BIOMATERIALS, BIOMECHANICS, TISSUE HEALING, AND IMMEDIATE-FUNCTION DENTAL IMPLANTS

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KEY WORDS

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Selected factors and opinions are reviewed specific to immediate function of dental implants in terms of biomaterial and biomechanical properties and how they might influence postsurgical tissue healing. Comparisons are made among plate, rod, and screw vs plateau, finn, and porous geometry endosteal dental-implant designs with and without alterations in device body-surface microchemistry and microtopography. Available information introduces more questions than answers, and recommendations are made for ongoing studies of bone responses specific to the implant fit and fill parameters focused on the kinetics of postsurgical osteotomy healing and applied loading. The clinical literature supports opportunities for immediate function; however, proposals about pathways for bone healing need further investigation. The current trends within the discipline of implant dentistry offer opportunities to reevaluate current vs previous immediate-function systems.

INTRODUCTION

A number of considerations and issues continue to exist regarding the clinical aspects of treatment when reconsidering dental-implant systems intended for immediate function. The various decisions and selections reside with the dentist or team providing the clinical procedures; however, from the viewpoint of those involved in the biomaterial and biomechanical disciplines, at least 4 areas should be interrelated and appropriately evaluated before selecting any given dental-implant system.

The first area is the functional requirements within the overall patient profile, which should be fully assessed at the outset. Any abnormal considerations such as clenching or bruxing could influence the fundamental biomechanics of the implant and intraoral restorative selections. Another consideration is the quality and quantity of the available tissues, which is equally critical, especially the bone and the zone of attached gingiva.

A second area is related to implant design. In each situation certain implant types, shapes and sizes, locations of connections, and the restorative scheme might be more or less advantageous. Therefore, the selection of the implant system (eg, endosteal, transosteal, subperiosteal) should follow the patient profile. A related issue is how the construct best satisfies the surgical, restorative, and maintenance aspects of care. Within the endosteal systems, which will be the focus of this paper, a central consideration will be the fit and fill of the available anatomical dimensions of the craniofacial bones. In each situation, opportunities to minimize the trauma of the surgical procedures and the ability to maintain cleanliness and sterility relates directly to the system selected. From a biomechanical perspective, attempts are normally made to maximize fit and fill while keeping the procedures as simple as possible.

A third area of consideration, about selection, is the biomaterial or biomaterials of construction plus the regional surface chemistry and topography where the implant and abutment systems come into contact with bone, gingival tissues, and the environment of the oral cavity. Again, the location (sub-, per-, or supragingival) and type (monoblock, external or internal hex, morse taper, slide-lock, etc) of abutment connection must be determined at the outset. Again, this would need to be coevaluated along with the crown and bridge selection (the fourth area, ie, the prosthodontics) in terms of type and timing for esthetic and functional (loading) considerations.

Most critically, these decisions that must be made at the time of initial selection determine the subsequent analyses of how biomaterial and biomechanical properties might be correlated with assessments of clinical outcome.

Related to assessments of biomaterial and biomechanical properties, it seems worthwhile to review some definitions. As an outgrowth of multidisciplinary meetings held in the 1980s, definitions of a biomaterial and biocompatibility were published as follows.[1]A biomaterial is defined as a nonviable material used in a medical device, intended to interact with biological systems, whereas biocompatibility is defined as the ability of a material to perform with an appropriate response in a specific application.

A number of interpretations exist for immediate function of dental implants. In this short paper, immediate function will be taken as intraoral restoration of the crown and bridge prosthodontic components at the time of endosteal implant placement without restrictions specific to immediate loading (fully functional teeth). The term *fit and fill* is specific to the endosteal implant body and the size and shape that maximally fits and fills the bone osteotomy within the dimensions of the host anatomy for the system selected.

From an historical perspective, the basis for many of the ideas, concepts, and proposals included in this paper have come from the following. Our group has followed a central theme of laboratory, laboratory in vivo, and human clinical research focusing on interfacial interactions and transfers of biomaterials (elements) and biomechanics (forces). Also included have been in vitro analyses of explanted devices and tissues (retrieval and analysis), the properties of tissues (especially bone), computer-based Finite Element Models and Analyses (eg, FEM/FEA), concepts of rigid fixation in medical orthopaedic surgery, and classic dental materials (metallics, ceramics, polymerics, mechanical mixtures, and composites).

The current paper will provide opinions about the interrelations among basic and applied properties from biomaterials, biomechanics, and tissue healing and how these assessments of properties may be used to evaluate opportunities and limits of immediate-function dental-implant systems.

MATERIALS AND METHODS

A number of sources have been used for the development of this paper. Over the past 3 decades, these have included (1) discussions with practitioners of dentistry and medicine; (2) more than 200 laboratory and laboratory in vivo studies as Master of Science (MS), Doctor of Philosophy (PhD), resident, and undergraduate projects; (3) laboratory studies of explanted and in situ (cadaveric) implant devices; and (4) information from professional conferences and the published literature. Any materials included that have not been formulated within our program will be referenced to the source. The approach will be to proceed from simple to more complex models and to provide bioengineering calculations based on listed assumptions. A theme over time has been hypothesis-driven research, and the reader is referred to "student" studies specific to theses (MS) and dissertations (PhD) and related publications to obtain more details. In most situations, the basis of study has been to establish cause-and-effect relationships with intent to provide translational information from the laboratory (the bench) to the clinic (dental chairside or medical bedside).

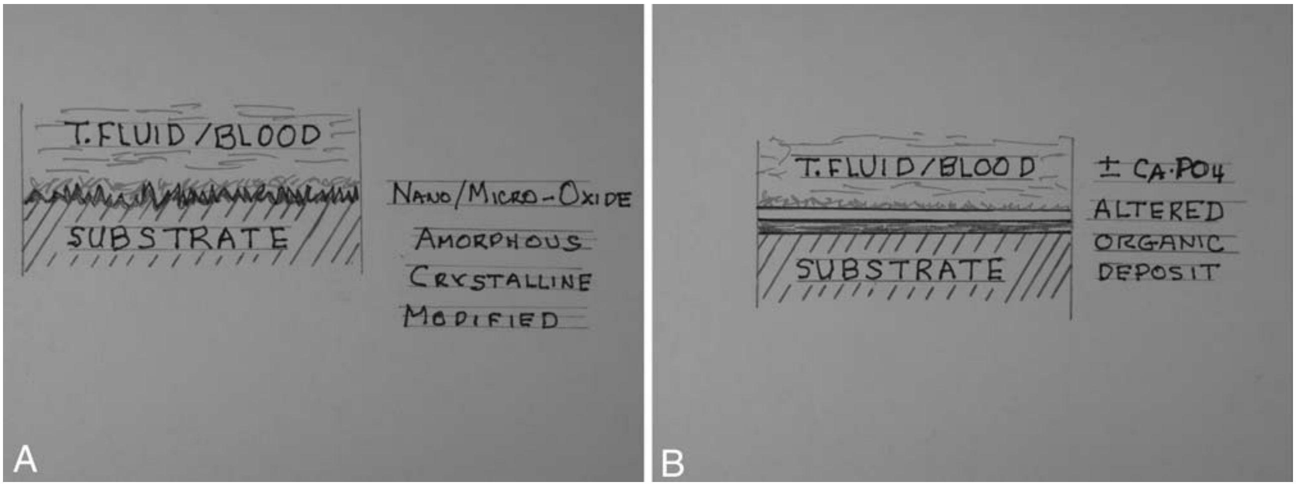

FIGURE 1. Schematics of biomaterial surface-tissue fluid interactions: prebone integration. (A) Altered nano- and microtopography. (B) Nonmetallic coatings.

RESULTS AND DISCUSSION

Biomaterial consideration

The many different synthetic biomaterials that could have been selected for the construction of the more commonly available and utilized endosteal dental implants have evolved from many to metallic titanium (Ti) and alloys and ceramic or ceramic-like calcium phosphate compounds (HAs) as coatings. The more common surfaces include conditions of as-machined metallics, additions to metallics such as Ti or calcium phosphate plasma sprays (TPS or HA), or reductions (blasted, etched, or combinations) of the metallic surfaces.[2–8] The bulk material selection of Ti or alloys of Ti (Ti-Al-V or Ti-Al-Nb)[9–11] is normally made on a basis of physical and mechanical property criteria. These criteria include tensile, fracture, and fatigue strengths; ductility; and toughness plus the bulk structural modulus of elasticity.

The biomaterial surface conditions related to chemistry and topography, usually at the microdimension level, are often associated with the intent to prefabricate the surfaces for additions of organic-type morphogens or mitogens or chemical modifications intended to directly influence tissue healing.[12–15] Schematics of possible interactions are shown in Figure 1. Considerable interest has been specific to biomaterial surface microtopographies with or without added oxidation through anodizing. These procedures are provided in part to influence the initial interactions with the organic deposits from blood and tissue fluids plus subsequent tissue development.[16–20] Some studies support that microtopography directly influences organic (primarily fibrin) deposits and the local healing characteristics of bone. It should be remembered that this general idea was one of the initial central themes of osseointegration, where nanopits along as-machined Ti surfaces were proposed to directly influence the attachment of osteoblasts.[21]Other surface micro- and nanotopographies have been introduced to influence soft- and hard-tissue integration. For example, the early microtopographies of "coined" Ti for some plate-form endosteal implants were fabricated and finished to control implant biomaterial properties and to replicate a surface that would be similar SEM images of dental cementum.[7]

Considerable laboratory in vivo and human cadaveric specimen studies support that a unique difference exists for Ti oxide vs hydroxyapatite implant surfaces. Schematics of these dif- ?3 ferences have been previously published.[22,23] Other studies support that the plasma-sprayed calcium phosphate coatings decrease in thickness with time in vivo, and that about 5 μm of thickness is lost within the first weeks of implantation into trabecular bone sites.[24,25] If one assumes a dental implant with an average surface area from 100 to 400 mm^2, and if this transfer was for an average-density calcium phosphate biomaterial, approximately 0.6 to 1.2 mg of calcium and phosphorous (assuming dissolution) would be transferred to the local interfacial region. One could ask if this dose-response-time relationship would directly influence bone healing. One could hypothesize "yes"; however, several studies have reported on the capacity of the in vivo bone environment to liberate and supply any needed calcium and phosphorous ions for normal bone healing.[16] The question of local influence (altered microchemistry) remains to be fully answered, and clinical experience "reports and measurements" of more rapid stabilization of hydroxyapatite-coated dental implants could be qualitatively related to a localized "controlled delivery process."[26] Thus, is the best environment for a dental-implant interface associated with altered microtopography or microchemistry, specific to more rapid bone healing and maturation? Additionally, the role or roles of simultaneous force transfer must be taken into consideration and tested under controlled experimental conditions to obtain nonconfounded results. With the move to immediate-function systems within the clinical community, this may be an academic question to be determined with time and experience.

Biomechanics and implant design

The focus of this section on the biomechanical aspects of dental-implant designs will consider relative differences among endosteal devices under categories of plate, rod, and screw vs plateau, finn, and porous systems. Considerable experience, theory, and practice have been associated with the macroscopic features of implant body shape, size, and relative orientations and positions of implant body geometry.[2–8,12,13] Many designs have been introduced to better optimize bone and soft-tissue loading under conditions of applied axial and oblique direction pushing (compression), pulling (tension), and twisting (torque). In general, these macroscopic geometric characteristics are used to distribute applied forces under conditions of compression, tension, and shear loading along the device to tissue interfaces (the biomechanically active surface areas). One might ask what roles could microroughness play in terms of both biochemical and biomechanical transfers to the regional interfacial tissues. With a simple model where individual uniformly dispersed surface features are 1- × 1-μm squares that are 1-μm deep (apex to base as a uniform pyramid), the unit increase in surface area would be approximately 2.5 times. Electrochemistry studies have shown that ionic transfers from surfaces of Ti oxide on Ti and Ti alloy increase in proportion to surface area.[27–29] Also shown was that thickening of the oxide by anodizing can decrease these type transfers by more than 2 times.[30] Additionally, these transfers are in the part-per-billion magnitudes, and electrochemical and tissue culture studies have not raised concerns about biocompatibility for these low-magnitude ion exchanges.[31–33] However, in terms of calcium phosphate compounds along implant surfaces, these type magnitudes of surface area change could possibly influence the local interfacial transfers. In general, SEM studies show that most plasma-sprayed calcium phosphate coatings demonstrate a rough, irregular, and cracked microtopography.[34]

Another significant consideration relates to the intraoral restorations. The abutment design, location, and type of connection between the abutment and the implant body and the prosthodontic aspects of occlusion[2] determined, for the most part, the load magnitude and load direction specific to each construct. In this regard, multiunit splinting, especially in irregular angle (unit-to-unit) and cross-arch configuration, tends to dissipate the forces into multiaxial orientations (a combination of bending and torquing moments).[35–37] Most critically, the timing of significant intraoral loading plus the prosthodontic occlusional scheme determines the forces to be transferred and dissipated during the tissue-healing period.

Tissue healing and surgical site

Several studies have described the sequence of interactions and reactions during normal and implant-related tissue healing.[12,13,38] This sequence is reemphasized schematically in Figure 2, where some tissue-healing events are considered over time and expressed as the log of time in seconds. After the initial organic depositions (in less than 1 second), the sequence normally follows periods of cellular infiltration and inflammation, vascularization, the initial formation of fibrocartilage and osteoid, and the events of initial (modeling) and subsequent maturation (remodeling) of bone. Under normal bone-healing conditions, these events extend over 5 or more orders of magnitude, from milliseconds to years (100 000s of seconds). Considerable research effort has focused on how to decrease 1 or more of these time sequences, especially the osteoid-to-remodeling interval. One aspect has been the concepts of rigid fixation and minimization of the fibrocartilage-osteoid-trabecular bone-healing sequence within the area of long-bone fracture healing.[39] Studies in orthopaedic surgery have shown that primary fixation with rigid metallic hardware can result in conditions of "primary healing"

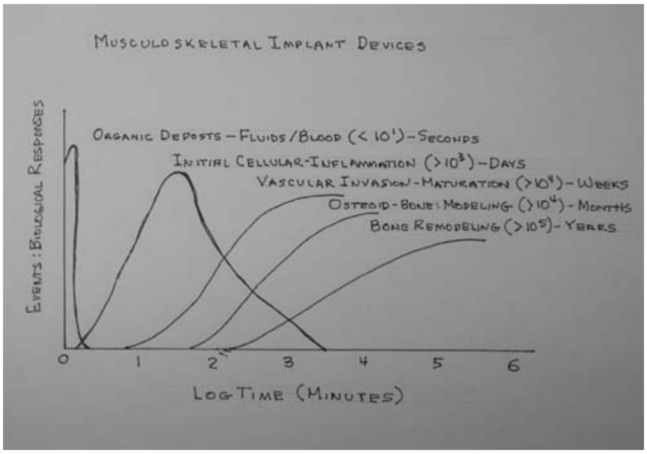

FIGURE 2. Schematic of biological events associated with bone healing expressed as a function of log times (in seconds). The kinetics of bone healing under normal conditions are shown.

of long bone. This situation is somewhat related to the "passive healing" concept of implant dentistry. This assumes that the orofacial bones (mandibulae and maxillae) transfer some loads from the bone to the endosteal implant during the passive-healing period. At first this seems probable, although the details of the interrelated biomechanics have not been published.

Under the conditions of these concepts, the healing aspects of different dental-implant body designs and the associated osteotomies will be considered. For example, when an osteotomy is developed for a plate, rod, or screw design, the site is normally intended to be fitted and filled by the implant with only microgaps between the implant surfaces and the surgically cut and taped prepared bone. This space subsequently heals through appositional growth of bone where the growth in the region is from the bone side. Some studies propose that the dynamics of this process may be altered by controlled alterations in implant surface microtopography or implant coatings (calcium phosphate compounds).[14,17,22,23,40–42] These conditions are proposed to result in bone filling simultaneously from the bone-to-implant and implant-to-bone directions. If confirmed, this could decrease the time to bone remodeling and increased mineralization. A related biomechanical question is, when the bone fills the open spaces between the implant and the original bone surfaces, how strong is the new bone before reaching a fully mineralized condition? A significant need exists for controlled studies specific to the roles of immediate loading and micromotion within the interfacial zones.[43] These studies would need to be specific to the surgical, fit and fill, and restorative aspects of clinical procedures. Recent clinical studies support opportunities for healing under conditions of immediate function.

In contrast to the systems described above, plateau, finn, and porous designs are often placed into osteotomies where the site is fitted (often pressed-in conditions) to the outer perimeter of the implant body section. Previous studies have demonstrated that bone healing for these type systems follows a vascularization and filling sequence that includes woven (callus-like) bone.[13,16,41] This sequence would again depend on the implant microsurface conditions and if the healing were uni-or bidirectional. However, the process would be very different from the fit and fill (plate, rod, screw) designs. One could propose that this evolution and maturation of fibrocartilage, osteoid, and trabecular bone would also provide relatively rapid biomechanical stabilization. Once again, clinical studies support that these type designs are appropriate for immediate-function systems.[44,45] In this regard, the plate-blade and other designs were introduced as immediate-function systems.[7,46]

The discussion above introduces more questions than answers. However, once again, an opportunity exists to reevaluate the biomaterial and biomechanical aspects of healing and microstrain transfers along biomaterial-to-tissue interfaces. Some years past, the idea of progressive loading was introduced to better optimize the clinical restorative aspects of clinical restoration of implant systems.[47] With the reintroduction of immediate function to the dental-implant discipline, the opportunities for reassessments of previous concepts is strongly recommended. The relative value of hard- and soft-tissue integration and the limits of restorative treatments to provide an esthetic and functional oral environment seem most worthwhile. A combination of in vitro and in vivo laboratory and human clinical trials is therefore proposed.

SUMMARY

A number of ideas and questions have been presented specific to dental-implant biomaterials, biomechanics (designs), and tissue healing as related to the reintroduced concept of immediate-function (loading) systems. The decisions and selections of "what and when" reside with the clinical professionals. To better optimize the more recent concepts and systems, a multidisciplinary approach including in vitro laboratory and in vivo clinical research is proposed. A significant opportunity exists to compare the plate, rod, and screw with the plateau, finn, and porous designs and how the process of tissue healing is related to basic differences in implant fit and fill of the osteotomy sites. Additionally, the roles of altered-device surface chemistries (with or without coatings of calcium phosphates and active biological factors) could be compared with differences in surface microtopographies (as machined, addition, and reduction). Related studies could then address factors associated with immediate loading and possible advantages or disadvantages of force transfers as microstrain within the interfacial zones. The current evolution of the dental-implant discipline is most exciting and challenging. Clearly, the overall intent is enhanced patient care and ever-improvements in the success ratios for a broader range of patient conditions.

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