Dental Implants: An Overview

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1.1 Medical Implants: An Introduction

An implant is an artificial device that can repair the functions of biologic tissues and organs or provide a support structure for compromised tissue or replace an entire biologic structure that is missing or damaged beyond repair [1]. Since it is an artificial structure, an implant needs to possess the property of biocompatibility, which in turn refers to the ability of materials to remain passive and non-reactive in human biologic tissue. An ideal biocompatible material can even induce the formation of reparative tissue around it and result in a harmonious union of function and form. A material that is not biocompatible results in a foreign body reaction with the implant material recognised as an invader and being rejected in the form of bone resorption or tissue necrosis, corresponding to the tissue housing the implant prostheses [2].

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Implants can be used for a variety of applications, the totality of which can be categorised into two broad modalities—Therapeutic and Cosmetic. Therapeutic uses of implants can further be categorised according to the primary purpose of the implant. (1) Support—surgical meshes which could be metallic (titanium) and used for supporting hard tissue following trauma or it could be synthetic (polypropylene, polyethylene terephthalate, polytetrafluoroethylene and the newer polyvinylidene fluoride, a type of nanofibrous mesh that is resistant to hydrolytic degradation and induces neo-angiogenesis). (2) Replacement—artificial heart, artificial heart valve, coronary stent and dental implant. (3) Repair— intraocular lens, intracorneal ring segment, myringotomy tube, cochlear implant, neurostimulation devices, pacemaker, electric implant, intrauterine devices and diaphragm pacers.

Cosmetic uses of implants are, as the name suggests, related to the improvement of appearance for each individual and are performed solely based on everyone's subjective requirement. The various cosmetic uses can be injectable fillers, which could be transplanted fat or synthetic polymers such as calcium hydroxide, polymethylmethacrylate, polycaprolactone, nasal implants, ocular implants, mammary implants and penile implants. The list of prostheses categorised above are some of the most common usage scenarios

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and is not intended as a definitive list of commercially available implantation modalities.

A newer application for implants involves the transhumanism approach wherein electronic devices are implanted into an individual's biologic tissue to surpass human limitations. This approach has been termed 'Body Hacking' and a few individuals have succeeded in implanting small electronic devices such as RFID chips into their biologic systems. The most notable examples of this application include the electrode array implanted by British scientist Kevin Warwick in the year 2002 and the antenna implant utilised by British artist Neil Harbisson in the year 2005 [3]. Kevin Warwick succeeded in placing a 100-electrode array into his nervous system. The same procedure was implemented in his wife, which in turn enabled the first direct communication between two nervous systems. The antenna implant utilised by Neil Harbisson is claimed to expand his range of colour sensitivity. It should be noted, however, that this application cannot be adequately supported by valid scientific documentation or evidence and is not recommended as a routine treatment modality by any medical professional.

Implants are currently manufactured using metals and polymers in conjunction with various surface treatments to enable their intended effects. The most common metals used for implants are commercially pure titanium (CpTi), titanium alloy, zirconia, titanium–zirconium alloy, tantalum, stainless steel and cobalt–chrome alloy. The most common polymers used for implants are polypropylene, polyamide, polymethylmethacrylate, polyethylene terephthalate, polytetrafluoroethylene, polyhydroxyalkanoates and polyvinylidene fluoride [4, 5]. A comprehensive dissection on materials used for implantology will be expounded further in the following sections of this chapter.

1.2 Dental Implantology

Till the advent of dental implantology, the most common treatment options for replacing missing teeth involved the detrimental reduction of tooth structure for a fixed prosthesis or the provision of extensive acrylic or metal frameworks for a removable prosthesis. The fixed option involved reduction of multiple teeth for replacing a single tooth and necessitates endodontic therapy in case of unfavourable abutment positions. The removable option involved routine removal of the prostheses for hygiene maintenance and the adjustment of the patient towards the optimal protocol of using a removable appliance [6].

The introduction of dental implants by Per Ingvar Branemark marked the commencement of a revolution in the therapeutic approach for the provision of fixed restorations [7]. The concept of a root analogue for anchorage to the underlying bony tissue marked a paradigm shift in the provision of both fixed and removable prostheses for the replacement of missing teeth. This newer concept eliminated the need for the reduction of adjacent teeth for support and provided the advantage of maintaining alveolar bone height wherever the implants are located. Cumulative evidence from scientific literature show that implants are effective as a definitive restoration modality with success rates ranging from 92 to 95%, depending on the span of the restoration [8, 9]. Other advantages of implants include the elimination of incidence of secondary caries, improved bite force and proprioception. It has been observed that patients develop a sense of proprioception and tactility following implant therapy. Many theories have been proposed to explain this occurrence, with current evidence leaning towards the Bonte theory that hypothesises that re-innervation may occur from stimulation by functional loading [10]. The re-established tactile sense also enables the improvement of bite force magnitude in patients [11]. It should be noted, however, that the tactility and proprioception gained around implants do not reach the same magnitude or intensity of natural teeth, with the active tactile threshold value of implants measured three times higher than that of natural teeth [12].

Success rate is a parameter indicating the treatment outcome following a particular therapy, which could be positive or negative. This parameter has been used as a prognostic indicator with

multitudes of studies analysing the success rates for various treatment modalities and suggesting a decision tree for corresponding modalities of therapy. Many studies have reported a 92–95% success rate for dental implant therapy in different scenarios. It has been observed that the success rate is inclusive of implants, whose patients have been subject to confounding factors, such as implants placed after the commencement of a study, which are factors to be excluded from the final analysis. The parameter Cumulative Survival Rate (CSR) is a more appropriate indicator since it would remove confounding factors when analysing failure rates. CSRs usually denote a lower value than success rates but are a far more reliable prognostic indicator. Very few studies have analysed the CSR of dental implants and data remains scarce on these values [13].

Even with the data currently available and the plethora of techniques and equipment, accurate prediction of the treatment outcome for every single case is not yet achievable. Factors such as environment, habit, stress and everyone's biologic response render the treatment modality a measure of probability rather than certainty. It may not be feasible to gain control of each of these factors, yet the implant itself could be rendered conducive to functional adaptation to these conditions. Therefore, most studies attempt to identify favourable characteristics of dental implants to achieve universal acceptability. This task is made doubly difficult due to the existence of hundreds of implant manufacturers as well as the variability in methods that are employed to fabricate implants [14]. Despite the heterogeneity, there are several factors in scientific literature demonstrating the ideal features necessary for a dental implant. A dissection of the constituent portions of an implant is, hereafter, necessary for the identification of ideal features for each portion.

1.2.1 Design Aspects of the Dental Implant: The Current Trend

The term 'Dental Implant' refers only to the fixture that is anchored to the bone. The superstructure that supports the crown, or any prostheses, is termed an abutment. A typical endosseous dental implant can be divided into coronal, middle and apical thirds for the sake of description.

Implants were initially manufactured in a cylindrical shape with the same diameter from the coronal to apical aspect. The fixtures currently available commercially are tapered in a sequentially incremental manner in the apical third to simulate the tapered anatomy of a natural root. The taper also allows easier placement into the prepared osteotomy site whereas a parallel-sided fixture would require more force for complete placement and would, in turn, generate greater torque on the alveolar wall. There were concerns, initially, that the taper would reduce the amount of surface area contacting the bone and would thus, result in poorer osseointegration. These concerns were assuaged when scientific literature displayed that there were no significant differences between cylindrical and tapered implants even in poor density bone, denoting that tapered implants could be used in all conditions.

Implants have transitioned from a smooth, non-threaded surface to a roughened threaded surface since the threads serve a dual purpose of increasing the functional surface area as well as aid in favourable force distribution into the supporting bone. The term favourable force distribution is intentionally used here to highlight the fact that bone is strongest against loads of a compressive manner and weaker against oblique loads. The threads in an implant change the direction of force imparted longitudinally along the axis of the fixture into a transverse direction, which is compressive on the bone [6]. Fixtures with various thread geometries have been implemented by commercial manufacturers across the world with each entity claiming superior osseointegration and clinical longevity due to their thread designs. The thread shapes that have been used till date are square (power thread), fixture (V-thread), acme, buttress thread, reverse buttress, vertical slot, rounded power and spiralock designs [15]. Studies on stress concentrations have shown that there is no difference between various designs, and this has been directly observed in clinical practice as well [16–18].

A direct correlation between the quality of osseointegration in different bone densities and thread size has been observed in scientific literature. Larger threads (increased thread depth and thread pitch) have been found to be advantageous when used in the field of penurious bone density, such as in the posterior maxilla or in cases of immediate implant placement after extraction and smaller threads with reduced depth and pitch perform well in cases of moderate to highly dense bone structures [19].

Microthreads in the coronal portion of the fixture have been observed to retain the marginal bone around an implant after loading. Loading of bone is highest at the crestal region since it is the most superior point of contact of the fixture with bone. The crestal region is thus subjected to the highest magnitude of forces around the implant. Consequently, marginal bone catastrophe is expected to occur till the first thread of the implant. Implementation of microthreads serves to transfer these high-intensity loads into transverse compressive stresses, which the anchoring bone can resist in a more efficient manner. Clinical studies have also shown that the presence of microthreads results in reduced crestal bone loss when compared to implants with a non-threaded smooth surface [20–22].

In addition to microthreads, the method known as platform switching can be used for reducing crestal bone. Platform switching was incidentally observed when a narrower abutment was secured to a wider implant platform and resulted in reduced crestal bone loss [23]. Most implants currently implement platform switching by widening the implant platform diameter and employing an abutment with the same diameter as the implant body. The implant platform is, therefore, wider than the implant body and the overlying abutment and provides the effect of platform switching. Current evidence suggests that platform switching is an effective method of reducing crestal bone loss [24–27].

Implant diameter and length have been established as directly correlative to the main stability of the implant fixture. Implant with wider diameters increases the functional surface area by 200% with every 0.25 mm increase in width [6, 28]. Conversely, implants with a width greater than 6 mm result in a phenomenon known as stress shielding [29]. Stress shielding results from the higher elastic modulus of the implant fixture relative to biologic hard tissue. This mismatch results in viscoelastic flexure of bone under loading conditions whereas the stiffer fixture remains resolute and can cause weakening of the bone–implant interface. There is no evidence, however, to establish the incidence of this shielding phenomenon in routine clinical practice [29]. The lack of evidence could be hypothesised to the fact that implants wider than 6 mm are required to a negligible extent since the alveolar bone is very rarely wide enough to accommodate such diameters. Longer implants engage deeper into the anchoring bone and increase the insertion torque values [30, 31]. Areas of minimal bone, such as the posterior maxilla, may not be able to house implants of increased dimensions. In such cases, a shorter implant with roughened surfaces has been observed to provide an acceptable treatment outcome [32, 33].

It is common knowledge that successful osseointegration occurs once bone remodelling is complete along the implant–bone interface [34]. Remodelling usually requires a duration of 3–6 months depending on the bone density, induction of formative strain and presence or absence of contributing factors, such as infection, diabetes, smoking, bisphosphonate therapy, radiotherapy and so forth [25, 35–37]. It has been observed in scientific literature that modifying the surface area of implants by roughening serves to hasten the rate of remodelling and augments the anchorage of bone to implant. This observation has resulted in a vast swath of laboratory and clinical studies focussed on discovering and/or establishing an optimal method to induce surface roughness and the analysis of optimal intensity of surface roughness that promotes maximal bone integration around the implants [18, 38].

An attempt to identify and categorise the optimal roughness level that hastens bone integration was undertaken by Wennerberg et al., who propounded that a roughness level of 1–2 μm was the most advantageous in improving osseointegration [39]. The research group analysed the surface

microtopography of implants and arrived at the conclusion that Sa values of 1–2 μm are the optimal height parameter for a dental implant. They categorised implant surface roughness as mild for Sa values less than 1 μm, moderate for Sa values between 1 and 2 μm and maximal roughness for Sa values greater than 2 μm [14]. These findings are at the micrometre level and it is currently observed that certain surface treatments produce alterations at the nanometre level as well, which further influences the remodelling process.

Surface treatments for implants include additive and subtractive methods, sometimes even a combination of both [40]. The subtractive methods include acid etching, sandblasting/grit-blasting and laser etching. Additive methods are titanium plasma spraying, hydroxyapatite plasma spraying, anodic oxidation and sol-gel deposition. To increase the effectiveness, a combination of subtractive and additive methods such as sandblasting and acid etching, sandblasting, acid etching and ion beam assisted deposition are followed.

Most implant manufacturers employ a combination of surface treatment methodologies rather than rely on any single mechanism. The earliest instances of surface modification were titanium plasma spraying and hydroxyapatite plasma spraying. While titanium plasma spray resulted in rough surfaces (Ra values of 4–5 μm), it resulted in a high incidence of complications and marginal bone loss. The hydroxyapatite plasma spray resulted in high initial stability with eventual coat flaking and delamination which resulted in a foreign body reaction and macrophage induced resorption [38]. Thus, these two methods were discontinued, and the other methods listed above were optimised for dental implant surfaces [18, 41]. Table 1.1 briefs different methods that have resulted in enhanced bone apposition on the implant surfaces when compared with untreated surfaces.

With such an emphasis on implant microgeometry and surface alterations, it is logical to assume that the primary stability of an implant would correlate directly with successful treatment outcomes [20, 42]. Primary stability is a measure of the amount of rigid anchorage attained during implant placement. It is measured through insertion torque using manual torque wrenches, implant stability quotient values using resonance frequency analysis [43], and recently, by value of micromotion as advocated by Trisi's research [44, 45]. While primary stability is a good indicator of a successful outcome following stage 1 implant surgery, studies have found that there is no correlation between insertion torque values and implants under loading conditions [46, 47].

Table 1.1 Different surface treatment methods of dental implants currently in use

Surface treatment modality	Brand name for implant	Manufacturer
Acid etching and anodic oxidation	TiUnite	Nobel Biocare
Grit-blasting, dual acid etching and sol–gel method	NanoTite Prevail	Biomet 3i
Sandblasting (alumina) and acid etching	SLA	Straumann
Sandblasting (zirconia) and acid etching	ZLA	Straumann
Sandblasting, acid etching and ion beam assisted deposition	NanoTite	Bicon
Sandblasting with resorbable blast media	Ossean	Intralock
Sandblasting (titanium) and acid etching	Osseospeed	Astratech

These criteria for endosseous dental implants have been sequestered and compiled from stringently curated scientific literature and have proven to be solid indicators for a successful therapeutic outcome. However, the presence of these factors alone may not guarantee a reliable prognosis since the operator's skill in treatment planning, clinical acumen, presence, or absence of endodontic and/or periodontal infections, systemic factors, play a significant contributory part to the successful outcome of an implant restoration.

1.2.2 Biomaterials in Implant Dentistry: A Historical Outlook

Dental implant materials have a long history from using gold in early 2500 BC to advanced

functional "smart" materials in the current generation [48]. The successful osseointegration of the dental implant lies in the design and the material which is chosen for the purpose. Several materials such as metals, ceramics, alloys, polymers and glasses were tried and tested for the dental implant application. In addition to osseointegration, biocompatibility and bio functionality are the factors considered important for the dental implant material [49]. Branemark's monumental discovery of "osseointegration" of titanium to the rabbit bone is considered the benchmark till today. From there, the exploration of different materials for the dental implants began with researchers finding biocompatible materials and modifying the materials having a functional role is in steady progress.

Oral environment is one of the dynamic environments with ever-changing temperature, pH, chemical and physical reactions, making it a challenge for the implant to sustain in such conditions. Thus, an "ideal" implant is required to possess biocompatibility, corrosion resistance, modulus elasticity like bone, wear resistance and strength. These properties of the dental materials are classified as bulk and surface properties [49]. While bulk properties deal with strength and stability of the material, surface properties are crucial for effective osseointegration and increased lifetime. Both the bulk and surface properties define the biocompatibility of the material chosen. Bulk properties of the implant material include modulus of elasticity that should be comparable to bone (10–20 Gpa), high tensile strength for functional stability, improved yield strength to prevent fracture and increased hardness and toughness. Surface properties such as surface tension, energy and topography play an important role in successful host–implant contact [50].

Another important factor is the bio-tribological properties that analyse implant performance based on mechanical wear and electrochemical corrosion [51]. Such tribological tests are important to understand the degradation of the material in the oral environments, which directly translates to the success of the implant. In the case of metals and alloys, crack generation, degradation product and ions releases should be accounted to ensure safe clinical outcome of the implant. Hence the success of the dental implant depends on the different aspects of the material ranging from bulk properties to tribological properties [52].

Dental implant materials can be widely classified as metallic and non-metallic materials. Metallic implant materials include metals and its alloys, which are reliable for implant purposes for a long time.

1.2.2.1 Metal and Its Alloy

Titanium possesses a low density and high strength-to-weight ratio in addition to being biocompatible making it a preferred candidate in the field of dental implants since its introduction in 1981. The integrity of the titanium and the ability to osseointegrate is adequate with a survival rate greater than 90% in the long run. The two most widely used titanium alloys are cpTi and Ti-6A1-4V (titanium–aluminium–vanadium alloy) and they both can readily osseointegrate. The cytotoxicity of Ti-6A1-4V is comparable to that of cpTi despite having vanadium and aluminium. The major alloy used is cpTi, which predictably interacts with air or tissue fluids to form a titanium oxide layer and maintains it without corrosion or breakdown in physiological conditions. Interestingly, this oxide layer directs the implant-tissue interaction such as adhesion of osteoblasts and is a key player in determining the success of osseointegration. Given the major roles played by the implant surfaces in promoting biocompatibility, surface modification remains one of the obvious approaches that influences the outcome of the process. Myriad methods are available for modifying the surface with almost all of them aimed at enhancing the roughness of the surface as it would eventually favour the deposition of proteins promoting soft tissue and osseointegration [53].

Zirconium, like titanium, is a transition metal with excellent biophysical properties. However, with respect to survival and success rates its potential in dental implantology is low when compared to titanium [54]. In the case of fine implants that experience high stress, an alloy of titanium and zirconium (TiZr1317) is employed

due to the possession of better mechanical properties such as improved elongation and strength when compared to cpTi [55].

The cobalt–chromium (Co–Cr) alloys contain almost 60% of cobalt and carbon is often added to increase the strength of the alloy. Like titanium, chromium forms the chromium oxide layer on its surface that can resist corrosion. The major advantages of Co–Cr alloys are affordability and mechanical properties such as high elastic modulus and strength thereby allowing the production of fine implants with reduced dimensions. Given that chromium and cobalt are allergens, their application cannot be extended to fixed prosthodontics. They are increasingly used in European countries and it is seen as an alternative to nickel–cobalt alloy in the United States [56, 57].

1.2.2.2 Ceramics

Although metal and its alloys have proven to be durable in the oral environment, especially titanium having strong osseointegration characteristics, the limitations of metal-based implants are many—due to the ever-fluctuating pH of the oral environment, they tend to leach and release the metallic ions into the oral environment, which might trigger an allergic response in some individuals [58]. Previous studies show that on average 0.6% of the population tested show an allergic response to the metallic ions [59]. Furthermore, titanium implants have a lower aesthetic likableness as their distinct metallic colour is often visible through the mucosal tissue [60]. Reports of discolouration of the soft tissue around the region of the implant during the use of titanium implant have also been studied [61]. Thus, the need for novel breakthroughs in material science has provided an alternative to the metal-based approach—ceramics. One of the first ceramics that was used in oral implants was Alumina, but its weak mechanical properties have created a strong need for further research in the ceramic of dental implants [62].

The recent developments have shown zirconia to be a very suitable ceramic-based dental implant approach. Zirconia has excellent osseointegration and mechanical properties to titanium [55] and hence has already been adopted into the implant industry. Zirconia has additionally a lower plaque and bacterial adhesion as compared to titanium, which implies lower fouling tendencies of the implant [63]. It does not have the mucosa decolourisation, host immune reaction that is commonly found with titanium implants.

Hydroxyapatite is a calcium phosphate-based bio ceramic material that has garnered a lot of attention from the Dental Restorative Sciences. Hydroxyapatite is the same material that is known to make up natural teeth and bone. Hence, it has excellent biocompatibility and strong osseointegration characteristics. The major use case of hydroxyapatite in dental implantology has been in the form of coating over pre-existing implant materials [64]. This allows the implant to have a biocompatible surface characteristic while retaining the core mechanical structural integrity of the stronger materials. Since it is made up of the same material as the teeth, it is also subject to the demineralisation–remineralisation dynamics of natural teeth. A much more suitable alternative to hydroxyapatite would be fluorapatite, which is much more resistant to the demineralisation effects of low pH oral micro-environment [65].

1.2.2.3 Polymers

The discovery of synthetic polymers was one of the key innovative concepts of the twentieth century that has revolutionised the way of life in the twenty-first century. Although many polymers have been discovered to date, not all of them have strong relevance in the medical industry due to various factors like biocompatibility. Specifically, for dental implants, osseointegration is also a key criterion for choosing the material among many others, and with titanium having well-studied favourable osseointegration characteristics, it has continued to be the material of choice [66]. But the discolouration and allergic reactions still pose a challenge to be overcome. Among many polymers tried for dental implants, including PTFE, PSU, PMMA, one of the most promising polymers in the dental implant industry is PolyEtherEtherKetone (PEEK) [66, 67].

PEEK has many favourable characteristics and is already used in the medical industry in orthopaedic and vertebral surgery [68]. One of

the most common problems with titanium implants is the overloading of the bone via the implant through "stress shielding" [69]. The main cause of stress shielding is the difference in the moduli of elasticity of the materials at the implant junction. PEEK does not have the problem of stress shielding as the mechanical properties of PEEK are similar to bone, thereby reducing the risk of damage to the bone [70]. PEEK by itself has poor osseointegration as compared to titanium [71] but can be used to form composites or be used as a substrate for surface coating [72]. Through this, PEEK-composites and coated-PEEK implants seem to be strong contenders for the future of the implant industry [73]. Hybrid ceramic material with the dual certain-polymer network has been marketed by VITA (VITA Zahnfabrik, Germany) under the ENAMIC brand name. Such hybrid materials with properties from the best of both materials are the need of the hour.

1.2.2.4 Smart Biomaterials

The long-term understanding and the use of dental implants being "passive" is replaced with the concept of "active" biomaterials. In general, such "active"/"smart" materials are known to respond to stimuli in a controlled, reproducible and reversible manner [74]. The application of such smart materials ranges from household supplies to automotive components to biomedical applications.

The concept of "Smart" materials is itself inspired from the natural biological systems. It is well known that simple and complex biological pathways function in response to the stimulus from their environment [75]. The same principle is applied in the design and development of smart materials. Depending on the kind of external stimulus which can be physical (light, electric and magnetic fields, temperature, etc.), chemical (analyte concentrations, change in pH, biological fluids, etc.) and mechanical including stress and strain, the "smart" response is determined. The ability to reverse back to its original state is an important property of such smart materials.

The introduction of smart materials in dentistry was nickel–titanium alloys used for orthodontic wires. The properties of super elasticity and shape memory were utilised in root canal treatment. Furthermore, pH responsive composites are well explored as filler composites, which are self-healing in nature with enriched clinical performance. Smart ceramics mainly zirconia are well explored for their application as dental crowns [76].

With respect to dental implants, the smart response is often associated with surface functionalisation of the dental implants [77]. The primary aspect of such functionalisation is the ability to release antimicrobial compounds such as fluorides and antibiotics to prevent infection in the oral cavity. Nanotechnology is the first choice for such functionalisation purposes owing to its versatile properties. Nanoparticle based surface functionalisation proves advantageous in several aspects in terms of drug stability, minimal cytotoxicity, sustained drug release, improved healing and enhanced osseointegration. Researchers have developed active implant coatings with hydroxyapatite having antibiotics [78]. A sustained release of the antibiotics namely ciprofloxacin and gentamicin were observed. Recently, pH responsive titania nanotube arrays (TNT) which release silver nanoparticles was reported [79]. The TNTs were designed to release silver nanoparticles when the oral environment pH becomes acidic. It is well known that acidogenicity and aciduricity are one of the key virulence drivers which promote peri-implantitis. These properties are practically useful in preventing the biofilm formation on the surface of the dental implants. Even though stimuli responsive dental implants are still in the nascent stage of development, it is to be noted that such implants will prove to be useful on a longer run. While designing a "smart" dental implant, infection management, osseointegration and longevity should be the focus.

1.3 Conclusion

Dental implants are the one-stop solution to the missing tooth. Implant material and design form the basis for successful tooth replacement. This

chapter gives a brief outlook on the design and material aspects of the dental implants. The current approach to the dental implants holds the promise to restore the function of the missing tooth. But, with an improved understanding of the dynamic oral environment and oral microbiome, there is huge scope for the development of "smart" dental implants.

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