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Modal analysis for implant stability assessment: Sensitivity of this methodology for different implant designs

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ABSTRACT

Objective. To investigate the influence of implant design on the change in the natural frequency of bone-implant system during osseointegration by means of a modal 3D finite element analysis.
Methods. Six implants were considered. Solid models were obtained by means of reverse engineering techniques. The mandibular bone geometry was built-up from a CT scan dataset through image segmentation. Each implant was virtually implanted in the mandibular bone. Two different models have been considered, differing in the free length of the mandibular branch ('long branch' and 'short branch') in order to simulate the variability of boundary conditions when performing vibrometric analyses. Modal analyses were carried out for each model, and the first three resonance frequencies were assessed with the respective vibration modes.
Results. With reference to the 'long branch' model, the first three modes of vibration are whole bone vibration with minimum displacement of the implant relative to bone, with the exception of the initial condition (1% bone maturation) where the implant is not osseointegrated. By contrast, implant displacements become relevant in the 'short branch' model, unless osseointegration level is beyond 20%. The difference between resonance frequency at whole bone maturation and resonance frequency at 1% bone maturation remained lower than 6.5% for all modes, with the exception of the third mode of vibration in the 'D' implant where this difference reached 9.7%. With reference to the 'short branch', considering the first mode of vibration, 61–68% of the frequency increase was achieved at 10% osseointegration; 72–79% was achieved at 20%; 89–93% was achieved at 50% osseointegration. The pattern of the natural frequency versus the osseointegration level is similar among different modes of vibration.

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Significance. Resonance frequencies and their trends towards osseointegration level may differ between implant designs, and in different boundary conditions that are related to implant position inside the mandible; tapered implants are the most sensitive to bone maturation levels, small implants have very little sensitivity. Resonance frequencies are less sensitive to bone maturation level beyond 50%.

1. Introduction

As it is well known, implant stability plays a major role in successful dental implantology. Primary stability (a mechanical phenomenon) is achieved when an implant has just been set in place and is related to bone quality [1], implant geometry [2,3], and to the surgical technique [4]. Secondary stability (a biological phenomenon) is achieved via implant osseointegration, where new bone formation leads to an increase in stiffness of the peri-implant bone, and to bone-implant interlocking.

Optimizing secondary stability requires limiting micromovements between the implant and the bone below 100 μm [5], since they can potentially lead to fibrous bone formation [6]. Therefore a healing period, during which the implants are unloaded, is required.

On the other hand, load application to an implant is necessary to provide stimulus for bone maturation [6]. Consequently, improved implant designs and surface treatments have led to new loading protocols, such as 'early loading' or 'immediate loading' [7].

The question is therefore: how long should the healing period last? This debate is still open and is the object of many research studies [8,9]. Seemingly, absolute indications cannot be given since the patient bone quality, the kind of implant and the outcome of surgical technique play a fundamental role [7,10,11].

Establishing patient-specific loading protocols requires a non-invasive quantitative assessment of implant stability. An objective, quantitative measurement of implant stability prior to loading is very desirable, even if patients self-regulate masticatory load levels in relation to implant stability, to a certain extent [12].

Vibrometry techniques could realize this aim, according to extensive data reported in the literature where numerical, experimental and clinical methods have been employed to establish the relationship between resonance frequencies and cortical bone thickness [13,14], trabecular bone density [13,15–19], implant length [14,20,21], implant diameter [22,23] and time elapsed since implant placement [18,21,24].

Clinical studies have also been performed, to gain quantitative data about the lower limit of resonance frequency providing optimal primary stability [21,25,26], or the required frequency to start implant loading [25].

However, it is not clear if, and to what extent, the sensitivity of this technique, i.e. resonance frequency variation during osseointegration, is affected by implant design. Very different implant shapes are now available (long or short; cylindrical or tapered), with different threads (single or double thread; short or large pitch, etc), and the most sensitive vibration mode – the mode undergoing the highest frequency variation during osseointegration – might differ amongst implant designs.

The aim of the present study was to assess the influence of implant design on the resonance frequency variation during osseointegration, using Resonance Frequency Analysis (RFA). Details concerning the experimental set up and the boundary conditions of bone were also investigated, since they can have a considerable influence on the sensitivity of resonance frequencies to the osseointegration level: under specific circumstances the osseointegration effect could become completely uninfluential, as detailed in the following section.

2. Materials and methods

Modern CAD–FEM (Computer Aided Design and Finite Element Method) methodologies have been extensively used in biomedical investigations to characterize biomechanical responses in dental applications [27–32].

Starting from these methodologies, four implants from the same manufacturer (ISOMED® Dental Implant, Italy) were considered and analyzed to investigate the influence of implant geometrical factors, such as shape and thread pitch, on the change of the natural frequency (i.e. resonance frequency) of bone-implant system during osseointegration.

These implants were designated as: A (cylindrical implant with internal hexagon connection TIC-10); B (conical implant with inside hexagon connection and medium thread TICc-10 BL); C (conical transmucous implant with internal hexagon connection and double thread TVI5-3-Tr-PLUS) and D (conical implant with internal hexagon connection and progressive thread PROGRESSIVE 5-10). The geometrical features of these implants are shown in Fig. 1.

2.1. Generation of solid models

Solid models of ISOMED® Dental implants were obtained by means of reverse engineering techniques [11]: the outer shape was digitised by a laser scanner: CAM2 Edge SCANARM HD – FARO (accuracy ±25 μm). Point clouds were imported into Geomagic Studio® software, where 3D tessellated surfaces were created, and sharp edges and cross section curves were obtained through feature detection algorithms [33]. Finally, the implant parametric 3D CAD model was created using SolidWorks® software ver. 2017 (SolidWorks Corporation, Concord, MA, USA).

The mandibular bone geometry was established using CT scan images (slice thickness 1 mm, standard energy and current levels: 120 kV and 200 mA). Image data sets were pro-