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Technical note

# A noncontact resonance frequency detection technique for the assessment of the interfacial bone defect around a dental implant

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ABSTRACT

This study employed a noncontact resonance frequency (RF) detection technique that was developed by our group to evaluate the interfacial bone in *in vitro* implant-bone models. Based on our method, the implant-bone structure was excited by the acoustic energy of a loudspeaker, and its vibration response was acquired with a capacitance sensor. The spectral analysis was used to characterize the first RF value. Two types of *in vitro* defect models, Buccal-Lingual (BL) and Mesial-Distal (MD), were constructed for the verification. The measurements of the RF for a defect model clamped at four different heights (9, 10, 11, and 12 mm) were performed in two sensing directions (BL and MD). Moreover, each model was also analyzed using an Osstell Mentor. The obtained two parameters, RF and ISQ (Implant Stability Quotient), were statistically analyzed through one-way analysis of variance (ANOVA) and linear regression analysis for comparisons. The RF and the ISQ values obtained for all of the defect models at the four clamp heights decreased significantly ($p < 0.05$) with an increase in the severity of the defect. The two parameters for each imperfection increase significantly ($p < 0.05$) with an increase in the clamp height. Additionally, the RFs of all of the defect models are linearly correlated with their corresponding ISQs for the four clamp heights and the two measuring orientations. Therefore, our developed technique is feasible for the assessment of the postoperative healing around a dental implant.


## 1. Introduction

In the past decade, dental implants have become an available treatment for completely and partially edentulous patients [1,2]. Before the prosthesis placement, the surgery may fail if the interfacial osseointegration between the implant and the alveolar bone is not yet developed. Osseointegration is defined as a direct structural and functional connection between ordered, living bone and the surface of a load-carrying implant [3]. In cases with incomplete osseointegration, the thread exposure of the implant is often observed, especially in the post-extraction site or where the alveolar ridge is thin. The lack of bone adjacent to the implant can be considered a true bone defect, and several techniques have been proposed to promote the filling of this defect with newly formed bone [4]. Therefore, the continuous monitoring of the osseointegration and the early assessment of bone defects are important as well as necessary during implant rehabilitation.

To evaluate the interfacial conditions, destructive methods, such as histomorphometry and remove torque analysis, have been experimentally used to observe the completion of the osseointegration [5]. The clinical periodontal probe test and the radiographic estimation are common subjective methods for interfacial assessment [6]. However, these techniques are apt to damage the interfacial structures and are not suitable for long-term monitoring. X-ray examinations are inappropriate for the detection of osseointegration because the bone losses were less than 30% [7]. Thus, follow-up studies based on nondestructive methods have been extensively applied to estimate the postoperative conditions.

To avoid damaging the implant-bone interface, it is necessary to develop effective and quantitative noninvasive assessing techniques. Thus, objective and reliable measuring devices are being developed. Based on the differences in the damping characteristics between teeth and the surrounding tissue, the detection apparatus (Periotest) was originally designed to evaluate the interfacial conditions through a comparison of the variations of the tooth impact mobility [8]. Unfortunately, this device often reflects inaccurate peri-implant biomechanical characteristics because the Periotest

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value is easily affected by the excitation direction and the impact location [9]. Hence, the Periotest is not yet a reliable device to investigate the implant-bone structural problem. The mobility test continues to exhibit drawbacks in the post-implantation evaluation.

Since the 1990s, another nondestructive technique (RF analysis) has been widely applied for the postoperative assessment of dental implants and has gradually become important. The first designated instrument (Osstell and Osstell Mentor) was developed [10], and the measured ISQ was used to evaluate the dental implant stability [11–13]. Additionally, another RF detector (Implomates), which consisted of an electromagnetic impact rod and a microphone, was developed for post-implantation prognosis. Some *in vitro*/*in vivo* tests have been performed to confirm the reliability and the feasibility of this device [14,15]. Additionally, Hayashi et al. developed an available electromagnetic vibration apparatus and used three useful mechanical parameters to measure the simulated atrophic bone defects of *in vitro* models [16]. Kim et al. applied a new Periotest-inductive sensor method to analyze the impulse response of the dental implant stability and were able differentiate between different stability changes in the simulated implantation conditions [17]. Zhuang et al. developed a new noncontact vibroacoustic RF detection technique and performed *in vitro* and *in vivo* tests. According to their experimental results, these researchers demonstrated that this technique was feasible and that the implant-bone interfacial conditions could be assessed by significant RF differences [18].

Based on previous studies, the developed techniques and commercial detection devices were applied to assess the interfacial states after dental implantation. However, the previous findings mainly presented the overall osseointegration estimation in the bone-implant interface and did not evaluate the interfacial bone imperfection in specific directions. Although our detection technique was developed and previously tested in the 45° direction [18], the peri-implant defect variations in other directions still needed to be clarified. In this study, we used the developed noncontact RF detection technique to perform an interfacial bone defect evaluation in other peri-implant directions. The RFs corresponding to various *in vitro* BL (in the 0° direction)/MD (in the 90° direction) bone defect models were measured to compare the peri-implant differences. Furthermore, for each measuring direction, different clamping heights imitating adjacent bone qualities were designated to estimate various alveolar conditions. For the verification, all of the noncontact RF measurements were extensively compared with the measurements obtained with the Osstell Mentor. The completed experimental validation shows that the method will likely be able to provide dentist information on bone imperfections through clinical observations during the healing period.

## 2. Materials and methods

### 2.1. Experimental setup of the noncontact RF detection technique

The noncontact RF detection device consists mainly of two parts: a loudspeaker (diameter: 40 mm, depth: 18 mm, VSP-03T, AUTOBACS SEVEN) to generate the acoustic excitation and a noncontact cylindrical capacitance sensor (diameter: 5 mm, length: 28 mm, C3-D, LION PRECISION) to detect the vibration displacement. During the RF characterization, the healing abutment (length: 5.5 mm, diameter: 4.5–7 mm, taper shape, Astra Tech AB) was mounted on the dental implant-bone block model, and various defect models were vised by a metal clamp (Fig. 1 a). Fig. 1b illustrates the actual experimental setup with an *in vitro* model gripped in the clamp. The exposed healing abutment was excited by the loudspeaker, and the opposite capacitance sensor was employed to measure the structural vibration response. Through an I/O DSP card, swept sinusoidal signals were provided to the loudspeaker, and the vibration signatures were digitized. Before being stored in the desktop personal computer, the acquired data were amplified, low-pass anti-aliasing filtered, and sampled with 10 kHz.

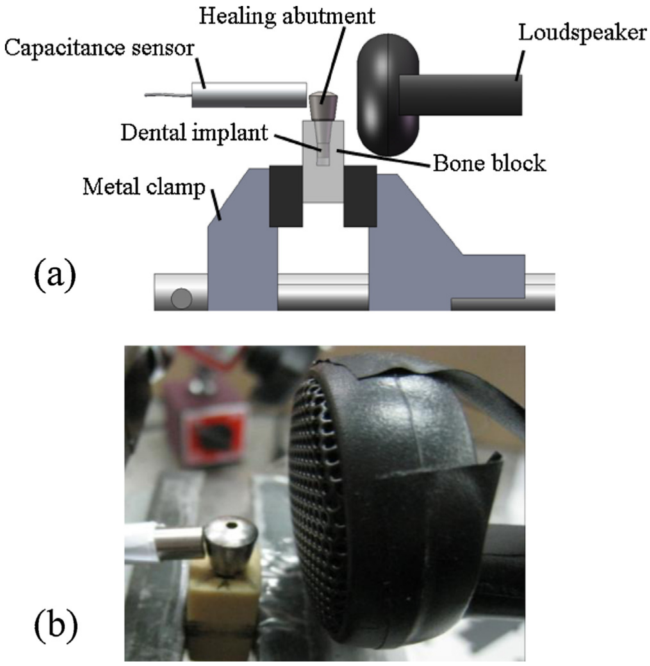


**Fig. 1.** (a) Diagram of the noncontact RF detection device consisting of a loudspeaker and a capacitance sensor. The *in vitro* model was vised by a metal clamp. (b) The real noncontact experimental setup.

### 2.2. Experimentation of in vitro interfacial bone defect models

According to the bone defect classification [4], we constructed similar *in vitro* imperfection models for the experiments. As shown in Fig. 2, the solid and the dotted arrows represent the BL and the MD orientations, respectively, in the left mandibular side. These orientations are also the noncontact measuring directions of the RF characterization. Every model was composed of a dental implant (diameter: 4.5 mm, length: 11 mm; Osseospeed$^{TM}$, Astra Tech AB) and an artificial bone block (10 mm × 10 mm × 20 mm; solid rigid polyurethane block, #1522-04, SAWBONES®) that was employed to simulate the surrounding cancellous bone. To mimic the boundary condition (BC) in the MD direction of the jawbone, defect models were vised by a metal clamp with a torque of 10 N-cm. Each pair of two bold lines represents the clamping side. In contrast, the free-free side imitates the BC in the BL direction (Fig. 2).

Additionally, the defect was 8 mm in depth and 1 mm in width, and six bone blocks were prepared for each imperfection model. Comprehensive measurements were performed in the verification of the employed detection technique. The structural response data for each model were acquired 10 times from the swept sinusoidal acoustic excitation in each of two sensing directions and for each of the four clamping heights. Hence, we obtained 60 strings of data for each specific imperfection type and BC using six samples. In addition, the ISQ values were also recorded using the Osstell Mentor for the same defect models. The first RF peak of each response spectrum was singled out. The mean and standard deviation (SD) of the measured RF and ISQ values for each defect model and clamping height were calculated for comparison purposes. Moreover, ANOVA was applied to examine the defect variations and the clamping-height increments for two parameters. The relevance between the

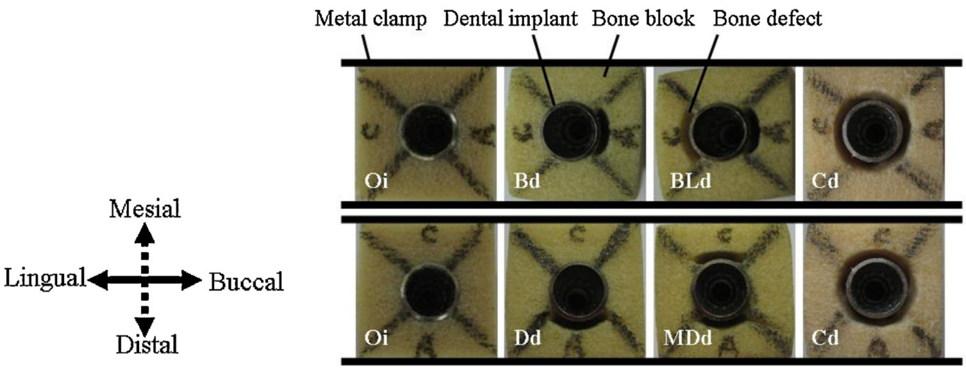


**Fig. 2.** The solid and the dotted arrows represented the BL and the MD directions in the left mandibular side, respectively, and the two directions are the noncontact RF measuring orientations (left). Each pair of two bold lines indicates the clamping side. The *in vitro* models were classified into two types of bone defects: BL (Osseointegration, Oi; Buccal defect, Bd; BL defect, BLd; and Circular defect, Cd) and MD (Oi; Distal defect, Dd; MD defect, and MDd; Cd) (right).

RF and the ISQ was tested through linear regression analysis with a commercially available statistical software (SPSS 17.0, SPSS Inc.). In the study, the preparation of the defect bone blocks was performed carefully with the insertion of dental implants, the creation of various defects, and vise clamping at the designated height. Then, the RF measurement and the ISQ evaluation were conducted by the same investigator to ensure the consistency of the experiments.

## 3. Results

As shown in the example in Fig. 3, the first RF peak values can be used to assess the interfacial imperfections. Fig. 4 illustrates the comparisons of the RF and the ISQ for two detection directions with four types of bone defects combined with four clamping heights. In accordance with the RF and the ISQ experimental results, the RFs and the ISQs of two defect-type models for all clamping heights decrease significantly ($p < 0.05$) with an increase in the defect extent. These two measuring values for each imperfection increase significantly ($p < 0.05$) when the clamp height is increased from 9 to 10, 11, and 12 mm.

To validate the employed detection technique, a linear regression analysis was used to statistically examine the relationship between the RF and the ISQ values for all bone-defect models measured in the two sensing directions and with various clamping heights. The RFs of all of the models linearly correlate with their ISQ values. As shown in Table 1, the RF and ISQ detections show a close relationship, as determined through the simple Pearson correlation coefficients ($R$), which ranged from 0.914 to 0.985 ($p < 0.05$).

## 4. Discussion

In the orthopedic and the dental fields, the hammer-impact excitation has been widely used to examine the interfacial RFs. This technique requires an accelerometer attached directly to the structure to acquire the response [19]. In previous studies [15–17], various methods have been proposed and verified through experimentation. All of the above studies focused on contact measurements and cannot eliminate the loading effect. In this study, a fully noncontact loudspeaker-capacitance sensing technique was developed and used to measure the interfacial response of *in vitro* bone-defect models. The new method can prevent the decrease in the RF due to the loading effect, and the spectral band of the acoustic excitation is tunable to individual interfacial structures. Alternatively, the commercial electromagnetic device Osstell Mentor requires that a special "smartpeg" attachment be screwed on the implant before the measurement of the ISQ. Due to its detection method, this device is apt to be affected by the surrounding EM noises, *e.g.*, from answering a cell phone, and the consumption of AC power during the test. Furthermore, the additional attachment to a dental implant may introduce a mass loading effect on the structural resonance. Moreover, the interfacial contact may be damaged when this smartpeg is screwed on the dental implant. Conversely, our acoustic excitation-displacement response (noncontact) technique is not affected by EM noises. During the RF measurement, the mass loading effect and the interfacial destruction can be avoided because the healing abutment is directly applied as a sensing target. However, it should be noted that our proposed and developed sensing-detection technique is still an in-laboratory used prototype, and on-site considerations for clinical use need to be addressed.

Compared with previous studies [12–14,16,17], bone blocks were applied to imitate the surrounding cancellous bone and thus represent the interfacial contact conditions. However, previous studies have not explored the boundary variations around the dental implant. In our previous paper, a different fixed method was designed [18]. Furthermore, the different clamping heights used in this study mimic the rigidity variations in the bone structure, *i.e.*, a larger clamping height may strengthen the alveolar structure and thus increase the bone resonant frequency. Additionally, according to the clinical classification [4], the defect types designated in the study belong to the bone wall imperfection around the dental implant. These single-depth models were used to test and confirm the feasibility of our defect evaluation technique.

**Table 1**
Linear regression analysis between the RF and the ISQ values for all defect-type models with four clamp heights and in two directions.

| Clamping height (mm) | Regression coefficients ($\beta_0$, $\beta_1$) | | Simple Pearson correlation coefficient ($R$) | | Determination coefficient ($R^2$) | |
|---|---|---|---|---|---|---|
| | BL | MD | BL | MD | BL | MD |
| 9 | (346.793, 40.783) | (−16.529, 48.680) | 0.943 | 0.979 | 0.889 | 0.959 |
| 10 | (210.801, 43.868) | (68.593, 46.798) | 0.943 | 0.966 | 0.890 | 0.932 |
| 11 | (254.906, 44.116) | (−1431.828, 81.882) | 0.946 | 0.958 | 0.895 | 0.917 |
| 12 | (271.643, 44.592) | (−1434.500, 80.389) | 0.914 | 0.985 | 0.835 | 0.970 |

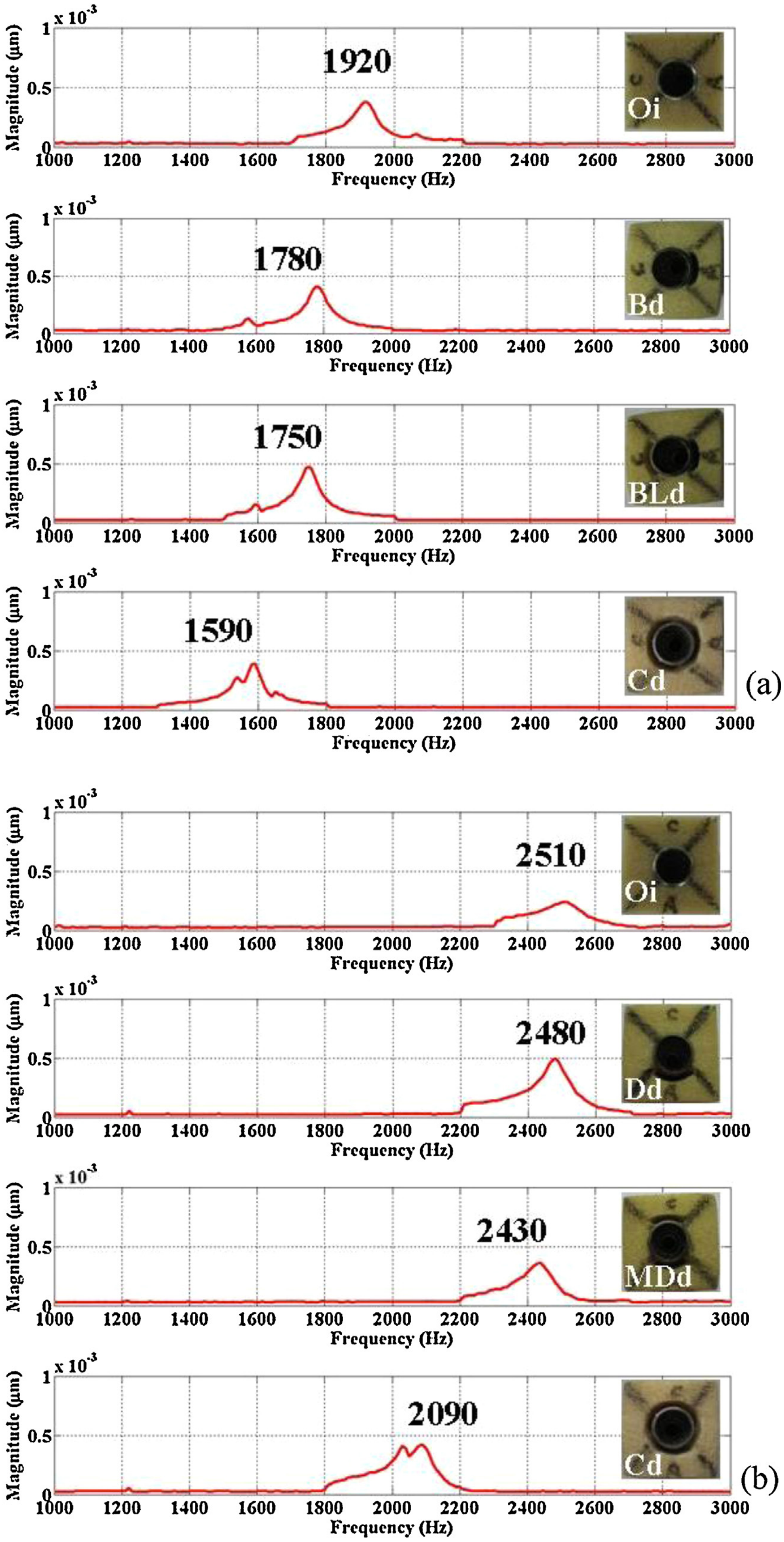


**Fig. 3.** Frequency spectra for the (a) BL and (b) MD defects using model 1 with a 9-mm clamping height as an example. (For interpretation of the references to spectra in figure legend, the reader is referred to the web version of the article.)

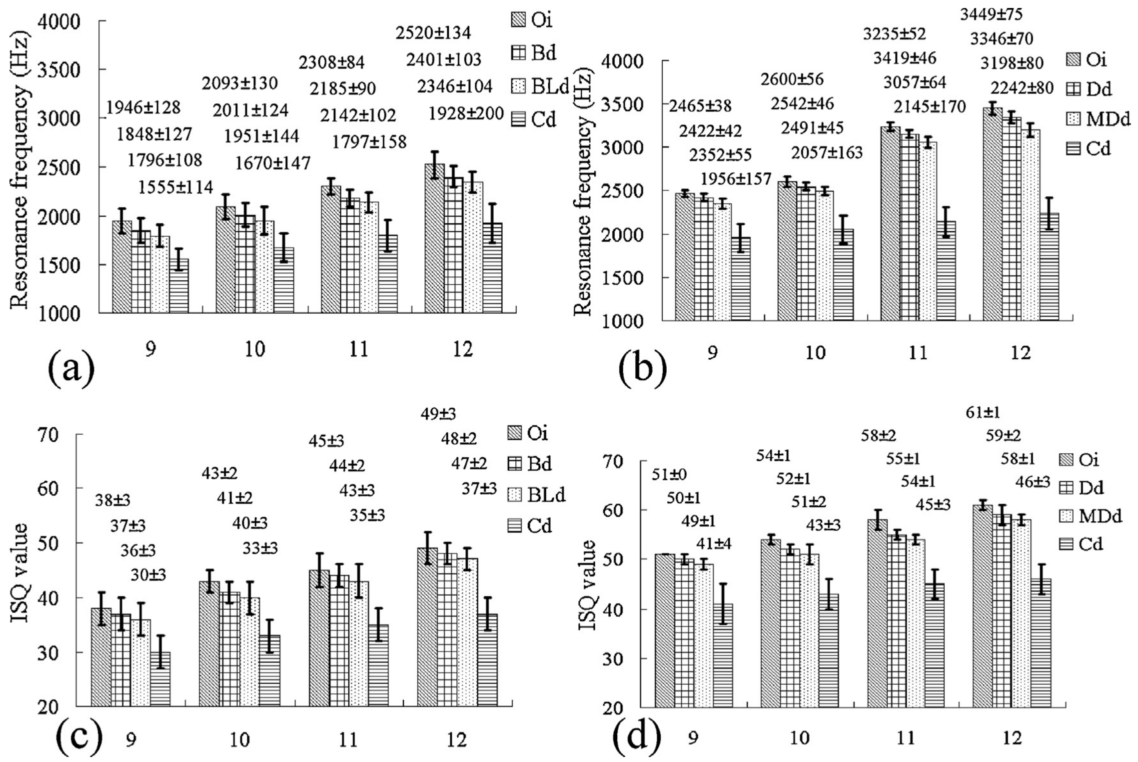


**Fig. 4.** Comparisons of the RF and ISQ values for the BL (a and c) and MD (b and d) detection directions with four types of defects combined with four clamping heights.

As shown in Fig. 5, the average decrements in the RF and the ISQ for different severities of bone defects compared with the osseointegration at all clamp heights and in the two measuring directions were calculated. In the BL imperfections, RF and ISQ decreases obtained with three increases in the defect severity are consistent with the imperfection quantities measured. The RF decrements from Oi to Bd, BLd, and Cd are 5%, 7%, and 21%, respectively, and the ISQ decrements are 3%, 5%, and 23%, respectively. Similarly, in the MD imperfections, the RF decrements from Oi to Dd, MDd, and Cd are 2%, 5%, and 28%, respectively, and the ISQ decrements are 4%, 5%, and 22%, respectively. Therefore, these measurement features can be considered a clinical assessment reference for the bone-defect detection in the BL and MD orientations without the requirement of an X-ray examination.

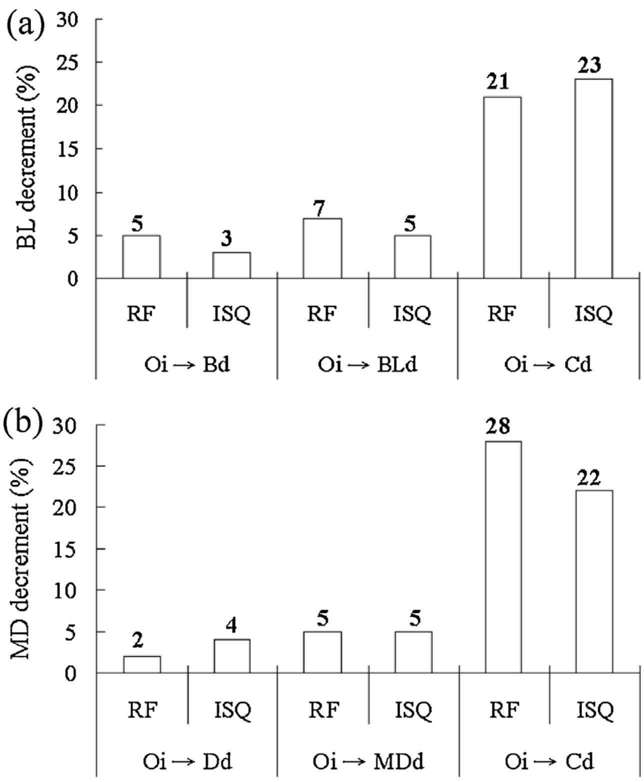


**Fig. 5.** Average percent decreases in the RF and ISQ values for various defect types using the $O_i$ condition as the baseline for the comparison: (a) BL- and (b) MD-direction defects.

The cause of the RF and ISQ decrease based on the severity of the bone defects will be discussed below. The changing of the boundary condition surrounding a dental implant, *i.e.*, the adjacent bone quality and the interfacial osseointegration, affects the stiffness of the whole structure. As shown in Fig. 4, the RF and ISQ values in the two detecting directions vary with the clamping heights and the interfacial conditions. An increase in the clamping height results in a relatively stable bone quality. In addition, the appearance and worsening of the bone defect leads to an increase in the exposed height of the implant in the *in vitro* models. The model with a 12-mm clamping height is apparently strong with the highest RF and ISQ values compared with the other clamping heights. The sound model (Oi) in both the MD and BL directions is rather stable, and the other defect models, such as Bd, BLd, Dd, MDd, and Cd, in the two detection directions are apparently weak. The results correspond to those obtained in previous studies [10,20] and demonstrate that the detection technique can be applied to monitor the postoperative healing states.

As shown in Table 1, a significant linear relationship was obtained between the RF and the ISQ in two directions and with four clamping heights. It is noted that our defect evaluation method is feasible. Although structure dynamics theories have been developed, the existing detection techniques and devices are still unable to provide a critical value for determining the success, the failure, or the on-going prognosis of dental implantation. The attraction of more investigators to this field is demanding [21]. This study shows that the imperfection assessment obtained with the proposed noncontact RF detection technique is promising and that the method can be used to estimate the interfacial conditions during dental surgery. When a dental implant is embedded in the alveolar bone, the detection technique can be subsequently applied to assess the interfacial conditions for primary stability in all BL (0°), MD (90°), and 45° directions. During the healing phase, this type of detection procedure could be used to measure the secondary stability. Hence, imperfections or bone defects can be detected by dentists and used to gauge further treatment.

## 5. Conclusion

In this study, we applied and verified the developed noncontact RF detection technique to assess the interfacial conditions around a dental implant. Various *in vitro* bone-defect models clamped with designated heights in the two sensing directions were measured. Both the RF and the ISQ values of each model were estimated. The RF values measured significantly correlate with the ISQ values. These two detection parameters were employed to evaluate various bone defects in two sensing directions. The results show evident correlation among the defect parameters, such as orientation, depth, extent of defects, and shifts in the resonance frequencies, and thus confirm the usefulness of the technique for defect characterization. Further studies in the design of a miniature detection device suitable for the oral test and *in vivo* animal tests are to be performed because it is nontrivial to develop an effective detection device for the assessment of the osseointegration of dental implantation.

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*Ethical approval*: This study justified the proposed technique using in-vitro models. The clinical trials and animal tests have not included yet.

*Conflict of interest statement*: There is no conflict of interest with regard to this paper.

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