Anodized Dental Implant Surface

Abstract

Purpose: Anodized implants with moderately rough surface were introduced around 2000. Whether these implants enhanced biologic effect to improve the environment for better osseointegration was unclear. The purpose of this article was to review the literature available on anodized surface in terms of their clinical success rate and bone response in patients till now. Materials and Methods: A broad electronic search of MEDLINE and PubMed databases was performed. A focus was made on peer-reviewed dental journals. Only articles related to anodized implants were included. Both animal and human studies were included. Results: The initial search of articles resulted in 581 articles on anodized implants. The initial screening of titles and abstracts resulted in 112 full-text papers; 40 animal studies, 16 studies on cell adhesion and bacterial adhesion onto anodized surfaced implants, and 47 human studies were included. Nine studies, which do not fulfill the inclusion criteria, were excluded. Conclusions: The long-term studies on anodized surface implants do favor the surface, but in most of the studies, anodized surface is compared with that of machined surface, but not with other surfaces commercially available. Anodized surface in terms of clinical success rate in cases of compromised bone and immediately extracted sockets has shown favorable success.

Keywords: Branemark rough surface implants, controlled oxide texture implant, oxidized implants

Introduction

Branemark implant system was introduced to clinical dentistry in 1965. Since then, these machined dental implants have shown high success rate in implant-supported oral rehabilitation.[1,2] Machined surface implants were used almost till 2000.[3] One of the key factors for the success of dental implants is the amount of primary stability they achieve immediately after their surgical placement, and to achieve the required primary stability, thread design and surface roughness are the contributing factors.[4-6] Dental implants with moderately rough surface created by anodization were introduced in 2000 by the name TiUnite (TU), a commercial name from Nobel Biocare, Sweden. Anodized implant surfaces were having a combination of controlled oxide texture and porosity for an enhanced biologic effect and to improve the environment for better osseointegration. It was documented that anodized implant surface increases the amount of surrounding bone formation, and the initial healing process increases the adsorption of protein and also accumulation and activation of platelets with fibrin retention.[7,8] However, certain researchers documented that, when the implants are exposed in the oral cavity, the surface roughness on them will enhance plaque accumulation, which can lead to peri-implantitis.[9-11]

With the aim to understand the influence of anodized surface in enhancing osseointegration, the present systematic review was planned through documented literature in terms of its clinical success rate and the response of the bone to its stimulation.

Materials and Methods

Source of data and search strategies

The present systematic review was designed based on the PRISMA guidelines.[12] A broad electronic search of MEDLINE and PubMed databases was performed for articles published within the present systematic review was planned through documented literature. The following key words were used in the search strategy: “TiUnite dental implants,” “TiUnite implants,” “oxidized TiUnite implants,” “anodized implants” and “prospective study,” “TiUnite” and “retrospective study,” and “anodized surface implants.”

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The titles and abstracts were first read by all the authors for identifying studies meeting the eligibility criteria. The articles which fulfill the inclusion criteria were included for the full-text reading. Manual searches of the references of all full-text articles selected from the electronic search were also performed for additional papers that might meet the eligibility criteria for inclusion in the study. If there was any disagreement regarding the inclusion or exclusion of the selected articles, it was resolved by a discussion between reviewers.

**Inclusion criteria**

Only articles related to anodized implant surface were included. Both abstract and full-text articles were included. The inclusive criteria of the search were limited to articles written in English only.

Inclusion criteria for each study group were included as follows:

**Group 1**

*In vivo* studies (animal studies) on peri-implant soft tissue responses around anodized implants, studies investigating the tissue response around anodized implants, histomorphometric analysis of animal experiments and torque analysis, and histological analysis of peri-implant soft tissue were included.

**Group 2**

Group 2 included in vitro studies on the surface properties of anodized implant including those on cell adhesion and bacterial adhesion onto this implant surface. Anodized as material or substrate for cell adhesion and bacterial adhesion had a description not only about the microbiologic analysis but also about the surface topography of the substrate or material.

**Group 3**

Clinical trials with follow-up of 2 years and above were only included. The included studies reported clinical results of anodized surface and had a minimum number of 14 participants at the baseline examination. Both prospective and retrospective studies were included.

**Exclusion criteria**

Studies composed of languages other than English were excluded. Simple case report articles and review articles were excluded although references to potentially pertinent articles were noted for further follow-up. Articles unrelated to the topic of anodized implants were excluded. Studies not meeting any of the inclusion criteria were excluded from the review.

**Outcomes and variables**

For each of the selected article included in this review, the following data were obtained and presented: Year of publication, type of study, number of implants, observation period, implant type, area of implant placement, years of follow-up, number of patients, age range, type of prosthesis, number of failed implants, mean marginal bone loss, and success rate.

**Results**

Initial search of articles in MEDLINE and PubMed databases with the given key words resulted in 581 articles on anodized implant surface. The reviewers independently screened the abstracts for the articles related to this surface. The initial screening of titles and abstracts resulted in 112 full-text papers, out of which 40 articles were animal studies [Table 1].[13-52] 16 studies were on cell adhesion and bacterial adhesion on anodized implants [Table 2].[53-68] and 47 were related to human studies [Table 3 and Figure 1].[3,69-114] Nine studies, which did not fulfill the inclusion criteria, were excluded.

Animal studies showed that anodized surface exhibits osteoconductive properties with benefits of rough surfaces.[15,19] Results were not very clear as studies described that the bone-to-implant contact was significantly higher for the anodized implants, but other studies showed additional bone loss after treatment.[28,32] In studies where implants with different surfaces were connected together, the implants placed distally with machined surface showed more bone loss.[69]

An in vitro study showed the bone growth into the porous structure of the coating of anodized implants and also the surface that reduced the adhesion of *Streptococcus mitis* compared to the machined surface implants.[94,64] Anodized surface has showed a potential to prevent long-term implant failure due to corrosion in a complex in vivo environment.[68]

Human clinical trial on patients treated with immediately loaded anodized implants and restored with single crown showed 94% success rate after 3 years and 95% after 5 years.[75,89] Another clinical trial on complete maxillary arch rehabilitated with anodized implant supported fixed prostheses showed a survival rate of 98.6% in comparison to machined surface implants (92.1%) after 3-year follow-up and 97.3% and 94%, respectively, after 5 years of follow-up.[69,90] A 2-year prospective study showed 100% success rate of implant-supported mandibular overdenture.[78] Seven-to-eight years of follow-up of delayed loaded anodized implant showed no failure of implants.[100] Immediately loaded anodized implants on patients treated in postextraction site showed a cumulative survival rate of 100% in 5-year follow-up and 96.52% at 10-year follow-up.[95,97] Ten percent higher success rate was obtained in a study following immediate loading of fixed partial dentures (FPDs) in the posterior mandible supported by TiU implants.[101] A study found that oxidized surface implants are more suitable for patients who are...
Table 1: Animal studies on peri-implant soft tissue responses around anodized implants

| Authors                | Type of study | Number of implants | Purpose | Observation period | Implant type | Animal | Area | Type/site/others | Conclusions                                                                 |
|------------------------|---------------|--------------------|---------|--------------------|--------------|--------|------|-----------------|----------------------------------------------------------------------------|
| Zechner et al. (2003)  | PCS           | 72                 | Study the time course of local bone formation following the application of PRP during implant placement | 3-12 weeks | Mk III, replace, Mk III, TiU | Minipigs | Mandibular premolar region | Immediate and healed | PRP has significant effect on peri-implant bone healing |
| Weibrich et al. (2004) | PCS           | 40                 | Effect of the platelet count in PRP on bone regeneration in vivo | 1-28 days | Branemark Mk III TiU | New Zealand Rabbits (male) | Distal femur | Immediate and healed | Advantageous biological effects seem to occur |
| Xiropaidis et al. (2005)| PCS           | 40                 | Evaluate osteoconductivity by comparing bone-implant contact | 3-8 weeks | TiU (TO) and calcium phosphate (CO) coated | Hound Labrador mongrel dogs | Mandibular premolar and molar region | Healed | TO surface exhibits osteoconductive properties exceeding that of the CP surface |
| Sul et al. (2006)      | PCS           | 60                 | Compared the speed and strength of osseointegration and osteoconductivity of different implants | 3-6 weeks | Mg implant, TiU implant, OSSEOTITE implant | Rabbits | Tibiae | Immediate and healed | More rapid and stronger osseointegration of the Mg implants |
| Al-Nawas et al. (2006) | PCS           | 160                | Compare insertion torque and resonance frequency analysis of different implant systems | 8 weeks to 3 months | Bränemark implants and Straumann implants | Beagle dogs | Various regions | Healed |Judge implants with caution on the basis of resonance frequency analysis and torque |
| Wikesjö et al. (2006)  | PCS           | 72                 | Characteristics and use of the critical size, supraalveolar, peri-implant defect model | 3-8 weeks | TiU | Hound Labrador mongrel dogs | Mandibular third and fourth premolar region | Healed | Models were rigorous tool for alveolar reconstruction and osseointegration of implants |
| Al-Nawas et al. (2008) | PCS           | 196                | Osseointegration with respect to optimum BIC in a loaded animal model | 8 weeks to 3 months | Minimally rough control; Bränemark machined Mk III; TiU; Mk III and Mk IV; ZLTi cer; Straumann SLA; rough control: TPS | Beagle dogs | Various | Healed | The benefit of rough surfaces relative to minimally rough ones in this loaded animal model was confirmed histologically |
| De Maeztu et al. (2008) | PCS           | 72                 | To compare CO ion implantation as a surface treatment with diamond-like carbon and commercially treated implants | 3-6 months | OSSEOTITE, TiU, SLA | Beagle dogs | Mandible | Healed | No significant differences were observed between the three groups of commercially treated implants |
| Authors          | Type of study | Number of implants | Purpose                                                                                   | Observation period | Implant type                                      | Animal         | Area                                      | Type/site/others | Conclusions                                                                                                                                                                                                 |
|------------------|---------------|--------------------|-------------------------------------------------------------------------------------------|-------------------|-------------------------------------------------|----------------|------------------------------------------|------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Albouy et al. (2008) | RCS           | 4                  | Tissue reactions to plaque formation at implants exposed to experimental peri-implantitis - radiographical observation | 36 weeks          | Implant Group A (turned), B (TiO blast), C (sandblasted acid-etched; SLA), and D (TiU) | Labrador dogs | Mandibular premolars and maxillary anterior premolars on both sides |                    | The bone loss during the “active breakdown” period varied between 3.5 and 4.6 mm. Progression was most pronounced at implants of type D (TiU surface). |
| Albouy et al. (2009) | RCS           | 4                  | Tissue reactions to plaque formation at implants exposed to experimental peri-implantitis Histological observation | 36 weeks          | Implant Group A (turned), B (TiO blast), C (sandblasted acid-etched; SLA), and D (TiU) | Labrador dogs | Mandibular premolars and maxillary anterior premolars on both sides |                    | Overall surface area of the infiltrated connective tissues were larger at implants of Group D. Progression of peri-implantitis is associated with severe inflammation and tissue destruction. |
| Lee et al. (2009)  | PCS           | 80                 | Nano-technology-modified, micro-structured zirconia implant surfaces relative to local bone formation and osseointegration | 3-6 months        | Surface-modified (CaP) zirconia implants, micro-structured zirconia implants (ZiUnite), and Ti porous oxide implants (TiU) | New Zealand White rabbits (male) | Hind legs                                           |                    | Addition of CaP nano-technology to the ZiUnite surface does not enhance the already advanced osteoconductivity displayed by the TiU and ZiUnite implant surfaces. Modified Ti implants showed higher mean ISQ values than did topographically changed implants. |
| Sul et al. (2009)  | PCS           | 6                  | Resonance frequency measurements of topographically changed and/or surface chemistry-modified implants | 6 weeks           | Oxidized, cation-incorporated implants (Mg and MgMp implants); TiU, OSSEOTITE, SLA, and TiO blast | Rabbits        | Tibia                                                  |                    | MgMp implants showed the most significant mean ISQ. Modified Ti implants showed higher mean ISQ values than did topographically changed implants. |
| Carmagnola et al. (2009) | PCS          | 8                  | Evaluate the early phases of bone healing around two different implant surfaces | 3 days to 7 weeks | ITI sandblasted/acid-etched and Branemark TiU | Minipigs       | Maxillae                                              |                    | Replacement of blood clot and bone debris with a provisional connective tissue in the first few weeks. Both rough surfaces allowed for “contact osteogenesis” to take place. |
| Gedrange et al. (2009) | PCS         | 20                 | Hard tissue integration of two different implant types | 70 days           | TiU; Nobel Replace Tapered Groovy and Replace Select Tapered | German domestic pigs | Canine and premolar region of mandible |                    | The immediate loading of the different implant types does not have any negative effect on the bone apposition. |
Table 1: Contd...

| Authors                  | Type of study | Number of implants | Purpose                                                                 | Observation period | Implant type | Animal | Area          | Type/site/others                 | Conclusions                                                                                                                                       |
|--------------------------|---------------|--------------------|--------------------------------------------------------------------------|--------------------|--------------|--------|---------------|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Al-Ahmad et al. (2010)   | PCS           | -                  | Evaluation of biofilm formation on Ti and zirconia implants               | 3 and 5 days       | Machined Ti (Ti-m), modified Ti (TiU), modified zirconia (ZiUnite), etc. | Bovine | Enamel slabs | Immediate                        | The influence of roughness and material on biofilm formation was compensated by biofilm maturation.                                            |
| Albouy et al. (2011)     | PCS           | 24                 | Effect of surgical treatment of peri-implantitis without systemic antibiotics at different types of implants | 4 weeks            | Turned (Biomet 3i), TiO blast (Astra Tech AB), SLA (Straumann AG), and TiU (Nobel Biocare AB) | Dogs   | Mandible     | Resolution of peri-implantitis was achieved in tissues surrounding implants with turned and TiOblast surfaces | At TiU implants, additional bone loss was found after treatment                                                                               |
| Jimbo et al. (2011)      | PCS           | 30                 | In vivo bone apposition during the early stages of osseointegration     | 2-6 weeks          | TiU; Surface-modified TiU implants (ModTiU) | Rabbits | Tibiae       | ModTiU demonstrated a significantly greater degree of bone-to-metal contact than TiU | Photo-induced hydrophilicity of the NH4F-HF (2)-modified anodized implants promoted bone apposition during the early stages of osseointegration |
| Grüner et al. (2011)     | PCS           | 13                 | Investigation of implants with a brittle porous oxide layer and of bone/implant interfaces | 4 weeks            | Nobel Biocare TiU | Minipigs | Various       | Characterization is possible with energy dispersive X-ray spectrometry | Bone growth into small pores (<1 µm) can be unambiguously confirmed.                                                                                     |
| Kang and Cho (2011)      | PCS           | 10                 | Compare the removal torques of LT surface of dental implants with TiU    | 8 weeks            | LT and commercial porous TiU | Rabbits | Femoral metaphysis | The mean removal torque was 32.83 and 48.5 for anodized and LT screws, respectively | The removal torque of the LT Ti implant was stronger                                                                                             |
| Jimbo et al. (2011)      | PCS           | 20                 | PCA to evaluate osseointegration                                         | 6 weeks            | OSSEOTITE and TiU | Rabbits | Tibiae       | PCA analysis helps to interpret and correlate results obtained                      | The bone-to-implant contact was significantly higher for the TiU                                                                                 |
| Poulos et al. (2011)     | PCS           | 80                 | Evaluation of osseointegration of a novel CaP-coated Ti porous oxide implant surface | 2-4 weeks          | TiU and CaP-coated Ti porous oxide-surface implants | New Zealand White rabbits (male) | Tibiae | Immediate and healed | Novel CaP-coated surface effectively supports osseointegration |                                                                                                                                                   |
| Authors                  | Type of study | Number of implants | Purpose                                                                 | Observation period | Implant type                                      | Animal              | Area                      | Type/site/others                  | Conclusions                                                                 |
|-------------------------|---------------|--------------------|--------------------------------------------------------------------------|--------------------|--------------------------------------------------|---------------------|---------------------------|-----------------------------------|--------------------------------------------------------------------------------|
| Gostovic et al. (2012)  | PCS           | 32                 | Immediate loading protocol in implant systems with different surface properties | 6 months           | Mk III TiU, ITI TPS, 31-OSSÉOTITE and XiVE Cell-Plus | Mongrel dogs, Maxillary and mandibular premolar regions | Resonance frequency was significantly higher for mandibular implant | Endoseal implants did not show different degrees of osseointegration |
| Albouy et al. (2012)    | RCS           | 20                 | Progression of ligature-induced peri-implantitis at implants with different surface characteristics | 6 months           | Turned and TiU                                   | Dogs, Maxilla and mandible | The amount of bone loss was significantly larger at TiU surface | Implant surface characteristics influence progression of peri-implantitis |
| Manfrin Arnez et al. (2012) | PCS           | 20                 | Osteogenic potential of angiogenic latex proteins (LP for improved bone formation and osseointegration) | 4-12 weeks         | TiU Mk III                                       | Dogs, Mandible      | LPP showed bone regeneration similar to BG and Cg | Treatment with LPP exhibits no advantage in terms of osteogenic potential |
| Choi et al. (2012)      | PCS           | 10                 | Investigated whether bioactive surfaces were more favorable to bone than bioinert surfaces | 2 weeks            | Bioactive fluoride-modified implants (OsseoSpeed) and bioinert oxidized implants (TiU) | New Zealand white rabbits (male), Tibia | No significant differences in bone-to-implant contact and bone area | Bioactive fluoride-modified surface shows no superiority in early bone response |
| Gottlow et al. (2012)   | PCS           | 90                 | Compare the bone tissue responses and implant stability between two commonly used dental implants | 10 days to 6 weeks | Replace Select Tapered, TiU (OX) and Standard Plus, SLActive (HSBA) | Rabbits, Distal femur and tibia | Higher BIC for HSBA implants after 10 days and 3 weeks, Significantly higher BIC for OX implants after 6 weeks | The HSBA implant showed significantly higher shear strength after 3 and 6 weeks |
| Carcuac et al. (2013)   | RCS           | 20                 | Analyze the tissue reactions following ligature removal in experimental periodontitis and peri-implantitis | 10 weeks           | Mk III NP; (implant group A; turned surface and implant group B; TiU surface) | Dogs, Maxillary premolar region and mandibular molar region | Bone loss was significantly larger at implants with a modified surface | Implant surface characteristics influence the inflammatory process |
| Gomes et al. (2013)     | PCS           | 32                 | Demonstrate the degree of stability of dental implants at early implantation times | 8 weeks            | Straumann SLActive surface and Nobel Speedy Replace RP with TiU surface | Beagle dogs, Mandibular premolar and molar regions | Interfacial bone remodeling and initial woven bone formation around both implants | The biomechanical stability of dental implants initially decreased and subsequently increased |
| Park (2013)             | PCS           | 32                 | Comparison of Grit-blasted Ti implants with commercially available phosphate-incorporated clinical implants. | 4 weeks            | Hydrophilic phosphate-incorporated grit-blasted Ti implant (P) and TiU | New Zealand White rabbits (male), Femoral condyle | P implants exhibited significantly higher bone-implant contact percentages | Phosphate-incorporated Ti oxide surface obtained by hydrothermal treatment achieves rapid osseointegration |

**Table 1: Contd...**
| Authors                  | Type of study | Number of implants | Purpose                                                                 | Observation period | Implant type | Animal    | Area            | Type/site/others | Conclusions                                                                 |
|-------------------------|---------------|--------------------|-------------------------------------------------------------------------|--------------------|--------------|-----------|-----------------|------------------|-----------------------------------------------------------------------------|
| Al-Ahmad et al. (2013)  | PCS           | 6                  | Study of the initial bacterial adhesion on different implant materials | 30 and 120 min     | Ti-m, TiU, ZiUnite, ATZ-m, ATZ-s, TZP-A-m | Bovine    | Enamel slabs   |                  | The highest level of colonization was on ZiUnite                             |
| Charalampakis et al. (2014) | RCS       | 20                 | Analyze the microbial profile around teeth and implants in experimental periodontitis and peri-implantitis | 10-25 weeks        | Implant A: Tumed/implant B: TiU; Nobel Biocare AB | Dogs      | Mandible       |                  | Total bacterial load increased during the period following ligature removal |
| Stockholm et al. (2014) | PCS          | 24                 | Bone reaction around immediate-loaded non-splinted single implants versus delayed loaded nonsplinted single implants placed in healed ridges | 3-6 months        | Replace Select Tapered with a moderately rough surface (TiU) | Macaca fascicularis monkeys | Mandible       |                  | Large variation in regard to the microbial profiles                         |
| Dagher et al. (2014)   | PCS          | 32                 | Compare RFA, IT, and BIC of different implant surfaces                  | 1-2 months         | SLA, SLActive, Euroteknika, and TiU | Sheep     | Mandible       |                  | No statistically significant differences between groups                     |
| Carcuac et al. (2014)  | RCS          | 24                 | Evaluate the effect of surgical treatment of experimental peri-implantitis at implants with different surfaces | 3 months           | TiO blast, OsseoSpeed, AT-I, TiU | Labrador dogs | Mandible       |                  | Significant difference was found in RFA between the four surfaces            |
| Stübinger et al. (2015) | PCS         | 72                 | Performance of local cancellous bone amelioration by a 70:30 poly-(L-lactide-co-D, L-Lactide) copolymer | 4 and 12 weeks     | Conditioned, sandblasted, thermal acid-etched micro-rough surface implants (TH) and highly crystalline and phosphate-enriched anodized Ti oxide surface implants (NB) | Sheep     | Pelvic bone    |                  | Local use of chlorhexidine has minor influence on treatment outcome          |
| Lee et al. (2015)      | PCS          | 10                 | Combined effects of physical and chemical surface factors on in vivo bone responses | 1 week             | Chemically modified hydrophilic sandblasted, large-grit, acid-etched (modSLA) and anodically oxidized hydrophobic implant surfaces | Rabbits   | Tibia          |                  | Enhanced primary stability of dental implants after local amelioration without long-term sequelae and irrespective of implant design |

Contd...
| Authors          | Type of study | Number of implants | Purpose                                                                 | Observation period | Implant type                                      | Animal   | Area                     | Type/site/others          | Conclusions                                                                 |
|------------------|---------------|--------------------|------------------------------------------------------------------------|--------------------|--------------------------------------------------|----------|--------------------------|----------------------------|----------------------------------------------------------------------------|
| Koretake et al. (2015) [49] | PCS           | 20                 | Investigate how the connection of superstructures to implants with different surface properties affects the surrounding bone | 24 weeks           | Machined and anodized implants                   | Dogs     | Mandibular premolar and molar regions           |                             | The removal torque values were significantly different between the distal anodized and distal machined implants, implants at the most distal sites might be a potential risk factor for implant-bone binding |
| Kohal et al. (2016) [50]     | PCS           | 56                 | The histological and biomechanical behavior of moderately roughened implants | 14 and 28 days     | ATZ; electrochemically anodized Ti (TiU)          | Rats     | Femoral bone             |                             | The mean mineralized bone-to-implant contact showed the highest values of TiU (58%/75%) compared to ATZ (24%/41%)  |
| Sharma et al. (2016) [51]    | PCS           | 40                 | Effect of anodizing the surface of TiZr discs with respect to osseointegration | 4 weeks            | Ti; TiZr; anodized Ti and Anodized TiZr          | Sheep    | Femurs                   |                             | The anodized implants displayed hydrophilic, porous, nano-to-micrometer scale roughened surfaces, surface modification of Ti-zirconium by anodization is similar to anodized Ti. It enhances early osseointegration compared to machined implant surfaces  |
| Duncan et al. (2016) [52]    | PCS           | 30                 | Compare commercially available sandblasted (RBM) implants, treated with hydrothermal anodization | 1 month            | Ti with RBM surface (control) and Ti with RBM + anodized surface | Sheep    | Maxillary sinuses       |                             | Early integration of RBM implants placed into thin maxillary sinus walls was not enhanced by hydrothermal anodization of implant surfaces  |

PCS=Prospective study, RCS=Retrospective study, ATZ=Alumina-toughened zirconia, BIC=Bone-to-implant contact, PCA=Principal component analysis, LT=Laser-treated, PRP=Platelet-rich plasma, TiU=TiUnite, Mg=Magnesium, BIC=Bone-implant contact, TPS=Titanium plasma sprayed, CO=Carbon-oxygen, CaP=Calcium phosphate, ISQ=Implant stability quotient, Ti=Titanium, RFA=Resonance frequency analysis, Ti-Zr=Titanium-zirconium, SLA=Sandblasted acid-etched, RBM=Resorbable blast media, IT=Insertion torque, HSBA=Hydrophilic sand-blasted and acid etched
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Table 2: In vitro studies on the surface properties of anodized implant including those on cell adhesion and bacterial adhesion on to this implant surface

| Authors                  | Type of study | Purpose                                                                                                           | Results                                                                                                                                                                                                 |
|--------------------------|---------------|-------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Göransson et al. (2006)  | In vitro      | Investigate whether placement into bone causes enough mechanical damage to alter implant corrosion properties     | The highest number of adhered mononuclear cells were seen on anodized implants                                                                                                                          |
| Giannuzzi et al. (2007)  | In vitro      | Analysis of bone/dental implant interfaces with the use of focused ion beam and electron microscopy                  | Bone was observed to grow into the porous structure of the coating, yielding direct evidence of a mechanical locking mechanism of the bone/implant interface                                                     |
| Sawase et al. (2007)     | In vitro      | Studied the characteristics of porous Ti oxide implants                                                            | An amorphous layer that was about 10 mm thick was observed on the TiU implant surface                                                                                                                    |
| Jarmar et al. (2008)     | In vitro      | To identify and separate out a particular set of surface features of the implant surfaces that can contribute as factors in the osseointegration process | The provision of osseointegration is not exclusively linked to a particular set of surface features if the implant surface character is a major factor in that process                                                 |
| Sul et al. (2008)        | In vitro      | Investigate surface properties of surface-modified Ti implants in terms of surface chemistry, morphology, pore characteristics, oxide thickness, crystal structure, and roughness | Well-defined surface characterization may provide a scientific basis for a better understanding of the effects of the implant surface on the biological response. The surface-engineered implants resulted in various surface characteristics, as a result of different manufacturing techniques |
| Kang et al. (2009)       | In vitro      | Demonstrate the major differences of surface properties, mainly dependent on the surface treatment used             | TiU implants contain >7% of P in oxide layer and higher amounts of hydroxides compared to the other implants in XPS analysis                                                                             |
| Messer et al. (2010)     | In vitro      | Investigate whether placement into bone causes enough mechanical damage to alter implant corrosion properties      | The current study suggests that the corrosion risk of the enhanced oxide implant is lower than its machined surface Ti implant counterpart under simulated conditions of inflammation, elevated dextrose concentrations, and after implantation into bone |
| Dohan Ehrenfest et al. (2011) | In vitro | Describe the chemical and morphological characteristics of 14 implant surfaces available on the market and to establish a simple and clear ID card for all of them | From a chemical standpoint, of the 14 different surfaces, 10 were based on a commercially pure Ti, 3 on a Ti-aluminum alloy and one on a calcium phosphate core. Nine surfaces presented different forms of chemical impregnation and 3 surfaces were covered with residual alumina blasting particle |
| Chang et al. (2011)      | In vitro      | Evaluation of the effect of a cordless retraction paste material, Expasyl (Acteon), on TiU (Nobel Biocare) implant surfaces | Alteration of the initial surface after exposure to Expasyl was identified, with the implant collar showing the most changes                                                                              |
| Chai et al. (2012)       | In vitro      | To examine the ultrastructural features of soft tissue attachment to various Ti implant surfaces                     | There was evidence of hemidesmosome-like structures at the interface on the four types of Ti surfaces, which suggests that the tissue-engineered oral mucosa formed epithelial attachments on the Ti surfaces that were not significantly different |
| Chai et al. (2012)       | In vitro      | Compares the quality of the BS achieved for four types of Ti surfaces: polished, machined, sandblasted, and anodized (TiU) | The biological seal of the tissue-engineered oral mucosa around the four types of Ti surface topographies was not significantly different                                                                   |
| Caous et al. (2013)      | In vitro      | Investigated if different pH, atmosphere, and surface properties could restrict bacterial adhesion to Ti surfaces used in dental implants | The anodized surface reduced the adhesion of Streptococcus mitis compared to the machined surface                                                                                                           |
| Liu et al. (2015)        | In vitro      | To compare surface properties of four commercial dental implants and to compare those implant systems’ cell adhesion | Implant systems’ distinct differences in surface properties                                                                                                                                               |

Contd...
Table 2: Contd...

| Authors          | Type of study | Purpose                                                                 | Results                                                                                                                                                                                                 |
|------------------|---------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Liu et al. (2015) | In vitro     | To improve the antibacterial and mammalian cell compatibility properties of TNTs anodized into Ti | Improved antibacterial properties and, at the same time, greater stem cell osteogenic capacity when decorating TNTs with nanosized TiO₂ particles, which may significantly improve implant efficacy |
| Sharma et al. (2015) | In vitro   | To anodize TiZr and study its surface characteristics                    | Proliferation, alkaline phosphatase activity, and calcium deposits were significantly higher on anodized surfaces compared to machined surfaces. Anodization of TiZr resulted in a more nanoporous and hydrophilic surface than aTi, and osteoblast biocompatibility appeared comparable to a Ti |
| Grotberg et al. (2016) | In vitro | Determine the effects of electrochemical anodization (60 V, 2 h) and thermal oxidation (600°C) on the corrosive behavior of Ti-6Al-4V | Anodized surface has a potential to prevent long-term implant failure due to corrosion in a complex in vivo environment |

XPS=X-ray photoelectron spectroscopy, ID=Identification, TNTs=Titania nanotubes, Ti=Titanium, TiZr=Titanium-zirconium, BS=Biological seal, aTi=Anodized titanium, TiU=TiUnite

Figure 1: Flow chart presenting the screening of articles on anodized implant surface in MEDLINE and PubMed databases to be included in the review

smokers and are susceptible to periodontitis.[76,106] Another follow-up study from 1985 to 2011 found the success rate of TiU as 95.4% and machined surface as 84.9%. TiU implant has played a critical role in single-stage implant survival rate.[105]

Discussion

The original Branemark protocol underwent many modifications to increase the success of implant treatment. One of the modifications was the introduction of anodized,
### Table 3: Human follow-up studies on TiUnite implant. The included studies reported results of anodized surface implants in terms of their clinical success rate and bone response in patients

| Author/year | Design of study | Total number of patients (available for follow-up) | Age (years), range (mean) | Implant type | Follow-up (mean) | Type of prosthesis | Total implant placed (available for follow-up) | Failed implants (n) | Mean marginal bone loss (mm), range or SD | Success rate (%) |
|-------------|-----------------|----------------------------------------------------|--------------------------|--------------|-----------------|-------------------|---------------------------------------------|-------------------|------------------------------------------|------------------|
| Balshi et al. (2005)²⁵ | Prospective study | 82 | 13-86 (58.1) | 840 | 3 (2.6) | Complete fixed maxillary prostheses | 840 | 14 (n=11 TiU implants, n=3 zygoma implants) | 98.6% (TiU implants, 93.5%, zygoma implants excluding pterygomaxillary positions Ti oxide implants 99.0%, machined surface implant 93.0%) |
| Brechter et al. (2005)²⁶ | Prospective study | 47 (45) | 17-77 (53) | Mk III, TiU | 2 years, 6 months (12-48 months) | Implant-supported bridges | 200 | 3 | 2.2 (0.5) after 1 year | 98.5% |
| Glauser et al. (2005)²⁷ | Prospective study | 38 (36) | 19-77 (51) | Branemark System Mk IV TiU | 42-58 months (4 years) | Implant-supported fixed prostheses | 102 (93) | 3 | 1.3±0.9 | 97.1% |
| Renouard and Nisand (2005)²⁷ | Retrospective study | 85 | 58.6 | Branemark System, machined (n=54) Oxidized TiU (n=42) | 2 (37.6 months) | Single crowns and partial restorations | 96 | 5 (n=4 machined surface, n=1 oxidized surface) | 0.44±0.52 | 92.0% machined surface; 97.6% oxidized surface |
| Alam and Nowzar (2005)²⁸ | Prospective study | (74) | 23-80 (52.8±14.2) | n=58 TiU implants; n=52 OSSEOTITE implants; n=88 machined implants | 2 | Single unit, fixed partial dentures, overdentures | (198) | None | Greater coronal bone loss in the TiU group was detected | 100% |
| Degidi et al. (2006)²⁹ | Prospective study | 29 | 23-65 (52) | TiU implant n=127 Mk III and n=15 Mk IV | 3 | Fixed restorations | 142 immediate loaded | None | 1.0 | 100% |
| Turkyılmaz et al. (2006)³⁰ | Prospective study | 19 | 20-53 (39±10.5) | Branemark System Mk III RP TiU implants n=60 anodized, n=64 machined-surface | 3 | Single tooth crowns/immediate loading | 36 | 2 | 0.97 | 94% |
| Watake et al. (2006)³¹ | Retrospective study | 50 (31) | 52-86 (67.55) | 29.8-47.4 months (35.94 months) | 124 | n=1 anodized surface implant | 59 | 3 (test group n=2, control group n=1) | Smokers showed -1.83 mm bone loss around machined surface implants versus -1.08 mm around anodized surface implants | 100% machined surface; 98.4% anodized surface |
| Turkyılmaz et al. (2007)³² | Prospective study | 29 | 20-60 (40±11) | Branemark System Mk III TiU implants | 4 | Implant-supported single crowns | 59 | 3 | 1.11 | Test group 94.4%; control group 95.7% |

Contd...
| Author/year | Design of study | Total number of patients (available for follow-up) | Age (years), range (mean) | Implant type | Follow-up (mean) | Type of prosthesis | Total implant placed (available for follow-up) | Failed implants (n) | Mean marginal bone loss (mm), range or SD | Success rate (%) |
|-------------|------------------|-----------------------------------------------------|--------------------------|--------------|------------------|-------------------|-----------------------------------------------|-------------------|------------------------------------------|------------------|
| Turkylmaz and Tumer (2007) | Prospective study | 20 | 62 | TiU surface implants | 2 | Maxillary complete denture and mandibular implant supported over denture | 40 | None | 1.1±0.3 | 100% |
| Balkhi et al. (2007) | Retrospective study | (39) | 29-82 (58.5) | 44 (n=24 TiU; n=20 machined-surface) | 6 months to 11 years (4.05) | Partial or complete prosthesis/n=15 immediate loading; n=29 delayed loading | 459 | 8 (n=2 TiU; n=6 machined surface) | - | 82% (TiU 91.7%; machined-surface 70%) |
| Alsaidi et al. (2007) | Retrospective study | 2004 | - | n=6316 machined; n=630 TiUs surface | - | - | 6946 | 252 (n=228 machined; n=24 TiUs surface) | - | The TiUs surface did not influence the outcome as no statistical difference was found |
| Maio et al. (2007) | Retrospective and Prospective study | 184 | 22-86 (56) | n=283 TiU; n=150 machined surface | 6 months to 8 years (44 months) | Single restoration, short-/long-span FPD, fixed complete dentures | 433 | 14 (n=2 TiU; n=12 machined-surface) | 1.7 (1.0) | Oxidized surface (more osseoconductive) there is a tendency for higher bone levels |
| Alsaidi et al. (2008) | Retrospective study | 412 | - | n=198 anodized surfaces; 2 n=1316 machined surface | - | - | 1514 | 101 (n=8 anodized surface; n=93; machined-surface) | - | No significant difference in late failure rate; yet there is a trend for more implant loss with machined surface |
| Ostman et al. (2008) | Prospective study | 77 | 32-82 | n=77 turned; n=180 TiU implants | 4 | Fixed partial dentures | 257 | n=3 turned; n=1 TiU implants | Turned implants 0.5 mm (0.8); oxidized implants 0.7 (0.8) | 98.4% |
| Balshe et al. (2009) | Retrospective study | (1498) | 51.3±18.5 (smooth surface) n=2425 rough surface; n=2182 smooth surface | 5 | - | - | 4607 | n=85 rough surface; n=111 smooth-surface | - | 96.1% and 99.4% for turned and oxidized implants, respectively Rough surface 94.5%; smooth-surface 94% Rough surface implants performed better in the maxilla. |

Contd...
### Table 3: Contd...

| Author/year | Design of study | Total number of patients (available for follow-up) | Age (years), range (mean) | Implant type | Follow-up (mean) | Type of prosthesis | Total implant placed (available for follow-up) | Failed implants (n) | Mean marginal bone loss (mm), range or SD | Success rate (%) |
|-------------|-----------------|--------------------------------------------------|--------------------------|-------------|-----------------|-------------------|---------------------------------------------|-------------------|------------------------------------------|-------------------|
| Eliasson et al. (2009) | Retrospective study | 109 (83) | 51-90 (70) early loaded; 47-89 (69) delayed loaded | n=117 TiU; n=253 machined surface; n=74 TiO blast; n=46 mono-type SLA | 3.5 | Fixed prosthesis | 490 (378) | n=7 TiU implants, n=9 machined surface | No significant differences in bone losses in the different implant systems | 94.4% with early loading and 97.9% with delayed loading |
| Friberg and Jemt (2010) | Retrospective study | 111 (84) | 17-87 (59.4) | Mixed group (n=110 turned and n=68 TiU implants); TiU group (n=212) | 5 | Implant-supported prosthesis | 390 (286) | 6 (n=1 turned, n=2 TiU implants in mixed group and n=3 implants of the TiU group) | Mixed group (turned 0.6 TiU implants, 0.7) TiU group (0.8) | TiU group (98.4%) |
| Lee et al. (2010) | Prospective study | 54 (50) | 36-78 (57.6) | n=37 (Branemark TiU Mk III); n=38 (Restore; Lifecore); n=45 (Hexplant) | 3 | Single or 2-3 units | 135 (120) | None | Hexpant 0.59±0.30 | 100% |
| Liddelow and Henry (2010) | Prospective study | 35 | 50-89 (68) | n=27 anodized; n=8 machined surface | 3 | Single implant mandibular overdenture | 35 | n=3 machined surface | 2 machined surface; 0.63 oxidized surface | 100% oxidized implants; 57.1% machined surface implants | 95% |
| Calandriello and Tomatis (2011) | Prospective study | 33 | 27-72 (52) | TiU wide platform Mk III implants | 5 | Implant-supported single molars | 40 immediate loading | 2 | 1.17±0.90 | 95% |
| Jemt et al. (2011) | Retrospective study | 185 (148) | Early group (60.1) Late group (65.1) | Early group (450 turned implants), late group (360 turned and 310 TiU implants) | 5 | Fixed prostheses supported by implants | 1120 (906) | 45 (n=29 early group, n=16 late group) | Early group 0.5±0.46 and late group 0.7±0.76 | 93.4% and 97.3% for the early and late groups, respectively |
| Hatano et al. (2011) | Retrospective study | 132 (109) | 35-85 (62.6) | n=253 oxidized; n=143 machined surface | 1-10 (5) | Fixed bridge/Immediate loaded | 396 | n=3 oxidized; n=10 machined surface | More machined than oxidized implants failed, 7% versus 1.2% | 95.1% |
| Malo and de Araújo Nobre (2011) | Retrospective study | 147 | 26-77 (47.5) | n=127 machined; n=120 TiU surface | 1-11 (5) | Fixed prosthetic implant-supported rehabilitations in the posterior region of the jaw | 247 | 12 (n=3 TiU and n=9 machined) | 1.74 | 95.73% (TiU 96.03%; machined surface 92.31%) |
| Balshi et al. (2011) | Prospective study | 140 | 15-88 (45) | n=151 (TiU); n=13 (machined surface) | 5.5 | Single crowns/ immediate provisionalization | 164 | 7 (n=6 TiU); n=1 (machined surface) | - | 95.73% (TiU 96.03%; machined surface 92.31%) |

Contd...
| Author/year       | Design of study | Total number of patients (available for follow-up) | Age (years), range (mean) | Implant type | Follow-up (mean) | Type of prosthesis | Total implant placed (available for follow-up) | Failed implants (n) | Mean marginal bone loss (mm), range or SD | Success rate (%) |
|------------------|-----------------|----------------------------------------------------|---------------------------|--------------|-----------------|-------------------|-----------------------------------------------|---------------------|------------------------------------------|-------------------|
| Bahat et al (2012) | Retrospective study | 39 (27)                                           | -                         | Mk IV, TiU   | 3-7             | Fixed partial denture, delayed loaded         | 103 (80)           | 3                                        | 1.21±0.86          | 97.08%                          |
| Degidi et al. (2012) | Prospective study | 59 (48)                                           | 18 and above (49.9)       | Porous anodized TiU surfaces | 10             | Fixed prosthesis/ immediate loading           | 210 (158)          | 5 (peri-implantitis)                         | Healed site 98.05% and postextraction sites 96.52% |
| Mabó et al. (2012)  | Retrospective clinical study | 242 (222)                                        | 25-87 (55.4)             | Porous anodized TiU surfaces | 3-5            | Fixed complete arch maxillary all acrylic prostheses | Immediate loading | 19 (n=5 Mk IV, n=14 Nobel speedy)           | 1.52 (3 years) | 100% Mk III, 85.7% Mk IV, Nobel speedy 94.1% |
| Mura (2012)        | Retrospective study | 56 (48)                                           | 21-76 (50.9)             | Replace select tapered TiU implants | 5              | 43 patients’ single implants and 13 patients’ splinted implants | None              | 79 (66)                                   | 0.56                        | 100%                          |
| Nicu et al (2012)  | Prospective randomized controlled trial | 14                                               | 62.1                      | Turned implant and TiU implant | 3              | Fixed bridges and overdentures                 | 78 (n=39 turned; n=39 TiU)/ delayed loaded | None                        | 53.8% turned implants and 64.1% of the TiU implants | 100%                          |
| Sánchez-Garcés et al. (2012) | Retrospective study | 136                                              | -                         | n=80 anodized; n=154 machined-surface | 18 months to 12 years (81 months) | Delayed loaded | 273 (n=6 anodized surface implant; n=13 machined surface) | None               | -                                       | 8.4% failure rate of machined surface; 5.9% nonmachined surface | 94.8%                          |
| Gelb et al. (2015)  | Retrospective study | 57 (52)                                           | 35-82                     | Branemark System TiU Implants (n=11 Mk IV, n=96 Mk III) | 7-8 (7.33±0.47) | n=38 (single tooth restoration) | 107 (n=70 healed sites) | None                                | 1.49±0.03 for 77 implants (no data for 30 implants) | 94.3%                          |
| Amlhart et al. (2013) | Retrospective study | 114 (47)                                          | 71.2±9.8                  | n=136 anodized surfaces; n=52 machined surface | 64-117 months (85.5 months) | Delayed loading | 188 (n=2 anodized; n=2 machined surface) | Overdenture/delayed loaded | Anodized surface had peri-implant bone level (1.53±0.25 mm) than turned surface implants (2.42±0.34 mm) more favorable considering vertical bone changes | Anodized 98.53%; machined surface 96.15%; roughened implant surfaces are more favorable |
| Rocci et al. (2013) | Prospective study | (44)                                              | 20-69 (51)                | 121 (n=66 TiU; n=55; machined surface) | 9              | Fixed prosthesis/ immediate loaded | 121 (n=3 TiU; n=8 machined surface) | TiU 0.1 (0.4); machined surface 0.2 (0.5) | TiU 95.5%; machined surface 85.5% | 94.8%                          |

Contd...
| Author/year             | Design of study     | Total number of patients (available for follow-up) | Age (years), range (mean) | Implant type                                      | Follow-up (mean) | Type of prosthesis                                                                 | Total implant placed (available for follow-up) | Failed implants (n) | Mean marginal bone loss (mm), range or SD | Success rate (%) |
|------------------------|---------------------|---------------------------------------------------|---------------------------|--------------------------------------------------|------------------|-----------------------------------------------------------------------------------|-------------------------------------------------|-------------------|------------------------------------------|-------------------|
| Mozzati et al. (2013)  | Retrospective study | 90                                                | 21-82 (55.9)              | Brånemark TiU implants (Mk III or Mk IV TiU)     | 11.0 (9.6-12.4) | Single-tooth and partial restorations                                             | 209                                             | 6                 | 0.60±1.17                                | 97.1%             |
| Pettersson and Sennerby (2015) | Retrospective study | 88 (51)                                           | 65±12                     | Replace (Select Tapered, Nobel Biocare AB) with an oxidized surface (TiU, Nobel Biocare AB) | 5                | Single tooth replacements, fixed full bridges, fixed implant, and tooth connected bridges | 271 (160) (n=244 healed sites; n=27 extraction sockets) n=262 immediate loading; n=9 delayed loading | 1                 | 0.1±2.4                                  | 99.0%             |
| Bakshi et al. (2013)   | Retrospective study | (981)                                              | 14-90 (58)                | n=898 TiU; n=710 machined surface Pterygomaxillary implants | From year 1985 to 2011 | All acrylic provisional prosthesis/immediate loaded | 1608                                            | n=41 TiU; n=107 machined surface, - | TIU 95.4%; machined surface 84.9%; TiU implant has played a critical role in single-stage implant survival rate 96.2% for oxidized implants and 84.9% for turned implants in smokers |                  |
| Sayardoust et al. (2013) | Retrospective study | 80 (n=40 smokers, n=40 nonsmokers)                | 53.5-54.2 smokers 59.8-63.2 nonsmokers | Smokers (n=56 oxidized and 78 turned in); nonsmokers (n=52 oxidized and 66 turned in) n=257 turned and n=243 TiU implants | 5                | Partial/full arch superstructure                                                  | 252                                             | 17 (n=4 oxidized and n=13 turned) | 1.54 (0.21) mm at turned and 1.16 (0.24) mm at oxidized implants in smokers |                  |
| Polizzi et al. (2013)  | Retrospective study | 122 (96)                                           | 23-81 (59)                | Brånemark System Mk III (n=146); Mk IV TiU (n=22) | 10 (7.3-7.5) TiU implants                          | Full arch, partial, and single tooth fixed prosthesis | 500                                             | 23 (n=19 turned implants and n=4 TiU implant) | -1.36 for TiU implants and -2.13 for turned implants | 90.3% turned implants and 96.6% TiU implant |
| Jokstad and Alkumru (2014) | RCT                  | 42 (35)                                            | 18 years and above        | Brånemark System Mk III (n=146); Mk IV TiU (n=22) | 5                | Permanent 10-12 units FDP for both groups                                           | 168                                             | 4                 | 1.2±0.7 both groups                      | Immediate loading may be associated with a slightly higher risk of unsuccessful osseointegration | Contd... |
Table 3: Contd...

| Author/year            | Design of study     | Total number of patients (available for follow-up) | Age (years), range (mean) | Implant type                              | Follow-up (mean) | Type of prosthesis                        | Total implant placed (available for follow-up) | Failed implants (n) | Mean marginal bone loss (mm), range or SD | Success rate (%) |
|------------------------|---------------------|----------------------------------------------------|---------------------------|-------------------------------------------|------------------|------------------------------------------|------------------------------------------------|---------------------|------------------------------------------|-------------------|
| Jungner et al. (2014)  | Retrospective study | 103                                                | 32-90 (67.4)              | n=133 turned surface Mk III; n=154 oxidized surface Mk III, TiU, Nobel Biocare | 60-93 months (82 months) | Single crowns, partial bridges, full bridges | 287 Early loading protocol (14 patients/54 implants), a one-stage protocol (32 patients/59 implants), or a two-stage protocol (57 patients/174 implants) | 8 (n=7 turned implants, n=1 oxidized implant) | 1.8±0.8 for turned and 2.0±0.9 for oxidized implants | Turned implants 94.7% |
| Wagenberg and Froum (2015) | Retrospective study | 312                                                | -                         | Anodic oxidized surface (TiU) implants | 2-12 (7.4)       | -                                        | 312 immediate extraction sockets | -                  | 0.4±0.80mm                             | Mesial - distal bone loss of anodic oxidized surface (TiU) implants was significantly less compared with machined implants 95.7% for turned implants and 97.7% for oxidized implants CSR ranging between 97.0% and 99.7% |
| Jungner et al. (2014)  | Retrospective study | (28)                                               | 57-82 (69)                | n=45 oxidized; n=47 turned               | 5-19 (10)        | Delayed loaded                           | 92 3 (n=1 oxidized, n=2 turned) | 1.4±0.7 mm turned and 1.7±0.7 mm oxidized implants 1.8 (0.72) and 1.7 (0.72) in the younger and the older patient groups, respectively |
| Friberg and Jemt (2015) | Retrospective study | 385 (2.9)                                          | 36-98 (70)                | n=750 anodized; n=1088 machined surface | 5                | Fixed prosthesis                        | 1838 (1230)                            | n=9 anodized surface implant; n=22 machined surface implants n=3 anodized surfaces; n=5 machined surface | 1.89 (0.81) at 10 years Cumulative implant survival rate 98.5% after 10 years (99.1% anodized implants) |
| Måké et al. (2015)     | Retrospective study | 199                                                | 26-84 (53)                | n=374 anodized surfaces; n=107 machined surface | 1-13.5 (7)       | Fixed partial rehabilitation/immediate loaded | 481                               | n=2719 turned; n=131 TiU | -                         | Introduction of moderately rough implant surfaces reduced mean annual bone loss Early failures 2.3% for TiU and 2.4% for other surfaces |
| Jemt et al. (2015)     | Retrospective study | 8528                                               | 9-99 (55.7)               | n=27,914 turned; n=10,774 TiU | January 1986 to December 2013 | -                                        | 39,077                               | n=2719 turned; n=131 TiU | -                         | Introduction of moderately rough implant surfaces reduced mean annual bone loss Early failures 2.3% for TiU and 2.4% for other surfaces |
| Måké et al. (2015)     | Retrospective study | 332 (2.78)                                         | 16-82 (47)                | n=424 anodized; n=170 machined surface | 10               | Single crown/immediate loaded            | 594                               | n=15 anodized surface implant; n=10 machined surface | 1.75                          | 95.7% |
porous implant surface. The questions raised during this systematic review were answered with the help of literature which included in vivo, in vitro, and clinical studies published on anodized surface implants.

**In vivo studies (animals)**

Many animal studies on peri-implant soft tissue responses around anodized implants were conducted and the main question raised was whether anodized implant surface promotes bone growth. A study by Xiropaidis et al. in Labrador dogs showed TiO₂ surface exhibiting osteoconductive properties more than that of the calcium phosphate-coated implant surface. Histological studies in Beagle dogs showed benefit of rough surfaces relative to minimally rough ones. The bone growth was seen into small pores (<1 µm) of anodized implants placed in minipigs. Gedrange et al. in their study in German domestic pigs found that the immediate loading of the different implant types does not have any negative effect on the bone apposition. In a study done by Jimbo et al., the bone-to-implant contact was significantly higher for the anodized implants, whereas result of another study done by Stokholm et al. in monkeys found no statistically significant differences between anodized implants for bone reaction around immediate-loaded and delayed-loaded nonsplinted single implants. Result of a study demonstrated that the removal torque of the laser-treated titanium implant placed in rabbits was stronger than anodized implants. Albouy et al. in their study in dogs found that the amount of bone loss was significantly larger in implants with an anodized surface than in implants with a turned surface when the plaque was accumulated. The histological analysis showed that there was increase in vertical size of the lesion at anodized implants. The pocket epithelium and extension of the biofilm apically were significantly larger at anodized implants than at turned implants. When implants with different surface properties are connected, machined implants at the most distal sites might be a potential risk factor for implant–bone binding. A study showed that surface modification of titanium–zirconium by anodization is similar to anodized titanium. It enhances early osseointegration compared to machined implant surfaces. Animal studies provide mixed result on the success of anodized surface implants, so further investigation with the help of clinical trials and in vitro studies is required to comment on anodized surface implants.

**In vitro studies**

Surface properties and microbiologic response of anodized implants were analyzed in different in vitro studies. In a study by Giannuzzi et al., the bone growth was seen in the porous structure of the coating of anodized implants, yielding direct evidence of a mechanical locking mechanism of the bone/implant interface. The anodic-oxidized surface has inherent photocatalytic activity, which can enhance osseointegration. Under simulated conditions of inflammation, elevated dextrose concentrations, and after implantation into bone, the corrosion risk of the enhanced oxide implant is lower than machined surface titanium implant counterpart. The biological seal of the tissue-engineered oral mucosa around the four types of titanium surface (polished, machined, sandblasted, and anodized) in an in vitro study was not significantly different. Another in vitro study showed that the anodized surface reduced the adhesion of S. mitis compared to the machined surface. Proliferation, alkaline phosphatase activity, and calcium deposits were significantly higher on anodized surfaces compared to machined surfaces. Improved antibacterial properties, and at the same time, greater stem cell osteogenic capacity seen, when decorating titania nanotubes with nanosized TiO₂ particles, may significantly improve implant efficacy. The results obtained in in vitro studies were quite encouraging about anodized surface implants.

**Clinical studies**

Many clinical questions were raised in this review and an attempt was made to find how anodized implants perform in various clinical situations.

**Success rate of anodized implants in maxillary posterior quadrant**

Maxillary posterior quadrant presents many problems and limitations to implant placement such as poor bone quality and quantity, pneumatization of the maxillary sinus, and difficulty in accessibility of the area. Sinus floor bone grafting may provide sufficient bone quantity and quality for implant placement; however, it is a costlier affair to the patient and there is a risk of morbidity when compared to other alternate treatment options available such as zygomatic implants. As mentioned earlier, titanium oxide-surfaced implants can be used successfully in the ptgromaxillary region for achieving successful osseointegration. In a study, ptgromaxillary region had shown 8% more survival rate with anodized surface implants. Glauser et al. in their prospective clinical study mentioned that immediately loaded anodized Branemark System Mk IV had a success rate of 97.1% after a 4-year follow-up even though the majority of all implants were placed in posterior regions (88%) and in soft bone conditions (76%). It was found that in regions exhibiting soft bone, modified implant surface texture had shown a successful treatment alternative. Renouard Nisand evaluated the survival rate of short implants (6–8.5 mm) in the resorbed maxilla, four out of five lost implants had a machined surface and one had an oxidized surface, giving survival rates of 92.6% and 97.6% for the different surfaces, respectively. A 5-year cross-sectional retrospective study by Friberg and Jemt mentioned that one turned and two anodized implants failed in the mixed group, thus indicating no significant difference of anodized
surface in compromised bone. Rocci et al.\[102\] found 10% higher success rate following immediate loading of FPDs in the posterior mandible supported by TiU implants. Combination of controlled oxide texture and porosity in anodized surface has made it unique for an enhanced biologic effect. There is increase in initial healing process due to textured surface of anodized implants. Increase in the bone surrounding the implant was observed due to the adsorption of protein and also there was accumulation of platelets and their activation and fibrin retention.\[7\] Microtextured surface is produced by anodic oxidation of the titanium, resulting in increased thickness of the native oxide layer and provides good primary stability in areas of soft bone quality and thus leads to better secondary stability of implants.\[8\]

**Success rate of anodized implants in grafted sites**

Patients with insufficient bone volume may require bone reconstructive procedures before implant placement. Sinus floor augmentation and onlay bone grafting are commonly used in cases of severely resorbed maxilla.\[122-127\] To achieve and maintain primary stability in such cases is a very difficult challenge. Brechter et al.\[70\] studied the survival and stability of anodized implants placed in patients with reconstructive jaw surgery. In a mean follow-up period of 30 months, there was successful outcome of 200 consecutive oxidized implants in various reconstruction situations, with only three failures. Grafting of the maxillary sinus floor with intraorally harvested bone and delayed placement of either turned or oxidized implants result in equally high long-term survival rates (95.7% for turned implants and 97.7% for oxidized implants).\[100\] Bahat et al.\[98\] studied the radiographic outcome of Branemark Mk IV implants in compromised and grafted bone after 3–7-year follow-ups. Long-term clinical outcome of oxidized titanium oxide surface implants were very predictable and successful. They observed that in case of poor bone quality and grafted sites, anodized Branemark MK IV implants inserted with a modified surgical protocol were successful. MK IV implants are fully body-tapered implants and they distribute progressive forces more uniformly into the bone then the parallel-walled self-tapping implants.

**Immediate loading of anodized implants**

The standard protocols in implant dentistry recommend a healing period of 6 months for the maxilla.\[128\] However, sometimes, patients did not opt for implant treatment due to more time required for treatment and additional surgical procedures required in case of two-stage implant surgery.\[6\] An immediate or early loading protocol of dental implants has overcome these patients’ problems and has given a good treatment option to them. Some reports indicate that immediate loading in soft bone was very discouraging.\[129,130\] but many recent studies have demonstrated encouraging results for immediately loaded anodized implants, where bone quantity and quality were not sufficient for implant placement.\[71,74,75,78,89\] Degidi et al.\[74\] did a 36-month follow-up study of immediately loaded implants with a porous anodized surface. All implants appeared to be osseointegrated. Immediate-loaded implants with a porous anodized surface in the long-term were found to work well with a success rate of 100%. In a prospective study by Turkyilmaz,\[75\] Branemark System MK III TiU implants were placed in the maxilla. The success rates for both implant and prosthesis were 94% after 3 years. Results showed that early loading of anodized surface implants in the maxilla may offer an alternative treatment option to the standard loading protocol. Turkyilmaz and Tumer\[78\] carried out another prospective study of 2 years on early versus late loading of unsplinted TiU surface implants supporting mandibular overdentures. The results of the study showed that 1-week early loading approach for implants supporting mandibular overdentures does not adversely influence their clinical performance. No implant was lost, and 100% implant success with both early and delayed loading protocols was obtained. Calandriello and Tomatis\[89\] did a follow-up study for 5 years, for the clinical and radiological performance of anodized Branemark System wide platform implant-loaded immediately supporting single molars in the lower jaw. The cumulative success rate at 5 years was 95.0%. The results of this study encourage the use of immediately loaded anodized implants. Anodized implants with pore diameter of <8 mm facilitate the growth of bone into the pores and thus show better osseointegration and can be successfully used for immediate loading of implants.\[133\] Maló et al.\[112\] in their long-term study (1–13.5 years) found that anodized implants inserted using an immediate function protocol to support fixed partial rehabilitations (FPR) in both jaws is a viable and safe concept. The cumulative survival rate of anodized implants for ten years in their study was 99.1%. Liddelow and Henry\[89\] found that immediately loaded overdenture with oxidized implants provides beneficial treatment outcome with 100% success rate of oxidized implants and 57.1% that of machined surface implants.

**Anodized implants, marginal bone loss, and peri-implantitis**

Many longitudinal studies have shown the marginal bone level to resorb to the first thread after functional loading. This phenomenon could be explained as biomechanical adaptation of bone to the occlusal loading. The problem with rough-surfaced implants was that they accumulate more plaque than smooth-surfaced implants.\[132-136\] Many studies showed low levels of plaque and marginal bone loss around anodized implants in spite of early concerns of increased plaque accumulation on rough-surfaced implants when compared to machined implants.\[3,87,96-98,100,103,108,109\] Lee et al.\[87\] in their 3-year prospective radiographic study evaluated the level of marginal bone around different implant systems. They found that functionally loaded rough surface implants with microthread might
maintain marginal bone level more positively than anodized implants and hybrid of smooth and rough surface implants. Gelb et al.[100] studied 7–8 year functional loading performance of anodized surface Branemark implants by clinical and radiographic analyses. No implant failure was found. It was found that around 95% of implants in the peri-implant mucosa was healthy. Caous et al.[64] concluded in an in vitro study that the anodized surface reduced the adhesion of S. mitis compared to the machined surface. Mozzati et al.[103] studied the long-term clinical and radiological results in a group of patients having single-tooth and partial restorations supported by Branemark TiU implants, they showed an excellent survival rate of anodized implants; the marginal bone response and soft tissue conditions to anodized implants were favorable. Jungner et al.[108] compared the clinical performance of turned and oxidized implants after more than 5 years of loading. Seven turned implants and one oxidized implant failed, with an overall cumulative survival rate of 94.7 and 99.4%, respectively. After 5 years of function, there was no difference in the rate of implant failure and marginal bone loss around oxidized implants when compared to turned titanium implants. Polizzi et al.[3] in their study found a small but significant difference in bone level in favor of the TiU implants. Thus, the current data are in contrast with other studies reporting similar bone remodeling values for turned and moderately rough surface implants or, most frequently, showing better outcomes for turned implants.[6,137] Wagenberg and Froum[109] retrospectively evaluated bone stability around implants with anodic oxidized surfaces and compared this with variables which were compared in a previous study. They found that the mesiodistal bone loss of anodic oxidized surface (TiU) implants over a period of 2–12 years was significantly less when compared with machined implants placed with the same immediate implant placement protocol. Watzak et al.[76] in their study found less peri-implant bone loss around rough implant surfaces, which had beneficial effects at distal implants and in smokers. Nicu et al.[98] did a 3-year prospective randomized controlled trial. They compared the clinical, microbiological, and biochemical results of minimally turned (machined) and moderately rough (anodized) implant surfaces in a split-mouth design. In patients more prone to periodontitis, the moderately rough, TiU implants placed in both postextractive and healed areas demonstrated similar clinical results when compared with the smoother, turned implants in 10 years of clinical performance. Five of over 210 implants included in this study (2.38%) were treated for recurrent peri-implantitis, but were lost because treatment failed to completely eradicate the infection.[99] Good treatment outcome with regard to implant survival, condition of the soft tissue, and response of marginal bone was obtained when implants were immediately loaded in postextraction sockets.

Success rate of anodized implants in postextraction sites
Balshi et al.[69] in their complete arch maxillary prospective study evaluated the survival rates of anodized Branemark implants and also compared them with similar study on machined surface implants. Implants were placed in immediate extraction or healed sites. TiU implants had a significantly higher survival rate of 98.6% in comparison to 92.1% for machined surface implants. Degidi et al.[95] in their prospective study evaluated 10-year performance of TiU implant-supported fixed prostheses with an immediate loading protocol in both postextracted and healed regions. The implants placed in healed sites obtained a cumulative survival rate of 98.05%, and in postextractive sites, it was 96.52%. In a 5-year retrospective study by Mura,[97] it was found that there was no implant failure when immediately loaded in postextracted sites, which could be because of anodized surface favoring faster bone healing without either soft or hard tissue problems.

Conclusion
The findings of the systematic review on anodized surface can be concluded as follows:

- Animal studies showed mixed result. There was increase in bone loss after treatment with anodized surface implants. However, when implants with different surfaces were connected in such cases, distal implant with machined surface showed more bone loss
- Favorable results were obtained in in vitro studies with bone growth into the porous structure of the coating of anodized implants. Proliferation, alkaline phosphatase activity, and calcium deposits were significantly higher on anodized surfaces compared to machined surfaces
- Long-term clinical studies on anodized surfaced implants do favor the surface, but in most of the studies, anodized surface is compared with that of machined surface, but not with other surface commercially available. Anodized surface in terms of clinical success rate in cases of compromised bone and immediately extracted sockets has shown favorable success with more than 95% of clinical success. Anodized surface did show plaque accumulation in marginal bone losses when compared to machine surfaces in one study, but several other studies showed decreased levels of plaque and reduced marginal bone loss around anodized implants. Many recent studies have demonstrated encouraging results for immediately loaded anodized implants where bone quantity and quality were not sufficient for implant placement with success rate of more than 94%.

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Conflicts of interest
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Mishra, et al.: Anodized dental implant surface
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