Methods Used to Assess Implant Stability: Current Status

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Successful osseointegration is a prerequisite for functional dental implants. Continuous monitoring in an objective and quantitative manner is important to determine the status of implant stability. Historically, the gold standard method used to evaluate degree of osseointegration was microscopic or histologic analysis. However, due to the invasiveness of this method and related ethical issues, various other methods of analysis have been proposed: radiographs, cutting torque resistance, reverse torque, modal analysis, and resonance frequency analysis. This review focuses on the methods currently available for the evaluation of implant stability. (More than 50 references.) Int J Oral Maxillofac Implants 2007;22:743–754

Key words: *cutting resistance analysis, implant stability evaluation, radiographic assessment, resonance frequency analysis, reverse torque test*

Successful osseointegration has been viewed as a direct structural and functional connection existing between ordered, living bone and the surface of a load-carrying implant[1,2] under a light microscope. Histologic appearance resembled a functional ankylosis with no intervention of fibrous or connective tissue between bone and implant surface.[3–7]

Osseointegration is also a measure of implant stability, which can occur at 2 different stages: primary and secondary.[8] Primary stability of an implant mostly comes from mechanical engagement with cortical bone. Secondary stability, on the other hand, offers biological stability through bone regeneration and remodeling.[5,9,10] The former is a requirement for successful secondary stability.[10] The latter, however, dictates the time of functional loading.[11] Degree of implant stability may also depend on the condition of the surrounding tissues. It is, therefore, of an utmost importance to be able to quantify implant stability at various time points and to project a long-term prognosis based upon measured implant stability. Presently, various diagnostic analyses have been suggested to define implant stability: standardized radiographs, cutting torque resistance analysis, reverse torque test, modal analysis, and resonance frequency analysis (RFA). Therefore, the purpose of this paper was to review methods currently used to evaluate implant stability.

An online search for studies in English and Japanese was performed using MEDLINE, Pre-MEDLINE, and the Cochrane Oral Health Group trials register. Publications from January 1970 to March 2006 were selected based on the following search terms: "implant mobility," "Periotest," "resonance frequency test," "insertion torque," "reverse torque," "cutting resistance," "implant stability," and "mobility." All of the search terms were combined with the term "implant." A hand search of *International Journal of Periodontics and Restorative Dentistry, Journal of Clinical Periodontology, International Journal of Oral & Maxillofacial Implants, Clinical Oral Implants Research, Journal of Periodontology,* implant-related textbooks, and implant-related journals was also executed. Papers were considered relevant if they included the aforementioned key words and were published in English or Japanese. Articles published in peer-reviewed publications and current publications were

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Table 1 Factors that Influence Implant Stability

Factors Affecting Primary Stability
Bone quantity and quality
Surgical technique, including the skill of the surgeon
Implant (eg, geometry, length, diameter, surface characteristics)
Factors Affecting Secondary Stability
Primary stability
Bone modeling and remodeling
Implant surface conditions

preferred to non-peer-reviewed and early publications. More than 200 papers matched the inclusion criteria; however, only 114 most relevant articles/chapters were selected and reviewed.

IMPLANT STABILITY

Implant stability, an indirect indication of osseointegration, is a measure of the clinical immobility of an implant.[5,9] It is achieved at 2 levels: cortical bone (primary stability) and cancellous bone (secondary stability). Secure primary stability leads to predictable secondary stability.[12] Secondary stability has been shown to begin to increase at 4 weeks after implant placement.[13] At this time point, the lowest implant stability is expected. Therefore, the original Brånemark protocol[2] suggested a 3- to 6-month nonloaded healing period to achieve adequate stability before functional loading.

Osseointegration is, however, a patient-dependent wound healing process affected by various factors (Table 1). Quantification of implant stability at various time points may provide significant information as to the individualized "optimal healing" time. Raghavendra et al[13] proposed that measurement of osseointegration be approached in a quantitative manner, as primary and secondary stability are in an inverse relationship. However, in clinical practice, experience-driven decision still dominates, as objective guidelines have not been established.

Table 2 summarizes currently available methods for the objective assessment of implant stability at pre-, intra-, and postsurgical time points. Histologic or histomorphometric analysis, however, is not feasible for daily practice, as this may require unnecessary biopsy.

RADIOGRAPHIC ANALYSIS

Radiographic evaluation is a noninvasive method that can be performed at any stage of healing. Bitewing view is used to measure crestal bone level, which has been suggested as an important radiographic indicator for implant success.[14–16] It has been reported that 1.5 mm of radiographic crestal bone loss can be expected in the first year of loading in a stable implant, with 0.1 mm of subsequent annual bone loss.[17–20] However, several problems must be addressed. First, 1.5 mm is a mean value. Second, due to a low incidence of implant failure, changes in radiographic bone level alone cannot precisely predict implant stability. Third, it is impractical for a clinician to detect changes in radiographic bone loss at 0.1 mm resolution. Fourth, crestal bone changes can only be reliably measured without distortion when the central ray of the x-ray source is perfectly parallel with the structures of interest. This would necessitate a series of standardized radiographs with a customized template for reliable and repeatable measurements, which is impractical. Lastly, conventional periapical or panoramic views do not provide information on a facial bone level, and bone loss at this level precedes mesiodistal bone loss.[21] Neither bone quality nor density can be quantified with this method. Even changes in bone mineral cannot be radiographically detected until 40% of demineralization had occurred.[22] Numerous limitations exist with the use of a conventional radiograph alone in making an accurate, independent assessment of implant stability. Computer-assisted measurements of crestal bone level change may prove to be the most accurate way to use radiographic information, as a standard deviation within 0.1 mm (0.01 to 0.51 mm) has been reported.[23] However, this method is not convenient for use in clinical practice.[24]

CUTTING TORQUE RESISTANCE ANALYSIS

In cutting resistance analysis (CRA), originally developed by Johansson and Strid[25] and later improved by Friberg et al[26–29] in in vitro and in vivo human models, the energy (J/mm^3) required for a current-fed electric motor in cutting off a unit volume of bone during implant surgery is measured. This energy was shown to be significantly correlated with bone density, which has been suggested as one of factors that significantly influences implant stability.[26,29] To minimize the interoperator variation, hand pressure during drilling was controlled.[27] CRA can be used to identify any area of low-density bone (or poor-quality bone) and to quantify bone hardness

Table 2 Currently Available Methods to Evaluate Implant Stability and the Time of Use for Each Method

	Pre	Intra	Post	Noninvasiveness	Objectivity
Histologic analysis	+	+	+	–	+++
Percussion test	–	++	++	+	+
Radiographs	++	++	++	++	–
Reverse torque	–	–	++	–	++
Cutting resistance	–	+++	–	+	++
Vibration analysis					
Periotest	–	++	++	++	++?
RFA	–	+++	+++	+++	++?

+++ = method with highest reliability; ++ = method with certain reliability; + = method with doubtful reliability; – = application is impossible; ? = More information is needed.

during the low-speed threading of implant osteotomy sites. A torque gauge incorporated within the drilling unit (eg, Osseocare; Nobel Biocare, Göteborg, Sweden) can be used to measure implant insertion torque in Ncm to indirectly represent J/mm^3. Insertion torque values have been used to measure bone quality in various parts of the jaw during implant placement.[30]

CRA gives a far more objective assessment of bone density than clinician-dependent evaluation of bone quality based on Lekholm and Zarb classification.[31] Clinical relevance was demonstrated by studies that showed the highest frequency of implant failures in jaws with advanced resorption and poor bone quality, often seen in maxilla.[17,18,32–34] Therefore, cutting resistance value may provide useful information in determining an optimal healing period in a given arch location with a certain bone quality.[26]

The major limitation of CRA is that it does not give any information on bone quality until the osteotomy site is prepared. CRA also cannot identify the lower "critical" limit of cutting torque value (ie, the value at which an implant would be at risk).[29] Furthermore, longitudinal data cannot be collected to assess bone quality changes after implant placement. Its primary use, therefore, lies in estimating the primary stability of an implant. For instance, in Misch's 6 time-dependent stages of implant failures—*(1)* surgical, *(2)* osseous healing, *(3)* early loading, *(4)* intermediate, *(5)* late, and *(6)* long-term[35]—CRA can only provide information on the first 2 stages. Estimation of implant primary stability alone from CRA is still of value, as high implant failure rates are observed in the first 3 phases.[36,37] Nonetheless, long-term evaluation of implant stability after implant placement, phases 3 to 7, is desired and should not be overlooked. This limitation has led to development of other diagnostic tests. Table 3 summarizes CRA.

Table 3 Advantages and Disadvantages of CRA

Advantages

1. Detect bone density
2. High correlation between cutting resistance and bone quality
3. Reliable method to assess bone quality
4. Identify bone density during surgery
5. Can be used in daily practice

Disadvantages

1. Can only be used during surgery

REVERSE TORQUE TEST

Unlike CRA, which measures the bone density and the resistance to cutting torque, the reverse torque test (RTT), proposed by Roberts et al[38] and developed by Johansson and Albrektsson,[39–41] measures the "critical" torque threshold where bone-implant contact (BIC) was destroyed. This indirectly provides information on the degree of BIC in a given implant. In the study conducted by Johansson and Albrektsson, a reverse torque was applied to remove implants placed in the tibiae of rabbits 1, 3, 6, and 12 months postsurgery. Reverse torque value and histologic evaluation showed that greater BIC could be achieved with a longer healing time. Similar observations at the histologic level have been made in other animal studies.[42–44] Removal torque value (RTV) as an indirect measurement of BIC or clinical osseointegration was later reported to range from 45 to 48 Ncm in 404 clinically osseointegrated implants in humans.[45] Sullivan et al further speculated that any RTV greater than 20 Ncm may be acceptable as a criterion for a successful osseointegration, since none of the implants in their study[45] could be removed during abutment connection at 20 Ncm. It was further suggested that RTT is, therefore, a reliable diagnostic method for verification of osseointegration.

Table 4 Implant Stability Measurement Based on Modal or Vibration Analysis

Theoretical Modal Analysis
1. Finite element method
Experimental Modal Analysis
1. Percussion test
2. Impact hammer method (Periotest, Siemens, Bensheim, Germany; Dental Mobility Checker, J. Morita, Suita, Japan)
3. RFA (Osstell, Integration Diagnostics, Göteborg, Sweden; Implomate, Bio Tech One, Taipei, Taiwan)
4. Others (pulsed oscillation waveform by Kaneko)

However, this method has been criticized as being destructive.[8] Brånemark et al[2] cautioned about the risk of irreversible plastic deformation within peri-implant bone and of implant failure if unnecessary load was applied to an implant that was still undergoing osseointegration. Furthermore, a 20-Ncm threshold RTV for successful osseointegration has not yet been supported by scientific data. The threshold limit varies among patients depending on the implant material and the bone quality and quantity. A threshold RTV may be lower in type 4 bone than in denser bone, for instance. Hence, subjecting implants placed in this bone type to RTV may result in a shearing of BIC interface and cause implant failure. Furthermore, RTV can only provide information as to "all or none" outcome (osseointegrated or failed); it cannot quantify degree of osseointegration. Hence, RTT is mainly used in experiments.

MODAL ANALYSIS

Modal analysis measures the natural frequency or displacement signal of a system in resonance, which is initiated by external steady-state waves or a transient impulse force (Table 4). Modal analysis, in other words, is a vibration analysis. It is widely used as an effective test method for structural analysis in engineering and the health-care field.[46,47] Dental applications include the quantification of osseointegration.[48–51] Modal analysis can be performed in 2 models: theoretical and experimental.[52]

Two or 3-dimensional finite element modeling (FEM) is an example of computer-simulated theoretical modal analysis, which is mathematically constructed using known biomechanical properties (eg, Young's modulus [Pa], Poisson ratio, and density in g/cm^3) of structures of interest. Theoretical modal analysis such as FEM may be useful in investigation of the vibrational characteristics of objects that may be difficult to excite because of a damping effect from boundary conditions such as the periodontal ligament (PDL) in an in vivo model.[49] By altering boundary conditions such as the bone level, FEM can theoretically be used to calculate the anticipated stress and strain in various simulated peri-implant bone levels.[50,51]

Experimental or dynamic modal analysis, on the other hand, measures structural changes and dynamic characteristics (eg, natural characteristic frequency, characteristic mode, and attenuation) of a system that is excited in an in vitro model via vibration testing (eg, impactor or hammer). This in vitro approach provides a more reliable assessment of an object than a theoretical model. This analysis has been applied in dentistry to quantify the degree of osseointegration and implant stability.[49] Frequency analysis and mechanical impedance analysis can be used for detecting response waves in modal analysis.[52] By combining the vibration and response detecting methods, various kinds of vibration analyses can be performed.[53] Some techniques derived from these theoretical concepts are being tested for use in evaluating implant mobility.

Percussion Test

A percussion test is one of the simplest methods that can be used to estimate the level of osseointegration.[8,54–56] This test is based upon vibrational-acoustic science and impact-response theory. A clinical judgment on osseointegration is made based on the sound heard upon percussion with a metallic instrument. A clearly ringing "crystal" sound indicates successful osseointegration, whereas a "dull" sound may indicate no osseointegration. However, this method heavily relies on the clinician's experience level and subjective belief. Therefore, it cannot be used experimentally as a standardized testing method.

Impact Hammer Method

Impact hammer method is another example of transient impact as a source of excitement force during experimental modal analysis.[53,57] It is an improved version of the percussion test except that sound generated from a contact between a hammer and an object is processed through fast Fourier transform (FFT) for analysis of transfer characteristics. By enhancing the response detection using various devices, such as a microphone, an accelerometer, or a strain gauge, and by processing the detected response with FFT, it becomes possible to quantify and qualify the response wave in the form of dislocation, speed, acceleration, stress, distortion, sound, and other physical properties. Periotest (Siemens, Bensheim, Germany) and Dental Mobility Checker (DMC;

J. Morita, Suita, Japan) are currently available mobility testers designed according to the impact hammer method. The former has an electromagnetically driven and electronically controlled tapping head that hammers an object at a rate of 4 times per second. Contact time between the tapping head and the object is also measured. DMC utilizes the same principle of tapping a tooth or implant with a dental hammer. A frequency response function is built-in to detect bone-quality–dependent sound.

Pulsed Oscillation Waveform

Kaneko et al[58,59] described the use of a pulsed oscillation waveform (POWF) to analyze the mechanical vibrational characteristics of the implant-bone interface using forced excitation of a steady-state wave. POWF is based on estimation of frequency and amplitude of the vibration of the implant induced by a small pulsed force. This system consists of acoustoelectric driver (AED), acoustoelectric receiver (AER), pulse generator, and oscilloscope. Both the AED and AER consist of a piezoelectric element and a puncture needle. A multifrequency pulsed force of about 1 kHz is applied to an implant by lightly touching it with 2 fine needles connected with piezoelectric elements. Resonance and vibration generated from bone-implant interface of an excited implant are picked up and displayed on an oscilloscope screen.[58,59] An in vitro study showed that the sensitivity of the POWF test depended on load directions and positions.[58] Sensitivity was rather low for the assessment of implant rigidity.

IMPLANT STABILITY EVALUATION METHODS

DMC and Periotest are based on the impact hammer method, in which impact force is used as the excitation force. In this theory, "the width of the first peak on the time axis of the spectrum generated by transient impulse is inversely proportional to the time axis of the impulse."[57,60,61] Therefore, in the presence of impact force, lower rigidity of the tested substance results in a longer time axis.

Dental Mobility Checker

The DMC, which was originally developed by Aoki[60] and Hirakawa,[61] measures tooth mobility with an impact hammer method using transient impact force. Aoki and Hirakawa successfully detected the level of tooth mobility by converting the integration (ie, rigidity) of tooth and alveolar bone into acoustic signals. A microphone was used as a receiver. The response signal transferred from the microphone is processed by FFT for conversion for analysis in the time axis. Hence, the duration of the first wave generated by the impact was detected.[62] DMC uses a small impact hammer as an excitation device. It is easily used even in molar regions. DMC may provide quite stable measurement for osseointegrated implants.[63] There are some problems, however, such as the difficulties of double-tapping and difficulty in attaining constant excitation. Furthermore, the application of a small force to an implant immediately after placement may jeopardize the process of osseointegration.[2]

Periotest

Periotest has been thoroughly studied and advocated as a reliable method to determine implant stability.[8,64–71] Unlike DMC, which applies impact force with a hammer, Periotest uses an electromagnetically driven and electronically controlled tapping metallic rod in a handpiece. Response to a striking or "barking" is measured by a small accelerometer incorporated into the head. Like DMC, contact time between the test object and tapping rod is measured on the time axis as a signal for analysis. The signals are then converted to a unique value called the Periotest value (PTV), which depends on the damping characteristics of tissues surrounding teeth or implants.[72]

Although they use different types of receivers for impulse responses, DMC and Periotest are similar in terms of their theoretical background. They both use a transient impulse as an excitation force, and in both cases analysis is conducted on the time axis. In addition, both were originally developed to measure the mobility of a natural tooth.[64,65]

In the case of a natural tooth, the buffering capacity of the PDL poses a problem in analyzing the distribution of impact force exerted on a tooth. When dynamic characteristics are analyzed based upon an assumption that the whole periodontal structure functions as a mechanical unit, it is difficult to model the attenuation from the PDL. The soft tissue, including the periosteum, is considered a viscoelastic medium; thus, Hooke's law does not apply to the behavior of the PDL under an applied load. Thus, viscoelasticity of the PDL has always posed a difficulty in analysis of the physical characteristics of periodontal tissue. By contrast, bone-implant interface with no PDL is believed to be similar to the serial spring model which follows Hooke's law, and mobility measurement is considered easier.

Most reports of the use of a natural tooth mobility detector such as Periotest to measure implant mobility have pointed out a lack of sensitivity in these devices.[55,68] Such devices permit a very wide dynamic range (in case of Periotest, PTV is –8 to +50) to permit the measurement of a wide variety of natural tooth mobility.[68] However, the dynamic range used for measuring implant mobility is very limited. Thus, the sensitivity of these devices is insufficient to measure implant mobility.

Although many similarities do exist between the tissue structures around an implant and a natural tooth, conclusions from periodontal studies may not be directly applicable to implants.[73] In the use of mobility measurement to assess implant stability, the presence or absence of a PDL makes a crucial difference. Similar to impact/vibration testing, values measured with Periotest are significantly influenced by excitation conditions, such as position and direction. The Periotest user's manual contains clear instructions about striking point position and angle: "The Periotest measurement must be made in a midbuccal direction" and "During measurement the Periotest handpiece must always be held perpendicular to the tooth axes."[72] Considering the intraoral environment, and the pen-grip–shaped handpiece of the Periotest, it is clear that it can be used quite easily for the anterior region. However, its use for the molar region is extremely difficult because of the presence of buccal mucosa.[74] Derhami et al[75] used a fixing device to hold a handpiece at the correct angle. This fixing device was used for an in vitro measurement using a cranial bone model, and its clinical application seems difficult. However, Periotest is believed to be an effective evaluation method once the difficulty of controlling impact force is solved.

Long-term data on Periotest have shown that it can be an objective clinical measurement of the stability of bone-implant anchorage.[70,71] Aparicio used Periotest to measure implant stability and found a direct correlation between PTV and the degree of initial osseointegration.[69] It was further suggested that PTV should be included in the current success criteria. Another study with sample size of more than 2,900 implants showed a similar finding.[70,71] However, differences with respect to implant design, diameter, length, and bone quality and quantity were not accounted for in that study; analysis in a pattern of changes over time may be more reasonable. A measured bone value only represents its condition at the moment of measurement. Bone is subject to lifelong metabolism, which will in turn affect PTV over time. Thus, average value is not a proper way to determine a critical value for implant stability.

Even if it could be assumed that PTV precisely reflects the condition of BIC as reported by previous studies,[76,77] an average PTV has no importance. Johansson and Albrektsson observed that "implants inserted in different people do not necessarily attain the same degree of integration."[39] Despite a wide variation in host factors such as bone density, normal PTV of an osseointegrated implant falls in a relatively narrow zone (–5 to +5) within a wide scale (–8 to +50).[64] Other studies have indicated that the PTVs of clinically osseointegrated implants fall within an even narrower zone (–4 to –2 or –4 to +2).[76,78] Therefore, the measured PTV may falsely be interpreted as having a small standard deviation and therefore viewed as having a good accuracy. PTV cannot be used to identify a "borderline implant" or "implant in the process of osseointegration" which may or may not continue to a successful osseointegration.[77] No conclusion has been made with regard to this issue.

It has been suggested that these limitations of Periotest measurement have been suggested to be strongly related to the orientation of excitation source or striking point. In vitro and in vivo experiments demonstrated that the influence of striking point on PTV is much greater than the effects from increased implant length due to marginal bone resorption or other excitation conditions such as the angle of the handpiece or repercussion of a rod.[55,75] Unfortunately, controlling these influential factors is extremely difficult. Despite some positive claims for Periotest,[68,69] the prognostic accuracy of PTV for implant stability has been criticized for a lack of resolution, poor sensitivity, and susceptibility to operator variables.[8,79]

RFA

RFA has recently gained popularity. It is a noninvasive diagnostic method that measures implant stability and bone density at various time points using vibration and a principle of structural analysis.[57] RFA utilizes a small L-shaped transducer that is tightened to the implant or abutment by a screw. The transducer comprises 2 piezoceramic elements, one of which is vibrated by a sinusoidal signal (5 to 15 kHz). The other serves as a receptor for the signal. Resonance peaks from the received signal indicate the first flexural (bending) resonance frequency of the measured object. In vitro and in vivo studies have suggested that this resonance peak may be used to assess implant stability in a quantitative manner.

Currently, 2 RFA machines are in clinical use: Osstell (Integration Diagnostics) and Implomates (Bio Tech One). Osstell has combined the transducer, computerized analysis and the excitation source into one machine closely resembling the model used by Meredith. In the early studies, the hertz was used as the measurement unit.[28,54,56,80–89] Later, Osstell created the implant stability quotient (ISQ) as a measurement unit in place of hertz.[90–103] Resonance frequency values ranging from 3,500 to 8,500 Hz are translated into an ISQ of 0 to 100. A high value indicates greater stability, whereas a low value implies instability. The manufacturer's guidelines suggest that a successful implant typically has an ISQ greater than 65. An ISQ < 50 may indicate potential failure or increased risk of failure.[104]

It is assumed that an implant and the surrounding bone function as as a single unit; thus, a change in stiffness is considered to represent the change of osseointegration of an implant. A steady-state sinusoidal force in a form of sine wave is applied to the implant-bone unit to measure the implant stability via resonance. Frequency and amplitude are then picked up as a response.[90,91] An in vitro model showed that resonance frequency of an implant placed in an aluminum block ranged from 8 to 9 kHz.[8,54] An in vivo human study also showed that, although amplitude of the resonance peak was smaller than in vitro data, the peak resonance frequency of clinically osseointegrated implants was also about 8 to 9 kHz.[8] Moreover, resonance frequency increased as polymerization of the resin progressed.[54]

Effective implant length (EIL) was a value calculated by adding the amount of exposed implant threads and the length of each abutment. EIL has been shown to be inversely proportional to the level of resonance frequency, with a correlation coefficient of $r = -0.94$ in vitro and $r = -0.78$ in vivo.[8,54] Several in vivo animal and human clinical studies have concurred with this finding.[56,80,102] No resonance peak was observed in failed implants with clinical mobility.[8]

Longitudinal changes in resonance frequency have also been evaluated. Implants placed in the rabbit tibia were measured over 168 days from the time of implant placement[81]; resonance frequency increased over time. Other studies have evaluated longitudinal changes in ISQ more in detail.[90–92,94,95,98,105] ISQ was found to decrease significantly after implant placement for several weeks. However, a recovery to the initial ISQ level was found at the time of implant loading. Furthermore, a greater increase of resonance frequency over time was observed with implants placed in softer bone.[28,91,98] In the case of an implant placed in grafted bone in an in vivo human study,[106] very low resonance frequency (4 to 5 kHz) was observed.

Based upon these findings, the following 3 conclusions have been suggested.[106] First, "stiffness" of an implant is a function of its geometry and material composition (length, diameter, overall shape). Second, the stiffness of the implant-tissue interface depends on the bond between the surface of the implant and the surrounding bone. Third, the stiffness of the surrounding tissue is determined by the ratio of cancellous to cortical bone and the density of the bone with which an implant engages.[8] Stiffness found at the bone-implant interface (second point) changes over time. The factors affecting stiffness remain relatively stable, as the mechanical properties of implant and bone are constant. The only factor that could significantly influence the stiffness and resonance frequency of the implant would be the exposed implant length, as shown in several studies.[8,56,80,102,107–109] Therefore, measurement of the stiffness at the interface provides reliable information as to the implant stability.

Stiffness of supporting structure may, however, influence the stiffness of the interface of an area of interest.[80,81,109–111] In most in vitro studies,[107,109,110] such as that of Meredith et al,[54] an aluminum block material with uniformity and linearity has been used as a supporting structure. Therefore, in this model, an implant behaves in a mathematically predictable manner in which resonance frequency is inversely proportional to the length of the cantilever beam. Bone, on the other hand, is composed of calcium phosphate (85%), calcium carbonate (10%), and fluoride ions (~ 5%), the amounts of which continuously change to maintain a dynamic equilibrium.[112] There is great interindividual variation. Furthermore, bone does not behave like a uniform material under functional loading. Hence, in modal analysis, the sharpness and amplitude of the resonance peak of an implant embedded in bone tend to be lower than those of an implant in an aluminum block. In a nonlinear object with a large attenuation (eg, PDL), a theoretical modal analysis is a more feasible analysis than an experimental modal analysis, as stress and strain do not behave proportionally to one another. Many influencing factors render interpretation of implant stability difficult from a single resonance value.

Like Osstell, Implomates, which was developed by Huang et al,[52,107–110] uses RFA. However, it utilizes an impact force to excite the resonance of implant instead of a sinusoidal wave. Impact force is provided by a small electrically driven rod inside the transducer. The received response signal is then transferred to a computer for frequency spectrum analysis (range, 2 to 20 kHz). The first biggest amplitude indicates the resonance frequency of interest. Higher frequency and sharp peak indicate a more stable implant, whereas a wider and lower peak and lower frequency indicate implant failure. Currently, few studies have been reported regarding the efficacy of this machine.

CLINICAL APPLICATION OF RFA

Presently, clinical application of RFA includes establishing *(1)* a relationship between exposed implant length and resonance frequency or ISQ values; *(2)* differential interarch and intra-arch ISQ values for implants in various locations;[83,90–92,98,103,105] *(3)* prog-

Table 5 Factors that Influence RFA

Constants
Implant length
Implant diameter
Implant geometry (implant system)
Implant surface characteristics
Placement position
Abutment length
Variables
Bone quality
Bone quantity
Damping effect of marginal mucosa
BIC (3-dimensional)
EIL
Connection of transducer
Primary stability
Secondary stability

nostic criteria for long-term implant success; and *(4)* diagnostic criteria for implant stability.[94,95,105]

EIL has been shown to significantly influence ISQ value.[8,54,56,80,102,107–109] Although the stiffness of the implant is generally constant, it can sometimes vary in the presence of other contributing stiffnesses (Table 5). Classification of ISQs based upon various conditions may be a grand task. However, if these variables are ignored, the reliability of the measurement will be low.[101,102] Therefore, only series of intrapatient RFA values over various time points may provide useful information as to the stability of an implant under investigation. Furthermore, these series of values may not indicate the success or failure of the implants.[105]

This concurs the research of Friberg et al with respect to cutting torque resistance measurement.[28,29,83] Insertion torque was also highly associated with resonance frequency of implants.[30] Lower resistance and lower resonance frequency values were associated with poor bone quality. This may be related to the finding that implant success and survival rates are greater in the mandible than in the maxilla.[101,113,114] Prolonged healing time is required in cases with poor bone quality. Therefore, even though an implant placement in softer bone shows low stability, it seems to “catch up” to dense bone sites over time.[28]

The prognostic value of RFA machines such as Osstell and Implomates has, therefore, been investigated. The most challenging factors to overcome are the dynamic characteristics (eg, damping effect, total mass, and stiffness) of various factors surrounding the object of interest,[111] bone-implant interface. Without controlling these factors, information gained from RFA is no better than guessing value. To improve its prognostic value of RFA, longitudinal studies and comparison of RFA values with histologic studies are essential. Development of simulation models on various EILs associated with various defect types may further assist in the assessment of implant stability.

The shape of the transducer (an L shape) restricts its orientation, which adds a significant length to the exposed implant length, potentially masking a small amount of bone resorption.[54] Osstell Mentor (Integration Diagnostics) eliminates the use of an attached L-shape transducer by generating “pulse trains” from a contact-free probe. Impact signals are then picked up by a receptor called a “smart-peg.” Hence, the measurement is believed to be more accurate than the original Osstell machine. Moreover, in cases of Kennedy III partial edentulism, this contact-free smart-peg allows assessment of implant stability from any direction. However, due to the difference in EIL and various bending forces from the different design of the transducer, data collected with the original Ostell machine and that collected with the new contact-free Osstell should be compared with caution.

The establishment of diagnostic criteria for success, survival, and/or failure is another clinical application with RFA. However, RFA can only give information regarding success; it cannot provide information with respect to survival or failure. ISQ can be fairly reliable when an implant has achieved osseointegration and the bone-implant interface is rigid.[98] In cases where rigid integration is doubtful, however, the ISQ tends to fluctuate. Some doubtful implants result in failure, whereas some implants showing low ISQ later stabilize and achieve a satisfactory outcome.[83] Hence, clinicians will continue to test the implant stability until they get a reasonable value. When unacceptable values are displayed, however, these values are often rejected. If the repeated measurements still indicate an unfavorable result, these values are unwillingly accepted. Hence, small standard deviation is often reported with high ISQ.

The evaluation of implant stability using RFA machines such as Osstell and Implomates still has some uncertain issues. It is clinically being used without much conclusive data on the bone-implant interface and resonance frequency values.[79,91] Further research is needed to establish higher reliability of these diagnostic devices.

CONCLUSION

To date, no definite method to evaluate implant stability has been established. Although the theory behind RFA is sound, the technology cannot provide a critical value that can determine the success, failure, or long-term prognosis of an implant. Hence, present position from this review is that information should be assembled from many diagnostic aids to assure long-term implant stability. More research in this field is certainly needed.

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