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Design and optimization of the fixing plate for customized mandible implants

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A B S T R A C T

Customized mandible implants are used as the most effective surgical option for the reconstruction of the mandible after resection, and have become more prevalent, especially with the development of reverse engineering and rapid prototyping (RP). The fixing plate is the most important and complicated part; however, improper structures of the fixing plate often cost unnecessary workloads during surgery and might lead to fracture failure eventually. The fillet radius, cross-section, and countersinks distribution of the fixing plate are the three most significant factors to affect the strength of the implant. The fillet radius on the plate–body transition determines the amount of grinding bone and can also affect the strength of the fixing plate. In addition, both the different cross-sections of the fixing plate and the different distributions of the countersinks can influence the strength and anti-bending capacity of the fixing plate. Various structures of the fixing plate have been designed, and theoretical calculations and finite element analysis on its strength have been conducted in this study, and results presented an optimized design of the structure of the fixing plate. Moreover, for validation purposes, several clinical applications were successfully implemented with the optimized structure.

1. Introduction

Compared with mandible implants manufactured by using traditional methods, customized implants have the significant advantages of accurately restoring the esthetic appearance and function of the missing part. Customized implants are implemented mainly by digital design and additive manufacturing (AM), which has been recognized as one of the most suitable techniques for designing and fabricating customized implants (Yaxiong et al., 2003a, 2014; Singare et al., 2004, 2006; Cohen et al., 2009; Giannatsis and Dedoussis, 2009). The in situ–designed model of a mandible implant is shown in Fig. 1.

A mandible implant includes two parts: the body and the fixing plate. The fixing plate is designed by thickening a portion of the buccal surface of the remaining mandible model and is surgically fixed by medical screws onto the host tissue, which is similar to a cantilever beam. It is used to connect and position the implant to the remaining mandible as well as for load bearing (Yaxiong et al., 2002a; Dean et al., 2003; Chungeng, 2006; Qian et al., 2009). The countersinks weaken the strength of the fixing plate, so the distribution of the countersinks has marked influences on the strength of the fixing plate.

In addition, for osteotomy of bone tumor, the cutting section at mandible is usually a plane; therefore, for a close fit to the cutting section, the implant should be designed to have a similar planar end. Thus, a 90° corner will be generated between the end plane of the implant body and the buccal (inside) surface of the fixing plate. The sharp corner may cause severe stress concentration and stimulate the fatigue mechanisms of the fixing plate at the corner.

However, few studies have been reported on designing and optimizing the structure of the fixing plate. In this article, on the basis of models simplified for mandible implants, the influence of different fixing plate structures on the strength of prostheses and the efficacy of repair are examined. An optimized method of designing the fixing plate structure is proposed. Finally, several clinical cases are presented for validation purposes.

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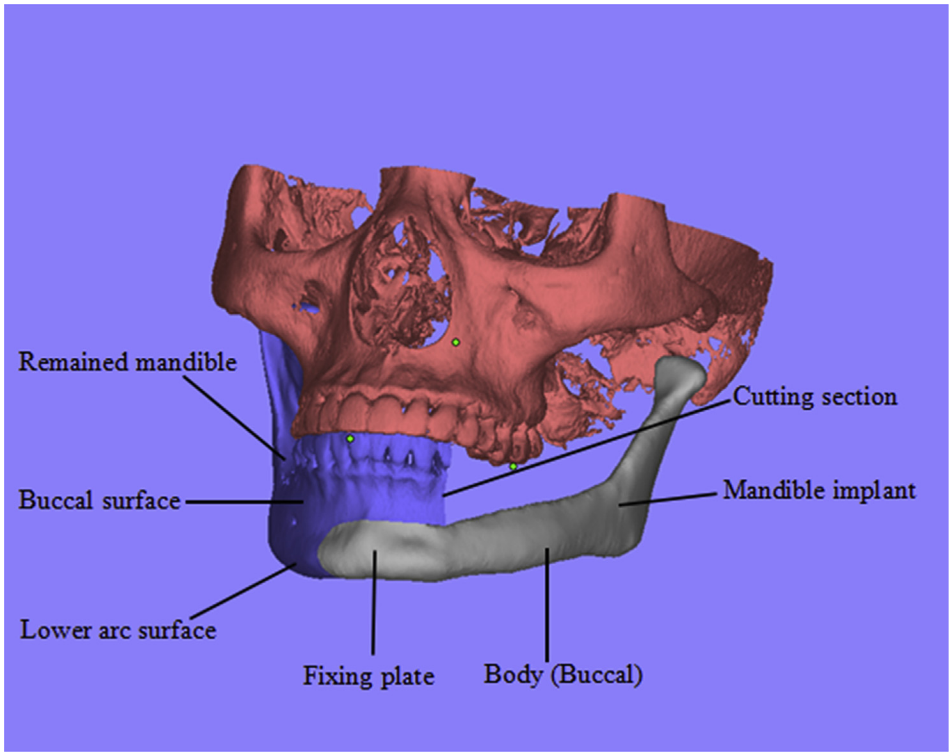

Fig. 1. In situ–designed model of mandible implant.

2. Material and methods

2.1. Optimization of plate–body transitional fillet radius

According to our knowledge of mechanics, the corner with a smooth fillet on the plate–body transition can reduce the stress concentration and increase the strength of the implant. However, the remaining mandible should be ground to match the fillet radius of the implant. Because bone grinding is dependent on surgeon's experience, the larger the volume of bone is being ground, the greater the possibility of mismatch. In addition, autologous bone is very limited and valuable. Therefore, there should be a balance between the radius of the fillet and the volume of grinding bone. The radius of the fillet has to be optimized according to the stress distribution for various clinical cases.

The CAD model of the customized mandible implant and longitudinally sectional view of the simplified implant are shown in Fig. 2. As shown in Fig. 2b, the volume of grinding bone can be calculated by applying the following equation:

$$Q = 0.75\ \pi t R^2 \tag{1}$$

where Q is the volume of grinding bone, R is the radius of the fillet, and t is the height of the fixing plate. Given that $t = 5$ mm, the volume of grinding bone was calculated by use of a different radius of the fillet.

For obtaining the optimal radius R, finite element analysis of the stress distribution of the plate–body transition was conducted by using ANSYS version12.1 software (ANSYS Inc, Houston, TX, USA). The human mandible has various functions such as biting and chewing. The loading environment is difficult to implement realistically; therefore simplifications were made for the model in this study (Xin et al., 2000; Wei et al., 2010) (Fig. 3). The planar was simulated as 5 mm thick with a homogeneous isotropic linearly elastic property of titanium alloy with a Young modulus and Poisson ratio of 110 Gpa and 0.3, respectively. The analysis was carried out under static loading conditions, and all stress values were recorded in MPa. The element type of the model was set as PLANE 82. The biting force was approximately 60 N from previous analysis (Ilavarasi and Anburajan, 2011). The component force on the longitudinal section of the implant was 30% of the biting force. The concentrated force applied along the line AE was 6 N (one-third of the component force). The largest part of the fixing plate was fixed by screws, so this part of the fixing plate was fully constrained (Jian et al., 2004; Atilgan et al., 2010; Narra et al., 2014). Finite analysis was carried out with the fillet radius ranging from 0 to 2 mm sequentially at intervals of 0.5 mm. Fig. 3 shows the loading and boundary conditions of the finite element model.

2.2. Design and optimization of the fixing plate structure

The fixing plates were generally designed with uniform thickness. Here the cross-sections of the plate (Fig. 2a) were simplified to be constant for the quantitative study of the impact of different structures on the final strength. Cross-sections of two simplified fixing plates are shown in Fig. 4. The fixing plate could be designed by thickening a portion of the buccal surface of the remaining mandible (Fig. 4a) or both the buccal surface and the lower arc surface (Fig. 4b). In this case, the inner surface of the fixing plate can match up with the buccal surface of the remaining mandible and navigate the implant to the remaining mandible accurately.

As shown in Fig. 4, two kinds of fixing plate structures have the same height of 20 mm and thickness of 1.5 mm; among them, Fig. 4a shows the cross-section of the straight structure of the fixing plate, the “l style.” Fig. 4b shows the cross-section of a combined plate consisting of a narrow planar part and an arc part (a quarter of