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Influence of implant surface modification on integration with bone tissue

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Problems connected with the improvement of medical implant fixation in bone tissue are addressed by the formation of a highly developed surface and by the activation of the implant surface with an electret coating. The realization of such surface modifications is expedient for implants manufactured from tantalum or niobium or finished by coatings made from these metals, as they are chemically more inert than titanium. The techniques have been tested on animals followed by histological and mechanical analysis.

Keywords: electret, electrostimulation, implant, niobium, osteointegration, oxide, porous coating, tantalum

1. INTRODUCTION

One of the basic requirements for medical implant assimilation is reliable fixing in bone tissue [1]. The form of the fixing elements is advantageously modified by adding features such as cross flutes or grooves and porous coatings. This leads to both an implant surface area increase that strengthens mechanical implant fixing in the bone tissue and an increase in the flow of ions derived from the implant material into the organism with resultant accumulation in internal organs [2]. Whether ion exchange between implant and bone takes place depends on chemical thermodynamics, but the kinetics of the process depends on the state of the materials.

The basic materials for implant manufacturing are metals and their alloys [3]. Such materials have the property to form an oxide film on the surface, which provides good biotolerance [3, 4]. Titanium is the most widely used for manufacturing implants [3] but insufficient corrosion resistance decreases its lifetime.

According to the literature [5], tantalum and niobium are often used as alternatives. The corrosion resistance of tantalum and niobium measured by electrochemical tests is 3 to 4 orders better than that of titanium [6], and allows an increase in the area of the basic implant surface with fewer corrosion-related problems. The oxide film that can be grown on tantalum and niobium surfaces has lower electroconductivity in comparison with titanium oxide and hence limits the speed of electrochemical corrosion.

The electrostimulation of processes in bone tissue near to the implant surface may also promote increased stability of the implant. This technique is based on the piezoelectric properties of bone and its ability to generate electrical potentials at various deformations [7]. Electrical fields created by deformation damage to bone tissue activates an ionic exchange process promoting restoration of the damaged area. *Mutatis mutandis*, artificially created electrical fields can activate osteosynthesis and accelerate healing; for example, after an implant operation electrostimulation will promote better fixing of the implant.

The use of an electret coating on the implant surface is the most expedient among various methods of producing an electrical field [7]. Such coatings generate electrical fields due to their ability to maintain a polarized condition or to accumulate and retain an electrical charge. Tantalum and niobium oxides with electret properties formed by an anodic oxidation method can be used as such coatings. Nevertheless, there is presently incomplete information concerning the interaction between such metals and living tissue in comparison with titanium, especially at the implant metal surface.

In this work, the morphological features of bone tissue organization were investigated in experiments on animals using implants made from titanium, tantalum and niobium, and a comparative analysis of implant stabilization in bone tissue at the modified surface was carried out.

2. METHODS

The implant samples were made from titanium, tantalum and niobium. The first series of samples used titanium plates with a polished surface simulating currently widely used types of implants. The second series of samples was made from tantalum or niobium. As these metals demonstrate higher resistance to corrosion than titanium, the porous coating was formed on this series of sample surfaces using sintering of tantalum and niobium powder

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on the implant surface to increase its surface area. The third series of samples was similar to the second one, except that the porous coating had an electret oxide coating made by anodic oxidation of the porous implant surface in a high electric field. This processing considerably raises the implant inertness (by a factor of at least 50)[1] at the expense of increased oxide thickness compared with the native oxide and produces an electret surface. After processing, the implant surface had a negative surface charge; the oxide had an amorphous structure.

The lower jaws of rabbits were used for the implant experiments. Channels of thickness 1 mm were formed in the jaw where plate implants of size 2 × 3 mm were placed (Fig. 1). The animals were divided into four groups: control (animals without implants) and three experimental ones (animals with implants). The titanium implants were fitted to the first experimental group of animals. Tantalum and niobium implants with a porous coating (pore diameter 50 to 150 μm) were fitted to the second group. These coatings were formed by sintering tantalum or niobium powder to compact metal in a vacuum ($P \sim 10^{-3}$ Pa) at $T \sim 2000$ K for 30 min. The tantalum and niobium implants with porous and electret coatings were placed in the third experimental group.

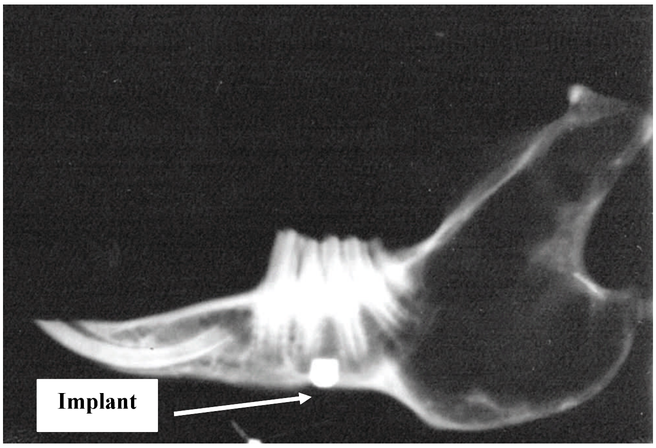

Figure 1. X-ray photograph of an implant inserted in the lower jaw of a rabbit.

The animals were removed from the experiment after 1, 2 and 3 months by air embolism.[2] Histological sections of thickness 6 to 8 μm were made using a Reichert microtome and stained and investigated using a Rathenow microscope.

Destructive tests for comparing the concrescence of the implants with bone used a 2038 P 005 machine. Fragments of bone with implants were investigated after three months in the rabbit's jaws.

3. RESULTS

The behaviour and feeding of the animals during the experiments were clinically supervised and the same for each group. The healing of the wounds after implant insertion passed without complications. None of the materials used in the implants were toxic to rabbits according to pathomorphological research data. Both the dystrophical and structural changes of the bone revealed no adverse or toxic effects nor was metal ion accumulation in tissue detected. The macroscopic investigation showed that for all terms after the operation (1, 2 and 3 months) all implants remained fixed. Bone tissue showed no changes of colour nor was diffusion of metallic material otherwise detected. Detailed observations are described below.

First group

Microscopic investigation at 1 month after implantation revealed a compact bone layer adjacent to the implant with a thin connective capsule consisting of several layers of collagen fibres assembled in bunches with fibroblasts between them (Fig. 2a). In bone tissue adjacent to the capsule, reactive changes connected with reorganized osteoblast structure were found. Osteoblasts within the narrow central channel contained fragmentary structures.

In the spongy bone tissue, the small centres of fibrous tissue in the intertrabecular spaces settled down in the implant contact zone. Bone trabeculae showed reactive changes. In some zones the lamellar bone tissue was combined with coarse fibrous tissue that indicated incompleteness of the reorganization process; the osteoblast density was lower.

Two months after the operation, a capsule containing dense connective tissue remained around the implant. In trabeculae of the spongy and compact bone, osteoblasts with inset plates and extended bone channels were observed. Some of the channels had sharply expressed basophil edges and the osteoblast density was high.

After three months with the titanium implants, the capsule remained and in some zones it consisted of dense bunches of collagen fibres, between which was a zone of fibroblasts.

Second group

In the compact bone of the second experimental group, after 1 month a connective capsule with variable thickness could be seen around the implants (Fig. 2b). On the whole, the compact bone tissue adjacent to the

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[1] The activity was compared under conditions simulating the influence of biotissue by measuring corrosion currents and the changes of mass or thickness of a specimen as it dissolved.

[2] Carried out in accordance with the international requirements for the humane manipulation of animals.

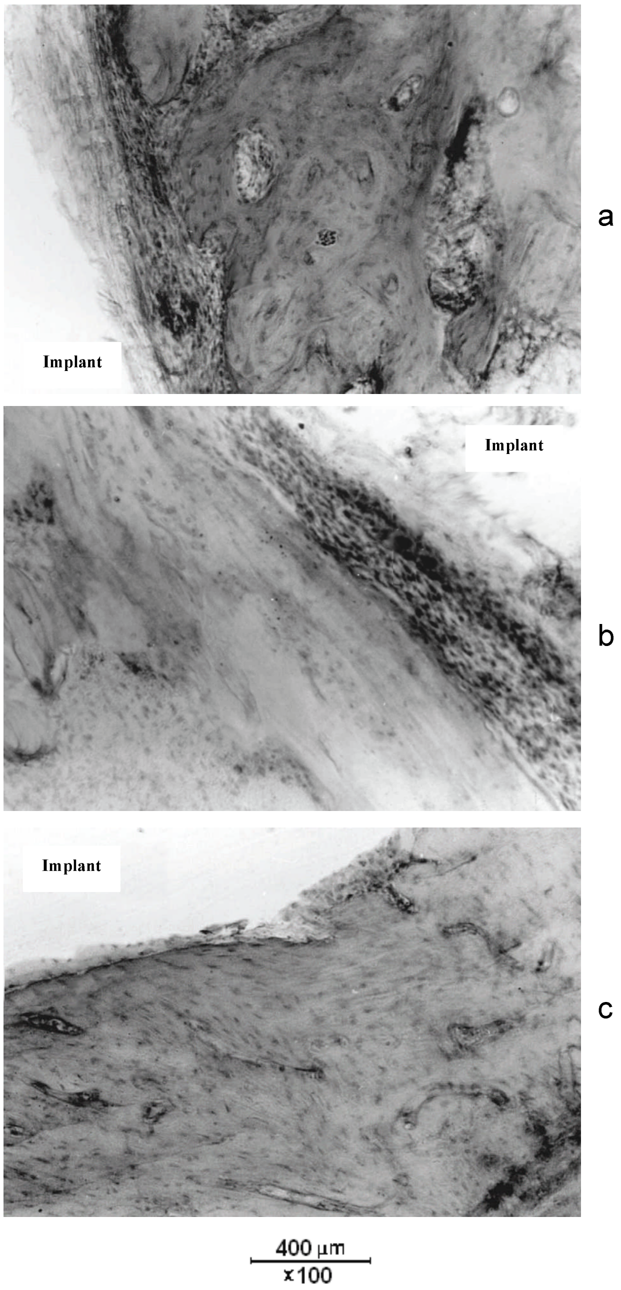

Figure 2. Contact zone of implant and bone tissue one month after implantation: a, titanium implant (first experimental group); b, tantalum or niobium implant with porous coating (second experimental group); c, tantalum or niobium implant with porous and electret coatings (third experimental group).

implant revealed no pathological changes. However, in a small zone reactive changes in the form of structure connected with loss of compactness and osteoblast absence were observed. In the spongy bone tissue zone, the implants were surrounded by a friable connective capsule.

After 2 months the reorganization processes in the compact bone around the implant were complete; osteoblast density was low. Small zones without osteoblasts were observed.

From 3 months after implantation the compact bone tissue adjacent to the implant became coarse and fibrous. Microcracks and spacious zones without osteoblasts were found.

Third group

At 1 month the implants in the third experimental group of animals were close to the compact bone layer. Only small zones had centres of connective tissue (Fig. 2c) and the bone tissue had attributes of reactive reorganization.

Two months after implantation the changes of bone tissue were displayed in small zones of compact bone.

Beyond 3 months, the centres of microdestruction and the zone of bone tissue reactive reorganization were in the compact and spongy bone tissue. Around the implants a sharp basophil border with lines of bone tissue cementation was formed that indicated the bone-forming processes; osteoblast density was high. Vessel channels of various calibres were surrounded by a friable connective tissue and the connective capsule was thinner in comparison with other groups.

4. DISCUSSION AND FURTHER RESULTS

Around all of the implants, in the zone of contact with compact bone and the bone marrow of the intertrabecular spaces of spongy bone, a connective capsule was formed but differed in structure in the three groups. The processes of bone tissue reorganization were observed in all groups but the greatest difference in biological reaction of the bone tissue to the implant was found for the third group where the extent of bone destruction was much less. Such features can be explained both by the ability to restrict blood clotting by the porous implant surface that is important for the adhesion of osteoblasts and the direct deposit of albumin on the surface and by the electrical field of the electret coating that stimulates these processes. Hence, histological investigation has shown that using implants made from tantalum and niobium with a modified surface leads to essential activation of bone tissue regeneration processes by the electret properties of the oxide film.

Test results of implants and bone tissue adhesion are shown in Table 1. In the second column, the adhesion of the porous coating on the implant surface after sintering is shown. The adhesion of the porous coating per area unit was 1.5 ± 0.1 kg/mm^2 which exceeded the adhesion of the implant from bone tissue in all cases (range of values from 0.4 up to 0.8 kg/mm^2). Hence, in all the experiments the bone tissue and/or implant broke and separation of the porous coating from the implant surface did not occur.

The minimal adhesion was observed for the polished samples, as expected. The separate fragments of bone

Table 1. Bond strength of implant with bone tissue.

Sample	Bond strength of porous coating with implant metal (niobium)	Ti	Ta, Nb with porous coating	Ta, Nb with porous and electret coating
Adhesion / kg	24.1 ± 0.1	4.3 ± 0.1	6.2 ± 0.1	7.4 ± 0.1
Surface area / mm^2	16	10	10	10

tissue accreted with the coating are visible under the microscopic on the sample surfaces with porous coatings (Fig. 3). Additional passivation connected with the formation of the electret layer on the porous implant surface resulted in an approximately 20% increase of adhesion.

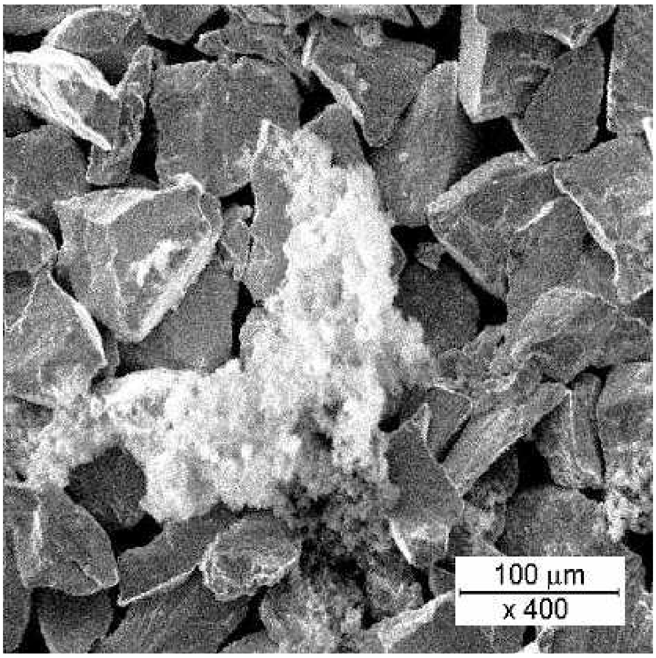

Figure 3. Surface of niobium implant with porous coating and separate fragment of bone tissue after implant extraction.

Considering that the implant duration in the rabbit jaws was short (about 3 months), the difference in chemical properties between the titanium and tantalum or niobium was not expected to be so dramatic. According to electrochemical research [5, 6], the difference of corrosion resistance of these metals becomes appreciable only after 25 to 30 months of use. Hence, it can be inferred that the improved implant stabilization for the second experimental group of animals is due only to the presence of a porous coating.

The further stabilization of the third group is due to the presence on their surface of an electret layer with a negative volume charge that accelerates transport of Ca^{2+} and ions to the implant surface an essential providing, thereby the base material for new bone tissue formation.

In conclusion, an increase of implant stabilization in bone tissue can be achieved by several means. First, it is necessary to increase the implant surface supporting area which imposes the use of more inert tantalum and niobium in comparison with titanium. Further benefit arises from the effect of the electret properties of tantalum and niobium oxide films. The cumulative application of both measures will enable a reduction of rehabilitation time for patients after the implant operation compared with the conventional titanium coating.

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