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Review

A review of improved fixation methods for dental implants. Part II: Biomechanical integrity at bone–implant interface

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ABSTRACT

Purpose: The purpose of this article is to review the mechanical requirements of the tissue–implant interface and analyze related theories.
Study selection: The osseointegration capacity of titanium implants has been investigated over the past 50 years. We considered the ultimate goal of osseointegration to which form a desirable interfacial layer and a bone matrix with adequate biomechanical properties.
Results: Occasionally, the interface comprises porous titanium and bone ingrowth that enables a functionally graded Young's modulus, thereby allowing reduction of stress shielding. However, the optimal biomechanical connection at the interface has not yet been fully clarified. There have been publications supporting several universal mechanical testing technologies in terms of bone–titanium bonding ability, although the separation of newly formed bone quality is unlikely.
Conclusions: The understanding of complex mechanical bone behavior and size-dependent properties ranging from a nano- to a macroscopic level are essential in the biomechanical optimization of implants. The requirements of regenerated tissue at the interface include high strength, fracture toughness related to ductility, and time-dependent energy dissipation and/or elastic–plastic stress distribution. Moreover, a strong relationship between strain signals and peri-implant tissue turnover could be expected, so that ideal implant biomechanics may enable longevity *via* adaptive bone remodeling.

Contents

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1. Introduction

Orthopedic and dental titanium implants must function as rigid osseous anchors. The biomechanical integrity of implants comprises the mechanical behavior of implant materials, surface-induced bone micromechanics, and adaptive bone remodeling.

A diagram of the events presumed to occur at the bone–implant interface is shown in Fig. 1 [1,2]. Once implants are placed with intimate apposition of bone at the surgical site, the immediate response at the interface involves adsorption of tissue fluid and cell binding proteins [1,2]. This critical gap between host bone and the implant surface is likely filled by newly formed bone and a non-collageneous protein-rich cement line [3–5]. Early studies indicated that osteocalcin, osteopontin and bone sialoprotein, as well as certain plasma proteins such as α_2HS-glycoprotein, predominate in the cement line [3,4]. Although this protein layer may be responsible for biological bonding to the titanium surface, the inherent mechanical weakness of the protein layer needs to be further stabilized by bone–implant mechanical interlocking [6,7]. Nevertheless, there have been a range of biomechanical issues with titanium implants, such as reduced shear load-bearing properties associated with poor mechanical interlocking at the interface [8,9].

Implant surfaces have been developed by means of several engineering processes, such as grid-blasting, which involves coating the titanium substrate with sintered beads or particles to create a porous layer [10–13], so that the micro–nanoscale external surface textures may address the aforementioned biomechanical issues. Aside from the mechanical interlocking achieved by surface processing parameters, the mechanical requirements of regenerated bone at the interface also need to be addressed. As a consequence of unfavorable osseointegration processes, the implant surface often generates fibrous woven bone and is not replaced by mature lamellar bone [14–17]. Therefore, new biomaterials for bone regenerative purposes, such as titanium implants, need to feature a surface that promotes osteogenic differentiation and proper mineralization during the initial integration stage.

The biomechanical integrity of titanium implants has been evaluated based on bone–titanium contact and bone volume fraction by means of histological observation [18,19] and micro-computed tomography [20–22], respectively. However, there has been a mismatch between such observations and the mechanical stability of titanium implants [23,24], allowing us to assume that the mechanical properties of regenerated bone are not entirely associated with observed bone micro-histology or densitometry.

Understanding of basic mechanical properties for titanium and intact bones are indispensable prerequisite so that scientists will begin to adjust the concept of surface modification (characterization) techniques for titanium implants, whether such concepts achieve the biomechanical integrity at bone–implant interface. Bone is a complex hierarchical tissue with different structural levels, namely cortical and trabecular bone at the macroscale, Haversian osteons and lamellae at the microscale, and hydroxyapatite crystals and collagen fibers at the nanoscale [25,26]. The macro–microscale structural variations of bone tissue compromise a precise mechanical evaluation. In this respect, nanoscale mechanical testing technologies enable a measurement of bone mechanical properties at a material level [27] so that more accurate case simulation, according to three-dimensional finite element models, is possible. Moreover, an accurate bone remodeling algorithm in the peri-implant region (adaptive bone remodeling) would be obtainable as bone morphology often relates to the stress-strain response associated with the bone mechanical properties at material level [28,29].

2. Basic mechanical and fatigue properties of titanium

The mechanical mismatch between host bone and metallic implants has been a longstanding concern. For instance, the elastic modulus of bone is presumed to be 10–30 GPa, while just around 100 GPa for pure titanium, although titanium and its alloys have elastic moduli less than 50% that of cobalt-chrome (approximately 230 GPa) [30]. In this context, contacted bone is often inappropriately stress shielded, and hence, implants lose supportive tissue at the peri-implant region over time [31]. Implant elasticity and the long-term bone integrity associated with adaptive bone remodeling are strongly related, as this has been well-established in a range of animal model experiments and clinical trials [32–36]. The mechanical properties of titanium previously reported are summarized in Table 1.

Besides its usage in implants, titanium is mainly used as a hard tissue substitute; hence, increased fracture toughness is the basic requirement. In this respect, Ti–6Al–4V alloys have been widely applied as biomedical materials, despite the fact that the toxic element in this alloy is concerning [37]. Meanwhile, β-type titanium alloys are composed of non-toxic elements with a greater strength and toughness balance than that of $\alpha + \beta$ alloys, such as Ti–6Al–4V [37]. The elastic moduli of β-type titanium alloys are between 55–85 GPa, resulting in elasticity that is much greater than pure titanium and $\alpha + \beta$