DENTAL IMPLANTS: BIOMATERIAL, BIOMECHANICAL AND BIOLOGICAL CONSIDERATIONS

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Review Article

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ABSTRACT

Currently many dental implant systems with varied and numerous components are available commercially, and with new implant systems and designs emerging, it is essential that the user understands that any system selected should be based on sound scientific principles and capable of osseointegration. This has been defined in many different ways, with biomaterial, biological and biomechanical factors being the main considerations. The final restoration is based on both biological tissue and mechanical components. As the success of osseointegration is based on the clinical outcome, clinicians must ensure that the stresses that the superstructure, implant, and surrounding bone are subjected to are within the tolerable limits of the various components, even though the degree of tolerance has not yet been fully defined.

Key words: dental implant, biomechanical, biomaterial, review.

INTRODUCTION

Dentists and scientists have for a long time been researching materials and techniques for providing predictable, efficient and effective methods of restoring a depleted dentition. Amongst the most versatile of these are osseointegrated implants. Dental implant therapy has realised significant progress in the last thirty years. Since the first scientifically documented clinical successess of Brånemark and his co-workers in the edentulous milieu (1), application of dental osseointegrated implants have progressed to be used in the partially dentate (2,3), prosthetic rehabilitation of oral and maxillo-facial defects (4), and reconstruction of congenital defects in children and adolescents (5). One-step surgical implant techniques are currently being used (6,7), besides the original Brånemark protocol of two-stage surgery for implant placement. Preliminary reports have also shown that placement of implants in irradiated jaws may give good results even wihout adjunctive hyperbaric oxygen therapy to provide support in areas with compromised blood flow after irradiation (8,9,10,11). Osseointegration is also used in orthopaedic reconstruction of various parts of the human body (12).

Osseointegration was first described as a relationship where "bone tissue is in direct contact with the implant, without any intermediate connective tissue". It was later defined as a "direct structural and functional connection between ordered and living bone and the surface of a load carrying implant" (13). These definitions were based on retrospective radiographic and light microscopic observations, and implied that direct bone contact occurs around the entire implant. However, with current techniques of ultrastructural investigation, this interpretation appears to have been overestimated, as 100% bone apposition is not necessarily obtained at the surface of the endosseous implant. Albrektsson and Johansson (14) indicated that the proportion of direct bone-to-implant contact varies with the material and design of the implant, as well as the state of the host bed, the surgical technique, and the time and conditions of loading. There is also varied morphology of bone apposing the implant, showing that osseointegration is a healing response consistent with the dynamic environment into which the prosthesis is inserted (15). Therefore, osseointegration is best defined as a "process whereby clinically asymptomatic rigid fixation of alloplastic materials is achieved, and maintained, in bone during functional loading" (16). Later, in 1994, Skalak and Brånemark (17) proposed that osseointegration be considered as the sum total of the following definitions, obtained from the clinical, biological, biomechanical, and microscopical points of view:

a. a fixture is osseointegrated if there are no signs and symptoms under functional load.

b. at the light microscopic level, osseointegration is seen as a direct structural and functional connection of new bone to the fixture without the interposition of connective or fibrous tissue, and that this connection is capable of carrying normal physiological loads.

c. there should be no progressive movement between the fixture and surrounding bone under functional loading.

d. at the electron microscopic level, structures found within nanometres of most of the surface of the fixture should be identifiable as mineralised normal bone.

These definitions describe the end result of osseointegration, and while they are appropriate, the process of osseointegration itself is a lifelong activity of bone formation, adaptation to function and repair at the bone-implant interface. Cooper (18) pointed out that there is therefore, still a need, to define the cellular and molecular events controlling bone formation and maintenance at this site so that the process of osseointegration is predictable, especially in areas where bone is deficient.

Criteria for the success of osseointegration

Osseointegration is a highly successful clinical protocol, although this is influenced by many factors. These include the implant system and the status of the bone at the implant site (19,20). Esposito *et al.* (21) provided a comprehensive review of the many parameters which have been developed and used over the years to evaluate the success and failure of osseointegrated implants. Zarb and Albrektsson (22) proposed that the following set of criteria be used to assess the outcome of implant supported prostheses. It highlights the essential clinical features of the successful osseointegration of implants, and includes:

a. the lack or absence of signs of infection (either early on in the healing period, or later during function) attributable to the implants,

b. no pain, discomfort, or sensitivity around the implants,

c. no observable mobility (which is always a clear sign of failure) when tested clinically, and

d. the mean vertical bone loss is less than 0.2 mm annually following the first year of function, compared to baseline measurements made after abutment connection.

Wide-ranging and extensive data to support the success of osseointegrated implants is available for the Brånemark implant system (19,23,24). Other implant systems are relatively new, and adequate data is needed to form the basis for reliable statistics for a 10-year follow-up period to meet the minimum success criteria proposed by Albrektsson *et al.* in 1986 (19).

Esposito *et al.* (25) reviewed in detail the factors that can lead to implant failure. The reasons for the loss of implants after osseointegration has occurred may be multifactorial, with prosthetic factors (usually due to overload) and bacterial infection as the major causes. However, the reasons for the implant's failure to osseointegrate are still unknown. Experimentally, excessive interfacial micromotion, rather than early loading *per se*, is acknowledged as one detrimental factor (26).

Factors which determine the success of osseointegration

Albrektsson *et al.* (19) first referred to the six important factors which determine the success of osseointegration. These are: implant biocompatibility, design characteristics, implant surface characteristics, state of the host bed, surgical technique, and implant loading conditions. LeGeros and Craig (27) categorised these factors into biomaterial, biomechanical and biologic determinants. In addition, patient motivation and oral hygiene procedures are also important considerations (28,29). These factors are interdependent and interrelated, and their recognition has led to the long-term success associated with osseointegrated implants.

Biomaterial factors

Dental implants are used in the oral cavity to improve the stability of a prosthesis. In order to be successful clinically, implant materials must satisfy two essential requirements:

a. they must not be toxic to the cells in the surrounding tissues, or undergo dissolution and cause systemic damage to the patient;

b. they must be able to form a stable bone-implant interface that is capable of carrying occlusal loads, and transferring or distributing stresses to the adjacent bone so that bone vitality is maintained over long periods (30).

Three basic types of synthetic materials have been used for fabricating endosseous dental implants. These are metals and metal alloys, ceramics and carbons, and polymers. Metals and metal alloys used for clinical and experimental implants have included titanium and titanium alloys, tantalum, stainless steel, cobalt-chromium alloys, gold alloys and zirconium alloys among others (31). These materials are selected based on their high corrosion resistance, strength, rigidity, ease of shaping and machining, and suitability for a wide range of sterilisation techniques. Although the mechanisms that lead to osseointegration with titanium implants are not fully known, metals in general do not form an interfacial bond with bone. The implant is typically connected to bone via a micro-mechanical interlock using a variety of surface designs and textures that are used to promote bony in-growth and improve the interfacial attachment (32).

Ceramics are generally hard materials with high compressive strengths. Carbon based materials are similar to ceramics, and due to their brittleness and low impact strengths, are not suitable for use in their bulk form in load-bearing applications. The choice of ceramics as implant materials is primarily due to efforts to develop materials based on crystalline structures which are bone-like and have similar physical properties to bone. Bioceramics may form two types of interfacial bond with bone: a bioactive ceramic is partially soluble, and forms bone via chemical reactions at the interface, while bioresorbable or biodegradable ceramics have a

higher solubility, degrade gradually, and with time are replaced with bone (27,30).

Different chemical compositions of calcium phosphate ceramics based on specific ratios of calcium and phosphorus are used clinically, both as a dense sintered material in non load-bearing areas, and as a plasma-sprayed coating for titanium implants (33,34). These hydroxyapatite (HA) coatings may contribute to more rapid osseointegration and greater amounts of bone-implant contact than is associated with uncoated titanium in the early stages of healing. However, HA coated implants are not seen as superior to titanium devices in the long-term because the difference does not appear to be clinically significant after 12 months of implantation (35). In fact, bone contact with titanium may be more favourable in the long-term (36). This is attributed to interfacial problems related to the dissolution and weakening of the HA coatings, which have a tendency to become loose or dissociated from the central titanium implant (37).

In comparison to metals and ceramics, polymers are weak, and generally flexible. They may however, be synthesised in a variety of compositions and fabricated into many complex shapes and structures. They are mainly used as additives to give a beneficial secondary purpose, for example, as structural isolation for shock-absorption in load-bearing metallic implants (38).

Two forms of titanium (Ti) are principally used for endosseous dental implants. They are commercially pure titanium (cpTi, at least 99.5% pure Ti) and a titanium alloy, titanium-aluminium-vanadium (Ti-6Al-4V). CpTi is available in four grades which vary in their oxygen content. Oxygen functions as a controlled strengthener in cpTi. As oxygen content increases, the strength of the metal increases and its ductility decreases (39). Nitrogen, carbon, hydrogen and iron are also present, but vary little between grades. Grade I cpTi is the purest and therefore the softest. Grade 4 cpTi has the most oxygen at 0.4% by weight, and is the material used for dental implants.

Ti-6Al-4V also contains low concentrations of nitrogen, carbon, hydrogen, iron and oxygen, but additionally approximately 6 per cent by weight aluminium and 4 per cent by weight vanadium. Besides reducing the melting and casting temperatures, alloying other metals with Ti also increases the strength of the alloy and decreases its density (40). A stronger bone-implant interface may be achieved with cpTi than with Ti-6Al-4V, as greater removal torque forces were needed to loosen the interfacial connection between cpTi implants and the surrounding bone (41). This may indicate that cpTi is more favourable to bone cell differentiation than Ti-6Al-4V (42). The impaired bone formation with the Ti alloy may be related to the release of aluminium ions, which can be detrimental to bone cell differentiation (14,43,44).

Ti is the 'material of choice' in implant dentistry (45). Its excellent corrosion resistance is due to the surface which oxidises spontaneously upon contact with air or tissue fluids. This layer, normally approximately 2-5 nm thick is primarily TiO_2, but may contain TiO and Ti_2O_3 depending, partly on its method of preparation (46,47). However, the oxide layer is not uniform or constant. The type and thickness of the oxide layer also depend upon other factors such as roughness of the surface, and treatments to passivate or sterilise the surface (48,49,50,51,52). The oxide layer may undergo dissolution and allow a finite rate of diffusion of the oxide in the body (53,54,55). However, there is little evidence that this has any clinical significance, and no case of local or systemic reaction to Ti has been reported (56).

As with all materials implanted in living tissues, Ti is not entirely inert and will elicit a response from the host tissue. Williams (57) described a biocompatible material as one "which possesses the ability to perform with an appropriate host response in a specific application", and consequently, Stanford and Keller (58) proposed that the term "osseointegration" reflects the results of a lack of a negative tissue response to Ti, rather than the presence of an advantageous one. This is because Ti does not stimulate or induce mineralised tissue formation at the bone-implant interface. Rahal *et al.* (59) showed that Ti does not have the ability to induce osteogenesis from potential osteogenic precursor cells in mice marrow. Various studies have also shown that bone healing around machined Ti implants takes place by a gradual mineralisation process directed towards, but does not start, at the implant surface (52,60,61).

A bioactive implant (i.e. an implant which bonds to bone) forms a hydroxycarbonate-apatite (HCA) layer on its surface when implanted (30). Ti is a reactive material, and Hanawa (62) found that it naturally forms calcium phosphate on its oxide layer in a neutral electrolyte solution simulating body fluids. The ratio of calcium and phosphate (Ca/P) in the Ca-P layer formed was 1.63, which is close to that of hydroxyapatite (1.67). He suggested that this layer may therefore present itself as a suitable surface for osseointegration. However, this Ca-P layer was very thin (less than 8 nm on the cpTi and Ti alloy plates studied). This may indicate that the layer was due to the transfer and adsorption of these elements from the tissue fluids, rather than a true apatite formation. In a similar investigation, Li and Ducheyne (63) showed that the Ca/P ratio formed was only 1.44. This is lower than HA, as Ca was deficient on the surface oxide. They termed the layer a quasi-biological apatite, formed as phosphate ions bind to the Ti hydroxide layer on the surface of cpTi in contact with aqueous solution. It is not known whether the intimate bone-Ti implant contact found in the normal clinical situation is due to the effect of the Ca-P layer formed on the surface of the oxide layer, since at the time of implantation, this layer is not present on implant surfaces.

Biomechanical factors

There are numerous designs of implant systems currently available. However, as mentioned above, the original Brånemark implant system is the best documented and researched implant system in current

use. The Brånemark implant system was based on a two-stage surgical procedure followed by the construction of either a fixed or removable precision attached prosthesis. It is assumed that when an implant is osseointegrated, the titanium implant and bone may be regarded as having a perfect fit, similar to the ankylosis of teeth in bone, with no stress in either material prior to loading.

However, flexibility in the Brånemark implant system may be found in the following:

1. gold cylinder and abutment which are fastened to the fixture by gold alloy and abutment screws, and

2. the connection between the superstructure and the abutments, which has been assumed to have perfect fit, by following an arbitrary designation of fit (64,65).

An accurately fitting casting where the rigid prosthesis fits passively to all implants is essential to ensure that occlusal loads istributed to all fixtures, and unacceptable torquing stresses which may lead to loosening or fracturing of components, bone resorption and implant failure will be avoided. This is because the osseointegrated implants do not move in bone as teeth do, and therefore may not be able to compensate for a possible imperfect adaptation between the teeth and abutments (66). Nevertheless, it is generally believed that it is impossible to achieve a totally passive fit of a superstructure to more than one implant.

Presently we do not know the loads that individual implant units are subjected to when a superstructure is fixed and loaded. Brunski (67) pointed out that loads on a superstructure are not in general equal to loads on an implant. Several implants may be used to support a prosthesis *in vivo*, and this problem of load sharing or load partitioning among implants has not been completely solved. He also stated that detailed understanding is lacking of the consequences of screw-fastening misfitting prostheses to integrated implants.

Theoretically, passive adaptation involves the exact placement of a series of premachined parts in a casting to a strictly tolerated metal-metal interface. Practically this may be difficult to accomplish within the limits of presently available casting materials and techniques. This is due to the cumulative clinical and laboratory variables that are involved in making the casting (68).

It is also difficult to evaluate the passivity of fit of the castings in the clinical situation. Clinicians have been using the arbitrary term 'acceptable fit' in accepting castings clinically. Clinical evaluation of fit has been subjective and usually been desribed in the literature in terms of visual and tactile methods (69). Generally a casting is assessed to have acceptable fit by carefully seating the casting on one of the abutments, and visually checking the contact of the other gold cylinders on their respective abutments. One of the terminal abutments is then tightened, and a poor fit is revealed as a gap between the framework and an abutment. This gap might be a vertical gap, or a horizontal gap (skewed contact), with one side more open than the other. The rest of the other screws are then located one at a time, and contact between the casting and abutment assessed each time.

Distortion is inevitable in one-piece castings for multiple unit fixed bridges, and several authors have described techniques to overcome these problems (65,70,71,72,73). However, even with careful soldering techniques, a discrepancy in fit of less than 30 mm in over 90% of prosthesis-abutment interface was described in one study (68). This means that single piece cast frameworks that appear to fit accurately by following an arbitrary designation of fit, will be seated through multiple screw-retained anchorage points by bending a casting to place during the tightening procedure, or by deforming the surfaces in contact (70). This was shown by Millington and Leung (74) who demonstrated *in vitro* using photoelastic stress analysis, stresses on the surface of the superstructure with gaps as small as 6 mm between the superstructure and abutments.

The Nobelpharma implant is a complicated multi-component device joined by two screws, the abutment screw and the gold screw. When a screw is tightenend, a tensile force (preload) is built up in the stem of the screw (75,76). This preload creates a compressive force to the components being clamped together, (in this case the abutment to the fixture, and the gold cylinder/ superstructure to the abutment). Assuming that there is perfect fit between the implants and all the gold cylinders in the superstructure, this compressive force is inevitable, as this will always be inherent in all screw joints, and the abutments will never be stress free. However it is the tensile stresses, or stresses that would tend to separate the components that would be more significant clinically. These stresses would undoubtedly be present in a situation where there would be variations in the degree of fit of contacting surfaces between the implants and the superstructure.

In vivo strain gauge measurements directly attached to the transmucosal abutment of a Brånemark implant (24) and the intramobile element of the IMZ system (77) showed that the stress loading of the implant begins with fixation of the superstructure, even before any masticatory function occurrred. This implies that even though the connected implants had an acceptable fit, it may not be a completely passive fit and the cast framework that appears to fit can be torqued into position during the seating procedure. This would mean that a significant force may be introduced as the prosthesis is secured to the abutments. On the basis of these findings, a poor fit of the superstructure could introduce large stresses in the system and the bone around the implants (78,79). This has been shown to be one common cause of fracture of abutment screws (80).

Another point to consider is the flexure of the mandible itself. It is conceivable that with varied openings of the mandible, the precise angulations of the fixtures and hence the transfer copings may change. The phenomenon of mandibular distortion in function has

received little attention (81). Mandibular distortion will result in changes in the relationships of the dental arch across the midline, and is thus of considerable relevance in implant treatment because of the rigid fixation of the devices employed, and its deformation during impression making may result in inaccurately fitting frameworks.

Even though it has been agreed that complications can occur when a passive fit is not obtained, there is no data available to quantify what degree of imperfect fit is acceptable without leading to complications. This information is crucial for the following reasons:

1. It is impossible to achieve perfect fit of casting to abutments

2. Although osseointegrated implants are described as being immobile, the surrounding bone is viscoelastic, and it is likely that some degree of stress is induced as a result of accommodating to non-passive fit of the superstructure. This is probably one of the reasons for the high levels of long term success achieved by the Brånemark implant.

Obviously it is useful to quantify the degree of fit required of the cast superstructure in order to prevent complications as a result of stress induced from a non-passive fit. However, until a more objective method of measuring the fit of superstructures is established, the acceptance or rejection of the fit of an osseointegrated prosthesis will ultimately be based on the judgement of the clinician. Poor fit may cause failure of abutment screws, failure of gold screws and possible loss of integration between the bone and implant. Injudicious implant placement is another factor which could generate high stresses on the implant components and the surrounding bone.

When a superstructure and final restoration are built upon an implant, the whole structure is based on both biological tissue and mechanical components. Rangert *et al.* (82) analysed data obtained from authors who reported failures in the literature due to fractured implants, and concluded that the fractures were caused by excessive bending overload on the implants. These excessive bending moments were basically a combination of different adverse loading conditions due to poor bone support, long cantilevers and broad buccolingual width of the teeth. Failures due to fractured implants may be prevented if these potential overload situations were identified before treatment (83).

The connection of the natural dentition to implants via a rigid attachment posed a theoretical concern that it may be hazardous to both implant and natural tooth survival (2). It is hypothesised that failure of either or both components might be due to the differences in the mobility of teeth and the deformation of the bone supporting the implant. Long-term studies had shown however, that there were no changes in implant or tooth failure rates where prostheses were supported by implants and natural teeth via a rigid connection (84,85). This suggests that the tooth and bone-implant components were able to undergo some deformation under functional load to compensate for the differences in their resiliency.

Biologic factors

The patient's medical status, type and quality of bone at the implant site, minimising tissue trauma at the time of surgery, prevention of infection, and good post-operative care are critical factors in the formation and maintenance of osseointegration (19,86). Another factor which can affect the prognosis of oral implant treatment is smoking. Nicotine and other toxic materials absorbed into the blood stream through smoking have been proposed to cause adverse local and systemic effects which can affect the survival of the natural teeth (87). Local effects which have been proposed are altered salivary flow and microbial growth, while some systemic effects which have been associated with smoking are vasoconstriction, impaired wound healing after surgical treatment, and increased prevalence of bone loss.

Bain and Moy (88) and Lindquist *et al.* (89) showed that smoking may be directly related to the soft tissue changes and marginal bone loss around dental implants. As such, it should be considered a risk factor in implant therapy, separated from the other factors mentioned in a review article by Meffert *et al.* (28), which are primarily related to the maintenance of the implant in general.

CONCLUSION

Dental implants provide wider treatment options for replacing missing teeth, and most implant systems depend on an osseointegrated interface to achieve this. The results depend upon careful case selection, and good teamwork, and above all proper training and understanding of the clinical and biomechanical aspects of dental implants for all engaged in this form of treatment. However, with or without implants, an appropriate diagnosis and treatment plan must be formulated to address the patient's wishes and best interests, as the vast majority of partially and totally edentulous patients will receive functional and aesthetic prosthodontic care using the remaining teeth and mucosa without implant placement.

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