Non-contact Vibro-acoustic Detection Technique for Dental Osseointegration Examination

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Abstract

This study develops a non-contact vibro-acoustic detection technique for measuring the defect quantity and determining the imperfection orientation surrounding a bone-implant interface. Acoustic excitation through a miniature loud speaker and vibration response measurement using a capacity-type displacement sensor are applied to accomplish this task to prevent the mass loading effect on the structure to be examined. The proposed non-contact excitation-response measurements are verified using a series of designated in vitro defect models, and the measured resonance frequencies (RFs) are used to discriminate interfacial structure variations. A finite element modal analysis is conducted to validate the measured RFs. Additionally, a prototype device is developed and applied to assess the osseointegration between dental implants and tibia in an in vivo animal model. A comparison of in vitro experimental results with numerical simulations shows that the RFs in the defective orientation are significantly smaller than those in the complete direction (p < 0.05), and that the values decrease with increasing defect quantity (p < 0.05). Moreover, the defect depth affects RF variation. In the in vivo experiments, the RF levels in the lateral direction of the tibia are much higher than those in the axial direction (p < 0.05) of the tibia. The RF values in the axial direction for two implants have no significant difference (p = 0.552), but the RFs in the lateral direction for implant 2 are higher than those for implant 1 (p < 0.05). The RF changes can be compared to assess osseointegration development. The proposed technique is promising for assisting dentists in the assessment of implant stability after surgery.

Keywords: Dental implant, Osseointegration, Bone defect detection, Non-contact vibro-acoustic measurement

1. Introduction

The evaluation of interfacial osseointegration development for dental implants embedded in alveolar bone is of interest to clinical dentists and researchers. Complete osseointegration around the dental implant provides immobility and rigid fixation, which are prerequisites for favorable long-term clinical outcomes [1,2]. Osseointegration development is highly related to implant stability, and thus its assessment is very important after dental implantation. Primary implant stability has been identified as a prerequisite for osseointegration, and secondary implant stability is increased by bone formation and remodeling at the implant-bone interface [2]. Incomplete osseointegration results in a reduction in implant stability and dental surgery failure. Bone loss and defects surrounding dental implants usually develop along with foregoing conditions of the implant-bone interface. Many techniques and devices have been proposed to assess interfacial osseointegration and quantify bone defects. Invasive methods such as histomorphometry observation and removal torque analysis have been applied to detect implant stability [3,4]. However, these measurements frequently damage the tissues of interfacial osseointegration, and are unsuitable for long-term clinical assessment. Hence, non-invasive methods are widely used to evaluate implant stability and monitor osseointegration variation.

Radiographic observation is a convenient method for the clinical assessment of interfacial osseointegration; however, this method is unsuitable for long-term follow-up, early prevention, and diagnosis because the X-ray radiation may impose health hazards. Incomplete osseointegration cannot be

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detected when bone loss is less than 30%, and quantification is difficult [5]. Radiographic examination for implant-bone interface evaluation often has human error. Other detection methods are thus required to verify diagnostic results when radiography indicates normal osseointegration. The unsuccessful osseointegration becomes obvious while the dental implant presents the high mobility. To measure implant instability, mobility tests and devices for quantitative detection, such as the Periotest (Siemens AG, Germany), have been developed. Periotest is designed to assess tooth mobility and monitor implant stability via the damping characteristics of the periodontal ligament [6,7]. Unfortunately, because the Periotest value is strongly related to the excitation direction and location, readings from this device correspond imprecisely to the biomechanical parameters. Many studies have indicated that Periotest is not an ideal tool for investigating the interfacial conditions because it is incapable of providing sensitive responses to minor changes in the implant-bone interface [8,9]. Therefore, the clinical application of Periotest for implant assessment is limited.

Resonance frequency (RF) analysis has been applied to measure the condition of interfacial osseointegration. The RF, an important dynamic parameter of a structure, is related to the stiffness, damping, boundary conditions, and density of the vibrating object. RF measurement is non-destructive and non-invasive. Thus, it is widely applied for the biomechanical research of orthopedic and dental implants. Meredith et al. excited a dental implant with a sinusoidal force and measured the corresponding responses with an L-shape transducer mounted on the implant in in vitro and in vivo experiments. Their results demonstrated that RF analysis is a feasible tool for analyzing the degree of interfacial osseointegration [8,10,11].

A designated instrument (Ostell and Oststell Mentor, Integration Diagnostics AB, Sweden) was developed to measure and evaluate clinical implant stability using the implant stability quotient (ISQ) value [12,13]. Huang et al. applied a hammer-microphone set to examine the vibration behavior of a dental implant in in vitro/in vivo models. Their results showed that the RF values of the implants are linearly related to the boundary heights and contact characteristics [14,15]. Huang et al. then developed an RF analysis device for dental implant stability detection and conducted experiments to validate its reliability and feasibility [16]. Ito et al. employed screws to design an in vitro partial defect model. Their results demonstrated that the RF values greatly decreased when the screw was loosened near the implant neck [12]. These studies assessed interfacial osseointegration, but did not indicate the orientation and location of bone defects around the dental implant.

Although the RF detection technique has been proven effective for the evaluation of implant stability, many factors, including bone density and bone adaptation, which affect the RF of an implant, have not been explored and their effects remain unclear. Finite element analysis (FEA) is generally applied to investigate the effects of surrounding bone quality on the implant-bone interface. It has been applied to study the osseointegration between a dental implant and the alveolar bone. Huang et al. established a three-dimensional (3D) finite element (FE) cylinder dental implant model with marginal bone for analysis, and then computed and discussed the RFs of the model for various bone heights and qualities [14]. Pattijn et al. used the FEA to investigate the modal behavior of a bone-implant-transducer system (Ostell). Their findings showed that the Ostell transducer is suitable for follow-up evaluations of implant stability, but not for quantitative comparison [17]. Pérez et al. predicted the evolution of the RF of the bone-implant interface in a dental implant using FE simulation, and compared the results with experimental results for rabbits. They found a quantitative agreement with the experimental measurements and suggested that the model could be useful for evaluating the influence of mechanical factors [2].

The above-mentioned studies assessed interfacial osseointegration after dental implantation, but they only evaluated the overall structure between the implant and the alveolar bone, without considering defect locations and orientations. The sensitivity and repeatability of commercially available detection devices need to be improved. The evaluation of both the severity and location of bone defects is desirable. To overcome existing limitations, this study develops a detection technique that can determine defect orientation and quantify the severity of osseointegration surrounding dental implants. Non-contact excitation and sensing procedures are developed to actuate a series of in vitro bone defect models with various vise fixation heights. The corresponding vibration responses, i.e., RFs, are measured. The FEA is used to compute the first bending mode for various in vitro models and vise fixation heights are used to verify experimental results. Moreover, in vivo measurements are performed to evaluate osseointegration on rabbit tibia. The developed technique can assist clinical observation as well as the monitoring of interfacial osseointegration after dental implantation. Using the detected orientations and locations of bone defects, dentists can estimate osseointegration development and provide further treatment to enhance it.

2. Materials and methods

2.1 Experimental in vitro models

To determine bone defect orientation and location around a dental implant, a series of in vitro defect models were designed and established. Every model was composed of three parts: a healing abutment (length: 5.5 mm, diameter: 4.5-7 mm, taper shape), a dental implant (length: 11 mm, diameter: 4.5 mm; MicroThread™, Astra Tech AB, Mölndal, Sweden), and a polyurethane-foam artificial jawbone (10 × 10 × 20 mm²; 1522-04, Pacific Research Laboratory, Vashon Island, WA, USA) that was used to simulate the human cancellous bone of the mandible. To define the severity of a bone defect, as shown in Fig. 1(a), the artificial bone block was divided into four portions (A, B, C, and D) and two layers (1: upper and 2: lower), where the AC (X-) and BD (Y-) directions were defined as defective and complete orientations, which indicate bone defects and complete osseointegration, respectively. The bone
defect had one of two depths (4 or 8 mm) and a width of 1 mm. Various defects were made by six bone blocks at the same time. Figure 1(b) shows in vitro models with embedded dental implants, and their defect-types were classified, namely one with complete osseointegration, two with one-column defects (A4 and A8), two with opposite-column defects (AC4 and AC8), and one with a severe (surrounding) bone defect.

![Figure 1. Diagram of bone defect models.](image)

2.2 Non-contact excitation and response measurements

In the experimental in vitro model, the fixed and free sides of the model represented the mesial-distal (MD) and buccal-lingual (BL) directions of the jaw, respectively. During the RF measurement, the healing abutment was connected to the model, and the fixed side of the model was clamped by a metal vise to mimic the boundary conditions in the human molar region. Figure 2 illustrates the test bench with a complete osseointegration model fixed 9 mm high in the vise. The exposed outside of the healing abutment was excited by a loud-speaker (VSP-03T, diameter: 40 mm, frequency response: 2000-20000 Hz, power: 40 W, AUTOBACS SEVEN, Japan), and the vibration response was measured by a non-contact capacity-type displacement sensor (C3-D, LION PRECISION, St. Paul, USA). An acoustic tapping force was applied and the vibration response signals were acquired using a 16-differential-channel I/O digital signal processor card (SIMD86XX, SHELDON INSTRUMENTS, San Diego, USA). The spectra of the structural response and their associated RF values were processed and obtained using MATLAB® (The MathWorks, Natick, USA). For two directions (AC and BD) and four fixation heights (9, 10, 11, and 12 mm) of each model, 30 measurements were performed, with their means and standard deviations calculated for comparison. The one-way analysis of variance (ANOVA) was applied to test the relevance between each bone defect model and its corresponding RF value.

![Figure 2. Experimental setup for excitation and detection on testing models.](image)

2.3 Numerical analysis of in vitro models

To verify the experimental results, FEA was performed on a series of in vitro bone defect models. Figure 3 shows a full-scale FE mesh model that contains three parts and six FE defect block models. The dental implant was simplified to be a cylinder without a screw since stress analysis was not performed. Because the healing abutment was screwed to the dental implant, the interface between the abutment and implant was assumed to be the bond connection. Frictional contact between the dental implant and the artificial bone block was assumed to simulate the initial implant-bone situation after implantation; the friction coefficient was set to 0.68 [18]. The displacements of the two sides of the FE model were constrained, which represented two vise-fixed sides of the in vitro model. The FE models contained 18953 to 20662 nodes and 18156 to 19596 hexahedral solid elements. Of note, for the in vitro models, artificial bone blocks instead of alveolar bone were applied in the experiments. The computation model was assumed to be homogeneous, isotropic, and linear elastic. Table 1 lists the material properties used in the numerical computation, where the titanium alloy was used for the dental implant and the healing abutment, and the solid rigid polyurethane was used for the artificial bone block [19]. To investigate the interfacial dynamic characteristics, the first resonance frequency and the associated bending mode shape were computed using the FEA package ANSYS® (ANSYS Inc., USA) for pre-processing, modal analysis, and post-processing. The numerical results were compared with those from experiments. The relationship between RF variation, defect orientation/location, and vise fixation height was determined.
Table 1. Material properties of the FE computation models.

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healing abutment</td>
<td>Titanium alloy</td>
<td>114</td>
<td>0.34</td>
<td>4.43</td>
</tr>
<tr>
<td>Dental implant</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artificial bone block</td>
<td>Polyurethane</td>
<td>0.59</td>
<td>0.3</td>
<td>0.48</td>
</tr>
</tbody>
</table>

2.4 In vivo animal model for non-contact measurements

To assess the feasibility of the proposed non-contact vibro-acoustic measurement technique, the prototype device shown in Figs. 4(b) and (c) was constructed for preliminary in vivo animal model testing. The experimental protocol and the design of the experimental work were approved by the Medical Research Institute and the Animal Center of the Cathay General Hospital. One 3-kg healthy female New Zealand rabbit was used as a test subject. To anaesthetize the rabbit, before the implant was embedded, Zoletil 50 (Virbac, Carros, France) at a dose of 15 mg/kg was used for muscle injection, and then a local infiltration injection of Scandontest 2% Special (Septodont, Créteil, France) at a dose of 1.8 ml was given. During surgery, iodine was used to decontaminate the skin of the left leg above the tibia before it was shaved. The proximal tibia near the medial epicondyle of the femur was exposed after the skin incision and periostium stripping. Two customized titanium dental implants (diameter: 3.75 mm, length: 10 mm; INTAI Corp., Taichung, Taiwan) with two healing abutments (diameter: 7 mm, length: 15 mm; INTAI Corp., Taichung, Taiwan) were then placed in the tibia according to the standard procedure provided by the manufacturer. The implants were screwed into the tibia until the collar margin reached the boundary of the cortical bone. Physiological saline solution was applied to cool the drill and clean the tibia during the surgery.

The implantation and measurement setup on the left rabbit tibia are shown in Fig. 4, where ‘1’ and ‘2’ indicate uncoated and coated implants, respectively. According to radiographic observation, the interfacial osseointegration of the tibia completely developed after 16 weeks. The rabbit was anaesthetized using the above anesthetic injection before the RF measurement. The first RF values in the axial and lateral axis of the tibia were measured using the prototype detection device, which comprised a fixed stand, an acrylic holder, a miniature loud-speaker (AK-1008RA-8W, diameter: 10 mm, frequency response: 1050 ± 20%–20000 Hz, power: 0.3 W, Advanced Acoustic Technology Corp., Taiwan), and a displacement sensor. To confirm the plateau of the interfacial osseointegration after long-term healing, a second RF measurement was performed 25 weeks later [11]. The RF values of the two tests in the axial and lateral directions were recorded in 15 trials, with their means and standard deviations calculated for comparison. The ANOVA was applied to test the variation of RF values corresponding to the two implants in two directions.

3. Results

Figure 5 summarizes the RF histograms of six defect situations and four vise fixation heights in the defective and complete directions. The RF values in the defective and complete directions are labeled at the top of the histogram. The results show significant differences (p < 0.05) of the RF values for bone defects and sound osseointegration for all defect models and vise fixation heights. Of note, the RFs in the defective direction are consistently smaller than those in the complete direction if defects exist. The RF values in the defective direction for all vise fixation heights (9 mm: 2357 ± 89 to 1249 ± 72 Hz; 10 mm: 2532 ± 105 to 1349 ± 83 Hz; 11 mm: 2825 ± 110 to 1366 ± 82 Hz; 12 mm: 3067 ± 95 to 1388 ± 77 Hz) decrease significantly (p < 0.05) with increasing defect quantity (DQ). Significant increases were found between the smallest depth (sound) and the largest depth (severe) and among cases with four different depths (A4, A8, AC4, and AC8).
The computed first-bending mode shapes and their associated RFs of the 'sound' and 'severe' models with a 9-mm fixation height in the defective direction are shown in Fig. 6, where an arrow indicates the interfacial defect in the FE model. The RF values obtained with various vise fixation heights using FEA were also evaluated. Table 2 lists RF values of six defect situations and four vise fixation heights in the two directions obtained using FEA. According to the simulations, the RFs in the defective direction are always smaller than those in the complete direction for all defect models and vise fixation heights. The RFs in the defective direction for all vise fixation heights (9 mm: 2371 to 1390 Hz; 10 mm: 2615 to 1420 Hz; 11 mm: 2908 to 1435 Hz; 12 mm: 3247 to 1439 Hz) greatly decrease with increasing DQ. Significant increases were also found between the smallest depth (sound) and the largest depth (severe) and among cases with four different depths (A4, A8, AC4, and AC8). A comparison between the FE computation and RF measurement results shows that the trend of the computed RF values is the same as that of the measured values, and that the computed values are generally slightly higher than the measured values. As to a comparison for various bone situations, the changing of RFs from high to low is sequentially sound, A4, AC4, A8, and AC8. The RFs between the two defects of A4 and AC4, AC4 and A8, A8 and AC8 differ from each other to an extent.

To further characterize the above observation, six bone models, namely those with complete osseointegration, and A4, A8, AC4, AC8, and severe defects, were set to have DQs of 0, 1, 2, 4, and 8, respectively. The defects A8 and AC4 have the same DQ ( = 2). The RF decrement percentage (RFDP) was calculated as:

$$RFDP = \frac{\Delta RF}{RF_{base}} \times 100\%$$

where $RF_{base}$ is the base RF and $\Delta RF$ is the decrease of RF due to further bone defect. The RFDP values were compared to
reveal defect variation. For instance, the RF values of A4→A8 can be expressed as:

$$\text{RFDP}_{A4\rightarrow A8} = \frac{\text{RF}_{A4} - \text{RF}_{A8}}{\text{RF}_{A4}} \times 100\%$$

The RF values of the defect from A4 to AC4 and A8 were calculated using Fig. 5 and Eq. (1). The RF values from A4 to AC4 and A8 were (9 mm: 6.4, 10 mm: 2.2, 11 mm: 6.9, 12 mm: 6.4) are consistently higher than the RF values from A4 to AC4 and A8 (9 mm: 3.1, 10 mm: 1.2, 11 mm: 2.3, 12 mm: 3.5) for various vise fixation heights although the DQs are the same. This demonstrates that an increase in the defect depth (e.g., A4→A8) decreases RF levels. This is helpful for distinguishing similar DQ situations surrounding a dental implant.

For in vivo validation, Fig. 7 shows the box-whisker plot of non-contact measured RFs in the axial and lateral directions for the two implants on the left tibia of the rabbit. Significant differences ($p < 0.05$) of the RF values between the axial and lateral directions of the tibia were observed. It is noted that the RFs in the axial direction (1: 768 ± 11, 2: 770 ± 9 Hz) are smaller than those in the lateral direction (1: 833 ± 8, 2: 935 ± 14 Hz). The RF values in the lateral direction for the two implants have no significant difference ($p = 0.552$), but the RF levels in the lateral direction for implant 2 are higher than those for implant 1 ($p < 0.05$). The reasons are discussed later. The developed detection technique can be applied to estimate the bone defect situation (location, orientation, and severity) and to assess interfacial osseointegration after surgery.

### Table 2. Comparison of RF values obtained from FE simulation of various defect situations and vise fixation heights in the X (defect) and Y (sound) axes. The RF variations are similar to the experimental results (Fig. 5).

<table>
<thead>
<tr>
<th>Vise fixation height (mm)</th>
<th>X</th>
<th>Resonance frequency (Hz)</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound</td>
<td>A4</td>
<td>A8</td>
<td>AC4</td>
</tr>
<tr>
<td>9</td>
<td>2371</td>
<td>2330</td>
<td>2267</td>
</tr>
<tr>
<td>10</td>
<td>2615</td>
<td>2567</td>
<td>2493</td>
</tr>
<tr>
<td>11</td>
<td>2908</td>
<td>2842</td>
<td>2731</td>
</tr>
<tr>
<td>12</td>
<td>3247</td>
<td>3153</td>
<td>3014</td>
</tr>
</tbody>
</table>

### 4. Discussion

#### 4.1 RF differences between measurements and numerical simulations

RF analysis and FEA computation have become commonly used in oral science. However, various experimental inaccuracies may lead to incorrect results. To verify the RF experiments, FE simulation has been extensively performed to compare first bending RFs [8,14]. Hammer excitation was carried out here to measure the RF of in vitro bone defect models. The present study developed a non-contact vibro-acoustic excitation-sensing technique for the measurement. The loading effects on the dental implant that cause measurement errors can be prevented. The developed technique characterizes bone imperfection in terms of defect amount, orientation, and depth. As shown in Fig. 5 and Table 2, the results of measurement and computation have the same trend of RFs, whose levels decrease with increasing severity of defects. The sound (all complete) and severe (all defective) models had no significant differences in RFs in the X and Y directions because they had the same interfacial situation. This indicates that the synthesized FE models are reliable for structural analysis.

Artificial bone blocks instead of alveolar bone were applied in the in vitro models for experimentation. The computation model was thus assumed to be homogeneous, isotropic, and linear elastic. From Fig. 5 and Table 2, the measured RF levels are lower than the computed values. There are two reasons for this. One is that no real osseointegration occurs when the dental implant has just been pushed and screwed into an artificial bone block. The second is that in the simulation, frictional contact pairs are set between the implant and artificial bone block. This assumption and simplification may yield overestimation of the RF values. To explore interfacial conditions, Mellal et al. used a numerical model to analyze the effect of implant loading on the surrounding bone. Bone-implant interfaces were classified as a fully bonded (osseointegrated implant) surface or a frictional (non-integrated) surface. They used contact elements to allow minor relative displacements in the pre-integration interface [20]. Wang et al. investigated the influence of the buccal (lingual) type of bi-cortical anchorage on the primary implant stability using 3D FE models, and further clarified the relationship between the primary stability and various bi-cortical engagements. They assumed a frictional contact to simulate the initial conditions of the implant-bone interface after implantation [21]. Thus, the in vitro model can be regarded as the immediate implantation situation, and the implant-bone interface is a non-integrated
(not bonded) surface. Frictional contact between the implant and the artificial bone block was thus assumed here. It is worth noting that in this study, the dynamic characteristics instead of the static stress/strain distribution were examined to distinguish defect severity. The implant thread was thus not modeled in the numerical analysis. The surface nodes in the MD side were fixed to mimic the circumstances of the artificial bone block clamped in the vise.

4.2 Interfacial bone defect detection

In order to determine probable bone defects during the period of dental osseointegration, the RF changes for the in vitro models were used to develop a bone defect detection method. As shown in Fig. 5, the RF levels of the defective direction are lower than those of the complete direction, i.e., $R_{FX} < R_{FY}$, for various vise clamping heights except the cases of complete integration and severe defects. The RF values decrease with increasing DQ. The significant differences in the RF values between the defective and complete directions is employed to decide the defect orientation. Moreover, when the dental implant has just been inserted into the alveolar bone, interfacial osseointegration has not developed yet, which may be considered as the situation of a severe defect. The initial RF (iRF) measurement should be performed in both the MD and BL directions as a reference for later osseointegration detection. The iRF values are recorded at the early stage. The final RF (RF) recording should be performed in the two directions at the end of full osseointegration development. iRFs are higher than iRFs, and RFs obtained with defects in the measured direction are smaller than those without defects. Hence, the defect orientation can be determined by comparing RF changes.

After the defect orientation has been determined, e.g., in the X direction, the defect location can be evaluated from the RF variations according to Fig. 5. The RF levels of sound osseointegration models vary from 2357 ± 89 to 3067 ± 95 Hz with clamping heights which mimic various bone situations. For severe bone defect models, the RF levels vary from 1249 ± 72 to 1388 ± 77 Hz. In the one-column defect model with A4 changing to A8, the decrease in the RF levels is consistent, i.e., $R_{FA8} < R_{FA4}$, for various clamping heights. For the opposite-column defect model, the trend of the RF level decrease is the same as that for the one-column defects, i.e., $R_{FOA8} < R_{FOA4}$. It is worth noting that although A8 and AC4 have the same DQ ($= 2$), the RF values are smaller than the RF values. RFDP for A4→A8 is larger than that for A4→AC4. Based on the above discussion, defect locations can be predicted according to RF change features. A preliminary assessment procedure for determining the orientation, location, and severity of bone-implant interfacial osseointegration is shown in Fig. 8.

When the proposed detection technique is eventually used in clinical applications, the assessment procedure can be as follows. As soon as the dental implant is embedded in the maxilla, iRF measurements are performed in the MD and buccal-palatal (BP) directions to obtain baseline values. Then, the oral evaluation measurement is performed once every two weeks, and a radiographic examination is conducted to assist the observation of the interfacial condition. These measured RF values can be used to sketch two evaluation curves in the MD and BP directions, respectively, until the osseointegration development completes. To assess the stability of dental implant osseointegration, Veltri et al. employed OsstellTM to measure in patient’s upper jaw. According to their results, the iSQ values in the BP direction were smaller than those in the MD direction, and the MD orientation had a higher stability [22]. Therefore, if the RF values in the MD direction during the osseointegration period are inversely smaller than those in the BP direction, the first estimation indicates that bone loss (or defect) may appear in the MD orientation; the result can be confirmed by radiographic observation. Alternatively, if the RF levels in the BP direction are smaller than those in the MD direction throughout the osseointegration period and never significantly increase, bone loss or a defect may exist in the BP orientation. The defect location can be determined from the BP-RF curve. The in vivo patient RF measurement during the interfacial osseointegration will be performed in a later study using the proposed detection technique.

![Figure 8. Preliminary bone-defect assessment flow chart for orientation and location (9-mm vise clamping height used as an example).](image-url)
Ito et al. fastened or released screws to imitate contact conditions around an implant [12]. An artificial bone block was applied to simulate the alveolar cancellous bone, which is appropriate because this bone material has similar mechanical properties and can thus fully present the implant-bone contact situation. The vise fixation heights mimic and correspond to the alveolar bone quality. For a given design of implants, differences in their RF values mainly arise from implant-bone osseointegration, the surrounding bone quality, and the effective vibrational length, i.e., the implant exposed height. As shown in Fig. 5, the RF values vary with the structural conditions of artificial bone blocks surrounding the dental implant and the boundary conditions, i.e., vise fixation height. Here, to increase vise fixation height represents a relatively stable bone quality on the in vitro model. The implant-bone block model in the defect direction is weaker and has a lower RF compared to that in the complete direction. Figure 5 shows that the model with a 12-mm fixation height is stronger (higher RF) than that with a 9-mm fixation height. This shows that the defect severity and bone resorption in various orientations that affect structural mobility can be used to predict the location of bone defects.

To measure the RF levels of an implant-bone structure, Kay et al. employed a hand-held electromagnetic shaker and a piezoelectric impedance head transducer to detect bone lysis at the external fixation pin-bone interface [23]. Because the pin axial natural frequency can only be determined by vertical excitation and detection, the method and device were not able to assess the lateral vibration of the implant. In addition, impact excitation has been widely used to obtain RF values of a structure in orthopedic and dental research. A transient force with a broad-bane spectrum is applied by giving an impact force with a hammer. This yields a structural response with specific frequencies corresponding to structural resonances. The impact technique uses an accelerometer (attached firmly to the structure) for acquiring the response [24]. This always introduces the mass loading effect, which lowers the RF values, especially when the structure is extremely tiny (e.g., a dental implant). Moreover, hammer excitation requires practice; double hitting may introduce resonant peaks. To eliminate the loading effect, Lowet et al. used a microphone as a transducer to measure the RF of the tibia [25]. Huang et al. applied a sensitive microphone to measure response signals, although the microphone also acquired surrounding acoustic noise, and designed an implant stability detector that comprised a miniature-sized electromagnetic triggering rod and an acoustic receiver [16]. In their study, an impact rod driven by electromagnetic force was used to exert excitation, eventually a contact force. The optimal spectral energy that enters the implant requires further investigation. These two methods are contact measurements. Hayashi et al. developed a non-contact electromagnetic vibration device for monitoring tooth mobility and periodontal tissue conditions of in vitro models. They used three mechanical parameters, namely resonant frequency, elastic modulus, and viscosity coefficient, to measure simulated atrophic bone defects in periodontal tissues. However, they directly attached an acceleration sensor to the cylindrical titanium rod as the detector [26]. This detection is not actually non-contact and the mass loading effect still exists. In the present study, a non-contact excitation and sensing technique was proposed and the associated devices were implemented. A tiny louder-speaker is used to excite defect models and a capacity-type displacement sensor is used to measure the structural response. This design avoids the mass-loading effect, and the spectral band of the acoustic-energy excitation is tunable.

4.3 Assessment of interfacial osseointegration

To correlate the RF variations with implant-bone interfacial osseointegration during the healing process, Meredith et al. used a small transducer oriented perpendicular and parallel to the long axis of a rabbit tibia to measure the RF values of implants. Their findings demonstrated that the RF values in the parallel direction are lower than those in the perpendicular direction after 14 and 28 days [11]. As shown in Fig. 7, the RF levels in the axial direction of the tibia for the two implants are lower than those in the lateral direction. The RF values in the lateral direction for implant 2 (coated) are higher than those for implant 1 (uncoated). The experimental results are consistent with a previous study, and demonstrate that the coating on the implant aids the development of interfacial osseointegration. For the two implants, the RF values in the axial direction are insignificantly different. Because the distance between the two implants is quite close, tibial destruction leads to a decrease in the axial stability of the implant, and thus independent RF variances. The proposed non-contact sensing technique is thus a feasible tool for evaluating interfacial osseointegration and confirming radiographic discrimination.

5. Conclusion

This study established a procedure for discriminating defect orientation and location around a dental implant using RF measurement and numerical analysis. Defect orientation is first determined by comparing the RF values between defective and complete directions. The defect location is then determined using RF variation. In the preliminary in vivo (animal model) experiment, the non-contact sensing technique was used to assess interfacial osseointegration. In this procedure, the severity and orientation of osseointegration instability can be differentiated. Although the detection procedure is effective, the sensitivity of the developed sensing technique with a low signal-to-noise ratio (SNR) can be improved. Using the device is also time-consuming. For the measurement probe, the excitation-detection pair need to be mounted aligned with and vertical to the implant-bone structure to enhance the detection sensitivity and SNR. Detailed in vitro artificial mandible and in vivo animal tests have been organized for future study.

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