Abstract: This study used finite element (FE) analysis to investigate the stability of miniscrews (screws) placed at the median palate. FE models with variable suture maturity and screw-suture distances were used to examine the relationship with screw stability. Four groups were classified by extent of maturation of the midpalatal suture (0%, 60%, 75%, and 100%). The placement position was set at the center of the suture (0.0 mm), or 0.5, 1.0, and 1.5 mm to the side of the suture, and von Mises stress values in bone and screw displacement were compared among models. The stress value for the unsutured model, in which the screw was placed at the center of the suture, was greater than 30 MPa. Stress values for models in which screws were placed to the side (0.5-1.5 mm) were less than 28 MPa. Maximum screw displacement was greater in the 0.0-mm incomplete suture model than at other placement positions. Because bone conditions vary among patients, placement position and suture maturation should be examined on cone beam-computed tomography images, to ensure screw stability.

Keywords: finite element method, midpalatal suture, miniscrew, screw-stability.

Introduction

Anchorage is important for orthodontic treatment. Miniscrews (screws) used for absolute anchorage have clinical advantages: they do not require patient cooperation, are relatively noninvasive, can be used in various regions, and can be easily inserted and removed. Therefore, they are frequently used in orthodontic treatment [1,2]. Screws are typically placed in the buccal alveolar area of the maxilla and mandible. Because of the lower risk of complications affecting the root and maxillary sinus [3-6], screws inserted in the midpalatal area are used to treat refractory cases of maxillary full-arch distalization and molar intrusion. However, the risk factors for failed screw placement in the median palate are unclear. Previous studies have evaluated the thickness and width of the midpalatal suture and examined the association between age and screw placement success rate [7-9]. Ichinose et al. reported that the success rate was significantly higher when the screw was placed away from the midpalatal suture [10] and that screw stability was associated with maturation of the midpalatal suture [7-10]. However, few studies have explored screw placement in relation to suture maturation. This study used finite element (FE) analysis to evaluate maturation of the midpalatal suture and investigate the biomechanical effects of maturation and screw-suture distance on screw stability.

Materials and Methods

Three-dimensional (3D) FE models of the maxilla—including the cortical bone, cancellous bone, midpalatal suture, and screws—were constructed with a 3D computer-aided design program (SolidWorks 2016; SolidWorks Japan, Tokyo, Japan). The maxillary bone model was constructed with a midpalatal suture width of 0.5 mm [11], a cortical bone thickness of 2.0 mm, and a cancellous bone thickness of 5.0 mm [12]. The screw model was constructed with a tapered shape, a maximum diameter of 2.0 mm, and thread length of 6.0 mm.

The suture ratio was defined as the ratio of suture depth to total depth in the midpalatal suture region (Fig. 1). Four groups were created and classified according to maturation thickness (from the nasal side on the coronal plane; suture ratios of 0%, 60%, 75%, and 100%) (Fig. 2). A suture ratio of 60% assumes an age younger than 17 years, and a ratio of 75% assumes an age of 18 years or older, as indicated by unpublished cone beam-computed tomography (CBCT) image data from the authors’ laboratory. Screws were placed at the center of the suture (0.0 mm) or 0.5, 1.0, or 1.5 mm to the side (Fig. 3). This study analyzed 16 models, which differed in suture ratio and placement position.

Loading conditions were a loading force of 2 N [13], a loading point at the center of the screw head, and a loading direction parallel to the midpalatal suture (Fig. 4). The material properties of the screw and maxilla models were based on those described previously, as shown in Table 1 [14-16]. In this study, we used the properties of persons younger than 15 years (among whom the suture is considered incomplete) for the unsutured midpalatal suture in FE models [16], and those of cortical bone for the completely sutured midpalatal suture. The coefficient of friction between the screw and the bone was set to 0.3 [17]. The lateral sides of the palatine bone were restricted to three degrees of freedom (X, Y, and Z) (Fig. 4). Screws and the cortical and cancellous bone consisted of tetrahedral elements and were modeled as isotropic, homogeneous, and linear elastic materials. All models were meshed by using SolidWorks 2016 and analyzed. Table 2 shows the number of nodes and the number of elements of all models. Von Mises stress is often used for bone stress analysis in dental FE studies [12, 18-20] and was thus used in this study, to evaluate plastic deformations such as microfracture. Maximum von Mises stress values in bone and maximum screw displacement were then compared among models.

Results

Stress distribution in bone

The stress distribution values in each model with screw placement positions of 0.0 mm and 1.5 mm are shown in Figs. 5 and 6, respectively. In each model, maximum stress was observed in bone around the screw neck. At a placement position of 0.0 mm, stress was approximately 25.0 MPa over the entire screw in the 0% model and 5.0 MPa or less in the 100% model, excluding the screw neck. In the 60% and 75% models, stress was 30.0 MPa or more at the boundary region of ossification.

Figure 7 shows the maximum stress in bone in each model. At a placement position of 0.0 mm, stress in all models, except the 100% model, exceeded 30.0 MPa. At a placement position of 1.5 mm, stress was 26.5 MPa in the 0% and 100% models, similar to the 60% and 75% models. In the 0%, 60%, and 75% models, maximum stress was significantly lower at placement positions of 0.5, 1.0, and 1.5 mm than at a placement position of 0.0 mm. No significant change in stress was observed in the 100% model.

Screw displacement

Figure 8 shows maximum screw displacement in each model. Screw displacement at a placement position of 0.0 mm was 2.59 μm in the 0% model and 1.75 μm in the 100% model. Screw displacement at a placement position of 1.5 mm was 2.31 μm in the 0% model and 1.75 μm in the 100% model. Maximum displacement of the screw in the 100% model did not differ in relation to screw-suture distance.
Screw displacement in the 0% model decreased in relation to the increase in screw-suture distance. In addition, screw displacement in the 60% and 75% models showed a decreasing trend at 0.0, 0.5, and 1.0 mm, in relation to screw-suture distance, and tended to increase at 1.5 mm, but displacement at a placement position of 1.0 mm was less than that at 1.5 mm (Fig. 8). Maximum screw displacement was less influenced by screw-suture distance in the 100% model than in the other models.

**Discussion**

The FE method can be used to analyze structural mechanics because it reflects the biophysical properties of a model; moreover, the force and direction of a load can be customized, and displacement and stress can be analyzed in all areas within the model. For these reasons, the FE method has been used to evaluate local stress, strain, and displacement of orthodontic screws [21,22]. This study constructed a 3D image of the screw and obtained geometrical equivalence by performing element division. Furthermore, FE models in this study included cortical bone, cancellous...
bone, and the midpalatal suture and approximated biological structures by using values that reflected actual physical properties. The loading direction on the screw was parallel to the midpalatal suture, and the loading force was set to 2 N.

Age-related suture maturation is important in screw stability [23,24]. Therefore, this study assumed age-related suture maturation when setting the suture ratio of the midpalatal suture and analyzed the results by using the FE method. Ichinohe et al. [10] examined the effect of screw-suture distance on screw placement success rate, as evaluated by dental CBCT images, when a screw 2.0 mm in diameter and 6.0 mm in length was placed in the median palate. They reported that the success rate was higher for a screw-suture distance of ≥1.5 mm than for distances of ≤1.4 mm. This study thus examined the suture ratio and the effect of screw-suture distance.

The present study simulated and visualized stress in surrounding bone and the screw when the screw was placed in the midpalatal suture with different suture ratios, and to examine screw stability. However, the present biomechanical models of the maxilla were based on a number of assumptions and simplifications. First, the maxilla model is simplified; thus, the FE model and actual bone differ in shape—the actual maxilla has a curved, more complex morphology. Second, the maxilla was modeled as linear, isotropic material. For more-accurate results, a detailed representation of the material properties of bone (anisotropy, nonlinearity, and architecture of the cortical and cancellous bone) is necessary.

Screw stability depends mainly on support from cortical bone and interdigitation of the screw thread. Stress was minor in cancellous bone in this study (Figs. 5, 6) and in previous studies [21,22]. Furthermore, the screw placement position was correlated with stress in cortical bone. In all models, stress in cortical bone tended to decrease as the placement position moved laterally away from the midpalatal suture. However, stress tended to be higher at a screw-suture distance of 1.5 mm (Fig. 7), perhaps because bone surrounding the screw at the 1.5-mm placement position contained cancellous bone. In this study, the maximum stress in bone was less than 40 MPa in all models, which was smaller than the yield stress of cortical bone [25]. This suggests that microcracking of the bone would not occur with a screw placed in the midpalatal suture with a loading force of 2 N or less. However, microcracks are believed to be caused by excessive placement torque [26], which should be considered in clinical settings. Li et al. reported a critical stress curve for overload bone resorption and observed an equivalent stress (von Mises stress) of greater than 28.0 MPa in the resorption region at a high bone density (1.8 g/cm³) [27]. In this study, the density of cortical bone in this study was 1.8 g/cm³, and stress exceeded 28.0 MPa when the screw-suture distance was 0.0 mm in the 0%, 60%, and 75% models, which suggests bone resorption (Fig. 7). Thus, to avoid bone resorption around the screw, the placement site of the screw must be distinguished from the midpalatal suture.

Maximum displacement of the screw, which was observed at the screw head in all models, decreased as the distance of the placement position from the midpalatal suture decreased, in all models (Fig. 8), perhaps because the screw was separated from the midpalatal suture because of bone instability. Maximum screw displacement in the 60%, 75%, and 100% models increased at a placement position of 1.5 mm, similar to data for maximum stress. As mentioned above, this may be because the screw location was distant from the cortical bone adjacent to the suture—an area containing cancellous bone.

As shown in Fig. 5, the maximum stress in bone was distributed on one side of the screw in the 60% and 75% models. Previous studies reported that screw shape and starting position of the screw thread affected the results of stress analysis [28,29]. In addition, when bone stress increased locally, the starting position of the screw thread made contact with the edge of the cortical bone. The stress was nonuniformly distributed because the starting position of the screw thread overlapped with the cortical bone edge. Namely, at 60% and 75%, inferior sutured bone that has the same
properties as cortical bone is a continuous piece. At the superior layer of unsutured bone, 25% to 40%, bone with a low Young’s modulus as unmatured suture intervenes between both sides of maxillary bone. Therefore, stress was observed at the boundary between sutured bone and unsutured bone at the inferior region. At the superior region of unsutured bone, because stress can be affected by the location of screw thread, as previously reported [28,29], stress concentrated around the screw neck on the left side, which includes the starting point of the screw thread.

Screw placement in the midpalatal area does not require consideration of root proximity, which is often accidental during placement in the alveolar bone area. Because of the bone thickness, the midpalatal region may be a safer area for screw placement. Melsen et al. reported that maturation of the midpalatal suture begins in females at age 16 years and in males at age 18 years [30]. Stockmann et al. reported that a screw could be placed in the median palate area in 16-year-old females and 18-year-old males [7]. Schlegel et al. reported skeletal ossification in the midpalatal suture in only 40% of patients aged 23 to 30 years [23], and Knaup et al. reported that the youngest patient with ossification was a 21-year-old male and the oldest patient without ossification was a 54-year-old male [24]. These reports suggest that maturation of the midpalatal suture is not necessarily complete in adults.

In this study, the suture ratio of the midpalatal suture was arbitrarily set and analyzed by using the FE method. The present results indicate that the stability of screw placement can be increased by avoiding the midpalatal suture. Furthermore, previous reports suggest that there are differences among individuals in the rate of complete suture closure, even in adults. Therefore, to ensure screw stability, the insertion site should be investigated on CBCT images before screw placement.

In summary, this study used FE analysis to examine the effect of maturation of the midpalatal suture and screw-suture distance at the placement site on screw stability. The conclusions were as follows:

1. In the incomplete suture model, maximum stress in bone tended to decrease as screw-suture distance increased, but minimal change was seen in the complete suture model.
2. In the incomplete suture model, maximum screw displacement was larger in the 0.0-mm model than in other placement positions.
3. Screw stability can be ensured by placing the screw away from the center of the midpalatal suture. To ensure screw stability in patients with bone conditions, screw placement position and suture maturation should be thoroughly examined by CBCT scanning.

Conflict of interest
None declared.

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