Finite Element Analysis

Biomedical Aspects

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Edited by **Connie Mcguire**

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Preface

This book has been an outcome of determined endeavour from a group of educationists in the field. The primary objective was to involve a broad spectrum of professionals from diverse cultural background involved in the field for developing new researches. The book not only targets students but also scholars pursuing higher research for further enhancement of the theoretical and practical applications of the subject.

Finding approximate solutions to partial differential equations and integral equations, allowing numerical assessment of complicated structures based on their material properties is best represented by the mathematical method of Finite Element Analysis. This book presents varied topics on the utilization of Finite Elements in biomedical engineering under two sections on "Dentistry, Dental Implantology and Teeth Restoration" and "Cardiovascular and Skeletal Systems". The structure and language of the book has been so written that it is useful for graduate students learning applications of finite element and also encompasses topics and reference material useful for research and professionals who want to gain a deeper knowledge of finite element analysis.

It was an honour to edit such a profound book and also a challenging task to compile and examine all the relevant data for accuracy and originality. I wish to acknowledge the efforts of the contributors for submitting such brilliant and diverse chapters in the field and for endlessly working for the completion of the book. Last, but not the least; I thank my family for being a constant source of support in all my research endeavours.

Editor

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Part 1

Dentistry, Dental Implantology and Teeth Restoration

FEA in Dentistry: A Useful Tool to Investigate the Biomechanical Behavior of Implant Supported Prosthesis

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1. Introduction

The use of dental implants is widespread and has been successfully applied to replace missing teeth (Amoroso et al., 2006). Although high success rate has been reported by several clinical studies, early or late dental implants failures are still inevitable. During mastication, overstress around dental implants may cause bone resorption, which leads to infection on the peri-implant region and failure of oral rehabilitation (Kopp, 1990). The way in which bone is loaded may influence its response (Koca et al., 2005). The results of cyclic loading into the bone differ from those of static loading (Papavasiliou et al., 1996). In case of repetitive cyclic load application, stress microfractures in bone may occur (Koca et al., 2005) and may induce osteoclastic activity to remove the damaged bone (Papavasiliou et al., 1996). So far, it is imperative to understand where the maximum stresses occur during mastication around the implants in order to avoid these complications (Nagasao et al., 2003).

Considering that stress/strain distribution at bone level is hard to be clinically assessed, the finite element analysis (FEA) has been extensively used in Dentistry to understand the biomechanical behavior of implant-supported prosthesis. To date, FEA was first used in the Implant Dentistry field by Weinstein et al. (1976) to evaluate the stress distribution of porous rooted dental implants. Nowadays, owing to the geometric complexity of implant-bone-prosthesis system, FEA has been viewed as a suitable tool for analyzing stress distribution into this system and to predict its performance clinically. Such analysis has the advantage of allowing several conditions to be changed easily and allows measurement of stress distribution around implants at optional points that are difficult to be clinically examined.

Therefore, this chapter provides the current status of using FEA to investigate the biomechanical behavior of implant-supported prosthesis. The modeling of complex structures that represents the oral cavity is described, and comparisons between two-dimensional (2D) and three-dimensional (3D) modeling techniques are discussed. Additionally, the application of microcomputer tomography to develop complex and more realistic FE models are assessed. Some sensitive cases are also illustrated.

2. Biomechanical behavior of implant-supported prosthesis

In order to enhance treatment longevity, it is important to understand the biomechanics of implant-supported prosthesis during masticatory loading. And the way that the stress/strain is transmitted and distributed to the bone tissue dictates whether the implant treatments will failure or succeed (Geng et al., 2001). Several variables affect the stress/strain distribution on the implant/bone complex such as prosthesis type, implant type, veneering and framework materials, bone quality, and presence of misfit.

2.1 Prosthesis and implant types

The implant-supported prosthesis can be classified as single- or multi- unit prosthesis. From a biomechanical point of view, the multi-unit prosthesis is subdivided into implant-supported overdentures and implant-supported fixed prosthesis (cantilevered design or not). The nature of FEA studies for these prosthesis designs is much more complex than for single-unit design (Geng et al., 2001).

Implant-retained overdentures are considered a simple, cost-effective, viable, less invasive and successful treatment option for edentulous patients (Assuncao et al., 2008; Barao et al., 2009). However, controversies toward the design of attachment systems for overdentures still exist (Bilhan et al., 2011). Our previous study (Barao et al., 2009) used a 2D FEA to investigate the effect of different designs of attachment systems on the stress distribution of implant-retained mandibular overdentures. The bar-clip attachment system showed the greatest stress values followed by bar-clip associated with two distally placed o'ring attachment systems, and o'ring attachment system (Fig. 1). Other 2D (Meijer et al., 1992) and 3D FEA studies (Menicucci et al., 1998) also showed stress optimization in overdenture with unsplinted implants (e.g. o'ring attachment system). The flexibility and resiliency provided by the o'ring rubber and the spacer in the o'ring system assembly may be the driven force toward the lower stress values with o'ring attachment system. Additionally, the stress breaking effect of the o'ring rubber can also decrease the stress in implants, prosthetics components and supporting tissues (Tokuhisa et al., 2003).

Tanino et al. (2007) evaluated the effect of stress-breaking attachments at the connections between maxillary palateless overdentures and implants using 3D models with two and four implants. Stress-breaking materials (with elastic modulus ranging from 1 to 3,000 MPa) connecting the implants and denture were included around each abutment. As the elastic modulus of the stress-breaking materials increased, the stress increased at the implant-bone interface and decreased at the cortical bone surface. Additionally, the 3-mm-thick stress-breaking material decreased the stress values at the implant-bone interface when compared to the 1-mm-thick material. Knowing that overdentures are retained by implants but are still supported by the mucosa, and facing the difference in displacement between implants (20-30 μm) and soft tissue (about 500 μm), our previous study (Barao et al., 2008) investigated the influence of different mucosa thickness and resiliency on stress distribution of implant-retained overdentures using a 2D FEA. Two models were designed: two-splinted-implants connected with bar-clip system and two-splinted-implants connected with bar-clip system associated with two-distally placed o'ring system. For each design, mucosa assumed three characteristics of thickness (1, 3 and 5 mm) varying its resiliencies (based on its Young's modulus) in hard (680 MPa), resilient (340 MPa) and soft (1 MPa), respectively. In general, the stress decreased at the supporting tissues as mucosa thickness and resiliency increased (Fig. 2).

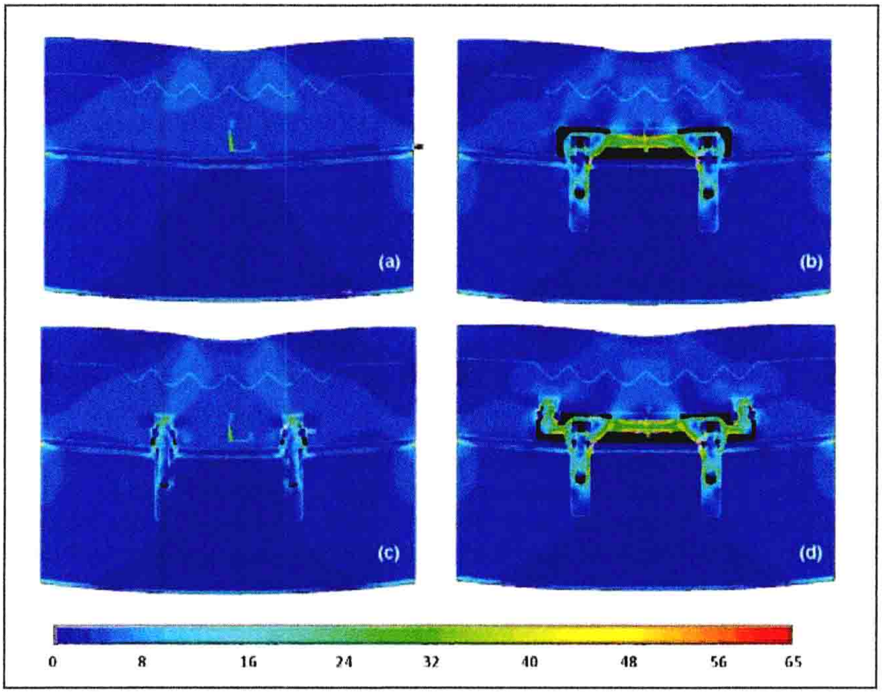

Fig. 1. First principal stress distribution (in MPa). (a) conventional complete denture. (b) overdenture - bar-clip system. (c) overdenture - o'ring system). (d) overdenture - bar-clip associated with distally placed o'ring system. Colors indicate level of stress from dark blue (lowest) to red (highest).

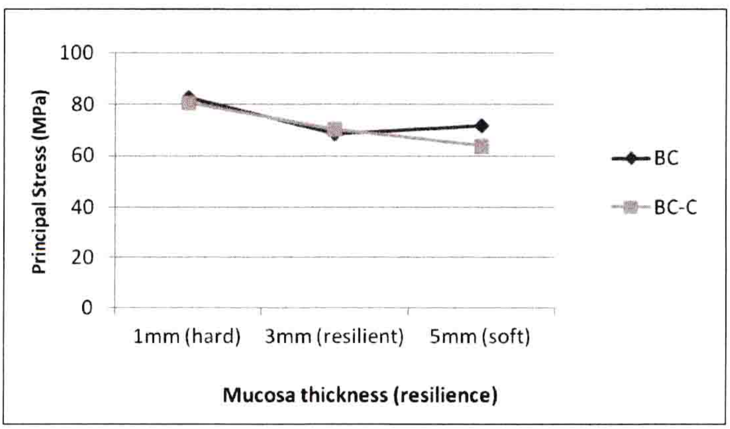

Fig. 2. Distribution of first principal stress (MPa) in supporting tissues for groups BC (bar-clip) and BC-C (bar-clip associated with two-distally placed o'rings) considering different mucosa thickness (1, 3 and 5mm) and resilience (hard, resilient and soft).

In relation to the implant-supported fixed prosthesis, the variety of factors that affect the stress distribution into the bone-implant complex comprise implant inclination, implant number and position, framework/veneering material properties, and cross-sectional design of the framework (Geng et al., 2001). The use of tilted implants mostly affected the stress concentration in the peri-implant bone tissue when compared to vertical implants (Canay et al., 1996). However, tilted implants have been used in case of atrophic jaw, to avoid maxillary sinus, and to reduce the cantilever extension (Silva et al., 2010). Caglar et al. (2006) investigated the effects of mesiodistal inclination of implants on the stress distribution of posterior maxillary implant-supported fixed prosthesis using a 3D FEA. Inclination of the implant in the molar region resulted in increased stress. Similar results were found by a Iplikcioglu & Akca (2002) who investigated the effect of buccolingual inclination in implant-supported fixed prosthesis applied to the posterior mandibular region using a 3D FEA. Bevilacqua et al. (2011) investigated the influence of cantilever length (13, 9, 5 and 0 mm) and implant inclination (0, 15, 30 and 45 degrees) on stress distribution in maxillary fixed dentures. This 3D FEA study showed that tilted implants, with consequent reduction of the posterior cantilevers, reduced the stress values in the peri-implant cortical bone.

Zarone et al. (2003) evaluated the relative deformations and stress distributions in six different designs of full-arch implant-supported fixed mandibular denture (six or four implants, cantilevered designed or not, cross-arch or midline-divided bar into two free-standing bridges) by means of 3D FEA. When the implants were rigidly connected by one-piece framework, the free bending of the mandible was hindered. The flexibility of the mandible was increased as the more distal implant supports were more mesially located. The use of two free-standing bars also reduced the overall stress on the bone/implant interface, fixtures and superstructure. Contradicting these findings, Yokoyama et al. (2005) observed that the use of single-unit superstructure was more effective in relining stress concentration in the edentulous mandibular bone than 3-unit superstructure. Other study (Silva et al., 2010), using a 3D FEA, assessed the biomechanical behavior of the "All-on-four" system with that of six-implant-supported maxillary prosthesis with tilted implants. The stress values were greater to the "All-on-four" concept, and the presence of cantilever increased the stress values about 100% in both models.

It is believed that loading distribution pattern in implant-retained overdentures differs from those in implant-supported fixed restorations (Tokuhisa et al., 2003). Our ongoing project has compared the effect of different designs of implant-retained overdentures and fixed full-arch implant-supported prosthesis on stress distribution in edentulous mandible by using a 3D-FEA based on a computerized tomography (CT). Four 3D FE models of an edentulous human mandible with mucosa and four implants placed in the interforamina area were constructed and restored with different designs of dentures. In the OR group, the mandible was restored with an overdenture retained by four unsplinted implants with O'ring attachment; in the BC-C and BC groups, the mandibles were restored with overdentures retained by four splinted implants with bar-clip anchor associated or not with two distally placed cantilevers, respectively; in the FD group, the mandible was restored with a fixed full-arch four-implant-supported prosthesis. The masticatory muscles and temporomandibular joints supported the models. A 100-N oblique load (30 degrees) was applied on the left first molar of each denture in a buccolingual direction. Qualitative and quantitative analysis based on the von Mises stress (σ_{vM}), the maximum (σ_{max}) (tensile) and minimum (σ_{min}) (compressive) principal stresses (in MPa) were obtained. BC-C group exhibited the highest stress values (σ_{vM} = 398.8, σ_{max} = 580.5 and σ_{min} = -455.2) while FD group showed the lowest one (σ_{vM} = 128.9, σ_{max} = 185.9 and σ_{min} = -172.1) in the implant/prosthetic components. Within overdenture groups, the use of unsplinted implants (OR group) reduced the stress level in the implant/prosthetic components (59.4% for σ_{vM}, 66.2% for σ_{max} and 57.7% for σ_{min} versus BC-C group) and supporting tissues (maximum stress reduction of 72% and 79.5% for σ_{max}, and 15.7% and 85.7% for σ_{min} on the cortical bone and the trabecular bone, respectively). The cortical bone exhibited greater stress concentration than the trabecular bone for all groups. We concluded that the use of fixed implant dentures and removable dentures retained by unsplinted implants to rehabilitate completely edentulous mandible reduced the stresses in the peri-implant cortical bone tissue (Fig. 3), mucosa and implant/prosthetic components.

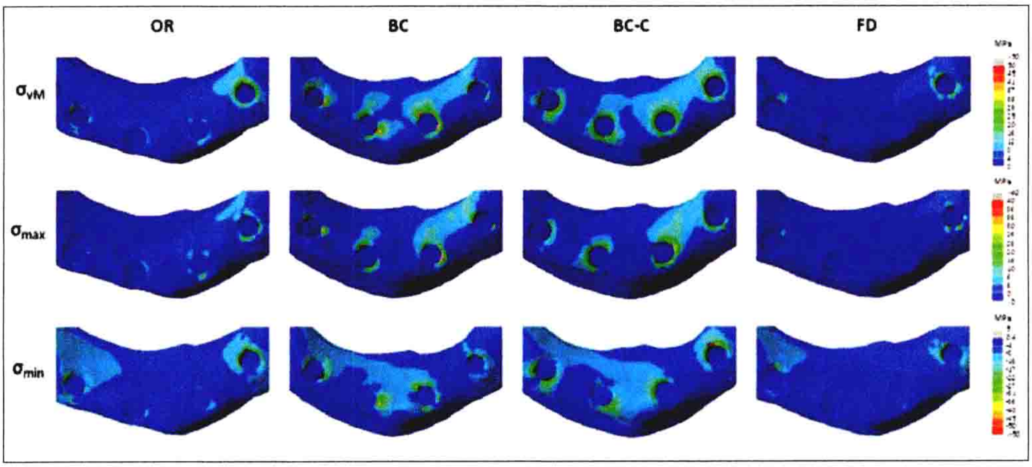

Fig. 3. von Mises stress (σ_{vM}), maximum (σ_{max}) and minimum (σ_{min}) principal stress distributions (in MPa) within cortical bone for o'ring (OR), bar-clip (BC), bar-clip with distally placed cantilever (BC-C) and fixed denture (FD) groups.

Concerning the implant design, Ding et al. (2009) analyzed the stress distribution around immediately loaded implants of different diameters (3.3; 4., and 4.8 mm) using an accurate complete mandible model. The authors observed that with the increase of implant diameter, stress/strain on the implant-bone interface decreased, mainly when the diameter increased from 3.3 to 4.1 mm for both axial and oblique loading conditions. Other studies also showed more favorable stress distribution with the use of wide-diameter implants (Himmlova et al., 2004; Matsushita et al., 1990). Huang et al. (2008) analyzed the peri-implant bone stress and the implant-bone sliding as affected by different implant designs and implant sizes of immediately loaded implant with maxillary sinus augmentation. Twenty-four 3D FE models with four implant designs (cylindrical, threaded, stepped and step-thread implants) and three dimensions (standard, long and wide threaded implants) with a bonded and three levels of frictional contact of implant-bone interfaces were analyzed. The use of threaded implants decreased the bone stress and sliding distance about 30% as compared with nonthreaded (cylindrical and stepped) implants. With the increase of implant's length or diameter, the bone stress reduced around 13-26%. The immediately loaded implant with smooth machine surface increased the bone stress by 28-63% versus osseointegrated implants. The increase of implant's surface roughness did not reduce the bone stress but decrease the implant-bone interfacial sliding.

2.2 Veneering and framework material

The literature is scarce about the best material to fabricate superstructures of implant-supported prosthesis (Gomes et al., 2011). Originally, the protocol consisted of gold alloy framework and acrylic resin for denture base and acrylic resin or composite resin for artificial denture teeth (Zarb & Jansson, 1985). Rigid occlusal material such as porcelain on metal may increase the load transfer to the implant and surrounding bone tissue (Skalak, 1983). So far, the use of occlusal veneering based on resin material is indicated to absorb shock and consequently to reduce the stress on the implant-bone complex (Skalak, 1983). Gracis et al. (1991) stated that the use of harder and stiffer materials to fabricated implant-supported restorations increased the stress transmitted to the implant. On the other hand, some studies (Ciftci & Canay, 2001; Sertgoz, 1997) showed that the use of softer restorative materials lead to a higher stress on implants and supporting tissues.

Our previous studies (Delben et al., 2011; Gomes et al., 2011) evaluated the influence of different superstructures on preload maintenance of retention screw of single implant-supported crowns submitted to mechanical cycling and stress distribution through 3D FEA.

Twelve replicas for each group and 3D FEA models were created to simulate a single crown supported by external hexagon implant in premolar region. Five groups were obtained: gold abutment veneered with ceramic (GC) and resin (GR), titanium abutment veneered with ceramic (TC) and resin (TR), and zirconia abutment veneered with ceramic (ZC). During mechanical cycling, the replicas were submitted to dynamic vertical loading of 50 N at 2 Hz for detorque measurement after each period of 1×10^5 cycles up to 1×10^6 cycles. The FEA software generated the stress maps after vertical loading of 100 N on the contact points of the crowns. Significant difference ($P<.05$) between group TC (21.4 ± 1.78) and groups GC (23.9 ± 0,91), GR (24.1 ± 1.34) and TR (23.2 ± 1.33); and between group ZC (21,9 ± 2,68) and groups GC and GR for initial detorque mean (in N.cm) was noted. After mechanical cycling, there was significant difference ($P<.05$) between groups GR (23.8 ± 1.56) and TC (22.1 ± 1.86), and between group ZC (21.7 ± 2.02) and groups GR and TR (23.6 ± 1.30) (Fig. 4). The stress values and distribution in bone tissue were similar for groups GC, GR, TC and ZC (1574.3 MPa, 1574.3 MPa, 1574.3 MPa and 1574.2 MPa, respectively), except for group TR (1838.3 MPa) (Fig. 5). Group ZC transferred lower stress to the retention screw (785 MPa) than the other groups (939 MPa for GC, 961 MPa for GR, 1010 MPa for TC, and 1037 MPa for TR) We concluded that detorque reduction occurred for all superstructure materials but torque maintenance was enough to maintain joint stability in this study. The different materials did not affect stress distribution in bone. However, group ZC presented the best stress distribution for the retention screw. Previous study conducted by our research group also found similar stress distribution to single implant-supported prosthesis regardless of the type of veneering/framework material through a 2D FEA (Assuncao et al., 2010).