
Hydroxyapatite-clay bone fixation for loaded implants

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A clay containing hydroxyapatite (HA clay), which was made by mixing HA granules (range of sizes: 0.1–0.3 mm) and a saline solution of sodium alginate, was inserted into the medullary canal of an osteotomized rabbit's tibia with a Ti-6Al-4V titanium alloy implant. Each implant had a conical portion for bearing load. The shear strength of the bone-implant interface for the implant with HA clay was significantly greater than that for the implant without HA clay 3 months postoperatively ($P < .02$), while there

was no significant difference between the two strengths 1 week postoperatively. Under microscopic observation, the percentage of area of newly developed bone was also significantly greater for the implant with HA clay than for the implant without HA clay 3 months postoperatively ($P < .04$). This study suggests that HA clay encouraged adequate bone fixation of the loaded implant in 3 months, while the clay was not effective for immediate fixation. © 1995 John Wiley & Sons, Inc.

INTRODUCTION

In an earlier study, hydroxyapatite (HA) clay was easy to handle for filling any irregular gaps, and showed adequate bone ingrowth into the gaps under a static (unloaded) condition.¹ However, most biomaterials and implants such as joint prostheses must sustain load bearing *in vivo*. The purpose of this study was to investigate the biologic behavior of HA clay under load-bearing conditions. National regulations similar to NIH guidelines for the care and use of laboratory animals were observed.

MATERIALS AND METHODS

Hydroxyapatite clay was made by mixing fine-granulated HA [$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$], sodium alginate [$(\text{C}_6\text{H}_7\text{O}_6\text{Na})_n$] powder, and saline solution. The weight ratio of HA granules:sodium alginate powder:saline solution in the clay was set for 9.8:1:7. HA granules (Sumitomo Cement Co., Ltd., Japan) had a homogeneous pore distribution as well as a pore size of 0.05–0.3 mm and a porosity of 35–48 vol%. The range of HA granule sizes in the clay was set for 0.1–0.3 mm. Sodium alginate powder (Kyosei Pharmaceutical Co., Ltd., Japan) was slowly dissolved in water to form a viscous solution.

Intramedullary implants with smooth surface were manufactured from Ti-6Al-4V titanium alloy, and a

pair of interlocking mechanisms was obtained. Using sterile surgical techniques, the tibiae of 16 skeletally mature Japanese white rabbits weighing between 3.5 and 4.5 kg were osteotomized unilaterally. Minimum reaming was applied to preserve the vascularity of the endosteum. Then, the implant with HA clay was installed in the distal medullary canal of osteotomized tibia and the paired implant in the proximal medullary canal (Fig. 1). The other 16 tibiae containing implants without HA clay were used as controls. The implants were subjected to 1.0 ± 0.5 mm lateral-medial movements at the tips. Postoperatively, all implanted extremities were cast below the knee joint to prevent excessive movement for 1 week.

Twelve implanted tibiae (including six controls) were harvested at 1 week, and 20 (including 10 controls) at 3 months postoperatively. After radiographic examination, shear strengths at the bone-implant interfaces and host tissue adaptations were analyzed as follows: Each distal tibia was cleared of soft tissue and fixed with acrylic for the mechanical test. The specimen was set on the jig of a universal testing machine (Imada Co., Ltd., Japan). Then, the implant was pulled out from the surrounding bone at a rate of 3 mm/min and each force was recorded. The force needed to detach the implant was determined by the load-displacement curves. The shear strength was equal to the pull-out force divided by the surface area of the implant. For reference, the shear strength at the bone-implant interface by the use of polymethylmethacrylate (PMMA) bone cement (standard viscos-

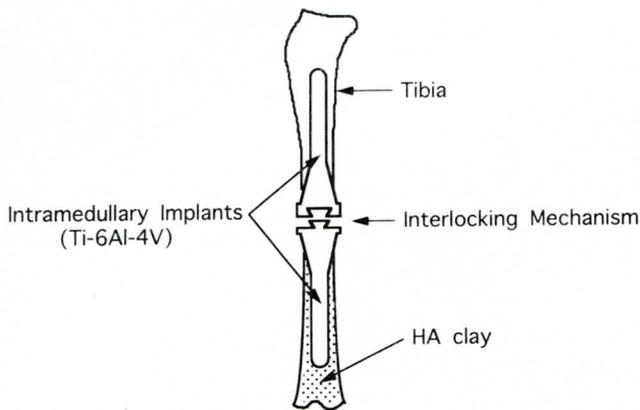


Figure 1. Schematic illustration of a load-bearing model. Intramedullary implants, 3 mm in outer diameter at the middle portion and 40 mm in length, were manufactured from Ti-6Al-4V titanium alloy. They had conical portions for load bearing and a pair of interlocking mechanisms. One implant was installed in the distal tibia with or without HA clay, and the other in the proximal tibia. After that, both implants were interlocked.

ity) (CMW-1®) was evaluated in the other five distal tibiae 1 week postoperatively.

After the mechanical test, the explanted tibiae were fixed with 10% formalin and embedded in acryl. The tibiae were cut at the distal third portion of the implant. The undecalcified and polished histologic specimens of these cross sections were stained with toluidine blue for light microscopy. An image analyzer (LUZEX-III; Nireco Co., Ltd., Japan) was used for measurement of the histologic areas. Cross-sections of the new bone were measured. Then, the percentage of this area was calculated by dividing the whole area of the gap between the implant and cortical bone, and multiplying by 100.

Statistical analyses of these results were done by unpaired *t* tests, and *P* values of $<.05$ were considered to be significant.

RESULTS

All intramedullary implants were clinically functional in this experiment until each rabbit was killed. Macroscopically, there was no migration of HA granules to the soft tissues around the tibiae. The proximal tibiae were not used for the mechanical and histologic studies because their sizes were not constant.

Radiographs 3 months postoperatively showed no radiolucency and no loosening in the HA-clay group (Fig. 2A). On the other hand, the presence of a continuous radiolucency at the bone-implant interface was observed in all examples of the control group, and endosteal bone formation (pedestal) in six (Fig. 2B).

Mechanical test showed that the shear strength of the HA-clay group was significantly higher than that of the control group 3 months postoperatively ($P <$

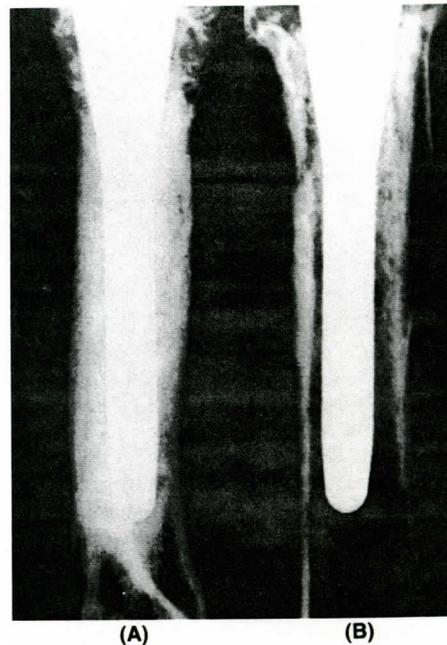


Figure 2. Radiographs 3 months postoperatively. (A) No radiolucency or loosening was observed in the implant with HA clay. (B) Radiolucency all around the implant and endosteal bone bridging (pedestal) were observed in the control.

.02). On the other hand, there was no significant difference between the strengths of either group 1 week postoperatively. Of the five examples, three implants were pulled out with PMMA bone cement and the other two were pulled out without cement. As a result, the shear strengths of PMMA bone cement were measured for the three examples at the bone-cement interface (Fig. 3).

Histology showed that new cancellous bone was developed in the gap between the implant and the

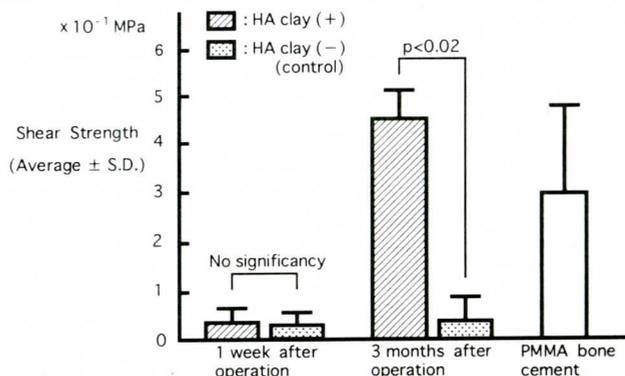


Figure 3. The average shear strength at the bone-implant interface was $(3.1 \pm 2.6) \times 10^{-2}$ MPa for the implanted tibia with HA clay and $(2.6 \pm 2.1) \times 10^{-2}$ MPa for that without HA clay 1 week postoperatively. The strength increased to $(4.5 \pm 0.6) \times 10^{-1}$ MPa for the implanted tibia with HA clay 3 months postoperatively, while the strength for the implanted tibia without HA clay was $(3.7 \pm 4.4) \times 10^{-2}$ MPa. For the implant with PMMA bone cement, the average shear strength of $(3.1 \pm 1.8) \times 10^{-1}$ MPa was required to pull out the implant at the bone-cement interface.

cortical bone, and the gap was filled with new bone and HA granules. No evidence of fibrous tissue seam was recognized, although there was micromotion. A characteristic of the bone formation was contact with the HA granules. No adverse tissue response to the implant and HA clay was recognized (Fig. 4). However, the histologic point of view in the control group showed minimum bone ingrowth and seams of fibrous tissue responding to the implant instability (Fig. 5). The mean cross-section area of the new bone was $35.2 \pm 11.4\%$ (range 23.7–52.0) for the implant with HA clay and $17.3 \pm 14.2\%$ (range 2.6–34.0) for the implant without HA clay 3 months postoperatively. There was a significant difference between the two values ($P < .04$).

DISCUSSION

A cardinal point for an uncemented prosthesis is a sound fixation to the host bone in the initial stage

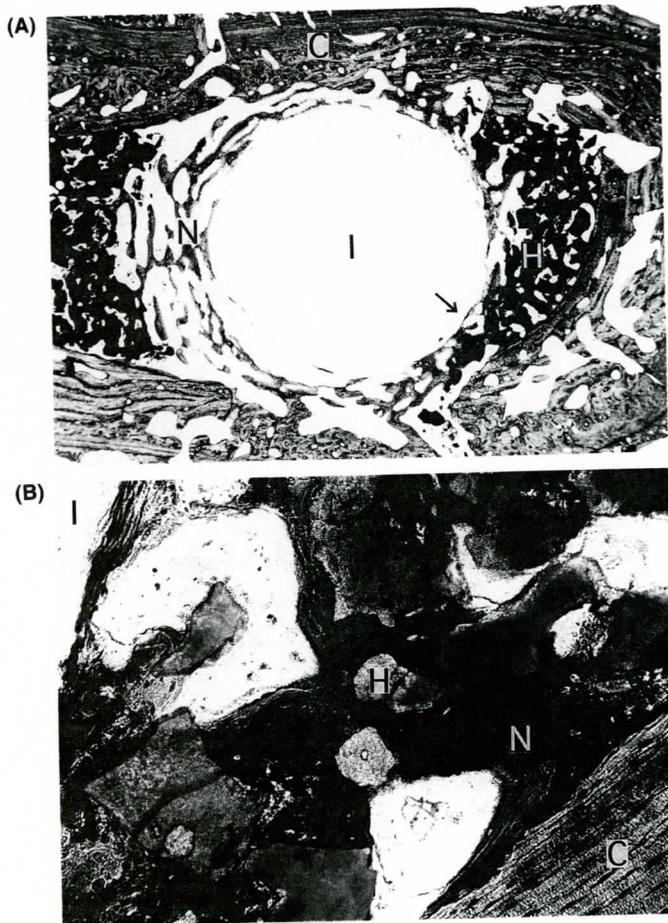


Figure 4. (A) The implant with HA clay was entirely surrounded by newly developed bone. There was no intervening fibrous tissue; even HA granules were displaced by the implant's micromovement. (B) The bone was in direct apposition to HA granules and bridged the gap between the implant and the cortical bone. (Toluidine blue, A: $\times 20$; B: $\times 200$. Closeup view of the area indicated by arrow in A.) N: newly developed bone; H: hydroxyapatite (HA) granules; I: implant (removed); C: cortical bone.

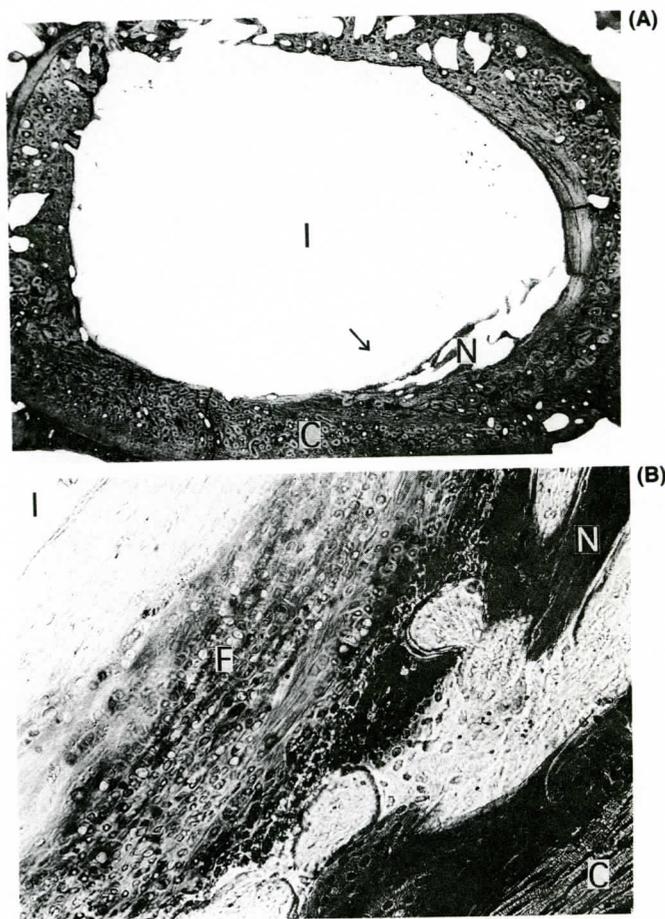


Figure 5. In the control group, histology showing minimum bone ingrowth and seams of fibrous tissue around the implant. (Toluidine blue, A: $\times 20$, B: $\times 200$. Closeup view of the area indicated by arrow in A.) F: fibrous tissue; N: newly developed bone; I: implant (removed); C: cortical bone.

after surgery, but it is not always achieved under weight-bearing loads. The uncemented prosthesis showed a larger micromotion at the prosthesis–bone interface compared to the cemented prosthesis.^{2–4} Studies of uncemented porous-coated components retrieved from patients showed only fibrous tissue ingrowth⁵ or only a small amount of bone ingrowth into the surface.⁶ Like these studies, the histology in the control group showed seams of motion-induced fibrous tissue and a small amount of bone ingrowth. An implant without cement would be firmly fixed in the bone if the gap between the implant and the bone bed were filled with bone ingrowth.

This study indicates the potential advantage of HA clay in achieving adequate bone fixation of the implant in a shorter time by filling the gap under load-bearing conditions. The significant, high shear strength of the implant with HA clay 3 months postoperatively depended on osseointegration bonding to the implant, not filling with HA clay, because there was no significant difference 1 week postoperatively.

In fact, the amount of bone ingrowth for the implant with HA clay was also significantly greater than that for the implant without HA clay 3 months postoperatively. The shear strength at the bone-implant interface by the use of HA clay compared to that of PMMA bone cement at the bone-cement interface.

Based on the results of this fundamental research, HA clay was used for a case of revision hip arthroplasty. No radiolucency around the stem was recognized 6 months postoperatively (Fig. 6).

To make a complete total fit for the entire surface, it may be appropriate to use a custom-made prosthesis whose geometry conforms closely to that of the internal anatomy of the cortical bone. However, it is difficult to manufacture this type of prosthesis routinely. Furthermore, it is questionable whether there would not be loosening between two physically different products, such as the prosthesis and the cortical bone, attached without a shock-absorbable material. *In vivo*, cancellous bone has a shock-absorbable property. HA clay encouraged cancellous bone ingrowth.

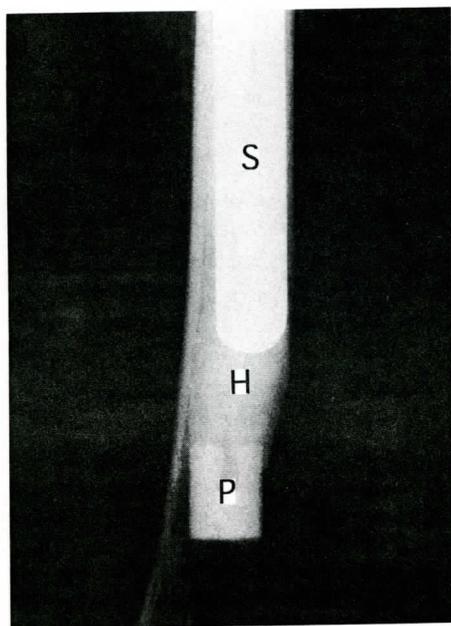


Figure 6. Lateral radiograph of the left thigh in a 72-year-old woman 6 months after revision hip arthroplasty. The gap between the long stem and the femur was completely filled with HA clay. S: stem; H: HA clay; P: plug.

Despite unsatisfactory immediate fixation allowing micromotion, HA clay demonstrated an osteoconductive property in stabilizing the loaded implant within 3 months after surgery. Soballe et al.⁷ reported that HA coating also had the capacity to replace the motion-induced fibrous membrane with bone around loaded implants. An amount of bone ingrowth conducted by HA, however, might depend on host bone quality and metabolic status.

CONCLUSION

Hydroxyapatite clay was useful for obtaining adequate bone fixation of the loaded implant as a supplementary procedure.

The author thanks Sumitomo Cement Co., Ltd., and Kyosei Pharmaceutical Co., Ltd., for supplying materials. He acknowledges the excellent technical assistance of Professor Michio Ito and Dr. Toshio Yamagishi, Institute for Dental Science, Matsumoto Dental College.

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Received June 27, 1994

Accepted October 6, 1994