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POROUS CERAMICS AS A BONE SUBSTITUTE IN THE MEDIAL CONDYLE OF THE TIBIA

An Experimental Study in Sheep. Long-Term Observations

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A recent 3-month implantation study indicated that a new porous ceramic material might be suitable as a bone substitute in regions exposed mainly to compressive forces. The porous ceramics were implanted into the medial condyle of the tibia of sheep. In the present study the implants were left for 10 months in three animals, and 12 months in two. In the two animals with 12 months' observation, the plate which had been used to stabilize the implant was removed at 10 months. The implants and the adjacent bone tissue were studied macroscopically, radiographically and by microradiography and transmitted light microscopy. All the implants were bound to the adjacent bone by ingrowth of bony tissue. The depth of the bony invasion was slightly greater than that observed at 3 months, being maximally 3–4 mm. Some signs of ossification were still seen within the pores. The bony bridges between the implants and the surrounding bone were particularly well developed in regions of maximal stress. This was interpreted as a sign of active adaption of the bone formation to the actual stress to which the shearing surfaces were exposed. It is concluded that the properties of the porous ceramic implants justify a clinical trial in man.

Key words: bone substitute; porous ceramics; tibial condyle fracture

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In a previous study (Benum et al. 1976) a new porous ceramic material was tested for possible use as a bone substitute in regions exposed mainly to compressive forces. The porous ceramics which mainly consisted of Al_2O_3 were implanted into the medial condyle of the tibia in sheep and left in position for 3 months. The implants were found to be bound to the adjacent bone by ingrowth of bony tissue. It was concluded that a clinical trial was justified if the results of long-term observations proved equally satisfactory.

In the present investigation we have studied the fate of the implants for up to 12 months and have paid particular attention to the anchorage of the implants to the surrounding bony tissue.

MATERIAL AND METHODS

The implants were similar to those used in the short-term observations. The pore size was 100–1000 μ (Benum et al. 1976).

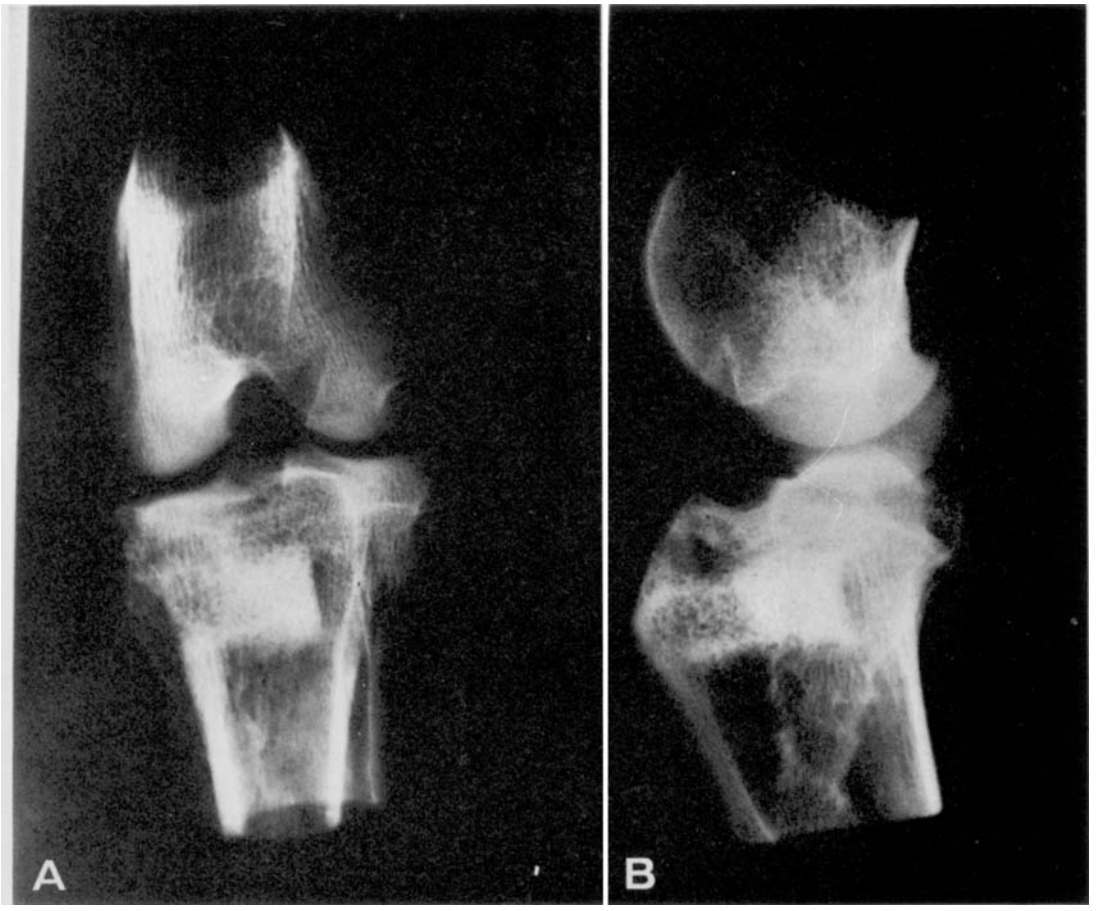


Figure 1. Radiographs of an implant 12 months postoperatively. The plate which was used to keep the implant in position was removed 2 months prior to sacrifice. A. Frontal view. B. Medial view. There is no sign of collapse of the tibial plateau and no sign of osteolysis around the implant.

Animals

Six female sheep, weighing 45–60 kg, were used. Their age varied from 6 to 8 years; epiphyseal fusion of the tibia had occurred in all animals.

Surgical procedure, postoperative regimen

The operations were performed in exactly the same manner as described earlier; the postoperative regimen was also unchanged (Benum et al. 1976). One animal died of intercurrent disease; the five others appeared totally unaffected by the operation.

Investigative procedure

Three animals were sacrificed 10 months after operation. In the remaining two the operated knee was X-rayed at 10 months, the AO-fingerplate was then removed, and the animals allowed to resume their normal activities for another 2 months before they were sacrificed.

After sacrifice the operated knee and the proximal part of the tibia were removed and inspected, the specimens were fixed in formaldehyde, X-rayed and dehydrated in alcohol, and finally embedded in methylmethacrylate as described earlier (Benum et al. 1976).

The subsequent investigative procedure was also similar, except that all sections were cut in the coronal plane.

Contact micro-radiographs were taken of 300 μ thick sections, as described by Jowsey et al. (1965). The sections were then ground down to a thickness of 40–50 μ and stained with Paragon

1301 ("Paragon PS 1301", Paragon C & Co, 1 nc, Bronx, N.Y., USA).

Both contact micro-radiographs and stained sections were examined by light microscopy.

RESULTS

Function and macroscopic appearance

All the surviving animals recovered normal function after the operation. At sacrifice there were no signs of local infection or reaction around the implants. All the implants appeared firmly anchored to the surrounding bone, and there were no macroscopic signs of fracture of the implants or the tibial condyles.

Radiological examination

No signs of fracture or collapse of the impants or the tibial condyles were seen at sacrifice. There were no signs of resorption of bone above or below the implants. In the two cases where the plate had been removed 2 months prior to sacrifice, no radiographic changes were seen after removal of the plate (Figure 1).

Microradiography

The findings were almost identical in all the animals. In all parts of the implants which were in contact with bone, all surface irregularities and the most peripheral pores appeared to be filled with bone. The invasion of bony tissue was most extensive in the part of the implants which rested upon the supporting peripheral ring of cortical or cancellous bone. The maximal depth to which the pores appeared to be filled with bone was 3–4 mm. The depth of bone invasion was considerably less in the superior surface of the implants. Here the ingrowth of bone appeared most pronounced along the periphery of the implants, in particular medially.

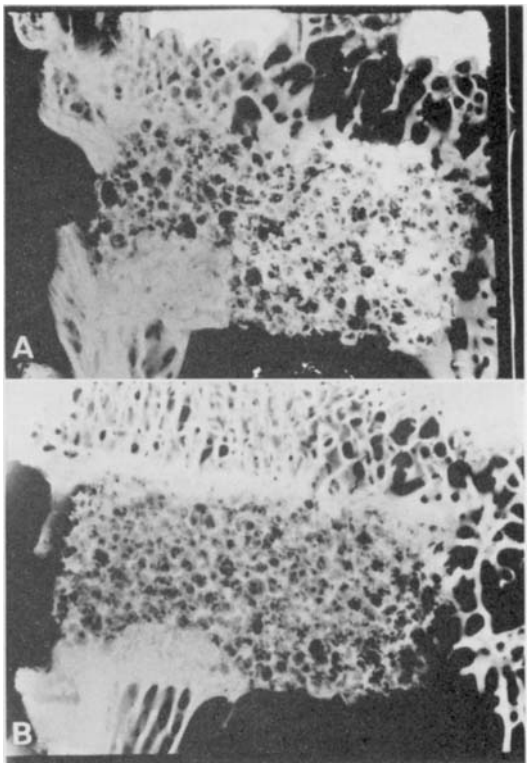


Figure 3. Microradiographs of sections through an implant. Observation period: 10 months. (× 2.5). A. From the transition zone between the anterior and middle third of the implant. B. From the most posterior region. Ingrowth of bone is most extensive in the area corresponding to the supporting peripheral ring of bone. The maximal depth of bone invasion is approximately 4 mm (A). On the superior surface of the implant the bone invasion is also most pronounced medially. In both microradiographs the adjacent bone at the undersurface appears thickened.

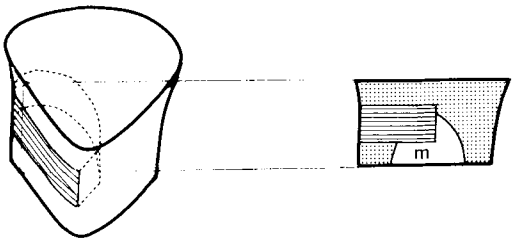


Figure 2. Schematic illustration of a specimen and a section removed from the middle part of the implant. The dotted area represents bony tissue. m.: medullary cavity. (The anterior and posterior regions and also the lateral part of the implant were surrounded by bone).

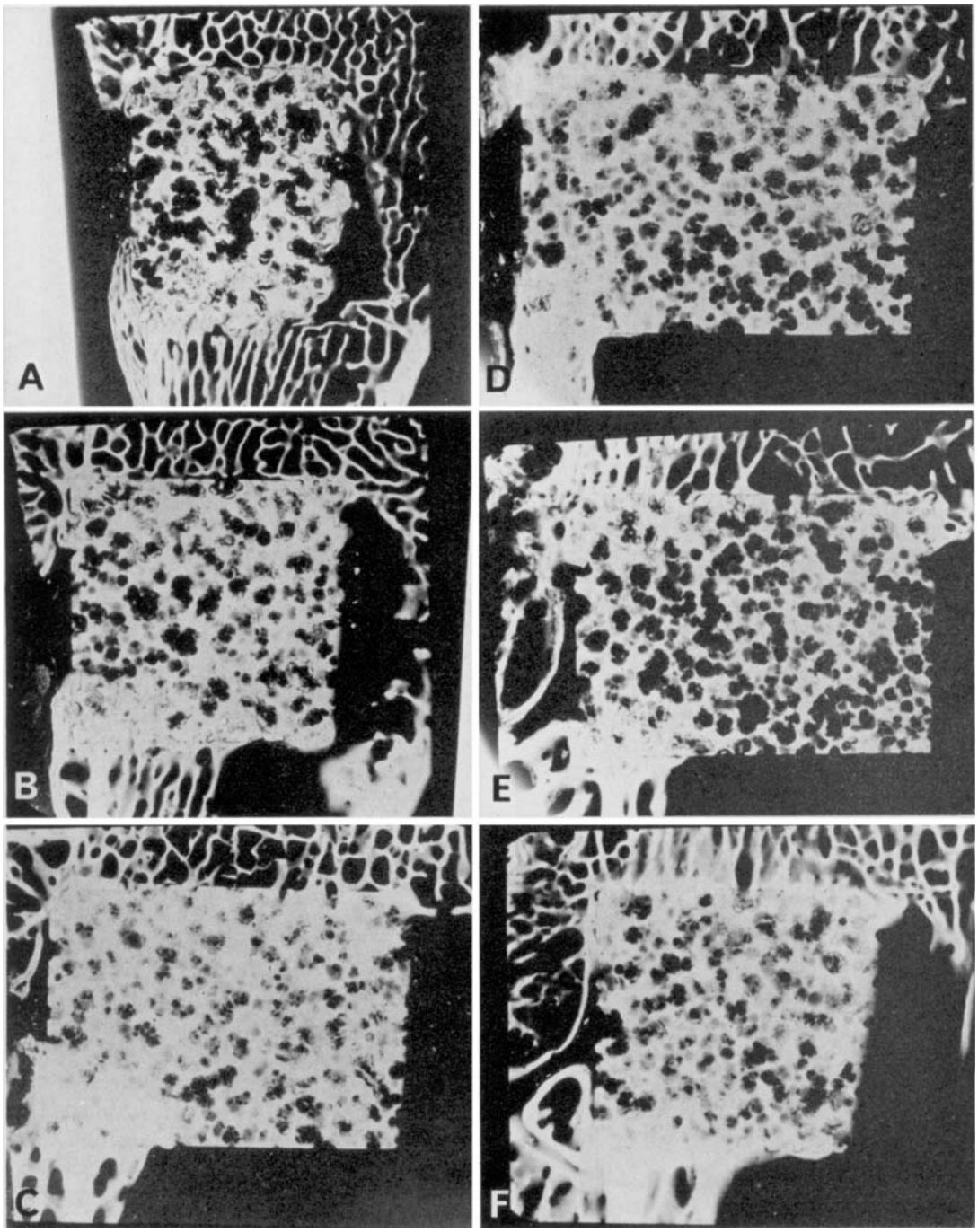


Figure 4. Microradiographs of sections of an implant (same implant as Figure 1) at 12 months (× 4). The microradiographs demonstrate the ingrowth of bone in the most anterior part (A), and further posteriorly to the most posterior part (F). The relation of bone invasion to the adjacent bone is similar to that shown in Figure 3 but the extent of the invasion is slightly less pronounced. There is no ingrowth of bone in those parts of the implant which are not in contact with bone.

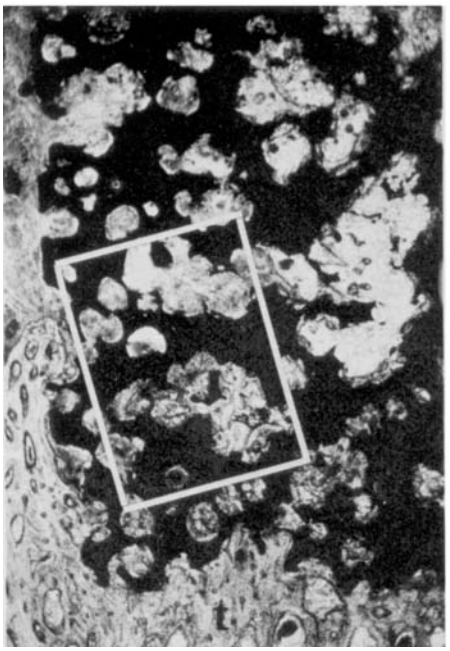


Figure 5 A. General view from the lower part of the implant (× 11.5). The picture demonstrates that the pores of the lower part of the implant are filled with bone. The pores of the more central region are filled with connective tissue. (Compare Figure 5, B and C). The lower part of the implant is completely surrounded by bone. The bone trabeculae (t) of the adjacent bone are directly continuous with those of the bone within the pores (details in Figure 5 B).

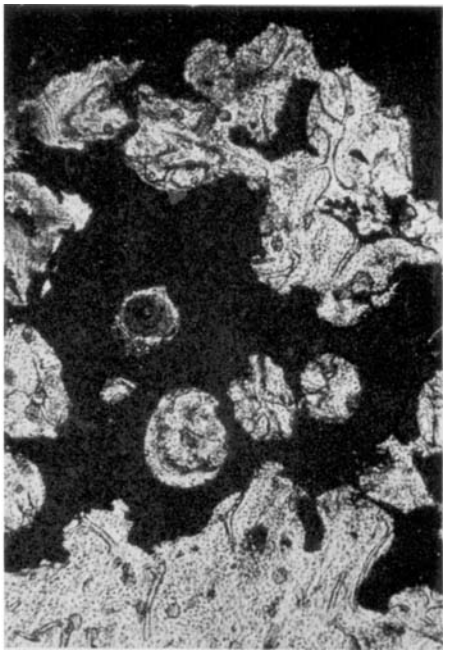


Figure 5 B. Detail from the lower part of Figure 5 A (× 28).

Figure 5. Photomicrographs of a slide from the anterior part of an implant. The slide was prepared from the section demonstrated microradiographically in Figure 4 A. (Paragon).

The adjacent bone was markedly thickened on the undersurface of the implants, corresponding to the area of maximal invasion. This was particularly true in the supporting peripheral ring of bone (Figures 3 and 4).

Histological examination

The histological examination verified the occurrence and distribution of bony tissue as found by the microradiographic investigation. The most peripheral pores were completely filled with bone in all areas of the implant surrounded by bony tissue, and bony invasion in the deeper pores was found in the area adjacent to the peripheral ring of cortical or cancellous bone. Generally no connective tissue was seen interposed between the bony tissue and the ceramics in these regions. Most parts of the bony tissue appeared trabecular. The trabeculae of the adjacent bone were directly continuous with those of the new bone in the pores (Figure 5, A and B). Occasionally Haversian channels could be observed (Figure 5 D). In the central regions of the implants, and in those parts of the implants which were not adjacent to bone, the pores appeared to be filled with connective tissue (Figure 5 C). Occasionally narrow bone trabeculae surrounded by connective tissue were seen in these regions.

Osteoblasts and osteoid tissue were found on the surface of the bone trabeculae in some pores, indicating appositional bone growth (Figure 5 E). Intramembranous

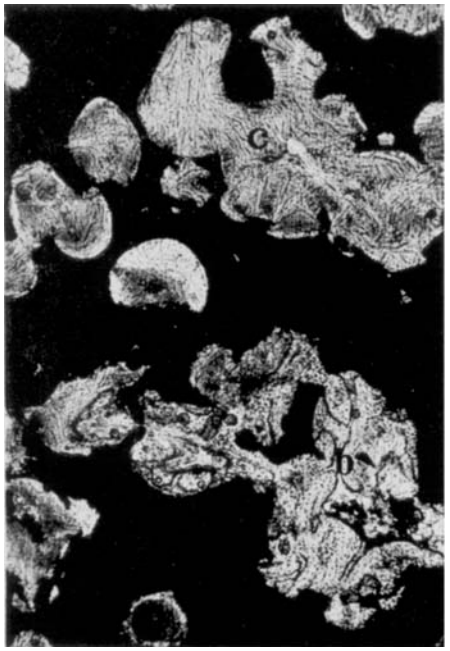


Figure 5 C. Detail from the area demarcated in Figure 5 A (× 28). The occurrence of bone (b) within the lower pores and connective tissue (c) within the overlying pores (details in Figure 5 I) are demonstrated.



Figure 5 D. This picture demonstrates a Haversian channel (indicated by arrow) (× 115).



Figure 5 E. A row of osteoblasts (indicated by arrow) on the surface of the bone trabeculae (b). The dark zone between the osteoblasts and the bone represents osteoid tissue (× 115).

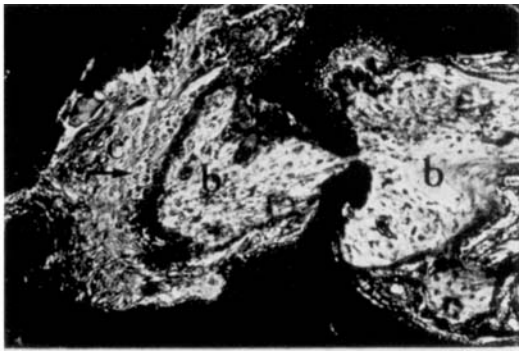


Figure 5 F. Demonstrating intramembranous ossification. Osteoblasts (indicated by arrow) are seen at the border between the connective tissue (c) and the intramembranous bone (b). The dark zone lining the bone represents osteoid tissue (× 115).

ossification was seen within some of the pores which contained connective tissue (Figure 5). Osteoclasts were rarely observed.

The connective tissue within the pores was generally well vascularized and contained fibroblasts (Figure 5, I and J). No special infiltration of round cells or

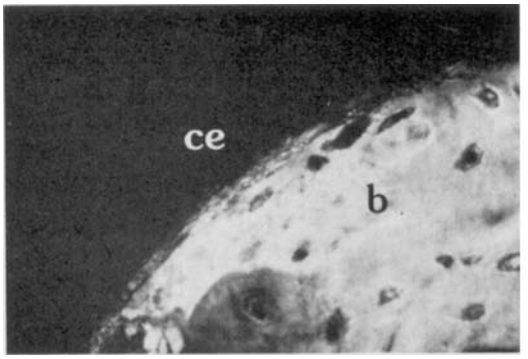


Figure 5 G. Detail from the contact area between bone and ceramics. No connective tissue is interposed between the bone (b) and the ceramics (ce). The osteocytes are lying close to the ceramics (× 360).

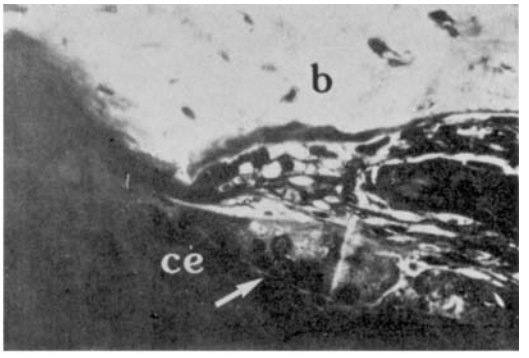


Figure 5 H. Foreign body cells (indicated by arrow) lying between the bone (b) and the ceramics (ce). (The picture is overexposed in order to distinguish the cells from the dark surroundings) (× 360).

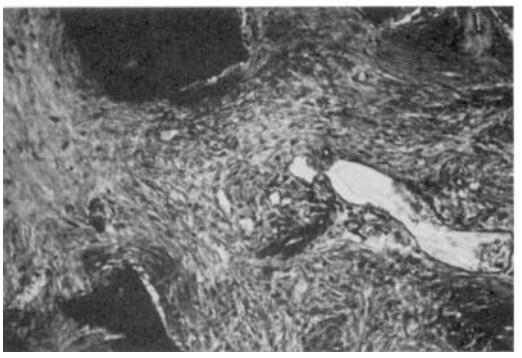


Figure 5 I. This picture shows highly vascular connective tissue within a pore (× 15).

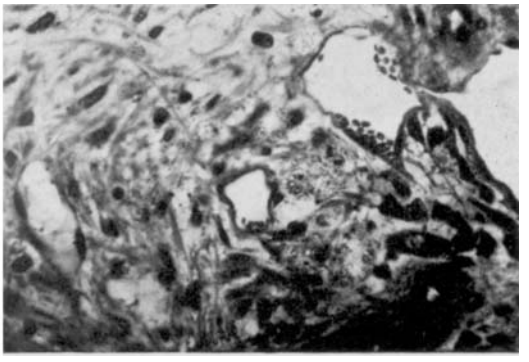


Figure 5 J. Detail from Figure 5 I demonstrating that the connective tissue contains a considerable number of fibroblasts (× 360).

leucocytes indicating inflammatory reaction could be observed within the implants. Osteocytes were observed close to the ceramics (Figure 5 G); in some regions, however, some foreign body cells could be observed (Figure 5 H).

There were no changes in the implants observed for 12 months which indicated loosening after removal of the plate.

DISCUSSION

We have previously reported that after 3 months porous ceramic implants were found to be bound to the adjacent bone by ingrowth of bony tissue, in some regions to a depth of 2–3 mm. Some osteoid tissue and signs of osteoblastic activity were still seen (Benum et al. 1976).

In the present study some ossification was still taking place within some pores of the implants. Since osteoclasts were rarely observed, it seems reasonable to assume that the appositional bone formation on the surface of the bone trabeculae leads to an increased bone mass, and not only reflects a process of remodelling. The finding of intramembranous ossification undoubtedly indicates that bony tissue is still being formed within pores previously occupied by connective tissue.

The maximal depth of bone invasion

was only slightly greater at 10 and 12 months, compared with that at 3 months. However, the bone bridges between the host bone and the implants corresponding to the areas of high stress had developed considerably. It seems reasonable to assume that the bone formation within the pores during the earliest period after implantation represents a phase of unorganized callus formation. Remodelling then probably takes place due to the actual mechanical stress on the bone bridges between the bone and the implant. Such remodelling is of the utmost importance, not only if porous ceramics are to be used as a bone substitute, but even more so if this material should be employed in fixation of endoprostheses.

In the present experiments the connective tissue appeared highly active metabolically, being vascular and rich in fibroblasts. Intramembranous bone formation was observed within this tissue and appositional trabecular bone formation was still taking place. It seems unlikely, however, that larger porous ceramic implants would become completely filled with bone, if applied clinically. Hence the strength of such impants cannot be expected to increase significantly with the invasion of bone. According to the specifications of compressive strength given earlier (Benum et al. 1976), it seems unlikely, however, that the porous ceramics should be weaker than the surrounding cancellous bone if used as a bone substitute in regions mainly exposed to compressive forces. The compressive strength of the porous ceramics employed in our studies compares favourably with the strength of cancellous bone in the tibial condyles reported by other investigators (Behrens et al. 1974).

Porous alumina ceramics have previously been found to be chemically inert and it has further been shown that such ceramics do not produce any significant adverse reactions after implantation. (Klawitter et al. 1969, Hulbert et al. 1970, 1972, Rhinelander et al. 1971, Nilles et al. 1973). The findings of the present study, that osteocytes were lying close to the ceramics, without interposition of connective tissue, and furthermore the lack of significant foreign body reactions around or within the implants, confirm that the ceramics possess a high degree of biocompatibility.

Due to the present knowledge of the properties of porous ceramics we feel that a clinical trial of porous ceramics as a bone substitute in regions mainly exposed to compressive forces is justified.

REFERENCES

Behrens, J. C., Walker, P. S. & Shoji, H. (1974) Variations in strength and structure of cancellous bone at the knee. *J. Biomechan.* **7**, 201–207.

Benum, P., Lyng, S., Bø, O., Rafn, I. & Haffner, J. F. W. (1976) Porous ceramics as a bone substitute in the medial condyle of the tibia. *Acta orthop. scand.* **47**, 158–166.

Hulbert, S. F., Morrison, S. J. & Klawitter, J. J. (1972) Tissue reaction to three ceramics of porous and non-porous structures. *J. biomed. Mater. Res.* **6**, 347–374.

Hulbert, S. F., Young, F. A., Mathews, R. S., Klawitter, J. J., Talbert, C. D. & Stelling, F. H. (1970) Potential of ceramic materials as permanently implantable skeletal prostheses. *J. biomed. Mater. Res.* **4**, 433–456.

Jowsey, J., Phil, D., Kelly, P. J., Riggs, B. L., Bianco, A. J., Scholtz, D. A. & Gershou-Cohen, J. (1965) Quantitative microradiographic studies of ,normal and osteoporotic bone. *J. Bone Jt Surg.* **47**-A, 785–806.

Klawitter, J. J., Hulbert, S. F. & Talbert, C. D. (1969) *Materials of construction for bone gap bridges.* Orthopaedic Surgery Papers of the Duke University Medical Center and Affiliated Hospitals, USA.

Nilles, J. L., Coletti, J. M. Jr. & Wilson, C. (1973) Biomechanical evaluation of bone-porous material interfaces. *J. biomed. Mater. Res.* **7**, 231–251.

Rhinelander, F. W., Rouweyha, M. & Muner, J. C. (1971) Microvascular and histogenic responses to implantation of a porous ceramic into bone. *J. biomed. Mater. Res.* **5**, 81–112.

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