Current and Emerging Approaches to Osseointegration Assessment in Dental Implantology: Limitations, Clinical Utility, and Future Directions

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ABSTRACT

This review evaluates existing methods for the measurement of osseointegration, which is the biological mechanism that assures long-term stability of dental implants. Invasive techniques, such as histology and pull-out torque measures, provide direct objective evaluation; however, they cannot be employed clinically due to their invasive nature. Non-invasive methods such as radiographic imaging, resonance frequency analysis, Periotest, and newer methods utilizing ultrasound have been used clinically. These are mainly based on indirect measurements or incomplete measures regarding bone-to-implant contact. Clinical measures of implant osseointegration are often subjective and vary significantly. Research into biochemical blood markers, biochemical markers in peri-implant fluids, and the use of digital technologies associated with decision-making shows promise for generating more personalized assessment outcomes and possibly predictive capacity. Many factors, including implant design, bone density, surgical technique, systemic disease, and others, influence the accuracy of measurement. Future research assessment will likely be based upon the usage of a multimodal protocol (involving mechanical, radiographic, biological, and computational data) so that the oral surgeon will consider all available data to assist decision-making, evaluation, and enhance long-term assessment of implants.

KEYWORDS

osseointegration; dental implants; resonance frequency analysis; biomarkers

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INTRODUCTION

Osseointegration refers to the biological process wherein an implant becomes osseointegrated, allowing for a successful long-term outcome due to its functional connection to bone tissue (1). To assess osseointegration accurately and therefore have a measure of implant stability to aid in a clinician's prediction of the clinical outcome for the patient, osseointegration measurement techniques have evolved since their conception. One should differentiate between implant stability and osseointegration. They are different phenomena. Osseointegration is a biochemical condition characterized by a close structural association between the bone and the surface of an implant (2). Stability, on the other hand, is a mechanical property. Primary stability is the mechanical bonding of the implant to the bone immediately after surgery, whereas secondary stability is the biological process of bone remodeling and biochemical connection to implant (osseointegration) (1, 2). The most urgent stage towards the success of the implant is the transition period between the two phases.

Although the different types of osseointegration assessment techniques have evolved over the years and are clinically relevant for their usefulness, each type has its own unique advantages and disadvantages (3). In Table 1, a brief comparison of various methods, such as level of invasiveness, clinical utility, advantages, and disadvantages, is presented. Information from research on osseointegration has led to the development of addressing difficult challenges associated with immediate-function clinical protocols, which require a detailed understanding of the relationship between implant biomechanics, biomaterials, and early bone tissue response to mechanical loading (4). The use of dental implants in restorative dentistry has radically changed the face of restorative dental procedures, providing a more stable and, in many cases, permanent prosthetic solution for patients who have lost their teeth. Success with the use of dental implants can be attributed to the osseointegration of the implant into the surrounding bone (1, 2, 5–7). The intent of this article is to address how osseointegration is assessed. Clinical protocols in implant dentistry do not generally include an objective and standardized assessment method for osseointegration. As such, current quantitative methods have not been uniformly applied.

The purpose of this narrative literature review is to analyze presently available and former methods of assessing osseointegration of dental implants focused on clinical relevance, limitations, and clinical interpretability. In addition, new biological and digital technologies are also considered as potential adjuncts to future multimodal assessments.

MATERIAL AND METHODS

The chosen narrative review approach for this project enables a holistic analysis of multiple assessment techniques used for assessing osseointegration. The existing body of evidence consists of experimental, clinical, biological, and digital studies that differ in their strengths of study design, outcome measures, and levels of validation. Due to this variance in study types and measures, systematic reviews with quantitative analysis would have limited applicability. Using a narrative review allows for a comparison of different methods used to assess osseointegration, and for discussion of future developments and techniques on osseointegration that do not yet have a sufficient standardization across the available data.

This narrative review integrates contemporary and developing techniques for determining osseointegration of dental implants. The literature was searched through a targeted investigation of PubMed, Google Scholar, and Scopus. A selection of keywords to identify current and emerging techniques in osseointegration assessment, such as invasive/non-invasive, RFA, Periotest, ultrasound,

Tab. 1 Primary reference method; direct BIC visualization.

Method	Invasiveness	Clinical Use	Accuracy/Strengths	Limitations	Key Citations
Histological Analysis	High (destructive)	Experimental only	Primary reference method; direct BIC visualization	Requires implant removal, contraindicated due to its destructive nature	11, 12
Removal Torque Testing	High (destructive)	Experimental	Quantifies anchorage via torque (Ncm)	Damages bone/implant	13, 14
Radiographic Evaluation	Non-invasive	Routine practice	Assesses bone levels (periapical, CBCT)	Subjective, no true BIC	15, 16, 35
Resonance Frequency Analysis (RFA)	Non-invasive	Common in studies/clinics	ISQ score, repeatable	Varies by implant/bone	3, 17
Periotest	Non-invasive	Limited clinical	Measures mobility via damping	Angle-sensitive, variable	3, 18, 36
Quantitative Ultrasound	Non-invasive	Investigational	Sound propagation/bone quality	Lacks standardization	19, 37
Clinical Parameters	Non-invasive	Routine practice	No pain/mobility, low probing depth	Subjective, unquantified	5, 20, 21
Biomarkers (GCF/salivary)	Minimally invasive	Emerging	Real-time remodeling indicators	No standardization	22

biomarkers, digital/AI, with Boolean operators (AND/ OR) used.

This review included publications written in the English language and published between 1977 and 2025. Publications have been evaluated using clinical, experimental, or review methods to assess either invasive or non-invasive approaches to evaluate clinical parameters, biomarkers, or other digital techniques in both humans and animals. This paper excludes case studies, reports, and non-peer-reviewed research, as well as dental implant studies that do not meet the criteria set within this study. To manage the heterogeneity of the studies included in this review, an approach of grouping the studies into 5 thematic domains of study design (invasive, non-invasive, clinical, biochemical, and digital) was taken. Conclusions were drawn based predominately within their respective thematic domains and not via a direct cross-comparison of results. From the original search, a total of 40 papers were selected that provided key information about the limitations, accuracy of measurement, and future development, which provided the background for Tables 1 and 2. The possibility to group the chosen papers based on the five types or themes, which include invasive, non-invasive, clinical, biochemical, and digital, allows the comparative review of the literature. This is a summary of the shift in the literature towards stability-based methods, which are traditional, to predictive and data-driven methods of modeling.

A purposive sampling methodology was employed to identify 40 publications and create a representative sample of the various methods currently being used to measure osseointegration. As the range of studies designed to evaluate osseointegration is inherently diverse, this sample size will provide adequate information to develop themes related to the five major areas of study discussed in this paper (invasive, non-invasive, clinical, biochemical, and digital measurement techniques) and will enable the establishment of thematic saturation to be reached within this sample size. Considerable emphasis was placed on the requirement that each of the publications included in this selected sample contain sufficient data to describe either a limitation in measurement, clinical value, or a new trend regarding the use of technology for measuring osseointegration in order to support the framework for comparison between measurement techniques shown in Tables 1 and 2. Because of the goal of achieving a high standard of evidence and reducing data variance, case studies (individual cases) that were not subjected to peer review were excluded from the initial selection (screening) process. Therefore, the analysis of the selected publications included only the qualitative assessment of empirical and clinical data from validated studies and included the transition from conventional physical measures to computational and biological models being discussed in this paper.

A total of 40 publications were included in this review. Of these, 30 studies focused on specific assessment methodologies (Non-Invasive, Clinical, Digital, Invasive, and Biochemical methods), while 10 provided essential theoretical background and biological foundations.

The first of many steps employed in completing this review was to conduct a qualitative review or assessment of the included studies. In order to provide an adequate framework to interpret the findings of the included studies, evidence has been organized by study design (e.g., experimental animal studies, clinical observational studies, randomized clinical trials and systematic reviews) and evaluated based on methodological transparency, adequacy of the sample size, reproducibility of the outcome, and clinical relevance. This evaluation process allowed classification of the level of evidence as low, moderate or high, based on the design and quality of reporting without using a full tool for assessing risk of bias as the use of such a tool would have been limited in validity due to the large amount of heterogeneity present in the methodologies and outcome measures of the included studies.

RESULTS

All relevant studies were grouped based upon their main theme; should any study include more than one thematic domain, it was categorized into its primary domain as reflected in its methods and conclusions. The horizontal bar chart (Figure 1) was derived from the frequency distribution of all 30 included publications within five core thematic domains (invasive, non-invasive, clinical, biochemical, and digital) based upon the study's primary focus. Consequently, the chart depicts the comparative quantity of study findings for each thematic area, independently from their methodological rigor, and relevance to clinical practice. Numbers depict the quantity of included publications categorized by thematic area (n=30): Non-Invasive Methods (n=9, 30%), Clinical Parameters (n=7, 23%), Digital Innovations (n=6, 20%), Invasive Methods (n=5, 17%), and Biochemical Methods (n=3, 10%). It also illustrates

Tab. 2 Comparison between measurement techniques.

Emerging Technology	Description	Potential Benefits	Challenges	Key References
Quantitative Ultrasound	Measures sound wave speed through implant-bone interface for stability	Non-radiation; sensitive to healing stages	Needs standardization; early validation stage	19, 37
AI-Driven Prediction	Machine learning analyzes radiographs for success trends	Early failure detection; personalized risks	Training and data needs	23–25
Digital Twins	Simulates patient-specific healing outcomes	Scenario testing without invasion	High infrastructure costs	26, 27, 39, 40
Biochemical Standardization	GCF markers like osteocalcin for remodeling	Real-time biological insights	Lack of validated threshold	22

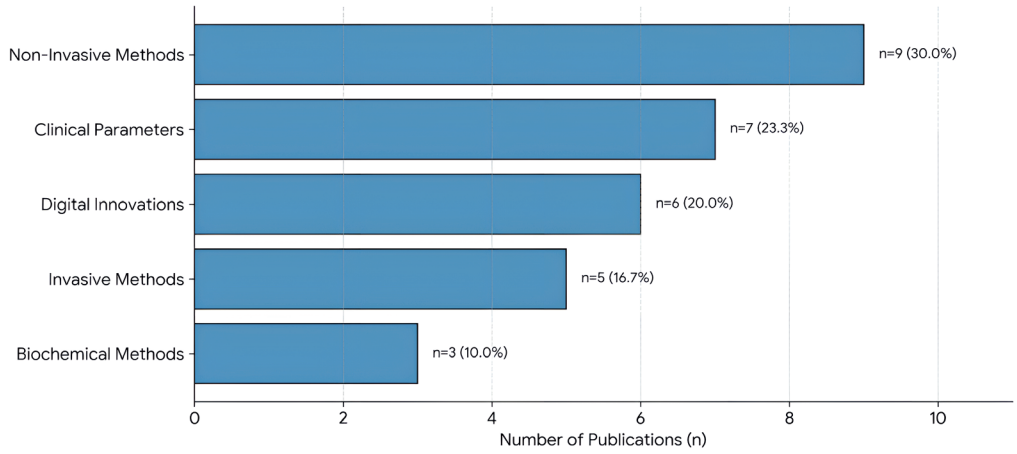

Fig. 1 Distribution of core thematic publications (N=30).

the quantity of evidence found in the literature reviewed, where the majority of the literature focused on noninvasive and digital techniques. Because of this disparity, there is a proportionately smaller number of biochemical papers compared to noninvasive and digital, which indicates that there is not yet sufficient clinical standardization regarding molecular diagnostic procedures, as there are established mechanical and emerging computational techniques. Furthermore, the data extracted from these studies provide information regarding study focus, methodology, main findings, and clinical implications.

Osseointegration is a multifactorial, complex biological phenomenon that starts immediately after the dental implant is placed in the alveolar bone, and the healing cascade (similar to a fracture healing cascade) begins (1, 2). The first inflammatory cells arrive at the surgical site to clear any cellular debris from the tissue and to release cytokines to stimulate the arrival of osteoprogenitor cells (the cell type that produces bone) (8). The next stage of healing is the differentiation biomechanically of the osteoprogenitor cell to an osteoblast, which begins to lay down adapting osteoid and will eventually mineralize into bone (9). In animal study, few weeks after the dental implants are placed, a direct interface occurs between the implant surface and the alveolar bone, described as bone-to-implant contact (BIC) (10). BIC is among the prototypical histological determinants of osseointegration, but it cannot be measured clinically. We will be left with only our surrogates to rely upon in the clinical environment to make osseointegration assessments that include mechanical stability, resonance frequency, or radiographic bone levels.

INVASIVE METHODS OF ASSESSING OSSEOINTEGRATION

a) Histological Analysis

Histology is an objective reference because it supplies photographic records of the bone-implant interfaces (contact points). However, this method necessitates the removal of both the implant and the surrounding bone (11). While the data from histomorphometry is statistically valid as a calculation of the proportion of BIC, it should be considered more of an overall descriptor rather than a measure of performance or effectiveness (12). As with histological techniques, histomorphometric analyses are invasive and include ethical considerations in dentistry. Thus, there are no applications of this method in clinical practice.

b) Removal Torque Testing

The implant removal torque testing, Torque Testing Method (TTM), measures the torque required to unscrew the implant from the bone (13). Higher torque values in Newton Centimeter (Ncm), indicate greater bone anchorage (14). Like histology, it damages the bone and implant. Its primary use is experimental, not clinical. The torque test can interrogate the effectiveness of bone quality, implant design, and surface treatment. The torque test is not used in a routine patient setting.

NON-INVASIVE METHODS OF OSSEOINTEGRATION ASSESSMENT

a) Radiographic Evaluation

In implantology, radiographic images (15) are very common and are simple and non-invasive to obtain. Radiographs, including periapical, panoramic, and cone-beam images, have provided electronic evaluations of the bone level surrounding the implant or other implant-related process. Although marginal bone loss can be identified on radiographic images, as indicated by the change in the bone height surrounding the implant, radiographs do not allow for confirmation of the presence and percentage of bone-to-implant contacts (BIC) surrounding the implant. Radiographs can show changes in marginal bone height, although the presence of connective tissue at the implant surface cannot be identified through these images. Interpretations of radiographs are of a subjective nature (16).

b) Resonance Frequency Analysis (RFA)

Resonance frequency analysis (RFA) is one of the most accepted methods of assessment in implant studies. RFA is accomplished with a device that attaches to the implant. This device creates vibrations in the desirable frequency range through the implant, and the frequency of the sinusoidal pattern of the vibrations is recorded to represent the Implant Stability Quotient (ISQ score). Higher ISQ scores measure stability (17). RFA is a non-destructive method allowing for repeatability and a measure that removes an

aspect of investigator bias. RFA is very useful to monitor the physiological process of bone to implant healing.

c) Periotest

The Periotest device measures damping characteristics and determines the implant's mobility by tapping on the implant and quantifying its damping characteristics (18). For Periotest, a lower Periotest value represents higher stability. However, the Periotest is more sensitive to angulation and positioning than RFA and has more variation than RFA. Other devices for assessing implant stability are also available, including systems based on resonance frequency analysis as well as percussion-based approaches, each with specific methodological limits (3).

d) Quantitative Ultrasound

Ultrasound is demonstrated as a diagnostic tool that measures sound waves traveling through the implant site (19). The speed of sound propagation would indicate bone quality and bone-to-implant contact. Currently, ultrasound has been proposed as safe and potentially useful. It may become one of the options in the future.

CLINICAL PARAMETERS OF OSSEOINTEGRATION

A clinician recognizes the successful fusion of an implant to the bone (osseointegration) by looking for specific clinical signs, which include no pain, no inflammation, and no movement (5). Although there are no standard criteria for assessing osseointegration, these signs can all be used by the clinician to make judgments regarding potential osseointegration.

One additional method of assessing osseointegration is using the probing depth observed around the area of the implant. When probing depth measurements are taken and found to be low without any bleeding, this may help support the possibility of osseointegration having been achieved (5, 20). Proper technique should be utilized during probing to prevent trauma to either the implant or patient.

Percussion sound is another option that clinicians might choose to evaluate osseointegration. Percussion sounds can be evaluated by tapping on the implant with a metal instrument to produce sound, giving some indication of osseointegration status based on the sound produced. If the implant produces a sharp, high-pitched sound when tapped, this may be an indication that osseointegration has occurred. If tapping produces a low-pitch or dull sound, it may indicate that the implant does not support adequate stability and has not fused (integrated) with bone (21).

BIOMARKERS AND MOLECULAR INDICATORS

Biochemical markers are also a recent focus of research. Biochemical markers are proteins found in the products of crevicular fluid that can suggest bone activity. Biomarker studies are focusing on markers, such as osteocalcin, alkaline phosphatase, and interleukins. When possible, localized and relatively non-invasive methods of collection, such as salivary or gingival crevicular fluid (GCF), if the product of the implant, could provide insight into real-time bone remodeling (22). However, a lack of standardization presents a challenge, and clinical use is nonexistent currently.

DIGITAL INNOVATIONS

Artificial intelligence (AI) enhances healthcare diagnostics. In implantology, AI provides analysis of radiographs and predictive abilities for healing and bone density trends (23–25). Machine learning algorithms can predict trends of success associated with implants, in addition to the various types of radiographic options from multiple manufacturers today. Digital workflows allow for the development of 3D models of the patient's cortical bone. These models allow for the determination of stress distribution and osseointegration, providing assistance over time. Potentially in the future is to have patient "digital twins" that may rely entirely on digital and model workflow (26).

An individual's digital twin is a digital representation of a person's medical history, a digital copy of the actual patient, constructed from a combination of detailed patient records and various other aspects of the person's health status. In essence, this virtual replica of the individual allows simulation, forecasting of outcomes, and tailoring of therapies in a way that closely represents the patient themselves. The idea has been adapted from engineering to allow better applications within the field of personalized medicine (27).

DISCUSSION

Evaluation of osseointegration is undoubtedly one of the most important clinical issues for all forms of implant dental procedures. Multiple variables can impact measurement. For example, implant type and materials, surface properties, bone density, and operative technique. Patient factors such as smoking, uncontrolled diabetes, osteoporosis, and vitamin D deficiency are all variables that can impact osseointegration. Measurement figures should account for all of these variables in order to obtain reliable values (28–31). The future is multifactorial. Radiographs, RFA, biomarkers, and computer modelling when used collectively will account for all potential measures and provide a holistic view of the process. Personalized medicine will likely play a more dominant role (32). Patient-specific risk profiles or timelines with risk determinations assessed through artificial intelligence enhancement could direct clinicians on treatment timelines and reduce overall adverse events while improving functional outcomes (23–25). Research should seek to standardize procedures. A standardized protocol can facilitate comparison between studies and clinical implementations.

Although researchers have conducted numerous studies regarding osseointegration, there is no available clinical method that offers a definitive and thorough understanding of the biological and mechanical components of bone-to-implant attachment. The following are four key findings from the body of evidence reviewed here, indicating that, despite being helpful in some situations, current

diagnostic techniques fail to provide complete and reliable information in a wide variety of clinical scenarios (33, 34). Evidence strength varies significantly based on the assessment modalities used in the evaluation of mechanical stability. Clinical validation for mechanical stability tools, such as radiographic assessment and RFA, is robust, while evidence of clinical validity for biochemical markers and AI predictive systems is mostly from developing or exploratory studies; thus, limiting their ability to make clinical generalizations.

Although invasive methods like histological assessment and removal torque are evident experimentally, they cannot be applied in clinical practice since they are destructive and unethical in the clinical practices (11, 12). The direct measurements obtained from these processes can only be used for research experiments since this type of information is not available for in vivo studies (13). These techniques primarily serve to validate indirect measures, but they do not currently play a significant role in the everyday practice of clinicians.

Radiography is a widely used non-invasive assessment technique. It only provides inferences, at best (usually marginal bone levels), without ever informing us of true osseous contact at the interface with the implant. Further, radiographs are subjective, and their usefulness as a diagnostic tool is limited without comparative images or clinical follow-up (15, 16). Cone-beam computed tomography (CBCT) offers higher spatial resolution. However, the fact that it comes with costs and radiation exposure, and that it does not clearly show soft tissue pathology or true soft tissue-implant connection, limits its diagnostic value (15, 35).

Resonance Frequency Analysis (RFA) with its metric Implant Stability Quotient (ISQ) offers reproducible, operator-independent evaluations of primary and secondary stability with many clinical applications (3). RFA and ISQ have entered the clinical decision-making process, particularly in operative protocols or non-removable loading relative to loading decisions. Generally, an ISQ >70 is indicative of high primary stability, providing a clinical value for immediate or early loading protocols. Values ranging between 60 and 70 are considered acceptable for standard loading after a conventional healing period, while an ISQ <60 typically suggests low stability (3, 17, 36). However, ISQ values are not standardized or equal and vary with implant design, transducer calibration, and the bone quality that surrounds the interface. Although Periotest measures have been made ostensibly similar to ISQ, Periotest success is defined by values ranging from −8 to +5, where lower or more negative values indicate higher stability. However, this method demonstrates higher variability than RFA because measurements are significantly influenced by the vertical position and angulation of the instrument (18, 36).

Quantitative ultrasound, as a novel domain, investigates the acoustic propagation of contact with the bone surface estimation in vivo. In theory, this might be a more sensitive option, and it is certainly safe and practical from a cost perspective. However, the field is currently exploratory. Interpreting valid criteria of standardization and correlating to outcomes has not yet progressed at a level fit for clinical use (19, 37).

The resultant adoption of percussion testing, an older clinical technique reassembled with an acoustic analysis bent, also reflects a broader attempt to identify clinically valuable data from basic, empirical observations. While the sounds produced by a metallic device may provide some qualitative indicators of implant stability, they lack quantification and reliability because they depend on operator reproducibility. As such, its continued existence in clinical practice demonstrates the ongoing demand for methods to evaluate stability that are inexpensive, easy to use, and do not require sophisticated machinery (21, 38).

Molecular and biochemical markers also represent an interesting area. They potentially offer the advantage of inferring osseous activity in real time via peri-implant fluids or serum (22). However, we are not at a point at which we can use those markers as actionable biomarkers within patient populations, because the thresholds are not currently validated, and discrepancies exist between different patient populations. Research has shown that osteocalcin, alkaline phosphatase (ALP), and interleukin-1β (IL-1β) are potential biomarkers found in peri-implant crevicular fluid (PICF) and saliva but currently is not an established clinical threshold universally accepted for immediate surgical or prosthetic intervention. Non-validated data and differing systemic health conditions prevent concentration-dependent fluctuating values from guiding clinicians in their determinations of osseointegration success or failure. Therefore, these markers are only used in research settings. For a biomarker to attain clinical acceptance it must be embedded within a rapid, cost-efficient point-of-care (POC) test that can provide results during the patient visit.

The implementation of Artificial Intelligence in implantology has transformed from being merely a notion to being comprised of an array of scientifically based applications that deliver considerable value in developing diagnostic accuracy. Currently, a technique has been validated for the automated identification and numbering of dental implants from panoramic radiographs, thus reducing human error associated with the documentation of clinical records (24, 25). In addition, machine learning algorithms and radiomics techniques are issued for the analysis of bone density and quality derived from CBCT scans (23). Thus, producing objective, quantitative data for practitioners to use when developing surgical plans. Although these tools are currently being used as a supportive decision-making tool, rather than as independent diagnostic devices, they provide a statistically modified data methodology for estimating the probability of an individual's long-term success in implant therapy and for customizing treatment protocols.

Digital innovation has the greatest potential to disrupt the status quo going forward. The integration of AI and advanced analytics of diagnostic imaging and longitudinal datasets, or workflow-based assessment tools like surgical planning diagnostics, offers clinical solutions never before possible (23–27, 39, 40). Even as hypothetical concepts, "digital twins", which involve simulation modeling based on multimodal data of a virtual patient, may allow clinical users to digitally simulate predicted implant capability or clinical performance (26, 27). However, like any

new technology, the value of these new predictive digital assessment or simulation methods is largely dependent on infrastructure, data flow, data interoperability, and clinician user training. If small practices cannot integrate these new digital products directly into workflows to maximize efficiencies in healthcare delivery, then generalizability will become limited to individual practitioners or academic and specialized centers (39, 40).

Implant geometry, surgical method, bone density, systemic health, and loading regimes will all affect the accuracy and interpretation of measurement. Therefore, both qualitative and quantitative assessments integrated with clinical (mixed models with whole patient assessments) will be optimal, where it could be realized using various methods that include mechanical testing, radiographic imaging, biochemical monitoring, and computational modeling methods to create a more comprehensive dynamic understanding of osseointegration over time. A goal is to inform, not to replace clinical decision-making.

Future studies should not only emphasize improved technology, but also the methodology for calibrating technology and standardize the processes when possible. If we can harmonize the measuring schemes, calibrating protocols, and reporting outcome definitions, we may preserve the integrity of the clinical trials and accelerate the transfer of new technology into the clinic. Biological (secondary) stability assessment remains the clinical benchmark for implantology. The combination of biological and computational monitoring is the next frontier in the field. Otherwise, we will continue assess osseointegration largely on the basis of concept and not precise measurements. The characteristics, advantages, and challenges associated with these emerging technologies are summarized in Table 2.

CONCLUSION

Assessment of osseointegration remains difficult due to the absence of a consistent technique to detect osseointegration, with many different ways of measuring it all having their own benefits and drawbacks. Decisions about how to treat patients based on assessment of osseointegration usually involve combining multiple measurement types. With advances in technology, there exists the opportunity for future non-invasive, accurate assessments of osseointegration, as more will be learned about biology and biomechanics, which will allow for more confidence in the reliability of assessments of osseointegration. The more improved our measurement techniques for osseointegration are, the more improved care will be available to patients. Therefore, better measurements provide patients with greater certainty regarding the safety, security, and durability of the implant supra-structure.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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