Functional Assessment of Dental Implant Osseointegration

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Functional ankylosis of dental implants in alveolar bone is the current criterion to assess implant osseointegration from a biomechanical standpoint. In this literature review, the clinical significance and current available assessments of implant stability are discussed. However, these assessments demonstrate a variety of correlations to peri-implant structures and as such are difficult to translate to the clinical arena. Calculating the effective stiffness from homogenization of peri-implant tissues appears to be a more reliable approach to predict implant stability in preclinical studies, but the structure-biomechanical relationship remains a clinical challenge. Despite the limitations in functional assessments of dental implant stability and oral implant biomechanics, this review highlights some emerging approaches to adapt these measures to clinical situations. (Int J Periodontics Restorative Dent 2012;23:e147–e153.)

The aim of dental implant treatment is to restore function and esthetics within acceptable biocompatibility. Formation of a direct structural and functional connection between the implant and supporting tissues, termed osseointegration, has emerged as the criterion used to evaluate long-term success.[1] Much effort has been devoted to facilitating osseointegration, including the improvement of surgical procedures and postsurgical care, developing favorable implant geometry and surface properties, and incorporating bioactive factors (Table 1).[2]

Osseointegration is a dynamic process that involves mechanical and biologic fixation.[11] Upon insertion, the implant is immediately secured in the host bone by mechanical interlocking (primary implant stability). Subsequently, the biologic remodeling process occurring at the tissue-implant interface determines the functional adaptation of implants (secondary implant stability).[12] Peri-implant structure analyses and biomechanical examinations could be feasible approaches to evaluate the progres-

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Table 1 Factors affecting osseointegration

Factors	Ways to evaluate
Bone quality and quantity[3]	Histology, radiography, tactile perception
Implant design[4]	Finite element analysis, biomechanical assessments
Surgical technique[5,6]	Radiography, histology, biomechanical assessments, finite element analysis, perceptions from surgeon and patient
Postsurgical care[7,8]	Radiography, histology, biomechanical assessments, local symptoms and signs, local biomarkers, perception from patient
Bone modeling/remodeling[9,10]	Histology, radiography, local biomarkers
Systemic health[7]	Hematology and clinical chemistry, radiography, physical examinations

sion of osseointegration.[13] However, limitations still exist, and it remains of value to develop an effective modality to evaluate the dynamics of osseointegration for the purposes of diagnosis and prognosis of implant placement. The purposes of this review were to summarize the state of the art in assessing osseointegration and provide a brief overview of the scientific fundamentals as well as the clinical significance of osseointegration.

Clinical significance of implant stability

The initial stability of implants is considered to be one of the prerequisites of implant success. Histologically, the primarily unstable implant prevents direct bone-implant contact and results in fibrous tissue attachment.[14] Thus, several surgical techniques were suggested to improve primary implant stability, including atraumatic surgery to maintain the cellular viability and prevent tissue loss,[15] greater final insertional torque to ensure implant fixation,[16] and a bone-condensing technique (eg, osteotome) to increase the area of bone-implant contact.[17]

Biomechanical assessments for preclinical investigations

Implant stability relies on the contact stiffness between the implant and surrounding tissue, and a variety of biomechanical assessments have been utilized for this purpose (Table 2).

An early attempt to evaluate implant stability was the tensional test, referring to the application of a lateral force to detach titanium plates or cylinders from the supporting tissue.[18] Implant stability was presented as lateral resistance, but the peri-implant structure was significantly destroyed, resulting in difficulty translating the results to any area-independent property (Fig 1a).[18] Applying a force parallel to the interface to push or pull out the implant from host bone then appears to be feasible and possibly the most accessible approach to evaluate contact stiffness (Fig 1a).[19] The applied load and implant displacement are recorded during the procedure, and the interfacial failure (detaching of the implant) occurs with the maximum load applied. Interfacial stiffness is defined as the slope of the tangent on the load-displacement curve before the breakpoint.[19] This method causes minimal interfacial tissue damage for cylinder-type implants and is considered suitable for preclinical proof-of-concept investigations.[20] However, the disadvantage of push-out tests is that the implant must be placed transcortically, which is only possible for cylinder smooth-surfaced implants. The destructive nature provided limited information for fully osseointegrated or screw-type implants.[20]

Removal torque testing, introduced by Roberts et al[26] and modified by Johansson and Albrektsson,[27] measures the contact stiffness by unscrewing the implant. The removal torque is equivalent to the interfacial shear calibrated in Newton centimeters (Ncm) by a torque manometer (Fig 1b). The critical torque value occurs while breaking the tissue interface. The main criticism of this method is that implant surface specifications may significantly influence the results, and the process is still destructive.[2]

Clinical implant stability assessments

The prerequisite for the clinical assessment of implant stability is no destruction of the surrounding host tissues. Thus, measurement during implant insertion was developed to predict primary implant stability, including cutting resistance and insertional torque. Both measurements consider the lateral compression force and friction during implant placement. Therefore, indirect measurement revealed some correlation but also a discrepancy from the direct measurement of removal torque, and the correlation between cutting resistance and insertional torque is still unclear.[28]

Percussion testing is a common clinically used method to evaluate osseointegration based on visual and acoustic observations. However, this methodology is relatively subjective and not sensitive to minor changes over time.[13] Damping characteristics, referring to tissue recovery after applying a signal, were recommended for implant stability assessment.[29] The Periotest (Medizinktechnik Gulden), originally designed to evaluate the stability of natural teeth based on electromagnetically driven forces, has been used for the evaluation of implant stability since 1990 (Fig 1c).[30] However, the limitation of the Periotest measurement is the narrow range permitted, leading to a lack of sensitivity in osseointegration. This limitation is presumably due to the physical differences between the periodontium and implant-supporting structure. The position of the percussion rod may also influence the results.[31]

Resonance frequency analysis (RFA) was also developed based on the damping characteristics of vibration, thereby overcoming the limitations of the Periotest by using an L-shaped transducer to fix the position and allowing a wider range of detection (Fig 1d).[13] The contact stiffness is converted from the peak of the frequency-amplitude plot, and a higher frequency as well as a sharp peak indicates better implant stability.[2,13] However, damping is a complex mechanical phenomenon, and the reading value of RFA (the implant stability quotient) is not a linear unit. The clinical value of RFA is still questionable. Further studies are needed to better utilize this metric in clinical dentistry. Nevertheless, it is believed that the firm initial fixation of the implant facilitates the process of osseointegration and confers permanent implant stability. However, at present, the correlation between primary and secondary implant stability still cannot be confirmed scientifically.[32]

Correlation between implant stability and the peri-implant structure

Alveolar bone provides major support for dental implants and is considered to affect implant stability. Early histologic and radiographic studies on human cadavers demonstrated a significant correlation between primary implant stability and cortical bone thickness.[32] Three-dimensional computed tomography (CT) assessment revealed that the radiographic density of bone may contribute to primary bone stability,[22] and this relationship tended to be closer in a wider-dimensioned implant.[33] Interestingly, the CT measurement also demonstrated that greater trabecular thickness and density of the cancellous bone lead to stronger primary stability, whereas trabecular separation might reduce the stability.[23]

The correlation between secondary implant stability and the peri-implant structure has been reported since the late 1990s when Johansson and colleagues observed a similar trend in the histologic change between the bone in contact with the implant and

Table 2 **Biomechanical assessments of implant stability**

Methodology	Property investigated	Parameters	Primary stability
Tensional[18]	Lateral resistance	Maximal lateral load	Yes
Push-/pull-out[19,20]	Interfacial shear	Maximal force, interfacial stiffness	Yes
Cutting resistance[21]	Bone quality	Cutting energy	Yes
Insertional torque[22,23]	Interfacial shear	Torque load, peak insertional torque	Yes
Removal torque[24,25]	Interfacial shear	Torque load, loosening torque	No
Periotest[9]	Ultrasonics/ damping	Periotest value	Yes
Resonance frequency analysis[23]	Vibration/ damping	Implant stability quotient	Yes
In vivo finite element optimization[20]	Effective tissue stiffness	Functional apparent moduli	NA

+ = method with mild/doubtful precision/relevance; ++ = method with definite precision/relevance; NA = relevance not determinable/has not been determined.

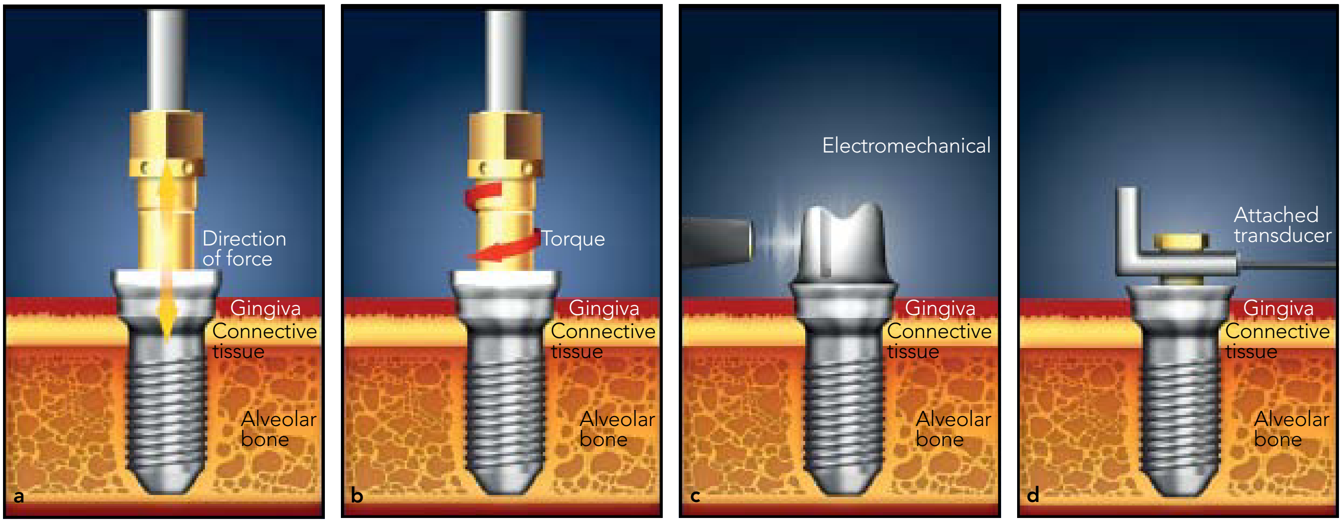

Fig 1 *Currently available biomechanical assessments of implant stability.* (a) *Tensional/pull-out/push-out test;* (b) *insertion/removal torque;* (c) *Periotest; and* (d) *resonance frequency analysis. Arrows indicate the direction of external load from the devices.*

removal torque.[24] Brånemark et al[25] demonstrated that both bone observed in contact with the implant histologically and total bone thickness were correlated with removal torque. However, an implant pulling out after unscrewing might still cause significant damage and influence the assessment of the peri-implant structure. Given the development of nondestructive assessment devices (Periotest, RFA), researchers demonstrated that histologic bone-implant contact and bone density tended to correlate

Secondary stability	Clinical use	Destructive	Precision	Relevance to structure
Yes	No	Yes	++	NA
Yes	No	Yes	++	++
No	Yes	Yes	++	++
No	Yes	No	++	++
Yes	No	Yes	++	++
Yes	Yes	No	+	+
Yes	Yes	No	+	+
Yes	Yes	No	++	++

with the mechanical impedance.[9,34] Recent preclinical studies using micro-CT imaging indicated moderate to strong correlations between peri-implant structural parameters and biomechanical assessments.[10,20] However, information from CT imaging should be interpreted carefully because of the inability to eliminate radiographic artifacts.[35]

Finite element analysis and functional apparent moduli

Finite element (FE) analysis has been widely applied to the field of implant dentistry to assess biomechanical influences on the dental implant and supporting tissue.[2] The analysis is based on a theoretic model whereby the structure and conditions are predetermined by reference landmarks and assumptions based on the physiologic condition, and the result is usually presented as the distribution of stress and strain in the model.[2] FE models have been used to design dental implants and implant-supported prostheses, evaluate the quality of supporting bone, determine the implant treatment plan, and predict the long-term survival of implants.[2] Bone-implant contact stiffness is usually considered as a predetermined variable, and the effective stiffness could only be calculated via the homogenization of the peri-implant structure (Fig 2).[20] In a recent study, the functional bone apparent modulus (FBAM, referring to the stiffness of the bone of interest) and functional composite tissue apparent modulus (FCAM, referring to the stiffness of the entire tissue of interest) were calculated,[20] and it was demonstrated that both FBAM and FCAM had stronger correlations to interfacial stiffness than any of the individual structural parameters. FBAM and FCAM became consistent when reaching a certain tissue thickness, which was named as the functionally relevant peri-implant layer. This layer may be regarded as a reference range for assessing the functional dynamic of dental implant osseointegration.

Conclusions

Unfortunately, to date, there is still no ideal assessment that can translate directly to the level of osseointegration, and a degree of discrepancy still exists among assessments used to determine dental implant stability. CT and micro-CT imaging appears to provide comprehensive information, but radiographic artifacts on the measurements can limit clinical

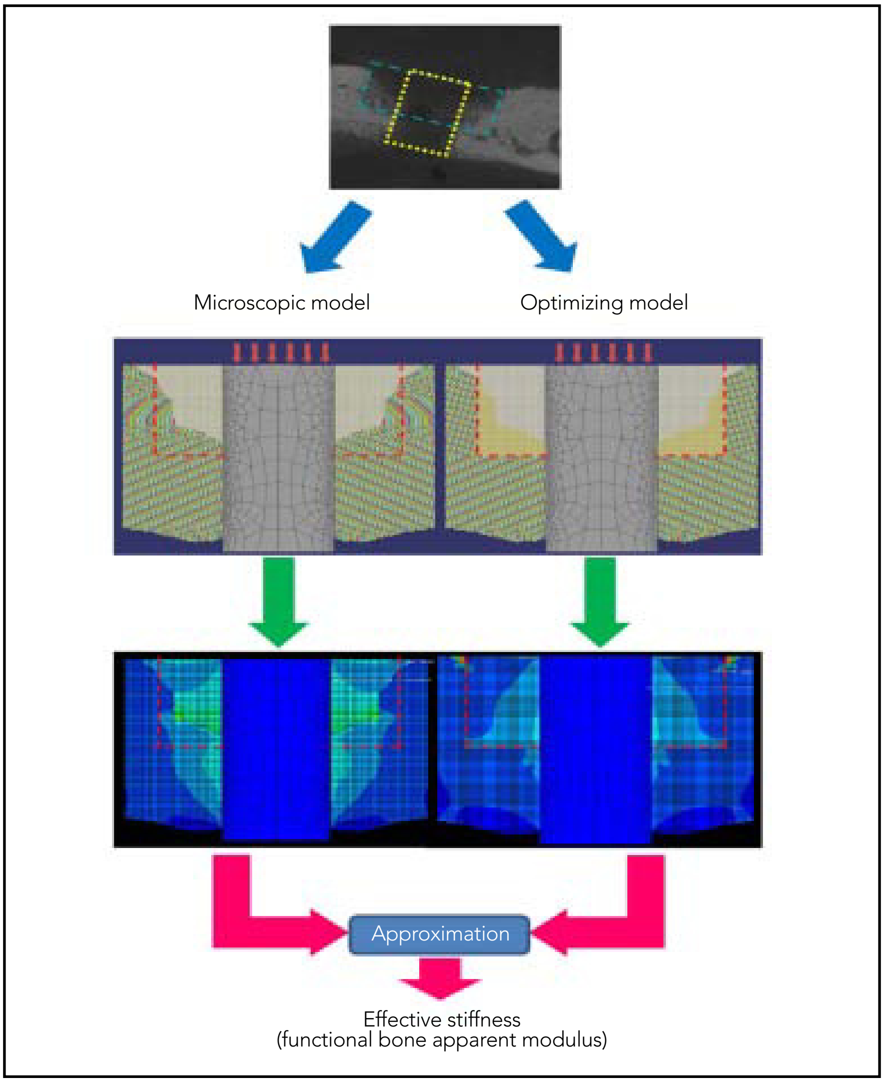

Fig 2 *Effective tissue stiffness calculated from in vivo FE optimization for application to implant stability. This figure demonstrates an example calculating the functional bone apparent modulus (one of the effective tissue stiffness, referring to the effective stiffness of the bone structure in this area) in a specific peri-implant zone. The peri-implant structural information is acquired from a three-dimensional micro-CT image* (top panel). *The position of the dental implant* (yellow box in top panel) *and range of peri-implant structure* (blue box in top panel) *are identified. The radiographic information is then transferred to establish FE models* (middle panel). *In the microscopic model, each element presents unique mechanical properties according to the radiographic density. In the optimizing model, the effective stiffness of bone tissue within the area of interest* (deep yellow portion within the area bound by the red lines) *is assumed homogenous and unknown. After applying an equivalent simulated load on both models, the strain distribution is recorded in both models* (bottom panel). *The simulated result within the area of interest* (area bound by red lines in middle and bottom panels) *in both models is approximated and optimized to calculate the effective stiffness (functional bone apparent modulus) of the bone structure within the area of interest.*

implementations. Nondestructive devices for biomechanical assessments are being developed, but their precision and clinical relevance still needs to be elucidated. The effective stiffness from homogenizing the peri-implant structures seems feasible to present the dynamics of osseointegration. These advances have certainly improved understanding in the development of improved surrogates for osseointegration and implant biomechanics; however, there remain significant challenges in the measurement of dental implant stability in the structure-biomechanical relationship.

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