SYSTEMATIC REVIEW

Recent advancements in surface modifications of dental implants

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Abstract

Objective: Implantology is one of the most investigated topics in modern dentistry. The current review was planned to systematically summarise all industrial, mass production and experimental trends in dental implant manufacturing relative primarily to their surface modification conducted between January 2017 and January 2020.

Materials and methods: The review was conducted in Army Medical College, National University of Medical Sciences, Rawalpindi, Armed Forces Institute Of Dentistry, Combined Military Hospital, Rawalpindi, Foundation University College of Dentistry, Fauji Foundation Hospital, Islamabad, and the Higher Education Commission Library, Islamabad. Literature was searched on PubMed, Scopus, Medline, Cochrane and Science Direct databases. The key words employed were "dental Implants", "surface modification", "surface morphology", "surface treatment" and "surface augmentation".

Results: A total of 38 articles were short-listed and reviewed in detail. There was abundant evidence suggesting the importance of these surface modifications on improving the implant success. Several strategies have been suggested to modify the implant surface topography as well as surface chemistry in order to achieve a micro-porous structure with nano-scale architecture, with increased bio-activity; hydrophilicity and anti-bacterial properties.

Conclusion: There has been commendable success with many of these strategies in laboratories. However, following the success in ex-vivo studies, very few of these surface modalities have found their way to clinical set-ups.

Keywords: Dental implants, Surface modification, Surface morphology, Surface treatment and Surface augmentation.

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Introduction

Dental implants, according to the glossary of prosthodontics, is defined as "any object or material, such as an alloplastic material, which is inserted either partially or completely into the body for therapeutic, diagnostic, prosthetic or experimental purposes".[1]

Branemark, an orthopaedic surgeon, used first titanium (Ti) dental implant in humans in 1965.[2] Its success led to a major change in the treatment strategies for the replacement of missing teeth. In early 1980s, it was Branemark who gave the concept of directly anchoring the implants to bone without the presence of any intervening fibrous tissue capsule, which is referred to as osseo-integration.[3]

When an implant is inserted into the body, it is surrounded by body fluids and connective tissues. A scaffold forms around the implant, while bone-forming cells arrive at the site of implantation from bloodstream and lay down the bone matrix which is later mineralised to form the new bone on and between the surface irregularities of the implant.[4] A lot of research has been focussed on altering the surface chemistry and topography to improve bio-mechanical fixation of the implant to ensure short- and long-term success.[5]

Dental implants are called root analogues, as they not only replace the missing tooth structure, but also restore the symmetry of arch, maintain bone shape and thickness, and ensure adequate mastication, articulation and aesthetics.[6] But, according to the two-step surgical protocol for implant procedures, at least a period of 3-6 months is required before functional loading of the prosthesis to allow for sufficient bone formation to occur around the implant.

The current systematic review was planned to address the latest trends in surface modifications of dental implants for rapid and effective osseo-integration. Several approaches can be used to achieve a better implant stability, including the bioactive approach, to induce in-vivo apatite formation, or it can be based on tailoring its surface morphology.[7] The target was to systematically summarise all industrial, mass production and experimental trends in dental implant manufacture relative primarily to their surface modification seen over the 2019-20 period.

Methodology

The systematic review was conducted at the Army Medical

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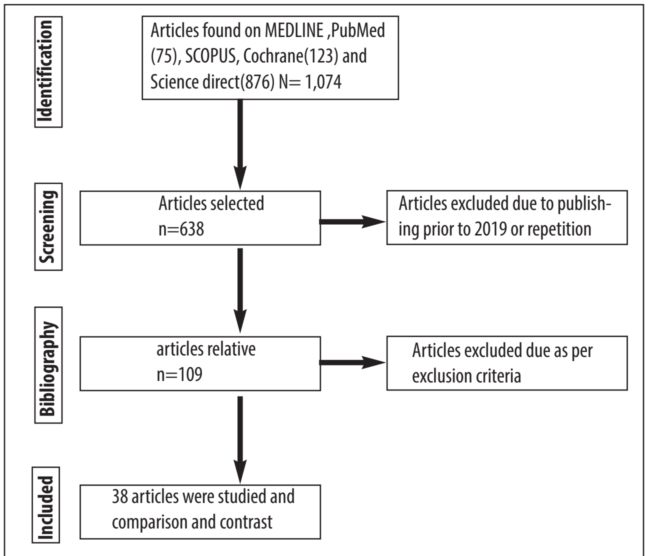

Figure-1: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow chart.
Source: http://www.prisma-statement.org/PRISMAStatement/Default.aspx

College (AMC), National University of Medical Sciences (NUMS), Rawalpindi, the Armed Forces Institute of Dentistry (AFID), Combined Military Hospital (CMH), Rawalpindi, the Foundation University College of Dentistry, Fauji Foundation Hospital, Islamabad, and the Higher Education Commission (HEC) Library, Islamabad. Literature was searched on PubMed, Scopus, Medline, Cochrane and Science Direct databases. The key words employed were "dental Implants", "surface modification", "surface morphology", "surface treatment" and "surface augmentation".

Inclusion criteria

Articles included were studies with case report conducted up till January 20, 2020, on commercially available implants, including human trials and full-mouth rehabilitation. Also included were studies reviewing evidence based in the past about surface modifications, including ex-vivo or cell cytotoxicity analyses as well as studies with immediate or delayed implant placement.

Exclusion criteria

Studies excluded were those with auto-transplantation of missing teeth, those with periodontally compromised dental arches, those with systemic diseases that compromised dental arches, those with biologically grown factors as well as studies with cell-homing strategies, or those conducted before January 1, 2017.

The article selection is shown in the Prisma flow chart as shown in Figure 1.

Result

The success of implant depends on a number of factors which include implant design, bio-materials, surgical technique, health and bone quality, bio-mechanical factors, oral hygiene and surface characteristics.[8] The most important of all these factors affecting the immediate interaction between the implant and the host tissue and is the surface characteristics of implant. Surface characteristics include surface topography,[9] surface chemistry,[10] surface hydrophilicity[11] and anti-bacterial surface properties.[1۲]

These parameters depend upon various surface treatments carried out on implants to improve their osseo-integration. To date researches all over the world have modified the implant surface using different techniques, which can be classified as additive techniques, such as, plasma spraying,[13] sol-gel coating,[14] sputter-deposition,[15] biomimetic precipitation[16] and electrophoretic deposition.[9] Or they may be subtractive techniquesm such asgrit blasting,[17] acid etching[18] and anodisation.[19]

These may also be classified as methodologies of coating as done by Ferraris et al., including surface treatments done by chemical methods, like sol-gel,[20] biomimetic,[21] electrochemical deposition,[22] electrophoretic deposition,[23] micro-arc oxidation[24] and ultrasonic spray pyrolysis.[25]

These may also be accomplished by physical methods, like plasma spraying,[26] magnetron sputtering(9, 15), ion beam-assisted deposition[27] or pulsed laser deposition.[28]

Discussion

Methods for producing roughened surfaces

Plasma spraying: This process uses a direct current (DC) electric arc to generate a stream of high temperature ionised plasma gas, including argon, helium, hydrogen and nitrogen, which acts as the spraying heat source. The coating material, in powder form, is carried in an inert gas stream into the plasma jet where it is heated and propelled towards the substrate.

Various coating materials can be added on the implant surface to produce the desired roughness. Initially, the main purpose of this process was to produce a roughened surface which increased the contact area with newly formed bone, thus providing better biomechanical fixation. For this purpose, titanium powder was used as the coating material[29] but later researches aimed at producing a roughened as well as bioactive surface by depositing hydroxyapatite particles through plasma spraying on the implant surface.[30] Hydroxyapatite is a calcium phosphate bio-ceramic with nearly the same chemical composition as the human bone.[31] It is highly biocompatible and osteoconductive.[32]

Major drawbacks with plasma spraying include high temperature process; thick coatings (>50µm); presence of a number of different phases, with variable solubilities in case of calcium phosphate as a coating material; delamination of surface and ineffective procedure for tiny and complex structures.[33]

These were overcome by Pierre et al. in 2019 by proposing a soaking process, in phosphate and then calcium solutions in a stepwise manner, at lower temperatures which can be done on complex structures of all sizes. This processing included an additional centrifugation step between two soaking procedures to create a thin layer of ~2µm. This methodology also allowed coating of functionalised thermosensitive molecules (growth factors and antibiotics) without altering their chemistry.[6] Similarly, Ferraris et al. in 2015 developed a multiple scale topography and bioactive surface without high temperature treatments.[34]

Grit blasting: In this process, ceramic particles comprising alumina, titanium oxide and calcium phosphate, are bombarded onto the surface of the implant at a very high speed through compressed air to produce variable surface topography, and, depending upon the blasting material, its dimensions, speed of projection and distance of surface from the nozzle and the diameter of the nozzle.[29]

A major disadvantage of grit blasting procedure is that the blasted material may remain embedded in the implant surface even after ultrasonic cleaning and acid passivation, for example, alumina. These particles can be released into the surrounding tissues locally and may sometimes be distributed systematically.[29] For these reasons, it is now always used as an adjunct to other techniques.

Anodisation: This is an electrochemical process in which the oxide layer on titanium dental implants is thickened and modified by using strong acids as electrolytes. Strong acid dissolves the oxide layer along current convection lines to form a nanotubular structure.[29,35] This nano-tubular structure has higher surface-area-to-volume ratio, demonstrated increased osteoblastic cell activity and can also be used as drug delivery system.[36] Different drugs that can be added include anti-bacterial agents, metallic particles, bone morphogenetic proteins, bone remodelling drugs.[37]

Kim et al. anodised implant surfaces to produce micropores and nanotubes at high and low voltages, respectively. After that pre-treated surfaces were placed in a compartment filled with tetra-calcium phosphate (TTCP) to generate a bioactive surface. Apatite formation was highest on anodised surfaces.[38] Similarly, plasma electrolytic oxidation (PEO) was done on titanium alloy (Ti–13Nb–13Zr (titanium-niobium-zirconium)) in a solution containing ammonium dihydrogen phosphate and tricalcium phosphate at high voltage to produce porous oxide layer with incorporated calcium and phosphate ions.[39]

Acid etching: Strong acids like hydrofluoric acid, sulfuric acid, nitric acid and hydrochloric acid are employed to generate micro-pits on implant surface. Dual acid etching or etching in the presence of fluoride solutions can be done to generate roughened surfaces.[29] However, acid etching is not used alone for surface modifications, but it is always combined with one or more of the treatments described above to achieve the desired results.[40]

These techniques can be used alone or in combination to obtain the desired configuration. For example, many manufacturers use sand-blasted, large-grit, acid-etched (SLA) technique which involves sand-blasting followed by acid etching to improve implant anchorage in jaw bone.[11]

Surface characteristics

Surface chemistry: Surface chemistry depends upon the type of the material and the surface treatment it has undergone.[29] titanium and titanium alloys are the most commonly used and preferred material for dental implants owing to their biocompatibility, superior mechanical properties and corrosion resistance.[37]

Surface chemistry also plays a major role in surface wettability of implants by biological fluids.[6] titanium and titanium alloys most commonly used for implants are considered bio-inert and corrosion-resistant due to the presence of surface-oxide (TiO) layer. This layer, however, can be broken down due to the occlusal loads and may result in leakage of metallic ions into the surrounding tissue. So, a number of surface treatments can be done to improve the hardness of this layer. Huang et al. in 2019[37] gave the concept of treating the surface of Ti-6Al-4V (titanium-aluminium-vanadium) with nitrogen plasma immersion ion implantation to create a layer of titanium nitride (TiN) on the surface of implants. This improved the surface hardness, corrosion resistance and cellular response of implants in in-vitro testing.[9]

Plasma immersion ion implantation (PIII) and optical emission spectrometery (OES) were used to produce a surface which had argon atom and oxygen ion which improved protein adsorption, decreased carbon content and increased hydroxyl groups. This in situ coating ultimately generated a more hydrophilic surface.[40]

Ti surface can also be modified by deposition of nano-particles and bio-active molecules. An example of this is the 2016 study by Nyoung Heo et al. which immobilised gold nano-particles on titanium surface and showed an improve osseo-inductive potential both in-vitro and in-vivo.[41]

Surface hydrophilicity: Furthermore, hydrophilic surfaces of implants are recommended because it favours interactions with bio-fluids, proteins and cells.[1] Hydrophilic surfaces increase alkaline phosphatase and prostaglandin E2 (PGE2) and transforming growth factor beta 1 (TGF-ß1).[7,42]

Hydrophilic implant surfaces are more desirable than hydrophobic ones as they will promote the adhesion of proteins and cells.[29] Surface wetting characteristics depend on surface energy, functional groups as well as micro- and nano- topography.[43] titanium implants are covered with an inert oxide layer which on coming in contact with body fluids generate hydrogen peroxide and its oxidation products, like hydroxyl functional groups, that impart hydrophilicity to the surface due to free surface energy of these groups. Upon insertion, initially sodium and then phosphate ions get adsorbed onto implant surface which, in turn, increases adsorption of extracellular matrix proteins (ECM).[44]

Murphy et al. developed SLA-modified surfaces by sterilising the sand-blasted and acid-etched surface in the presence of nitrogen which is an inert environment, followed by storage in sterile saline solution. This resulted in surfaces with micro-protrusions and increased hydrophilicity, meaning decreased surface carbon, which improved osseo-integration and decreased the waiting time before functional loading of implant.[20]

Surface topography: Surface topography deals with the surface roughness which should be around more than 1µm but less than 2 µm. Roughness of >2µm will favour more pellicle formation.[6] Surface roughness can be macro, micro or nano, depending upon topographical features which can be in the range of millimetres to tens of microns, 1-10µm, or in the nanometer respectively.[1] Implant geometry and macro-level morphology provides primary or immediate implant fixation whereas micro and nano levels determine the cell response.[34] Nano level surface features are explored more recently as far as biological activity is concerned because they allow interactions to occur at the scale of biological molecules and cells.[45]

Events that follow the placement of implant include an immune response to both the surgical insult as well as to a foreign body.[46] Immune cells migrate to the site which primarily constitutes macrophages which, in turn, decides if this inflammatory response will resolve quickly or will be prolonged. Macrophages can be activated to a pro-inflammatory or anti-inflammatory state depending upon the surface oxide chemistry, hydrophilicity and morphologies.[47] Once the initial inflammatory reaction has subsided, bone-formation begins by osteoblasts. Hotchkiss et al. in 2019 did an in-vitro comparison between surface roughness produced on different commercially available implants and concluded that variable surface morphologies resulted in different macrophage and mesenchymal stem cell gene expression, but showed similar cellular attachment. Implants showing lower surface roughness values, hydrophobic surfaces and oxide layer with increased carbon content resulted in the expression of pro-inflammatory genes in macrophages.[42]

Surface roughness is produced using different methods.[1] Machined surface is almost smooth (0.3-1µm), whereas sand-blasting, acid-etching and SLA have a roughness of 0.5-2µm, 0.5-2µm and 1-2µm, respectively

Ferraris et al. in 2015 gave the concept of producing a multi-scale topography, a nano-texture overlapped on micro-scale porosity by using conventional sand-blasting with zirconia micro-spheres and acid-etching with hydrofluoric acid to produce a micro-scale topography (1-2µm). This was followed by a second acid-etch treatment in a solution of sulfuric acid and hydrochloric acid (dual-acid etch technique) to superimpose a nano texture (approx. 10nm). He also increased the wettability and bioactivity of the treated implant surface by increasing the number of functional hydroxyl groups after final oxidation in concentrated hydrogen peroxide in his previous studies.[34]

Antibacterial surface properties: titanium and titanium alloys used most commonly as dental implant materials have excellent bio-compatibility, but they do not have inherent antibacterial properties. In addition, different modifications are done to produce micro- and nano-roughened surfaces of implants to improve their biomechanical fixation.[2] The combined effect of these two factors promotes bio-film formation on implant surfaces, ultimately leading to failure.

Two approaches can be used for inhibiting bacterial growth; either bacteria can be killed in the vicinity of the implant by a released bactericidal agent, or microbial growth on anti-bacterial surfaces behaviour can be decreased.[48]

Antibiotics can be added onto the modified implant surfaces to be released into the surrounding host environment, but the problems will be a controlled release over a period of time instead of bulk release, limited adhesion to surface plus development of resistance to these antimicrobials.[49] To overcome these problems, metallic ions with antibacterial properties, such as argentum (Ag), Copper (Cu) and zinc (Zn) can be used because of their known antibacterial properties and non-toxic effects on human cells in case of systemic distribution of these ions.[37,48] Hempel et al. evaluated plasma immersion ion implantation and deposition of Cu into Ti.[48] Similarly, Huang et al. coated a TaN-Ag (titanium nanotubular-silver) nano composite coating on titanium implant by a twin gun magnetron sputtering system to verify bacterial colonisation on implant surface.[37] Both these studies concluded that coated implant surfaces exhibited better antibacterial effects.

There are two major drawbacks with these inorganic metallic ions or nano-particles; firstly, they display a dose dependent effect, both as bactericidal as well as cytotoxic behaviour. To overcome this problem, anti-bacterial metal atoms / ions can be doped, coated or alloyed to titanium surface[24] or a stable bioactive modulating matrix, for example, thick hydroxyapatite coatings can be doped with metallic ions.[7]

In alloying metal atoms to Ti-phase segregation creates a problem so plasma processes can achieve a more homogenous surface deposition.[3] But there is always a chance of coating delamination, which was overcome by Surmeneva et al. who gave the concept of a three-layer coating made of amorphous calcium-phosphate outer layer, Ag nano-particles and nano-crystalline hydroxyapatite interlayer on titanium (Ti) implants. The top and bottom calcium phosphate layers were produced by radio-frequency magnetron sputtering was used to deposit top and bottom calcium phosphates layers, while Ag nano-particles were added by electrophoretic deposition.[49]

Another approach to reducing peri-implant inflammation is to produce functionalised surfaces without alteration in surface topography. These surfaces showed increased cellular activities, but inhibited bacterial accumulation due to change in its surface chemistry, i.e., decreased carbon content and increased hydrophilicity. Thus, adherence of hydrophobic bacteria is decreased. Lee et al. in 2013 designed a study to evaluate drug delivery efficacy of nano-tubular titanium implants loaded with N-acetyl cysteine (NAC). NAC is an anti-oxidant and a direct reactive oxygen species (ROS) scavenger. So these modified implants reduced post-implantation inflammation and increased bone healing.[9] Similar approach was used in 2017 which proposed the idea of treating the roughened titanium and titanium alloy surfaces with non-thermal atmospheric pressure plasma jet (NTAPPJ).[12] An illustrative diagram shown the variable modification for titanium surface implants is as shown in figure 2

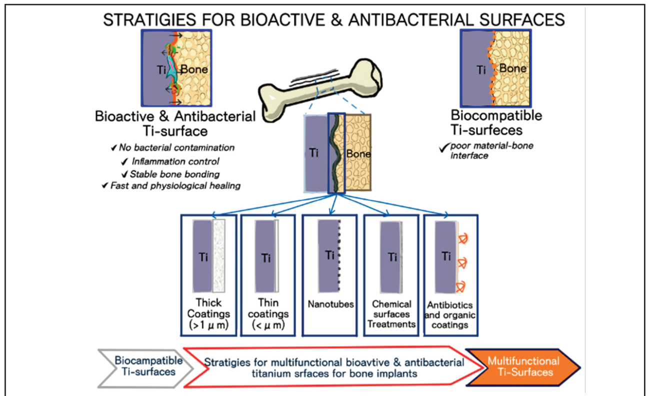

Figure-2: Multiple approaches to modify bioactive and antibacterial properties of titanium (Ti) surfaces through different types of surface coatings.

Conclusion

There is abundant evidence suggesting the importance of surface modifications on improving the implant success. Several strategies have been suggested to modify the implant surface topography as well as surface chemistry in order to achieve a micro-porous structure with nano-scale architecture, with increased bio-activity; hydrophilicity and anti-bacterial properties. There is commendable success with many of these strategies in the laboratory. All these efforts are focussed on developing an implant system with characteristics that favour rapid and durable osseo-integration to improve short-term as well as long-term survival rate of implanted prosthesis to avoid patient pain, inconvenience and expense. However, to the very best of our knowledge, very few of these surface modalities have found their way to clinical set-ups. From practicality viewpoint, efforts should be directed at developing cost-effective, less time-consuming and reproducible surface modifications.

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