the large difference in the mandibular plane angle of different patients. The angle of maxillary traction with the fixed end of the traction arm ranges from 90°-180°.

The traction titanium plate designed in this paper has the following advantages: (1) the small form reduces the surgical incision and the irritation to the mucosa. (2) The titanium plate can be flexibly matched with different traction arm bending angles according to the required traction direction. (3) Provides a theoretical basis and reference for the selection and design of the titanium plate for most patients with intermaxillary traction of skeletal branch resistance class III.

The limitations of this study are as follows: (1) lack of long-term clinical evaluation to guide the improvement of the titanium plate morphology, (2) the titanium plate alone was subjected to simulation experiments in this study, and the future research direction is to assemble it on bone and explore the mechanical analysis of the whole orthopedic system including bone tissue structure. In addition, during the actual clinical application, patients should still be asked whether there is discomfort in the wounds and tissues around the titanium plate after surgery and at each follow-up visit, with emphasis on checking whether there is loosening and falling off of the titanium plate, redness and pus flowing from the mucosa in the local area, tissue hyperplasia, and ulceration of the labial and buccal mucosa[10].

5. Conclusion

When using intermaxillary traction therapy for skeletal bracing resistance, it is recommended to use a titanium plate with a traction arm bend angle of 120° for the mandible, and to determine the traction arm bend angle of the maxillary titanium plate and the position of the fixation plate according to the clinically required traction angle for different types of patients. This plan has comparable clinical applicability.

Acknowledgments

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