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Optimal design of an individual endoprosthesis for the reconstruction of extensive mandibular defects with finite element analysis

Peng Li [a,1], Longduo Shen [a,1], Jia Li [a], Rui Liang [b], Weidong Tian [a,b,**], Wei Tang [a,*]

[a] Department of Oral and Maxillofacial Surgery, West China College of Stomatology, Sichuan University, No. 14, 3rd Section, Renmin South Road, Chengdu 610041, PR China
[b] State Key Laboratory of Oral Disease, Sichuan University, No. 14, 3rd Section, Renmin South Road, Chengdu, Sichuan 610041, PR China

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A B S T R A C T

Aim: The aim of this study was to evaluate the finite element analysis (FEA) approach to assess biomechanical performance of individual endoprostheses used in the reconstruction of extensive mandibular defects, and to explore an available strategy for the optimal design of prostheses.
Material and methods: A female patient experienced fracture of a titanium mandibular endoprosthesis one year after reconstructive surgery. The endoprosthesis was placed during resection of a mandibular carcinoma. Using CT data, a finite element analysis (FEA) of the implant was performed to identify potential causes for this mechanical failure. Based on the first FEA analysis, modifications of the prosthesis geometry and screw configuration were carried out. FEA was performed for each subsequent modification until no stress concentration areas were identified. The final version of the titanium prosthesis was implanted during the second mandibular reconstruction.
Results: The FEA model was constructed, based on the geometrical data of the patient. Two areas of stress concentration were identified in the original prosthesis:
- at the top surface of the left stem, 1.5 cm away from the corner (the peak stress was 616 MPa) and
- on the exterior surface of the right stem, close to the mandibular stump margin.

The mechanical failure occurred at the top surface of the left stem. Some common characteristics of the biomechanical performance were noted in the two models, but lower overall stress was achieved in the second, optimized prosthesis. By thickening the recognized high stress areas, and attenuating those areas subject to less stress, then adopting a quadrilateral screw configuration, this dispersed the stress more evenly in the optimized endoprosthesis. Function in the optimized reconstructed mandible was observed for 3 years without significant endoprosthesis related complication.
Conclusion: In some patients with extensive mandibular defects, the individually tailored endoprosthesis constructed with regard to minimizing stress concentration using this method seems to have a place. The prosthesis geometry and screw configuration influence the stress–strain distribution on the reconstructed mandible. Our FEA approach can optimize the design of individual endoprostheses and give the reconstructed mandible improved biomechanical performance.

1. Introduction

Mandibular continuity defects are common findings in the maxillofacial area resulting from trauma, tumour resection, and osteomyelitis. Surgeons have been seeking the ideal method of mandibular reconstruction for centuries. Free and pedicled bone grafts, particulate cancellous marrow graft, tissue engineered bone, reconstruction plates, distraction osteogenesis, and modular endoprosthesis (e.g., Christensen system) have been used to this end (Lee et al., 2009). Bone grafts are most commonly used, but may not be suitable for patients with microcirculatory disease or advanced cancer. Reconstruction plates have some drawbacks such as screw loosening and fracture (Head et al., 2003).

With the development of computer-assisted surgical techniques, the individual endoprosthesis has become a choice for patients who unable or unwilling to undergo other methods (Ettl et al., 2010). It has better adaptation to bone surfaces and

* Corresponding author. Tel.: +86 028 85503456; fax: +86 028 85582167.
** Corresponding author. Department of Oral and Maxillofacial Surgery, West China College of Stomatology, Sichuan University, No. 14, 3rd Section, Renmin South Road, Chengdu 610041, PR China. Tel.: +86 028 85503456; fax: +86 028 85582167.
E-mail addresses: drtwd@sina.com (W. Tian), mydrtangwei@yahoo.com.cn (W. Tang).

[1] The first two authors, Drs Li and Shen contributed to the study equally.

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function for a longer time than reconstruction plates or modular endoprostheses. The ideal endoprosthesis-screw system for the reconstruction of mandibular defects must be rigid enough to withstand the forces transmitted during occlusal function and still achieves restoration of the mandibular contour. Any surgical approach which ignores the forces acting on the reconstructed mandible will ultimately fail. An analysis of biomechanical performance of endoprosthetics seems important in design processing (Schupp et al., 2007).

Finite element analysis (FEA) has been used alone or in combination with other methods to study the accuracy and feasibility of various reconstruction methods. The forces acting on the intact or reconstructed mandible have been studied (Meyer et al., 2006; Hannam et al., 2010; Ramos et al., 2011). Unfortunately, it is not currently possible to perform a validation of mechanical testing, such as strain gauge experiments, to predict the outcome in human use.

We have previously reported that individual prefabricated titanium implants were well suited for condylar replacement after tumour resection (Tang et al., 2009). These findings lacked any biomechanical analysis. In the current study, we use a finite element analysis (FEA) approach to study the biomechanical performance of an endoprosthesis used in the reconstruction of a mandibular defect. By evaluating a clinical failure, use of the FEA approach was validated. The prosthesis was composed of two parts, the stem which replaced the material at the mandibular defect, and the extended plate which is used to fix the prosthesis to the mandible. The optimal design of the endoprosthesis and screw configuration was analyzed and modified to improve its biomechanical performance. The technical processes involved and the directions for future research are discussed.

2. Material and methods

2.1. Case history

A 56-year-old woman was referred to the Department of Oral & Maxillofacial Surgery of the West China College of Stomatology, Sichuan University in June 2008 with a diagnosis of ameloblastic carcinoma of the left mandible body. Facial computed tomography (CT) images were imported into the 3DMSR software (Jimafei Science and Technology Development, Beijing, China) system. 3-D reconstructions demonstrated an extensive defect involving the mandibular symphysis and angle. An individual endoprosthesis was designed and manufactured with rapid prototyping technology. Mandibular reconstruction was performed after preoperative radiotherapy. One year later, the patient was referred to our department for evaluation of a small submental fistula, exposure of the titanium prosthesis, and malocclusion. Physical and radiologic examination revealed the prosthesis had broken down at the left stem (Fig. 1a–c).

Using the geometrical CT data, a FEA was performed to identify the cause of this clinical failure. This study was approved by our institutional ethics committee. Full informed consent was obtained from the patient.

2.2. Construction of the FEA model

CT images were imported in DICOM (Digital Imaging and Communications in Medicine) format into *MIMICS 14.0* (Materialise, Belgium) in a personal computer system. To minimize the project size, the "crop project" operation was performed to eliminate other parts of the skull and to concentrate the modelling effort on the mandible. A threshold based Hounsfield scale (range: 280–3071 HU) was used to isolate the mandible and exclude soft tissues. The three dimensional outer shape was generated using a surface triangularization technique according to its original morphology (Li et al., 2012, 2013). The designed prosthesis was imported into the software and nine 2.4 mm-diameter virtual screws without threads were designed. All parts of the model were assembled and were fitted together optimally using Boolean operation. The model was saved using STL (Standard Triangle Language) format for further processing (Fig. 2a).

After mesh processing in the software *Geomagic Studio 11.0* and *pro/E 4.0*, the assembled model was imported into the FEA *ANSYS workbench 12.0* in IGES (Initial Graphics Exchange Specification) format. The model was meshed with C3D10M-modified 10 node

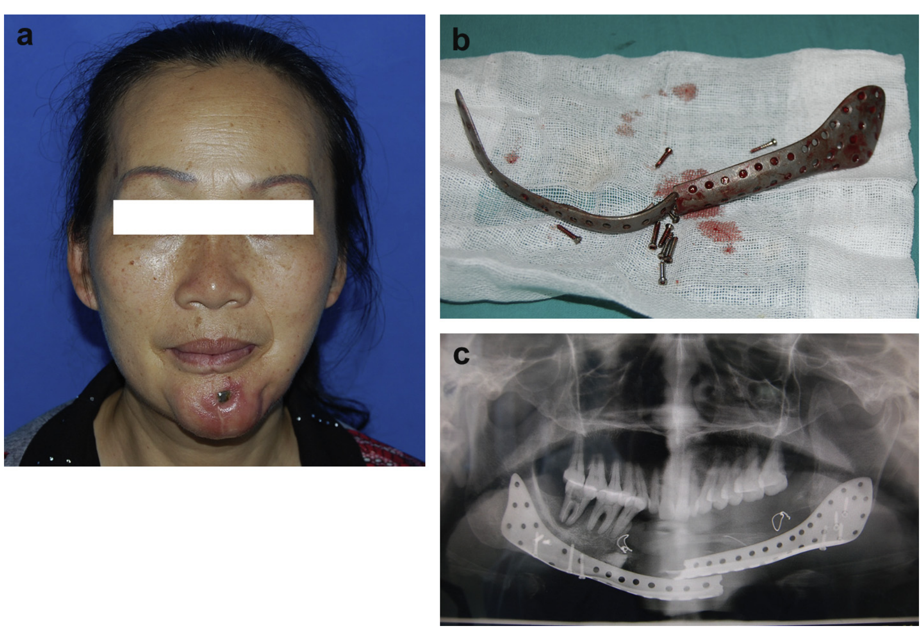

Fig. 1. Clinical condition of the patient. a: Exposure of the titanium prosthesis at the submental fistula. b: Radiologic examination revealed the prosthesis has fractured at the left stem. c: The fractured prosthesis after removal from the patient.