

Vascular changes following hip arthroplasty

The femur in goats studied with and without cementation

Jan de Waal Malefijt¹, Thomas J. J. Slooff¹, Rik Huiskes¹, Erik A. T. de Laat¹ and Jelle O. Barentsz²

We studied two groups of 6 adult female African pygmy goats, which received cemented or uncemented femoral endoprostheses in their right hip. One additional goat was used for in vivo angiography preoperatively and postoperatively. The blood supply to the proximal femur at a macroscopic level was not severed by the operation. Until the 6th postoperative week, the animals were killed at weekly intervals.

Microangiography and fluorescence microscopy revealed that rapid revascularization of the metaphyseal trabecular bone in the vicinity of the implants occurred as early as the first postoperative week in both groups. However, in general, the revascularization of the bone around the uncemented prostheses occurred more rapidly, resulting in earlier bone remodeling when compared with the cemented group. Surprisingly, the apposition of periosteal bone was longer lasting and more intensive in the uncemented group, particularly at the metaphyseal level. We suggest that this phenomenon may be enhanced by mechanical stimuli; the restoration of function was delayed in the noncemented goats.

We developed an animal model in which the early features of cemented and uncemented fixation of a femoral endoprosthesis were compared histologically, radiographically, and functionally. As a part of this study, this paper contains our observations on the postoperative vascular changes in the proximal femur, studied by means of in vivo angiography and by post-mortem microangiography. We also performed fluorescence microscopy to visualize newly formed bone (Milch et al. 1958).

Materials and methods

Thirteen healthy skeletally mature female African pygmy goats were used. Their right hip joints were surgically exposed using a standardized technique (de Waal Malefijt, submitted). One animal was used for in vivo angiography preoperatively and postoperatively with the objective to determine to what extent the operation compromised afferent arteries supplying the proximal femur.

In this 1 goat, a 5 F Cobra-type catheter was inserted, locating the tip in the right external iliac artery. The catheter was flushed with heparin-saline. Subsequent-

ly, 25 mg Angiographin 65 was injected with a flow rate of 12 mL/s. A series of 10 images of the right hip were obtained (rate 2/s). Radiologic enlargement was used. Two days later, the animal was operated on under general anesthesia. The surgical approach to the right hip was performed up to the dislocation of the femoral head. The periosteum of the collum femoris was circumferentially incised, but no osteotomy was performed. The hip was reduced and the wound was closed routinely. Two days postoperatively, in vivo angiography was performed again in the same way as before, this time introducing the Seldinger catheter via the left carotid artery. There were no specific postoperative complications.

In the remaining 12 animals, a femoral endoprosthesis was implanted in their right hip joint under general anesthesia, using the routine surgical approach and an identical preparation technique of the medullary canal. After an osteotomy of the femoral neck, the medullary canal was carefully reamed and a plastic plug was inserted. Next, lavage and drying of the bone were performed. In 6 of the goats a cemented CoCr-prosthesis was implanted into the proximal femur using Sulfix-6 low-viscosity cement for fixation. Current cementing techniques were practiced in a programed mixing and handling time schedule. The other animals received an uncemented prosthesis. After preparation of the bone as in the cemented cases, a print of the femoral canal was manufactured by means of a two-component non-toxic silastic, supplied by the dental department (Xan-

Laboratory for Experimental Orthopedics¹ and Department of Radiology², University of Nijmegen, P. O. Box 9101, 6500 HB Nijmegen, The Netherlands

topren/Elastomer). The snap-cured silastic mould thus obtained served as a guideline model to cut and grind a polyacetal prosthetic stem in visual approximation with the geometry of the femoral canal. The plastic plug that had been inserted initially was removed from the femur. A CoCr-head was adjusted to the neck of the plastic prosthesis, which was then inserted "press fit" into the proximal femur (Robert Mathys Co., Bettlach, Switzerland).

Postoperatively, the animals from both groups were kept in a special hammock to prevent them from loading the right hip. After 3 days, they were transferred to a commodious pen to start weight bearing. All the animals received a subcutaneous injection of a fluorochrome label daily, changing the dye at weekly intervals. Four fluorochromes were administered in the following sequence and dosage: oxytetracycline 15 mg/kg, calcein blue 30 mg/kg, alizarine complexon 30 mg/kg, calcein 20 mg/kg, and again oxytetracycline 15 mg/kg. Thus, sequential labeling of newly formed bone was obtained.

In both groups, microangiography was carried out when the animal was killed, which took place at weekly intervals up to 6 weeks postoperatively. The angiographic technique followed the procedure of Danckwardt-Lillieström (1969). Heparin 5,000 IU was injected intravenously into a nembutal-anesthetized animal, followed by an intravascular injection of 30-mg papaverin to provide maximal dilatation of the vascular system. The peritoneum was opened and exsanguination was obtained by perfusion of saline through a catheter inserted distally in the abdominal aorta, regulating the infusion pressure at 120 mmHg with an automatic system controlled by a mercury manometer. At the same time, the animal was bled via a cannula in the inferior vena cava. The animal was killed by an overdose of nembutal, and perfusion was continued with 1 liter of 30 percent barium sulfate (micropaque) in sa-

line, followed by 1 liter of 15 percent barium sulfate in a 4 percent buffered formol solution. Both femurs were harvested by careful exarticulation of the hip and the knee joint, leaving an ample muscular cover and the periosteum intact. The left femur served as a control.

After fixation in the buffered formol solution for several days, the femurs were sectioned transversally by means of a water-cooled diamond saw (WOCO, Conrad, Germany). Transverse cuts were made through the greater and lesser trochanters, the diaphysis, and near the distal tip of the prosthetic stem.

After decalcification in formic acid, the sections were cut into 1-mm slices. Microangiograms of these slices were made on Kodak 35-mm Stereoscopic Safety film in the Faxitron 43805 N-x-ray system. The x-ray films were placed between glass, embedded in plastic, and photographed with a Zeiss Photomicroscope 2.

One-millimeter-thick cross sections were used for fluorescence microscopy. After staining with 2.5 percent basic fuchsin in 40 percent alcohol for 12 hours, these specimens were flushed in 40 percent alcohol and carefully polished. Subsequently, they were studied using incident fluorescent light and photographed with a Zeiss-Tessovar camera. Next, the sections were dehydrated in alcohol, embedded in a specific epoxy resin, and slices with a thickness of 80–100 μ m were cut with a rotating diamond saw. For examination of the sections, we used a modified Zeiss Universal microscope with fluorescence equipment and the vertical illuminator 3 RS using incident light excitation.

Results

Recovery after the operation was uneventful, and there was no infection. The majority of animals in the cemented group loaded the operated on leg normally aft-

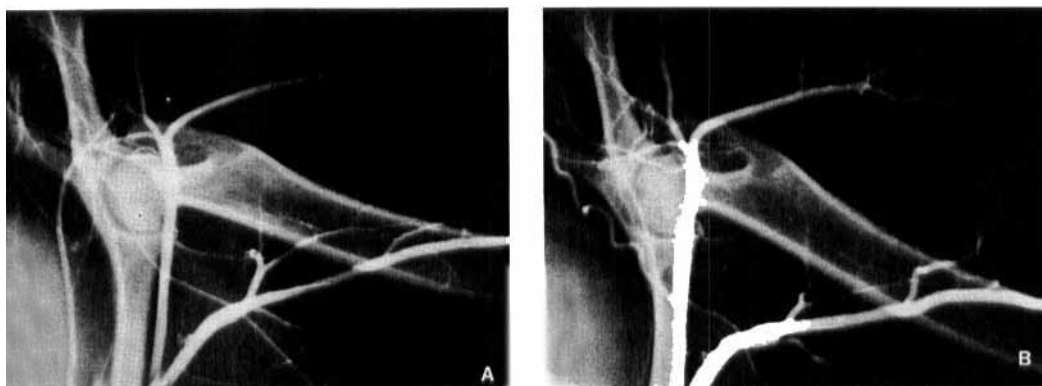


Figure 1. Preoperative in vivo angiography. A demonstrates the arterial blood supply to the hip joint and the proximal femur, which was not altered by the surgical procedure, B.

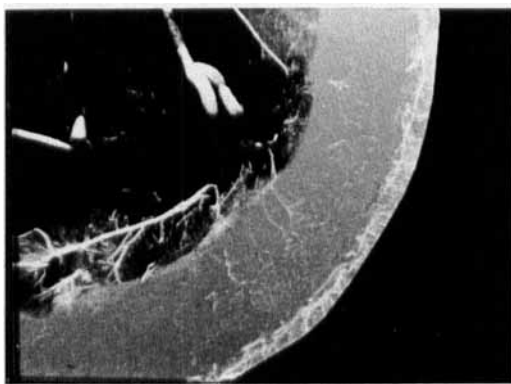


Figure 2. Microangiogram from the metaphysis of a control femur showing the normal vascular pattern of the cortex. The contribution of medullary vessels is clearly demonstrated. (x5)

er 3 weeks, whereas a comparable result in the uncemented group was not obtained until 5 weeks postoperatively (de Waal Malefijt et al. 1989). Preoperative *in vivo* angiography clearly demonstrated the arterial blood supply to the right hind limb (Figure 1).

Repeated postoperative angiography indicated that the operation did not affect the arterial blood supply in any way at a macroscopic level (Figure 1). Microangiograms from all the control femurs yielded constant and representative pictures of the normal blood supply to the proximal femur at different anatomic levels (Figure 2).

Cemented group

One week postoperatively, the periosteal circulation of the operated on femur in the cemented group was found to be increased at both the metaphyseal and the diaphyseal level. The inner third of the cortex was avascular (Figure 3). From the extraosseous circulation, only a few micropaque-filled vessels were observed entering the cortex transversely. Conversely, abundant vascularization was found within the metaphyseal cancellous bone up to the surface of the cement. At 2 weeks, the endosteal cortex still showed no revascularization. The same image was obtained at 3 weeks, although a circumferential pooling of barium sulfate was observed in the middle third of the cortex at the diaphyseal level. Not until the 5th postoperative week were the first signs of endosteal revascularization seen, with gradual progression in the 6th week (Figure 3F). Meanwhile, the periosteal hypercirculation appeared to be substantially reduced.

This course of revascularization was substantiated by the formation of new bone labeled with fluorochromes. There was abundant labeling of the metaphyseal trabecular bone from the first postoperative week.

Cortical bone remodeling was not clearly recognized until the 5th and 6th postoperative weeks, most prominently in the metaphyseal sections (Figure 5). The fluorescent labels in the diaphyseal cortex demonstrated that bone remodeling at this level was mainly confined to the middle third of the cortex. Moderate periosteal bone apposition was noticed, particularly marked in the anterior metaphyseal area.

Uncemented group

At 1 week postoperatively, the metaphyseal trabecular bone in the uncemented group was equally richly vascularized as compared with the cemented cases (Figure 4). A similarly increased periosteal vascularity was consistently seen metaphyseally and diaphyseally from the first postoperative week. However, in contrast to the cemented group, the radially oriented vessels through the cortex were more numerous, and extended up to the endosteal part of the cortex. At 3 weeks, the gaps between the plastic prosthesis and the bone, which remained in spite of our efforts to produce a precise fit, were undoubtedly crossed by micropaque-filled vessels.

A progressive regeneration of the medullary circulation through these gaps was seen from the 4th to the 6th postoperative week. Simultaneously, the periosteal circulation still increased to some extent, while the radial orientation of the cortical vessels became less prominent.

Fluorochrome labeling illustrated early bone remodeling activity in the metaphyseal trabecular bone, as was also shown in the cemented group. In contrast to the cemented group, all the anatomic levels showed intracortical and endosteal bone remodeling already from the 2nd postoperative week. Some new bone formation was demonstrated between the prosthesis and the bone. Periosteal bone apposition was much more prominent as compared with the cemented group, most strikingly at the anterior aspect of the metaphysis (Figure 5B).

Discussion

Reaming and introduction of bone cement and/or a prosthetic stem into the medullary cavity cause damage to the endosteal circulation, as described by many investigators (Danckwardt-Lillieström 1969, Rhineland 1973, Sund and Rosenquist 1983). It has been generally accepted that the morphologic changes in the femur following interference with the arterial blood supply take an identical course in humans and test animals (Trueta 1968, Rhineland et al. 1979).

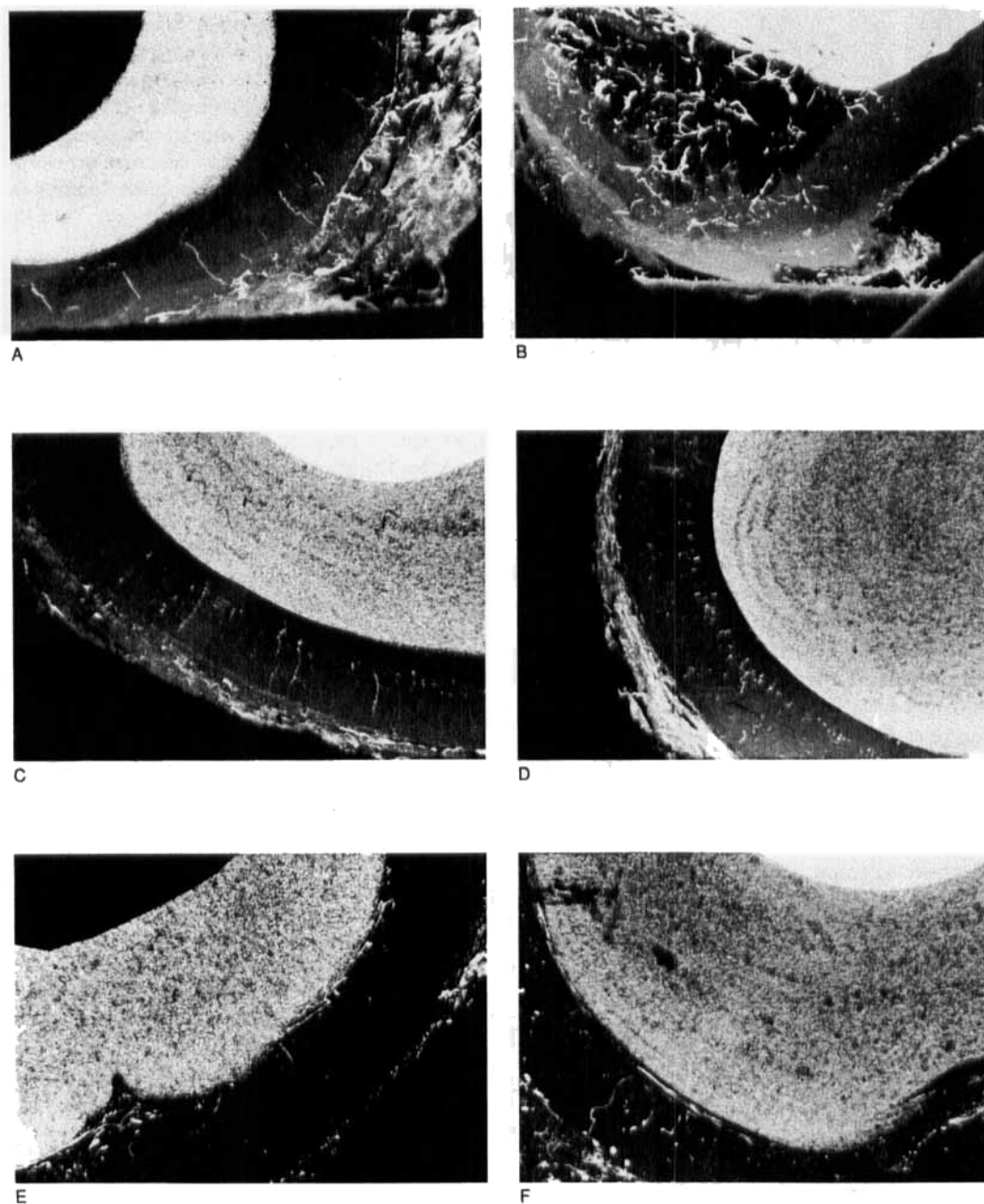


Figure 3. Microangiography in the cemented group of goats. (x5)

- A. 1 week. Increased periosteal vascularity metaphyseally, and some radially oriented vessels in the outer cortex.
- B. 1 week. Extensive vascularity in the metaphyseal trabecular bone, even adjacent to the cement.
- C. 2 weeks. At the diaphyseal level a somewhat decreased periosteal circulation revascularizing the cortex. Avascular endosteal cortex still present.
- D. 3 weeks. Same picture as at 2 weeks; circumferential pooling of blood in the middle third of the cortex.
- E. 5 weeks. Periosteal hypercirculation decreased at the metaphyseal level. Some revascularization of the endosteal cortex.
- F. 6 weeks. Further normalization of the periosteal circulation at the diaphyseal level, and increased vascularity of the endosteal cortex.

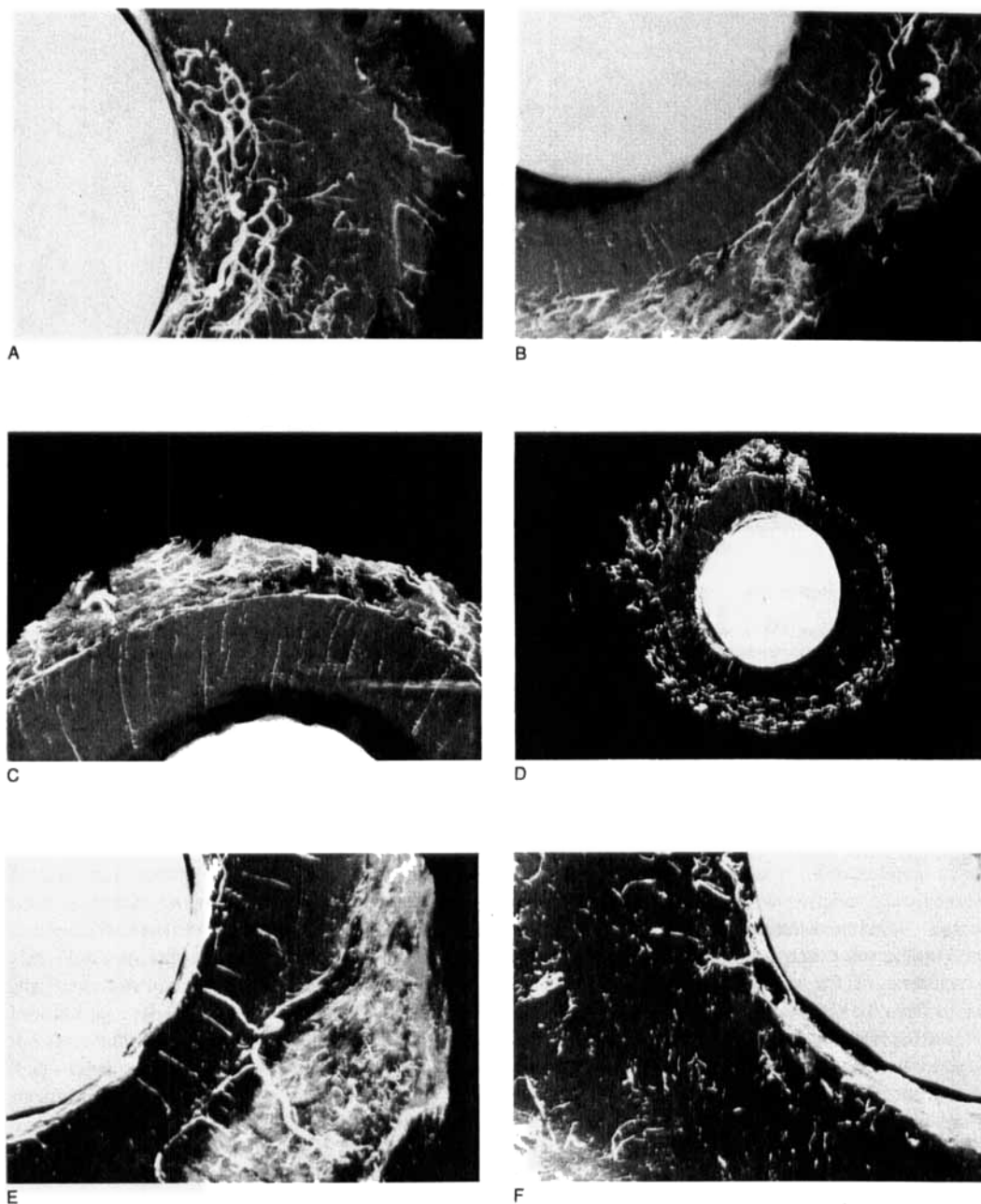


Figure 4. Microangiography in the uncemented group of goats. (x5)

- A. 1 week. Extensive blood supply of the metaphyseal trabecular bone, whereas revascularization around the plastic prosthesis is already occurring.
- B. 1 week. At the metaphyseal level, revascularization of the cortex up to the endosteal side, originating from increased periosteal circulation.
- C. 2 weeks. Periosteal circulation is still increased, with radial revascularization of the entire cortical thickness. No signs of vascular regeneration through the gaps between the prosthesis and bone at the diaphyseal level.
- D. 3 weeks. The same picture as at 2 weeks; however, also an obvious regeneration of medullary blood supply in the gaps. (x2)
- E. 5 weeks. Progressive regeneration of medullary circulation at the metaphyseal level.
- F. 6 weeks. Still increased periosteal circulation at the diaphyseal level, but decreasing number of radially oriented intracortical vessels.

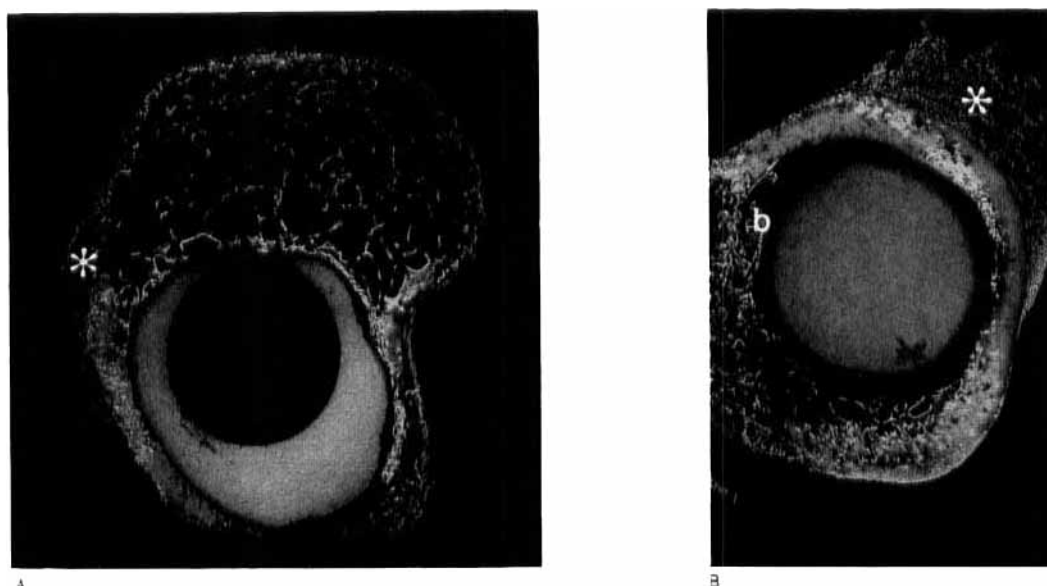


Figure 5. Overall fluorescence picture of the metaphyseal level 6 weeks postoperatively with the implants in situ.

In the cemented specimen (A), newly formed bone is seen in the trabecular bone adjacent to the cement. Periosteal bone apposition is moderate and most prominent anteriorly(*), labeled mainly with alizarine complexon (3 weeks) and bordered by a thin calcein-labeled zone (4 weeks). The uncemented specimen (B) demonstrates a bad fit of the prosthetic stem at this level; gap filling by newly formed bone is seen (b). Vigorous periosteal bone apposition is seen anteriorly(*), bordered by a broader calcein-labeled zone, which illustrates active bone formation even at 4 weeks postoperatively. (x3)

Albrektsson (1981) stressed the relative value of microangiography by continuous infusion of micropaque or other dyes. In animal experiments, he observed a wide variation in the degree of filling of small vessels, whereas differentiation between arterioles and venules was nearly impossible. Nevertheless, the consistency of the microangiographic images obtained from the control femurs in our experiment increased the significance of the microradiograms of the operated on femurs. Our findings corroborated the so-called centrifugal circulation concept as postulated by Brookes (1971) and Rhineland (1972). They suggested that the entire cortex is supplied mainly by the medullary circulation. The blood flow may be temporarily reversed when the medullary cavity is completely blocked by an implant, which induces the periosteal circulation to become the principal source of cortical revascularization. It was remarkable that the endosteal cortex in our cemented specimens remained avascular until the 5th postoperative week, and that even pooling of barium sulfate in the inner third of the cortex occurred. We suggest that this could be explained by the total occlusion of the medullary canal, and possibly by residual bone marrow or debris being pressed into the cortex by the acrylic cement (Danckwardt-Lillieström

1969). Perhaps, endosteal necrosis caused by the heat of polymerizing acrylic cement also played a role. In contrast, the radially oriented cortical vessels in the uncemented group were filled with barium sulfate up to the endosteal side already from the first postoperative week. Although the fixation of the plastic prostheses seemed to be press-fit macroscopically, clear gaps were found in the cross sections. These gaps allowed early regeneration of the medullary circulation to occur, as was earlier assumed by Rhineland et al. (1979). An early revascularization around uncemented implants has also been described by Kofoed and Backer (1986). The fact that all our specimens showed a more extensive vascularity of metaphyseal trabecular bone in comparison with diaphyseal compact bone can be explained by the specific architecture and blood supply of cancellous bone (Clemow et al. 1981).

Danckwardt-Lillieström (1969) demonstrated that the typical vascular proliferation of extraosseous vessels following intramedullary procedures in rabbit femurs was more pronounced after 2 weeks, diminishing after 4 weeks, and returning to normal after 8 weeks. In accordance with that, we found that the reactive periosteal vascularization in the cemented group had normalized at the 5th to 6th postoperative week, synchro-

nous with the regeneration of the vascularization at the bone-cement interface. The same phenomena were even more likely to occur in the uncemented group, in which the early regeneration of the medullary circulation should result in a simultaneous return of the periosteal hypercirculation to normal. In contrast to this, we still found an increased periosteal vascularization at 6 weeks postoperatively, accompanied by marked periosteal bone apposition. At the same time, the radial orientation of the cortical vessels became less obvious. This suggests that the periosteal reaction in the uncemented group cannot be attributed to vascular changes only.

In the past, several other explanations have been suggested for periosteal bone apposition following intramedullary interventions. These include chemical or physical irritation of the bone caused by the implant (Küntschner 1940), periosteal venous stasis and edema (Richany et al. 1965), and bone formation induced by

bone marrow that is pressed subperiosteally through the cortical canals after intramedullary reaming (Danckwardt-Lillieström 1969). Feith (1975) observed a correlation between the amount of subperiosteal bone formation and the extent of the cortical necrosis in rabbit femurs filled with cement. He emphasized that the extent of subperiosteal bone formation also depended on the animal species used and their age. Rewitzer and Draenert (1984) suggested, based on animal experiments, that bone deformation by intramedullary implants together with circulatory changes may be responsible for extraosseous bone formation. With this in mind, it seems justifiable to suggest that mechanical effects played a role in the intensified periosteal bone apposition in the uncemented group. The delayed restoration of function (de Waal Malefijt et al. 1989) in these animals also substantiates this assumption.

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