ADVANCED MATERIALS

## Biomaterials Highlights III

# Bone Replacements: Implant Materials and the Modes of Implant Fixation**

By Günther Heimke*

### 1. Introduction

During the last three decades the success rates of hard tissue replacements have increased considerably and have, thus, become a standard way of treatment. Based on early experiences, and taking advantage of the progress in material technology,[1, 2, 3] most of the directly material related reasons for reoperations could be either excluded completely or confined to extreme situations, like, for example, accidents in which the natural bone concerned would also have suffered severely. The causes for the remaining necessity for reintervention are essentially implant loosening or, in other words, failure of the implant fixing method.

This demonstrates that the kind of implant anchorage used is the key issue for any further improvement of the success rates of permanent orthopedic and dental implants. Many different ways of implant anchorage have been, and still are discussed, tested in-vitro and in animal experiments, and studied clinically. Some of them have successfully contributed to the improvements mentioned above and to the understanding of the remodeling reactions and the processes controlling them. A systematic survey of the modes of implant fixation[4] can facilitate the understanding of some of the different success rates and may even help to prevent some waste of effort and failure.

### 2. The Material Aspect of Implant Fixation

Like in all other fields, there are many viewpoints from which the materials used for a particular purpose can be surveyed and categorized. For implant materials a grouping according to the tissue reaction they stimulate in their environment can be regarded as adequate, as shown in Table 1.

The three terms characterizing the tissue reactions indicate some of possibilities of implant fixation in a bony environment. The list of influences on the sequence of reaction of the adjacent tissue, however, is not yet complete. Besides the essentially biochemical reactions mentioned in Table 1, there are nonmaterial-controlled influences on the remodeling of the bony tissue around implants. In addition to general aspects like age, health, and previous operations, the mechanical situation along the implant to bone interface plays an important role.[6, 7, 8] There is some similarity to fracture healing: a complete and stable union along a fracture site can be achieved only if the two surfaces can be brought together and maintained sufficiently motionlessness relative to each other during the healing period. The lack of rest along the interface will inevitably result in the formation of a soft tissue layer essentially consisting of bundles of collagen fibers mostly oriented parallel to the surfaces and containing only a few cells. Such creation of an artificial joint results in an additional mobility which, of course, is highly undesirable in this kind of treatment.

In fracture healing, the required motionlessness can be achieved by the application of a cast around the fractured bone, and if possible the two adjacent joints. Because of the remaining relative mobility of the two surfaces, the essential steps of fracture healing do not procede until a callus has been formed around the fracture site which provides the required additional stability. Another possibility is that the fragments are stabilized by pins (or so called nails) intro-

Table 1. Classification of implant materials according to the material influenced reactions in the surrounding bony tissue.

| Class of material | Kind of influence | Tissue reaction | Typical materials in this class |
|---|---|---|---|
| biotolerant | ions and/or monomers go into solution, biochemical effects on differentiation and proliferation | distance osteogenesis[a] | stainless steels, polymethylmethacrylate (PMMA bone cement) Co based alloys, polyethylene |
| bioinert | no matter influencing the adjacent tissue goes into solution | contact osteogenesis[a] | $Al_2O_3$-ceramic, carbon, titanium |
| bioactive | bond formation by not yet completely understood processes | bonding osteogenesis[a] | Ca-phosphate based ceramics and Ca-phosphate containing glasses and glass-ceramics |

a) These termes and definitions have been coined by Osborn [5].

[*] Prof. G. Heimke
Department of Engineering, College of Engineering
Clemson University, Clemson, SC 29634-0905 (USA)

[**] For Part II see *Adv. Mater. 1989, 234; Angew. Chem. Int. Ed. Engl. Adv. Mater. 28* (1989) 956; *Angew. Chem. Adv. Mater. 101* (1989) 980.

duced into the medullary canal or by plates screwed onto the bone parts, if possible in a way in which the fracture site is under compression (pressure osteosynthesis).

Because the trauma caused by the insertion of an implant into a bony environment can be expected to be similar to that at a fracture site, the sequence of reactions along an implant to bone interface following this trauma cannot be expected to be more favorable than in fracture healing. However, there are additional handicaps for implants as nearly all their mechanical properties are different from those of bone. Thus, even after the most favorable healing processes, the differences of the mechanical compliances will result in a lasting discontinuity along all bone to implant interfaces.

Besides biochemical and mechanical compliance, two further material dependent aspects must be considered which influence the reliability of implant anchorage: the enzyme controlled immune response of the host tissue, and long term systemic effects. This latter point of view has been dealt with in the previous contribution (Biomaterials Highlights II[9]).

## 3. Mechanical Aspects of Implant Fixation

The forces acting along the bone to implant interfaces must be considered in two stages: first, for the healing period until a reliable equilibrium between the bone forming and the bone resorbing processes has been achieved around the implant and, second, for the rest of the lifetime of the implant which, hopefully, will be identical with the lifetime of the patient.

During the first stage, optimum conditions for fracture healing must be provided for all those interfaces along which a close bone to implant contact is vital for the correct functioning of the implant. The easiest way to realize this requirement is to keep the implant unloaded during this period. However, this is possible only in exceptional cases. The main problems of the second stage are the different mechanical compliances of the bony tissue, or tissues, and the implant. The possibilities and limitations for the design of implants resulting from these mechanical considerations have been dealt with in detail elsewhere[6, 7, 8] and have recently been summarized.[10]

The essential statement is: if all other influences are, or can be, excluded it is the stress and strain field created in the bony tissue around an implant that controls the interface remodeling. If, thus, the implant can be designed allowing for motionlessness along all those interfaces which are necessary for a stable anchorage, usually all load bearing interfaces, the conditions for fracture healing as well as for long term stability can be met.

## 4. The Modes of Implant Fixation

Table 2 summarizes the modes of implant fixation either realized, attempted, or aimed at in bone and joint surgery, and dental implantology.

Table 2. Modes of fixation for bone and joint replacements and dental implants.

| Mode | Kind of interface | Kind of load transmission | Comments |
|---|---|---|---|
| Soft tissue encapsulation | identical with non-union of a fracture site | via soft tissue deformation | not reliable, but successful in exceptional cases for up to 20 yrs |
| Mechanical interlocking | | | |
| a) macroscopic porous coatings | partially soft, partially direct bony tissue contact | mixed, via direct bone contact partially only | not reliable, some severe difficulties in implant removal |
| b) microscopic surface porosity (flame sprayed powders) | direct bone contact | via direct bone contact | reliable and stable anchorage |
| c) controlled surface undulations | direct bone contact | via direct bone contact | reliable and stable anchorage |
| Isoelasticity | soft tissue encapsulation | via a soft tissue layer | not reliable |
| Bond formation via bioactivity | direct bone contact | via direct bone contact | fatigue of bioactive materials |

### 4.1. The soft tissue mode

The reasons for soft tissue encapsulation are twofold: either the implant material is only partially biotolerant and the differentiation and proliferation of the bone forming cells is prevented or disturbed, or the shape of the implant does not provide sufficiently large surfaces along which relative movements can be prevented. The correlation between a soft tissue interlayer and implant failure has been clearly established for dental implants.[11] The stability of a soft tissue layer around total joint replacements anchored via the polymethylmethacrylate bone cement (PMMA) suffers severely from interactions with polyethylene wear particles resulting from the articulation between the polyethylene sockets and metal balls. The use of ceramic balls[2] can reduce the production of such wear debris considerably and, thus, extend the life expectancy of these implants.

### 4.2. Mechanical fixation modes

A mechanical interlocking between the bony tissue and the implant surfaces can be achieved in different ways with very different results:

#### *4.2.1. Macroscopic porous coatings*

Porous coatings mostly consisting of one or more layers of metal spheres sintered or otherwise attached to the surface of CoCrMo-alloys allow for the on- and ingrowth of load bearing bony structures as deeply as the stress and strain field reaches and, of course, only at interfaces along which a sufficient motionlessness can be provided during the healing

period. This mode of implant fixation has reached relatively wide application in the US. It has been stated recently that the success rates of such knee replacements are no better than with cemented devices.[12] Some initially very successful femoral components of hip prostheses had to be abandoned because of the severe destruction necessary for their removal.[13]

#### 4.2.2. *Coatings of sprayed powders*

Coatings consisting of microscopic titanium powder particles flame or plasma sprayed onto the surfaces of the anchoring portions of several dental implants have achieved very high success rates in more than ten years of application. These implants are kept completely unloaded during the healing period by initially placing them underneath the gingiva and supplying them with a superstructure only after about three months. Figure 1 shows an example.

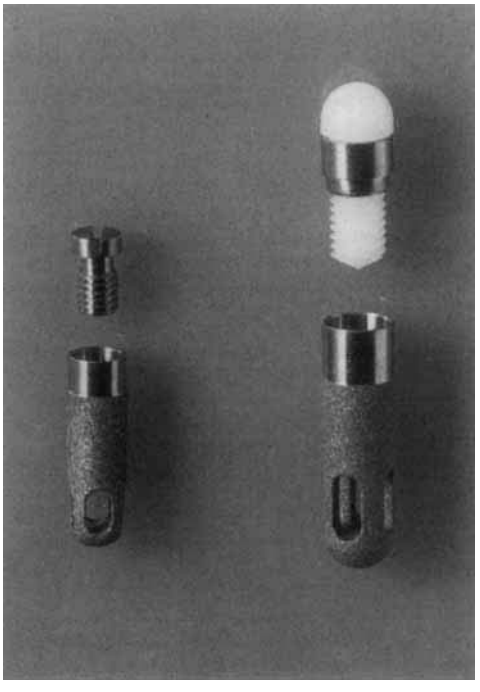

Fig. 1. Titanium dental implant (IMZ-implant) with Ti-powder particles flame sprayed onto the cylindrical surface. Note the openings for bony ingrowth and additional stabilization.

#### 4.2.3. *Controlled surface undulations*

Controlled surface undulations can be regarded as a combination of shape elements of an implant which allow the control of the stress and strain field in the adjacent bone in order to minimize the effect of the differences in stiffness, and an optimization of the concept of porous coatings by providing the biomechanically favorable shape of the surface undulations (Fig. 2). This can result in an interlocking by which a close bone contact can be achieved[8] and maintained even along tangentially loaded interfaces.[8, 14]

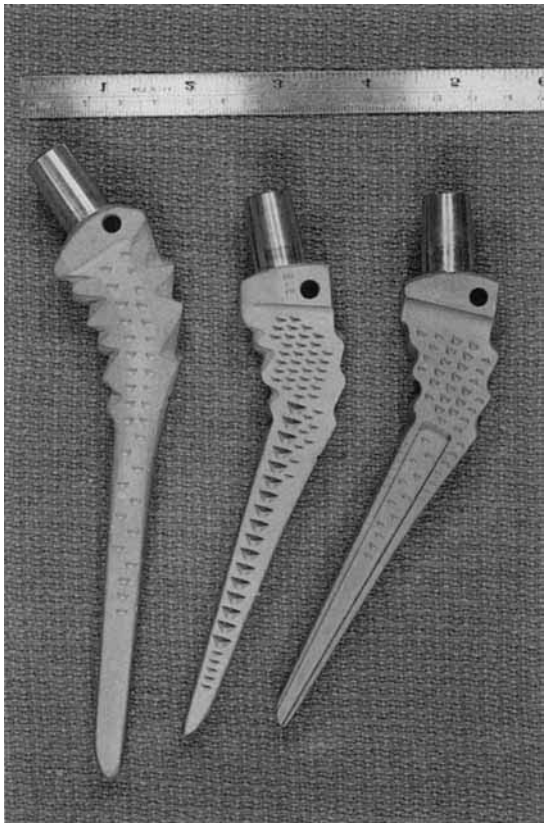

Fig. 2. BMO- (biomechanically optimized-) Stepped Stem of the femoral component of the FRIALIT total hip replacement system made of the vanadium free TiAlFe alloy. Note the macroscopic steps and additional fine surface undulations providing for an interlocking along otherwise tangentially loaded interfaces.

#### 4.2.4. *The interfacial bonding mode*

The anchorage of implants via an interfacial bond made possible by bioactive materials would very much facilitate implant design, the operation procedure, and, if it enhances bone formation, the post-operative treatment. Unfortunately, none of the bioactive materials have been found stable enough to withstand many years of shear loading. The same reactivity that allows for the bond formation obviously also accounts for the high mechanical fatigue. Presently, many attempts are underway to overcome these handicaps by coating the bioactive glasses, glass-ceramics, and ceramics onto mechanically strong substrate materials. Whether the aging and dissolution phenomena of such coatings can be overcome remains to be seen.

## 5. The Concept of Isoelasticity

The concept of the so-called isoelastic prosthesis is another attempt to avoid the problems resulting from the large differences of the mechanical performance of all metals and ceramics as compared to bony tissue. At a first glance, it might appear a reasonable approach to make the implant as

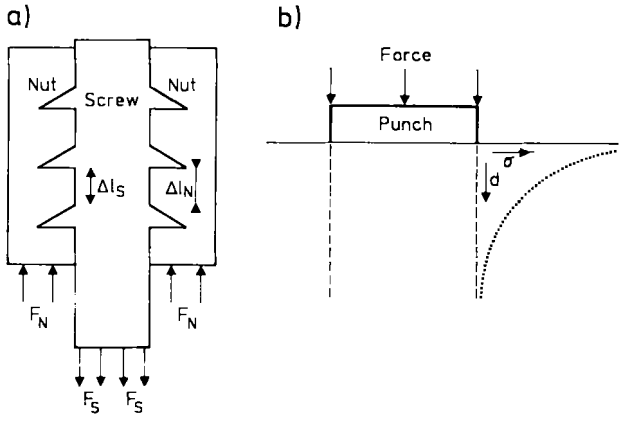


Fig. 3. a) The "nut and bolt" of identical materials results in a severe stress concentration on the first thread. $\Delta l_S$ = elongation, $\Delta l_N$ = compression. If the cross sections are equal $|\Delta l_S| = |-\Delta l_N|$, $\sum F_S = \sum F_N$. The cylinder underneath the circular punch (b) represents the situation of complete isoelasticity and of an ideal bonding to its environment within this half space. The dotted curve shows the stresses along the dashed interface between this cylinder and the environment and the extreme stress concentration towards the surface. It is this stress concentration that allows for all punching processes! σ stresses along d, d distance along dotted line.

stiff as the surrounding bone. As such an implant can be realized only with fiber reinforced plastics, this idea has found much attention in chemically oriented research groups. This concept, however, violates very basic and old rules of mechanical engineering. This has already been shown previously for two special cases[15, 16] and is explained on general terms in Figure 3.

### 6. Final Remark

The application of bone forming stimulants along implant to bone interfaces might be beneficial during part of the healing phase. As the stability of implant fixation essentially depends on the load pattern in the adjacent bony tissue and on the biochemical influences of the implant materials, hardly any contribution of such extracts can be expected for long term implant reliability.

The recent observation[17] of a particularly favorable adhesion of fibroblasts onto controlled surface undulations with dimensions in the one to two microns range can be regarded as a means to understand the bond formation on the Ti-powder coated surfaces. It appears that further results from this ongoing study will provide deeper insights into such surface mediated responses of cells and, thus, allow for further improvements of implant anchorage.


[1] M. Lorenz, M. Semlitsch, B. Panic, H. Weber, H. G. Willert, *Eng. Med. 7* (1978) 241.
[2] M. Semlitsch, M. Lehmann, H. Weber, E. Dörre, H.-G. Willert, *J. Biomed. Mater. Res. 11* (1977) 537.
[3] G. Heimke, P. Griss, *Arch. Orthop. Traumat. Surg. 98* (1981) 165.
[4] G. Heimke, in G. Heimke (Ed.): *Osseo-Integrated Implants*, CRC-Press, Inc., Boca Raton, FL. 1989 (in press).
[5] J. F. Osborn: *Implant Material Hydroxylapatite Ceramic. Basic Considerations and Clinical Applications*, Quintessenz-Verlag, Berlin 1985.
[6] G. Heimke, P. Griss, E. Werner, G. Jentschura, *J. Biomed. Eng. 3* (1981) 209.
[7] G. Heimke, W. Schulte, P. Griss, G. Jentschura, P. Schulz, *J. Biomed. Mater. Res. 14* (1980) 537.
[8] G. Heimke, W. Schulte, B. D'Hoedt, P. Griss, D. Stock, *J. Artificial Organs 5* (1982) 207.
[9] G. Heimke, *Adv. Mater. 1989*, 234; *Angew. Chem. Int. Ed. Engl. Adv. Mater. 28* (1989) 956; *Angew. Chem. Adv. Mater. 101* (1989) 980.
[10] G. Heimke, *Adv. Mater. 1989*, 7; *Angew. Chem. Int. Ed. Engl. Adv. Mater. 28* (1989) 111; *Angew. Chem. Adv. Mater. 101* (1989) 113.
[11] H. Spiekermann, in G. Heimke (Ed.): *Dental Implants*, Hanser, München 1980, p. 49.
[12] J. N. Insall, *Clin. Orthop. 226* (1988) 38.
[13] G. A. Lord, in *Proc. Symp. Uncemented Total Joint Replacement*, Phoenix, AZ, Harrington Arthrites Research Center, (Nov. 1984) p. 49.
[14] B. d'Hoedt, C. M. Büsing, *Fortschr. Zahnärztl. Implantol. 1* (1985) 150.
[15] R. Scholten, H. Röhrle, in S. K. Gupta (Ed.): *Trends in Biomedical Engineering*, CBME Publications, New Delhi, 1978, p. 148.
[16] R. Huiskes, in P. Ducheyne, G. Van der Perre, A. E. Aubert (Eds.): *Biomaterials and Biomechanics*, Elsevier, Amsterdam 1984, p. 7.
[17] C. E. Campbell, A. F. von Recum, *J. Investigative Surg.*, (1989) in print.


## Conference Reports

# Graphite Intercalation Compounds in Berlin


## By Ralph Setton*


The fifth international symposium on graphite intercalation compounds sponsored by the Freie Universität Berlin, was held in Berlin (West), on May 22.–25., 1989. It was attended by 137 scientists from 17 countries, with West Germany, France, Japan and the United States contributing about 85% of the participants. Fourteen invited talks were presented, as well as 41 other papers and 73 posters. Following a well-established custom of these symposia, seventeen


[*] Dr. R. Setton
Solides à Organisation Cristalline Imparfaite
Centre National de la Recherche Scientifique
45071 Orléans (France)