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Original Article

Surface Modifications of Dental Implant and its Clinical Performance: A Review

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ABSTRACT

Objectives: *This review paper aims to provide an overview of various commercially available dental implant surface modifications and treatments, as well as their reported clinical performances. This knowledge would be useful for the practicing clinician in understanding the healing mechanism associated with each type of implant and in selecting the right type of implant for a specific clinical condition.* **Methods:** *An electronic search of literatures was performed in PubMed and Scopus database dated from January 1990 until July 2021. The search keywords were dental implant, surface modification, surface treatment, survival rate and/ or clinical performance as MeSH term. Only relevant studies that were published in English, journal article are summarized and discussed in this review.* **Results:** *In the last decade, implant surfaces were manufactured in a concerted effort to provide bone in a faster and improved osseointegration process. A variety of surface modifications have been developed and are currently being used to enhance clinical performance, including turned (machined), hydroxyapatite-coated surface, titanium plasma-sprayed, grit-blasted, acid-etched, anodization, laser-microtextured as well as combinations thereof.* **Conclusion:** *Dental implant survival rate relies heavily on the successful integration into the jawbone. Geometry and surface topography are critical to the short- and long-term performance of dental implants. Implant surface modifications expedited osseointegration process, which in turn, early and immediate loading of dental implants has emerged as a viable alternative to the conventional loading protocol.*

Keywords: *dental implant; surface modification; surface treatment; clinical performance*

INTRODUCTION

Dental implants have been widely used since the last few decades as artificial tooth roots to support prosthetic supra-structures from single crowns to complete mouth rehabilitations. Conventional dental implant placement involves two-stage, submerged surgical protocol to allow 3 – 6 months of bone healing prior to implant loading (Branemark et al., 2015; Erkapers et al., 2017). This prolonged treatment time inconvenience the patient and increase treatment cost as additional interim restoration is required. Hence, to reduce treatment time and cost, one-stage, non-submerged surgical technique along with an early or immediate loading protocol has been proposed and practiced, albeit not a regular basis. Primary implant stability is a prerequisite for successful osseointegration of dental implants and is significantly influenced by the surface of the implant. Thus, numerous methods of altering implant surface characteristics and topography have since been applied in order to enhance the primary implant stability and shorten bone healingperiod. As a result of advancements in the implant surface technology, the healing time has been reduced from 12 – 24 weeks to 6 – 8 weeks (Erkapers et al., 2017). In turn, early and immediate loading of dental implants has emerged as a viable alternative to the conventional loading protocol (Parelli & Abramowicz, 2015).

Hence, the aim of this paper is to provide an overview of various dental implant surface modifications and treatments as well as their effect on osseointegration and their reported clinical performances. This knowledge would be useful for the practicing clinician in understanding the healing mechanism associated with each type of implant and in selecting the right type of implant for a specific clinical condition.

EVOLUTION OF DENTAL IMPLANT SURFACE MODIFICATIONS

Brånemark invented the first dental implant with machined surface in 1965 (Figure 1). Machined surface was used for the next 15 years until Albrektsson et al. proposed rougher implant surface characteristics for better biological reaction and osseointegration of dental implants (Abraham, 2014). In the mid-1980s, implants with rougher surfaces were created by addition techniques such as hydroxyapatite-coated (HA) and titanium plasma sprayed (TPS) surfaces. However, clinical failures were common due to the delamination of HA–coating which caused peri-implantitis and severe marginal bone resorption (Albrektsson, 1998; Malmqvist & Sennerby, 1990). As a result, both the first generation of HA-coated and TPS surface implants were discontinued (Wennerberg et al., 2018).

To overcome the drawbacks associated with addition technique, subtraction techniques were introduced in the 1990s. These subtraction techniques include blasting and/ or acid-etching and oxidising the surface, to produce moderately rough surfaces within a range of 1 – 2 µm. Good clinical outcome of such surfaces especially in compromised cases have been reported (Jimbo & Albrektsson, 2015). However, moderately rough surfaces were allegedly more prone to harbour plaque and microbes compared to smooth machined surface but not as bad as the rough surfaces produced by surface coating (> 2.0 µm) (Albouy et al., 2011; Derks et al., 2016).

From 2000 onwards, researchers moved towards incorporating bioactive materials (eg. growth factors; peptides; extracellular matrix (ECM) protein) and biologically active drugs (eg. bisphosphonates; simvastatin; antibiotics) onto the implant surfaces (Suci Dharmayanti et al., 2020). These bioactive implants seem promising in enhancing the bone cells interaction with the implant surfaces, thus expediting implant healing, particularly in medically compromised patients (Wang et al., 2020). Another method of surface modification is by incorporating surface porosities through three-dimensional (3D) printing technology (e.g. selective laser melting, electron beam melting) or by metal injection moulding (MIM) (Bencharit et al., 2015). It has been shown that porous implants provide better and faster implant stability not just through osseointegration but also through osseoincorporation (bone ingrowth) into the porosity of the implants (Andani et al., 2014). However, the cost of producing porous implants through 3D printing technology is very high and such costly implants are not popular with the general dental practitioners and are used sparingly in compromised bone condition.

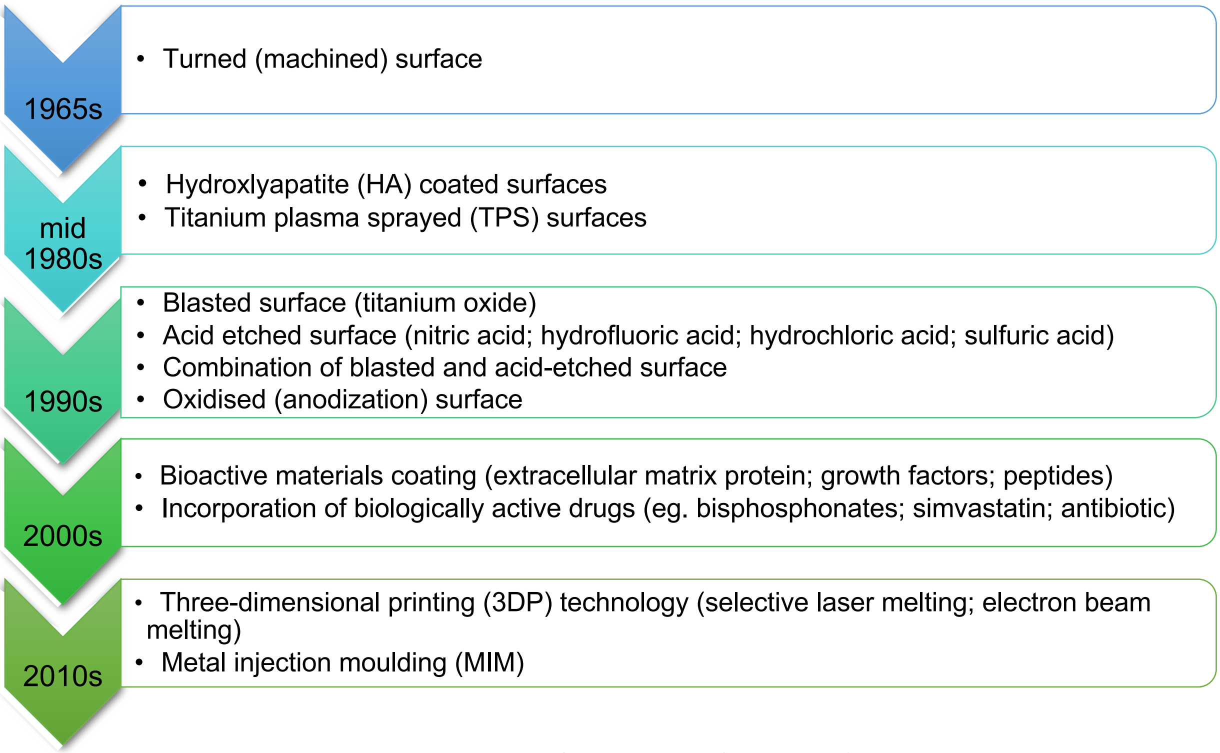

Figure 1: Evolution of implant surface modifications.

SURFACE MODIFICATIONS AND TREATMENTS OF DENTAL IMPLANT

Modification of dental implant topography can be classified into macro-, micro-, and nanoscale level. Implant macrotopography (millimetres to micrometre) is determined by its geometry modification such as threads, porosity and tapered design. Modification of implant microtopography (1 to 100 µm), mainly to increase surface areas by surface treatments like machining, blasting, acid-etching, and different coating procedures. While at nanoscale level (1 to 100 nm), implant modification focuses on improving cell-implant interactions at cellular and protein levels, such as by anodization, laser-microtexturing, discrete crystalline deposition, and increase hydrophilicity (Smeets et al., 2016). In recent years, scientific studies have mainly focused on modifications of implants' microtopography and nanotopography.

Implant surface treatment can be categorised either as additive or subtractive (Figure 2) depending on whether material is deposited or removed from the implant surface (Albrektsson & Wennerberg, 2004b; Bencharit et al., 2015; Smeets et al., 2016). Another method which does not fall into either group and is gaining popularity is 3D printing (3DP) technology and metal injection moulding (MIM) (Bencharit et al., 2014; Wang et al., 2020). However, implant surface modifications through 3DP and MIM are empirical and mostly at the laboratory stage with limited clinical performances being reported. Figure 2 summarises the surface modification techniques used for dental implants into three categories; additive process, subtractive process, & manufacturing technique.

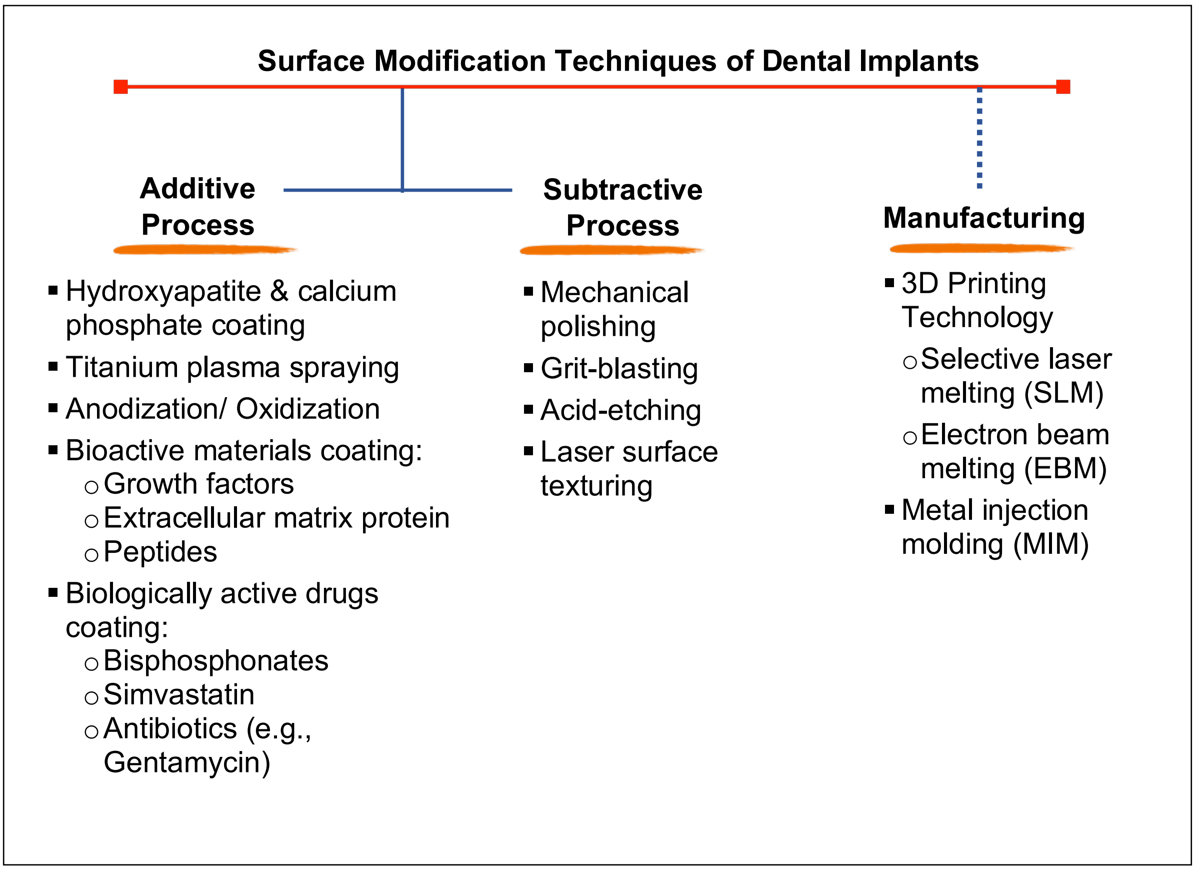

Figure 2: Surface modification techniques used for dental implants.

Additive process can be achieved through coating, plasma-spraying, or anodization. The materials used for coating have been titanium oxide, calcium phosphate, hydroxyapatite (HA), fluoride, bioactive materials and biologically active drugs of different thicknesses. Titanium plasma-spraying (TPS) involves injecting powdery forms of titanium into a plasma torch and spraying the implant surfaces. Anodization is an electrochemical process of roughening the titanium oxide layer on the implant surface. Subtractive process includes mechanical polishing, grit-blasting and/or acid-etching, or laser surface texturing. These processes produce dental implants of varying surface roughness (S_a) (Albrektsson & Wennerberg, 2004b) as classified in Table 1 and described in detail in the following section.

Table 1: Dental Implants with various surface roughness (S_a).

Surface Roughness (S_a)	S_a Values	Implant System
Smooth surface	0.0 – 0.4 µm	▪ "Machined" experimental implants
Minimally rough surface	0.5 – 1.0 µm	▪ Most implants used before 1995 ▪ Turned (machined) surface implants (eg. Brånemark System®; Nobel Biocare AB; Southern Implant System®)
Moderately rough surface	1.0 – 2.0 µm	▪ Most of currently marketed implants ▪ Blasted surface (eg. AstraTech TiOblast®; Zimmer MTX®) ▪ Acid-etched surface (eg. Biomet 3i Osseotite® and NanoTite®) ▪ Blasted and acid-etched surface (eg. Straumann® SLA and SLActive) ▪ Oxidised surface (eg. Nobel Biocare TiUnite®) ▪ Laser-microtextured surface (eg. BioHorizons® Laser-Lok®)
Rough surface	>2.0 µm	▪ Titanium plasma-sprayed (TPS) implants (eg. Straumann® TPS; Zimmer® TPS; BIOMET 3i TPS) ▪ Hydroxyapatite-coated implants (eg. Zimmer Calcitek Integral® and Omnilock®; BioHorizons HA-coated)

SURFACE MODIFICATIONS AND ITS RELATED CLINICAL PERFORMANCE

1. Turned (machined) surface

Turned surface implants were the first generation of dental implants invented by Brånemark. The surface appears to be relatively smooth but under scanning electron microscopy (SEM), grooves and ridges appear on the surface of the machined implant with S_a value ranging from 0.5 – 1 µm (Wennerberg et al., 2015). These surface defects provide resistance to bone interlocking as the osteoblastic cells tend to grow along the grooves, hence delaying the osseointegration process (Junker et al., 2009).

Clinical performances

The survival rate of machined implants was reported to be between 78 to 86% after 15 years of function in fully edentulous patients (Adell et al., 1990). The survival rate was lower when placed in poor quality bone (Cochran, 1999). Due to this low survival rate, this type of implants is no longer in use (Anil et al., 2011; Le Guéhennec et al., 2007).

2. Hydroxyapatite coated surface

Hydroxyapatite coated surface implant has an average roughness of approximately 6.2 µm and was layered with 47–130 µm coating thickness of calcium phosphate (CaP), mainly composed of hydroxyapatite (HA) (Hung et al., 2013; Le Guéhennec et al., 2007). After implant placement, CaP was released into the peri-implant region, which then increases the saturation of body fluids and precipitates a biological apatite on the implant surface (De Grootl et al., 1998). This biological apatite layer contains endogenous proteins and serve as a matrix for the attachment and growth of osteogenic cells and subsequently enhanced its biocompatibility and osseointegration (De Grootl et al., 1998; Eom et al., 2012; Hung et al., 2013).

Clinical performances

The cumulative survival rate (CSR) for HA coated implants ranged from 79.2% to 87% after 8 years follow-up (Lee et al., 2000; Wheeler, 1997). HA coated implants had better clinical success rates compared to the uncoated implants due to superior initial rate of osseointegration (Artzi et al., 2006; Lee et al., 2000). However, over the long-term, the success rates of HA-coated implants declined significantly due to delamination and/or loosening of the HA coating from the titanium surface and subsequently led to implant failure (Albrektsson, 1998; Tinsley et al., 2001). Artzi et al. reported a CSR of 54% for HA coated dental implants after ten years of follow-up (Artzi et al., 2006). Hence, the clinical use of this type of surface treatment was discontinued (Albrektsson, 1998; Le Guéhennec et al., 2007).

3. Titanium plasma sprayed (TPS) surface

TPS implant surface was created by spraying thermally melted titanium oxide powders onto the implant surface, forming 40-50 µm coating thickness with an average surface roughness of 7µm (Le Guéhennec et al., 2007; Roy et al., 2011). This increased surface area enhanced the tensile strength at bone-implant interface and expedited osseointegration (D. Buser et al., 1991). However, titanium wear particles at the peri-implant regions had been observed (D. Buser et al., 1991; Urban et al., 2000). Dissemination of this metallic wear particles to other organs such as liver, spleen, and lymph nodes had also been reported (Urban et al., 2000). These potential local and systemic carcinogenic effects limit their clinical application (Browne & Gregson, 2000). Hence, the production of rough TPS surface implants was ceased and replaced with moderately rough surface dental implants (Browne & Gregson, 2000; D. Buser et al., 1991; Urban et al., 2000).

Clinical performances

Despite the implant design and TPS surface been removed from the market, 89.5% survival rate and 75.6% success rates of TPS surface implants had been reported after 20 years follow-up period (Chappuis et al., 2013).

4. Grit-blasted surface

Another method for surface roughening is through subtractive process by blasting the implant surface with hard ceramic particles. Blasting materials should be chemically stable and biocompatible, such as; alumina oxide, titanium oxide and calcium phosphate particles. The blasting materials was projected through a nozzle at a high velocity under pressure to produce a moderately rough surface implant with average roughness of 1–2 µm (Le Guéhennec et al., 2007). However, grit-blasting process exposes the dental implant surfaces to contaminants, thus acid etching following grit-blasting is often required (Le Guéhennec et al., 2007; Marenzi et al., 2019).

Clinical performances

Grit-blasted roughened implant surfaces showed a tendency for more predictable clinical results than machined dental implants, with higher overall success rates and lower bone loss (Gotfredsen &

Karlsson, 2001). Under two stage and delayed loading surgical protocol, CSR rates for TiO_2 grit-blasted implant is 100% after five years and 96.9% after ten years (Gotfredsen & Karlsson, 2001).

5. Acid-etched surface

Etching with strong acid such nitric acid (HNO_3), hydrofluoric acid (HF), hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) is another subtractive process to roughen the implant surfaces (Albrektsson & Wennerberg, 2004a; Le Guéhennec et al., 2007). Acid etching erodes the titanium surface to produce micro-pits with size ranging from 0.5 to 2 μm, depending on the acid concentration, temperature and treatment time used (Massaro et al., 2002). Biomet 3i Osseotite® implant is one example of implant surface produced by acid-etching with average surface roughness of 0.7 μm (Albrektsson & Wennerberg, 2004a). It was surface treated using discrete crystalline deposition with CaP on a dual-acid etched (DAE) surface: where the implant was initially treated with HF to remove oxide layer to create macro-roughness, then treated with HCl and H_2SO_4 to create submicron complexity (Sul et al., 2008). DAE surfaces was found to improve implant's osteoconductive properties by enhancing the adhesion of fibrin and osteogenic cells and thus promote bone apposition (Davies, 2003; Park & Davies, 2000).

Clinical performances

The survival rate of early loaded acid-etched surface implants in partially and totally edentulous patients after 17 years follow up is 92.9% (Velasco-Ortega et al., 2020). When placed in low density bone, the CSR for DAE surface implants is higher than machined implants (Sul et al., 2008). For short-length implants (less than 10 mm), CSR of DAE surface implant was 96% and that of machined surface at 86.5% (Sul et al., 2008). While for standard length implants, CSR for DAE and machined surface implants were 98.4% and 90.6%, respectively (Sul et al., 2008). It was apparent that the short-length DAE implant performs as well as standard-length implants (Sul et al., 2008).

6. Sand-blasted, large-grit and acid-etched (SLA) surface

SLA surface was clinically introduced by Straumann in 1998, with an Sa value of 1 – 2 μm (Albrektsson & Wennerberg, 2004a). SLA implant was produced through large-grit sandblasting technique to create macro-roughness on the titanium surface, then followed by acid etching to superpose micro-roughness (Albrektsson & Wennerberg, 2004a; Galli et al., 2005). The created topography is ideal for cell attachment and potentially faster osseointegration (Bornstein et al., 2008; Galli et al., 2005; He et al., 2009; Kim et al., 2008). In 2005, chemically modified SLA surface (SLActive) with higher hydrophilicity was introduced in the market. SLActive surfaces are produced similar to SLA surface, but with additional rinsing under nitrogen protection and storage in isotonic NaCl solution (Rupp et al., 2006).

Clinical performances

SLA surface implants had 98.8% survival and 97% success rates after 10 year follow-up (Buser et al., 2012). Even in periodontally compromised patients under strict periodontal maintenance, the 10-year survival rate of SLA implant is higher than 95% (Roccuzzo et al., 2014). When used in irradiated patients, the CSR after 5 year follow-up is 96% and 100% for SLA and SLActive surfaces, respectively (Heberer et al., 2011; Nelson et al., 2016). For immediate and early-loaded implants, 97.6% CSR after 10 years was reported for SLActive surfaces implant in posterior maxilla and mandible (Nicolau et al., 2019).

7. Oxidised (anodization) surface

Anodization is an electrochemical process that increases the titanium oxide surface layer and roughness, making it more biocompatible with microporous surfaces, showing increased cell attachment and proliferation (Ivanoff et al., 2003). A commercially available oxidised surface implant is TiUnite® from Nobel Biocare. It is marketed as a hybrid surface design, where the coronal area is minimally roughen (0.5 – 1 μm Sa) with relatively thin oxide layer (~ a few hundred nanometres), while the apical area is rougher (2 μm Sa) and with thicker oxide layer (>10 μm) (Albrektsson & Wennerberg, 2004a).

Clinical performances

In a systematic review comparing clinical performances of different implant surfaces after 10 years, Wennerberg et al reported oxidised surface implants had the highest CSR with 96.6% to 99.2% (Wennerberg et al., 2018). A randomised clinical trial of immediately loaded implants, Rocci et al. reported 95.5% survival rates of anodized implant which is much higher than that of machined implants with 85.5% survival rates (Rocci et al., 2013).

8. Laser-microtextured surface

Laser ablation is another subtractive surface treatment also known as laser micro-texturing technique. A microchannels pattern around the implant collar was created as the high-intensity pulses of a laser beam strike the protective layer that coats the titanium implant surfaces (Smeets et al., 2016). Laser-lok® implants and abutments are the example of commercially available laser surface treatments introduced by BioHorizons®. Laser-lok® surface focuses on enhancing the biological seal especially around the implant collar, thus reducing marginal bone loss, and enhancing osseointegration (Smeets et al., 2016).

Clinical performances

The longest clinical performance available to date was after a 3 years follow-up, where the CSR of laser-microtextured surface as short implants (< 7mm) was 98% (Guarnieri et al., 2019). Guarnieri et al reported that Laser-Lok implant exhibited more gain in papilla level, lesser crestal bone loss and smaller probing depth in comparison with the non-Laser-Lok implant (Guarnieri et al., 2019). Laser-Lok® abutments were also found to support peri-implant soft tissue health (Geurs et al., 2011; Nevins et al., 2010, 2012a, 2012b, 2013). A combination of Laser-Lok® implant, Laser-Lok® abutment and platform-switching was found to encourage regeneration of crestal bone surrounding the implant (Nevins et al., 2013). Another recent prospective study by Guastaldi et al. discovered that resonance frequency analysis (RFA) of laser beam-modified surfaces implants placed in human edentulous mandibles revealed good implant stability at 3 months up to 1 year follow-up, comparable to the SLActive implant surface (Guastaldi et al., 2021). Despite encouraging positive results from laser-modified implant surfaces, long-term follow-up is required to confirm these findings (Guastaldi et al., 2021).

CONCLUSION

The overview of the commercially available surface modifications of dental implants as well as their reported clinical performance were summarised in Table 2. According to available clinical evidence, minimally rough surface implants with a S_a value of 0.5 – 1 μm (turned/ machined surface) and rough surface implants with a S_a value of > 2 μm (hydroxyapatite coated surface; titanium plasma sprayed surface) have a low long-term survival rate of less than 90%. Whereas, most commercially used dental implants today have a moderately rough surface, with an S_a value in the range of 1 – 2 μm. These moderately rough surfaces dental implants (grit-blasted; acid-etched; combination thereof; anodization; laser microtextured) have been shown to expedite the osseointegration process. They demonstrated more than 90% survival rates, even when used in challenging situations such as in low density bone, or when requiring early or immediate loading, or as short-length implants. Implant surface modifications have also resulted in the change of surgical protocol from a two-stage to a one-stage surgery, with the possibility of early or immediate loading. These improvements have significantly reduced the discomfort and inconvenient endured by patients undergoing implant therapy.

Table 2: Overview of commercially available surface modifications of dental implants and its reported clinical performances.

SURFACE MODIFICATION	CONCEPT	IMPLANT SYSTEM	CLINICAL PERFORMANCE
1. Turned (machined) surface	The first generation of dental implants developed by Branemark. Relatively smooth surface. Grooves and ridges were seen on the implant surface under SEM.	Brånemark System®; Nobel Biocare AB; Southern Implant System®	After 15-years follow-up, the estimated survival rate of 78% (maxilla) and 86% (mandible) were reported by Adell et al (Adell et al., 1990).
2. Hydroxyapatite (HA) coating	Coating with HA, an osteoconductive material that has the ability to form a strong bond between bone and implant.	Zimmer Calcitek Integral® and Omnilock®; BioHorizons HA-coated	The cumulative survival rate for HA coated implants ranged from 79.2% to 87% after 8 years follow-up (Lee et al., 2000; Wheeler, 1997; Block & Kent, 1994;). After 10 years follow-up, Artzi et al. reported a cumulative success rate of 54% for HA coated dental implants (Artzi et al., 2006).
3. Titanium plasma spraying (TPS)	Injection of titanium powders into a plasma torch at elevated temperatures, then sprayed onto implant surfaces.	Straumann® TPS; Zimmer® TPS; BIOMET 3i TPS	After 20-years follow-up, Chappuis et al. reported survival rate of 89.5% and success rate of 75.6% (Chappuis et al., 2013).
4. Grit-blasting	Projection of particles (eg. titanium oxide, aluminium oxide, and HA) through a nozzle at a high velocity onto the implant surface.	Zimmer MTX® and Inclusive® Tapered Implants	Cumulative survival rates for TiO_2 grit-blasted implant was 100% after five years and 96.9% after ten years (Gotfredsen & Karlsson, 2001)
5. Acid-etching	Etching with strong acids to increase surface roughness and surface area of titanium implants.	Biomet 3i Osseotite® and NanoTite®	The survival rate of early loaded acid-etched surface implants in partially and totally edentulous patients after 17 years follow up is 92.9% (Velasco-Ortega et al., 2020)
6. Sand-blasted, large-grit and acid-etched (SLA) surface	Grit-blasting process then followed by etching with strong acids.	Straumann® SLA and SLActive; AstraTech TiOblast®	After 10 years follow up, Buser et al. reported of 98.8% survival rate and 97% success rate (Buser et al., 2012). Nicolau et al. reported 97.6%survival rate after 10 years for immediate and early-loaded implants in posterior

			maxilla and mandible (Nicolau et al., 2019).
7. Anodization	An electrochemical process to thicken and roughen titanium oxide layer on the implant surface.	Nobel Biocare TiUnite®	Wennerberg et al reported oxidised surface implants had the highest cumulative survival rates with 96.6% to 99.2% after 10 years follow up (Wennerberg et al., 2018).
8. Laser-microtextured surface	High-intensity pulses of a laser beam strike a protective layer that coats the metallic surface to create a honeycomb pattern with small pores on the implant surface.	BioHorizons® Laser-Lok®	The longest clinical performance available to date was after 3 years follow-up, where the cumulative survival rate of laser-microtextured surface as short implants (< 7mm) was 98% (Guarnieri et al., 2019).

REFERENCES

Abraham, C. M. (2014). A Brief Historical Perspective on Dental Implants, Their Surface Coatings and Treatments. *The Open Dentistry Journal*, *8*(1), 50–55. https://doi.org/10.2174/1874210601408010050

Adell, R., Eriksson, B., Lekholm, U., Brånemark, P. I., & Jemt, T. (1990). Long-term follow-up study of osseointegrated implants in the treatment of totally edentulous jaws. *The International Journal of Oral & Maxillofacial Implants*.

Albouy, J. P., Abrahamsson, I., Persson, L. G., & Berglundh, T. (2011). Implant surface characteristics influence the outcome of treatment of peri-implantitis: An experimental study in dogs. *Journal of Clinical Periodontology*, *38*(1), 58–64. https://doi.org/10.1111/j.1600-051X.2010.01631.x

Albrektsson, T. (1998). Hydroxyapatite-coated implants: A case against their use. *Journal of Oral and Maxillofacial Surgery*, *56*(11 SUPPL. 5), 1312–1326. https://doi.org/10.1016/S0278-2391(98)90616-4

Albrektsson, T., & Wennerberg, A. (2004a). Oral Implant Surfaces : Part 2 — Review Focusing on Clinical Knowledge of Different Surfaces. *The International Journal of Prosthodontics*, *17*, 544–564.

Albrektsson, T., & Wennerberg, A. (2004b). 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. http://www.ncbi.nlm.nih.gov/pubmed/15543910

Andani, M. T., Shayesteh Moghaddam, N., Haberland, C., Dean, D., Miller, M. J., & Elahinia, M. (2014). Metals for bone implants. Part 1. Powder metallurgy and implant rendering. *Acta Biomaterialia*, *10*(10), 4058–4070. https://doi.org/10.1016/j.actbio.2014.06.025

Anil, S., Anand, P. S., Alghamdi, H., & Janse, J. A. (2011). Dental Implant Surface Enhancement and Osseointegration. In *Implant Dentistry - A Rapidly Evolving Practice*. https://doi.org/10.5772/16475

Artzi, Z., Carmeli, G., & Kozlovsky, A. (2006). A distinguishable observation between survival and success rate outcome of hydroxyapatite-coated implants in 5-10 years in function. *Clinical Oral Implants Research*, *17*(1), 85–93. https://doi.org/10.1111/j.1600-0501.2005.01178.x

Bencharit, S., Byrd, W. C., Altarawneh, S., Hosseini, B., Leong, A., Reside, G., Morelli, T., & Offenbacher, S. (2014). Development and applications of porous tantalum trabecular metal-enhanced titanium dental implants. *Clinical Implant Dentistry and Related Research*, 817–826. https://doi.org/10.1111/cid.12059

Bencharit, S., Byrd, W. C., & Hosseini, B. (2015). Immediate placement of a porous-tantalum, trabecular metal-enhanced titanium dental implant with demineralized bone matrix into a socket with deficient buccal bone: A clinical report. *Journal of Prosthetic Dentistry*, *113*(4), 262–269. https://doi.org/10.1016/j.prosdent.2014.09.022

Block, M. S., & Kent, J. N. (1994). Long-term follow-up on hydroxylapatite-coated cylindrical dental implants: A comparison between developmental and recent periods. *Journal of Oral and Maxillofacial Surgery*. https://doi.org/10.1016/S0278-2391(10)80074-6

Bornstein, M. M., Valderrama, P., Jones, A. A., Wilson, T. G., Seibl, R., & Cochran, D. L. (2008). Bone apposition around two different sandblasted and acid-etched titanium implant surfaces: A histomorphometric study in canine mandibles. *Clinical Oral Implants Research*. https://doi.org/10.1111/j.1600-0501.2007.01473.x

Branemark, P. I., Albrektsson, T., Johansson, C., Wenz, H.-J., Bartsch, J., Wolfart, S., Kern, M., Albrektsson, T., Johansson, C., Spinato, S., Zaffe, D., Felice, P., Checchi, L., Wang, H. H. L., Schlee, M. M., Pradies, G., Mehmke, W. U., Beneytout, A., Stamm, M., … Eldridge, D. (2015). Surface modifications of dental implants. *Clinical Oral Implants Research*, *6*(1), 1–9. https://doi.org/10.1111/j.1834-7819.2008.00038.x

Browne, M., & Gregson, P. J. (2000). Effect of mechanical surface pretreatment on metal ion release. *Biomaterials*. https://doi.org/10.1016/S0142-9612(99)00200-8

Buser, D., Schenk, R. K., Steinemann, S., Fiorellini, J. P., Fox, C. H., & Stich, H. (1991). Influence of surface characteristics on bone integration of titanium implants. A histomorphometric study in miniature pigs. *Journal of Biomedical Materials Research*, *25*(7), 889–902. https://doi.org/10.1002/jbm.820250708

Buser, Daniel, Janner, S. F. M., Wittneben, J. G., Brägger, U., Ramseier, C. A., & Salvi, G. E. (2012). 10-Year Survival and Success Rates of 511 Titanium Implants with a Sandblasted and Acid-Etched Surface: A Retrospective Study in 303 Partially Edentulous Patients. *Clinical Implant Dentistry and Related Research*, *14*(6), 839–851. https://doi.org/10.1111/j.1708-8208.2012.00456.x

Chappuis, V., Buser, R., Brägger, U., Bornstein, M. M., Salvi, G. E., & Buser, D. (2013). Long-Term Outcomes of Dental Implants with a Titanium Plasma-Sprayed Surface: A 20-Year Prospective Case Series Study in Partially Edentulous Patients. *Clinical Implant Dentistry and Related Research*, *15*(6), 780–790. https://doi.org/10.1111/cid.12056

Cochran, D. L. (1999). A Comparison of Endosseous Dental Implant Surfaces. *Journal of Periodontology*. https://doi.org/10.1902/jop.1999.70.12.1523

Davies, J. E. (2003). Understanding Peri-Implant Endosseous Healing. *Journal of Dental Education*. https://doi.org/10.1002/j.0022-0337.2003.67.8.tb03681.x

De Grootl, K., Wolke, J. G. C., & Jansen, J. A. (1998). Calcium phosphate coatings for medical implants. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*. https://doi.org/10.1243/0954411981533917

Derks, J., Schaller, D., Håkansson, J., Wennström, J. L., Tomasi, C., & Berglundh, T. (2016). Effectiveness of Implant Therapy Analyzed in a Swedish Population. *Journal of Dental Research*. https://doi.org/10.1177/0022034515608832

Eom, T. G., Jeon, G. R., Jeong, C. M., Kim, Y. K., Kim, S. G., Cho, I. H., Cho, Y. S., & Oh, J. S. (2012). Experimental study of bone response to hydroxyapatite coating implants: Bone-implant contact and removal torque test. *Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology*. https://doi.org/10.1016/j.oooo.2011.10.036

Erkapers, M., Segerström, S., Ekstrand, K., Baer, R. A., Toljanic, J. A., & Thor, A. (2017). The influence of immediately loaded implant treatment in the atrophic edentulous maxilla on oral health related quality of life of edentulous patients: 3-year results of a prospective study. *Head and Face Medicine*, *13*(1), 1–8. https://doi.org/10.1186/s13005-017-0154-0

Galli, C., Guizzardi, S., Passeri, G., Martini, D., Tinti, A., Mauro, G., & Macaluso, G. M. (2005). Comparison of Human Mandibular Osteoblasts Grown on Two Commercially Available Titanium Implant Surfaces. *Journal of Periodontology*. https://doi.org/10.1902/jop.2005.76.3.364

Geurs, N. C., Vassilopoulos, P. J., & Reddy, M. S. (2011). Histologic Evidence of Connective Tissue Integration on Laser Microgrooved Abutments in Humans. *Clinical Advances in Periodontics*. https://doi.org/10.1902/cap.2011.100005

Gotfredsen, K., & Karlsson, U. (2001). A prospective 5-year study of fixed partial prostheses supported by implants with machined anf TiO2-blasted surface. *Journal of Prosthodontics*, *10*(1), 2–7. https://doi.org/10.1053/jpro.2001.23470

Guarnieri, R., Di Nardo, D., Gaimari, G., Miccoli, G., & Testarelli, L. (2019). Short vs. Standard Laser-Microgrooved Implants Supporting Single and Splinted Crowns: A Prospective Study with 3 Years Follow-Up. *Journal of Prosthodontics*, *28*(2), e771–e779. https://doi.org/10.1111/jopr.12959

Guastaldi, F. P. S., Queiroz, T. P., Marques, D. O., Santos, A. B. S., Molon, R. S., Margonar, R., & Guastaldi, A. C. (2021). Comparative Evaluation of Implants with Different Surface Treatments Placed in Human Edentulous Mandibles: A 1-Year Prospective Study. *Journal of Maxillofacial and Oral Surgery*, 1–9.

He, F. M., Yang, G. L., Li, Y. N., Wang, X. X., & Zhao, S. F. (2009). Early bone response to sandblasted, dual acid-etched and H2O2/HCl treated titanium implants: an experimental study in the rabbit. *International Journal of Oral and Maxillofacial Surgery*. https://doi.org/10.1016/j.ijom.2009.03.716

Heberer, S., Kilic, S., Hossamo, J., Raguse, J. D., & Nelson, K. (2011). Rehabilitation of irradiated patients with modified and conventional sandblasted acid-etched implants: Preliminary results of a split-mouth study. *Clinical Oral Implants Research*. https://doi.org/10.1111/j.1600-0501.2010.02050.x

Hung, K. Y., Lo, S. C., Shih, C. S., Yang, Y. C., Feng, H. P., & Lin, Y. C. (2013). Titanium surface modified by hydroxyapatite coating for dental implants. *Surface and Coatings Technology*, *231*, 337–345. https://doi.org/10.1016/j.surfcoat.2012.03.037

Ivanoff, C.-J., Widmark, G., Johansson, C., & Wennerberg, A. (2003). *Histologic Evaluation of Bone Response to Oxidized and Turned Titanium Micro-implants in Human Jawbone*. International Journal of Oral & Maxillofacial Implants. http://web.b.ebscohost.com/ehost/detail/detail?vid=0&sid=e16ccfc2-08f1-4b08-a31e-09ee67de2773%40pdc-v-sessmgr01&bdata=JnNpdGU9ZWhvc3QtbGl2ZSZzY29wZT1zaXRl#AN=36846195&db=ddh

Jimbo, R., & Albrektsson, T. (2015). Long-term Clinical Success of Minimally and Moderately Rough Oral Implants. *Implant Dentistry*. https://doi.org/10.1097/id.0000000000000205

Junker, R., Dimakis, A., Thoneick, M., & Jansen, J. A. (2009). Effects of implant surface coatings and composition on bone integration: A systematic review. *Clinical Oral Implants Research*, *20*(SUPPL. 4), 185–206. https://doi.org/10.1111/j.1600-0501.2009.01777.x

Kim, H., Choi, S. H., Ryu, J. J., Koh, S. Y., Park, J. H., & Lee, I. S. (2008). The biocompatibility of SLA-treated titanium implants. *Biomedical Materials (Bristol, England)*. https://doi.org/10.1088/1748-6041/3/2/025011

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

Lee, J. J., Rouhfar, L., & Beirne, O. R. (2000). Survival of hydroxyapatite-coated implants: A meta-analytic review. *Journal of Oral and Maxillofacial Surgery*, *58*(12), 1372–1379. https://doi.org/10.1053/joms.2000.18269

Malmqvist, J. P., & Sennerby, L. (1990). Clinical report on the success of 47 consecutively placed Core-Vent implants followed from 3 months to 4 years. *The International Journal of Oral & Maxillofacial Implants*.

Marenzi, G., Impero, F., Scherillo, F., Sammartino, J. C., Squillace, A., & Spagnuolo, G. (2019). Effect of different surface treatments on titanium dental implant micro-morphology. *Materials*, *12*(5). https://doi.org/10.3390/ma12050733

Massaro, C., Rotolo, P., De Riccardis, F., Milella, E., Napoli, A., Wieland, M., Textor, M., Spencer, N. D., & Brunette, D. M. (2002). Comparative investigation of the surface properties of commercial titanium dental implants. Part I: Chemical composition. *Journal of Materials Science: Materials in Medicine*. https://doi.org/10.1023/A:1015170625506

Nelson, K., Stricker, A., Raguse, J. D., & Nahles, S. (2016). Rehabilitation of irradiated patients with chemically modified and conventional SLA implants: a clinical clarification. *Journal of Oral Rehabilitation*, *43*(11), 871–872. https://doi.org/10.1111/joor.12434

Nevins, M., Camelo, M., Nevins, M. L., Schupbach, P., & Kim, D. M. (2012a). Connective tissue attachment to laser-microgrooved abutments: a human histologic case report. *The International Journal of Periodontics & Restorative Dentistry*. https://doi.org/10.11607/prd.00.1084

Nevins, M., Camelo, M., Nevins, M. L., Schupbach, P., & Kim, D. M. (2012b). Reattachment of connective tissue fibers to a laser-microgrooved abutment surface. *The International Journal of Periodontics & Restorative Dentistry*. https://doi.org/10.11607/prd.00.1085

Nevins, M., Kim, D. M., Jun, S.-H., Guze, K., Schupbach, P., & Nevins, M. L. (2010). Histologic evidence of a connective tissue attachment to laser microgrooved abutments: a canine study. *The International Journal of Periodontics & Restorative Dentistry*. https://doi.org/10.11607/prd.00.0922

Nevins, M., Nevins, M., Gobbato, L., Lee, H.-J., Wang, C.-W., & Kim, D. M. (2013). Maintaining Interimplant Crestal Bone Height Via a Combined Platform- Switched, Laser-Lok Implant/Abutment System: A Proof-of-Principle Canine Study. *The International Journal of Periodontics and Restorative Dentistry*. https://doi.org/10.11607/prd.1773

Nicolau, P., Guerra, F., Reis, R., Krafft, T., Benz, K., & Jackowski, J. (2019). 10-year outcomes with immediate and early loaded implants with a chemically modified SLA surface. *Quintessence International*, *50*(2), 114–124. https://doi.org/10.3290/j.qi.a41664

Parelli, J., & Abramowicz, S. (2015). Immediate Placement and Immediate Loading: Surgical Technique and Clinical Pearls. *Dental Clinics of North America*, *59*(2), 345–355. https://doi.org/10.1016/j.cden.2014.10.002

Park, J. Y., & Davies, J. E. (2000). Red blood cell and platelet interactions with titanium implant surfaces. *Clinical Oral Implants Research*. https://doi.org/10.1034/j.1600-0501.2000.011006530.x

Rocci, A., Rocci, M., Rocci, C., Scoccia, A., Gargari, M., Martignoni, M., Gottlow, J., & Sennerby, L. (2013). Immediate Loading of Brånemark System TiUnite and Machined-Surface Implants in the Posterior Mandible, Part II: A Randomized Open-Ended 9-Year Follow-up Clinical Trial. *The International Journal of Oral & Maxillofacial Implants*, *28*(3), 891–895. https://doi.org/10.11607/jomi.2397

Roccuzzo, M., Bonino, L., Dalmasso, P., & Aglietta, M. (2014). Long-term results of a three arms prospective cohort study on implants in periodontally compromised patients: 10-year data around sandblasted and acid-etched (SLA) surface. *Clinical Oral Implants Research*, *25*(10), 1105–1112. https://doi.org/10.1111/clr.12227

Roy, M., Bandyopadhyay, A., & Bose, S. (2011). Induction plasma sprayed nano hydroxyapatite coatings on titanium for orthopaedic and dental implants. *Surface and Coatings Technology*. https://doi.org/10.1016/j.surfcoat.2010.10.042

Rupp, F., Scheideier, L., Olshanska, N., De Wild, M., Wieland, M., & Geis-Gerstorfer, J. (2006). Enhancing surface free energy and hydrophilicity through chemical modification of microstructured titanium implant surfaces. *Journal of Biomedical Materials Research - Part A*, *76*(2), 323–334. https://doi.org/10.1002/jbm.a.30518

Smeets, R., Stadlinger, B., Schwarz, F., Beck-Broichsitter, B., Jung, O., Precht, C., Kloss, F., Gröbe, A., Heiland, M., & Ebker, T. (2016). Impact of Dental Implant Surface Modifications on Osseointegration. *BioMed Research International*, *2016*. https://doi.org/10.1155/2016/6285620

Suci Dharmayanti, A. W., Dubey, R., Dubey, N. K., & Deng, W.-P. (2020). Implant surface modification strategies through antibacterial and bioactive components. In *Biopolymer-Based Formulations*. Elsevier Inc. https://doi.org/10.1016/b978-0-12-816897-4.00026-6

Sul, Y. T., Byon, E., & Wennerberg, A. (2008). Surface characteristics of electrochemically oxidized implants and acid-etched implants: surface chemistry, morphology, pore configurations, oxide thickness, crystal structure, and roughness. *International Journal of Oral and Maxillofacial Implants*.

Tinsley, D., Watson, C. J., & Russell, J. L. (2001). A comparison of hydroxylapatite coated implant retained fixed and removable mandibular prostheses over 4 to 6 years. *Clinical Oral Implants Research*. https://doi.org/10.1034/j.1600-0501.2001.012002159.x

Urban, R. M., Jacobs, J. J., Tomlinson, M. J., Gavrilovic, J., Black, J., & Peoc'h, M. (2000). Dissemination of wear particles to the liver, spleen, and abdominal lymph nodes of patients with hip or knee replacement. *Journal of Bone and Joint Surgery - Series A*, *82*(4), 457–477. https://doi.org/10.2106/00004623-200004000-00002

Velasco-Ortega, E., Jimenez-Guerra, A., Monsalve-Guil, L., Ortiz-Garcia, I., Nicolas-Silvente, A. I., Segura-Egea, J. J., & Lopez-Lopez, J. (2020). Long-term clinical outcomes of treatment with dental implants with acid etched surface. *Materials*, *13*(7), 1553. https://doi.org/10.3390/ma13071553

Wang, Q., Zhou, P., Liu, S., Attarilar, S., Ma, R. L. W., Zhong, Y., & Wang, L. (2020). Multi-scale surface treatments of titanium implants for rapid osseointegration: A review. *Nanomaterials*, *10*(6), 1–27. https://doi.org/10.3390/nano10061244

Wennerberg, A., Albrektsson, T., & Chrcanovic, B. (2018). Long-term clinical outcome of implants with different surface modifications. *European Journal of Oral Implantology*.

Wennerberg, A., Jimbo, R., & Albrektsson, T. (2015). Implant surfaces and their biological and clinical impact. *Implant Surfaces and Their Biological and Clinical Impact*, 1–182. https://doi.org/10.1007/978-3-662-45379-7

Wheeler, S. (1997). Eight-year clinical retrospective study of titanium plasma-sprayed and hydroxyapatite-coated cylinder implants. *Implant Dentistry*. https://doi.org/10.1097/00008505-199700610-00042