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Efficacy of Osseointegration of Traditional Dental Implant Compared To New Age Dental Implants – A Narrative Review

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Abstract

Dental implants are artificial dental roots that are implanted into the jawbone and attached to artificial teeth by fusing to an abutment. One or more teeth can be replaced with a dental implant. Osseointegration, a concept introduced by Per-Ingvar Branemark, leverages the clinical application of biotechnology and continues to be a boon for dental patients by expanding the restorative options for partially and completely edentulous patients. Successful osseointegration is influenced by a complex interplay of factors, including the biocompatibility of the implant material, the macro- and microscopic surface characteristics, implant design, the quality and morphology of the surrounding bone, surgical technique, the patient's local and systemic health during healing, as well as the loading conditions and protocols applied. Consistent and reliable monitoring of osseointegration is essential for ensuring the long-term success of dental implants. Among the various indicators, secondary implant stability is particularly important, as it directly reflects the quality of osseointegration. Among the physical modifications of titanium, micro-scale alterations most effectively enhance osseointegration, while nano-scale modifications are superior at reducing bacterial adhesion.

Successful osseointegration is solely based on successful natural tooth replacement with tissue-integrated implants. Therefore, an adequate understanding of the process of osseointegration, its prerequisites, and factors promoting and limiting osseointegration has been helpful and will help enormously shortly to exploit every related parameter and improve and hasten the process of osseointegration.

Keywords: Dental Implants, Fibroblastic Cells, Microcirculation, Osseointegration

Introduction

Dental implants are artificial dental roots that are implanted into the jawbone and attached to artificial teeth by fusing to an abutment. One or more teeth can be replaced with a dental implant[1]. The most common types of dental implants are endosteal and subperiosteal implants. The main difference is how they are attached to the jawbone. Endosteal implants are placed inside the bone. This implant is the standard in dentistry. It is a small screw, cylinder, or blade outline characterizes its overall form. Subperiosteal implants are positioned beneath the periosteum. These implants are inserted on top of the bone in the mandible or maxilla. This implant is indicated when there is not enough jawbone to support an endosteal implant and the patient doesn't want to undergo a bone augmentation procedure to build up the bone[2]. Osseointegration, a concept introduced by Per-Ingvar Branemark, leverages the clinical application of biotechnology and continues to be a boon for dental patients by expanding the restorative options for partially and completely edentulous patients[3].

Osseointegration is the process by which an endosseous dental implant forms a direct structural and functional link with the surface of a load-carrying bone to ensure the implant's long-term stability and clinical success. Interactions at the implant-tissue contact tend to be highly dynamic[4]. It comprises a cascade of complex physiological mechanisms similar to direct bone fracture healing. The drilling of an implant cavity resembles a traumatic insult to bony tissue, leading to distinct phases of wound healing. Initially, mechanisms of cellular and plasmatic hemostasis lead to fibrin polymerization and the formation of a blood clot, which serves as a matrix for neoangiogenesis, extracellular matrix deposition, and invasion of bone-forming cells[5]. New bone is generated from the borders of the drill hole (distance osteogenesis) or by osteogenic cells on the surface of the implant (contact osteogenesis). In distance osteogenesis, osteoblasts migrate toward the walls of the implant cavity, where they differentiate and initiate new bone formation. As a result, bone grows in an appositional fashion from the surrounding tissue toward the implant. In contrast, contact osteogenesis involves the direct migration of osteogenic cells onto the implant surface, where they begin forming new bone in situ[5,6]. The central focus of implant development is to minimize bacterial adhesion while promoting recruitment, adhesion, and proliferation of osteogenic as well as fibroblastic cells in order to achieve a high degree of hard and soft tissue integration[7].

History

At the Lund and Goteborg universities, the concept of osseointegration has been under extensive research since 1952. The concept stemmed from the microscopic studies on rabbit fibula bone marrow, uncovered with gentle surgery and inspected at high resolution under a modified intravital microscope[8]. In the early 1960s, researchers investigated how bone marrow and joint tissues responded to various forms of injury, including mechanical, chemical, thermal, and rheologic. As evidence for osseointegration began to emerge across multiple studies, Brånemark, in his work on microcirculation, made a pivotal observation: bone tissue was able to grow into the narrow spaces of titanium and titanium chambers, eventually becoming inseparably integrated with the metal[7,9]. In the mid-1970s, it was for the first time that Schroeder histologically demonstrated the evidence of osseointegration and successfully proved a direct bone-to-implant contact. Later, Cameron et al. in 1973 suggested that bone grows on a bio-compatible material only when the movement of both the bone and the implant is restricted[10].

Requisites for Successful Osseointegration

Successful osseointegration is influenced by a complex interplay of factors, including the biocompatibility of the implant material, the macro- and microscopic surface characteristics, implant design, the quality and morphology of the surrounding bone, surgical technique, the patient's local and systemic health during healing, as well as the loading conditions and protocols applied. For a successfully long-lived implant, the complex process of osseointegration needs to be thoroughly kept in check by controlling the various influential factors

Implant Characteristics

1. **Geometry of Implant:** The growth of the bone occurs preferentially on the elevated or the protruded extensions on an implant surface, such as the ridges, crests, and edges of threads. Moreover, the shape of the implant is also an essential determinant as it helps in the transfer of stresses and the primary implant stability. A threaded implant offers greater functional surface area than the smooth-sided cylindrical or tapering implants, as it can be rigidly fixated, thereby limiting the microenvironment during wound healing. Smooth-sided implants require an additional surface treatment, and the taper, when incorporated, reduces the surface area available for osseointegration[11].
2. **Width and Length of Implant:** The greater the dimensions of an implant, the greater will be the surface area provided for osseointegration. However, increasing the length beyond a limit must be avoided as it may unable the proportionate transfer of forces[11]
3. **Microdesign of Implant:** Surface modification of implants is performed to achieve a biocompatible and bioactive surface. Commercially, pure titanium has been the standard material for endosseous implants as it is highly reactive and forms a passivation layer of titanium oxides compatible with the tissues without becoming incorporated. Other treatments like sandblasting with aluminum oxide or titanium oxide have been shown to permit better adhesion, proliferation, and differentiation of osteoblasts[12]. The newly introduced technique of combining the advantages of sandblasting and acid-etching, known as the sandblasted, large-grit, acid-etch (SLA) implant surface, exhibits greater alkaline phosphatase activity in osteoblast-like cells than other techniques, machining, electrochemical anodization, plasma treatment.[13] Machining is regarded as the pioneering modification strategy applied to dental implants and it involves using harder metals to deform the base material with high rotation speeds, yielding macro to micro scale features, which have evolved from manual to digitally controlled. Another one is grit-blasting involves the bombardment of Ti, Al, $Al2O3$ or hydroxyapatite (HA) particles under the influence of high-pressure and high-speed blaster that imparts micro/ nanoscale indentations onto the implant material, with features dictated by particle type and size[14]. Acid-etching was initially developed for eliminating residues from implant manufacturing, enables the fabrication of roughened (micro/nano) surfaces but it requires standardization to control implant topography. A combination of sandblasting and acid etching (SLA or sandblasted large grit acid etched) is a clinically most used implant choice[15]. This dual physical and chemical process is regarded

as the most effective dental implant surface modification strategy that exhibits long-term success in pre-clinical and clinical investigations. Electrochemical anodization (EA) is a surface modification technique in which the implant serves as the anode and is paired with a counter electrode (cathode) in an electrolyte solution—typically containing fluoride ions and water. When an appropriate current or voltage is applied, this process facilitates the self-organized formation of metal oxide nanotubes or nanopores on the implant surface[16]. Plasma treatment involves implant modification with the desired material coated via melting and sintering achieved via plasma treatment in a vacuum or low-pressure environment. This coat implant surface with layers in the micro/nanoscale; however, this adherent layer may break or delaminate and require extreme surgical care during implant insertion[15,16].

4. **Bone Characteristics:** The bone is the bed in which the implant is placed, and its health is one of the most crucial determining factors in osseointegration. A bone that has been irradiated may suffer from osteoporosis which causes hurdles during osseointegration. Thus, some delay should be allowed after irradiation to place an implant, or the healing conditions are improved with hyperbaric oxygen therapy. Other factors include smoking history or systemic conditions like diabetes mellitus or hypertension may also cause a delay in osseointergartion. Moreover, ridge augmentation or bone grafting must be done to address resorbed or insufficient volume of alveolar ridges to allow sufficient osseointegration.
5. **Intraoperative Factors:** Restricting the tissue damage to minimal and maintaining temperatures of bone below the hazardous levels with low-speed surgical drilling are essential to avoid bone necrosis.

Assessment of Osseointegration

Consistent and reliable monitoring of osseointegration is essential for ensuring the long-term success of dental implants. Among the various indicators, secondary implant stability is particularly important, as it directly reflects the quality of osseointegration. Traditionally, microscopic and histological analyses have served as the gold standard for evaluating osseointegration. However, due to their invasive nature, less invasive alternatives—such as radiographic imaging, cutting torque resistance, reverse torque testing, and model-based analyses—are increasingly being utilized in clinical practice.

1. **Histomorphometric Assessment:** Histological assessment provides an in-depth information about the bone quality around the implant, contact percentage between bone and implant, type of bone formed, and morphological characteristics of the osteocytes, such as size, orientation, and alignment to the bone lamellae, number and density, proximation to blood vessels, and lacuno-canalicular interconnectivity between neighboring and distant osteocytes. But due to the invasiveness of the analysis, it is not used in a clinical scenario[17].
2. **Radiographic Assessment:** Radiographic visualization is a routinely used technique in a noninvasive way to assess osseointegration. Evaluating osseointegration using a digital orthopantomogram and cone-beam computed tomography (CBCT), computed tomography lures a clinician as a better technique for evaluating but must restrict its use to the point of benefit with the lowest radiation doses[18].
3. **Clinical Assessment:** The tests used in clinical practice are either invasive or noninvasive. The

tensional test is an invasive test used in the past, which involves detaching the implant plate from the supporting bone. Later, Branemark tested osseointegration by applying lateral load to the implant fixture[19]. Recently, the focus has shifted to noninvasive methods that can be enlisted from the simplest one, involving the perception of a surgeon acquired by the cutting resistance and seating torque during implant placement. However, this typically measures the primary stability of the implant but not reflecting the real picture of osseointegration at the healing stages. Similarly, insertion torque values can be used to assess the quality of bone in various parts of the jaw during implant placement, but they cannot evaluate the secondary stability provided by the new peri-implant bone formation and remodelling[20].

Recent Approaches And Future Perspectives In Implant Technology To Enhance Osseointegration

1. **Macrotopography Enhancements:** Since implant surface topography plays a crucial role in promoting cell adhesion and osteoblast differentiation necessary for osseointegration, careful consideration of thread dimensions is essential. The inner thread diameter should match the dimensions of the socket to ensure high primary stability through frictional engagement. In contrast, the outer thread diameter should correspond to the implant cavity diameter to facilitate granulation tissue formation and subsequent osseointegration. Furthermore, the surgical instrumentation should be designed to fall between the inner and outer thread dimensions, promoting bone remodeling through compression and creating healing chambers that support the migration of osteogenic cells[21].
2. **Microtopography Enhancements:** Microtopography is linked to microroughness, aiding the attachment of osteogenic cells and bone deposition in the range of 1-100µm[3].
3. **Nanotopography Enhancements:** While microtopography acts at the cellular level of osseointegration, nanotopography is supposed to act at an additional protein level. It has its effects through physical, chemical, and biological routes, increasing the adhesion of osteogenic cells and promoting osseointegration.
4. **Surface Wettability Improvements:** Improving the wettability that is making the surfaces as hydrophilic as possible will avoid denaturation of proteins. This also accelerates osseointegration by promoting the differentiation and maturation of osteoblasts[22].
5. **Photofunctionalization:** Implant surfaces treated with UV radiation have enhanced bioactivity and osseointegration potential due to alteration of the titanium dioxide surface layer. Also, it reduces surface hydrocarbon, improves wettability, increases protein adsorption and cellular attachment to titanium surfaces[23].
6. **Surface Coatings.** Implant surfaces coated with growth factors like platelet-derived growth factors, transforming growth factor-beta, fibroblast growth factor, vascular endothelial growth factor, and bone morphogenetic proteins, extracellular matrix proteins, peptides, and messenger molecules like sclerostin speed up the process of osseointegration[24].

Surgical Techniques to Enhance Dental Implant Osseointegration

One of the factors that influences successful osseointegration is the primary stability of the dental implant during insertion. Recently, undersized drilling has been introduced to achieve sufficient insertion torque especially in regions of the jaws where the alveolar bone has lower density. In the undersized drilling, the final drill is of a lesser diameter than the fixture diameter. This allows the lateral compression of the bone during the fixture installation and enables the fixture to achieve higher primary stability. The effectiveness of the undersized drill to achieve higher primary stability has been shown in an experimental study by Tobassum et al[25].

The osteotome technique is another surgical technique that improves osseointegration by improving the primary stability of the dental implant. This technique basically involves the sequential expansion-condensation of the alveolar bone using successive osteotomes of greater diameter. The technique is believed to reduce the microdeformations and maximize the preservation of the remaining bone. This technique is suggested to be an effective method to gain higher primary implant stability than the conventional drilling technique especially in low-density alveolar bone[26].

Osseodensification is a modern drilling technique designed to preserve and enhance bone density during implant site preparation. Unlike conventional drilling, which removes bone from the osteotomy walls, osseodensification is a non-subtractive approach that compacts the bone particles against the walls of the osteotomy. This compaction process creates a dense layer of autogenous bone surrounding the implant site, leading to greater initial primary stability. As a result, this technique promotes improved osseointegration compared to traditional methods[27].

Recent Advances in Implant Dentistry

Metals and their alloys have long been used as implant materials in the human body, largely due to their properties of biocompatibility and acceptable physical and chemical properties. When it comes to dental implants, titanium and titanium alloys have been the biomaterials of choice, but recently ceramic-based materials (e.g., zirconia, zirconia toughened alumina, and alumina toughened zirconia) are also gaining popularity as the biomaterials for dental implants. Zirconia has better flexural strength, higher fracture resistance, and releases fewer ions compared to titanium. Additionally, the zirconia implants have better osseointegration and esthetic properties compared to titanium implants[28]. Tantalum is another metal that is currently being studied as a biomaterial for dental implants. Porous tantalum has greater resistance against corrosion and has been used with success as an implant material in orthopedic surgeries for improving angiogenesis and wound healing. Piglioncio et al. concluded that porous tantalum has greater osseointegration capacity than the currently available smooth or roughened titanium implants[29].

Polyetheretherketone (PEEK) is an organic polymer that has been recently gaining popularity as a biomaterial for dental implants and prosthesis. The higher modulus of elasticity of PEEK compared to titanium allows it to dissipate masticatory forces evenly on the jaws. Moreover, PEEK also possesses superior colour stability and higher abrasion resistance than zirconia[30].

Nanostructured hydroxyapatite coatings for implant have attracted attention during the last decade. Hydroxyapatite promotes bone formation around implant, increases osteo-blasts function such as adhesion proliferation and mineralization. One more new families to coating is of “smart” nanophase (i.e. grain size less than 100 nm in at least one direction) coatings that will enhance bone integration and promote better device fixation are being developed by Spire Biomedical Inc. (Bedford Massachusetts, USA)[31]. These nanophase coatings are modified to selectively encourage hard tissue growth on implant while discouraging the format of soft-tissue growth that can result in implant failure. Nano-patterned surface provided a higher effective surface area and nanocavities when compared to the conventional micro-rough surfaces. These properties are crucial for the initial protein adsorption and very important in regulating the cellular interactions on the implant surface[32]. The goal of nanotechnology is emergence of active and intelligent implants and structures that will interact with their surroundings, respond to environmental changes, deliver appropriate molecules or drugs and actively direct cellular events. The motivation behind dental implant nano engineering is to fabricate isotropic or anisotropic nanoscale features that would stimulate cell bioactivity to augment implant integration or enable bactericidal functions. The nanoscale implant surface can lead to an altered/enhanced physicochemical (bone or soft-tissue bonding) or biochemical (protein/cell adhesion, cell behaviour) response[15].

Conclusion

Among the physical modifications of titanium, micro-scale alterations most effectively enhance osseointegration, while nano-scale modifications are superior at reducing bacterial adhesion. Chemically, nano-scale modifications improve surface hydrophilicity, promoting better integration with bone and deterring hydrophobic bacteria. Biological modifications offer even more targeted benefits: coatings with growth factors can significantly boost osseointegration, while antibacterial coatings directly inhibit bacterial colonization and improve implant performance. Compared to the conventional drilling technique for implant site osteotomy, the osseodensification drilling protocol significantly increases implant insertion torque and bone-to-implant contact, which is beneficial for implant stability in poor-density alveolar ridges.

Although alternative materials such as zirconia and PEEK have garnered increasing research interest, it remains challenging to establish clear advantages over titanium. One major limitation lies in the methodological variability across studies. Many investigations rely on in vitro models using flat discs, which do not accurately reflect the anatomical and functional characteristics of actual dental implants. These simplified models fail to account for macro-level features that influence implant behavior in vivo. Additionally, the comparative data are often limited by inconsistent testing conditions and a lack of standardized outcome measures. Beyond material properties alone, the suitability of each implant material must also be assessed within the context of clinical demands, including esthetic considerations, the desired timing of functional loading, and the quality and density of the patient's bone. These factors play a crucial role in determining the overall success of implant therapy.

Successful osseointegration is solely based on successful natural tooth replacement with tissue-integrated implants. Therefore, an adequate understanding of the process of osseointegration, its prerequisites, and factors promoting and limiting osseointegration has been helpful and will help enormously shortly to exploit every related parameter and improve and hasten the process of osseointegration.

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