Advances in Osseointegration for Dental Implants: Influencing Factors and Measuring Methods

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Abstract

AIM: To review the latest research data on osseointegration and understand influencing factors as well as measurement methods associated with osseointegration.
METHODS: A literature review was conducted using the PubMed and ScienceDirect databases, identifying and classifying articles from the last 15 years based on quality and relevance.
RESULTS: Dental implantology has advanced significantly since its inception 60-70 years ago. Current research showcases diverse methodologies and examines various aspects of osseointegration. While the primary past focus was on achieving osseointegration, contemporary research emphasizes broadening the limits of dental implantology. Dental implants can now be loaded immediately after achieving required primary stability, even before osseointegration occurs. Osseointegration is feasible in compromised patients with conditions like diabetes or HIV. Advancements in medical care and pharmacotherapy may introduce new effects influencing bone healing and osseointegration. Furthermore, manufacturers are enhancing the range of available products through surface and shape modifications, with certain modifications, including laser treatments or coatings, showing improved outcomes and expedited osseointegration.
CONCLUSION: Identified key influencing factors aid practitioners in achieving successful implant restorations. With this knowledge, practitioners can better anticipate treatment outcomes, considering all factors, including the patient, dental team, and implant itself.

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Archive of Orofacial Data Science

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1 Introduction

The term “osseointegration” originates from two Latin words, “osseus” and “integrare.” It denotes the direct connection between bone and a load-bearing implant in both functional and structural aspects (Albrektsson et al., 1981).

The history of dental implants can be traced back several thousand years to the ancient Egyptian Empire, where practitioners attempted to place carved seashells or stones into the human jaw to replace missing structures. Subsequently, noble metals were used in the form of the missing root and placed into the extraction socket (Lee et al., 2005). Practitioners have endeavoured to replace lost teeth and restore the missing chewing function by implanting various alloplastic materials into the bone; however, scientifically based implant therapy has only become feasible since the 1970s (Brånemark et al., 1977). Over the past five decades, implant dentistry has transitioned from an experimental phase to a predictable option for replacing missing teeth (Buder et al., 2017). With the advancement of research and an increase in published findings, the popularity of implantology has grown significantly. Today, dental patients are largely aware of the option to have their teeth replaced with dental implants, which has consequently increased the number of dentists specialising in dental implantology. Gradually, implantology is becoming the gold standard for replacing missing teeth (Deeb et al., 2017).

Despite this progress, the main factors influencing the success of dental implants and their osseointegration, as well as the general medical conditions affecting treatments, remain poorly understood by practitioners. When dental implants were first introduced, the primary objective was the successful osseointegration of the placed implants. Today, several decades later, the field of implantology has advanced substantially from its original principles. In 1988, there were 45 implant companies (English, 1988). By the year 2000, this number had increased to 98 implant producers (Binon, 2000). Later, in 2003, Jokstad et al. reported more than 78 manufacturers offering 225 implant brands (Jokstad et al., 2003), noting that 70 of these implant brands were no longer marketed. By 2008, more than 357 implant brands were reported. Furthermore, in 2001, it was estimated that over 450,000 dental implants were placed annually, combined with an expected 95% success rate for osseointegration (Sullivan, 2001).

Today, it would be challenging to estimate the number of dental implant producers and the brands available on the market. Essentially, a new implant brand enters the market on a weekly basis, while some brands or companies may no longer exist.

Current trends in implant dentistry indicate a growing demand for more aesthetic and predictable, yet less invasive, implant interventions. The long-term functionality, as well as the stability of hard and soft tissue, has become the primary focus of contemporary research. Although osseointegration is not typically the main concern — and most practitioners take it for granted during implant placement — it can still be influenced by various factors. When selecting an implant therapy for a patient, or deciding whether implant placement is a viable option, patients expect practitioners to explain all advantages and disadvantages of the various treatment types, including potential failure rates. Several factors may influence this decision, such as implant shape and design, surface treatment, insertion method, torque and speed, pre-drilling procedure, and whether the procedure is guided or non-guided.

The fundamental factors influencing osseointegration were established by Cooper et al. (1998), who studied the speed of osseointegration. Their review article indicates that the covalent binding of proteins begins within the first 10 minutes after implant insertion. Cellular attachment occurs within the initial half to four hours, while cellular spreading commences after the first four hours, continuing within the first twenty-four hours. Both cellular migration and proliferation are ongoing processes. The synthesis of proteins starts after the first hour, and mineralization begins after four hours (Masuda et al., 1998).

The main objective of the study was to find the newest innovations and researches those deal with osseointegration and to identify the up-to-date facts about the influencing factors. Secondary objective was to understand the best methods to clinically measure osseointegration.

2 Methods

A search of the electronic databases MEDLINE-PubMed and ScienceDirect was conducted in March 2019. Manuscripts published in English from 2004 to 2019 (a span of 15 years) were included. The keywords for the advanced search were "osseointegration" together with either "endosseous implant" or "dental implant". The combination of osseointegration and dental implant yielded 7,262 search results on PubMed, of which 5,174 were published in the last 15 years. The combination of osseointegration and endosseous implant produced 3,369 results on PubMed, with 2,178 published in the same period.

Regarding ScienceDirect, the combination of osseointegration and dental implant provided 5,174 search results, of which 4,225 were published in the last 15 years. The combination of osseointegration and endosseous implant resulted in 1,073 results, of which 669 were published in the specified 15-year period.

The searches were narrowed down to research articles and reviews, excluding non-dental or non-oral studies. Animal studies, as well as preclinical experiments, were included in the analysis. Only articles from peer-reviewed journals were considered, and the intention was to integrate all available information from the last 15 years concerning osseointegration and its influencing factors. Data were categorised into major topics, such as influencing factors of osseointegration, measurement of osseointegration, and speed of osseointegration. Within the topic of influencing factors, a subdivision was made into patient-related influencing factors and implant-related influencing factors.

From the identified studies, titles and abstracts were evaluated. When an abstract did not provide sufficient information to make a decision regarding inclusion or exclusion, the full manuscript was assessed before arriving at a final decision. Studies that appeared in both databases were considered only once.

To ensure the inclusion of the most reliable articles, primarily meta-analyses were incorporated. However, in certain critical areas where no meta-analyses were available, some review articles, basic research articles, as well as controlled, randomised clinical trials were included. These instances were noted, as they indicated a somewhat weaker scientific background. In cases where evidence-based research was available prior to the selected 15 years, as referenced in numerous articles, the original articles were utilised as references, rather than those citing them. After all these modifications, a total of 68 articles were used to reach the final conclusions.

2.1 Statistics

Descriptive statistics, frequency analysis, and content analysis were employed as part of the qualitative methodology to systematically analyze the textual content of the included studies. It is important to note that, given the narrative nature of this study, regression analysis and meta-analysis techniques were not deemed suitable for the analytical framework.

3 Results

The term "osseointegration" was described in the Glossary of Prosthodontics Terms in 2005. It refers to the direct connection, or even attachment, of hard tissue (bone) to inert, alloplastic materials without the intervention of connective tissue. Essentially, it represents the interface between the alloplastic material and the osseous tissue

3.1 Speed and success of osseointegration

Osseointegration is a process that has been extensively described. The fundamental principle is that osseointegration results in a permanent conjunction between the titanium surface and bone tissue. This can be established when a precise and fitting recipient site is prepared in the recipient bone, ensuring no major injuries to its anatomical structures. The recipient site must be perfectly adapted in shape to the dental implant being placed (Brånemark, 2005).

The entire healing process is quite similar to primary healing when a bone injury occurs, such as in cases where primary bone healing is achieved. The process begins with the presence of blood and the formation of a blood clot at the site adjacent to the dental implant, between the titanium and the bone. Subsequently, this is transformed by lymphoid cells, including macrophages and polymorphonuclear leukocytes (**Figure 1**), with peak activity observed one to three days following implant insertion (Jayesh & Dhinaksaramy, 2015).

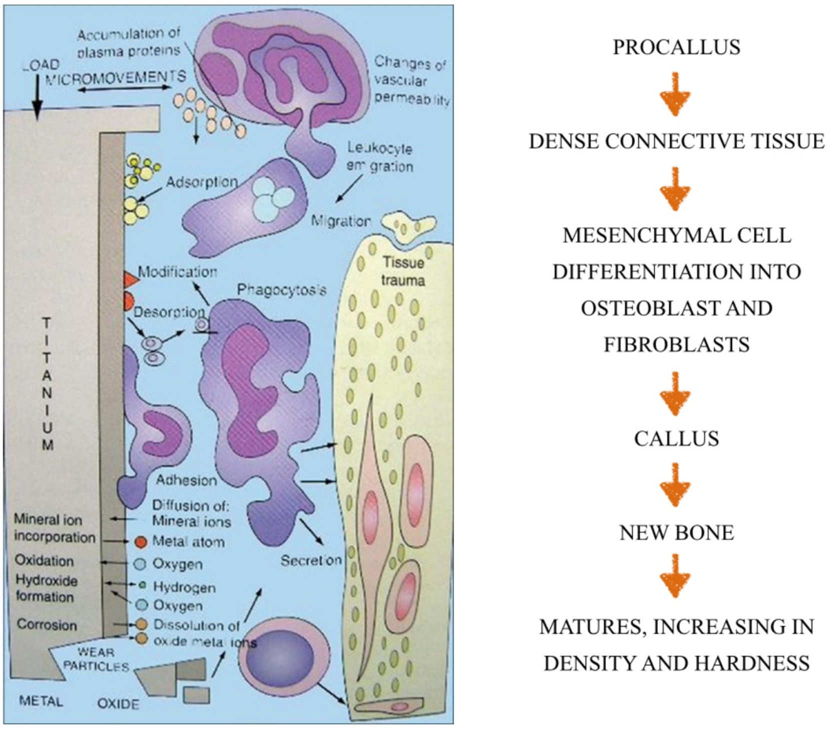

Figure 1. The process of osseointegration. Image source (CC BY-NC-SA 4.0): Jayesh & Dhinaksaramy (2015).

Osseointegration, as well as its speed, depends on several systemic and local factors. It should be noted that the process of osseointegration is not always successful following the placement of an implant. Numerous studies have documented high success rates; for instance, in a ten-year follow-up study, the survival rate and successful osseointegration were reported to be above 90% in totally edentulous jaws (Alghamdi, 2018). Nevertheless, dental implants can fail in certain cases.

A variety of complications may arise, and numerous reasons can contribute to the failure of dental implants, including misdiagnosis, inappropriate treatment plans, insufficient information regarding the medical history of the patient, the experience of the surgeon, or unforeseen factors during implant placement (Kate et al., 2016). Evidently, multiple elements can influence both the success and the speed of osseointegration.

This study aims to summarise the latest research data; therefore, we do not intend to include all factors in their entirety. Some factors, such as the influence of implant stability or severe inflammation at the surgical site, have been documented much earlier and are well known, having also been integrated into basic dental curricula.

3.2 Measuring osseointegration

Different methods have been developed to measure osseointegration. Several studies have examined and evaluated these various methods; however, only a limited amount of research has addressed the comparison of these measuring or evaluating techniques. Most methods primarily assess implant stability, which can be considered a clinical indicator of the absence of mobility (Sennerby et al., 2008). It is defined as "the ability to support axial, lateral and rotational loads" (Oh & Kim, 2012).

It has been documented that both radiological and clinical examinations have limited value in predicting the treatment outcomes of dental implants, such as their survival and osseointegration (Zix et al., 2008). Although there is insufficient evidence to indicate that any of these quantitative techniques possess a truly reliable predictive value for forecasting the loss of stability of dental implants, some methods are sufficiently objective to provide reliable data regarding the state of osseointegration (Aparicio et al., 2006).

Torque test. The torque test is often employed by dental professionals to assess the stability of dental implants. However, no evidence can be found regarding the reliability of this method. During implant insertion, the maximum achieved torque provides notable information, but it can only aid in determining the possibility of immediate implant loading (Misch et al., 2004). Implant stability changes over time (**Figure 2**). While primary stability is lost, secondary stability follows osseointegration (Raghavendra et al., 2005). Primary stability, which is the most important criterion for successful osseointegration and complete healing, primarily depends on the implant's design, including its threads, diameter, and length (Toyoshima et al., 2011).

As osseointegration occurs, the bone remodels around the threads of the implants, and secondary stability is achieved through direct contact between the implant and bone (Rodrigo et al., 2010). These facts suggest that primary stability, measured during implant insertion, will inevitably change; thus, it is not dependent on osseointegration alone. After a healing period of three months, a simple torque test does not provide accurate information about osseointegration; it only offers insights into secondary stability. This is somewhat contingent, as secondary stability cannot exist without osseointegration, but the resultant information lacks data concerning the extent of osseointegration.

A torque test using a ratchet set to 35 Ncm indicates that an implant is at least attached to the bone with a minimum of 35 Ncm. Conducting torque tests with higher values could lead to unintentional implant rotation. Consequently, torque tests are predominantly and

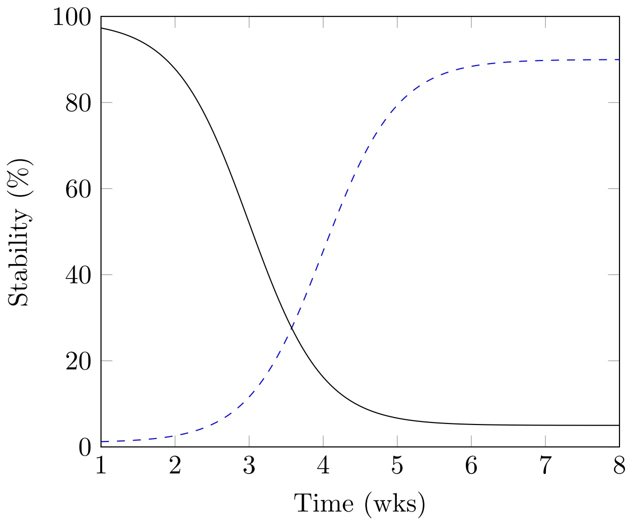

Figure 2. The changeover of stability from the initial stage (primary) to the final stage (secondary) what is created by the new bone formation. Solid line: Primary stability (old bone). Dashed line: Secondary stability (new bone). Graph adapted from Raghavendra et al. (2005).

predictably used in animal studies and in vitro experiments (Comuzzi et al., 2019; Stacchi et al., 2019).

Resonance frequency analysis. Several studies suggest the predictable application of Resonance Frequency Analysis (RFA). In the RFA method, a "smartpeg" sensor must be inserted and subsequently fixed within the dental implant. Following this, the tip of the measuring device, Ostell (Gothenburg, Sweden), needs to be positioned very close to the "smartpeg" unit in both buccolingual and mesiodistal directions. Electromagnetic pulses are emitted to perform the measurement. The measured resonance frequency values are automatically converted into a numeric scale known as the Implant Stability Quotient (ISQ) (Alsaadi et al., 2007).

According to the manufacturer, an ISQ value exceeding 70 indicates high stability, while an ISQ between 60 and 69 suggests medium stability. An ISQ value below 60 is considered low stability (Truhlar et al., 1997). Although several systematic review articles suggest the reliability of the RFA method for measuring implant stability, most articles assert that it is not comparable to insertion torque (Lages et al., 2017) or Damping Capacity Analysis (Andreotti et al., 2016). Therefore, researchers recommend using the same method throughout the entire process, and when assessing patient progress, the same device should be employed in all analyses (Andreotti et al., 2016).

Damping capacity analysis. Damping Capacity Analysis (DCA), referred to in some studies as Damping Capacity Assessment, pertains to the Periotest unit (Gulden Med. Tech, Modautal, Germany). This device employs an electromagnetic accelerator. Its tapping rod strikes an implant for 4 seconds (16 strikes) at a tempo of 0.2 m per second. The device measures the contact time between the dental implant and the tapping rod, converting this measurement into Periotest values (Wennerberg et al., 2009). These Periotest values can range from -8 (indicating maximum stability) to +50 (indicating clinical mobility). Although initially designed to measure tooth mobility, the device can also be utilised for assessing the stability of endosseous dental implants. Zix et al. (2008) concluded that the device is a reliable method for monitoring changes in and the stability of the implant-bone connection.

3.3 Patient related factors

There are several general medical conditions that can affect basic wound healing and, consequently, any surgical procedure. These conditions and diseases can have a direct or, more commonly, an indirect influence on bone healing and, therefore, on osseointegration. In the past, some of these medical conditions were considered exclusion criteria for placing dental implants; however, over the last 10 to 15 years, several studies have addressed such conditions.

Most of these studies have concluded that almost all of these exclusion criteria do not have a direct correlation with osseointegration when implants are placed using today's well-developed and minimally invasive surgical procedures. However, with advancements in treatments and medications, new trends and pharmacological agents have emerged that can affect both healing and osseointegration.

Research has been conducted on various medications, and some of these pharmacological agents have already been extensively examined for their role in the osteogenic process. Nevertheless, as newer innovations become available, further research is required to address these novel situations. Additionally, with improvements in disease management, the primary aim is sometimes not merely to save the life of the patient but also to enhance the quality of life.

Osteoporosis. Recent research has shown that osteoporosis is an increasing disease in both the female and male elderly population, primarily those aged above 65 (Alsaadi et al., 2007). In osteoporosis, both the quality and quantity of bone are compromised, which can have harmful effects on osseointegration (Montes et al., 2007).

Moreover, the biomechanical characteristics of the affected bone may not provide the same stability for dental implants as healthy bone. This situation may result in decreased clinical fixation and stability of dental implants (Kate et al., 2016). For this reason, the diminished osteogenic capacity should be considered a risk factor for dental implant failure. This can be associated with several factors that occur in osteoporosis and may influence the healing of bone onto the implant surface.

The reduction in bone regeneration capability in osteoporotic patients includes the unbalanced activity of osteoclasts. The function of osteoclast cells in bone modelling and remodelling can be compromised. Furthermore, both the proliferation and activity of mesenchymal cells appear to be affected, which may also impact osteoblastogenesis (Marco et al., 2005). Despite ongoing research on osteoporosis, our understanding of bone regeneration in such conditions, as well as its effect on the healing of dental implants, remains limited.

Anti-inflammatory drugs. Several experiments have addressed the effect of anti-inflammatory drugs, such as nonsteroidal anti-inflammatory drugs (NSAIDs). Some animal studies have reported direct changes and negative effects of NSAIDs on bone healing. NSAIDs can also adversely affect osteoblastic functions, specifically both proliferation and differentiation (Kalyvas & Tarenidou). Moreover, monocytes and macrophages may be influenced by long-term NSAID use (Meyer et al., 2006). However, negative influence appears to be temporary and does not affect the final outcome of osseointegration itself (Kalyvas & Tarenidou).

Diabetes. Diabetic patients have been addressed in several studies, particularly regarding the estimation of implant survival rates. According to the latest research, no significant differences were observed in osseointegration rates between diabetic and non-diabetic patients (Erdogan et al., 2015; Ghiraldini et al., 2016). However, diabetic patients are more susceptible to both systemic and localized infections. This increased vulnerability poses a risk for osseointegration failure due to infection (Al-Maskary et al., 2011). Altogether, these factors could account for a potential increase in implant failure rates among diabetic patients (Aghaloo et al., 2019).

Rheumatoid Arthritis. Rheumatoid Arthritis (RA) is a well-known autoimmune disease in which the patient's immune system generates inflammation, leading to the thickening of the synovium. This thickening results in edema and pain in the joints and surrounding areas, ultimately affecting the bone itself.

The disease is often accompanied by osteoporosis due to increased bone turnover and the effects of anti-inflammatory or immunosuppressive treatments (Aghaloo et al., 2019). Studies have demonstrated that RA patients exhibit osseointegration results similar to those of healthy patients. However, peri-implant soft tissue alterations and some bone resorption have been observed in patients with concurrent RA and connective tissue diseases (Krennmair et al., 2010).

Cardiovascular disease and antihypertensive medications. Of the various forms of cardiovascular disease, hypertension, atherosclerosis, vascular stenosis, coronary artery disease, and congestive heart failure appear to have the most direct effect on peripheral blood supply. These manifestations result in a lack of oxygen supply to local tissues, which decreases fibroblast activity, collagen synthesis, capillary growth, and macrophage activity (Diz et al., 2013).

Different studies have indicated somewhat controversial results. Although Khadivi (1999) found a lower success rate in patients with cardiovascular diseases, the small sample size rendered the difference insignificant when compared to a healthy group.

It is essential to address the discrepancies between earlier studies, such as the one previously mentioned, and some later investigations that found no difference in the success of osseointegration between healthy patients and those with cardiovascular compromise, even when taking antihypertensive medications. In a study, Alsaadi et al. (2008) concluded that certain factors, such as cardiac diseases, coagulation problems, hypertension, or hypercholesterolemia, did not contribute to an increased incidence of early failures.

Neurologic disorders. Historically, patients with neurological disorders were excluded from dental implant treatments. The primary reason for this exclusion was the association with poor access to oral health, inadequate oral hygiene, and harmful habits such as bruxism. However, the treatment of edentulism with removable dentures can also be quite challenging for these patients for similar reasons.

On the other hand, edentulism can lead to nutritional deficiencies, reduced social interaction, and decreased social acceptability. A recent study has shown that the cumulative survival rate for implants in patients with neurological disorders can exceed 85% after 10 years. Although peri-implant mucositis was diagnosed in more than 10% of cases, the incidence of peri-implantitis was below 5%.

This study also examined the prosthodontic aspects of the treatments. Some prosthodontic complications ranged from minor to more severe situations. Nevertheless, the authors concluded that implant therapy can be a reliable option for the intraoral rehabilitation of patients with neurological disorders (Ekfeldt et al., 2013).

Human immunodeficiency virus. Life expectancy for individuals living with Human Immunodeficiency Virus (HIV) has improved significantly over the past few decades. People living with HIV are now able to lead longer, healthier, and more active lives. However, there is a documented positive correlation between HIV-positive individuals and bone metabolic alterations. The underlying factors include low calcium and vitamin D intake, reduced testosterone levels, as well as potential alcohol and/or opiate abuse, smoking, and depression (Borderi et al., 2009).

A review article by Ata-Ali analysed the impact of HIV infection on endosseous dental implant osseointegration. The results of the systematic review suggested that dental implant placement in HIV-positive patients did not increase the risk of dental implant failure. Moreover, the authors concluded that prophylactic antibiotic treatment, the administration of highly active antiretroviral therapy, and the control of $CD4^{+}$ T lymphocyte counts were essential for the successful treatment of these patient groups (Aghaloo et al., 2019).

Hypothyroidism. Hypothyroidism is a common endocrine disorder, with increased prevalence among women and in older individuals. Specifically concerning bone metabolism, hypothyroidism has been linked to delayed bone regeneration, increased fracture risk, and delayed fracture repair (Sefati et al., 2018).

The treatment for hypothyroidism includes long-term levothyroxine therapy, which has also been associated with an increased risk of osteoporotic diseases and delayed fracture recovery in animal studies. This association raises concerns for patients seeking dental implants (Tsourdi et al., 2015).

Although some studies investigating implant survival in patients with hypothyroidism did not demonstrate a significantly higher rate of implant failures compared to control patients (Attard & Zarb, 2002), caution is still warranted in these cases.

Proton pump inhibitors. Proton Pump Inhibitors (PPIs) are among the most widely used drugs globally. Their use is primarily aimed at preventing and treating acid-related conditions, which may include esophageal and duodenal ulcers, stomach ulcers, NSAID-associated ulcers, gastroesophageal reflux disease (GERD), and Zollinger-Ellison syndrome.

Recent studies have mentioned a possible association between chronic PPI use and an increased risk of bone fractures, potentially due to a decrease in calcium absorption (Ito & Jensen, 2010). Another recent study retrospectively investigated the association between PPIs and the elevated risk of failed dental implants. Their statistical analysis indicated that failure rates were as high as 6.8% for patients using PPIs, compared to a 3.2% rate for non-users. Individuals using PPIs exhibited a significantly higher risk for osseointegrated dental implant failure compared to those who did not use these drugs. This suggests that long-term treatment with PPIs may be associated with an increased risk of dental implant failures (Wu et al., 2016).

In a study conducted in 2017, the intake of PPIs was shown to have a negative effect on implant survival rates, significantly decreasing them. This article suggested and concluded that regular use of PPIs might be linked to an increased risk of dental implant failure (Chrcanovic et al., 2017).

Influencing local factors. The ability to achieve good oral hygiene following dental implant placement significantly impacts its success rate. Poor oral hygiene may lead to local soft-tissue inflammation, which can have a direct effect on the osseointegration process in the long term (Raikar et al., 2017).

Local intraoral conditions, such as removable partial or full dentures, or even temporary restorations, can negatively affect the osseointegration process by causing overload on dental implants that have not yet fully integrated (Di et al., 2012). Furthermore, immediate loading may be a key factor in the failure of the osseointegration process if not appropriately designed and implemented. As previously described, achieving sufficient primary stability is essential for loading an implant immediately. Additionally, an immediate restoration must be both occlusally well-balanced and able to withstand all chewing forces to prevent overloading (Misch et al., 2004).

3.4 Implant related factors

Dental implants may differ in several aspects. Today, there are hundreds of implant manufacturers and brands, each differing in one or more characteristics. The major properties include the implant shape and surface characteristics. Additionally, there are minor influencing factors, such as the implant drilling protocol and instruments.

Practitioners sometimes exhibit a preference for certain brands and properties without sufficient knowledge or background. It is also important to note that the operator and the instrumentarium can significantly influence the success of the procedure, which will be addressed in detail below.

Material of the implant. In a recent study, Plecko et al. (2013) tested four different dental implant materials, all of which were either coated or polished, and examined their biocompatibility and osseointegration. The materials evaluated included a chrome implant (titanium coating), a cobalt-chrome implant (with titanium and zirconium coating), a pure titanium implant, and a steel implant.

During this animal experiment, all specimens were harvested after a period of eight weeks, and a macroscopic, radiological, histological, and biomechanical evaluation was performed. The biomechanical evaluation consisted of a torque-out test. The authors concluded that cobalt-chrome and steel implants exhibited significantly less osseointegration success compared to all other metals or metal alloys. Nonetheless, the zirconium and titanium coatings improved the successful osseointegration of cobalt-chrome implants, nearly achieving the success level of the pure titanium implants.

Surface modification with laser. The examination of lasers on the titanium surface has been performed in several studies. Some recent research showed that the roughness and tin layer formation induced by laser treatment improves the response of bone (Marticorena et al., 2007). In a review article, Goutam et al. concluded that bone remodeling and formation involve growth factors, cytokines, and other bone tissues. Therefore, several other factors might influence the success rate of osseointegration, not only the surface characteristics of the dental implant itself (Goutam et al., 2013).

Implant surface coating. Reliable osseointegration has been enhanced by several advancements, including new materials and implant shapes, as well as novel designs and surface treatments. Many of these improvements claim to result in better and/or faster osseointegration; however, most of them have associated drawbacks (Vaidya et al., 2017). Nonetheless, some of these studies demonstrate promising results. For example, titanium plasma spray is a method that increases the roughness and thus the surface area itself, which can be recommended for use in sites with low bone density (Coelho et al., 2009).

Ceramic particle blasting has been compared in animal models (dogs) and showed significantly higher bone-to-implant contact compared to sandblasted or acid-etched surfaces. The difference was significant after two weeks but was no longer significant after four weeks. This suggests that these surface modifications might interfere with bone apposition on the surface during the early stages of the healing process (Bornstein et al., 2008). A similar advancement was noted with Ca-Phosphate coatings. An article using rat models demonstrated that this modification could significantly increase osteoconduction (Mendes et al., 2009).

To summarise, implants with higher roughness can exhibit greater mechanical anchorage and improved primary fixation to hard tissue. Conversely, microscopic changes might enhance the host response by increasing osteoblast adhesion (Novaes et al., 2010).

Surgical technique / protocol. Improving the surgical technique has proven to be a reliable method for enhancing the implant success rate. Moreover, some new techniques, such as osseodensification, also increase primary stability as well as osseointegration success. This method does not require the drilling away and removal of bone for placing the implant, which results in higher primary stability and greater bone density. This technique is also referred to as the non-extraction method, developed by Huwais et al. (2013).

The procedure involves the use of specially designed implant drills that condense the bone during osteotomy, resulting in higher density. Compared to regular drills that remove bone to create the implant housing, this method preserves the bone, compacting and expanding the ridge instead. The drills used are called densifying burs, which operate in a high-speed rotational movement, counter-clockwise, with a high volume of irrigation. This forms a dense layer of bone around the implant housing, which, in addition to increasing bone density and preserving residual bone in situ, also secondarily enhances the primary stability of the implant, as this is related to the density of the surrounding hard tissue (Huwais, 2014).

In research conducted on animal models, a significant increase in ridge dimensions was noted compared to normal bone preparation, and the primary implant stability was also statistically higher (Trisi et al., 2016).

Heat production during drilling. During the preparation of an implant osteotomy, drills generate a certain amount of heat. This heat can affect the bone, particularly if the recipient site overheats, potentially causing local necrosis and loss of the implant due to inadequate osseointegration. The heat generated can be influenced by the irrigating solution used and its access to the site.

In a study conducted in 2015, Boa et al. investigated the cooling effect of irrigating solutions in the context of guided surgery. They concluded that although more soft tissue may be present in the surgical site and the surgical guide itself also surrounds the osteotomy site, irrigation can sufficiently control and cool down bone temperature to an acceptable range when using flapless surgery with guidance. In conclusion, they stated that according to their results, flapless surgery using 3D-printed surgical guides can be performed safely with the use of external cooling irrigation (Boa et al., 2015).

There is some controversial literature regarding heat production during drilling with the use of surgical guides. Misir et al. concluded that statistically significant temperature changes might occur when using surgical guides (Misir et al., 2009). Conversely, other studies have found guided surgery to be a safe method concerning heat generation. For instance, Jeong et al. found no significant difference when comparing flapless surgery with a guide to flap surgery performed without surgical guidance (Jeong et al., 2014). Barrak et al. concluded that to ensure safety, the optimal approach for guided implantology is to combine lower preparation speeds (800 RPM to 1200 RPM) with cooling of the irrigating solution prior to use (Barrak et al., 2019).

Several influencing factors and multiple theories. As documented decades ago, osseointegration remains partially unexplored. Although an increasing amount of data has been added to this topic, the interactions among various factors, as well as the effects of different agents, scenarios, and biological conditions, complicate the examination of one or more of these elements. In a recent publication, a summary was prepared that consolidates various research findings and theories which may also affect osseointegration (**Table 1**).

Table 1. Main causes which decrease or elevate the success of osseointegration (from Goutam et al. 2013).

Factors Enhancing Osseointegration	Factors Inhibiting Osseointegration
Implant design, shape, diameter	Excessive implant mobility and micromotion
Titanium coating on Co-Cr metal implant	Nonsteroid anti-inflammatory drugs especially selective COX-2 inhibitors
Laser treatment of Implant Surface	Warfarin and low molecular weight heparins
Human PTH (Parathormone)	Inappropriate porosity of the porous coating of the implant
Ostetrix factor	Osteoporosis, rheumatoid arthritis
Local delivery of transcription Factor	Radiation therapy
Bone source augment to socket	Smoking
Mechanical stability and loading conditions applied on the implant	Advanced age, nutritional deficiency and renal insufficiency
Pharmacological agents such as simvastatin and bisphosphonates	Pharmacological agents such as cyclosporin A, methotrexate, cis-platinum

4 Discussion

The fundamentals of osseointegration were examined several decades ago. Following the pioneering work of Per Ingvar Brånemark and colleagues, dental implantology began to spread globally. The industry has also recognised the potential in implant production, leading to the emergence of various new brands and manufacturers. In the initial era, researchers focused on fundamental questions regarding osseointegration. How does it work? What happens to the cells, and what reactions can be expected? In 1998, Masuda et al. (1998) delineated the steps and processes of osseointegration in their review. It is well known that the entire healing-osseointegration process begins on the first day, essentially a few hours after implant insertion. Primary modelling is characterised as the phase of primary healing immediately following implant placement. This phase is dependent on the initial congruence between the implant and the bone, which, in turn, is influenced by the implant surface. This underscores the importance of precise implant bed preparation and careful implant placement.

Recent studies have addressed the pre-drilling protocol, particularly concerning implants with a conical shape and self-tapping design. During drilling, heat can be generated, which depends on the drilling speed, the flow and access of the irrigating solution, as well as the sharpness and usage of the drills. Overheating at any stage of the process can adversely affect or prevent osseointegration.

Secondary remodelling is a continuous process that, if successful healing is achieved, culminates in osseointegration. Throughout this process, the initial primary stability may decrease, while the secondary stability, formed by bone growth, will provide the necessary implant fixation and stability. Therefore, it is imperative that primary stability is adequate for immediate loading; however, the temporary shape and design of the implant is related to its success, along with the prevention of overloading and ensuring sufficient cleaning by the patient.

Research over the last 15 years has started to explore borderline scenarios. Patients who were previously excluded from dental implant treatments, such as those with diabetes, rheumatoid arthritis, or AIDS, have been meticulously examined. In most general medical conditions, it has been observed that osseointegration is not less likely to occur, and odds ratios are comparable to those of healthy individuals. Of course, there are certain conditions where complications may arise due to compromised healing in the patient. Individuals suffering from diabetes exhibit good prospects for successful osseointegration; however, due to higher complication and wound healing rates, they face an increased risk of overall implant failure. Similarly, hypothyroidism has been noted to correlate with elevated implant failure rates compared to healthy individuals, although these rates remain within an acceptable range.

When preparing treatment plans for patients with such general medical disorders, it is essential to evaluate each case on an individual basis, weighing the potential higher risk factors while also addressing the negative implications of alternatives to implant treatments. Alternative solutions in various situations might include edentulism, with its well-documented social and physical consequences, necessitating a comparison of the risks associated with implant placement. Another alternative could be removable dentures; however, individuals with neurological disorders may be less likely to adapt to such restorations. The drawbacks of implant-retained solutions must be considered on a case-by-case basis.

Although titanium has been noted to achieve satisfactory osseointegration success rates, researchers continue to seek better solutions with even higher success rates. With today's modern techniques, the surfaces of dental implants can be enhanced through acid-etching, grid-blasting, or even laser modification. These approaches increase the surface roughness of titanium, thereby enlarging the surface area and enhancing titanium-implant contact. Various attempts at coating dental implants have shown promising results; however, no evidence-based research has yet concluded which surface treatment or coating method is superior. Nevertheless, reputable implant manufacturers can demonstrate osseointegration rates significantly exceeding 90%, with some reporting rates above 96-98%.

All of these findings must be approached with caution and critical analysis, as discussed above; osseointegration and, therefore, the success of dental implants represent a multifactorial process influenced by several different, sometimes independent, factors. Starting from implant quality and manufacturer, through the operator and the entire dental team, to patient compliance and the applicant's overall medical condition, all elements may positively or negatively affect the final outcome.

Patients continue to seek ideal solutions for restoring their missing teeth, and dental implant restoration appears to be increasingly predictable, becoming accessible to a larger demographic and broadening the scope of its application. Due to space limitations, it is impossible to summarise all factors and influences on osseointegration; however, the primary direction for research is clear: to make implant dentistry available to as many individuals in need as possible.

Conclusions

In recent decades, implant dentistry has evolved into a predictable and accessible solution for restoring missing teeth. Research has identified the most influential factors that may either increase or decrease the likelihood of successful osseointegration. Collectively, this knowledge assists practitioners in planning individualised implant dental restorations for their patients, enabling them to address and explain the expected success rates and probabilities relevant to each unique situation.

Meanwhile, research continues to deepen our understanding of this remarkable phenomenon, striving to approach a 100% success rate in osseointegration. However, it is important to acknowledge that a certain percentage of failure exists and may continue to exist, with rates varying widely from a few percentage points to significantly higher ratios. These outcomes depend on all participants involved in the implant restoration process: the manufacturer, the practitioner, the dental team, and the patient.

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Ethical approval

No ethical approval was required for this study as it did not involve human participants, animal subjects, or sensitive data. This study falls under the category of data collection without participant identification.

Consent for publication

Not applicable.

Authors’ contributions

The author(s) declare that all the criteria for authorship designated by the International Committee of Medical Journal Editors have been met. More specifically, these are: (a) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND (b) Drafting the work or revising it critically for important intellectual content; AND (c) Final approval of the version to be published; AND (d) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Competing interests

The author(s) declare that there are no competing interests related to this work.

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