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Comprehensive Review of Dental Implant Surface Characterization: Techniques and Clinical Implications

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Abstract

The surface features of dental implants are critical to their effectiveness because they affect the osseointegration process and biological interactions. This paper examines the many approaches to surface characterization of dental implants with a focus on additive and subtractive methods. The efficiency of subtractive techniques, such as laser microtexturing, sandblasting, acid etching, and anodization, in enhancing surface roughness and biocompatibility is examined. By using these methods, microstructural characteristics that promote cell adhesion and quicken osseointegration can be produced. The potential of additive techniques, including coatings made of zirconia and hydroxyapatite or calcium phosphate, to improve bone integration and production, is investigated. The evaluation also emphasizes how various implant manufacturers apply surface changes and cutting-edge technologies, which are critical for maximizing implant longevity and performance. The use of nanoparticles such as titanium dioxide, zirconium dioxide, and zinc oxide in recent developments in implant surface coatings is highlighted because of their potential to improve bioactivity and address issues such peri-implantitis. Enhancing antibacterial qualities and bone healing with the addition of chitosan and copper and silver nanoparticles is a potential strategy. In summary, this research highlights the significance of accurate surface characterization and continuous technological progress in improving the longevity and efficacy of dental implants. Subsequent investigations ought to concentrate on enhancing these techniques and converting discoveries into better medical results.

Keywords: *Characterization, Dental Implant, Implant Surface, Nanoparticle Coated Dental Implants.*

Introduction

Teeth are sensory organs that serve many functions in multiple parts of daily existence. Teeth play a crucial role in the process of mastication, which is closely linked to an individual's overall quality of life [1]. One's teeth are used for several daily activities, including talking and even smiling. Teeth have a crucial role in the overall quality of life due to their functions in aesthetics, mastication, and speaking [2]. When other organs in the body are affected, a significant amount of energy is expended to prevent additional harm or even attempt to reverse the existing damage. Regrettably, these essential organs are not impervious and can be destroyed due to several factors throughout a person's life, including disorders of the oral cavity such as periodontal disease, dental caries, and tooth trauma. In ancient times, the inability to bite and chew was regarded as a peril to one's existence [3]. As food processing improved, the focus shifted from simply surviving to the desire to savour a variety of meals and textures. This led to a greater incentive to preserve one's natural teeth

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or explore options for replacing lost teeth. Facial aesthetic elements have become increasingly important in preserving one's oral health in recent times. With advancements in dentistry technology, the replacement of lost teeth has become both feasible and desirable.

Edentulism, which refers to the total absence of teeth, is a global occurrence. As to the criteria set by the World Health Organization, those who are edentulous are classified as physically impaired, disabled, and handicapped due to their inability to effectively chew and talk. The literature has a discussion of the fluctuating rates of edentulism [4]. The American Association of Oral and Maxillofacial Surgeons' statistics indicate that 69% of individuals between the ages of 35 and 44 have experienced the loss of at least one permanent tooth due to factors such as accidents, gum disease, unsuccessful root canals, or tooth rot. In addition, it is worth noting that 26% of adults have experienced complete tooth loss by the time they reach the age of 74. Hence, the utilization of dental implants indicates that approximately 100,000-300,000 dental implants are inserted annually, which is like the amount of artificial hip and knee joints implanted each year [5].

According to the 2002 McGill Consensus Conference, the available evidence indicated that using a traditional denture to replace missing teeth in the lower jaw is no longer the most suitable initial treatment option in prosthodontics [6]. The objective of contemporary dentistry is to rehabilitate patients to their optimal level of function, speech, well-being, and appearance, irrespective of any degeneration, illness, or injury to the stomatognathic system. Dental implants are a suitable choice for those with good overall oral health who have experienced tooth loss, aligning with the final objective.

History of Implantology

Era of pre-osseointegration: The first written accounts of implantology date from the writings of Hippocrates and Celsus, who chronicled the first dental operations. Hippocrates reported in the fifth century BC that teeth lost because of mandibular trauma might be repositioned by adhering them to the gums or neighboring teeth with gold or silk threads [7]. In his dissertation "De Medicina," written in the first century AD, Cornelius Celsus explored the possibility of using teeth from live or deceased people to replace missing teeth [8]. It is amazing that even prehistoric societies were able to restore oral function and beauty using crude implants. The Mayans replaced their missing mandibular incisors with dental implants made of seashells around 600 AD. When Drs. Wilson and Dorothy Popenoe discovered these implants in 1931, they were found to be surrounded with dense bones, which suggested osteogenesis akin to that observed surrounding contemporary implants [9]. Radiological studies conducted in the 1970s verified that the implants, which belonged to a female patient of 20 years of age, were probably quite stable and similar to modern techniques [8]. The patient was able to chew and lead a most normal life again because of these seashell implants. Furthermore, a jawbone from Honduras included an old stone implant that dates to 800 A.D, providing more evidence of the early dental implantation procedure [10].

Various materials were used to fasten teeth damaged by periodontal disease in Europe throughout the 17th century. Teeth from the deceased or those facing financial trouble were extracted for allotransplantation. Notably, Dr. Hunter experimented in the eighteenth century when he watched the cock's blood vessels develop into the tooth pulp when he implanted a partially formed tooth into the comb of a cock. By 1809, Maggiolo attempted a more advanced technique, surgically placing a gold implant tube into a newly extracted tooth socket and crowning the tooth once the incision healed. Despite being novel, the procedure caused significant gingival irritation [9]. There were major breakthroughs in the 20th century. Created in 1966 by Dr. Linkow, the "blade implant" is intended to be placed into the alveolar bone and has support to hold restorations in place. Despite being novel, it was not very successful (less than 50%) and is already out of date [11]. Soon after, in 1968, Small unveiled the transosseous implant, a titanium and gold alloy device that passed through the mandible's lower to the upper section. These materials, while promising, are no longer in use.

Era of osseointegration: Dr. Per-Ingvar Brånemark, a research professor and orthopaedic surgeon, made an inadvertent discovery in 1952 that laid the groundwork for modern oral implantology. In the process of researching bone mending and regeneration, Brånemark implanted titanium chambers into rabbit femurs to monitor blood microcirculation in solid tissues. The titanium shards were well interwoven with the bone when he attempted to extract them, which made it challenging. Brånemark used this observation to develop the term "osseointegration," which he used to characterize the special bond between metal and bone. He quickly used this idea in dental implant treatments after realizing how outstanding titanium's resistance to fracture was. When fractures did occur during additional testing, they were always between bone and bone and never between bone and implant, proving the strength and dependability of titanium in this application [12, 13]. After this discovery, Brånemark carried out several clinical research projects, initially treating patients who had lost every tooth. He asked the Swedish government for assistance in 1977 and was granted to gather a significant amount of data regarding his dental implants. After receiving "full acceptance" from the American Dental Association, these implants were used for more applications, such as overdenture support, bridges for patients who were partially or completely edentulous, and single-tooth replacements [14]. In 1982, the idea of osseointegrated, endosseous implants was presented to the American market. Brånemark and his associates presented the findings of their 15-year study which was well-supported by data and involved substantial clinical follow-up during a critical conference. This marked a significant leap in dental implantology as the success of these implants was assessed by quantifying bone resorption by standardized radiographs, evaluating gingival health, examining functional results, and grading patient comfort [13].

Osseointegration

A direct and solid bond between organized live bones and the surface of a load-bearing implant is the original definition of osseointegration. In a clinical context, it describes how an implant is stable and ankylosis within the bone, meaning that there is no movement between the implant and the surrounding bone [15]. During research on blood flow in bone marrow in the 1950s, the idea of osseointegration came to be. A titanium implant was placed into the bone and allowed to grow into the bone and blood vessels because of its central canal and transverse hole design. Following this finding, a great deal of research and clinical applications involving titanium implants were initiated as it became clear that titanium screws fused with bone might offer long-term support for dental prostheses [16]. When titanium is exposed to air, a thin oxide layer grows on its surface naturally; this layer thickens when live tissues are present. Macrophages, which are immune cells that release enzymes and cytokines that aid in the creation of oxide, further improve this oxide layer [17]. According to the current theory, titanium differs from other metals in that it has a unique feature called a hydrated titanium peroxy matrix, which acts as an interface between titanium and living tissue. Improving the contact between the implant and bone has been the subject of research to improve implant stability and hasten bone repair. To encourage a more robust biochemical interaction between bone matrix proteins and the implant surface, one strategy is to chemically incorporate inorganic elements, like calcium phosphate, into the titanium oxide layer. Alternatively, the surface topography of the implant is addressed by its physical design. A rough surface promotes surface area and energy at the micro and nanoscales, which in turn improves cell proliferation, bone attachment, and overall osseointegration [18, 19].

Biological Aspect of Osseointegration

Osteonal remodeling plays a major role in cortical bone healing, whereas peri-implant trabecular bone healing occurs in three stages. Driven by platelet activation and the stability of fibrin clots, osteogenic cells migrate towards the implant surface during the first phase, known as osteoconduction. On the implant surface, these activities encourage the targeted proliferation of bone-forming cells. Before they reach the surface, differentiating cells release matrix, which stops their migration and enables osteoconduction to direct a bone spicule in the direction of the implant [20]. De novo bone synthesis, the second phase, produces a mineralized interfacial matrix that resembles the cement line in naturally occurring bone. In contact osteogenesis, where the implant surface facilitates bone bonding, osteoconduction and de novo bone creation work together [21]. The last stage, known as "bone remodeling," entails more gradual physiological processes. During several remodeling cycles, the structure and mechanical qualities of the bone around the implant are optimized. The characteristics of the implant surface, including its hydrophilicity, roughness, and ionic composition, have a major impact on the amount, quality, and rate of bone response. This eventually affects the stability and interface between the implant and the bone [22].

Surface Characterization of an Implant

The surface features of an implant have an impact on the biological reaction that is triggered when a substance is introduced into the body. Successful osseointegration requires direct bone-to-implant contact at the microscopic level, and surface changes at the microscale are used to accomplish this [23]. Interactions between cells and biomaterials allow biological signals to be exchanged, which triggers the activation of genes and tissue remodeling. At first, ions, proteins, lipids, and sugars stick to the implant surface and cause biological reactions that either encourage the implant's acceptance or rejection. This first reaction primarily determines the kind and number of cells interacting with the surface [24]. A strong link between the implant and bone is essential for osseointegration, and this can only be established by achieving significant bone-implant contact. The speed and quality of osseointegration are strongly influenced by the chemical and physical characteristics of the implant surface, such as its composition and level of roughness. These qualities are also essential for preserving the health of the surrounding soft tissue and bones. Much study has been done on managing surface characteristics such as morphology, roughness, surface energy, and chemical composition to increase the success of dental implants. These variables either speed up or slow down the healing process, which affects how well osseointegration proceeds [25]. Research indicates that rough surfaces promote faster adhesion of osteoblastic cells, which in turn influence cell morphology and function while directing cell direction and movement [5, 25]. It has been demonstrated that surface roughness, obtained by methods such as acid etching or grit-blasting, greatly improves the bone-implant contact. Larger rough surfaces (2–3 µm) appear to improve contact strength and resistance to shear pressures, despite the lack of a uniform roughness criterion [5]. Furthermore, the osteoconductive qualities of the implant are improved by chemical modifications, such as the addition of calcium phosphates or hydroxyapatite, which improve bone formation and bridge the gap between implant and bone [26, 27].

Chemical Composition of Surface of the Dental Implant

Protein adsorption and cell adhesion are significantly impacted by the surface charges and chemical makeup of titanium implants, which differ depending on the bulk composition and surface treatments used. Titanium alloys or commercially pure titanium (cpTi) are frequently used in dental implants. While grade 5 titanium alloy (Ti6Al4V) has higher yield strength and fatigue resistance compared to pure titanium, grade 4 cpTi is typically utilized because of its superior strength [28].

Furthermore, titanium implant surfaces' hydrophilicity plays a major role in how well they interact with biological fluids, cells, and tissues. In general, hydrophilic surfaces are preferable than hydrophobic ones. Titanium implant contact angle measurements span from 0° (hydrophilic) to 140° (hydrophobic) [29].

Types of Surface Characterization of Dental Implants

The surface characterization of dental implants has been given as a series of five generations. [30] (figure 1). Apart from the generational classification of dental implants, we have the classification of surface characterization based on the subjection of the implant surface, AKA, additive or subtractive characterization.

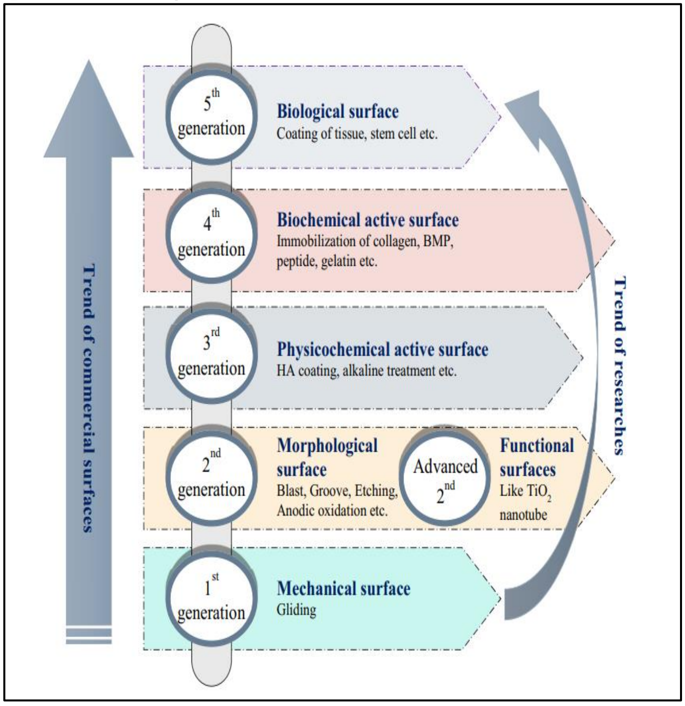

Figure 1: Generations of Surface Characterization of Dental Implants

Subtractive Surface Characterization of Implants

Sand Blasting

The three main objectives of sand-blasting are as follows:

To remove surface contaminants before proceeding with further operations,

To create a roughened surface that increases the effective surface area (in certain cases, the effective surface area can be twice as large as the original surface area), and

To generate advantageous surface compressive residual stress [31].

Compressive residual stress increases the fatigue strength and life of treated implant surfaces by increasing their surface energy and chemical and physical activity. Many mechanical surface alterations have been devised to improve the production of tissue and bone, including threading, grooving, porosity, and roughness [31].

Surface roughness, particularly in the 10 nm–10 µm range, affects interface biology, stress distribution, and mechanical interlocking to promote interactions between cells and macromolecules. Grain boundaries and dislocations are examples of defects that lead to microroughness, which promotes biomolecule contact. Studies show that rough surfaces enhance the adhesion of cells, biomolecules, and minerals, hence fortifying tissue connections and reducing inflammation. These surfaces also lessen the quantity of plaque and microbial adhesion in comparison to smooth surfaces [32].

Acid Etching

Acid etching is a process that creates tiny pits (0.5-2 µm) on the surface of metallic implants by immersing them in acidic solutions like HF or HCl [21]. Acid treatment temperature, duration, and concentration all affect the result. Enhancing cell adhesion and quickening osseointegration, this procedure produces a consistently rough surface with a greater active area [24]. For even better osseointegration, advanced methods such acid etching (SLA) in conjunction with sandblasting and dual-acid etching are used [5, 33]. More stability and bone contact are achieved by acid-etched implants than by machined screws, according to studies. Fluoride ions retained on hydrofluoric acid-etched surfaces, like the Astra fluoride surface, activate osteoblasts through the glycolytic pathway, improving osseointegration [34].

Anodisation

This method involves immersing the implant in an electrolyte and applying a current, which leads to the formation of micropores of different sizes and a rise in the oxide layer. The primary benefits of the anodization process include enhanced biocompatibility, heightened cell adhesion, and accelerated cell proliferation [5, 21, 24].

Laser Microtexturing

Using high-intensity laser pulses (5–15 GW/cm2) to create a shock wave via a transient plasma and induce compressive residual stress in the workpiece, laser peening is a novel non-contact surface treatment. Without contaminating the system, this procedure extends fatigue life and inhibits stress corrosion cracking [35, 36]. The removal torque of CpTi screws treated with laser after 8 weeks of implantation in rabbit tibias was higher (62.57 N-cm) than that of machined implants (23.58 N-cm). A micropore-filled honeycomb pattern was discovered by SEM research. Gaggl et al. observed laser-treated Ti surfaces with perfect roughness and regular micropores (10–12 µm intervals, 25 µm diameter, and 20 µm depth) [37]. This was done to increase osseointegration.

Additive Surface Characterization of Implants

Hydroxyapatite coating: Hydroxyapatite (HA) coating was first put on implants by Dr. De Groot in 1994. It is frequently used in conjunction with calcium phosphate and nanostructured calcium. HA coatings are applied by hydrothermal deposition or plasma spraying, and they offer biomechanical benefits and better stress distribution. When compared to uncoated implants, Fouda et al. discovered that titanium implants with HA coating sped up healing, while Xie et al. observed that the HA coating increased cell proliferation [38].

Calcium phosphate: Following implant implantation, a biological apatite layer forms on the implant surface because of the release of calcium phosphate, which also raises the concentration of body fluids. This layer of apatite, which contains body proteins, improves bone regeneration by acting as a scaffold for osteogenic cell adhesion and proliferation. Because titanium implants with the calcium phosphate layer osseointegrate more quickly than those without, the faster osseointegration leads to higher long-term clinical success rates [39, 40].

Zirconia coating: Just as ceramic is coated on crowns, zirconia ceramic is coated and sired in a furnace on a titanium core. The coating consists of Zirconium dioxide (43%), titanium dioxide (49%) and traces of phosphorous pentoxide (8%) [41]. Titanium coating also has a transitional phase of microcrystalline zirconium titanate.

Titanium sintering: Small millimeter size beads are sintered on the surface of the titanium core. This promotes bone growth into the space between the beads.

Plasma spraying: Using a plasma torch heated to a high temperature of around 15,000°C, titanium particles can be deposited onto a surface to modify titanium implants. High-speed (600 m/sec) molten titanium particles (0.05-0.1 mm) are produced by an argon plasma and sprayed onto the metal substrate. By permitting bone tissue penetration, which boosts tensile strength and shear force transmission, optimal surface porosities (150–400 µm) improve fixation strength. Surfaces roughened significantly by plasma spraying can be produced; titanium dioxide coatings, for instance, have an average roughness of about 20 µm [42].

Bioglass surface: Due to pH fluctuations, bioglass, a thick ceramic containing silicon, calcium, sodium, and phosphorus oxides [43], dissolves ions when implants are placed. The material's silicon dioxide condenses into silanol gel. Fibroblasts are drawn to the tissue by calcium and phosphate ions, which results in the synthesis of collagen. These ions then form a layer of hydroxy-carbonate-fluorapatite that crystallizes and forms a connection with collagen fibers.

Company Based Surface Characterization

Stages of implant processing involve a variety of surface modifications that finally helps influence and enhance the osseointegrative capacity of the implants [44] (Figure 2).

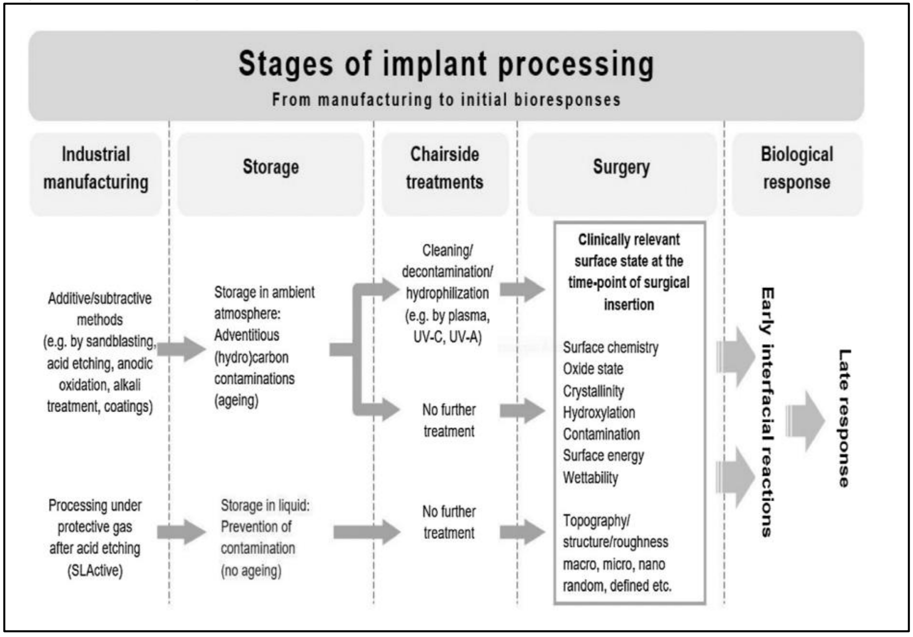

Figure 2: Stages of implant processing

Every company has taken up different strategies to provide their implants with a certain advantage in the osseointegrative phase post-implant placement (Table 1).

Table 1. The Implant Surface Modifications by Different Implant Companies

IMPLANT COMPANY	IMPLANT NAME	SURFACE CHARACTERIZATION
Dentsply	Ankylos plus, XiVe, Frialit	Sandblasted, large grit blasted, Acid etched
Nobel Biocare	NobelActive	Phosphate enriched titanium oxide – TiUnite Surface
Osstem	GS III	Resorbable blast media (RBM) – Calcium Phosphate Hydroxyapatite
Biomet3i	NanoTite	Calcium phosphate by Discrete Crystal Deposition (DCD)
Straumann	SLA Active	Sand blasted with large grit particles followed by acid etching
Biohorizon	Laserlok	Laser Peening
Sybron	Pitt Easy	Vacuum titanium plasma spraying (VTPS)
AstraTech	TiOBlast	Titanium oxide grit blasting
Zimmer	ScrewVent	Microtextured Hydroxyapatite surface
Adin Dental Implants	Osseofix	Calcium Phosphate Bioresorbable Blast Media (RBM)
Equinox	Nanopore surface	Caclium oxidized nanoporous surface with 3D interconnecting porosities
Alpha Bio Implants	Alpha Bio Implants	Nanotec surface
Straumann	Roxolid	15% Zirconium and 85% Titanium

Recent Trends in Implant Surface Coatings

Dental implants had a 95% survival rate, according to ten-year research, demonstrating their predictability [45]. Even with successful outcomes, problems like peri-implantitis and mechanical problems persist. Within five to ten years, 10% of implants and over 20% of patients develop peri-implantitis, which can result in implant failure and bone loss [46]. Coatings with nanoparticles have been developed to counteract this. Research indicates that when compared to other metal oxides, nanoparticles such as titanium dioxide (TiO2), zirconium dioxide (ZrO2), and zinc oxide (ZnO) have better antibacterial qualities at a lower toxicity.

Nanoparticles in Dental Implants: Enhancing Bioactivity and Infection Resistance

The antibacterial and anti-inflammatory properties of copper have long been recognized. Nowadays, titanium dental implants' bioactivity and antibacterial properties are enhanced by the application of copper nanoparticles (CuNPs). Because of its titanium dioxide coating, which contributes significantly to its corrosion resistance, low toxicity, and biocompatibility, titanium is preferred in medical applications [47-51]. This coating improves the material's interaction with living cells and inhibits corrosion. There are different pathological oral conditions and other conditions [52-55]. The antibacterial qualities of zinc oxide (ZnO) nanoparticles are highly prized, as is their ability to improve the mechanical and structural characteristics of dental materials [56]. Silver nanoparticles are utilized to prevent peri-implant infections. They have been demonstrated to boost bone mineral density while shielding surrounding tissues, and they have strong antibacterial qualities against infections including Pseudomonas aeruginosa and Staphylococcus aureus [57-59].

Zirconium oxide nanoparticles (ZrO2) have outstanding mechanical qualities and are biocompatible, which makes them useful in tissue engineering and dental implants. Nano-ZrO2 powders are created using processes including sol-gel and co-precipitation [60]. A polymer made from chitin called chitosan has demonstrated potential for improving implant integration and bone repair. Chitosan nanoparticles derived from human dental pulp stem cells have been shown in recent research to assist bone healing [61]. The mineralization of artificial substitutes such as calcium carbonate, PRF, and nano-hydroxyapatite has demonstrated clinical benefits in various fields [62-64]. There are different in silico model involved in determining the pathological conditions.

Conclusion

Important methods and their practical implications are highlighted in this study of dental implant surface characterization. To promote osseointegration and guarantee implant longevity, precise surface characterization is essential. Methods including surface roughness measurements, spectroscopy, and microscopy have revealed important information regarding the chemical and microstructural characteristics of implants. Roughening, bioactive coatings, and nanotechnology are examples of surface alterations that have greatly improved biological responses and accelerated and improved osseointegration. Clinical research attests to the fact that implants with optimized surfaces provide better stability, faster healing, and fewer problems. Standardizing characterization techniques and converting lab results into trustworthy clinical outcomes are still difficult tasks, nevertheless. Subsequent studies ought to focus on improving characterization methods, examining the enduring consequences of surface alterations, and incorporating these discoveries into medical procedures. Progress in implant dentistry and better patient outcomes depend on ongoing developments in surface characterization.

References

[1]. Yamamoto, S. and Shiga, H., 2018. Masticatory performance and oral health-related quality of life before and after complete denture treatment. *Journal of Prosthodontic Research*, 62(3), pp. 370-374.

[2]. Steele, J.G., Sanders, A.E., Slade, G.D., Allen, P.F., Lahti, S., Nuttall, N. and Spencer, A.J., 2004. How do age and tooth loss affect oral health impacts and quality of life? A study comparing two national samples. *Community Dentistry and Oral Epidemiology*, 32(2), pp. 107-114.

[3]. Block, M.S., 2018. Dental implants: The last 100 years. *Journal of Oral and Maxillofacial Surgery*, 76(1), pp. 11-26.

[4]. Khazaei, S., Firouzei, M.S., Sadeghpour, S., Jahangiri, P., Savabi, O., Keshteli, A.H. and Adibi, P., 2012. Edentulism and tooth loss in Iran: SEPAHAN systematic review No. 6. *International Journal of Preventive Medicine*, 3(Suppl1), p. S42.

[5]. Gupta, A., Dhanraj, M. and Sivagami, G., 2010. Status of surface treatment in endosseous implant: a literary overview. *Indian Journal of Dental Research*, 21(3), pp. 433-438.

[6]. Feine, J.S., 2002. The McGill consensus statement on overdentures. *Int. J. Prosthodont.*, 15, pp. 413-414.

[7]. Rodriguez, B.R., Rizzo, S. and Zampetti, P., 2002. Considerazioni storicocliniche sull'evoluzione dell'implantologia. *Rivista di Storia della Medicina* XII NS, 33(1-2), pp. 149-56.

[8]. Pasqualini, U. and Pasqualini, M.E., 2009. The History of Implantology. In Treatise of Implant Dentistry: The Italian Tribute to Modern Implantology. Ariesdue.

[9]. Abraham, C.M., 2014. Suppl 1: A brief historical perspective on dental implants, their surface coatings and treatments. *The Open Dentistry Journal*, 8, p. 50.

[10]. Kawahara, D. and Kawahara, D., 1959. Part 1-The history and concept of implant. *Journal of the Japan Prosthodontic Society*, 3(1), pp. 97-100.

[11]. Sullivan, R.M., 2001. Implant dentistry and the concept of osseointegration: a historical perspective. *Journal of the California Dental Association*, 29(11), pp. 737-744.

[12]. Pal, T.K., 2015. Fundamentals and history of implant dentistry. *Journal of the International Clinical Dental Research Organization*, 7(Suppl 1), pp. S6-S12.

[13]. Branemark, P.I., 1985. Tissue-Integrated Prostheses. Osseointegration in clinical dentistry, pp. 11-344.

[14]. Rao, B.S. and Bhat, V.S., 2015. Dental implants: A boon to dentistry. *Archives of Medicine and Health Sciences*, 3(1), pp. 131-137.

[15]. Albrektsson, T. and Zarb, G.A., 1993. Current interpretations of the osseointegrated response: clinical significance. *International Journal of Prosthodontics*, 6(2).

[16]. Branemark, P.I., 1983. Osseointegration and its experimental background. *The Journal of Prosthetic Dentistry*, 50(3), pp.399-410.

[17]. Sundgren, J. E., Bodö, P., Lundström, I., Berggren, A., an Hellem, S., (1985. Auger electron spectroscopic studies of stainless-steel implants. *Journal of Biomedical Materials Research*, 19(6), 663–671. https://doi.org/10.1002/jbm.820190606.

[18]. Albrektsson, T., and Wennerberg, A., 2004. Oral implant surfaces: Part 1--review focusing on topographic and chemical properties of different surfaces and in vivo responses to them. *The International journal of prosthodontics*, 17(5), 536–543.

[19]. Coelho, P. G., Granjeiro, J. M., Romanos, G. E., Suzuki, M., Silva, N. R., Cardaropoli, G., Thompson, V. P., and Lemons, J. E., 2009. Basic research methods and current trends of dental implant surfaces. *Journal of Biomedical Materials Research*. Part B, *Applied Biomaterials*, 88(2), 579–596. https://doi.org/10.1002/jbm.b.31264.

[20]. Lemons J. E., 2004. Biomaterials, biomechanics, tissue healing, and immediate-function dental implants. *The Journal of Oral Implantology*, 30(5), 318–324. https://doi.org/10.1563/0712.1.

[21]. Le Guéhennec, L., Soueidan, A., Layrolle, P., & Amouriq, Y., 2007. Surface treatments of titanium dental implants for rapid osseointegration. Dental materials: Official publication of the Academy of Dental Materials, 23(7), 844–854. https://doi.org/10.1016/j.dental.2006.06.025

[22]. Coelho, P.G., Granjeiro, J.M., Romanos, G.E., Suzuki, M., Silva, N.R.F., Cardaropoli, G., Thompson, V.P. and Lemons, J.E. 2009b. Basic research methods and current trends of dental implant surfaces. *Journal of Biomedical Materials Research Part B: Applied Biomaterials* 88: 579–596.

[23]. Stanford C. M., 2008. Surface modifications of dental implants. *Australian Dental Journal*, 53

Suppl 1, S26–S33. https://doi.org/10.1111/j.1834-7819.2008.00038.x

[24]. Krishna Kumar, U., Ramesh Bhat, T.R., Harish, P.V., Sameer, V.K. and Gangaiah, M., 2011. Nanobiotechnology Approaches to Design Better Dental Implant Materials. *Trends in Biomaterials & Artificial Organs,* 25(1).

[25]. Triplett, R.G., Frohberg, U., Sykaras, N. and Woody, R.D., 2003. Implant materials, design, and surface topographies: their influence on osseointegration of dental implants. *Journal of Long-Term Effects of Medical Implants*, 13(6).

[26]. Ehrenfest, D.M.D., Coelho, P.G., Kang, B.S., Sul, Y.T. and Albrektsson, T., 2010. Classification of osseointegrated implant surfaces: materials, chemistry, and topography. *Trends in Biotechnology*, 28(4), pp. 198-206.

[27]. Søballe K., 1993. Hydroxyapatite ceramic coating for bone implant fixation. Mechanical and histological studies in dogs. Acta orthopaedica Scandinavica. Supplementum, 255, 1–58. https://doi.org/10.3109/17453679309155636

[28]. Steinemann, S.G., 1998. Titanium—the material of choice?. *Periodontology* 2000, 17(1), pp. 7-21.

[29]. Buser, D., Broggini, N., Wieland, M., Schenk, R.K., Denzer, A.J., Cochran, D.L., Hoffmann, B., Lussi, A. and Steinemann, S.G., 2004. Enhanced bone apposition to a chemically modified SLA titanium surface. *Journal of Dental Research,* 83(7), pp.529-533.

[30]. Sadati Tilebon, S.M., Emamian, S.A., Ramezanpour, H., Yousefi, H., Özcan, M., Naghib, S.M., Zare, Y. and Rhee, K.Y., 2022. Intelligent modeling and optimization of titanium surface etching for dental implant application. *Scientific Reports*, 12(1), p.7184.

[31]. Oshida, Y. and Daly, J., 1990. Fatigue damage evaluation of shot peened high strength aluminum alloy. In Surface Engineering (pp. 404-416). *Dordrecht: Springer Netherlands.*

[32]. Wen, X., Wang, X. and Zhang, N., 1996. Microrough surface of metallic biomaterials: a literature review. *Bio-Medical Materials and Engineering,* 6(3), pp.173-189.

[33]. Coelho, Paulo G., José M. Granjeiro, George E. Romanos, Marcelo Suzuki, Nelson RF Silva, Giuseppe Cardaropoli, Van P. Thompson, and Jack E. Lemons. "Basic research methods and current trends of dental implant surfaces." *Journal of Biomedical Materials Research Part B*: Applied Biomaterials: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials 88, no. 2 (2009): 579-596.

[34]. Ellingsen, J.E., Johansson, C.B., Wennerberg, A. and Holmén, A., 2004. Improved Retention and Bone-to-Implant Contact with Fluoride-Modified Titanium Implants. *International Journal of Oral & Maxillofacial Implants*, 19(5).

[35]. DeWald, A.T., Rankin, J.E., Hill, M.R., Lee, M.J. and Chen, H.L., 2004. Assessment of tensile residual stress mitigation in alloy 22 welds due to laser peening. *J. Eng. Mater. Technol.*, 126(4), pp. 465-473.

[36]. Fairand, B.P., Wilcox, B.A., Gallagher, W.J. and Williams, D.N., 1972. Laser shock-induced microstructural and mechanical property changes in 7075 aluminium. *Journal of Applied Physics*, 43(9), pp. 3893-3895.

[37]. Gaggl, A., Schultes, G., Müller, W.D. and Kärcher, H., 2000. Scanning electron microscopical analysis of laser-treated titanium implant surfaces—A comparative study. *Biomaterials,* 21(10), pp. 1067-1073.

[38]. De Groot, K., Wolke, J.G.C. and Jansen, J.A., 1998. Calcium phosphate coatings for medical implants. Proceedings of the Institution of Mechanical Engineers, Part H*: Journal of Engineering in Medicine*, 212(2), pp. 137-147.

[39]. Morris, H.F., Ochi, S., Spray, J.R. and Olson, J.W., 2000. Periodontal-Type Measurements Associated with Hydroxyapatite-Coated and Non—HA-Coated Implants: Uncovering to 36 Months. *Annals of Periodontology,* 5(1), pp.56-67.

[40]. Barrere, F., Van Der Valk, C.M., Meijer, G., Dalmeijer, R.A.J., De Groot, K. and Layrolle, P., 2003. Osteointegration of biomimetic apatite coating applied onto dense and porous metal implants in femurs of goats. Journal of Biomedical

Materials Research Part B: Applied Biomaterials: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials, 67(1), pp.655-665.

[41]. Kohal, R.J., Weng, D., Bächle, M. and Strub, J.R., 2004. Loaded custom-made zirconia and titanium implants show similar osseointegration: an animal experiment. *Journal of Periodontology, 75*(9), pp. 1262-1268.

[42]. Martin, J. Y., Schwartz, Z., Hummert, T. W., Schraub, D. M., Simpson, J., Lankford, J., Jr, Dean, D. D., Cochran, D. L., and Boyan, B. D., 1995. Effect of titanium surface roughness on proliferation, differentiation, and protein synthesis of human osteoblast-like cells (MG63*). Journal of Biomedical Materials Research*, 29(3), 389–401. https://doi.org/10.1002/jbm.82029031.

[43]. Weinstein, A.M., Klawitter, J.J. and Cook, S.D., 1980. Implant-bone interface characteristics of bioglass dental implants. *Journal of Biomedical Materials Research*, 14(1), pp. 23-29.

[44]. Rupp, F., Liang, L., Geis-Gerstorfer, J., Scheideler, L. and Hüttig, F., 2018. Surface characteristics of dental implants: A review. *Dental Materials*, 34(1), pp. 40-57.

[45]. Degidi, M., Nardi, D. and Piattelli, A., 2012. 10-year follow-up of immediately loaded implants with TiUnite porous anodized surface. *Clinical Implant Dentistry and Related Research*, 14(6), pp. 828-838.

[46]. Berglundh, T., Armitage, G., Araujo, M.G., Avila-Ortiz, G., Blanco, J., Camargo, P.M., Chen, S., Cochran, D., Derks, J., Figuero, E. and Hämmerle, C.H., 2018. Peri-implant diseases and conditions: Consensus report of workgroup 4 of the 2017 World Workshop on the Classification of Periodontal and Peri-Implant Diseases and Conditions. *Journal of Periodontology*, 89, pp. S313-S318.

[47]. Niinomi, M., 2008. Mechanical biocompatibilities of titanium alloys for biomedical applications. *Journal of the Mechanical Behavior of Biomedical Materials*, 1(1), pp. 30-42.

[48]. Chokkattu, J.J., Mary, D.J., Shanmugam, R. and Neeharika, S., 2022. Embryonic toxicology evaluation of ginger-and clove-mediated titanium oxide nanoparticles-based dental varnish with zebrafish. The Journal of Contemporary Dental Practice, 23(11), p.1158.

[49]. Dharman, S., Maragathavalli, G., Shanmugam, R. and Shanmugasundaram, K., 2023. Current perspectives of nanotherapies in the prevention and treatment of radiotherapy/chemotherapy-induced oral mucositis in head and neck cancer—A narrative review. *Journal of International Oral Health*, *15*(6), pp.491-499.

[50]. Francis, T., Chokkattu, J.J., Neeharika, S., Ramakrishnan, M. and Thangavelu, L., 2023. Embryonic Toxicology Evaluation of Dental Varnish Using Titanium Oxide Nanoparticles Synthesized Using Ginger and Rosemary. *World Journal of Dentistry*, *14*(9), pp.791-796.

[51]. Khanna, N., Chokkattu, J.J., Neeharika, S., Ramakrishnan, M., Shanmugam, R. and Thangavelu, L., 2023. Anti-inflammatory Activity and Cytotoxic Effect of Ginger and Rosemary-mediated Titanium Oxide Nanoparticles-based Dental Varnish. *World Journal of Dentistry*, *14*(9), pp.761-765.

[52]. Rajasekaran, K., Renu, K., Sankaran, K., Veeraraghavan, V.P., Rengasamy, G., Ronsivalle, V., Cicciù, M. and Minervini, G., Determination of red blood cell parameters for signs of iron deficiency anemia in patients with oral diseases. *Minerva dental and oral science*. DOI: 10.23736/S2724-6329.24.04907-6.

[53]. Sundaravadivelu, I., Renu, K., Kavitha, S., Priya, V.V., Gayathri, R., Ronsivalle, V., Cicciù, M. and Minervini, G., 2024. Elucidating hematological profile and electrolyte balance in oral cancer patients. *Minerva Dental and Oral Science*. doi: 10.23736/S2724-6329.24.04902-7.

[54]. Rajendran, P., Renu, K., Abdallah, B.M., Ali, E.M., Veeraraghavan, V.P., Sivalingam, K., Rustagi, Y., Abdelsalam, S.A., Ibrahim, R.I.H. and Al-Ramadan, S.Y., 2024. Nimbolide: promising agent for prevention and treatment of chronic diseases (recent update). *Food & Nutrition Research*, *68*. DOI:10.29219/fnr.v68.9650.

[55]. Rajendran, P., Renu, K., Ali, E.M., Genena, M.A.M., Veeraraghavan, V., Sekar, R., Sekar, A.K., Tejavat, S., Barik, P. and Abdallah, B.M., 2024. Promising and challenging phytochemicals targeting LC3 mediated autophagy signaling in cancer therapy. *Immunity, Inflammation and Disease*, *12*(10), p.e70041. doi: 10.1002/iid3.70041.

[56]. Balhaddad, A.A., Kansara, A.A., Hidan, D., Weir, M.D., Xu, H.H. and Melo, M.A.S., 2019. Toward dental caries: Exploring nanoparticle-based platforms and calcium phosphate compounds for dental restorative materials. *Bioactive Materials,* 4, pp. 43-55.

[57]. Salaie, R.N., Besinis, A., Le, H., Tredwin, C. and Handy, R.D., 2020. The biocompatibility of silver and nanohydroxyapatite coatings on titanium dental implants with human primary osteoblast cells. *Materials Science and Engineering*: *C,* 107, p.110210.

[58]. Renu, K., Gopalakrishnan, A.V. and Madhyastha, H., 2024. Is periodontitis triggering an inflammatory response in the liver, and does this reaction entail oxidative stress?. *Odontology*, pp.1-14. doi: 10.1007/s10266-024-01032-x.

[59]. Renu, K., 2024. A molecular viewpoint of the intricate relationships among HNSCC, HPV infections, and the oral microbiota dysbiosis. *Journal of Stomatology, Oral and Maxillofacial Surgery*, p.102134.

[60]. Nie, L., Zhan, Y., Liu, H. and Tang, C., 2014. Novel β-type Zr–Mo–Ti alloys for biological hard tissue replacements. *Materials & Design*, 53, pp. 8-12.

[61]. Sanap, P., Hegde, V., Ghunawat, D., Patil, M., Nagaonkar, N. and Jagtap, V., 2020. Current applications of chitosan nanoparticles in dentistry: A review. *Int J Appl Dent Sci*, 6(4), pp. 81-84.

[62]. Kaarthikeyan, G., Jayakumar, N.D. and Sivakumar, D., 2019. Comparative Evaluation of Bone Formation between PRF and Blood Clot Alone as the Sole Sinus-Filling Material in Maxillary Sinus Augmentation with the Implant as a Tent Pole: A Randomized Split-Mouth Study. *Journal of long-term effects of medical implants*, *29*(2).

[63]. Kavarthapu, A. and Malaiappan, S., 2019. Comparative evaluation of demineralized bone matrix and type II collagen membrane versus eggshell powder as a graft material and membrane in rat model. *Indian Journal of Dental Research*, *30*(6), pp.877-880.

[64]. Manchery, N., John, J., Nagappan, N., Subbiah, G.K. and Premnath, P., 2019. Remineralization potential of dentifrice containing nanohydroxyapatite on artificial carious lesions of enamel: A comparative: in vitro: study. *Dental research journal*, *16*(5), pp.310-317.