

# The use of biodegradable scaffold as an alternative to silicone implant arthroplasty for small joint reconstruction: An experimental study in minipigs

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## Abstract

Biodegradable poly-L/D-lactide (P(L/D)LA) 96/4 joint scaffold arthroplasty is a recently clinically introduced concept in the reconstruction of small joints, however its histology and function *in vivo* is unknown. In this experimental study on 11 minipigs the fifth metacarpophalangeal joints were reconstructed using a P(L/D)LA 96/4 joint scaffold or Swanson silicone implant. They were evaluated until 3 years. The P(L/D)LA 96/4 joint scaffold formed a porous interposition spacer, which maintained the arthroplasty space and induced fibrous tissue in-growth *in situ*. No differences were found in the range of motion or arthroplasty space width between the study groups. The P(L/D)LA 96/4 joint scaffold was initially filled with vascular, loose connective tissue. Along with degradation of the scaffold, the in-grown connective tissue matured and condensed turning into dense fibrous connective tissue. After 3 years, the P(L/D)LA 96/4 joint scaffold had almost completely degraded and been replaced by dense fibrous connective tissue. These findings indicate that P(L/D)LA 96/4 joint scaffold arthroplasty leads to the formation of a functional fibrous joint. The avoidance of permanent foreign material makes the biodegradable joint scaffold an attractive alternative for small joint arthroplasty.

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## 1. Introduction

Small joint arthroplasty is a challenge in hand surgery. Several treatment modalities have been developed for reconstructive surgery including resection and soft-tissue interposition arthroplasties [1,2], silicone implant interposition arthroplasty [3], and total joint replacements.

However, none of these seems ideal. Silicone implant arthroplasty, introduced by Swanson in the 1960s [3], is the best documented and the most widely used method in the treatment of destructed metacarpophalangeal (MCP) joints in rheumatoid arthritis. The flexible silicone implant acts as a joint spacer and becomes encapsulated by a fibrous capsule, which is thought to be essential for a successful outcome [3]. These implants provide satisfactory results in terms of pain relief, improved range of motion (ROM), and correction of deformation [3–5]. However, in the long-term follow-up the outcome deteriorates and implant breakage and wear, as well as bone destruction

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around the implant become frequent [4,6]. Need for implants with improved biocompatibility and prolonged outcome is evident.

Modern tissue engineering technology has led to the development of biodegradable scaffolds for reconstruction of small joints of the hand [7–10]. The scaffolds, made of knitted poly-L/D-lactide (P(L/D)LA) 96/4, are designed to function as a temporary porous support in the joint and to enable guided in-growth and development of host tissue *in situ*. In the present work, the hypothesis was that the scaffold is gradually degraded and replaced by host tissues, thus presumably leading to the formation of a living neojoint.

In this experimental study on minipigs, the resected fifth MCP joints of fore limbs were reconstructed with either a P(L/D)LA 96/4 joint scaffold or a Swanson silicone implant. The aim was to compare the radiographic and ROM outcomes of the two arthroplasty methods. The guided tissue regeneration and the host response to the joint scaffold were histologically examined.

## 2. Materials and methods

### 2.1. Implants

The P(L/D)LA 96/4 joint scaffolds (Fig. 1) were manufactured of purified, medical-grade (residual monomer <0.5%) P(L/D)LA copolymer with an L/D isomer ratio of 96/4 (Purac Biochem b.v., Gorinchem, The Netherlands). Raw P(L/D)LA 96/4 polymer (intrinsic viscosity 4.98 dl/g in chloroform at 25 °C, heat of fusion 30.2 J/g, glass transition temperature ( $T_g$ ) 66 °C) was melt-spun to 4-ply multifilament using Gimac micro-extruder (Gimac, Castronno, Italy) having a die temperature of 265 °C and oriented by drawing in a two-step process to a draw ratio of 4.2. The 4-ply multifilament was knitted to tubular jersey structure using a tubular jersey knitting machine (Textilmaschinenfabrik Harry Lucas, Neumünster, Germany) and rolled to a cylindrical scaffold 8 mm in diameter and 3.5 mm thick (Fig. 1) and heat-treated above  $T_g$  in the molds. The scaffolds were washed with ethanol, dried in vacuum overnight and packed separately into double pouches before they were sterilized with gamma irradiation of a minimum dose of 2.5 MRads. Due to processing and gamma irradiation, the produced P(L/D)LA 96/4 scaffold had intrinsic viscosity of 3.17 dl/g, heat of fusion 26.2 J/g, and  $T_g$  59 °C. The fabrication method of the P(L/D)LA 96/4 scaffold is described in more detail elsewhere [8].



Fig. 1. The implants used in the present study. On the left, biodegradable P(L/D)LA 96/4 joint scaffold. On the right, Swanson silicone implant.

The commercially available Swanson silicone finger joint implant (Wright Medical Technology, Inc., Arlington, Tennessee) of size 00 (Fig. 1) was appropriate to meet the anatomical requirements of the fifth minipig MCP joint. The Swanson implant was 25.4 mm in total length, whereas the midsection was 7.9 mm in width, 3.0–3.5 mm in length and 3.3 mm in height.

### 2.2. Experimental animals

This experimental study was approved by the Research Animal Committee of Helsinki University and by the Provincial Administrative Board. Eleven skeletally mature female minipigs (Ellegaard Göttingen Minipigs Aps, Dalmose, Denmark) with a mean age of 3.5 years (range 2.1–4.4) and a mean weight of 42.4 kg (range 29–57) were used in the experiment.

### 2.3. Anesthesia

The animals were sedated with 0.5 mg/kg midazolam (Dormicum<sup>®</sup>, Roche Oy, Espoo, Finland) intramuscularly (i.m.) and 4 mg/kg azaperone (Stresnil, Janssen-Cilag Pharma, Vienna, Austria) i.m. After premedication with 0.01 mg/kg of glycopyrrone (Robinul<sup>®</sup>, John Wyeth and Brother Ltd., New Lane, Havant, Hants, England) i.m., anesthesia was induced and after intubation maintained with isoflurane (Forene<sup>®</sup>, Abbott Scandinavia, Solna, Sweden). During the operation, 500–1000 ml of fluid (Ringersteril, Baxter Ltd., Vantaa, Finland), benzylpenicillin sodium 35 000 IU/kg (Geepencil, Orion Pharma, Espoo, Finland) and 2.2 mg/kg flunixin meglumine (Finatyde, Schering-Plough Sante Animal, Segre, France) were administered intravenously. 0.1 mg/kg butorphanol tartrate (Torbugesic Vet, Fort Dodge Laboratories, Fort Dodge, Iowa) i.m. was used for analgesia.

### 2.4. Surgical technique

The operation was performed under sterile conditions on both fore limbs under tourniquet control. A longitudinal skin incision was made on the dorsum of the fifth MCP joint. The joint was exposed by a longitudinal capsular incision between the common digital extensor and extensor digiti quinti tendons. The metacarpal head and the base of the proximal phalanx were resected piecemeal with bone rongeurs and chisel so that the collateral ligaments remained intact. The sesamoid bones were not removed. The resected joint space was thoroughly irrigated with saline and all cartilage was removed. The joint was reconstructed using either a P(L/D)LA 96/4 scaffold or a Swanson silicone implant (Figs. 1 and 2). Two different implants were randomly implanted in each animal. The P(L/D)LA 96/4 scaffold was fixed in place by two colourless polydioxanone (PDS II, 4/0 USP, Ethicon<sup>®</sup>, Norderstedt, Germany) knots, one to each collateral ligament. The silicone arthroplasty was done following the principles proposed by Swanson [3]. The intramedullary canals of the metacarpal and proximal phalanx were reamed into a rectangular shape to accommodate the implant stems. The joint capsule and skin were closed with interrupted and continuous intracutaneous 4/0 PDS sutures, respectively. The tourniquet was released. The wound was covered postoperatively for 10 days by teat bandage (Animal Soft, Snøgg Industri As, Mosby, Norway), sterile gauzes and self-adherent wrap (Coban<sup>™</sup>, 3M Health Care, Borken, Germany).

### 2.5. Examination methods

Clinical follow-up preoperatively, immediately after the operation and at predefined follow-up time points until sacrifice consisted of clinical assessment for lameness by observation, radiological examinations (anteroposterior radiograph, 44 kV, 10 mAs, 42.2 ms, 125 cm) and ROM measurements with a goniometer. The preoperative radiographs served as baseline for comparison. The animals were sacrificed and tissue samples harvested postoperatively at 10, 26, and 52 weeks to obtain three

specimens in each group, as well as at 3 years to obtain two specimens in each arthroplasty group. The control minipig without an interposition implant in the resected MCP joint was sacrificed at 52 weeks. An overdose of pentobarbital (Mebunat vet, Orion-yhtymä Oyj, Espoo, Finland) was given first, followed by administration of an euthanizing agent (T61 vet.inject., Intervet International GmbH, Unterschleissheim, Germany). The operated areas with the surrounding tissues were resected en bloc, inspected, and plain radiographs were taken in two planes (40 kV, 8 mAs, 33.5 ms, 125 cm). Arthroplasty space width was calculated from the anteroposterior radiographs by measuring the distance between the bone ends of the metacarpal and proximal phalanx. Volar subluxation was determined from lateral radiographs by measuring the difference between dorsal levels of the metacarpal and proximal phalanx. In radiographs, the contour of the resected bone ends, the presence of possible osteolysis or cortical erosion, and silicone implant integrity were also assessed. The tissue samples were fixed in an increasing ethanol series from 70% to 90% and embedded in methylmethacrylate. For histological analysis, 20 µm uncalcified whole mount sections were cut through the longitudinal axis of the bones and the joint by using a cutting and grinding method [11] and stained by modified Masson-Goldner trichrome method [12]. As controls, three unimplanted intact P(L/D)LA 96/4 scaffolds were embedded in methylmethacrylate and prepared similarly for the microscopic analysis. Light microscope was used for histological evaluation. The quantitative measurements were performed with the use of a computer-assisted image-

analysis software (Image Analysis Software analysis 3.0, Soft Imaging System GmbH, Münster, Germany). Since the P(L/D)LA 96/4 is highly birefringent, its retention and biodegradation over time were also assessed under polarizing light. The porosity of the scaffold was calculated by defining the proportion of P(L/D)LA filaments in the field of view that was produced by using low-power magnification.

## 2.6. Statistical analysis

Statistical analyses were done using SPSS 12.0 programme (Chicago, IL). Analysis of variance (ANOVA) or, if non-normal data, Kruskal–Wallis test was used to assess differences between groups. If such differences were found, pair-wise comparisons using *t*-tests or Mann–Whitney *U*-tests (if non-normal data) were carried out to locate the differences. Two-tailed *p*-values < 0.05 were considered significant.

## 3. Results

All minipigs recovered uneventfully from the operation, stood up after the anesthesia and put weight on and used all limbs normally without any signs of limping. In the P(L/D)LA scaffold group, no swelling or thickening of the tissues was macroscopically seen in the skin or subcutaneous layers. The extensor tendons above the reconstructed joint could be freely moved. In the Swanson implant group of 26-week follow-up, one minipig developed a sinus at the operation site 2 months postoperatively, followed by an implant extrusion and sinus healing. No differences in the joint stiffness or stability were found between the arthroplasty groups in manual examination.

### 3.1. Range of motion

The mean preoperative and postoperative passive ROMs of the joints are documented in Table 1. The mean ROM of the P(L/D)LA scaffold and Swanson implant groups decreased significantly from the preoperative values of 140° to 89° and 94° in the early postoperative weeks, respectively (*p* < 0.01). No further statistically significant changes in ROM were observed during the 3-year follow-up (*p* > 0.05).

### 3.2. Radiography

The contours of the resected bone ends were initially sharp both in the P(L/D)LA scaffold and Swanson silicone



Fig. 2. Radiograph at 1 year follow-up showing a P(L/D)LA 96/4 joint scaffold (A) and a Swanson silicone implant (B) in the fifth MCP joint of the fore limb of a minipig (arrows).

Table 1

Mean passive range of motion and radiological evaluation of arthroplasty space width and volar subluxation after P(L/D)LA 96/4 joint scaffold and Swanson silicone implants at follow-ups

		Pre-operative	10 Weeks	26 Weeks	1 Year	3 Years
Passive range of motion (deg.)	P(L/D)LA scaffold	140 (SD 8)	89 (SD 11)	98 (SD 10)	94 (SD 10)	86 (SD 2)
	Swanson	140 (SD 7)	94 (SD 15)	96 (SD 18)	90 (SD 7)	74 (SD 6)
Arthroplasty space width (mm)	P(L/D)LA scaffold		4.9 (SD 1.1)	4.5 (SD 0.8)	4.3 (SD 1.0)	3.9 (SD 0.3)
	Swanson		4.4 (SD 1.0)	4.0 (SD 0.5)	3.5 (SD 0.5)	2.7 (SD 0.5)
Volar subluxation (mm)	P(L/D)LA scaffold		0.4 (SD 0.3)	0.5 (SD 0.9)	0.7 (SD 0.2)	0.8 (SD 0.5)
	Swanson		0.2 (SD 0.3)	0	0	0

SD = standard deviation.

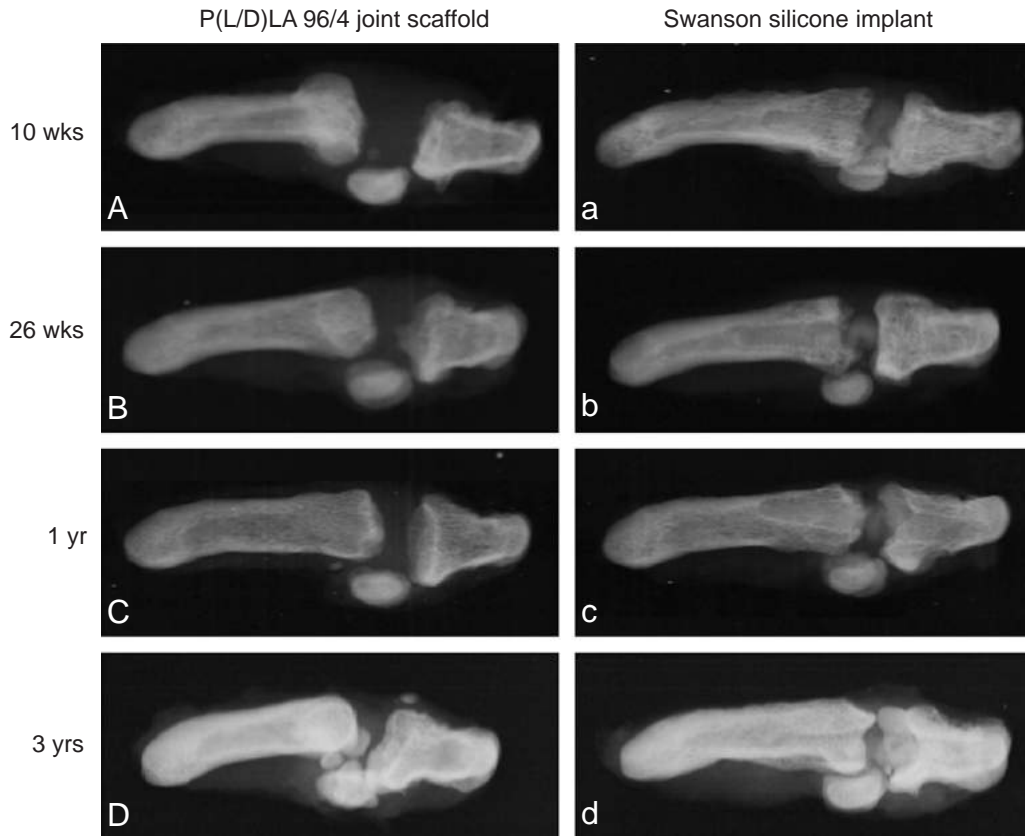


Fig. 3. Radiographs of the P(L/D)LA 96/4 joint scaffold and the Swanson silicone implant in lateral projection examined postoperatively at 10 weeks (A, a), 26 weeks (B, b), 1 year (C, c) and 3 years (D, d). On the left metacarpal bone and on the right proximal phalanx in each radiograph.

implant groups (Fig. 3A and a), but gradually became uneven and sclerosed (Fig. 3B–D and b–d). At 10 weeks, a periosteal reaction was seen at the resected bone ends in both groups (Fig. 3A and a). In the P(L/D)LA scaffold group after 26 weeks, the end of the metacarpal bone had remodelled into a rounded and convex shape, whereas the proximal phalanx had become concave due to new bone formation at the edges of the proximal phalanx (Fig. 3B). In the Swanson silicone group, bony spurs were noted at 10 weeks at the site of the metacarpal osteotomy on the volar and dorsal aspects of the ray (Fig. 3a). This became gradually more pronounced so that at 3 years the Swanson silicone implant was almost completely surrounded by bony spurs (Fig. 3d). No breakage of the silicone implant could be seen in the radiographs. After one year, cortical bone erosions were seen around the stems of the Swanson implants in all specimens (Fig. 3c and d). Bone remodelling was frequently seen at the end of the stems where the cortical bone became very thin (Fig. 3c and d).

The mean arthroplasty space width ranged 4.9–3.9 and 4.4–2.7 mm in the P(L/D)LA 96/4 scaffold and Swanson silicone implant groups during the follow-up, respectively (Table 1). The mean values were higher in the P(L/D)LA group, but the difference was not statistically significant ( $p = 0.077$ ). During the follow-up, no statistically significant decrease in arthroplasty space width was seen in either group ( $p = 0.516, 0.13$ , respectively). Volar subluxation

was present at all follow-up time points in the joints reconstructed with P(L/D)LA scaffolds (Table 1), with the mean value being 0.56 mm (range 0.0–1.1 mm). No statistically significant increase towards higher values of subluxation were seen during the follow-up ( $p = 0.790$ ). In the Swanson implant group, volar subluxation was seen only in one joint (Table 1).

### 3.3. Light microscopy of P(L/D)LA 96/4 joint scaffold arthroplasty

The P(L/D)LA scaffold remained in correct position between the resected bone ends during the whole study period. All histological sections showed fibrous connective tissue formation in the scaffold without any cartilage except for the articular surfaces of the sesamoid bones, which had been left untouched in the operation. The mean porosity of the unimplanted P(L/D)LA scaffold was 69% (SD 1.0) with a range from 62% to 74% (Fig. 4). The mean filament diameter of the unimplanted scaffold was 113  $\mu\text{m}$  (SD 2.1).

### 3.4. Ten-week follow-up

At 10 weeks, the P(L/D)LA scaffold was surrounded by a fibrous tissue capsule and became completely invaded by loose connective tissue rich in fibroblasts and capillaries

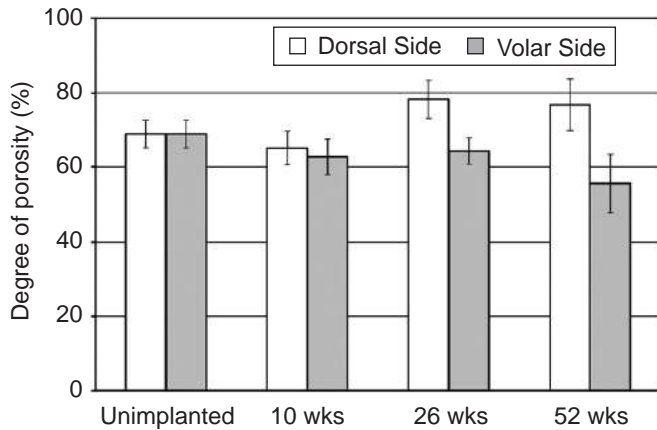


Fig. 4. The porosity of P(L/D)LA 96/4 scaffold before implantation and at follow-up time points in the dorsal and volar sides of the joint scaffold.

(Fig. 5A and a). The polymer filaments were practically intact when observed by the light microscope and only few cracks were seen. Their mean diameter throughout the scaffold was  $112\ \mu\text{m}$  (SD 2.7). The mean degree of porosity was 65% (SD 4.1) dorsally in the scaffold and 63% (SD 5.0) volarly in the scaffold (Fig. 4). This did not statistically differ from the porosity of the unimplanted PL(D/L)LA scaffold ( $p = 0.19$ ). Volarly, the in-grown connective tissue had matured and condensed forming now a dense collagen framework between the polymer filaments (Fig. 5a). Each individual filament was encapsulated by 3–7 layers of fibroblasts. In some parts of the scaffold, the 4-ply P(L/D)LA multifilament structure of the knitted scaffold was distinguishable. Dorsally in the scaffold, mainly unorganized cell-rich loose connective tissue was seen (Fig. 5A). A few macrophages were detected on the surface of the P(L/D)LA filaments, but neither lymphocytes nor neutrophils were present. The fibrous interface area between the scaffold and the resected bone end was 1.2 mm wide on the metacarpal side and 0.48 mm on the proximal phalangeal side. New bone formation was seen periosteally at the volar and dorsal edges of both resected bone ends (Fig. 5).

### 3.5. Twenty-six-week follow-up

At 26 weeks, most of the filaments of the P(L/D)LA scaffold were unfragmented and only few cracks were observed. The invasion of the granulation tissue into the cracked filament structure was still very minor. The 4-ply multifilament structure of the scaffold could no longer be clearly identified. The mean diameter of the P(L/D)LA filaments was  $116\ \mu\text{m}$  (SD 6.3) in the scaffold. The porosity volarly in the scaffold had remained similar (mean 64%, SD 3.0,  $p = 0.67$ ), but dorsally it had increased (mean 78%, SD 4.6,  $p = 0.02$ ) compared with the 10-week specimens (Fig. 4). The connective tissue inside the scaffold had matured and condensed into dense connective tissue, which was rich in compacted collagen bundles and

contained only a few scattered fibroblast-like spindle shaped cells. After 10 weeks, an obvious increase in collagen framework was observed inside the P(L/D)LA scaffold (Figs. 5 and 6). Especially in the volar side of the scaffold the dense collagen bundles were aligned between and around the P(L/D)LA filaments (Fig. 5b). Often only 1–2 fibroblast layers encapsulated each individual filament. However, in the dorsal and peripheral regions of the scaffold, all individual filaments were surrounded by a 1–5 fibroblast thick layer. A few multinucleated phagocytic foreign-body giant cells and macrophages were seen on the surface of the filaments, but no other inflammatory cell infiltrates were present. The mean width of the fibrous bone-scaffold interface was 0.84 mm on the metacarpal and 0.30 mm on the proximal phalangeal side. There still was a periosteal reaction at the edges of both bone ends (Fig. 5).

### 3.6. Fifty-two-week follow-up

At 52 weeks, the configuration of the P(L/D)LA scaffold was identifiable but had softened (Fig. 5). In histological specimens increased cracking of the P(L/D)LA filaments were seen, but the volume of granulation tissue penetrating into the filaments was still relatively minor. The mean diameter of the cracked P(L/D)LA filaments was  $120\ \mu\text{m}$  (SD 7.4) in the scaffold. The degree of porosity remained similar dorsally in the scaffold (mean 77%) compared to the 26-week specimens ( $p = 0.80$ ), but volarly the porosity had slightly reduced (56%,  $p = 0.19$ , vs. 26-week specimens) (Fig. 4). The difference in the degree of the porosity between the volar and dorsal sides of the scaffold was significant ( $p = 0.022$ ). The dense connective tissue was highly organized throughout the scaffold and formed a nearly acellular, dense collagen framework with only a 1–3 fibroblasts thick layer around each P(L/D)LA filament in most places, especially volarly in the scaffold. The increase in the collagen framework inside the scaffold was significant compared to the 10-week specimens ( $p = 0.002$ , Fig. 6). Macrophages and a few foreign-body giant cells were seen in close vicinity to the polymer indicating actively ongoing degradation. The number of macrophages had increased compared with 10- and 26-week specimens but they were still few in number. No other inflammatory cell infiltrates were seen. The mean width of the fibrous bone-scaffold interface was 1.33 mm on the metacarpal side and 0.19 mm on the proximal phalangeal side. This difference was statistically significant ( $p < 0.001$ ). Due to new bone formation the bone end of the metacarpal bone had remodelled into a rounded convex shape, whereas the bone edges of the proximal phalanx were “clumped” and thus formed a more concavely shaped bone end.

### 3.7. Three-year follow-up

At 3 years, the P(L/D)LA scaffold had almost completely degraded and disappeared (Figs. 5 and 7). Only very few

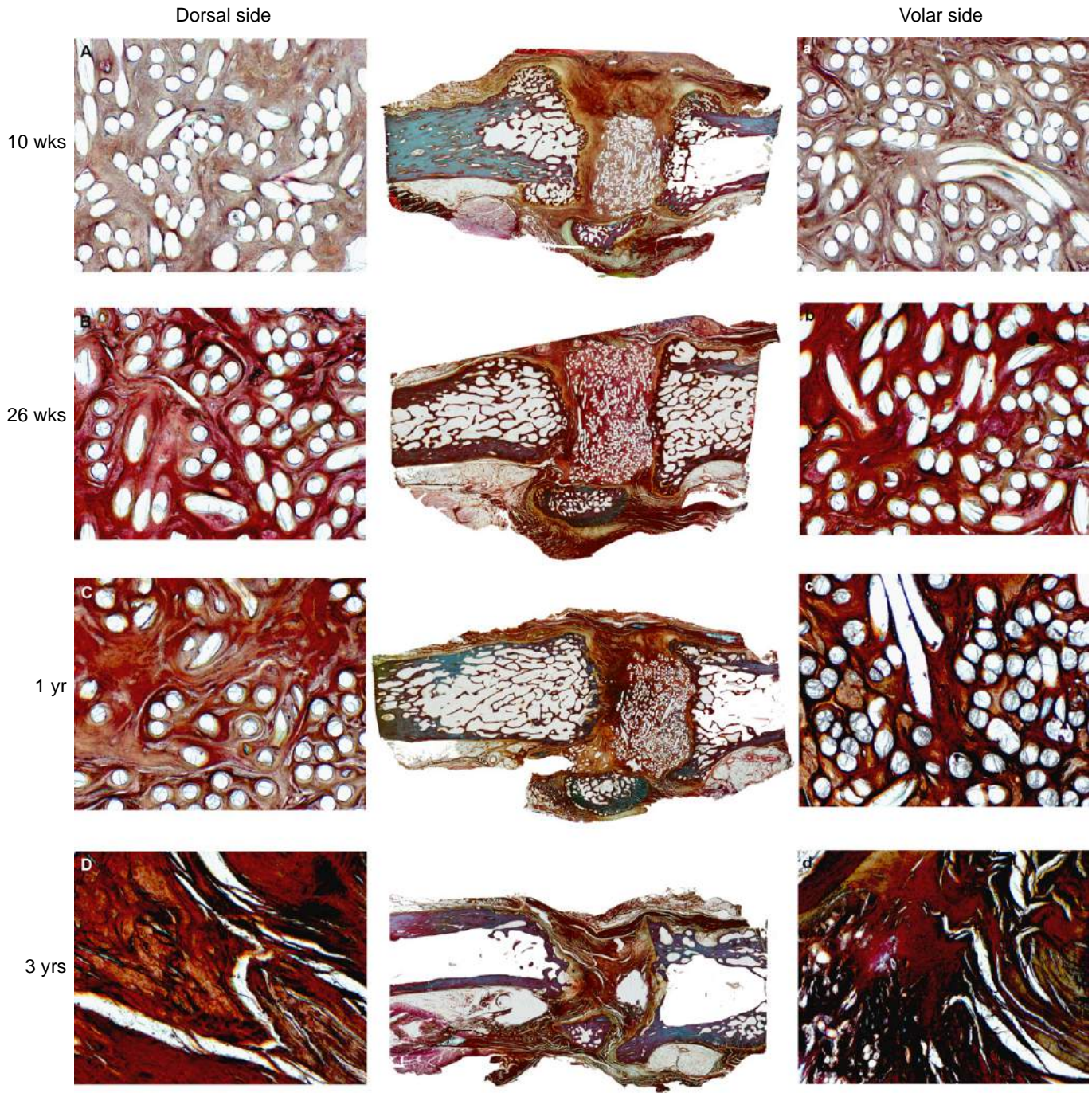


Fig. 5. Sagittal photomicrograph of the joints reconstructed with P(L/D)LA 96/4 scaffold at 10 (A), 26 (B), 52 (C) and 156 (D) weeks postoperatively. A histological detail of the P(L/D)LA 96/4 joint scaffold is presented in the dorsal (left column) and volar side (right column) of the reconstructed joint. Masson-Goldner trichrome; scale bar 500  $\mu$ m in the microscopic view.

tiny polymer particles were seen. The site of the scaffold had mostly been replaced with acellular dense connective tissue, characterized by abundant dense compacted collagen and a paucity of cells. The collagen fibres were mainly orientated in longitudinal arches. Patches of loose connective tissue with polymer debris being apparently actively phagocytosed by macrophages and some foreign-body giant cells were seen in some areas, especially

dorsally in the reconstructed joint (Fig. 7). Except for a few lymphocytes that were seen in these areas, no lymphocyte or neutrophil infiltrates were evident. Scattered clusters of adipocytes were seen in the marginal areas of the joint. The bone ends were similar to the 1-year specimens, except that the clumpy volar edge of the proximal phalanx had become more prominent than the dorsal one.

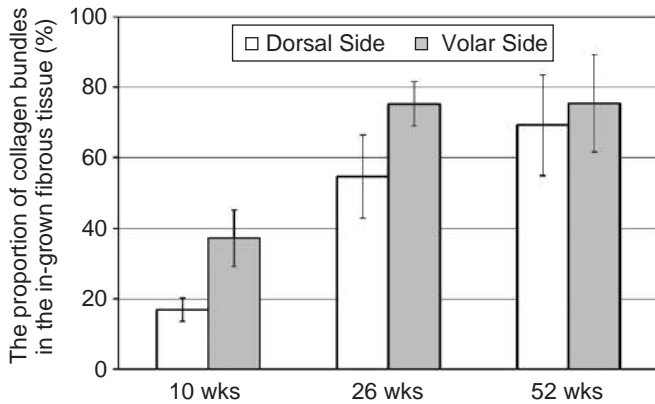


Fig. 6. Histomorphometric analysis of the proportion of collagen bundles in the in-grown fibrous tissue shows connective tissue maturation in the dorsal and volar sides of the scaffold as a function of time.

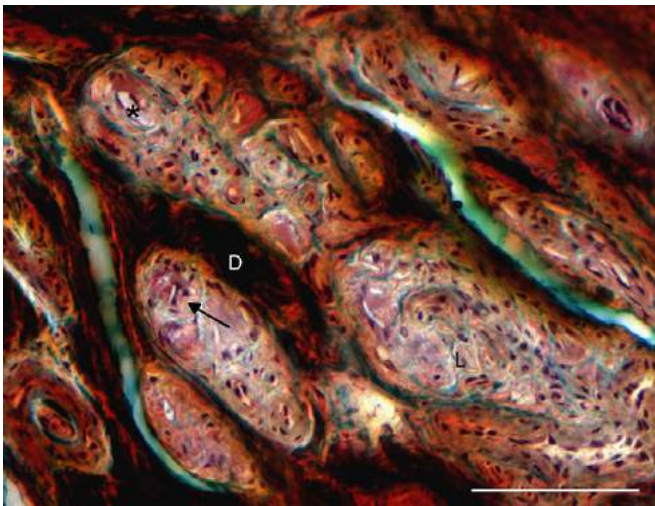


Fig. 7. At 3 years the P(L/D)LA 96/4 joint scaffold had almost totally degraded and been replaced by dense connective tissue (D) with abundant collagen fibres. In some areas, there were patches of cell-rich loose connective tissue with tiny P(L/D)LA 96/4 debris particles (star) being phagocytosed by macrophages and foreign-body giant cells (arrow). Masson-Goldner trichrome; scale bar 100  $\mu$ m.

#### 4. Discussion

The concept of biodegradable interposition scaffolds aims to avoid the foreign body evoked complications associated with the use of silicone implants, especially in the long term. In a preliminary clinical study in rheumatoid arthritis patients [9], the P(L/D)LA 96/4 joint scaffold provided an appropriate spacer leading to pain alleviation, increased motion and correction of deformation of MCP joints in the short-term follow-up. A great part of these operations were performed due to failure of earlier silicone implant arthroplasties that had caused bone destructions. As an advantage, the use of P(L/D)LA 96/4 joint scaffold enabled intramedullary bone grafting [13]. A recent assessment of these same 23 rheumatoid patients after 4.9 years in average showed that the structure and function of

the reconstructed joints were maintained despite the total degradation of the P(L/D)LA 96/4 scaffold. The authors concluded that the outcome was comparable with published data on silicone implant arthroplasties with medium-term follow-up without any significant periprosthetic osteolysis [10]. There were no given loading limitations for hand use after the 3-years scaffold dissolution because no permanent implant material remained [10]. A similar concept, a degradable polyurethane urea spacer, has shown a significantly better pinch strength for treatment of thumb carpometacarpal osteoarthritis than abductor pollicis longus tendon arthroplasty [14].

This study showed that the P(L/D)LA 96/4 joint scaffold engineered fibrous tissue joints *in situ*. The scaffold was initially invaded by vascularized and cell-rich loose connective tissue. In earlier histological studies with P(L/D)LA 96/4 scaffolds the connective tissue in-growth occurred in rat subcutis by 3 weeks [15]. Along the follow-up of this study, the loose connective tissue inside the joint scaffold construct matured to dense connective tissue with an abundant collagen framework containing only relatively few fibroblasts. The cell-rich interface zone immediately around all P(L/D)LA 96/4 filaments consisted of a fibroblast layer that became thinner during the follow-up. Recently, a somewhat similar connective tissue response to a P(L/D)LA mesh sheet after subcutaneous implantation in rat was described [16]. The type III collagen-rich area was found in the cell-rich interface zone immediately around the implant, whereas type I collagen and  $\alpha$ -actin were expressed in the outer dense connective tissue zone. Myofibroblasts rich in  $\alpha$ -actin formed a tight framework around the P(L/D)LA material and the type III collagen-rich interface zone providing contraction and stability [16–18]. A previous histological study on monkeys' thumb basal joint demonstrated that allograft tendon interposition promoted the repopulation of the arthroplasty space with dense fibrous tissue, whereas the specimens without an interposition tendon graft were filled with loose fibroadipose tissue [19].

The collagen framework inside the scaffold became more prominent during the follow-up and provided ultimate structural integrity and strength in the arthroplasty space after scaffold degradation. The collagen framework was more prominent volarly in the scaffold than dorsally which suggests that compression loading associated with joint flexion serves as a stimulus for fibrogenesis. At 3 years the structure of the P(L/D)LA 96/4 joint scaffold was almost completely disintegrated and replaced by dense connective tissue. Collagen fibres were orientated in a longitudinal fashion adapting to the flexion–extension movements of the joint. As a last sign of the degradation process, there were patches of cell-rich loose connective tissue with tiny polymer debris particles in some areas. In addition to the local resident cells, such as vascular endothelial cells, fibroblasts and mast cells, this cellular reaction was composed of macrophages and foreign-body giant cells, which are thought to be responsible for the ultimate digestion of the polymeric debris [20]. No accumulations of

lymphocytes, implying an immune-inflammatory process, were seen. These results are consistent with earlier clinical, histological and immunohistological studies on P(L/D)LA 96/4 implants [9,10,15–18,21]. The biocompatibility of implants made of different polylactides (PLA) is clinically well documented in trauma, orthopaedic [22], hand [23,24] and craniomaxillofacial surgery [25].

The maintenance of the joint space and joint alignment after interposition arthroplasty is essential for a successful outcome. *In vitro* compression testing has shown that the P(L/D)LA 96/4 joint scaffold withstand estimated *in vivo* stresses and axial loading in the human MCP joints [26]. In this study, the arthroplasty space was maintained in the P(L/D)LA 96/4 scaffold group during the 3 years follow-up despite the scaffold degradation and strength loosening. *In vitro* the half-life of the tensile strength of the P(L/D)LA 96/4 yarn made for scaffolds has been 13 weeks [9]. In the Swanson silicone implant group, a tendency toward lower and decreasing values of arthroplasty space width was noticed, but the difference was not statistically significant. A bony spur was noticed on the volar side and dorsally around the midsection of the silicone implant. In the P(L/D)LA 96/4 scaffold group, the head of the resected metacarpal bone remodelled into a rounded convex shape, whereas the proximal phalanx into a concave shape. The scaffold degradation did not induce any significant osteolysis or cortical erosion in the adjacent bones.

The original macroscopic configuration of the P(L/D)LA 96/4 scaffold was identifiable until follow-up of 52 weeks, but some changes on the surface and in the porosity developed during this observation period. The porosity of the scaffold reduced *in situ* volarly, probably due to compression caused by bones and ligaments and due to reduced strength of the polymer. On the other hand, the mean porosity dorsally increased at 26 and 52 weeks, which may be due to a distraction force generated on the extension side of the joint during joint motion.

The passive ROM values after the P(L/D)LA 96/4 joint scaffold and Swanson implant arthroplasties were similar in the present experimental study. However, the number of animals in each time group was not sufficient for adequate statistical analysis. The values may appear somewhat high when compared to the ROM values reported in human clinical studies for rheumatoid MCP joints after Swanson silicone arthroplasty [3,5]. In radiographs, a minimal radiological volar subluxation, without any progression during the follow-up, was seen in the P(L/D)LA 96/4 scaffold group. In the microscopic evaluation, the volar subluxation occurred at the fibrous interface area between the scaffold and the resected metacarpal bone end. It is likely that most of the hybrid joint motion occurs in this hinge area, whereas the scaffold itself functions as a cushion-like absorbing counterforce.

Previously, e.g. the rabbit knee has been used as an *in vivo* model for evaluating the implants used in the reconstruction of MCP joints [27] but the model has been criticized [28]. The fifth minipig MCP joint is a new *in vivo*

model for evaluating the implants used in the small joint arthroplasty. The joint is not a main weight-bearing joint, but, however, moves at each step simulating cyclic hand joint loading. Its shape and passive ROM are close to those of the healthy human MCP joints. As regards to the MCP arthroplasties, which are mainly done for rheumatoid arthritis patients, there were no inflammatory cell infiltrates in the reconstructed joints and their soft-tissue balance was favourable. In the present study, both bone ends of the joint were resected to simulate end stage of arthritis. In the Swanson silicone implant group the radiographical findings were similar to those reported in a clinical patient series [13]. The Swanson silicone implant caused cortical bone erosion around the stems, probably due to the piston movements and pressure from the implant [13].

## 5. Conclusion

This *in vivo* experimental study shows that biodegradable P(L/D)LA 96/4 joint scaffold provides a temporary porous spacer to enable guided and controlled fibrous tissue ingrowth and maturation *in situ*. While the scaffold is gradually replaced, a functional, fibrous functional joint without foreign materials is formed. This may be important in the long term. The physical and degradation properties as well as biocompatibility of the P(L/D)LA 96/4 scaffolds were favourable in this experimental study. Biodegradable P(L/D)LA 96/4 joint scaffold has potential for the reconstruction of the small joints in the hand, but its use in clinical medicine has to await validation of clinical patient series and controlled trials.

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