REVIEW ARTICLE

Corrosion and wear of titanium based dental implant connections: A review

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Abstract

Two-piece implant systems are widely used in contemporary dental implantology, in which an osseointegrated implant fixture is connected to an abutment that supports the definitive prosthetic restoration. The implant-abutment interface is susceptible to mechanical and biological complications because microgaps may permit the entry of oral fluids, microorganisms and biofilm. This review examined the degradation processes occurring at titanium-based implant-abutment interfaces, with particular emphasis on the combined effects of wear and corrosion within the oral environment. Most of the available investigations evaluated titanium-based implant and abutment materials under simulated oral conditions, particularly artificial saliva, using electrochemical and wear testing in combination with microscopic surface analyses. Relatively few investigations have focused on degradation of the internal connection surfaces following cyclic fatigue or repeated abutment removal. Available evidence indicates that micromovement between contacting components can increase internal surface wear. Although glycoproteins and biofilms may reduce friction by acting as boundary lubricants, they may simultaneously contribute to corrosion-related degradation. Repeated loading during mastication may consequently compromise the stability of the implant-abutment junction. Furthermore, the release of metallic ions and micro- or nanoscale particles generated through wear and corrosion may influence peri-implant inflammatory responses and contribute to pathological bone loss.

Keywords: *dental implant, corrosion, wear, titanium, peri-implantitis.*

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The oral cavity provides a particularly demanding setting for biomaterials because implant components are continuously exposed to mechanical loading, saliva, microorganisms, dietary substances and fluctuations in the local chemical environment. The clinical performance of implant-supported prostheses is therefore influenced not only by the properties of the constituent materials but also by implant design, manufacturing processes and conditions within the oral cavity.[1–3] Titanium and titanium alloys remain among the principal materials used for biomedical implants because of their favourable biocompatibility, capacity to support osseointegration, adequate mechanical performance during function and resistance to corrosion in physiological fluids.[4–8] Nevertheless, the corrosion resistance of titanium is not absolute. Exposure to acidic products generated by microbial metabolism and to fluoride-containing products, including some toothpastes and mouth rinses, may adversely affect the surface. Mechanical wear can also develop at the implant-abutment interface and the presence of acidic or fluoride-containing substances may intensify this degradation.[9,10]

Most dental implant assemblies comprise an implant fixture and an abutment that are joined by an abutment screw tightened to a predetermined torque. The appropriate torque depends on both the structural materials and the configuration of the implant-abutment connection. Because the abutment and implant are mechanically engaged rather than formed as a single continuous structure, a microscopic gap may develop at their interface. Such spaces can permit oral fluids, glycoproteins and microorganisms to enter the connection. At the same time, repeated contact between the opposing surfaces may produce both wear and corrosion.[11,12] Functional loading can induce small movements of the abutment, producing friction between the contacting surfaces and progressively increasing mechanical wear.[13]

With continued use, these processes may reduce the mechanical stability of the connection and promote the release of metallic ions and particulate debris into adjacent peri-implant tissues.[14,15]

The present review aimed to synthesize recent in vitro and in vivo evidence concerning the concurrent occurrence of wear and corrosion at titanium-based implant-abutment interfaces under simulated oral conditions and in the clinical environment. Particular attention was given to the influence of oral fluids, biofilms and mechanical micromovement on degradation processes. Understanding these interactions is relevant to oral rehabilitation, periodontology, implant dentistry and biomaterials engineering because degradation at the implant-abutment junction may have both mechanical and biological consequences.

Dental implant connections:

A range of implant-abutment connection configurations is currently available for implant-supported prosthetic treatment. Following osseointegration, the implant fixture and abutment are secured by an abutment screw tightened according to the torque recommended for the particular implant design and material combination. In broad terms, implant connections may be classified as external or internal hexagonal designs and Morse taper (MT) configurations. A precise interface between the implant and abutment is important for maintaining mechanical stability and ensuring appropriate transmission of functional forces. The accuracy of this fit is influenced by machining precision, component geometry and the mechanical characteristics of the materials involved.

An inadequate fit may increase the size of the interfacial microgap and allow greater movement of the prosthetic components during mastication. Imperfect seating or premature occlusal contacts may further increase the mechanical demand placed on the connection.[10–12,14] The external hexagon represented one of the earliest implant connection designs; however, clinical and laboratory investigations have identified abutment screw loosening as an important mechanical complication associated with this configuration.[6,13,16,17] Internal connection systems subsequently developed in several forms, including Morse taper, internal hexagon, octagonal and trilobed configurations.[19,20]

Morse taper connections have become widely used because the conical geometry allows close engagement between the implant and abutment. The intimate contact produced by this configuration has sometimes been likened to a cold-welding effect.[21] Comparative evidence has indicated greater mechanical instability with external hexagonal connections than with internal configurations.[6,23] The long-term mechanical condition of an implant-abutment joint can also be assessed clinically by determining removal torque at specified follow-up intervals.[24]

Despite the close fit achieved with conical connections, the interface may still permit the ingress of water, glycoproteins, acidic compounds and microorganisms when a microgap is present.[12,25] Glycoproteins, water and biofilm components can influence frictional behaviour at the titanium interface and may facilitate micromovement between the implant and abutment.[26] Bacterial leakage has been demonstrated across different implant connection designs, although Morse taper configurations generally provide a more effective fit than external hexagonal systems.[20,24,27,28]

Commercially pure titanium grade IV is widely regarded as a standard material for implant fixtures, whereas Ti-6Al-4V is frequently used for abutments and prosthetic components because of its favourable strength characteristics, including a reported tensile strength of approximately 940 MPa.[5,7] Despite these advantages, degradation of titanium-based components remains a concern because corrosion and wear may generate ions and particulate material that enter the peri-implant environment. Ceramic abutments, particularly yttria-stabilized tetragonal zirconia, have therefore been introduced as alternatives to metallic components. However, differences in mechanical behaviour between zirconia and titanium may increase stresses at the interface and contribute to mechanical complications.[8,19,22,29,30]

Condition of peri-implant environment:

The tissues surrounding an osseointegrated implant include the gingival sulcus, junctional epithelium and connective tissue, broadly corresponding to the soft-tissue components found around natural teeth.[21,32,33] The biological width around dental implants has been reported to comprise approximately 0.16 mm of gingival sulcus, 1.88 mm of junctional epithelium and 1.05 mm of connective tissue.[21,34] Collectively, these tissues provide a biological barrier that can limit the penetration of bacteria, microbial products, corrosive substances and externally derived particulate material.[31]

Despite these similarities, peri-implant tissues differ from periodontal tissues in the arrangement and attachment of collagen fibres.[28,31] Around natural teeth, connective tissue fibres insert into the root surface, whereas peri-implant collagen fibres generally run parallel to the implant surface. Obliquely oriented fibres have, however, been identified in association with Morse taper connections.[28] These anatomical differences may influence the biological response to microorganisms and foreign materials introduced around an implant.

Dental biofilm consists of a structured microbial community embedded within an extracellular matrix that incorporates components originating from food, saliva and microbial metabolism. Its composition and development are consequently affected by local nutritional and oral conditions.[2] Although implant surfaces and natural tooth surfaces differ in their chemical and physical characteristics, the fundamental processes involved in biofilm development appear to share several common features.[35,36] Surface roughness and chemical composition are important determinants of microbial attachment and subsequent biofilm formation.[2,37]

Biofilm can also modify the tribological behaviour of implant components by acting as a lubricating layer between contacting prosthetic surfaces and thereby reducing friction.[26]

Saliva contributes to protection of oral structures through its buffering capacity and its complex mixture of inorganic and organic constituents.[38] Nevertheless, salivary chemistry is dynamic and both intrinsic and external factors can alter its pH.[2] Under normal conditions, salivary pH generally ranges from approximately 6 to 7.7, although local variations may occur in response to biofilm accumulation, food intake and dietary or therapeutic agents.[39] The buffering capacity of saliva may become insufficient in localized areas with high microbial activity or reduced salivary flow. Consequently, acidic microenvironments with pH values of approximately 3 to 4 may develop around dense microbial populations or poorly irrigated implant-abutment interfaces, potentially creating conditions favourable for corrosion at the contacting surfaces.[1,2,37]

Degradation of titanium-based implant abutment connections:

Titanium and its alloys are extensively used in biomedical applications because they combine favourable mechanical, physicochemical and biological characteristics.[4,5] Their biological compatibility is closely related to the surface condition of the metal and, in particular, to the spontaneous development of a protective oxide film. A thin, amorphous and relatively low-crystalline titanium oxide layer forms naturally on the metal surface. This passive film is generally non-stoichiometric, has a reported thickness of approximately 1 to 20 nm and provides substantial protection against continued oxidation.[10,40,41]

Under simulated oral conditions, titanium-based materials generally demonstrate considerable resistance to corrosion.[42,43] However, this protection can be challenged by environmental factors such as low pH, fluoride-containing compounds, extracellular fluids and lactic acid produced during bacterial metabolism. These substances may alter or disrupt the protective surface film and consequently increase the susceptibility of titanium to corrosion.[3,10,37,44,45]

Various surface modification procedures are intentionally used to alter titanium surfaces in laboratory and clinical applications. These treatments are primarily designed to improve biological interaction with bone and promote faster or stronger osseointegration, thereby potentially reducing the period required for functional loading. The resulting biological behaviour depends substantially on the characteristics of the modified surface layer.[41] Anodization in acidic electrolytes, including sulfuric, nitric, phosphoric or hydrofluoric acid-containing solutions, can generate relatively thick and porous titanium oxide layers. Similarly, anodization in electrolytes containing calcium and phosphate may produce porous calcium-phosphate-containing oxide coatings.

The internal surfaces of implant and abutment connections are not necessarily smooth at the microscopic level. When two contacting surfaces undergo relative movement, disruption of the protective oxide film may occur. Direct interaction between the exposed surfaces can then produce adhesive wear. During mastication, cyclic loading generates repeated vibration and micromovement within two-piece implant assemblies, creating conditions conducive to fretting wear. The extent of material transfer and subsequent material loss depends on the hardness, strength and surface roughness of the materials forming the connection.[18,46]

Peri-implantitis caused by corrosion and wear:

Peri-implantitis is an inflammatory disease affecting tissues surrounding dental implants and is characterized by progressive loss of supporting crestal bone beyond the initial adaptive phase.[35,47,48] Epidemiological analyses have reported substantial prevalence of both peri-implant mucositis and peri-implantitis.[48] Evidence further suggests that degradation products generated at implant-abutment interfaces may contribute to biological disturbances in peri-implant tissues. Metallic ions and particles released through corrosion and wear have been associated with cytotoxic and inflammatory responses and may increase the susceptibility of gingival epithelial cells to microbial stimulation.[15,49]

Once released into the surrounding tissues, metallic particles and ions may be recognized as foreign material by the host immune system. Their presence can promote recruitment of polymorphonuclear leukocytes and macrophages and stimulate biochemical pathways associated with inflammation and bone resorption.[3,50,51] Metal ions such as titanium, cobalt, chromium, aluminum and vanadium may also interact with serum proteins, potentially forming metal-protein complexes capable of modifying immune responses.[49,52] Although the long-term systemic and local biological consequences of circulating metallic species remain incompletely established, characterization of these metal-protein interactions may help clarify their clinical relevance.

Experimental evidence has provided further support for a possible relationship between titanium release and cellular injury. One in vitro investigation reported cytotoxic effects, including necrotic changes, when gingival epithelial-like cells were exposed to titanium concentrations exceeding 11 ppm.[52] Increased titanium release has also been detected in peri-implant tissues following exposure to acidic fluoride conditions, such as sodium fluoride at pH 4.2, suggesting that fluoride can compromise the titanium surface when the protective capacity of salivary buffering is exceeded.[52] In approximately 75% of the evaluated samples, greater titanium accumulation was identified in particular tissue regions. Variation in host susceptibility may partly account for differences in the extent of tissue injury and disease progression.[47]

These observations are relevant to ongoing discussions concerning implant treatment in individuals with systemic or local inflammatory conditions, including diabetes. Management of peri-implantitis may involve either nonsurgical or surgical interventions, although no single treatment strategy has demonstrated consistent effectiveness across all clinical situations. Implantoplasty is one surgical approach in which exposed implant threads that are no longer surrounded by bone are mechanically smoothed.[50,53] Although this procedure may reduce surface irregularities and thereby limit biofilm retention, it can also generate or leave metallic particles on the surgical flap and surrounding tissues despite irrigation and chemical decontamination. Clinical observations have indicated reduced biofilm accumulation and subsequent adaptation of peri-implant tissues following treatment, but the long-term biological implications of residual metallic debris require further investigation.[50, 53]

Conclusion

A substantial body of in vitro research has investigated the mechanical and biological behaviour of implant-abutment connections, whereas comparatively few in vivo investigations have examined their performance under the complex and repetitive loading conditions encountered clinically and evaluated the corresponding response of the surrounding tissues. Laboratory models cannot fully reproduce the multifactorial environment of the oral cavity; nevertheless, controlled experimental systems allow individual variables to be isolated and their potential contribution to long-term degradation to be examined.

The mechanical behaviour of implant-abutment connections may initiate a sequence of interacting events in which microgap enlargement, micromovement, surface wear, corrosion and the subsequent release of metallic ions and particulate debris occur together. These processes may contribute to inflammatory changes in peri-implant tissues and, in susceptible circumstances, to peri-implantitis. Their severity is likely to depend on several interrelated factors, including implant design, material composition, the accuracy of the implant-abutment fit, manufacturing quality and patient-specific biological conditions.

The continuing development of new implant materials and connection geometries highlights the importance of understanding how these variables influence long-term clinical performance. At present, management of peri-implantitis remains challenging and neither nonsurgical nor surgical treatment has demonstrated uniformly predictable outcomes. Progressive mechanical and chemical degradation may ultimately compromise the integrity and function of an implant assembly. Therefore, the biological consequences of wear particles and the potential effects of corrosion occurring at micro- and nanoscale levels should receive greater attention in future investigations. Such research may support the development of improved materials, surface treatments and connection designs for more durable implant-supported prosthetic rehabilitation.

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