A new numerical approach for evaluation of dental implant stability using electromagnetic impulse

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Purpose: The aim of this study is to develop and evaluate computationally in detail a new non-contact method to access noninvasively the dental implant stability under various osseointegration stages and surrounding bone qualities.
Materials and Methods: The finite element analysis is performed with two steps: electromagnetic field analysis to obtain the electromagnetic forces and resonance frequency analysis subjected to the electromagnetic force. Osseointegration process is simulated by changing the Young's modulus and Poisson's ratio of the implant-bone interfacial tissue. Four types of surrounding bone quality are modelled by changing the geometry configuration and bone density.
Results: It is found that a significant increase in resonance frequency is related to the increase in Young's modulus ($p<0.0001$). Varying the Poisson's ratio has no statistically significant influence on the resonance frequencies ($p>0.99$). The bone quality has a significant effect on the resonance frequencies, with lower value in softer bone ($p<0.0001$).
Conclusion: The results suggest that the use of resonance frequency analysis by an electromagnetic pulse is sensitive and hence effective to determine the implant stability during osseointegration process and under various surrounding bone conditions. **(Int Chin J Dent 2008; 8: 1-9.)**
Key Words: bone, electromagnetic impulse, finite element analysis, osseointegration, resonance frequency.

Introduction

Osseointegration of a dental implant is a dynamic process strongly correlating to factors of biology, biomechanics as well as clinical technique. Both establishment and maintenance of osseointegration require implant stability.[1-5] The clinical measurement of implant stability and osseointegration is important to be able to assess the implant survival and clinical success. The implant stability is determined by the implant boundary condition.[6-8] Osseointegration is characterized by clinical stability of a functionally loaded implant.[9] When loading is to begin on a given implant, e.g., immediately loading, or loading after first/second-stage surgery, it would be advantageous if the structure and properties, or biomechanical behaviors of implant-bone interface could be measured noninvasively and nondestructively using some biomechanical means. A number of researchers have used an impulse oscillation method in an attempt to assess the biomechanical state of the implant-bone interface.[10-12] Huang et al.[6] proposed a new modal testing method in vitro experiment by applying a transient force on the tested samples by an impulse hammer. The vibration signal was obtained through a non-contact acoustic microphone. Subsequent spectrum analysis enabled the extraction of the resonance frequency values.

Meanwhile, the use of electronic percussive testing (e.g., Periotest, Siemens AG, Bensheim, Germany) and resonance frequency analysis (RFA, e.g., Osstell, Integration Diagnostics AB, Sweden) provides a possibility to clinically determine implant stability and the ongoing osseointegration process.[2,13-16] Many studies have shown the merit of Periotest device on measurement of implant stability. However, its ability to detect osseointegration status is still a matter of debate.[17,18] A number of in vivo/vitro experiments and numerical simulations have indicted that the RFA technique could provide relatively more sensitive and precise information compared with the Periotest device.[2,7,19,20] Recently, a new non-contact RFA device (Osstell mentor) has been developed to detect implant stability. This methodology uses a magnetic pulse from a wireless probe to excite the transducer (a metal rod with a permanent magnet on top) that is screwed to an implant or abutment. The hand-held resonance frequency analyzer is not directly contacted with the transducer.

It has been reported that this magnetic technique can detect changes in stability during early healing process,[21] but effect of several factors (e.g., the changes of the implant-bone interface and bone type) on the resonance frequency measured by means of this technique is not yet fully know. Therefore, the aim of this study is to develop and evaluate a new non-contact model to determine the resonance frequencies of the dental implant-bone structure under various osseointegration stages and quality types of surrounding cancellous and cortical bone by applying an electromagnetic (EM) impulse. A sequential coupled method is used for this simulation by a two-dimensional (2-D) finite element analysis (FEA). The interaction between the EM field and implant-bone structural field is accomplished via the EM force.

Materials and Methods

Sequential coupled physics analysis

The ANSYS 6.1 FEA software (ANSYS Inc., Canonsburg, PA, USA) is used to perform sequentially coupled physics analyses in our system, in which the input of one physics analysis depends on the results from the analysis of another physics. In this study, the EM field analysis and structural analysis are coupled in a sequential manner via the EM force. An EM field analysis is performed first to obtain the EM force field. The EM force is then applied on the dental implant-bone system to perform an analysis of structural dynamics. Since the electric excitation is harmonic, the resultant EM force will be harmonic. Therefore, harmonic response of the dental implant-bone system is computed in the form of frequency response. Fig. 1 illustrates the procedure used in this study.

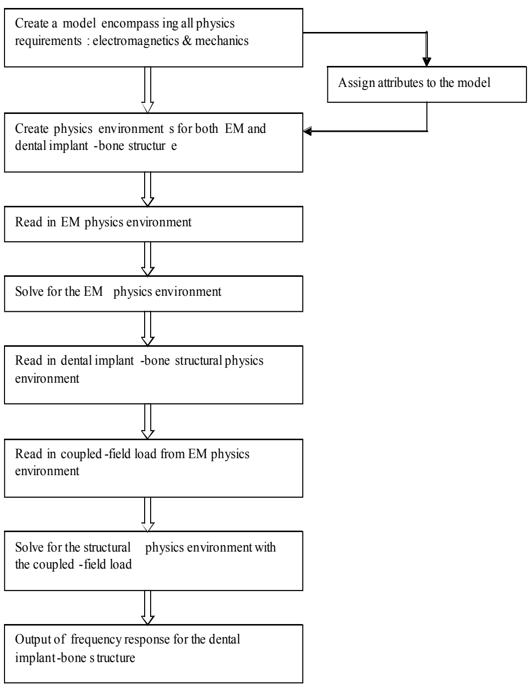


Fig. 1. Procedure for a sequentially coupled physics analysis.

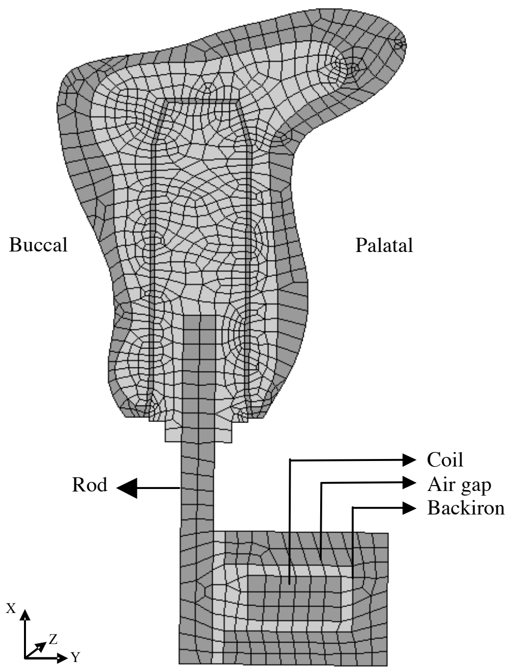


Fig. 2. Overall 2-D FEA model of a dental implant-bone structure with an EM pulse generator.

FEA modelling of implant-bone structure

A 2-D FEA model is created using ANSYS 6.1 (Fig. 2). This model presents a non-threaded titanium implant encased in a portion of the maxillary bone at the first left premolar region. The implant is modelled with 15 mm in length and 4 mm in diameter. The configuration of this maxillary cancellous and cortical bone is modelled using the computed tomography (CT) data of a patient of 68 years old. A layer of cortical bone (with a thickness of 0.3-2.5 mm) surrounds a core of dense cancellous bone. The material properties of the implant, maxillary cancellous bone and cortical bone are listed in Table 1.[22-24]

Table1. Material properties of bone, implant, and rod.

Material	Young's modulus (GPa)	Poisson's ratio	Density (g/cm^3)
Cancellous bone	0.48	0.3	0.55
Cortical bone	14.4	0.3	1.77
Implant	117	0.3	4.5
Rod	193	0.3	7.8

In the FEA model (Fig. 2), a 15 mm in length stainless steel rod is attached into the implant. This rod is excited by an EM force generated by a modified solenoid actuator with an alternating voltage-fed coil. A thin layer of air gap is modelled between the coil, the rod and the pole faces of the back iron. The details of the actuator geometry and material properties are listed in Table 2. The material properties of the rod are presented in Table 1. Both element types of the magnet and implant-bone structure and material properties of each component are stored in this FEA model.

As presently defined, the mechanism of osseointegration is a very high rate of living bone modelling and remodelling within about 1 mm of the implant surface.[25,26] Within this FEA model, a layer of 0.2-mm-thick implant-bone interfacial tissue is created to simulate its biologic change during osseointegration process. The implant is assumed to be inserted into the center of the alveolar ridge. The quadrilateral solid elements are used to mesh the implant-bone model. The interfaces between the cortical and cancellous bone, cancellous bone and interfacial tissue, implant and interfacial tissue are assumed to be perfectly connected.

Table 2. Parameters of the actuator geometry and material properties.

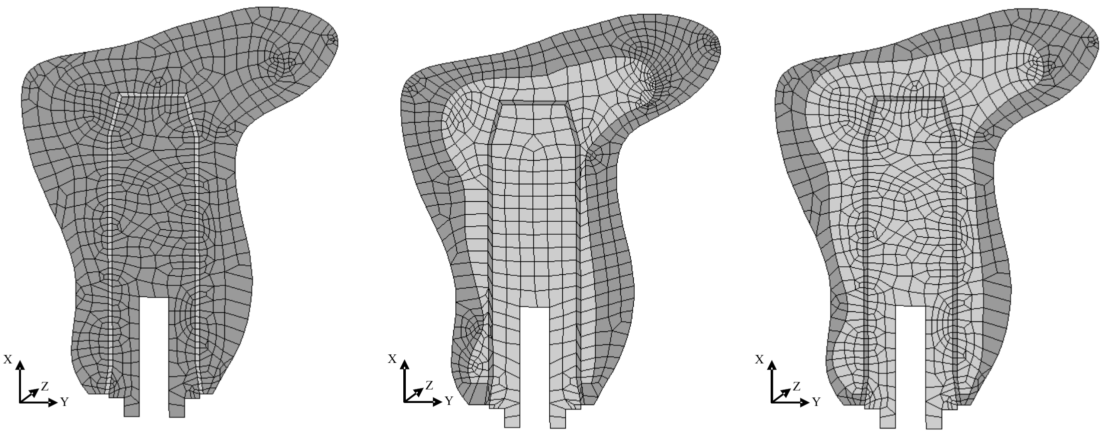
Coil			
Turns	Across area	Permeability	Resistivity
650	8×10^{-6} m^2	1*	3×10^{-8}*
Rod			
Length	Width	Permeability	Resistivity
1.5×10^{-2} m	1.4×10^{-3} m	2,000*	7×10^{-7}*
Back iron			
Thickness	Permeability		
1.5×10^{-3} m	1,000*		
Air			
Gap	Permeability		
5×10^{-4} m	1*		

*from ANSYS release 6.1 documentation. ANSYS Inc., Canonsburg, PA, USA.

The literature data for the mechanical properties of the dental implant-bone interfacial tissues are very scare.[27-29] In this study, the same value for Young's modulus of the interfacial tissue (E_{it}) is set both for the implant-cortical bone interface and the implant-cancellous interface at each healing stage. The E_{it} is given different values in a series of calculations, ranging from 10% of Young's modulus of cancellous bone (E_{ca}=480 MPa) up to 100% of E_{ca}, in steps of 10 % of E_{ca}, in order to simulate the healing process. The very low values of

E_{it} correspond to the very early stages of healing where provisional connective tissue (e.g., newly formed vessels, fibroblasts, mesenchymal cells, osteoid) bridges the interface, while the higher values of E_{it} correspond to later stages where formation of bony callus and mature bone (e.g., newly formed lamellar, woven bone) occurs. It is assumed that the value of E_{it} is equal to E_{ca} at the final stage of osseointegration. Although the real density of the interface tissue may be changing during the osseointegration process due to collagen reorganization and mineralization, the density of the interface tissue is held constant at 0.1 g/cm^3 since our main interest is on the influence of E_{it} on the vibrating behaviors of the implant-bone structure. For each of these FEA models, the Poisson's ratio of the interface tissue is varied: 0.1, 0.2, 0.3, and 0.4, to analyze its influence on the resonance frequencies.

According to the Lekholm and Zarb classification,[30] four types of surrounding bone quality (Q_1, Q_2, Q_3, and Q_4) are simulated to evaluate their effects on the resonance frequencies. The created bone model, as shown in Fig. 2, can be classified as Q_3 in which a thin layer of cortical bone (with a thickness of 0.3-2.5 mm) surrounds a core of dense cancellous bone (with a density of 0.55 g/cm^3). The Q_1, Q_2 and Q_4 bone are then created based on Q_3 model. In Q_1 model, the mechanical properties of the entire bone block are set as cortical bone (Fig. 3a). In Q_2 model, the material properties is equal to Q_3, but with a thick layer of cortical bone (0.8-3.0 mm, Fig. 3b). The Q_4 model has the same geometric configuration as Q_3 (Figs. 2 and 3c), but the density of cancellous bone is decreased to 0.275 g/cm^3. The correlation between the Young's modulus and density of bone can be expressed as follows: $E=C\rho^3$ (1), where E is the Young's modulus of bone, C is a constant, and ρ is the bone density. This formula is used to determine the Young's modulus of cancellous bone (E'_{ca}) in Q_4 model. According to the material properties of cancellous bone listed in Table 2, the constant C can be calculated as 2,885. E'_{ca} is then calculated as 60 MPa. In each of the four types of models, the E_{it} is altered form 48 to 480 MPa in increments of 48 MPa. The Poisson's ratio and density values for the interface are defined as 0.3 and 0.1 g/cm^3, respectively.



(a) (b) (c)

Fig. 3. 2-D FEA models of (a) Q_1 model: almost entire jaw is comprised of cortical bone; (b) Q_2 model: a thick layer of cortical bone surrounds a core of dense cancellous bone; (c) Q_4 model: a thin layer of cortical bone surrounds a core of low-density cancellous bone.

EM and structural physics environments

The EM physics environment is created by assigning the 2-D magnetic element and material properties to the actuator components. The implant and its surrounding tissues are specified as a null element type. A 2-D harmonic magnetic analysis is performed to calculate the EM force excited by a 12 V alternating voltage fed into the coil. The frequency of the alternating voltage is 20 kHz. The magnetic flux produced by the coil current is assumed to be so small that no saturation of the iron occurred. The flux leakage out of the iron at the perimeter of the model is assumed to be negligible. The structural solution is also a harmonic analysis. Before creating the structural physics environment, the boundary conditions and loads of the EM physics environment are completely removed. The 2-D solid structural element type and materials are reset to the rod, implant and its surrounding bones. The null element type is specified in the air, coil and iron regions. This model is restrained from motion in any direction at all nodes on the buccal and palatal sides of the cortical bone.

EM and structural solution

The EM analysis is performed by reading the created EM physics environment file. The resulting magnetic force will be used as input in the structural analysis. Then it reads the structural physics environment file and reads the magnetic force from the previous EM analysis for the solution of the harmonic response analysis of implant-bone structure. Finally, the resonance frequencies of the implant-bone structure can be obtained by identifying the frequency at which the peak response quantity of displacements is obtained. In this work we focus on only the fundamental resonance frequency.

Results

EM analysis

Fig. 4 shows the flux lines distribution in the components of the actuator. It can be observed that no flux leakage occurred out of the back-iron. As shown in Fig. 5, the maximum magnetic flux density can be found in the interface between the air and rod. The summarized magnetic forces on the rod by Maxwell stress tensor approach were 7.96E-5 N/m for Force-X, and 1.67E-2 for Force-Y. The forces along the Y-axis and X-axis present an attractive force and a drive force, respectively.

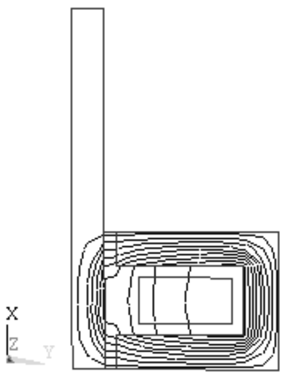


Fig. 4.

Contour of 2-D flux distribution in the EM field.

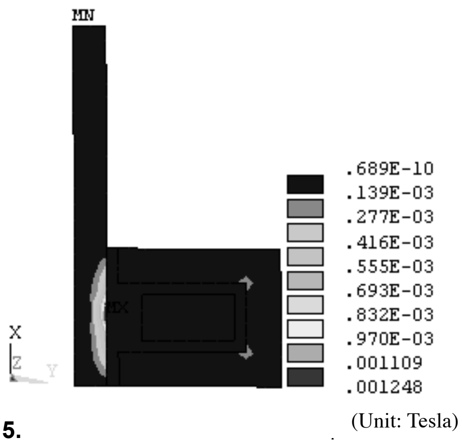


Fig. 5.

Magnitude of the flux density distribution in the EM field.

Structural analysis

Before applying the harmonic force generated from the EM filed, modal analysis is carried out to determine the first natural frequency of each FEA model. These frequencies are used as a reference data to verify the efficiency and accuracy of EM-structural sequential simulations. The computed resonance frequencies are very close to the nature frequencies of the dental implant-bone structure ($p>0.99$). The Young's modulus, Poisson's ratio of the implant-bone interfacial tissue and the surrounding bone quality affect the resonance frequencies. It is found that the Young's modulus of the interfacial tissue affects resonance frequency most significantly. The resonance frequency increases with the increase in the Young's modulus ($p<0.0001$; Fig. 6). An increase in Poisson's ratio results in small increase in resonance frequency, however, this influence is not statically significant ($p>0.99$; Fig. 6). The bone quality has a significant effect on resonance frequency, with lower resonance frequency in the implant's surrounding softer bone ($p<0.0001$; Fig. 7).

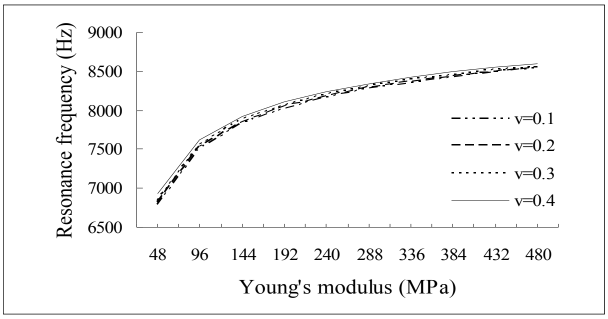


Fig. 6.
Influence of Young's modulus and Poisson's ratio (v) of the implant-bone interfacial tissue on the resonance frequency.

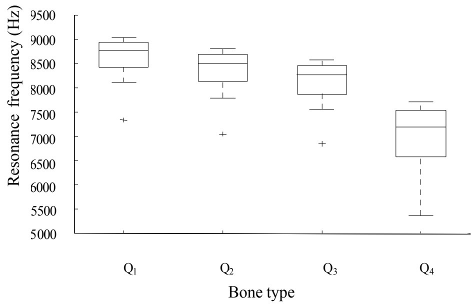


Fig. 7.
Influence of type of bone quality according to the Lekholm-Zarb index on the resonance frequency.

Discussion

It is well known that the resonance frequency can be used as an important parameter to determine the boundary conditions of a mechanical structure.[6,19,33] In implant dentistry, the RFA technique has been adopted as an effective means to evaluate the relationship between implant stability and implant surrounding conditions such as osseointegration degree. This study applies a sequential coupled physics analysis to compute the resonance frequencies of the dental implant-bone structure subjected to an excitation of an alternating voltage-fed actuator.

In the EM analysis, the coil is fed with an alternating voltage and produced a local alternating magnetic field (Figs. 4 and 5). There is no flux leakage occurring out of the back-iron. The maximum flux density can be seen in the interface between the air and rod. The magnetic forces acting on the rod obtained using Maxwell stress approach are very low and the resulted amplitude of the vibration is very small, hence stresses generated to the implant-bone interfacial tissue are also so small, so as to avoid any damage to the dental implant-bone system. The induced heating effect on the implant-bone interface tissue can also be negligible due to this pulse with intermediate frequency applied in a very short time and very low energy level.[34]

In the implant-bone structural analysis, the results confirm the fact that the resonance frequency is significantly influenced by the implant surrounding conditions[2,7,19,35,36] and suggest that this sequential coupled method is effective to obtain the resonance frequency that reflect the property of the implant surrounding tissues and hence the osseointegration status. Previous studies have indicated that the clinical success of an implant depends largely on the biomechanical state of the implant-bone interface.[25,27,30]

Recently, RFA combined with other destructive or nondestructive techniques, such as removal torque measurement, histological evaluation, radiography and CT have been applied to determine the dental implant biomechanical behaviors in vivo or in vitro tests. A number of observations have shown that the resonance frequency corresponds well to the measurements obtained by the techniques mentioned above because the bony modelling and remodelling on the implant-bone interfacial layer during healing process resulted in an increase in stability.[37-41] From a biomechanical point of view, the effects of material properties of this layer can be assessed by considering an increase in its stiffness during the process of osseointegration.[25,28,29,42]

In the present study, increasing resonance frequencies can be seen with increasing Young's modulus (Fig. 6), which suggests that the increase in implant stability observed are attributed to an increase in the interface stiffness of implant-bone structure duo to new bone formation there.[43] It is also interesting to observe in Fig. 6 that resonance frequencies increase a little with the increase in Poisson's ratio. These findings can also be interpreted based on the theory of vibration:[2,7,33,44] $f=(2\pi)^{-1}(k/m)^{0.5}$ (2), where k stands for the stiffness of the support of the surrounding tissue to the implant, m is the mass of the implant, and f is the fundamental resonance frequency. In the step of simulation of osseointegration process, the configuration of implant and the surrounding tissues and their density are the same. Therefore, the resonance frequency of the structure would only be associated with its mechanical properties. According to the relations between the elasticity constants of an isotropic material[45,46] and Equation (2), an increase in Young's modulus or Poisson's ratio would result in increase in the resonance frequency values, which is also in line with the previous findings and with the vibration theory. However, the Poisson's ratio has no significant effect on the resonance frequency ($p>0.99$) because the increment of Poisson's ratio is limited.

According to the degree of bone density and drilling resistance experienced by the surgeon, the bone quality is ranked from type 1 to 4.[30] It is evident that decrease in bone quality results in decrease in implant stability ($p<0.0001$; Fig. 7), which can be explained by the Equation (2). With Q_4 bone, for example, the overall stiffness of the bone is less because of the thin cortical layer and large cancellous bone core of low density. The data obtained also agree with the findings of previous studies.[38,47-49] They found a correlation between the bone quality, as assessed by using the installation/cutting torque measurement, CT evaluation, and RFA. In this study, the highest resonance frequency is found in Q_1 model. In contrast, the implant inserted in Q_4 bone has the lowest value, which suggests that lower interface restriction would result in lower initial stability of a dental implant at the time of placement. The results can be explained in part by the fact that implant replacement in Q_4 bone type has a higher failure rate than the other three types[50-52] and the fact that lower implant stability level are obtained for implant in the maxilla than in the mandible.[53,54]

In order to completely understand the healing process adjacent to the implant, a more realistic situation of the implant-bone-EM pulse system is needed in the future research. A detailed three-dimensional (3-D) nonlinear dental implant-bone model is needed for further determination of the implant stability in an EM field. A 3-D EM physics field, which is more difficult to generate than a 2-D modelling and requires much more computer resource, is demanded. The influence of the flux leakage out of the iron at the perimeter of the model and the saturation of the iron should be evaluated. The EM actuator model should be created with a layer of air surrounding the iron equal to or greater than the maximum radius of the iron or put in an open (infinite) domain. The changes of distance and angle between the actuator and the rod have to be modelled to study their effect on response of the implant-bone structure.

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