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Fixation of carbon fibre-reinforced carbon composite implanted into bone

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The push-out test of three types of biomaterials: carbon fibre-reinforced carbon (CFRC), hydroxyapatite (HA), and surgical steel (SS) implanted into rabbits' femurs was carried out. Hydroxyapatite was used as a positive control (good fixation expected in bone) and surgical steel was a negative one (potentially no fixation in bone). Regeneration of bone in contact with all implants was found three months after implantation. The shear strength between CFRC implants and bone was lower than with the HA implants and higher than the shear strength between the surgical steel and bone. Compressive strength of CFRC implants removed after the observation period was significantly lower than the compressive strength of non-implanted samples. It is concluded that the mechanical bonding between the CFRC implants and host tissues exists 3 months after intrabone implantation and is accompanied by a decrease of the strength of implants.

1. Introduction

Carbon fibre-reinforced carbon (CFRC) seems to be a promising material for use in orthopaedic surgery due to its good biocompatibility and low stiffness. It is used in the internal fixation devices and in the hip endoprosthesis as the material from which the stem is made [1]. Good contact between carbon implants of any kind and bone tissue has been reported by some authors based on morphological observations [1–6]. However, the nature of this junction remains unclear. Bone-bonding behaviour of bio-materials may be characterized in the push-out test, in which the shear strength between the implant and the tissue is measured while removing the implant from the bone [7–10]. The results of such a test for CFRC have been reported, as compared with titanium implants [9]. In this work the push-out test of three types of biomaterials: CFRC, hydroxyapatite (HA), and surgical steel (SS) implanted into rabbits' femurs was carried out. Since hydroxyapatite is well known as a bioactive material which encourages strong fixation in the bone, it was utilized as a positive control in this experiment. On the contrary, surgical steel, which is utilized in the internal fixation devices, and is classified as an inert biomaterial, was used as the negative control.

2. Materials and methods

2.1. Implants

Three types of materials were tested (Fig. 1). Carbon fibre-reinforced carbon implants were obtained from Dr J. Chłopek, the Academy of Mining & Metallurgy, Cracow, Poland. They consist of carbon fibres obtained from polyacrylonitrile (PAN) and carbon matrix manufactured on the base on phenol–formaldehyde resin. Their surface is covered by pyrolytic carbon. Open porosity of CFRC implants is equal to approximately 5%. Technological data on material is presented elsewhere [11]. Hydroxyapatite samples were acquired from Dr Ślósarczyk, the Academy of Mining & Metallurgy, Cracow, Poland. Metallic implants were obtained from surgical steel Steinmann pins. All the materials were implanted in the form of rods of 10 mm length and 3.2 mm diameter.

2.2. Surgical procedure

Adult male New Zealand White rabbits, weighing 3.0–3.5 kg were used. Holes, 3.2 mm of diameter were drilled bilaterally in the femurs by means of a trephine, under general anaesthesia. Implants were introduced transversally into cortical bone across both diaphyses. One implant was inserted into each femur. Six implants of each type were used. CFRC implants were inserted into the left femurs and hydroxyapatite implants into the right femurs of three animals. Three further animals were operated by implantation of CRFC into the right femurs and surgical steel into the contralateral ones. The remaining hydroxyapatite and steel implants were implanted in the left and right sides of another three rabbits, respectively. Animals were killed 3 months after implantation, the implants

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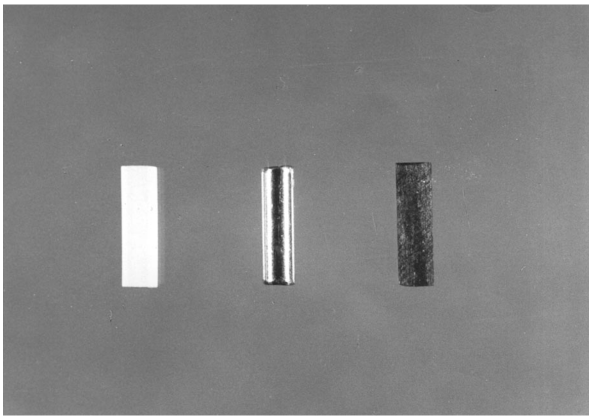

Figure 1 Three types of implanted materials: hydroxyapatite (HA), left; surgical steel (SS), centre; and carbon fibre-reinforced carbon (CFRC), right.

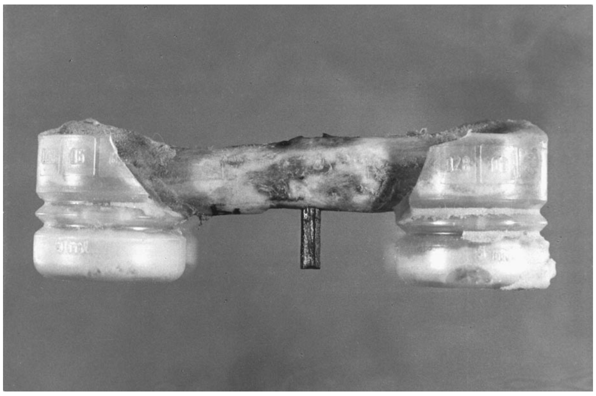

Figure 2 The sample after push-out test – illustration of the specimen position.

were removed by push-out tests and afterwards tissue surrounding the implants were fixed and prepared for histological observation.

2.3. Mechanical examination

Fresh bones underwent mechanical tests. Both ends of each femur were firmed with the aid of duracryl, as shown at Fig. 2. Then the bone was placed in the Instron machine so as the bone near the implant leaned upon the metal platform with circular opening of 4 mm diameter. A 3 mm diameter metal plunger was used to push-out the implant through this 4 mm opening at a constant rate of 2 mm min^{-1} and the applied force was registered at the diagram (the example shown in Fig. 3). The shear strength was obtained as the quotient of the maximum force and the interface area

$$S_s = F/(\pi d 2h) \qquad (1)$$

where: S_s is shear strength; F is maximum force needed to push-out the implant (obtained from the Instron diagram); d is implant diameter; h is cortical thickness. The cortical thickness was measured by slide calliper and was equal to 1.2 mm in all cases.

The values obtained for CFRC implants were compared independently with those acquired for both HA and steel samples by means of the Wilcoxon test.

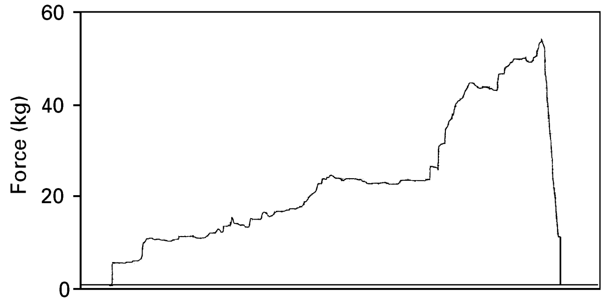

Figure 3 The example of "push-out" diagram obtained from the Instron machine.

Compressive strength tests of CFRC implants both removed after 3 months and non-implanted ones were carried out. Compressive strength was calculated as the quotient of the applied force and the surface area of the implant

$$S_c = P/\pi(d/2)^2 \qquad (2)$$

where: S_c is compressive strength; P is force needed to destroy implant in the compressive test; and d is implant diameter. The values obtained for non-implanted samples and specimens removed from the femurs were compared using the Wilcoxon test.

2.4. Histological procedure

Bone surrounding the implants removed 3 months after implantation was fixed, decalcified, embedded, sectioned, stained with haematoxylin and eosin and observed by means of light microscopy.

3. Results

3.1. Push-out test

The results of push-out tests are presented in Fig. 4. The shear strength between CFRC implants and bone is significantly lower when compared with the HA implants and is significantly higher when compared with surgical steel implants.

In the case of hydroxyapatite pushing-out was accompanied by the compressing of the implants. All HA samples were damaged after removal.

Compressive strength values of CFRC implants are presented in Fig. 5. It is almost six times lower for implants pushed out from the bone 3 months after implantation than for the non-implanted samples. The entire damage, including fibre failure, was observed rather than debonding between the fibres and carbon matrix in CFRC samples after compression tests.

3.2. Histological observations

There was no connective tissue encapsulation around the implants. Bone tissue was visible near the hole remaining after the implant removal in all analysed cases. Examples of histological pictures of such places are shown in Fig. 6. The surface of the bone tissue near the metallic implants seems to be smooth. The tissue surrounding both HA and CFRC implants has irregular surfaces. Carbon particles are observed on the

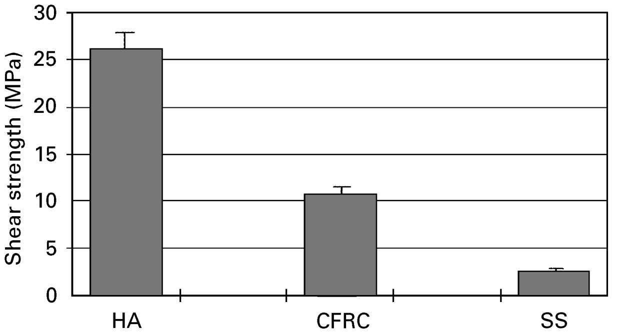

Figure 4 The results of push-out tests. Shear strength for hydroxyapatite (HA), carbon fibre-reinforced carbon (CFRC), and surgical steel (SS) are represented by mean values with standard errors marked.

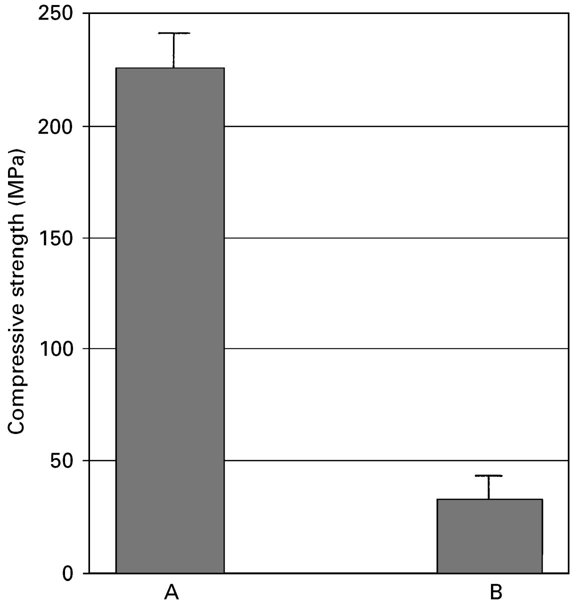

Figure 5 Compressive strength of CFRC implants both non-implanted (A) and removed 3 months after implantation (B); standard errors are marked.

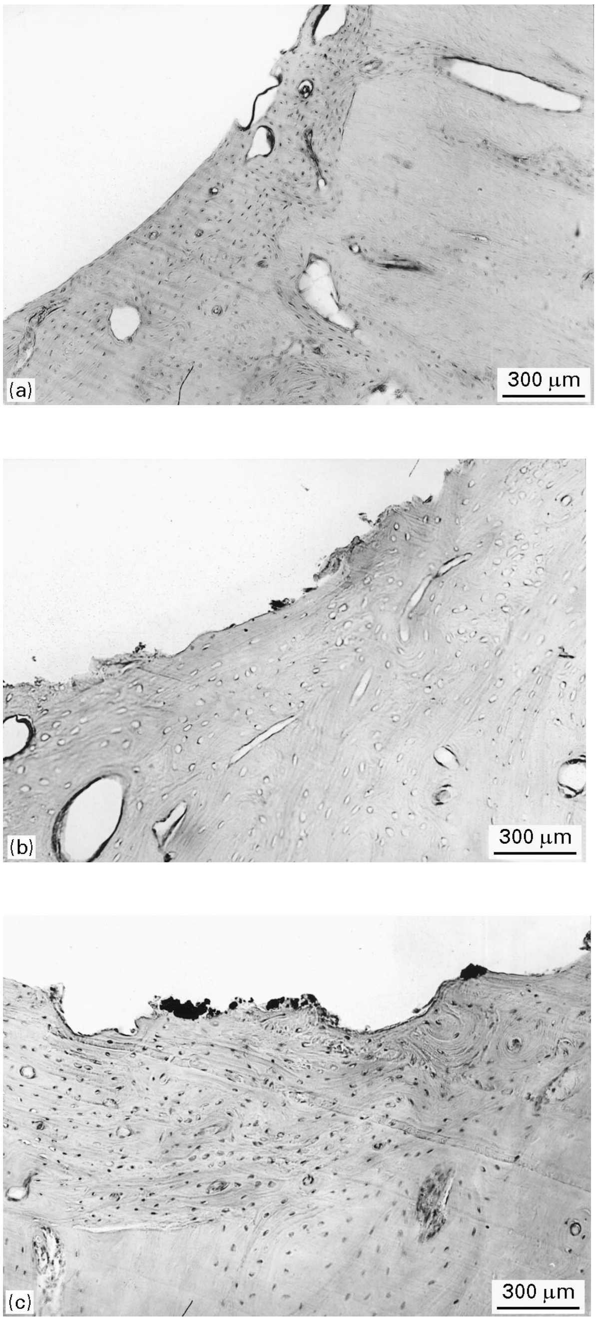

Figure 6 Histological pictures of bone tissue visible near the hole remaining after the implant removal; the implant was made of (a) surgical steel, (b) hydroxyapatite, (c) carbon composite; original magnification 100 ×.

surface of the bone which was in contact with CFRC implants.

4. Discussion

The results of the push-out test suggest that a kind of bonding between CFRC and bone must occur 3 months after intrabone implantation. Although the bonding is not as strong as the attachment between HA and bone, bonding osteogenesis seems to appear near the CFRC implants, in contrast to contact osteo-genesis which arises around implants made from surgical steel.

Since hydroxyapatite samples were damaged to some extent after removal from the bone, it seems that the shear strength between the HA implants and bone is higher than the compressive strength of HA 3 months after implantation. The CFRC compressive strength decreased significantly 3 months after implantation. However, it should be taken into account that the CFRC samples used in the compressive test were previously pushed out from the bone. Although implants did not appear damaged after removal from the bone, they might have been compressed to some extent while being pushed out. Due to the similar value of push out force (265 N) and the average compressive strength force (281 N) it cannot be excluded that the push out test had loaded the specimen such that when compressive testing was applied failure had already been initiated. Therefore reduction of compressive strength of CFRC may be not be as high as six times as compared with the control. Anyhow, it might indicate that some changes in the structure of CFRC implants appear in consequence of intrabone implantation. It would be in compliance with the morphological observation of the CFRC samples implanted into rat femurs, where the penetration of connective tissue deep inside the implants was found 5 weeks after implantation (unpublished data). It was combined with the disruption of fibre configuration within the matrix, as visualized by scanning electron microscope. Tissue growth inside the implants seems to be possible mainly due to the initial porosity of the material. However, the ability of cells in culture to make new voids inside CFRC implants was found [12]. In both cases a penetration of host tissue within the implants must influence the mechanical properties of implants and may be responsible for the bonding between the implants and host tissues.

5. Conclusions

A mechanical bonding between the CFRC implants and host tissues exists 3 months after intrabone implantation and this phenomenon is accompanied by a decrease in the strength of implants.

The shear strength between CFRC implants and bone was lower than with the HA implants and higher than the shear strength between the surgical steel and bone.

Three currently used implant materials, surgical steel, hydroxyapatite and CFRC, exhibit important differences in their physical characteristics. The average push-out force for surgical steel is considerably lower than its strength, whereas with hydroxyapatite pushing-out is accompanied by compression of implants. In the case of CFRC implants, however, the average push-out force and average compression strength 3 months after implantation are very similar.

Acknowledgements

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