Assessment of Bone Implant Micro-structure

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Abstract

One of the main problems in the development of implants is the handling of implant mechanical characteristics in a way that ensures both structure durability and an optimum load patterns in surrounding tissues. A significant challenge in implantology is the design of biomaterials that actively promote functional regeneration of the host tissue while avoiding undesirable tissue response. This paper reviews evaluation of integration of bone implant interface.

Keywords: Implant, osseointegration, interface and tissue.

Introduction

Osseointegration, which histologically is defined as "direct bone-to-implant contact" is achieved to provide firm fixation of a dental implant within the alveolar bone and may promote the long-term success of dental implants (Franchi et al., 2005; Joos et al., 2006). The process of osseointegration involves an initial interlocking between alveolar bone and the implant body (primary implant stability), and later biological fixation through continuous bone apposition (contact osteogenesis) and remodeling toward the implant (secondary implant stability) (Bergmann et al., 2001).

Stiffness of the tissue-implant interface and implant-supporting tissues are considered as the main determinant factors in osseointegration. While the structure and heterogeneity of mineralization affect the stiffness of bone (Hoshaw et al., 2006), Johansson et al. demonstrated that biomechanical testing may be a more suitable indicator to evaluate the dynamic changes of osseointegration than any single structural parameter. However, biomechanical testings such as push-out and pull-out measurements is destructive and only available for preclinical use (Berzins et al., 1997). Therefore, the clinical value of non-destructive measurements, such as resonance frequency analysis (RFA) or damping characteristics (Periotest®) techniques, are still limited due to the lower resolution and higher variability during measurement. Thus, it is still of interest to develop effective approaches to functionally assess osseointegration for the evaluation of peri-implant wound healing.

Assessment of Bone Implant Micro-structure

Bone microstructure has usually been assessed by obtaining samples by biopsy and analyzing them with conventional histomorphometric methods. Improvements in high-resolution image acquisition systems have enabled non-invasive assessment of bone morphology and a more precise 3D evaluation by means of "virtual biopsies", permitting bone assessment in regeneration or remodeling processes. This imaging technique can be used for the biomechanical analysis of bone and for studies of regeneration techniques, biomechanics in bone physiotherapy and periimplant bone healing. The interaction between mechanical signals and biological processes in cells and tissue is studied in mechanobiology. Mechanical load may influence cell proliferation, differentiation and metabolism and therefore have a crucial role in live tissue growth, adaptation, regeneration, and tissue-engineering. Mechanobiology combines experimental (histological techniques in vitro and in vivo models) and computational techniques (mathematical and computer models) to create interactions between mechanics and biology. Van der Meulen described skeletal mechanobiology as "the science that studies the mechanical forces that modulate morphological and structural fitness of skeletal tissue, i.e. bone, cartilage, ligament and tendon". These developments have led to major advances in bone mechanobiology in recent years by enabling models of structure - allowing analysis of the effects of physical force in the complex bone geometry. In mechanobiology, permitting detection of bone formation and implant synthesis after applying different mechanical forces, and a novel imaging technology revealing the micro- and nanostructural characteristics of tissue. Such high-resolution images can serve as a source of data for generation Finite Element (FE) computer programs, providing a more accurate simulation of different biomechanical load situations compared with conventional FE.

Finite Element Method

The Finite Element Method (FEM) is a computational numerical analysis technique used for determining the stresses and displacements through a predetermined model. The method was introduced in the 1960s in the aerospace industry and was applied in dentistry in the early seventies. With use human teeth are weakened by caries, abrasion, malocclusion and trauma. In an attempt to better understand the stresses in the tooth, a variety of methods have been used to predict tissue response to loads. These include theoretical (mathematical) techniques, photoelastic systems and laser holography measurements. However these techniques have the disadvantage of only measuring surface stress, while having the added problem of readily being applied. The new validated systems as judged by the current standards. The Finite Element method can be applicable to the problem of the stress strain levels imposed in complex structures. This method also has the potential of converting mathematical modelling in a real object of complicated shape and different material.

Applications of Finite Element Method

- Finite element analysis has been applied to the description of form change in biological structures (morphometrics) particularly in the area of growth and development.
- Finite element analysis as well as other related complimentary techniques such as the macro-element and the boundary integral equation method (BIE) is useful for the assessment of complex shape changes.
- The knowledge of physiological values of alveolar stresses is important for the understanding of stress related bone remodelling and thus provides a guideline reference for the design of dental implants.
- Finite element method is also useful in structures with different material properties and potentially complicated shapes such as dental implants.
- To study stress distribution in teeth in implants with different designs.[1]

There are some limitations to the creation of FE-based models. Bone stress and deformation depend on the properties of the material. FE studies have established different elasticity (Young's modulus) for cortical and cancellous bone. This limitation of not being able to distinguish between different degrees of bone mineralization is being overcome by means of conebeam radiation images. Because the sample does not need to be destroyed. µCT (micro-computed tomography) imaging is powerful tool to assess bone adaptation, allows to study of dynamic loads, examine crack propagation, the start of structural failure and accumulation of damage.

Dental implant osseointegration involves a continuous remodeling process that depends on the biomechanical loads applied to the maxillary-implant-bone complex. The biomechanical properties of the bone are governed by both its material content and its micro-architecture.

Biomechanical Causes of Peri-Implant Bone Loss : In threaded implant designs, maximal of high stress concentration develop in bone during implant loading especially adjacent to the superior most thread. This can lead to bone microfractures and resorption of the adjacent bone or formation of new bone formation preventing the reestablishment of osseointegration. Fibrous tissue forms if local strains are greater than a critical level; continued implant loading can result in progressive bone microfracture & resorption along the length of the implant resulting in implant loosening. For short threaded implants this is less likely which explains the low success rate of threaded implants of length less than 8mm.

Stress Shielding

Crestal bone loss can also result from underloading of bone next to implants, called as stress shielding. This occurs in regions of bone that are bypassed during implant loading. This has occurred in the smooth machined collar region of all implant designs including porous surfaced implants.

Reduction of Overstressing Effect:

Following strategies have been proposed:

1. Modification of the coronal implant region by introducing microgrooves (Hansson 1999). Microgrooves are intended to allow partial force transfer in more coronal regions, resulting in distribution of stress over a greater peri-implant bone volume, thereby lowering stress related to the regular threads.
2. Designing implants that allow effective force transfer over a greater portion of the bone-interfacing implant surface. Designs that result in 3D interlocking interface of bone & implant, (that) is by allowing transfer of tensile as well as shear & compressive forces across the interface. Porous surfaced (sintered) implants represent such a design.

Discussion

Development of an optimal interface between bone and dental implants has been under focus for many years. An important determine is whether a newly developed implant material conforms to the requirements of biocompatibility, mechanical stability and safety. It must undergo a convincing testing both in vitro and in vivo. The goal of achieving an optimal bone-implant interface has been approached by the alteration of implant surface topography, chemistry, energy and charge as well as bulk material composition.

Guidelines are provided for the dimensions of implants for use in vivo studies based on the size of animal and bone tissue, and on the implant design, in order to avoid pathological fractures of the animal.

Many studies aim to evaluate the effect of implant surface modifications on formation of the bone-implant interaction. In order to draw accurate conclusions regarding the effects of implant modification, one must first accurately determine the implant surface characteristics, with regard to the chemical composition of the material and the surface topography. This should be performed both visually (e.g. light microscopy, scanning electron microscopy) and numerically (e.g. profilometries, contact angle, X-ray photoelectron spectroscopy, energy dispersive X-ray spectroscopy). This includes both qualitative and quantitative data.

Currently used clinical dental implants show a wide variety of surface characteristics, both in terms of structural and chemical properties. Whereas the materials for the first generation of dental implants were selected mainly on the basis of their mechanical properties and corrosion resistance under physiological conditions, the current research can be regarded as the second generation. Their surfaces have been modified mainly with respect to surface topography. But in some cases also chemical composition in order to achieve a better biological response.

An electronically controlled mechanical tapping device (MTD) to measure implant mobility has been studied extensively for its ability to measure initial stability at the time of surgical placement and predict an implant's survival prognosis with few reported complications. The histologic images and changes in MTD values indicated that repeated MTD measurements at the time of implant placement surgery may damage the bone-implant interface and a stable or borderline implant may become mobile after repeated MTD measurements.

Bone-anchored implants are now being used in dentistry for supporting removable and conventional prostheses. Although high success rates have been reported, a small number of implants may fail during the early healing phase or later in function. Currently available clinical methods to determine implant stability and osseointegration are relatively crude and may entail measuring a torque with a hand instrument. Radiographs are of value, but a standardized technique is necessary to ensure repeatability. A significant increase in resonance frequency was observed related to the increasing stiffness.

A study introduced a new test procedure for identifying the elastic modulus (Young's modulus) of interfacial tissue around a dental implant using a neural network (NN) and finite element analysis (FEA). An NN model was trained using displacement responses obtained using FEA models with given material properties. It was then used to identify the interface elastic modulus by feeding in measured displacement of a dental implant-bone structure whose interface elastic modulus is unknown. The results indicated that the identified elastic modulus is sufficiently close to the original one. It offers a new possibility and means for the study of the implant-bone properties around dental implants.

An investigation was done to measure the resonance frequency of a number of implants placed in the tibial tibia of rabbits and to [illegible] thereafter and to correlate the results with histomorphometric measurements made when the animals were sacrificed. Resonance frequency measurements were made by screwing a small transducer onto a standard abutment connected to each fixture. In conclusion, it was shown that resonance frequency measurements can be made at placement and during healing. It is also the changes may be related to the increase in stiffness of the implant in the surrounding tissue.

A three-dimensional finite element study analysis has been used to investigate the influence that variations in the macrostructural geometry of a blade-type dental implant have on the stress distribution around LTI carbon and aluminium oxide implants. The finite element model was constructed based upon an analysis of serial sections of a retrieved implant specimen. In addition to the implant, the finite element model contained a [illegible] fixed bridge, cemented to a natural molar with periodontal membrane. The construct of the bridge allowed for the study of freestanding implants and [illegible]. Variations in the implant blade geometry were found to produce significant changes in the stress distributions around bridged and freestanding aluminium-oxide implants. Very little effect, however, was observed around the LTI carbon implants. A comparison of the stresses around the freestanding [illegible] and the bridged around the bridged and freestanding implants was made to determine the implant design that came closest to reproducing the stress state around the mono-dentition. The CFC carbon system was less improved the stress state was found to be a cylindrical implant used in conjunction with a cortical on alignment or a fixed bridge. The aluminum oxide system finished outside of the stress state was found to be of the positive short-Maxi design and of a freestanding implant.[4]

Transcutaneous osseointegrated implants (TOI) have been shown to improve functionality for patients with limb loss by allowing direct skeletal attachment between an exoprosthesis and host bone. However, a lengthy rehabilitation period has limited the expansion of TOI and may be accelerated with electrical stimulation. The bone implant construct was evaluated in the Group I animals using appositional bone index (ABI), mineral apposition rate (MAR), histological staining, and scanning electron microscopy (SEM). Group II implants were removed and subjected to mechanical push-out tests. Data indicated statistical differences for ABI, MAR, and porosity between the electrically stimulated implants (ESI) and non-stimulated control implants (NCI). This indicates that DC cathodic stimulation may improve osseointegration. Push-out tests showed an increase in indicating bone was most around the cathode in the ESI group. However, longer time duration animal studies and evaluations of alternate modalities may be required before electrically assisted osseointegration becomes clinically feasible.[5]

A study was performed to evaluate the performance of a contemporary dental implant. Assessments were made regarding implant survival and radiographic bone changes from surgical placement to subsequent time points. Results indicated that the survival rates for implants placed into healed ridges and fresh extraction sockets were 98.5% and 98.1%, respectively. With regard to proximal bone levels, mesial and distal bone loss from surgical placement to 12 months was 0.06 mm mesially and 0.23 mm distally. From 24 to 36 months follow-up, the mesial and distal bone changes were 0.16 mm and 0.19 mm, respectively. Up to 36 months after implants were placed into fresh extraction sockets, the mean distance from the implant-abutment interface to the first bone to implant contact was 1.04 mm mesially and 1.10 mm distally.[6]

Accurate assessment of mineral density (MD) provides information critical to the understanding of mineralization processes of calcified tissues, including bones and teeth. High-resolution three-dimensional assessment of the MD of teeth has been demonstrated by relatively inaccessible synchrotron radiation microcomputed tomography (SRμCT). While conventional desktop μCT (CμCT) technology is widely available, polychromatic source and cone-shaped beam geometry confound MD measurement. Recently, considerable attention has been given to optimizing quantitative data from CμCT systems with polychromatic x-ray sources.[7]

The success of orthodontics, and dentofacial orthopedic treatment depends on effective anchorage and a favorable osseous adaptation to applied loads. The quality of bone produced under therapeutic conditions depends on its internal organization, degree of mineralization and geometric distribution. To adequately assess the mechanical properties of orthodontic anchorage devices, such as dental implants, requires three-dimensional (3D) imaging of block specimens. Micro-computed tomography (micro-CT) has opened new scientific frontiers for analyzing mineralized tissue.

Digital microradiographic and conventional microradiographic images of the same implant integrated in cortical bone were compared with digital microradiography. It was concluded that the micro-CT is the new gold standard for assessment of bone supporting implants. Micro-CT of a threaded implant integrated into a dog femur showed intense remodeling activity at the interface and within supporting bone. Threaded implants are loaded by remodelling, associated with individual threads, while cylindrical devices have a more global response concentrated at the center of the endosseous portion of the implant. Micro-CT is a novel digital technology that shows great promise for detecting subtle changes in osseous structure that are related to dental implants, orthodontic responses and dentofacial adaptation.[8]

Conclusion

The progression of osseointegration may be accelerated by alteration of the implant interface as well as growth factor application and functional stimulation of peri-implant structure may be feasible to predict the implant function during osseointegration. Currently used clinical dental implants show a wide variety of surface characteristics, both in terms of structural and chemical properties. Whereas the materials for the first generation of dental implants were selected mainly on the basis of their mechanical properties and corrosion resistance under physiological conditions, the current focus is to be applied in the second generation. The development of the next, third generation, of dental implants will require further knowledge about the interface biology on a molecular and cellular level. Implant surfaces modified with or releasing biologically active substances, new microscopic and analytical tools, and the new, emerging understanding about stem and progenitor cells will play an important role in acquiring the knowledge necessary for specifying the optimal properties of the next generation of oral implants in an age of clinical innovation.

References

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