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The effects of implant angulation on the resonance frequency of a dental implant

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ABSTRACT

Dental implants are ideally placed in an orientation that allows vertical transfer of occlusal forces along their long axis. Nevertheless, optimal situations for implant placement are seldom encountered resulting in implants placement in angulated positions, which may affect their long-term success. The resonance frequency (RF) is an objective tool used to monitor stability of the implant tissue integration; however, little is known of the effect of the implant orientation in bone on the RF and its potential significance. The purpose of this research was to determine the relation between the dental implant orientation and the corresponding RF of implant. Three-dimensional (3D) modelling software was used to construct a 3D model of a pig mandible from computed tomography (CT) images. The RF of the implant was analysed using finite element (FE) modal analysis in software ANSYS (v.12). In addition, a cubical model was also developed in MIMICS to investigate the parameters affecting the relationship between RF and implant orientation in a simplified environment. The orientation angle was increased from 0 to 10 degrees in 1 degree increments and the resulting RF was analysed using correlation analysis and one-way ANOVA. Our analysis illustrated that the RF fluctuation following altering implant orientation was strongly correlated ($r = 0.97$) with the contacting cortical to cancellous bone ratio (CCBR) at the implant interface. The most extreme RF change (from 9.81 kHz to 10.07 kHz) occurred when the implant was moved 0.5 mm in positive z-direction, which resulted in the maximum change of CCBR from 52.9 to 54.8.

1. Introduction

The use of dental implants in the rehabilitation of partially and completely edentulous patients is considered a predictable and successful treatment modality with favourable long-term survival rates [1–3]. To achieve a successful outcome, meticulous planning for surgical and prosthetic stages is mandatory. Complications; however, may occur in various stages leading to the implant failure. Poor surgical techniques may result in poor implant placement in a compromised orientation in bone, which further complicates prosthetic rehabilitations. A poorly oriented implant may be jeopardized further by the lateral vector of the occlusal forces. In such situation, stress concentrates primarily at the neck of the implant instead of the entire long axis, which can result in early bone loss and eventual implant failure. Implant angulation also can insert excessive strain on the crown superstructure. Pellizzer et al. [4] investigated the stress distribution on straight and angulated implants with different crowns using photoelastic analysis. They reported that an increase in implant angulation resulted in an increase in stress intensities, independent of crown type. A poorly oriented implant can also affect the accuracy of the impression materials. Sorrentino et al. [5] found that implant angulation directly affected the accuracy of the impression by straining impression materials. The use of computer-milled or laboratory fabricated surgical guides have greatly improved placement angulation; however, problems such as fabrication accuracy, placement limitations, and high cost limit their use. Since implant angulation errors can occur during implant placement surgery, there is a need for an objective method to evaluate the health of the tissue and monitor the implant system.

An objective and quantitative method of monitoring implant/tissue integration is resonance frequency analysis (RFA) method which was first introduced for dental applications in 1996 [6]. Resonance happens in all physical structures and indicates their tendency to oscillate with higher amplitudes at some frequencies. The frequencies at which the maximum amplitudes occur are called resonance frequencies (RF). RFA has been used as a non-invasive method to monitor short- and long-term changes in implant stability [7–9]. It has been applied to implant stability measurement in humans [10–12], *in vivo* animal models [13–15]

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and *in vitro* models [6,14,16]. Most of the RF data available in the literature are obtained from the implants placed in an optimal orientation, and little data are available from RF of implants placed in compromised orientations.

RFA can be performed by computer simulation using finite element analyses (FEA). This method can simulate complex geometric shapes, material properties, and generate various boundary conditions of the real situation, which are often difficult to produce in the laboratory. The simulation method has the advantage of allowing independent control of each parameter in the FE model. This enables controlled and systematic evaluation of parameters such as implant orientation to investigate the overall implant stability. Wang et al. [17] used RFA in finite element method (FEM) to determine the identifiable stiffness range of interfacial tissue of dental implants. It was found that when the Young's modulus of the interfacial tissue is less than 15 MPa, the RFs are significantly affected by the interfacial tissue while other parameters such as geometry, bone boundary constraint, and material property of the bone did not play significant role in the initial implant stability.

This study is aimed to identify the relationship between the RF of a screw-shaped endosseous dental implant in an optimal or compromised orientation (1–10 degree) using FEA simulation. MIMICS, a three dimensional (3D) modelling software was used and a 3D model of a pig mandible was constructed from computed tomography (CT) images. In addition, a cubical model was also created in MIMICS to investigate the parameters concerning the relation between RF changes and implant's orientation in a simplified environment. The resulting RFs were then analysed using Pearson correlation analysis and one-way ANOVA.

2. Materials and methods

2.1. Simulation RF method

RF is a characteristic of a mechanical system (i.e. implant/tissue) and it indicates the frequency at which the exchange of potential and kinetic energy in the system is optimal. Therefore, a system vibrates at its RF when it is excited by an external source. RF of an object is related to its material stiffness, damping, and mass, as well as the supporting structures that determine its boundary conditions. As a result, RF can be employed to characterize a physical system and quantify its interaction with its surrounding support structures.

Modal analysis is an applied technique for identifying the RF of an object and it is widely used in engineering, health-care and dental application [18–21]. Although the experimental setup for performing modal analysis is relatively simple to implement, studying the dependency of RF to various systems parameters and boundary conditions requires fabrication of large number of samples. FEM is a numerical technique based on modal analysis concept. It provides a fast and accurate approach for RF analysis by providing a virtual environment where a 3D model of an object and its supporting structures can be generated and studied. FEM approximates the real structure with a finite number of elements and allows assigning mechanical properties such as Young modulus, Poisson ratio, and density. In FEM, the mass and stiffness matrices are defined based on the type of element used in modelling, the material properties and the boundary condition of the structure. These matrices describe the general equation of motion governed by the simulated model. The RF is then determined mathematically from the interaction of the mass and stiffness matrices. The free vibration of the undamped system is governed by the following equation:

$$[M]\{\ddot{X}\} + [K]\{X\} = 0 \quad (1)$$

where the $[M]$ is the mass matrix and the $[K]$ is the stiffness matrix. The candidate solution is assumed as

$$\vec{X} = \vec{U}e^{j\omega t} \quad (2)$$

where the $\vec{U}$ is the vector of amplitudes of $\vec{X}$ and ω is the frequency of vibration. This form of solution, when substituted into Eq. (1), will change it into a simple algebraic matrix equation:

$$[[M]\omega^2 - [K]]\vec{U}e^{j\omega t} = 0 \quad (3)$$

For this equation to have non-zero solution, the determinant of $[M]\omega^2 - [K]$ should be zero:

$$\left|[M]\omega^2 - [K]\right| = 0 \quad (4)$$

This is a polynomial equation of nth degree in ω^2 and it is called the characteristic equation of the system. The roots of the polynomial give the n eigenvalues, $\omega_1^2, \omega_2^2, \ldots, \omega_n^2$. The positive square root of each ω_i^2 is a RF of the system. In this paper, FEM was used to perform FEA in two models, a partial pig mandible and a simplified cubical epoxy resin mould.

2.2. Pig mandible model

The mandible of domestic young adult pig (*Sus scrofa*) was obtained from the slaughter house (Britco Pork Inc.) and a 3.75 × 13 mm MIS endosseous implant was placed at the edentulous space between 1st and 2nd premolars. MIS surgical protocole was followed to place the implant so that primary stability of the implant was established in bone. A 13 mm titanium MIS abutment was torqued to the implant body at 32 N/cm^2. The mandible was later block sectioned at the premolar areas to include the implant and adjacent teeth, Fig. 1a. X-ray imaging of the sectioned mandible was performed using a Kodak Cone Beam Computed Tomography (CBCT). Fig. 1b shows the transverse plane of a CT image slice of the sectioned pig mandible. DICOM X-ray images were imported into MIMICS (version 14.12) to create an accurate, 3D model of the sectioned mandible, teeth and implant. The model was later imported into FEA software, ANSYS (version 12.1) for RF analyses. In FEA, a physical system, such as the pig mandible model is converted into a number of discrete elements and the properties of each element is assigned from the library of standard reference data.

Tissues and implant were identified in MIMICS from individual DICOM images generated by CBCT using a default threshold technique. A radiologist expert also confirmed and corrected the threshold criteria for the identifiable structures. These structures included cancelous and cortical bone, enamel, dentine, soft tissue, as well as implant. Cementum and dental pulp were excluded because of their relatively low volume and thus minor contribution in the analysis. Fig. 1c shows a CT image slice of a segment of pig mandible, in which the cortical, cancellous, enamel and dentine are defined. Fig. 1d shows the 3D model of the sectioned pig mandible, teeth and implant.

The CBCT images of pig mandible were meshed in MIMICS (51,300 nodes/28,967 elements) and imported into ANSYS and a 3D 10-Node tetrahedral structural solid element is used for the RF analysis. A convergence analysis was conducted to select the number of nodes and elements. Moreover, we tried both finer and coarser mesh sizes compared to the selected mesh size to investigate the sensitivity of the analysis. We found the variations in the results small and within acceptable range (less than 20 Hz). The elements are defined by 10 nodes having three-dimensional motion at each node, which is ideal to model irregular meshes [22]. The boundary condition for the outer surfaces of the cortical and cancellous bones is set to fix. The boundary condition of the free surface of the implant is set to free. The coincidental nodes (those at the contact surfaces of cortical and implant, cancellous and implant) should