Shear-load carrying capacities of the distal rat femora after osteotomy fixed with self-reinforced polyglycolic acid and poly-L-lactic acid pins

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Distal femora of 40 rats were osteotomized and fixed with self-reinforced polyglycolide (SR-PGA) and self-reinforced polylactide (SR-PLLA) pin 2.0 mm in diameter and 15 mm in length. The shear-load carrying capacities of the osteotomized bones were compared with each other and with the intact control rat distal femora of the same age of 20 pairs. The follow-up times were 1, 3, 6, 12, 24, 36, 48, and 52 weeks. After killing all operated and control femora were examined macroscopically and radiographically. The shear-load carrying capacities reached their highest values at 24 weeks in the SR-PGA-fixed specimens, after that decreasing to the level where they remained. In the SR-PLLA-fixed specimens the strength values of the pins increased after three weeks, but there was a decrease at 24 weeks. After that the shear-load carrying capacities started to raise because of the influence of the healed osteotomy. In the control bones the shear-load carrying capacities were weaker than in the SR-PGA-and SR-PLLA-fixed specimens except at three weeks, as the osteotomies had not yet healed. During the whole follow-up period the mean shear-load carrying capacity of the SR-PGA-fixed specimens was 199.1 N, in the SR-PLLA-fixed specimens 214.6 N, the corresponding value of the control specimens being 148.2 N.

1. Introduction

For an orthopedic surgeon the most interesting factor in bone healing is the time required for the bone to repair its strength to bear forces caused by movements and the mass of body [1]. The fractured bone does not have any strength, and the implant has to carry all the load. Therefore at the beginning the implant must show its maximal mechanical properties [2].

In many cases tissues need only a temporary presence of a biomaterial to support, augment or replace tissues or to guide their regrowth. When the healing process increases the bone strength, the implant does not need its maximal strength and a lower stiffness would be preferable to transfer more load to the bone. When the bone healing has finished, the implant should have lost its mechanical function and also be totally degraded. In such cases bioabsorbable polymeric materials are good alternatives to metal implant materials [2].

Certain physical properties are essential for safe bioabsorbable implants, such as high initial strength, appropriate initial modulus, and controlled strength and modulus retention *in vivo*. The bioabsorbable polymers that are clinically most used today are polyglycolide and polylactide [3].

Bioabsorbable polymers retain their tissue-supporting properties for given lengths of time and they are gradually degraded biologically into tissue-compatible components which are for the most part absorbed by living tissues and replaced by healing tissue, where to the stresses are gradually transferred [3].

Yet there have been not many experimental studies on the biomechanical testing of the osteotomy or fracture site during the healing process [1, 4]. The devices made of self-reinforced poly-L-lactic acid (SR-PLLA) have lower initial strength values than those made of polyglycolic acid [5], but longer strength retention than polyglycolic acid (PGA) [6]. Mechanically strongest fixation devices have been made with self-reinforcing techniques [7].

The strength retention of bioabsorbable implants in hydrolytic conditions (*in vivo* or *in vitro*) varies typically between one month and one to two years depending, for example, on the molecular weight, size, and geometry of the implant, molecular orientation, crystallinity, porosity etc. [2, 8].

The aim of the present study was to compare the mechanical strength of cancellous bone after experimental osteotomy fixed with absorbable SR-PGA or SR-

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PLLA pins in order to find optimal fracture fixation devices for different types of fractures.

2. Materials and methods

2.1. Implants and operative methods

The implants studied were self-reinforced polyglycolide (Biofix® SR-PGA) and self-reinforced poly-L-lactide (Biofix® SR-PLLA) pins (Bioscience Ltd, Tampere, Finland). PGA sutures (Dexon ''S'', size USP 2, manufacturer Davis and Geck, Great Britain) were used as raw material of the SR-PGA pins for both matrix and reinforcing fibers. The pins were sterilized by ethylene oxide. The sutures were sintered into pins which had an initial three-point bending strength of 300 MPa and a bending modulus of 11 GPa (tested using a Lloyd 6000R materials testing machine at gross-head speed of 5 mm/min). The initial shear strength of the SR-PGA pins was 210 MPa (tested at gross-head speed of 10 mm/min by modifying standard BS 2782, method 340B) [5].

The PLLA raw material used for the manufacturing of the rods was purified medical grade polymer obtained from Purac biochem bv (Gorinchem, Holland). The SR-PLLA implants were manufactured by the die-drawing method [5]. The viscosity average molecular weight of the raw polymer was 660 000. The draw ratio was 9. The pins were sterilized by gamma radiation at a minimum dose of 2.5 Mrads (Kolmi-Set Ltd, Finland). The SR-PLLA pins had an initial three-point bending strength of 280 MPa and a bending modulus of 9 GPa (tested similarly to SR-PGA pins). The initial shear strength of the pins was 170 MPa (tested similarly to SR-PGA pins).

Forty Wistar-rats with a mean weight of 375 g (range 220–530 g) and a mean age of 13 weeks (range 8–19 weeks) were operated on. In addition, 20 rats of the same age group were left intact. The rats were anesthetized with subcutaneous injections of ketamine (Ketalar®, Parke-Davis, Barcelona, Spain) 25 mg/kg and medetomidine (Domitor®, Orion-Farmos, Turku, Finland) 0.3 mg/kg. Both hind legs were shaved and scrubbed with antiseptic fluid (Neo-Amisept®; Orion-Farmos, Turku, Finland). Using medial longitudinal parapatellar approach the patella was dislocated laterally, and the distal portion of the femur was exposed in both knees of the rat. Transverse transcondylar osteotomies were made with a circular saw in the cancellous bone of the distal femora (Fig. 1). The osteotomies were exactly reduced, and channels of 2.0 mm in diameter and 15 mm in length were drilled perpendicular to the osteotomy line from the intercondylar space of the distal femora towards the intramedullary canal through the metaphysis. The osteotomies were fixed with a 2.0 mm SR-PGA pin in the right femur and with a 2.0 mm SR-PLLA pin in the left femur. The pins were tapped into the level of the articular surface of the intercondylar notch to allow free mobility of the knee joints. The incisions were closed in layers with 3-0 polyglycolide sutures (Dexon® Davis and Geck, Gosport, United Kingdom).

Postoperatively, the rats were returned into their cages and they were given normal laboratory animal diet and care. They were free to move around without any external support. Post-operatively the rats were observed daily. The follow-up times were 1, 3, 6, 12, 24, 36, 48, and 52 weeks. The rats were killed with an overdose of sodium pentobarbital (Mebunat®, Orion, Espoo, Finland), both femora were exarticulated, and dissected free of all soft tissue. They were inspected macroscopically, and plain radiographs (anteroposterior and lateral views) were obtained after dissection. The distance between the roentgen tube (Siemens, Triardos S, Bi 125/30/50 RG) and the target was 90 cm, and the exposure factors were 40 kV, 5.0 mAs and 0.03 s. The visibility of the osteotomy line and the final healing of the osteotomy were examined from the radiographs.

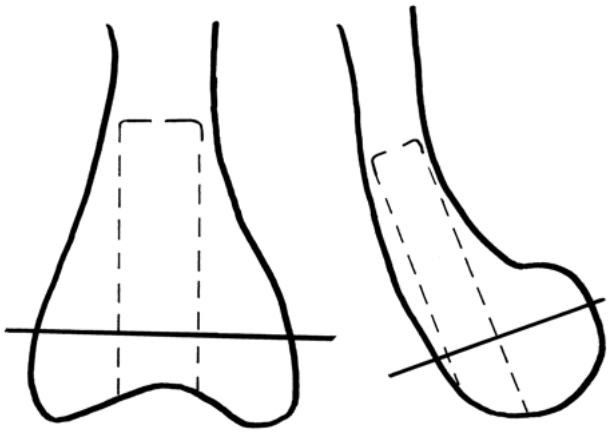

Figure 1 Schematic anterior and lateral views of the osteotomized rat distal femur where the absorbable pin was implanted.

The shear-load carrying capacities of the 40 pairs of femurs were measured within 24 h from the killing; the specimens were retained in 22–23 °C 0.9% NaCl solution. The proximal ends of the osteotomized bone specimens were embedded in Acryfix SQ® (Struers, RØdovre/Copenhagen, Denmark) cold-mounting acrylic resin. The shear-load carrying capacities (N) were measured using JJ 5003 tensile testing equipment (J. J. Lloyd Instruments, England) with a testing speed of 10 mm/min at room temperature (RT), from 22–23 °C (Fig. 2). The 20 pairs of the control intact femora were tested in the same way.

For the statistical analyses, the two-way analysis of variance (ANOVA) was used for determining time differences and Tukey's HSD (honestly significant differences) test for determining individual differences in the time direction [9].

3. Results

Wound infections were not seen at the operation site. The functional recovery of all rats was uneventful. The shear-load carrying capacities are presented in Table I. At one week the mean shear-load carrying capacity in the SR-PGA-fixed osteotomized femora was 108.7 N, while it was 132.6 N in the SR-PLLA-fixed femora. The values were statistically significantly higher than the control ones with 62.7 N ($p < 0.001$). At 6 and 12 weeks the shear-load carrying capacity increased from 164.7 N to 197.7 N in the SR-PGA-fixed femora and from 187.5 to 256.8 N in the SR-PLLA-fixed femora, while in the control femora it stayed nearly the same at 6 weeks but increased to 151.4 N at 12 weeks. The value of 197.7 N of the SR-PGA-fixed femora was statistically significantly

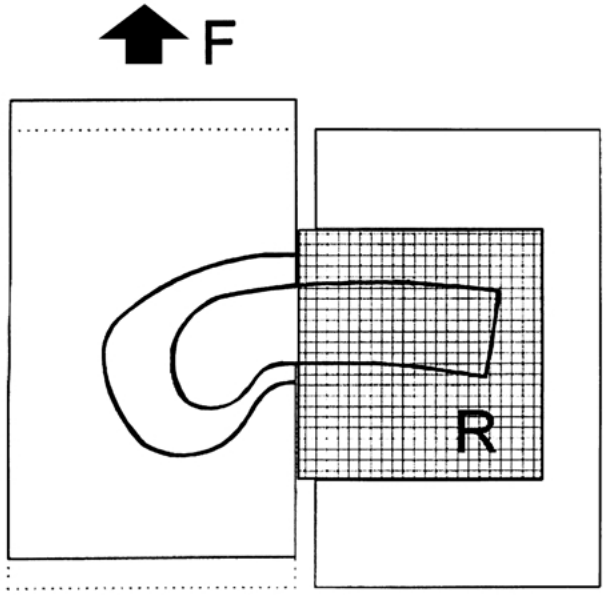

Figure 2 Measuring of the shear-load carrying capacity of the femurs. F = shear force at fracture. R = Acryfix SQ® cold mounting acrylic resin, in which osteotomized bone was embedded before testing. The testing speed was 10 mm/min.

($p < 0.001$) lower when compared to the value of 256.8 N of the SR-PLLA-fixed specimens.

At 24 weeks the mean shear-load carrying capacity increased to 286.1 N in the SR-PGA-implanted femora while it decreased to 222.6 N in the SR-PLLA-fixed femora. In the control femora it was 170.4 N which was a statistically significantly ($p < 0.001$) lower value when compared to the SR-PGA-fixed and SR-PLLA-fixed specimens. At 36 weeks the shear-load carrying capacity reached its highest values in the SR-PLLA-fixed femora, being 268.1 N, and in the control femora, being 207.9 N, but it decreased to 226.1 N in the SR-PGA-fixed femora. After that, however, the shear-load carrying capacity of the SR-PGA-fixed specimens gradually increased to the same value as in the SR-PLLA-fixed specimens, being at 52 weeks 263.5 N in the SR-PGA-fixed femora and 275.3 N in the SR-PLLA-fixed femora. These values were statistically significantly ($p < 0.001$) higher compared to the mean control value of 178.7 N.

4. Discussion

In studies of the biomechanical function of the implant not only its mechanical properties but also its behavior under *in vivo* conditions are important centers of interest. Comparison of the mechanical properties of various materials described in the literature is, however, difficult, as the material, as well as the processing and testing parameters vary and the data are often incomplete. It is obvious that the technique of fiber reinforcement improves the mechanical properties of bioabsorbable implants. Relaxation and creep are typical properties of polymeric materials under stress and have to be taken into consideration when manufacturing load-carrying implants of such materials [2].

The main purpose of the present study was to examine the shear-load carrying capacities with self-reinforced polyglycolide and self-reinforced polylactide, during time function at osteotomized cancellous bone in the same experimental animal. For the clinical application, the shear-load carrying capacity of the implant plays an important role in the fixation of cancellous bone fractures and osteotomies. To our knowledge there are no previous studies on shear-load carrying capacities of osteotomized cancellous bone in rats.

In one previous study [10], 40 distal rat femora were fixed with SR-PGA or SR-PLLA pins without osteotomy, intact femora of 20 rats serving as controls. The shear-load carrying capacities were examined. In that study the shear-load carrying capacities reached their highest values at 36 weeks in all groups and thereafter they gradually decreased. That study differed from the present one, as it included no evaluation of the influence of fracture healing processes. In the present study the shear-load carrying capacities reached their highest values at 24 weeks in the SR-PGA-fixed specimens, at 52 weeks in the SR-PLLA-fixed specimens and at 36 weeks in the control specimens. There were many factors affecting to the values, such as the strength retention of the pins, the degradation time of the pins, and the osteostimulatory effects of the pins, and also the osteostimulatory effects of the healing osteotomized bones.

An important question is what the necessary strength retention time is for absorbable fixation materials *in vivo*. The healing of cancellous bone fracture through trabecular bone growth is a much faster process (4–6 weeks) compared to the healing of cortical bone fractures (12–24 weeks). According to earlier experimental [6, 11, 12] and clinical [13–15] studies, SR-PGA implants seem to be suitable in the treatment of cancellous bone fractures and osteotomies, whereas SR-PLLA implants have been found sufficient for fixation of experimental cortical bone osteotomies in rabbits [16, 17].

TABLE I Results of shear-load carrying capacities at 1, 3, 6, 12, 24, 36, 48, and 52 weeks after fixation with self-reinforced polyglycolide (SR-PGA) and self-reinforced polylactide (SR-PLLA) pin in the same rat osteotomized femur and in the control rats at the same points of time

Implant	1 week ($n=5$)	3 weeks ($n=5$)	6 weeks ($n=5$)	12 weeks ($n=5$)	24 weeks ($n=5$)	36 weeks ($n=5$)	48 weeks ($n=5$)	52 weeks ($n=5$)
SR-PGA	108.7[1]	112.7	164.7[3]	197.7[5, 6]	286.1[8, 9]	226.1[11]	233.1[13, 14]	263.5[16]
SR-PLLA	132.6[2]	100.7	187.5[4]	256.8[5, 7]	222.6[8, 10]	268.1[11, 12]	273.7[13, 15]	275.3[17]
Controls	62.7[1, 2]	113.6	106.8[3, 4]	151.4[6, 7]	170.4[9, 10]	207.9[12]	194.4[14, 15]	178.7[16, 17]

n = number of rat analyzed femora
[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 15, 16, 17] $P < 0.001$ (Tukey's HSD test)
[11, 13] $P < 0.01$ (Tukey's HSD test)

In another previous study [18], the same transcondylar osteotomies of the distal femur were made as in the present study and fixed either with SR-PGA or with SR-PLLA pins, the intact femurs serving as controls. It was found that the most trabecular bone was seen at 48 weeks, which is in accordance with the present study, though the shear-load carrying capacities were not the greatest at that time but at the level where they stayed afterwards. In another words, when the pins seemed to have some osteogenetic potential, the shear-load carrying capacities stayed at a higher level in the SR-PGA- or SR-PLLA-fixed specimens than in the control femurs.

To summarize the present findings, both SR-PGA and SR-PLLA pins seemed to have sufficient fixation properties for internal fixation of cancellous bone fragments. In one study [19] self-reinforced fibrillated poly-96L/4 D-lactide (SR-PLA96) rods yielded promising results in the fixation of experimental cortical bone osteotomies. Since PLLA and its combinations of PLLA/PDLLA have also a low degradation rate, PLLA seems to be a promising material for developing degradable implants in the field of orthopedic surgery. It is of highest interest to develop fracture fixation devices which degrade and lose their strength within a suitable time in the fracture repair remodeling processes.

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