Influence of bone quality on initial stability of implantable distraction☆

A three-dimensional finite element analysis

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Received: 2010-06-23
Accepted: 2010-09-20
(20100323024/M)

Qiu M, Wang JL, Hui GY, Jia WM, Ding H. Influence of bone quality on initial stability of implantable distraction: A three-dimensional finite element analysis. Zhongguo Zuzhi Gongcheng Yanjiu yu Linchuang Kangfu. 2010;14(48): 9100-9103.

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Abstract

BACKGROUND: The initial stability of implantable distractor depends on the stress distribution of bone-distractor interface. The understanding of the biomechanical change in initial stage can improve the clinical success ratio of implantable distractor used in alveolar crest.

OBJECTIVE: To evaluate the influence of bone quality on stress distribution and deformation in initial distraction stage.

METHODS: Four three-dimensional models with 10 079–11 456 cells and 17 299–20 101 nodes were prepared by finite element methods (11 mm in length and 3.7–4.1 mm diameter). Implantable distractor was embedded in a segment of mandible. The elastic modulus of cancellous bone and the thickness of cortical bone, stress and deformation of bones and distractor were calculated.

RESULTS AND CONCLUSION: The highest stress in the bone was concentrated in transportable section and the maximum deformation of transportable section was observed at the edge of the cortical bone, both of which were increased with bone quality decreased. The subsidence of distractor was observed with bone quality decreased. Bone quality influenced the initial stability and the result of the implantal distraction. The decrease of bone elastic modulus would increase the failure risk of distraction osteogenisis.

INTRODUCTION

A modified version of the Ilizarov method of bone lengthening, known as distraction osteogenesis (DO), is now being used worldwide[1]. Of interest, here are its applications in the maxillofacial region, especially in the dental alveolus[2]. Many patients present for implantal treatment with complex ridge deformities. A common prerequisite treatment for these patients is the regeneration of sufficient vertical and horizontal alveolar support for implant placement. As a new and successful technique for ridge augmentation, alveolar ridge distraction based solely on a centrally fixed distractor has come into popular use since 1997[3]. It allows for minimally invasive surgery by using a single-stage surgical technique for distraction and implant placement, and can provide a much more predictable outcome in regenerating ridge height in many cases[4]. This technique is based on a “minidistractor” that is first used for distraction and then can be transformed into a dental implant[3].

The stability of distractor relies on favorable stress distribution at the bone-distractor interface[5]. Clinically, the distractor was inserted through osteotomy and the alveolar ridge was divided into two parts, the basal section and the transportable section. After 5–7 days' latency period, activation of the distractor was initiated under the condition of lack of osseointegration between the bone and the distractor[1-3, 5]. The subsidence of distractor and the bending of bone would be unavoidable. Relating to the reasons above, some complications were reported, such as the fracture or deformation of the basal and transportable section, the loosing of distractor, the failure to achieve prospective height of alveolar ridge, *etc*[6]. The alveolar bones were classified to 4 classes, based on the ratio of cancellous and cortical bone and rarefaction of cancellous bone[7]. In an attempt to clarify the relation between bone quality and stress in the bone and distractor, a three-dimensional finite elements analysis was performed to investigate stress distribution and deformation in bone and distractor in the presence of a bone defect of various qualities and dimensions.

MATERIALS AND METHODS

Design

A computer aided finite element analysis.

Time and setting

This study was preformed at Department of Stomatology, Qingdao 1st Sanatorium of Jinan Military Command between August 2009 and February 2010.

Materials

A personal computer with a 4 G memory and 1 TB hard disk was used. In the computer, AutoDesk Mechanical Desktop 2006 and Ansys Workbench 10.1 SP1 were installed.

Methods

The study was performed by means of three-dimensional finite element analysis. Theory of elasticity is applied [8-9].

Three-dimensional (3-D) model design

The distractor included two parts, the basal part and the transportable part. Its overall length was 11mm, and diameter was 3.7–4.0 mm. It was modeled in a personal computer, using a 3-D program (Mechanical Desktop 2006, Autodesk, Inc, USA). The dimensions of the distractor were indicated in Figure 1. Then 4 mandibular segments were modeled with the identical length (12 mm), height (15 mm) and width (8–12 mm) using the same software. All the 4 models had a cancellous core which surrounded by a cortical layer. The mesial and distal section planes were not covered by cortical bone. All the models were intersected and the height of the upper part is 5mm. It represented the transportable section and the lower part is the basal section. According to different class of bone quality, the thickness of the cortical layer was various. Class Ⅰ and Ⅱ were 1.6 mm, and classⅢand Ⅳwere 0.8 mm[10-11]. The model of distractor was inserted into the center of the bone model. The transportable bone section and transportable part of distractor were pulled out 0.25 mm, simulating the beginning of the distraction (Figure 1). All the models were meshed by Ansys Workbench 10.0 SP1 (SAS IP, Inc, USA).

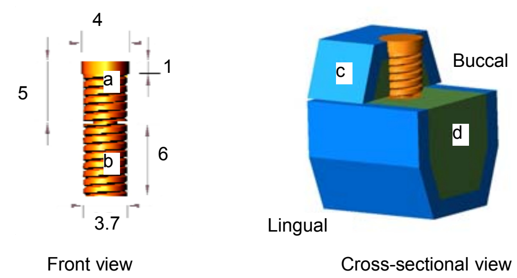

Figure 1 Symmetry plane of one model (a=transportable part; b=basal part; c=cortical bone; d=cancellous bone)

Material properties

All materials used in the models were considered to be isotropic, homogeneous and linearly elastic. The elastic properties were taken from the literature, as shown in Table 1.

Table 1 Mechanical properties of materials in finite elements models

Materials	Young's modulus (GPa)	Poisson ratio	Reference
Cancellous bone (I)	9.5	0.3	[9]
Cancellous bone (II)	5.5	0.3	[9]
Cancellous bone (III)	1.6	0.3	[9]
Cancellous bone (IV)	0.69	0.3	[9]
Cortical bone	13	0.3	[10]
Titanium	110	0.35	[11]

Interface conditions

The distractor was not rigidly anchored in the bone models. Separation of faces in contact was not allowed, but small amounts of frictionless sliding could occur along contact faces[12].

Elements and nodes

The models were meshed with 10-node-tetrahedron and 20-node-hexahedron elements. A finer mesh was generated around the distractor. All of the 4 models were composed of 10 079−11 456 elements and 17 299−20 101 nodes.

Constraints and loads

The models were constrained in all directions at the nodes on the mesial and distal bone surface of basal bone section. Since this study was aimed at investigating bone effects to loads at the beginning of the distraction, no occlusal force was applied. Tensile force of −20 kPa caused by basilaris substantia were applied axially to the inferior surface of the transportable bone segment, including cancellous and cortical bones[12-13]. Pressures of 10 kPa were applied to the superficies externa of the transportable cortical bone, simulating the tension caused by oral mucosa[14].

Main outcome measures

The analysis was performed for each model by means of the Ansys Workbench software. The Von Mises stress (equivalent stress, abbreviated EQV stress) distribution and maximum EQV stress were used to display the stress in the cortical and cancellous bones. The distribution of deformation in Y axis and maximum deformation in Y axis were used to display the subsidence of transportable segment and distractor.

Design, enforcement and evaluation

The first and second authors were responsible for experimental design and data evaluation. All authors participated in experimental procedure enforcement. The major participants had middle or high-rank professional titles and could use the computer expertly.

RESULTS

EQV stress and deformation patterns were shown as contour line with different colors connecting equivalent stress points between certain ranges (Figures 2−4). The maximum Von Mises stress in cortical and cancellous bone were shown in Table 2. The maximum deformation in transportable bone section and distractor are described in Table 3.

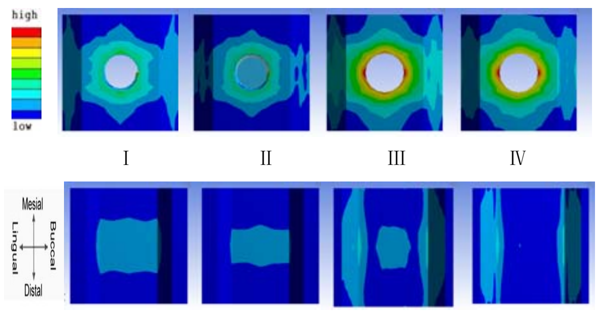

Figure 2 Equivalent stress distribution in cortical bone (Top view of models) Upper=transportable segment, inferior=basal segment. For comparison, the same scale was used in all the models

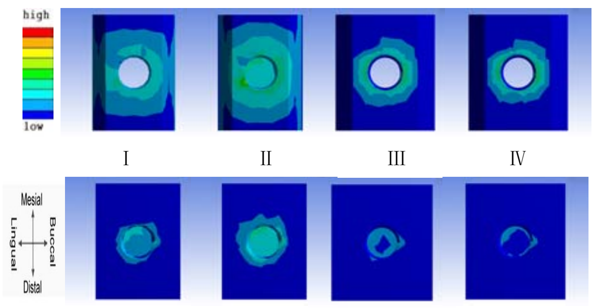

Figure 3 Equivalent stress distribution in cancellous bone (Top view of models) Upper=transportable segment, inferior=basal segment. For comparison, the same scale was used in all the models

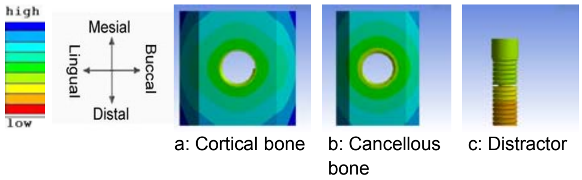

Figure 4 Deformation (Y axis) distribution in transportable bone section and distractor (Class Ⅰ), top view of bones and front view of distractor

Table 2 Maximum EQV stress in the cortical and cancellous bone (MPa)

Models	Cortical bone		Cancellous bone	
	Transportable	Basal	Transportable	Basal
Ⅰ	0.375 19	0.076 82	0.276 91	0.127 09
Ⅱ	0.505 38	0.086 07	0.264 1	0.119 07
Ⅲ	0.512 18	0.163 19	0.578 71	0.159 35
Ⅳ	0.618 01	0.243 04	0.673 12	0.157 82

Table 3 Maximum deformation in Y-axis in transportable bone section and distractor (10^{-3} mm)

Models	Transportable bone section		Distractor
	Cortical	Cancellous	
Ⅰ	1.554 9	1.371 6	0.662 99
Ⅱ	1.988 7	1.775 8	0.840 89
Ⅲ	5.072 7	4.845 6	1.953 1
Ⅳ	9.615 9	9.341 5	3.852 3

Stress distribution

In all loading situations, the highest stress in the bone was concentrated in transportable section. In class Ⅰ and Ⅱ, it was in cortical bone around the distractor. In class Ⅲ and Ⅳ, it was in cancellous bone. Because of a great difference between the stress values in the cortical and cancellous bone, the stress distributions in these bone regions were shown separately for better visualization.

Cortical bone: In all the models, the highest EQV stress of the cortical bone was observed around the distractor neck in transportable section. The value of the highest EQV stress increased as the quality of bone decreased. The distribution of the EQV stress was similar for all models.

The highest EQV stress of the basal section was much lower than the transportable section, and it also increased as the bone density decreased.

Cancellous bone: The highest EQV stress of the cancellous bone was observed around the distractor neck in transportable section. In class Ⅰ and Ⅱ, the value is lower than the cortical bone, and in class Ⅲ and Ⅳ, the value is higher. The value of the highest EQV stress increased as the quality of bone decreased. The distribution of the EQV stress was similar for all models.

The highest EQV stress of the basal section was much lower than transportable section, and did not change much as the bone density decreased.

Deformation

The deformation in Y axis showed the subsidence of the bone and distractor. So the transportable section and the distractor was the main target of observation.

Transportable section: The maximum deformation of transportable section was observed at the edge of the cortical bone. The value of deformation increased from the center of the section to the margin. All the models showed the similar tendency.

The value of the deformation in cancellous bone is lower than cortical bone and the distribution was much similar to it.

Distractor: The distractor showed much lower deformation than the bone, and with the decrease of the bone quality, the value of deformation increased.

DISCUSSION

Unlike other finite element analysis in dental implant, the models used in this study were different and complex. The bones were split into two parts, and osseointegration did not occur between the distractor and bones. When the distraction was performing, the distractor did not bear the occlusal force. That is why the interface conditions and loads were set[15-17].

The aim of this study was to find the pure effect upon the bone stresses and deformations of variations of the bone quality. So it was assumed that all the parameters of the models were identical except the composition of the bone and the elastic prosperities of cancellous bone. This makes it possible to make a comparison between different bone qualities[9, 11].

In each model, the highest EQV stress of the bone was observed around the distractor neck in transportable section. It confirmed the conclusion that previous research in dental implant achieved[8-9]. Therefore, unlike the previous literatures, the highest EQV stress was observed in the cancellous bone in Class Ⅲ and IV. This might caused by the insufficient thickness of cortical bone[3]. From the results of EQV stress, it could be seen that stress augmented as the bone quality decreased. Because the bone in molar area was always Class Ⅲ and Ⅳ, this disadvantage would certainly affect the achievement ratio of implantal distraction[4]. During the distraction, the tensile stress caused by basilaris substantia and tension caused by oral mucosa were gradually increasing. All the disadvantages would raise the incidence rate of transportable segment fracture[5].

Based on the results of distribution of deformation, subsidence of the bone and distractor increased when the bone quality decreased. As a strong internal fixation, the distractor made stress trending to the central area, which leading to the severely deformation of margin and less deformation of center[6]. The tendency was inevitable. So to the patient with unfavorable bone quality, the initial movement of distractor would be increasing and the completion of distraction would be delayed because of the subsidence[5, 7].

CONCLUSION

Based on the results from finite elements analysis, the following conclusions are obtained from the effects of bone quality on initial stability of implantable distractor:

(1) Stress distribution and maximum EQV stress in cortical and cancellous bone were greatly influenced by bone quality.
(2) Deformation distribution and maximum deformation of transportable segment were greatly influenced by bone quality.
(3) The initial range-of-motion of distractor intensified as bone quality decreased.
(4) The decrease of elastic modulus of bone might raise the risk of failure in implantal distraction.

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骨质量对种植牵张初期稳定性影响的三维有限元分析☆

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摘要
背景：种植体型牙槽嵴牵张器的初期稳定性取决于骨-牵张器界面适当的应力分布，了解植入初期的生物力学改变有助于提高种植体型牙槽嵴牵张器的临床成功率。
目的：通过有限元法了解骨质结构对牵张初期应力分布和牵张器、骨段变形情况的影响。
方法：利用CAD软件绘制由输送段和基段组成的牵张器模型(长11 mm，直径3.7~4.1 mm)，同一软件绘制4个下颌骨节段模型模拟4类不同骨质的下颌骨。装配后导入ANSYS软件形成由10 079~11 456单元和17 299~20 101节点构成的有限元模型，利用该系列有限元模型分析松质骨、密质骨的应力改变和输送骨段、牵张器的变形情况。
结果与结论：最大应力均出现在输送骨段，随骨质量下降而增大；骨最大变形出现在输送段边缘，随着骨质量下降而增大；牵张器的下沉也随着骨质量的下降而增大。结果表明随着骨质量的下降，最大应力与变形均明显增大。骨弹性模量的下降将增大牵张成骨失败的风险。

关键词：三维有限元分析；牙种植体；牵张成骨；骨质量；应力分布
doi:10.3969/j.issn.1673-8225.2010.48.040
中图分类号: R318　文献标识码: B
文章编号: 1673-8225(2010)48-09100-04
仇敏，王继玲，惠光艳，贾文敏，丁红. 骨质量对种植牵张初期稳定性影响的三维有限元分析[J].中国组织工程研究与临床康复，2010，14(48):9100-9103.
[http://www.crter.org　http://cn.zglckf.com]
(Edited by: Wang LJ/Zhao LJ/Wang L)