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Experimental and Clinical Methods for Assessing the Primary Stability of Dental Implants: Current Capabilities and Future Prospects

(Literature Review)

▷ **Abstract.** The success of implant-supported prosthetic treatment largely depends on primary stability, a critical determinant of successful osseointegration. Evaluating implant stability together with the condition of the surrounding bone enables clinicians to anticipate the integration process and detect potential complications during healing and bone remodeling. Modern clinical approaches include instrumental and imaging diagnostic techniques, such as resonance frequency analysis (RFA) and Periotest measurements; however, their objectivity and applicability in routine practice remain a matter of ongoing debate. In addition to established methods, experimental and less widely used hardware-based approaches are actively being investigated, allowing quantitative evaluation of implant–bone interactions and measurement of stability parameters in physical units. Among these technologies, ultrasound analysis is considered promising, as it enables comparison with histomorphological data on osseointegration and provides objective quantitative measures of primary implant stability.

Purpose: to evaluate current methods for determining the primary stability of dental implants and their correlation with objective indicators of osseointegration, specifically bone–implant contact (BIC), as well as to identify the potential for their clinical application.

Materials and Methods. For this review, a targeted search of scientific publications was conducted in three recognized international databases: PubMed, Scopus, and Web of Science, covering recent years. The search employed a combination of keywords related to the topic, including dental implants, primary stability, osseointegration, and implant stability assessment. Articles were selected based on strict criteria for relevance to the review topic and scientific merit. A total of 21 sources were included in the final analysis, comprising both review articles and original research. Each publication underwent a qualitative assessment, focusing on relevance, methodological rigor, and the novelty of the reported findings. This approach provided a comprehensive and up-to-date understanding of current methods for evaluating the primary stability of dental implants.

Results. Analysis of the literature indicates that resonance frequency analysis (RFA) and Periotest can be used to assess implant stability at various stages of osseointegration, but their precision is limited, and they do not fully capture either the mechanical or biological aspects of integration. Experimental methods, including ultrasound diagnostics, electromechanical impedance, and laser testing, provide more objective results expressed in physical units and demonstrate correlation with bone–implant contact (BIC), making them promising tools for clinical and research evaluation of both primary and secondary implant stability.

Keywords: *dental implants, primary stability, osseointegration, assessment of implant stability, resonance frequency analysis, ultrasound analysis, experimental approaches.*

Dental implantation is considered one of the most effective methods for the prosthetic rehabilitation in patients with partial or complete edentulism [1]. Despite this, routine monitoring of implant stability is relatively uncommon and often incomplete [2]. Although the literature describes detailed follow-up protocols for patients during both the early and late stages of implant function, these protocols are frequently applied only partially in clinical practice [3].

This can lead to delays in dental care when complications occur following implant placement.

The process of dental implant osseointegration involves a complex series of adaptive and biological responses to the implanted structure, including protein cascades, angiogenesis, cellular apposition, and the formation of new bone tissue around the implant [4]. The quality and density of the alveolar jawbone are critical for successful integration [5] and are typically assessed using radiographic methods. In recent years, particular attention has been paid to instrumental physical methods for evaluating implant primary stability. These methods can be applied at any stage after implant placement, allowing early detection of potential complications during osseointegration. The classical concept of osseointegration is defined as the formation of a structural and functional connection between the bone and the load-bearing surface of the implant [6]. Primary integration consists of bone matrix formation on the implant surface and the development of bone tissue in direct contact with it, followed by a prolonged process of bone remodeling, characterized by alternating cycles of resorption and formation throughout the lifespan of the implant-supported restoration [7]. The primary mechanism of new bone formation around the implant is contact osteogenesis, which may be supplemented by distant osteogenesis [8]. One of the key factors for successful osteogenesis and long-term implant function is the implant's primary stability [9]. This stability is defined as the mechanical immobility of the implant, characterized by the absence of detectable movement under horizontal and vertical loads of up to 500 g, a condition that is essential for the development of high-quality osseointegration [10].

Micromovements of an implant as small as 100 µm may trigger bone resorption at the implant–bone interface, thereby impairing bone remodeling [11]. As the morphological stages of primary osseointegration progress, secondary (biological) stability develops; however, implant loss is most common during the early stages [12]. Micromovements interfere with osteogenesis around the implant, stimulate osteoclast activity, increase bone resorption, and hinder the establishment of full mechanical and biological integration.

Experimental models have shown that osseointegration may occur successfully even without direct implant–bone contact, emphasizing the critical role of primary stability [13]. Various methods are used to monitor implant stability. The most biologically accurate method is histological analysis of bone–implant contact (BIC), which provides detailed insight into bone tissue responses at the implant surface, although it is impractical in routine clinical settings.

In clinical practice, indirect methods are employed to assess osseointegration and primary stability, including clinical examinations and instrumental techniques such as resonance frequency analysis (RFA), Periotest, torque testing, and biopotential measurement [14]. In addition, experimental hardware-based approaches leveraging physical phenomena—ultrasound, acoustic, and laser vibrations—are under investigation. Among these, physical methods evaluating the implant–bone system are regarded as the most objective.

A key technique is resonance frequency analysis (RFA), which assesses the relationship between the vibration frequency of an implant under forced excitation and the stiffness of the surrounding bone. RFA is applied to analyze the implant–tissue–bone (ITB) system, which serves as a mechanical analogue of bone–implant contact (BIC) [20, 22]. Using the Osstell device, a metallic magnetic peg ("SmartPeg") is mounted on the implant and stimulated by an electromagnetic pulse. The device records the frequencies of implant vibration and calculates two stability coefficients—maximum and minimum—representing the "strong" and "weak" regions of osseointegration on the implant surface.

This approach enables spatial assessment of implant stability and facilitates identification of areas with weaker integration.

Measurements in resonance frequency analysis (RFA) are recorded in hertz but, for clinical convenience, converted into implant stability quotient (ISQ) units ranging from 1 to 100. The ISQ scale enables clinicians to compare implant stability across cases and over time. However, the ISQ values are affected by multiple variables—implant design, bone density, and measurement conditions—complicating their interpretation. Despite these limitations, RFA remains among the most widely employed methods for assessing implant stability in clinical practice. Nevertheless, the ISQ scale does not yield direct information on bone–implant contact (BIC), the most objective indicator of osseointegration, which is typically assessed histologically or via computed tomography.

Animal studies have shown that bone resorption around implants is not consistently correlated with RFA values. Despite extensive evidence supporting the use of Osstell for predicting implant stability and potential complications, the precision and objectivity of ISQ continue to be debated. Some authors consider ISQ a relative measure lacking a direct physical equivalent [16] and note that it does not directly correspond to BIC or torque measurements during implant removal does not correspond directly to bone–implant contact (BIC) or to torque measurements obtained during implant removal. Changes in torque within the range of 30–100 Ncm exert minimal influence on ISQ, underscoring the weak correlation between these parameters and limiting the utility of ISQ for comprehensive assessment of primary stability. Furthermore, RFA is not a reliable method for assessing the stability of mobile implants.

The physical basis of RFA is the measurement of stiffness within the implant–bone system. Clinically mobile implants demonstrate low stiffness, thereby reducing the accuracy of the method [17]. Considering both the strengths and limitations of RFA, it can be concluded that this technique enables evaluation of implant stability at various stages of osseointegration and under functional load, but it cannot fully substitute for more objective approaches, including histological analysis or computed tomography.

Another widely used hardware-based method is Periotest, performed using the Periotest device. This method relies on mechanical stimulation of the implant and was originally developed to assess the damping properties of the periodontal ligament [18]. It is regarded as an objective tool for evaluating tooth mobility. The device delivers 16 percussive impulses over 4 seconds, with the response captured by an accelerometer. Results are reported in arbitrary units ranging from –8 to +50: more mobile structures show longer contact times and higher readings, whereas stable implants demonstrate shorter contact times and lower values.

The method enables assessment of implant mechanical mobility and its correlation with the damping properties of the surrounding tissue. However, comparing these values with bone density is not entirely objective, because under normal osseointegration, no connective tissue layer develops between the implant and the bone. The presence of such a layer signifies fibroosseointegration, a less favorable form of integration. Therefore, Periotest is applicable in both clinical practice and research; however, its results require cautious interpretation and cannot substitute for direct methods of stability assessment [19].

Literature data indicate that predicting implant stability and function on the basis of a single assessment method may be inadequately substantiated. Mobility values obtained via Periotest are expressed in arbitrary units and lack a direct physical interpretation. Nevertheless, several studies confirm that these devices can be objectively employed for the comprehensive evaluation of implant stability.

In addition to RFA and Periotest, less common but sufficiently objective hardware-based methods are reported. Laser testing enables simulation of implant loading in artificial bone-mimicking materials and measures the relationship between applied torque and the implant's rotation angle. Comparative analyses of laser testing, RFA, and Periotest have demonstrated both positive and negative correlations among these methods.

The electromechanical impedance method relies on piezoelectric transducers applied to bonemimicking materials. Stability is assessed by considering the mass, stiffness, and damping coefficient of the implant–material system, allowing objective evaluation of the implant's frequency characteristics [20].

Computer modal analysis determines the natural resonance frequency of a structure from its mechanical properties (Young's modulus, Poisson's ratio, and density). This facilitates modeling of the vibrational behavior of the implant and periimplant bone and allows calculation of stress and strain across different bone layers. The impact hammer method applies a brief force to the object, followed by analysis of the response wave in terms of velocity, acceleration, and deformation, allowing quantitative evaluation of implant stability [21].

Of particular interest is the quantitative ultrasound method, tested in animal models. Ultrasound evaluation allows measurement of implant biomechanical stability in objective physical units (megahertz). This approach was first introduced by De Almeida et al. (2007) as an alternative approach for assessing implant integration. Histological evaluation of bone–implant contact (BIC) was performed in parallel to validate the findings. Comparison of results indicated that the ultrasound response depends not only on BIC but also on the mechanical properties of the surrounding bone, making this combination particularly informative for comprehensive assessment of both primary and secondary implant stability. Additionally, ultrasound findings were compared with RFA results (Osstell), revealing a correlation between the methods and confirming the potential of ultrasound as an objective and reproducible tool for evaluating implant stability [21].

Conclusion

Comparison of different diagnostic systems indicates that, in addition to traditional methods such as RFA and Periotest, experimental hardware approaches show considerable promise. Assessing implant stability based on physical characteristics yields objective quantitative data that can be correlated with reliable morphological markers of osseointegration and may be implemented in clinical practice. Hardware-based monitoring enables measurement of stability in physical units and comparison with the bone–implant contact (BIC) coefficient. This approach appears promising among existing methods but requires additional theoretical refinement and practical validation.

Conflict of interest

The authors state that they have no conflict of interest.

Consent to publication

The authors have provided consent for publication of the manuscript.

Use of Artificial Intelligence

The authors affirm that no artificial intelligence was employed in the preparation of the manuscript.

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Експериментальні та клінічні інструментальні методи оцінки первинної стабільності дентальних імплантатів: можливості та перспективи (огляд літератури)

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Анотація. Успішність протезування з опорою на дентальні імплантати значною мірою залежить від їх первинної стабільності, що є ключовим фактором для успішної остеоінтеграції. Оцінка стабільності імплантата та стану навколишньої кісткової тканини дозволяє прогнозувати процес інтеграції та своєчасно виявляти потенційні ускладнення під час загоєння та ремоделювання кістки. Сучасні клінічні підходи включають використання інструментальних та візуалізаційних методів діагностики, таких як аналіз резонансної частоти (RFA) та вимірювання за допомогою Periotest; однак їх об'єктивність і застосовність у рутинній практиці залишаються предметом наукових дискусій. Окрім визнаних методів, активно досліджуються експериментальні та менш поширені інструментальні техніки, що дозволяють кількісно оцінювати взаємодію імплантата з кісткою та фіксувати параметри стабільності у фізичних величинах. Серед цих технологій перспективним вважається ультразвуковий аналіз, оскільки він дозволяє порівнювати результати з гістоморфологічними даними остеоінтеграції та надає об'єктивні чисельні характеристики первинної стабільності імплантата.

Мета: оцінити сучасні інструментальні методи визначення первинної стабільності дентальних імплантатів та їх кореляцію з об'єктивними показниками остеоінтеграції (BIC), а також визначити перспективи клінічного застосування цих методів.

Матеріали та методи. Для підготовки огляду було проведено цілеспрямований пошук наукових публікацій у трьох визнаних міжнародних базах даних: PubMed, Scopus та Web of Science, охоплюючи останні роки. У пошуку використовувалася комбінація ключових слів та термінів, що стосуються теми: дентальні імплантати, первинна стабільність, остеоінтеграція, оцінка стабільності імплантатів. Відбір статей здійснювався за строгими критеріями відповідності темі огляду та наукової цінності публікацій. В остаточний аналіз увійшло 21 джерело, включно з оглядовими статтями та оригінальними дослідженнями. Кожна публікація пройшла якісну оцінку з акцентом на актуальність, методологічну точність та наукову новизну представлених даних. Такий підхід дозволив сформувати комплексне та сучасне уявлення про методи оцінки первинної стабільності дентальних імплантатів.

Результати. Аналіз літератури показав, що аналіз резонансної частоти (RFA) та Periotest дозволяють оцінювати стабільність імплантатів на різних етапах остеоінтеграції, проте мають обмежену точність і не повністю зображають механічну та біологічну інтеграцію. Експериментальні методи, включаючи ультразвукову діагностику, електромеханічний імпеданс та лазерне тестування, демонструють більш об'єктивні результати у фізичних величинах і корелюють з BIC, що робить їх перспективними для клінічної та наукової оцінки первинної та вторинної стабільності імплантатів.

Ключові слова: *дентальні імплантати, первинна стабільність, остеоінтеграція, оцінка стабільності імплантатів, аналіз резонансної частоти, ультразвуковий метод, експериментальні методи.*

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