

Current trends to measure implant stability

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Abstract

Implant stability plays a critical role for successful osseointegration. Successful osseointegration is a prerequisite for functional dental implants. Continuous monitoring in an objective and qualitative manner is important to determine the status of implant stability. Implant stability is measured at two different stages: Primary and secondary. Primary stability comes from mechanical engagement with cortical bone. Secondary stability is developed from regeneration and remodeling of the bone and tissue around the implant after insertion and affected by the primary stability, bone formation and remodelling. The time of functional loading is dependent upon the implant stability. Historically the gold standard method to evaluate stability were microscopic or histologic analysis, radiographs, however due to invasiveness of these methods and related ethical issues various other methods have been proposed like cutting torque resistance, reverse torque analysis, model analysis etc. It is, therefore, of an utmost importance to be able to access implant stability at various time points and to project a long term prognosis for successful therapy. Therefore this review focuses on the currently available methods for evaluation of implant stability.

Key Words: Primary stability, resonance frequency analysis, secondary stability

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INTRODUCTION

Osseointegration is defined as a direct bone anchorage to an implant body which can provide a foundation to support prosthesis.^[1,2] Implant stability is a requisite characteristic of osseointegration. Without it, long-term success cannot be achieved. Continuous monitoring in a quantitative and objective manner is important to determine the status of implant stability. Osseointegration is also a measure of implant stability which can occur in two stages: Primary and secondary.^[3] Primary stability mostly occurs from mechanical attachment with cortical bone. Secondary stability offers biological stability through bone regeneration and remodeling.^[4,5] Primary

stability is affected by bone quality and quantity, surgical technique and implant geometry (length, diameter, surface characteristics). Secondary stability is affected by primary stability.^[6]

Objective measurement of implant stability is a valuable tool for achieving consistently good results that are influenced by:^[7]

Good decisions about when to load

When a surgeon makes a decision about early loading, objective measurement of implant stability can be valuable. A specified degree of implant stability can serve as an inclusion criterion for immediate loading.

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Advantageous protocol choice on a patient-to-patient basis

With objective measurement of implant stability, surgeons can make well-informed decisions about protocol choices on a case-by-case basis. In other words, when low implant stability measurements indicate that immediate loading will jeopardize treatment outcome, a two-step protocol can be applied. In cases where high implant stability measurements are recorded, the implant could be immediately loaded.

Situations in which it is best to unload

Objective measurement of implant stability also supports making the right decisions about unloading. Sennerby and Meredith point out that when replacing an immediately loaded temporary prosthesis with a permanent prosthesis, “low (secondary) values may be indicative of overload and ongoing failure.” To avoid failure, they suggest that surgeons should consider unloading, perhaps placing additional implants, and wait until stability values increase before loading the permanent prosthesis.

SUPPORTS GOOD COMMUNICATION AND INCREASED TRUST

Implant stability measurements can also help improve communication between surgeons and patients. When a surgeon refers to measurable values rather than subjective judgments as the basis for decision-making, it is easier to explain the treatment choices. The surgeons are also likely to appear more professional to colleagues alike and imbibe patient confidence.

PROVIDES BETTER CASE DOCUMENTATION

Objective implant stability measurements can be used to document the clinical outcome of implant treatments, which can be useful at a later stage if a problem should arise.

This review focuses on various methods to evaluate implant stability.

There are different methods to assess implant stability. They can be grouped as invasive/destructive methods and noninvasive/nondestructive methods.

Invasive/destructive methods

Following methods were included:

- Histologic/histomorphologic analysis
- Tensional test
- Push-out/pull-out test and
- Removal torque analysis.

Histomorphometric analysis

This is obtained by calculating the peri-implant bone quantity

and bone-implant contact (BIC) from a dyed specimen of the implant and peri-implant bone. Accurate measurement is an advantage, but due to the invasive and destructive procedure, it is not appropriate for long-term studies. It is used in the nonclinical studies and experiments. It is assessed at pre-, intra-, and post-surgical time points.^[8]

Tensional test

Tensional test was earlier measured by detaching the implant plate from the supporting bone. It was later modified by Bränemark by applying the lateral load to the implant fixture. However, they also addressed the difficulties of translating the test results to any area independent mechanical properties.^[9]

Push-out/pull-out test

Push-out/pull-out test investigates the healing capabilities at the bone implant interface.^[10] It measures interfacial shear strength by applying load parallel to the implant-bone interface. In the typical push-out or pull-out test [Figure I], a cylinder-type implant is placed transcortically or intramedullarily in bone structures and then removed by applying a force parallel to the interface. The maximum load capability (or failure load) is defined as the maximum force on the force displacement plot, and the interfacial stiffness is visualized as the slope of a tangent approximately at the linear region of the force displacement curve before breakpoint. It is assessed during the healing period. However, the push-out and pull-out tests are only applicable for nonthreaded cylinder type implants, whereas most of clinically available fixtures are of threaded design, and their interfacial failures are solely dependent on shear stress without any consideration for either tensile or compressive stresses (Brunski et al. 2000, Chang et al. 2010). It is also technique sensitive.

Removal torque analysis

Removal torque analysis implant is considered stable if the reverse or unscrewing torque was >20 Ncm. However, the disadvantage is that at the time of abutment connection implant surface in the process of osseointegration may fracture under the applied torque stress.^[11,12]

Reverse torque assessment; pull-out and push-out techniques are generally used only in preclinical applications and may be of value as research techniques. The clinical usage of destructive tests is limited due to ethical concerns associated with invasive nature of these methodologies.

Noninvasive/nondestructive methods for assessing implant stability

These include the following:

- The surgeon's perception
- Radiographical analysis/imaging techniques
- Cutting torque resistance (for primary stability)

- Insertion torque measurement
- Reverse torque
- Seating torque test
- Modal analysis and Implatest
- Percussion test
- Pulsed oscillation waveform (POWF)
- Periotest
- Resonance frequency analysis (RFA): Electronic technology
- Magnetic technology.

The surgeon's perception

One method of trying to evaluate primary stability is quite simply the perception of the surgeon. This is often based on the cutting resistance and seating torque of the implant during insertion. A perception of “good” stability may be heightened by the sensation of an abrupt stop when the implant is seated. An experienced surgeon's perception is, of course, invaluable and should under no circumstances be discounted. One's personal perception is difficult to communicate to others. However, most importantly, this type of measurement can only be made when the implant is inserted, it cannot be used later, for example, before loading the implant.

Imaging techniques

Imaging techniques are widely used to assess both quantity and quality of the jawbone.^[13] Following the surgery, imaging methods are used to assess the health of the implant, evaluating the bone quantity and quality changes, and estimating the crestal bone loss, which is a consequence of the osseointegration process. Numerous limitations exist with the use of a conventional radiograph alone in making an accurate, independent assessment of implant stability. Conventional periapical or panoramic views do not provide information on a facial bone level, and bone loss at this level precedes mesiodistal bone loss.^[14] At last, neither bone quality nor density can be quantified with this method. Even changes in the bone mineral cannot be radiographically detected until 40% of demineralization had occurred.^[15] Computer-assisted measurement of crestal bone level change may prove to be the most accurate radiographical information. However, this method is not convenient to use in clinical practice.

Cutting torque resistance analysis

This was developed by Johansson and Strid.^[16] It was later improved by Friberg et al.^[17,18] The amount of unit volume of bone removed by current fed electric motor and is measured by controlling the hand pressure during drilling at low speed. It determines areas of low density bone and quantifies bone hardness during implant osteotomy at the time of implant placement. Clinical studies showed that the highest frequency

of implant failures was seen in jaws with advanced resorption and poor bone quality, often seen in the maxilla.^[19] Therefore, cutting resistance value may provide useful information in determining an optimal healing period in a given arch location with a certain bone quality.

The major limitation of cutting torque resistance analysis (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 (i.e., the value at which the implant would be at risk).^[20]

Insertion torque measurement

Insertion torque values have been used to measure the bone quality in various parts of the jaw during implant placement.^[21,22] Insertion torque alone may be used as an independent stability measurement, but it may also act as a variable, affecting implant stability. In a different light, insertion torque is a mechanical parameter generally affected by a surgical procedure, implant design and bone quality at the implant site.^[23] However, it cannot assess the secondary stability by new bone formation and remodel around the implant. Hence, it cannot collect longitudinal data to assess implant stability change after placement. Furthermore, an increase in insertion torque may signify an increase in primary stability, but maximum insertion torque is produced by the pressure of implant neck on the dense cortical bone of the alveolus. Furthermore, it has been reported that if maximum insertion torque does not signify increased general bone density, it may indicate the insertion torque itself during tapping.

Reverse torque test

Reverse torque test was proposed by Roberts et al.^[13,24] and developed by Johansson and Albertsson. It is used to assess the secondary stability of the implant. Implants that rotate when reverse torque is applied indicate that BIC could be destroyed. Further, it cannot quantify the degree of osseointegration as threshold limits vary among patients, implant material, bone quality and quantity. The studies showed, the stress of the applied torque may in itself be responsible for the failure.^[11] It also does not measure lateral stability that is a useful indicator for successful treatment outcome.

Seating torque test

Like insertion torque, the final seating torque gives some information about the primary stability of the implant when the implant reaches its final apico-occlusal position. It is done after implant placement.^[22]

Modal analysis

Modal analysis also termed as vibration 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. It can be performed in two models: Theoretical and experimental.

The theoretical modal analysis includes finite element analysis. It investigates vibrational characteristics of objects. It is done to calculate stress and strain in various anticipated bone levels. It is used in clinical studies and experiments. The experimental modal analysis is a dynamic analysis. It measures natural characteristic frequency, mode and attenuation-via vibration testing. It is used in nonclinical studies *in vitro* approach. It provides reliable measurement.^[25]

Percussion test

A percussion test is one of the simplest methods that can be used to estimate the level of osseointegration. This test is based upon vibrational-acoustic science and impact response theory. The clinical judgment on osseointegration is 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.^[13,23]

Pulsed oscillation waveform

Kaneko^[26] described the use of a 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 an 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 two fine needles connected with piezoelectric elements. Resonance and vibration generated from the bone-implant interface of an excited implant are picked up and displayed on an oscilloscope screen. It is used for *in vitro* and experimental studies. An *in vitro* study showed that the sensitivity of the POWF test depended on load directions and position.^[7]

Periotest

Quantifies the mobility of an implant by measuring the reaction of the peri-implant tissues to a defined impact load. The Periotest was introduced by Schulte to perform measurements of the damping characteristics of the periodontal ligament, thus assessing the mobility of natural tooth.^[27,28] Periotest[®] [Figures 1 and 2] uses an electro-magnetically driven and electronically controlled tapping metallic rod in a handpiece. Periotest value range from -8 (low mobility) to +50 (high mobility). It can measure the bone density at the time of implant placement and postsurgical placement of the implant. Response to a striking or “barking” is measured by a small accelerometer incorporated into the head. The reliability of this method is questionable because of poor sensitivity, susceptibility to many variables.^[29]

Resonance frequency analysis

It was suggested by Meredith in 1998.^[30] 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. RFA [Figure 3] utilizes a small L-shaped transducer that is tightened to the implant or abutment by a screw. The transducer comprises of two ceramic elements, one

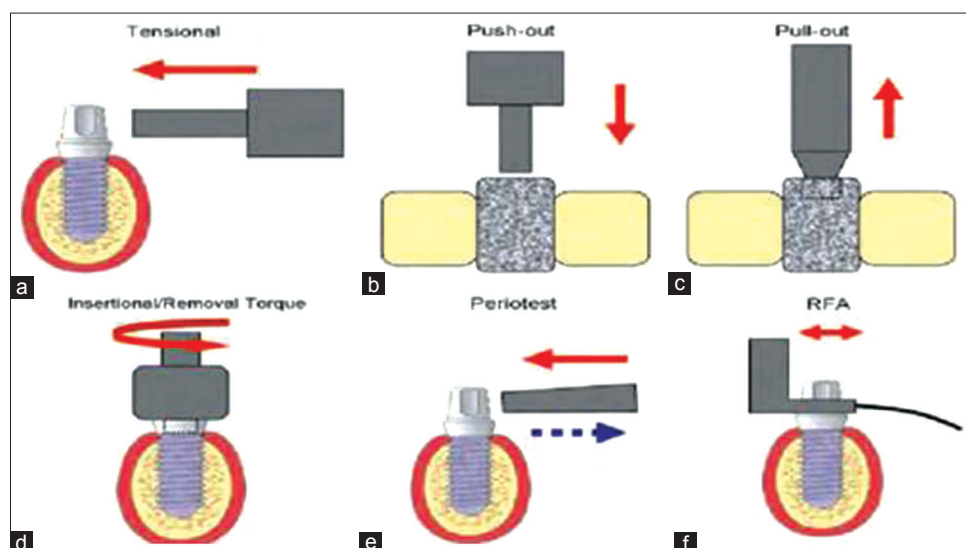


Figure 1: Stability analysis for oral implant osseointegration from clinical oral implants research (a-Tensional test, b- Pushout method, c-Pull out method, d-Insertion/removal method, e-Periotest, f-Resonance frequency analysis) 2010;21:1-12

of which is vibrated by a sinusoidal signal (5–15 kHz) while the other serves as a receptor. The transducer is screwed directly to the implant body and shakes the implant at a constant input and amplitude, starting at a low frequency and increasing in pitch until the implant resonates. High frequency resonance indicates stronger bone-implant interface. It also provides baseline reading for future comparison and postsurgical placement of the implant. RFA has been widely used for clinically assessing osseointegration, as well as for prognostic evaluation. However, the latter aspect still has to be questioned.

The most recent version of RFA is a wireless gadget. A metal rod is attached to the implant with a screw connection. The rod has a small magnet attached to its top that is stimulated by magnetic impulses from a handheld electronic device. The rod mounted on the implant has two fundamental resonance frequencies; it vibrates in two directions, perpendicular to each other. One of the vibrations is in the direction where the implant is most stable and the other is in the direction where the implant is least stable.

Currently, two RFA machines are in clinical use: [Figure 4] Osstell® (integration diagnostics) and Implomates® (Bio TechOne).

ELECTRONIC TECHNOLOGY RESONANCE FREQUENCY ANALYSIS (OSSTELL™)

It was the first commercially available product for measuring implant stability. The electronic technology combines the transducer, computerized analysis and the excitation source into one machine. Implant stability quotient (ISQ) is the measurement unit (ISQ of 0 to 100) used. When used at the time of implant placement it provides baseline reading for future comparison and postsurgical placement of the implant. Currently, Osstell (Integration Diagnostic AB, Goteborg, Sweden), a commercialized product utilizing the concept of RFA, has translated the resonance frequency ranging from 3000 to 8500 Hz as the ISQ of 0–100.^[31]

MAGNETIC TECHNOLOGY RESONANCE FREQUENCY ANALYSIS (OSSTELL™ MENTOR)

The transducer has a magnetic peg on top and is fixed to implant or abutment [Figure 4]. On activation by magnetic resonance frequency probe the peg is activated, which vibrates and induces electric volt sampled by magnetic resonance frequency analyzer. Values are expressed as ISQ of 0 to 100. At the time of implant placement, it provides baseline reading for future comparison and postsurgical placement of the implant. However, this method is expensive and technique sensitive as it requires respective transducer and magnetic peg. It should maintain a distance of 1–3 mm, angle of 90°, and should be



Figure 2: Periostest® (Siemens AG, Bensheim, Germany) measures tooth mobility and implant stability by Periostest value. (a) Periostest®, (b) Periostest®M

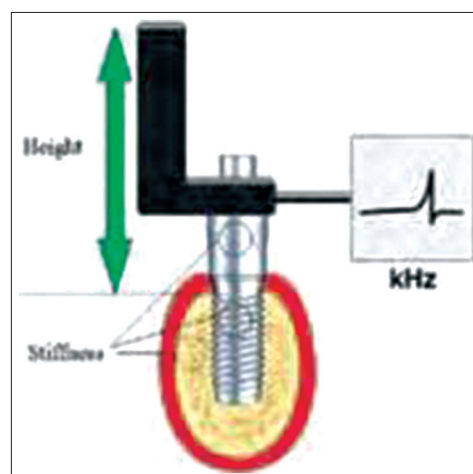


Figure 3: Picture showing the principle of electronic resonance frequency analyzer cited from Osstell website, www.osstell.com, April, 2011

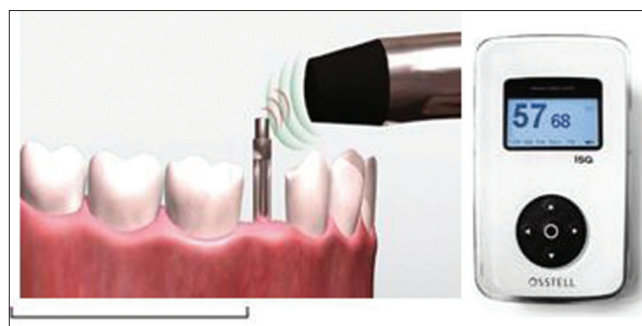


Figure 4: Principle of the Osstell Mentor™. Magnetic peg (smart peg™) works like a tuning fork and Osstell ISQ™ www.osstell.com, April 2011

3 mm above the soft tissue otherwise the measured value will be affected. Valderrama *et al.* reported in a study experimenting Osstell and Osstell Mentor that the two devices had high significant correlation.^[32,33]

Newer methods under research and development

Implatest conventional impulse testing

Conventional impulse testing of an implant requires fastening an accelerometer with associated wires and connectors to the implant, striking it with a calibrated hammer, and then recording and interpreting the data. The objective of testing implants with electrical impulse methods is to characterize, analyze and monitor their signatures.

Implatest (Q Labs Inc., Providence, R.I.) incorporates all of the features of a conventional impulse test into a compact, portable, self-contained probe. Data can be gathered in seconds and is operator independent (independent of the direction or position of test application on the implant). Complications may arise when attempting to test an implant with an attached multifixture prosthesis, owing to their splinting effect. The dynamic signature of a multifixture prosthesis is extremely complex owing to the supporting influence of all implants or natural teeth or a combination of these at the particular testing site.^[34]

Implomates was developed by Huang. This device utilizes impact force from a transducer to excite the resonance of implant. The received signal is transferred to computer for frequency spectrum analysis (2–20 kHz). Higher frequency and sharp peak indicates stable implant while wider frequency and low peak indicates implant failure. At the time of implant placement provides baseline reading for future comparison and the most surgical placement of implant.

Electro-mechanical impedance method

This test^[35] utilizes the electro-mechanical impedance of piezoelectric materials (work as both sensors and actuators) which is directly related to the mechanical impedance of the host structure. Piezoelectric zirconate titanate (PZT) is coupled to the monitored structure. After applying a voltage in 1 V in the kHz range, the PZT start to vibrate and any change of structural characteristics such as stiffness, damping, mass distribution, would influence the reading electrical admittance of PZT as read by impedance analyzer.

Micro motion detecting device

A customized loading device, consisting of a digital micrometer (Mitutoyo Absolute Digimatic, Mitutoyo America Corporation, Aurora, IL, USA) and a digital force gauge (Chatillon E-DFE-025, Chatillon Force Measurement Systems, Largo, FL, USA) (range of 10–2500 N 0.25% resolution over range) was used to determine implant micromotion. The forces were achieved by turning a dial, which controlled the height of the force gauge. This dialed in force was applied to the abutment via a lever. The digital micrometer was placed tangent to the crown of the abutment and detected the displacement after the load application.^[36]

Highly nonlinear solitary waves method

HNSWs (highly nonlinear solitary waves) are compactly supported lumps of energy, which are formed by a balance between nonlinear and dispersive effects in intrinsically nonlinear media, such as granular materials. They are characterized by unique physical properties, such as high acoustic energy and remarkable robustness, which make them extremely useful as information carriers in nondestructive evaluation (NDE) applications. To generate and propagate HNSW, a granular crystal to function as a combined sensor and actuator, which is composed of a chain of spherical particles in contact with each other with a piezoelectric gauge embedded in selected locations. Using the granular crystal, the surface of an orthopaedic implant with a single HNSW, and record the signals reflected from the interface between the granular crystal and the implant specimen under inspection.

Here, granular crystal actuator consisting of a one-dimensional tightly packed array of spherical particles, to generate acoustic solitary waves are assembled through direct contact with the specimen. Acoustic solitary waves into a biomedical prosthesis are injected, nondestructively evaluating the mechanical integrity of the bone-prosthesis interface, studying the properties of the waves reflected from the contact zone between the granular crystal and the implant. The granular crystal contains a piezoelectric sensor to measure the traveling solitary waves, which allows it to function also as a sensor.

Then a sequence of harsh mechanical loading on the samples is imposed to degrade the mechanical integrity at the stem-cement interfaces, using simulator that simulates aggressive, accelerated physiological loading. Implant stability is investigated via the granular crystal sensor-actuator during testing. Results showed that the reflected waves respond sensitively to the degree of implant fixation. In particular, the granular crystal sensor-actuator successfully detects implant loosening at the stem-cement interface following violent cyclic loading. This technique^[37] suggests that the granular crystal sensor and actuator has the potential to detect metal-cement defects in a nondestructive manner for orthopedic applications.

SUMMARY AND CONCLUSION

Evidence from the presented literature indicates that the advanced tests and equipment may play a greater role in the evaluation of implant stability compared to conventional methods. The ability to monitor osseointegration and the life expectancy of an implant is a valuable diagnostic and clinical tool that has far-reaching consequences on implant dentistry. RFA has attracted considerable scientific interest in recent years; it can also be used to evaluate the effect of early and delayed loading, assess stability over a period of time and early diagnosis of implant

failure. However, information should be established from many different diagnostic aids to assure long-term implant stability.

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Conflicts of interest

There are no conflicts of interest.

REFERENCES

- Albrektsson T, Zarb G, Worthington P, Eriksson AR. The long-term efficacy of currently used dental implants: A review and proposed criteria of success. *Int J Oral Maxillofac Implants* 1986;1:11-25.
- Albrektsson T, Talbrektsson B. *Implant fixation by direct bone anchorage*. New York: Raven Press Ltd.; 1983. p. 87-97.
- Meredith N. Assessment of implant stability as a prognostic determinant. *Int J Prosthodont* 1998;11:491-501.
- Brunski JB. Biomechanical factors affecting the bone-dental implant interface. *Clin Mater* 1992;10:153-201.
- Sennerby L, Roos J. Surgical determinants of clinical success of osseointegrated oral implants: A review of the literature. *Int J Prosthodont* 1998;11:408-20.
- Cochran DL, Schenk RK, Lussi A, Higginbottom FL, Buser D. Bone response to unloaded and loaded titanium implants with a sandblasted and acid-etched surface: A histometric study in the canine mandible. *J Biomed Mater Res* 1998;40:1-11.
- Mall N, Dhanasekar B, Aparna IN. Validation of implant stability: A measure of implant permanence. *Indian J Dent Res* 2011;22:462-7.
- Nkenke E, Hahn M, Weinzierl K, Radespiel-Tröger M, Neukam FW, Engelke K. Implant stability and histomorphometry: A correlation study in human cadavers using stepped cylinder implants. *Clin Oral Implants Res* 2003;14:601-9.
- Meenakshi S, Raghunath N, Raju SN, Srividya S, Indira PN. Implant stability a key determinant in implant integration. *Trends Prosthodont Dent Implantol* 2013;4:28-48.
- Brunski JB, Puleo DA, Nanci A. Biomaterials and biomechanics of oral and maxillofacial implants: Current status and future developments. *Int J Oral Maxillofac Implants* 2000;15:15-46.
- Sullivan DY, Sherwood RL, Collins TA, Krogh PH. The reverse-torque test: A clinical report. *Int J Oral Maxillofac Implants* 1996;11:179-85.
- Ivanoff CJ, Sennerby L, Lekholm U. Reintegration of mobilized titanium implants. An experimental study in rabbit tibia. *Int J Oral Maxillofac Surg* 1997;26:310-5.
- Atsumi M, Park SH, Wang HL. Methods used to assess implant stability: Current status. *Int J Oral Maxillofac Implants* 2007;22:743-54.
- Misch C. *Dental Implant Prosthetics*. St. Louis: Elsevier Mosby; 2005. p. 18-31.
- Wyatt CC, Pharoah MJ. Imaging techniques and image interpretation for dental implant treatment. *Int J Prosthodont* 1998;11:442-52.
- Johansson P, Strid K. Assessment of bone quality from cutting resistance during implant surgery. *Int J Oral Maxillofac Implants* 1994;9:279-88.
- Friberg B, Sennerby L, Roos J, Johansson P, Strid CG, Lekholm U. Evaluation of bone density using cutting resistance measurements and microradiography: An *in vitro* study in pig ribs. *Clin Oral Implants Res* 1995;6:164-71.
- Friberg B, Sennerby L, Meredith N, Lekholm U. A comparison between cutting torque and resonance frequency measurements of maxillary implants. A 20-month clinical study. *Int J Oral Maxillofac Surg* 1999;28:297-303.
- Adell R, Lekholm U, Rockler B, Brånemark PI. A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. *Int J Oral Surg* 1981;10:387-416.
- Friberg B, Sennerby L, Gröndahl K, Bergström C, Bäck T, Lekholm U. On cutting torque measurements during implant placement: A 3-year clinical prospective study. *Clin Implant Dent Relat Res* 1999;1:75-83.
- Irinakis T, Wiebe C. Initial torque stability of a new bone condensing dental implant. A cohort study of 140 consecutively placed implants. *J Oral Implantol* 2009;35:277-82.
- O'Sullivan D, Sennerby L, Jagger D, Meredith N. A comparison of two methods of enhancing implant primary stability. *Clin Implant Dent Relat Res* 2004;6:48-57.
- Bayarchimeg D, Namgoong H, Kim BK, Kim MD, Kim S, Kim TI, et al. Evaluation of the correlation between insertion torque and primary stability of dental implants using a block bone test. *J Periodontal Implant Sci* 2013;43:30-6.
- Roberts WE, Simmons KE, Garetto LP, DeCastro RA. Bone physiology and metabolism in dental implantology: Risk factors for osteoporosis and other metabolic bone diseases. *Implant Dent* 1992;1:11-21.
- Cairns NJ, Adam CJ, Pearcy MJ, Smeathers J. Evaluation of modal analysis techniques using physical models to detect osseointegration of implants in transfemoral amputees. *Conf Proc IEEE Eng Med Biol Soc* 2011;2011:1600-3.
- Kaneko T. Pulsed oscillation technique for assessing the mechanical state of the dental implant-bone interface. *Biomaterials* 1991;12:555-60.
- Schulte W, Lukas D. Periostest to monitor osseointegration and to check the occlusion in oral implantology. *J Oral Implantol* 1993;19:23-32.
- Schulte W, d'Hoedt B, Lukas D, Muhlbradt L, Scholz F, Bretsch J, et al. Periostest – A new measurement process for periodontal function. *Zahnartzl Mitt* 1983;73:1229-30, 1233-6, 1239-40.
- Salvi GE, Lang NP. Diagnostic parameters for monitoring peri-implant conditions. *Int J Oral Maxillofac Implants* 2004;19 Suppl:116-27.
- Aparicio C, Lang NP, Rangert B. Validity and clinical significance of biomechanical testing of implant/bone interface. *Clin Oral Implants Res* 2006;17:2-7.
- Park JC, Lee JW, Kim SM, Lee JH. Implant Stability – Measuring Devices and Randomized Clinical Trial for ISQ Value Change Pattern Measured from Two Different Directions by Magnetic RFA, Rapidly Evolving Practice 2011;5:111-30.
- Valderrama P, Oates TW, Jones AA, Simpson J, Schoolfield JD, Cochran DL. Evaluation of two different resonance frequency devices to detect implant stability: A clinical trial. *J Periodontol* 2007;78:262-72.
- Dario LJ, Cucchiario PJ, Deluzio AJ. Electronic monitoring of dental implant osseointegration. *J Am Dent Assoc* 2002;133:483-90.
- Lee SY, Huang HM, Lin CY, Shih YH. *In vivo* and *in vitro* natural frequency analysis of periodontal conditions: An innovative method. *J Periodontol* 2000;71:632-40.
- Boemio G, Rizzo P, De Nardo L. Assessment of dental implant by means of the electromechanical impedance method. *Smart Mater Struct* 2011;20:45-55.
- Freitas AC Jr, Bonfante EA, Giro G, Janal MN, Coelho PG. The effect of implant design on insertion torque and immediate micromotion. *Clin Oral Implants Res* 2012;23:113-8.
- Yang J. Nondestructive evaluation of orthopaedic implant stability in THA using highly nonlinear solitary waves. *Smart Mater Struct* 2011;1:01-12.