AI based Prediction Model and Influential Factors for Hypersensitivity in Dental Implants made of Ti alloys

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Abstract: This paper analysed influential factors governing the occurrence of hypersensitivity issues in patients with dental implants made of titanium (Ti) alloys. We presented tribological mechanisms affecting wear and fatigue in Ti alloys, outlined a method for identifying initial fatigue damage, and analysed AI-supported computational model to predict wear using experimentally obtainable input parameters. Wear debris from Ti alloy implant can trigger immune response. Fatigue cracks, driven by the material's behavior under long-term cyclic loading and harsh dental conditions, are identified using Small Crack Theory, an essential procedure for critical small-scale structures like Ti alloy implants. Various factors influence the formation of nano/micro-cracks and wear debris in implants, while computational models and emerging IoT-based in vivo sensing offer valuable tools for predicting loading regimes and enabling real-time, customised implant design.

Keywords: Dental Implants, Hypersensitivity, Wear, AI model, Small Crack Theory

1. Introduction

Titanium (Ti) alloys are commonly used in dental restorations [1], [2], but low wear resistance limits broader use. Hypersensitivity to alloying elements is another concern [3]. Tribological and fatigue properties [4], [5] affect implant durability. Computational models and AI tools [6] help material characterisation. This paper explores hypersensitivity risks in Ti restorations, influential factors and AI-based predictions.

2. Hypersensitivity reactions to titanium and titanium alloys

Hypersensitivity to titanium implants is rare but can cause serious health issues. It involves an exaggerated immune response to metal ions, likely triggered by alloying elements such as aluminium (Al), vanadium (V), and nickel (Ni) [1]. In predisposed patients, ions from wear or corrosion may form antigenic complexes [4], leading to peri-implant diseases, bone loss, delayed healing, or systemic effects like dermatitis and chronic fatigue (Figure 1).

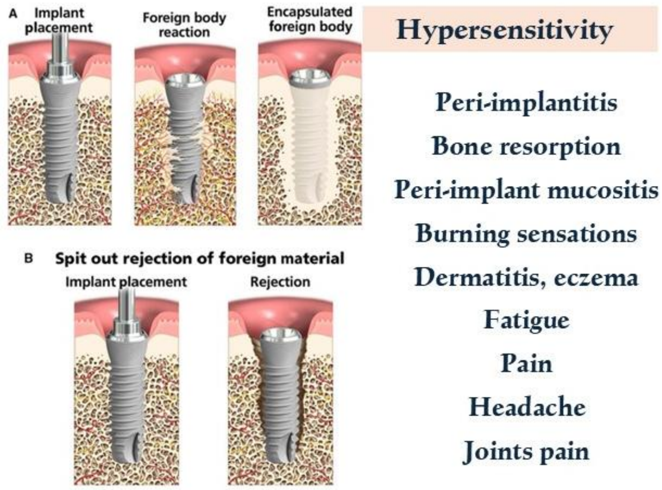

Figure 1. Manifestations of hypersensitivity to dental implants (left image copied from [2] Under a Creative Commons license CC BY 4.0)

Hypersensitivity to dental implants may present as persistent peri-implant inflammation, pain, burning sensations, implant failure, fatigue, or skin changes. Type IV hypersensitivity is typically assessed with patch tests for metals like titanium and nickel; LTT, imaging, biopsy, or histology may also aid diagnosis. Management can include implant removal [3]. Though rare, such reactions affect implant success, highlighting the importance of diagnosis, material choice (with cpTi showing slightly better long-term biocompatibility), and individualized care, especially for allergy-prone patients.

3. Tribological mechanisms

Tribological mechanisms in dental implants made of titanium (Ti) alloys involve friction, wear, and human saliva lubrication at the implant-tissue or implant-prosthetic interface. Predominant wear modes include abrasion and adhesion at interfaces, e.g., implant versus bone or prosthetic components, with fretting-corrosion as dominant failure mechanism. Corrosion triggered wear releases titanium particles and ions [4], which can be internalised by macrophages and trigger inflammatory responses, contributing to peri-implantitis and implant loosening over time. These mechanisms influence implant longevity and performance, as Ti alloys can experience wear due to mastication forces during the act of chewing, leading to particle release and potential inflammation. Surface oxide layers (like TiO_2) can act as solid lubricants, somewhat reducing friction yet still vulnerable to mechanical degradation. Surface treatments and coatings are often used to enhance wear resistance and reduce friction.

4. Fatigue mechanisms

Fatigue damage can cause wear in dental implants, with failure occurring either from static loads exceeding material strength or from damage accumulation due to cyclic loads like chewing [5]. These cyclic stresses degrade mechanical properties over time by initiating and growing micro-cracks, leading to fatigue failure. Fatigue in dental implants progresses through stages of initial damage accumulation, crack initiation, crack propagation, and ultimately, structural fracture.

Structural damage, shown by decreased material stiffness, is crucial for inverse optimization tasks like fatigue assessment and lifetime prediction of dental implants, where damage and wear localization is the first step in failure prevention. This procedure numerically evaluates implant durability in three phases: initial fatigue analysis (S-N approach), safe-operation and fracture prediction (Kitagawa-Takahashi diagram), and fatigue lifetime assessment through crack growth simulation using Paris' law. The Fatigue-to-Fracture Approach for integrity assessment is implemented in FEA post-processing and involves Stress-Based Fatigue Estimation, Safe-Operation Assessment, and Residual Lifetime Prediction for Fatigue Crack Growth; for damage like wear and hypersensitivity in dental implants, only Stress-Based Fatigue Estimation and Safe-Operation Assessment are needed.

5. AI model for prediction of wear rate

Pantić et al. [6] developed an AI model using an artificial neural network (ANN) optimized by a genetic algorithm (GA) to predict the wear rate and friction coefficient of lithium disilicate dental ceramics. Schematic of that AI model that can also be used for other materials like Ti alloys, is shown in Figure 2.

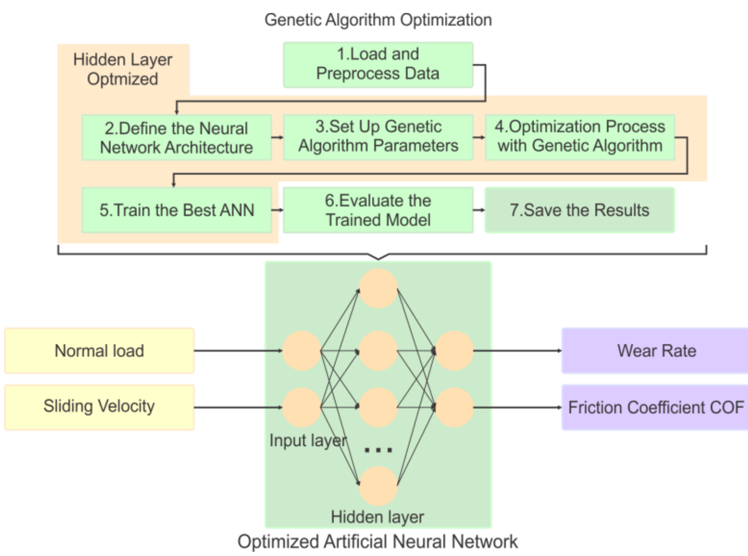

Figure 2. Visual representation of the artificial neural network (ANN) optimization process using genetic algorithm (GA)

The seven-step GA process included data preparation, ANN design, parameter tuning, optimization, training, evaluation, and model saving. Using load and sliding velocity as inputs, the ANN correlated well with tribological outcomes, reducing experimental needs. The model outputs are wear rate and friction coefficient.

5.1 IoT technologies for advanced sensing in dental implants

The Internet of Things (IoT) connects devices and sensors to the Internet for real-time data collection and analysis, supporting informed decisions through integration with AI, big data, cloud computing, and cybersecurity. IoT technologies for advanced sensing in dental implants integrate miniaturized sensors and wireless communication systems into the implant structure. These smart implants can monitor conditions such as bite force, temperature, pH, and inflammation, transmitting real-time data to external devices via Bluetooth or RFID. This enables early detection of complications like infection or implant failure, supporting personalized dental care and improving long-term outcomes.

6. Conclusions

Allergic reactions caused by degradation mechanisms in Ti alloys, associated with certain alloying elements, are rare but still present a significant challenge for dental restorations. The most influential factors include tribocorrosion, fatigue-induced cracking, and subsequent implant failure. Fatigue damage and AI-based simulations provide faster, more efficient material property predictions than traditional experiments.

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