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Numerical study of the influence of material parameters on the mechanical behaviour of a rehabilitated edentulous mandible

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ABSTRACT

Objectives: The study dealt with full dental prosthetic reconstruction on four implants. The aim was to analyse the influence of material parameters on the mechanical behaviour of the restored mandible compared to the natural mandible.

Methods: A finite element model of an edentulous mandible with prosthetic rehabilitation was established. Four materials were investigated for the framework of the prosthesis (zirconia, titanium, gold and nickel-titanium (NiTi)), as well as three cortical bone thicknesses. Various muscles were employed to simulate the main stages of mastication. Three distinct phases of mastication were modelled: maximum intercuspation, incisal clench and unilateral molar clench.

Results: The zirconia framework demonstrated the highest stresses and NiTi the weakest. The highest stresses in the framework were obtained during maximum intercuspation. The highest stresses at the bone-implant interface were recorded on the working axial implant during unilateral molar clench and on tilted implants during maximum intercuspation. The influence of the framework's material stiffness on the stresses at the bone-implant interface was insignificant for axial implants (except the right implant during unilateral molar clench) and slightly more significant for tilted implants. Mandibular flexion decreased with an increase of the cortical bone thickness and the stiffness of the prosthetic framework's material.

Conclusions: Among all materials, NiTi allowed a better preservation of the mandibular flexure, during all the mastication stages. Compared to stiffer materials, NiTi also permitted physiological mechanical conditions at the bone/implant interface, in almost all mastication stages.

1. Introduction

Prosthetic treatments for edentulous patients have been greatly improved by the development of implants. Solutions range from a full bridge sealed or screwed on several implants (between 2 and 10 implants), to a fully removable prosthesis stabilised by two implants and their attachments. The choice of the most appropriate of these solutions depends on an accurate diagnosis, including the socioeconomic point of view.

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Indeed, the aim is to provide a reliable prosthesis with the lowest cost of maintenance. Such cost is unavoidable because of biological and mechanical complications occurring over time as a result of fatigue and stress.

Several in vivo studies have reported various success rates and complications.[1–5] A systematic review of mechanical complications for fixed implant rehabilitation showed that the most frequent technical complications were related to the prosthesis rather than to the implants.[6]

Mechanical complications are not the only ones affecting fixed implant rehabilitation. Biological complications can also occur in the tissues around the prosthesis or at the bone/implant interface (with bone resorption or a loss of osteointegration).[6,7]

Mechanical and biological complications depend on several factors: the level of applied stresses and their duration (occlusal forces and para-functions), as well as the geometric and material characteristics of the prosthesis.

Several numerical studies have tried to analyse the influence of these factors.[8–11] Few authors took into consideration the interplay between the prosthesis and mandibular deformation.[12,13] But the influence of mandibular flexion on the design and durability of the prosthesis was not adequately studied.[14]

The study presented in this paper is a step in a global research programme, called SOPBIP (Optimisation System for Implant Screwed Bridges, Université de Lorraine), which aims to improve the reliability of prosthetic reconstruction screwed on four implants. Among fixed prostheses, a fully customised denture screwed onto four implants (called ''All-on-4'') is one of the least expensive and least invasive available solutions.[4,15]

In order to avoid biological and mechanical complications for such reconstructions, the selection of design and materials must be optimised. In this study, the focus is on the influence of the materials' parameters on the prosthetic reconstruction's behaviour. The aim is to analyse how those parameters modify the behaviour of the restored mandible compared to the natural mandible. Our null-hypothesis is that the optimised prosthetic reconstruction should tend to minimise the restriction of the natural mandibular flexure (i.e. without prosthesis) and also to reproduce physiological mechanical conditions in the bone tissues around the implants. To this end, the paper analyses the mechanical behaviour of the framework of the prosthesis, the mandibular deformation of the mandible supporting the prosthesis, and the stress-state of the bone-implant interface, depending on the prosthetic material stiffness and cortical bone thickness, during distinct phases of mastication.

2. Material and methods

2.1. CAD Parametric model

We developed a CAD (Construction Aided Design) parametric model of the mandible-prosthesis structure.

The geometry of the edentulous mandible was obtained by a 3D scanning of an artificial mandible. The scanning was performed with a three-dimensional measuring machine (TMM) equipped with a Kreon Zephir KZ25 laser captor (AIP Primeca Lorraine). The 3D points cloud was filtered and the volume of the mandible was reconstructed with the CAD CATIA® software (Dassault Systèmes). To distinguish cortical and cancellous bone, an inner surface was defined by duplicating the outer surface of the mandible: the mean distance between these two surfaces represents the thickness of the cortical bone (Tcb), and is one of the parameters taken into consideration in this study.

The prosthesis was an assembly of four basic structures: the framework, the four implants (two straight and two tilted), the screws and the multibases. Artificial teeth and cosmetics were not taken into account. The 'implant-multibase-screw' substructure was considered as a complete unit: contact and friction between the different parts were not taken into account in the present model.

The framework's geometry was defined using 31 parameters (including coordinates for the tooth locations determined from the mandible computer tomography, thickness, and width and length of the cantilever part of the framework).

Two anterior straight implants were placed in the right and left canine areas with another two posterior implants usually tilted at a 45° angle to the occlusal plane. Straight and tilted implant geometries were defined by 4 and 7 parameters, respectively (including the diameter of the implants and the angle of the tilted implants).

For this study, the following geometric parameters were selected: 4 mm for the framework's thickness and width, 13 mm for the length of the cantilever, 4 mm for the implants' diameter, 11 mm for their length and 45 degree for the tilted implants' angulation.

The final CAD model of the mandible-prosthesis structure was obtained from a Boolean operation between the mandibular and the prosthetic CAD models (Fig. 1).

2.2. Finite element model

Finite element simulations were performed using Abaqus® V6.10-2 software. An elastic linear framework was considered for the analysis of displacements, strains and stresses within the mandible and the prosthesis.

2.2.1. Mandible and prosthesis meshing

3-node triangular facets (R3D3) were used for the rigid plane, and 4-node linear tetrahedrons (C3D4) for the mandible and the prosthesis. The number of elements were 3628, 10,903, 281,007, 182,399, 1080 and 1050, for the rigid plane, the framework, the cortical bone, the cancellous bone, tilted implants and straight implants, respectively. These mesh sizes were obtained after a preliminary study of sensitivity to mesh refinement. They correspond to an optimal compromise between convergence and CPU-cost.

2.2.2. Materials

Four materials were examined for the framework: zirconia ceramics (Zr), titanium alloy (Ti), gold alloy (Au) and nickel-titanium alloy (NiTi). Only one (Ti) was considered for the implants, the multibases and the screws.

Three thicknesses of cortical bone were considered: Tcb = 1 mm, 1.5 mm and 2 mm.