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How to Choose between the Implant Materials Steel and Titanium in Orthopedic Trauma Surgery: Part 2 – Biological Aspects

Jak zvolit mezi ocelovými a titanovými implantáty v ortopedické traumatologii. Část 2 – biologické aspekty

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BIOLOGICAL ASPECTS OF STEEL AND TITANIUM AS IMPLANT MATERIAL IN ORTHOPEDIC TRAUMA SURGERY

The following case from the ICUC database, where a titanium plate was implanted into a flourishing infection, represents the clinical experience leading to preferring titanium over steel. (Fig. 1) (6).

Current opinions regarding biological aspects of implant function.

The "street" opinions regarding the **biological** aspects of the use of steel versus titanium as a surgical trauma implant material differ widely. Statements of opinion leaders range from "I do not see any difference in the biological behavior between steel and titanium in clinical application" to "I successfully use titanium implants in infected areas in a situation where steel would act as foreign body "sustaining" infection." Furthermore, some comments imply that clinical proof for the superiority of titanium in human application is lacking. The following tries to clarify the issues addressing the different aspects more through a practical clinical approach than a purely scientific one, this includes simplifications.

Today's overall **biocompatibility** of implant materials is acceptable but:

As the vast majority of secondary surgeries are elective procedures this allows the selection of implant materials with optimal infection resistance. The different biological reactions of stainless steel and titanium are important for this segment of clinical pathologies. Biological tolerance (18) depends on the toxicity and on the amount of soluble implant material released. Release, diffusion and washout through blood circulation determine the local concentration of the corrosion products. Alloying components of steel, especially nickel and chromium, are less than optimal in respect to tissue tolerance and allergenicity. Titanium as a pure metal provides excellent biological tolerance (3, 4, 16). Better strength was obtained by titanium alloys like $TiAl_6V_4$. The latter found limited application as surgical implants. It contains Vanadium (9). Today's high strength titanium alloys contain well tolerated alloying components[1] like Zr, Nb, Mo and Ta (ISO 5832-14) (7, 15).

The **corrosion** rate of surgical implants is kept low by the passive layer formed when immerged in body fluids (13, 14). The passive layer may be locally destroyed, for instance, by mechanical fretting or by local corrosion conditions like in pitting; it is renewed by an electrochemical corrosion process which releases alloying components like Ni and Cr (Fig. 2) (10). The amount of soluble component may vary markedly depending on the local electrochemical conditions (see below).

Adhesion, mechanical irritation, capsule formation and dead space

The **adhesion** of surrounding tissues onto the implant surface (11) plays an important role in respect to resistance to infection (Fig. 3). Without adherence mechanical irritation induces formation of a capsule that encompasses a dead space (Fig. 4, Fig. 5) The capsule diminishes the access of cells defending infection and favors growth and the propagation of bacteria.

In the ideal case a soft granulation tissue attaches to the implant immediately after implantation, providing a soft bridge from implant to moving tissue. Then the bridging tissue stiffens and the load together with increasing adherence maintains the contact and avoids dead space. This is a situation where titanium stands out in its support of infection resistance. Whether a tissue adheres depends on strength of contact between tissue and implant and on the peeling[2] force applied.

[1] With the exception of TiAl6V4 which contains with Vanadium (9) a toxic element tolerated due to very small release.
[2] The term peeling includes here classical peeling (pulling away) and displacement along the surfaces (shear).

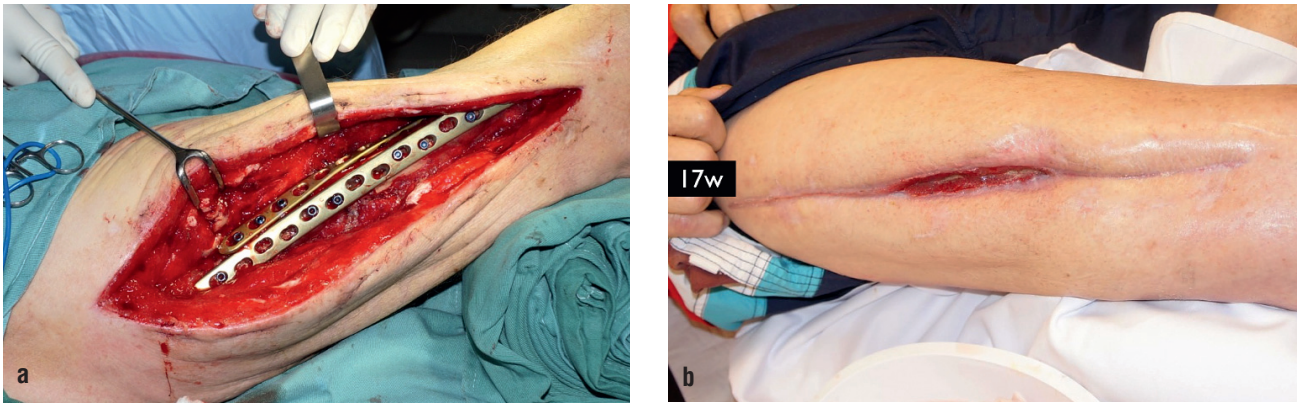


Fig. 1. ***Absent foreign body effect:*** *Double titanium plates used for stabilization of a flourishing S. aureus infected re-osteosynthesis. 17 weeks later, the wound is healed. How would the picture look after steel implantation?*

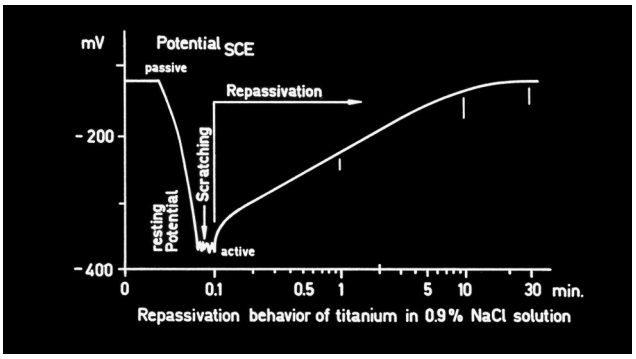


Fig. 2. ***Scratching destroys the passive layer****. Within minutes the passive layer is rebuilt. This process releases corrosion products. Steel and titanium differ in respect to speed of reformation of the passive layer (4).*

Different types of corrosion

When a bulk material of steel or titanium is immersed in biological fluids the corrosion rate of both intact materials is very low due to the protection offered by the passive layer. Once scratching destroys the **passive layer** locally the two materials behave differently. Steel is very sensitive to discontinuities in the local environment. Fretting and/or crevices may produce a local condition that maintains corrosion. When corrosion attack produces a small pit the local lack of oxygen in the pit or in a crevice may prevent passivation and the local conditions maintain a hundred-fold rate of corrosion compared to bulk material (Fig. 6). Titanium is not subject to similar conditions of corrosion but the product of abrasion does not dissolve (Fig. 7).

Fretting corrosion and abrasion

When an implant like a plate screw becomes loose mechanical fretting conditions between plate and screws arise. The passive layer will be repeatedly destroyed. In this situation steel and titanium behave differently. Even today in such a situation appreciable corrosion in steel may result (Fig. 6). Mechanical abrasion is different; in titanium it may form inert metallic deposits (Fig. 7).

BIOCOMPATIBILITY TESTING, OUR OWN EXPERIENCE

Biocompatibility testing *in vitro*

Tissue or bone organ cultures were used for preliminary screening tests (3). In organ culture bone rudiments were cultivated whereby soluble metal salts were added to the culture medium or where small metal pins were

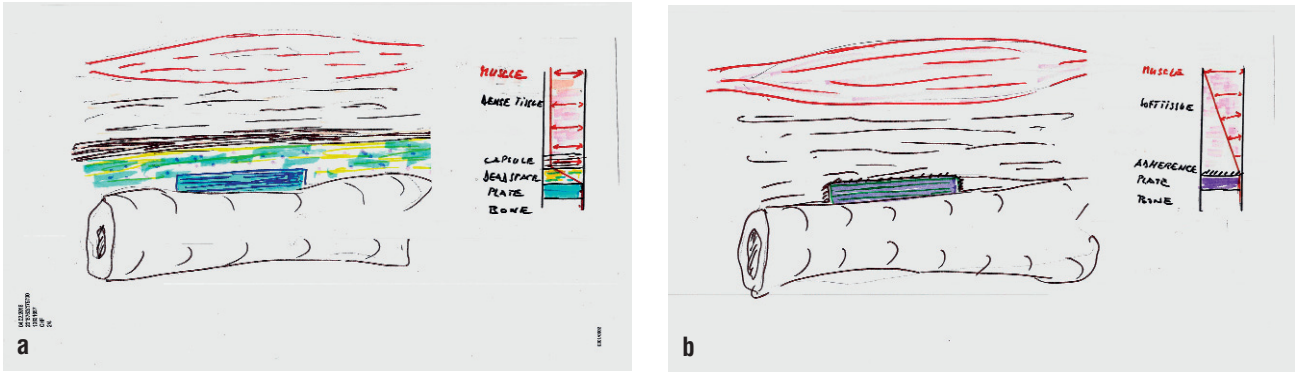


Fig. 3. The importance of ***initial tissue adherence*** *in respect to capsule formation and deleterious dead space around the implant. LEFT: when the tissue does not adhere to the implant a zone of high strain produces mechanical irritation and a dense capsule and a dead space develops. RIGHT: when the tissue adheres from beginning on the soft tissue takes deformation up in a gradient without discontinuity, no dead space, good resistance to infection.*

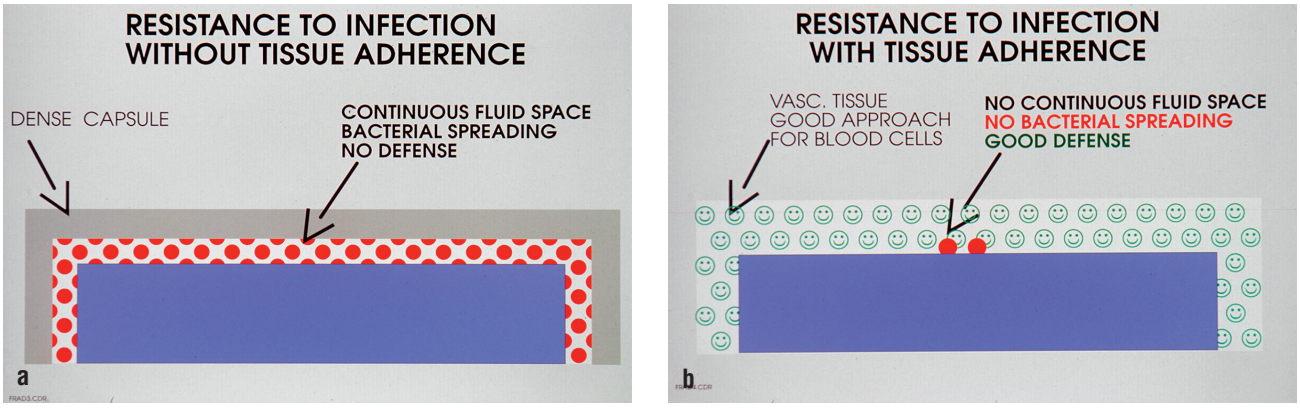


Fig. 4. ***Dead space****. LEFT: Lack of adherence results in dead space around the implant allowing bacteria to expand and the usually thick capsule impedes the access of body reaction to the infection site. RIGHT: Good adherence of soft tissue to the implant. In this case adherence prevents bacteria from spreading and the avoidance of capsule formation improves the access of body defenses.*

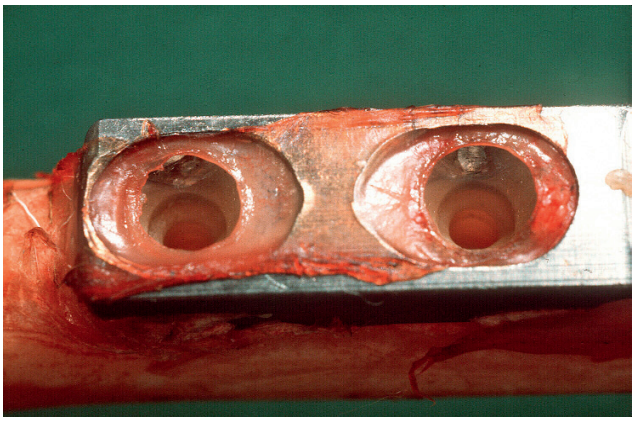


Fig. 5. ***Extremely strong adherence*** *of soft tissue to c.p. titanium surface. Observation with c.p. titanium, special edging. When the soft tissues were pulled appreciable force was required and still this layer stuck to the titanium.*

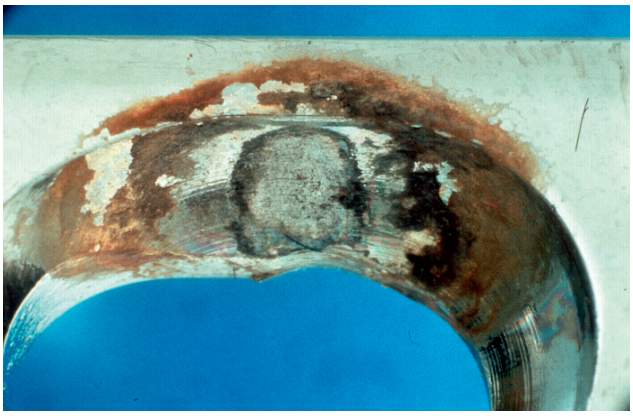


Fig. 6. ***Fretting conditions*** *with a plate screw moving and producing appreciable corrosion in steel, still today.*

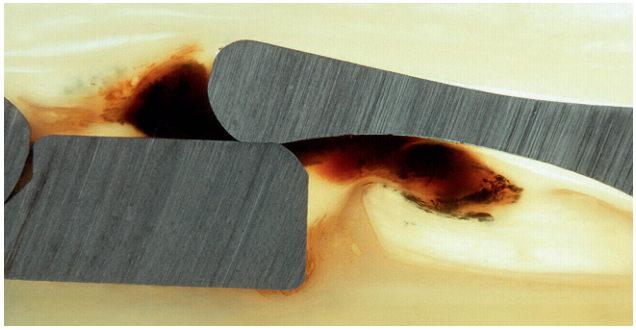


Fig. 7. Experimental production of ***mechanical abrasion*** *in vivo, producing non corroding metallic deposits in titanium.*

inserted into the bone rudiments. The length of the epiphysis was used as a parameter of growth. (Fig. 8)

Tissue tolerance in animals

Biological compatibility of different implant materials has been widely tested in animals. Because mechanical irritation through movement of the tissues in relation to the implant surface results in cellular reaction, the shape of the implant plays an important role (4). A small cylindrical implant will experience mechanical irritation while the so called "Davos implants" that meet ISO standards provide a segment of contact which is protected from mechanical irritation (Fig. 9.–Fig. 10).

Tissue tolerance in humans

The sampling of tissues at implant removal allows observation of the presence of blood vessels and cells at different distances from the implant. While the amount of round cells is similar, all the other elements of tissue reaction show important differences between steel and titanium implants in favor of titanium (Fig. 11) (16).

Allergy testing through measurement of leucocyte migration

It is today accepted that 25% of young female persons react to skin contact with nickel. Allergic reaction to implants containing nickel are less frequent. With this difference in mind patch testing is of limited value when selecting an implant material. Therefore, a test that measures **systemic** changes was used. The migration

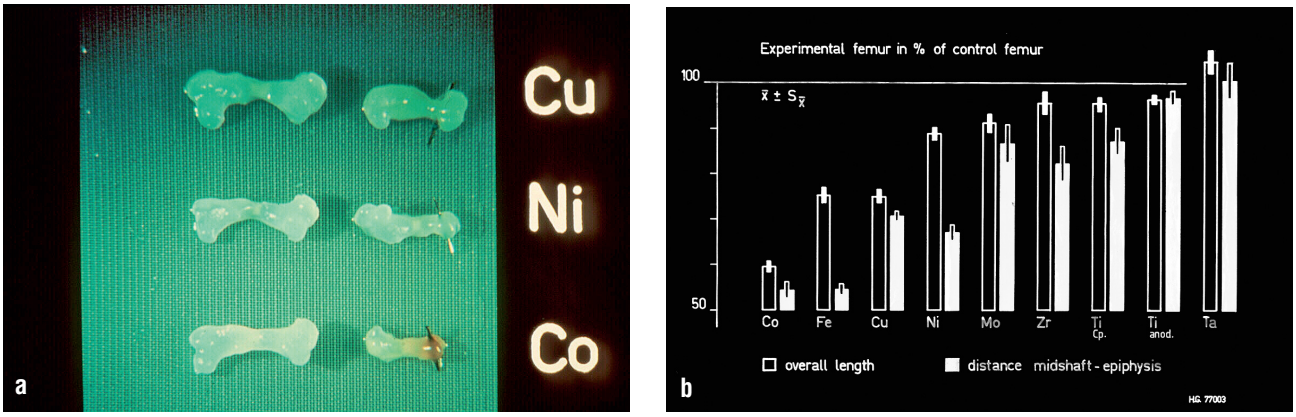


Fig. 8. ***Organ culture*** *testing reactions to implanted metal pins. LEFT: The length of the epiphysis was used as a parameter of growth (3). RIGHT: the results of different metal salts.*

of leucocytes reacts very sensitively to systemic immunological reactions (20). The effect of corrosion products on the migration of the blood cells was observed. The so-called Leucocyte Migration Test provides information on systemic reactions (Fig. 12) (20). Unfortunately, the migration test does not lend itself to prognosis.

Clinical observation

The testing of leucocyte migration in a patient with a steel implant was revealing. The patient, a medical doctor, repeatedly reported uneasiness with the implants used for stabilization of his malleolar fracture. Several blood tests with steel implants in place showed suppressed leucocyte migration. When the steel implants were removed, uneasiness subsided and the migration recovered to normal (Fig. 13) (19). We do not know of titanium allergy reported under conditions excluding all other allergens.

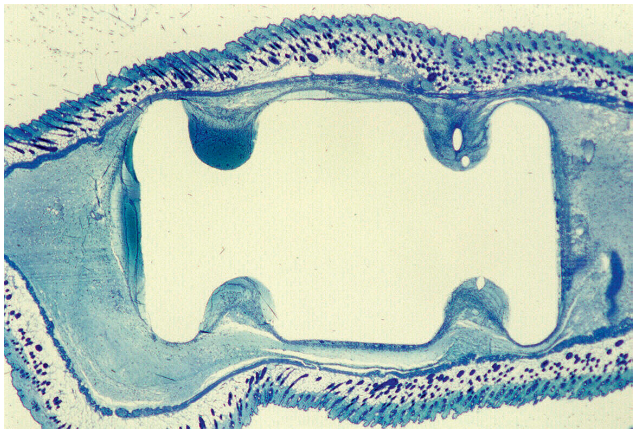


Fig. 9. Testing ***in vivo biocompatibility*** *using "Davos" cylinders eliminating artefacts due to mechanical irritation. The tissue between the grooves is stably connected and artefacts avoided (4).*

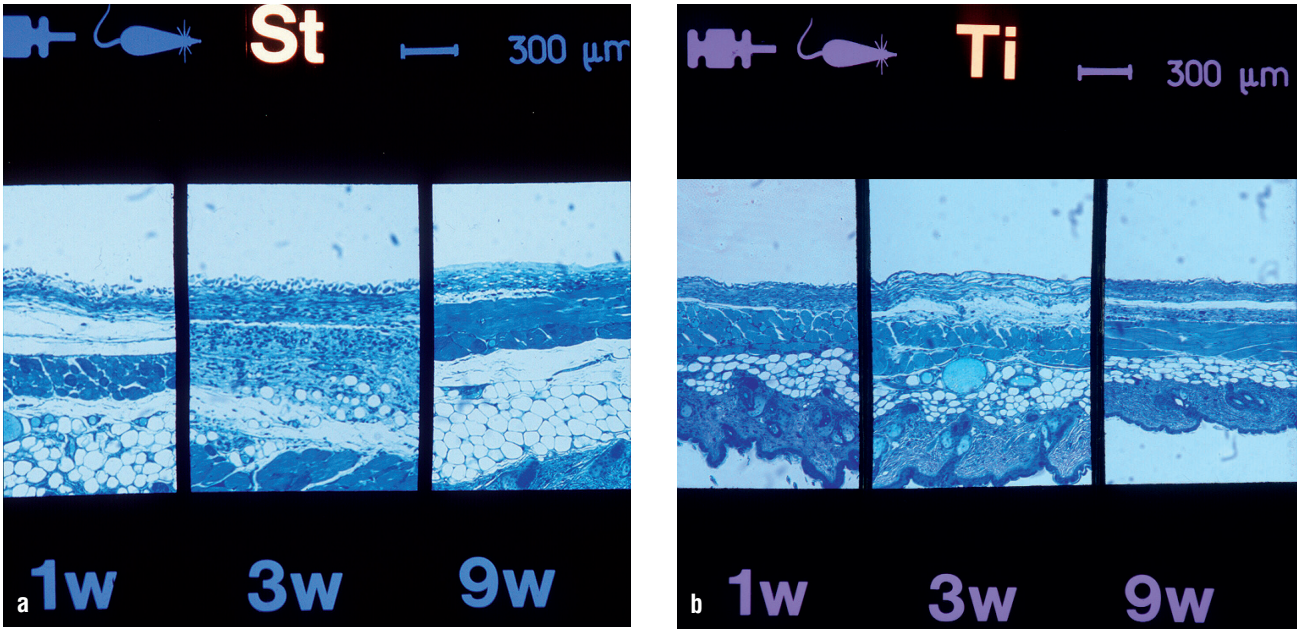
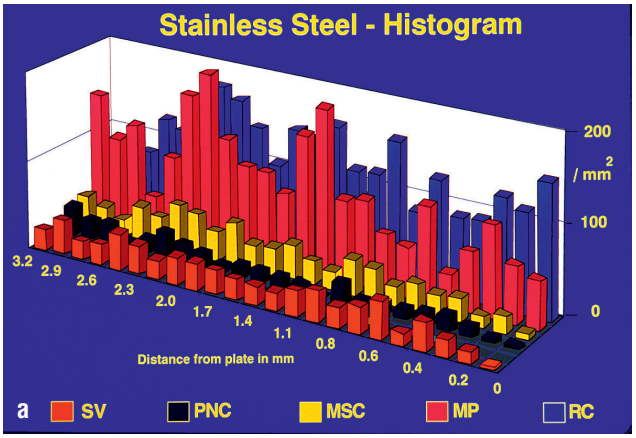


Fig. 10. The tissue reaction to ***steel and titanium bulk material*** *at 1, 3 and 9 weeks observation. Mechanically stabilized interface. Good acceptance of both as bulk materials with a low corrosion rate (4).*



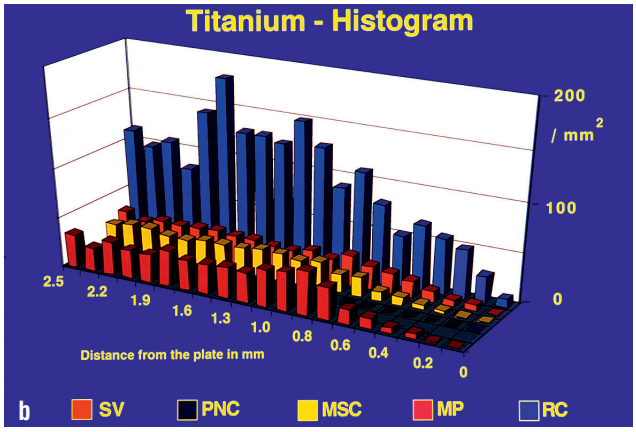


Fig. 11. ***Human biopsies*** *from steel and titanium at different distances from the implants. The MP shows a large count in steel; the small vessels are more prominent in titanium (16).*

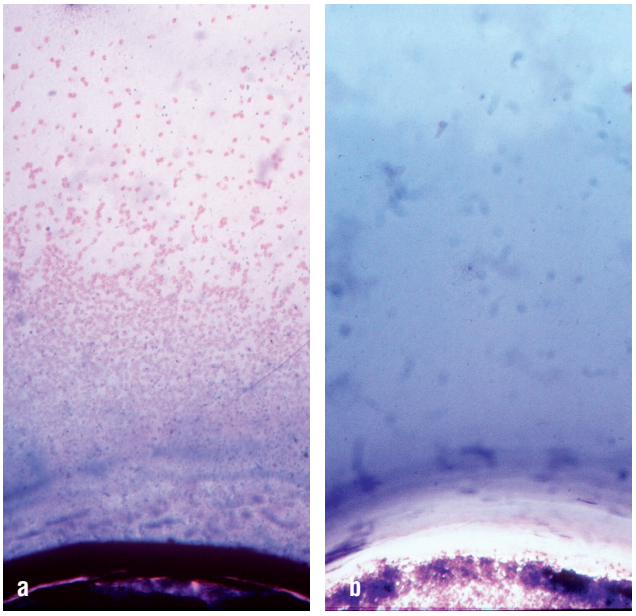


Fig. 12. ***Leucocyte migration*** *test. LEFT control: the cells migrate from the buffy coat below into the control medium; RIGHT: in a medium containing nickel, migration is inhibited (20).*

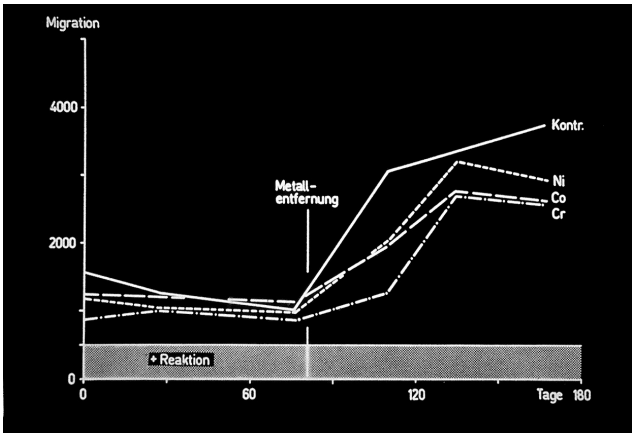


Fig. ***13. Leucocyte migration before and after removal of steel implants****. Suppressed migration and pain before implant removal (20).*

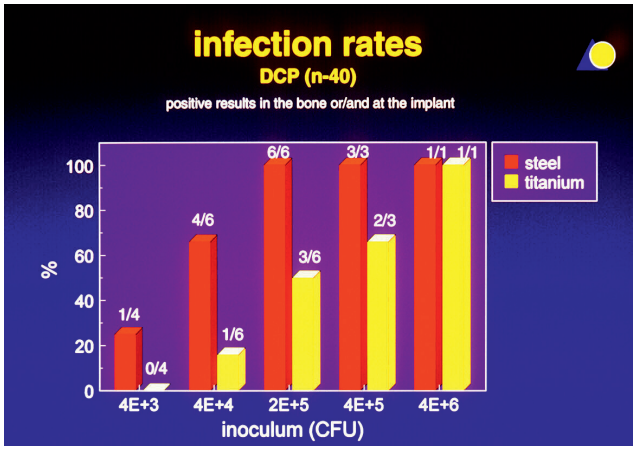


Fig. 14. ***Infection rate related to inoculum doses (CFU).*** *The numbers indicate the number of infected and the total number of animals at each inoculum dose Superior result with titanium (5).*

Infection

The superior infection tolerance observed with titanium implants has been repeatedly documented in animals (1, 5) (Fig. 14) and also in humans (16). Several surgeons switching from steel to titanium stated that for titanium implants implanted into infected areas the problems observed with steel were absent (2, 8).

Combined use of steel and titanium implants

Because of shortage of one of the materials but also to take advantage of the different characteristics of steel and titanium like the problem of galling mentioned above, it may make sense to combine steel and titanium implants, because each metal when submersed in a conducting fluid (like Ringers) undergoes polarization resulting in a material-specific electric resting potential. If two different materials are submersed and electrically connected, be it by contact or wired, the difference in the resting potential gives rise to an electric current corroding the one with the higher positive resting potential. The electrical isolation of titanium prevents galvanic corrosion (no current→no corrosion→no release). Rüedi (12) as well as Wächter (17) demonstrated that steel

screws applied to titanium plates do not produce galvanic corrosion and are tolerated as steel alone without diminishing the advantage of titanium biocompatibility.

CONCLUSIONS

Titanium is a biologically superior implant material, taking advantage of its biology requires careful attention to tissue adherence that is critical in the initial stages of tissue-to-implant reaction. Adequate adherence avoiding dead space formation which promotes deleterious expansion of bacteria is critical. Mechanical irritation between moving tissue and resting implant when adhesion fails is suspected to result in formation of a dense capsule that impedes access of mobile infection defense. We do not expect a single improvement to resolve all problems, but the way to an optimal implant is paved with research contributions and careful clinical consideration of an optimal balance between pros and cons.

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