

Original article

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Histomorphometric evaluation of the synovial membrane during osteosynthesis of intra-articular metaepiphyseal fractures with titanium screws in lambs (an experimental morphological study)

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Abstract

Introduction The complexity of treating intra-articular fractures in children is due to the anatomical features of the joint, its biomechanics, and the tendency to develop post-traumatic arthritis. This necessitates a detailed study of the structural organization of all elements of the joint synovial environment.

The **aim** of this study was to evaluate, using an experimental model, the severity of structural changes in the synovial membrane of the carpal joint during osteosynthesis of intra-articular metaphyseal fractures with titanium screws.

Materials and Methods The study was performed on six outbred male lambs (46.1 ± 3.0 days old, weighing 15.7 ± 2.0 kg). An oblique intra-articular metaphyseal fracture of the radius on the right limb was modeled. Fracture fixation was performed with two cannulated cancellous bone screws made of Ti6AL4V titanium. The experimental periods were 120 ($n = 3$) and 365 ($n = 3$) days after surgery. Histomorphometric analysis of the synovial membrane was performed using an AxioScope.A1 microscope and Zenblue software (CarlZeissMicroImagingGmbH, Germany). The synovium of the contralateral joint served as a control.

Results In the control joint, fibroblast-like synoviocytes predominated in the synovial membrane lining layer; no signs of synovitis were detected. After 13.5 months, a decrease in lining layer thickness ($p = 0.0326$) and synoviocyte density ($p = 0.0009$) was noted. In the experimental joint, mild synovitis, hyperplasia of the lining layer, increased synoviocyte density and macrophage-like synoviocyte representation (more than 50 % per field of view), formation of synovial villi, and the presence of focal and diffuse lymphohistiocytic infiltrates were detected after 120 days. After 365 days, signs of synovitis were absent, fibroblast-like synoviocytes predominated in the lining layer; elevated synoviocyte density values persisted ($p = 0.0141$), and lining layer thickness values were comparable to the control ($p = 0.1301$).

Discussion Non-bioresorbable fixators used for osteosynthesis of intra-articular fractures can cause a number of complications, including infection, pain, and arthritis. It was established that macrophage and fibroblastic synoviocytes perform various pro- and anti-inflammatory functions and can both prevent inflammation by forming an anti-inflammatory barrier and contribute to the development of synovitis.

Conclusion Osteosynthesis of intra-articular metaepiphyseal fractures of the distal articular end of the radius in lambs using titanium screws provoke mild synovitis after 120 days of the experiment. This synovitis was characterized by thickening of the lining layer, an increase in the numerical density of synoviocytes and in macrophage synoviocytes, and the presence of a lymphohistiocytic infiltrate. By the end of the experiment, the synovial membrane inflammation reversed, and histological signs of synovitis were absent.

Keywords: intra-articular fracture, titanium screws, lambs, synovial membrane, histomorphometry

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INTRODUCTION

Upper limb fractures account for a significant portion among all injuries in children, for up to 84 % of all limb fractures, according to various sources. The most common upper limb fractures are distal radius fractures, which make 10 to 35 % of all skeletal injuries [1, 2, 3, 4].

The main principles of surgical treatment of intra-articular fractures in children include: precise restoration of normal joint anatomy and alignment of bone fragments [2, 5]; ensuring stable fixation of the fracture using orthopedic means (external fixators, pins, screws, plates, wires, bioresorbable fixators) [6, 7, 8, 9]; minimally invasive techniques to reduce damage to soft tissues, blood vessels and growth zones, for complete restoration of joint function and minimization of complications [10].

The choice of treatment strategy for intra-articular metaphyseal fractures of the forearm bones in children remains relevant and not fully resolved issue in modern traumatology and orthopedics [3, 11].

Currently, there is no consensus on the choice of surgical treatment method for distal radius fractures in children. Treatment results using the methods presented in the literature are contradictory, with a high rate of complications and unsatisfactory treatment outcomes. The most common complications include malunion or slow fracture healing, post-traumatic arthritis, limb growth retardation, infections, vascular and nerve damage, pseudarthrosis, and muscle atrophy [12, 13, 14, 15].

The complexity of treating children with such fractures is related to the anatomical features of the joint, its biomechanics, the tendency for bone tissue to grow around the joint (periarticular ossification), and the development of contractures [2], which necessitates a detailed study of the structural organization of all elements of the joint's synovial environment.

The condition of the synovial membrane is crucial for the successful healing of an intra-articular fracture, maintaining a healthy joint environment, and preventing complications. It has been established that intra-articular fractures are associated with increased concentrations of proinflammatory cytokines and degradative enzymes produced by synovial cells [16]. Despite a growing understanding of the role of the synovial membrane in joint pathology, quantitative data on the structure of this tissue remains incomplete.

It is impossible to obtain information on the structural reorganization of the synovial membrane at the stages of osteosynthesis in clinical studies; experimental studies on animals are necessary.

The **aim** of this study was to evaluate, using an experimental model, the severity of structural changes in the synovial membrane of the carpal joint during osteosynthesis of intra-articular metaphyseal fractures with titanium screws.

MATERIAL AND METHODS

Study design

The study was conducted on six mongrel male lambs aged (46.1 ± 3.0) days and weighing (15.7 ± 2.0) kg. The study periods were 120 and 365 days (three animals per period).

Inclusion criteria: clinically healthy lambs in the period of active growth that did not have any diseases of the locomotor system.

Exclusion criteria: diseases of the locomotor system (rickets, limb deformities).

A complete oblique intra-articular metaphyseal fracture of the distal radius, corresponding to type 4 according to the Salter-Harris classification was modeled in all animals [17]. The osteotomy line was located on the anterior surface of the radius and passed through the metaphysis, growth plate, and epiphysis to the center of the articular surface of the bone. In all cases, the wrist joint capsule was dissected until the articular surface of the radius was exposed. The osteotomy was performed with an oscillating saw. Complete instability of the free fragment was considered a sign of an intra-articular fracture.

Fracture fixation was performed using two cannulated titanium Ti6AL4V bone screws with a partial thread of 3.5 mm (Registration Certificate No. FSR 2012/14220 dated April 8, 2021). Initially, the bone fragment was reduced and temporarily fixed with two 1.0 mm osteosynthesis wires. Screw insertion did not penetrate the radial growth plate. First, a guide wire was inserted in the medio-lateral direction at the insertion point. Next, a 2.5-mm cannulated drill was used to drill a canal for the screw along the wire. The drill was then removed, and a cannulated screw was inserted along the wire. The screw was tightened until complete stability of the bone fragment. Osteosynthesis was performed first at the metaphysis level, then at the epiphysis level of the radius. Fixation of the fragments at the level of the radial epiphysis was performed in a similar manner. After osteosynthesis of the fracture, the temporary wires were removed. The surgical wound was closed layer by layer with interrupted 3/0 Vicryl sutures.

Surgical interventions were performed under general anesthesia. Premedication consisted of 1 % diphenhydramine (0.02 mg/kg), 0.1 % atropine sulfate (0.02 mg/kg), and 2 % rometar (0.1 mg/kg) solutions. Anesthesia was administered using 1 % propofol emulsion at a dose of 4 mg/kg/min.

To prevent fragment displacement during the postoperative period, the limb was temporarily immobilized with a thermoplastic splint at 25–30° of carpal flexion. Immobilization was discontinued on days 10–14. To prevent the development of inflammatory processes, the animals were also given painkillers (intramuscular ketoprofen 50 mg, 0.5 ml) and antimicrobial drugs (intramuscular ceftriaxone 1.0, 7–10 mg/kg). The surgical wound was treated with solutions of 3 % hydrogen peroxide and furacilin 1:5000. Sutures were removed on days 10–14. Bone screws were not removed during the entire study.

Study object: synovial membrane of the carpal joint

In vivo examinations In the postoperative period, the general condition of the animals, the intensity and nature of motor activity were assessed; local examination assessed the course of surgical wound healing, the presence of hematomas, edema, the occurrence of segment deformity, and the range of motion of the limb in the carpal joint.

Radiographic study Radiography was performed in the frontal and lateral projections using a CANON CXDI-401C COMPACT veterinary flat-panel detector (Canon Inc. Medical Equipment Group, Japan); a TOSHIBA Rotanode Model E7239, N 10G749 X-ray tube (Japan). The current was 2.5–3.2 mA, the voltage was 43–44 kV, the focal length was 90 cm, and the exposure was set automatically.

Ethical approval The study was conducted in accordance with the principles of the European Convention ETS No. 123 for the Protection of Vertebrate Animals used for Experimental and other Scientific Purposes (with the appendix of 15.06.2006, Strasbourg) and the rules of good laboratory practice (GOST 33044-2014, GOST 33215-2014, GOST 34088-2017, PS SanPiN 3.3686-21). Institutional ethics committee dated 29.11.2024 No. 1 (76).

Euthanasia Animals were euthanized after premedication with a 1 % diphenhydramine solution (0.02 mg/kg) and 2 % rometar (0.1 mg/kg), followed by the administration of a lethal dose of barbiturates.

Histomorphological study

The synovial membrane of the carpal joint was dissected using a scalpel and placed in a fixative (10 % neutral formalin). Further standard histological processing was performed using a HISTOSAFE™ INFILTRA™ tissue vacuum processing apparatus (ErgoProduction LLC, Russia).

Sections (3–5 µm thick) were prepared from paraffin blocks using a Thermo Scientific HM 450 microtome (USA), which were then stained with hematoxylin and eosin or Masson's three-color method.

An AxioScope.A1 microscope with an AxioCam ICc 5 camera was used to obtain digital images of the sections. Zenblue software (CarlZeissMicroImagingGmbH, Germany) was used to determine the following parameters: thickness of the outer layer (µm) and the numerical density of synoviocytes per 1 mm of the lining layer length. Measurements and calculations were performed on average in 10 fields of view at 1000× magnification from each animal.

The severity of synovitis was assessed using the semi-quantitative scale of Krenn et al. [18] (0–1 point — no synovitis; 1 ≤ 4 points — mild synovitis; 5–9 points — severe synovitis) in 10–15 visual fields at 400× magnification from each animal. The synovial membrane of the carpal joint of the contralateral limb was examined as a conditional control.

Statistical methods Quantitative data were processed using Microsoft Excel spreadsheets. The Kolmogorov test was used to evaluate the distribution of samples. The measure of central tendency of the morphometric parameters is presented as the median and quartiles, minimum and maximum values (Me (p25; p75) [min–max]). The nonparametric Mann–Whitney test was used to analyze differences between the compared groups; differences were considered significant at $p < 0.05$.

RESULTS

The postoperative period was uneventful. The surgical wound healed by primary intention without septic complications. All lambs experienced limited motor and weight-bearing function of the limb during splint immobilization, thus carpal contracture developed. When immobilization was discontinued, limb function gradually recovered. On the 14th day after surgery, carpal flexion, at the time of splint removal, was 45–50°; by the 30th day after surgery, it was 170°. By the 45th day of observation, carpal flexion was fully restored (180°) and remained so until the end of the study.

Radiographic signs of fracture healing were recorded by the 30th day after surgery. Areas of complete restoration of the cortical plate were noted. The osteotomy line of the epiphysis and articular surface was filled with newly formed bone tissue. The articular surface line was anatomically correct, with no areas of layers or overgrowth. The height of the joint space was uniform throughout. The growth plate was continuous and had no areas of ossification in the projection of the osteotomy line (Fig. 1 a). By the 120th day, the osteotomy line was not visualized. The articular surface had no pathological formations. The joint space was clearly visible. The growth plate was open. Deformities of the articular surface were not noted (Fig. 1 b). At the final stage (365 days after surgery), radiographs showed complete bone remodeling in the osteotomy zone. The articular surfaces of the carpal joint had anatomically correct contours. No pathological changes in bone structures were detected (Fig. 1 c).



Fig. 1 Radiographs of lamb limbs in the AP and lateral views: (a) 30 days of fixation; (b) 120 days of fixation; (c) 365 days of fixation

Morphological characteristics of the synovial membrane of the carpal joint of the contralateral limb

The synovial membrane of the carpal joint of the contralateral limb had a normal structure (Fig. 2 a, b). After 120 days (the animals were 5.5 months old), the synovial membrane had a predominantly smooth surface, folds were poorly expressed, and synoviocytes of the lining layer

were arranged in two to three layers (Fig. 2 a). After 365 days (the animal age was 13.5 months old), the synovial membrane had a folded surface over a greater area, and synoviocytes were arranged in one to two layers (Fig. 2 b). As the age of the animals increased, the thickness of the lining layer and the numerical density of synoviocytes significantly ($p < 0.05$) decreased (Table 1), and the proportion of the fibrous component in the lining layer increased. The cells of the lining layer were polymorphic; the majority, based on their morphological characteristics, belonged to fibroblast-like synoviocytes; those cells had a flattened or polygonal shape (Fig. 2 c). Cell density in the upper subsynovial layer was normal in most cases, but in some cases it was characterized as slightly elevated, with fibroblasts and fibrocytes predominating (Fig. 2 d). The deep subsynovial (collagen-elastic) layer was more saturated with collagen fibers with areas of adipose tissue; as the experimental duration continued to increase, the proportion of the fibrous component and the thickness of the collagen fiber bundles grew. No inflammatory infiltrate was detected.

Krenn et al. [18] evaluation confirmed absence of synovitis (Table 1).

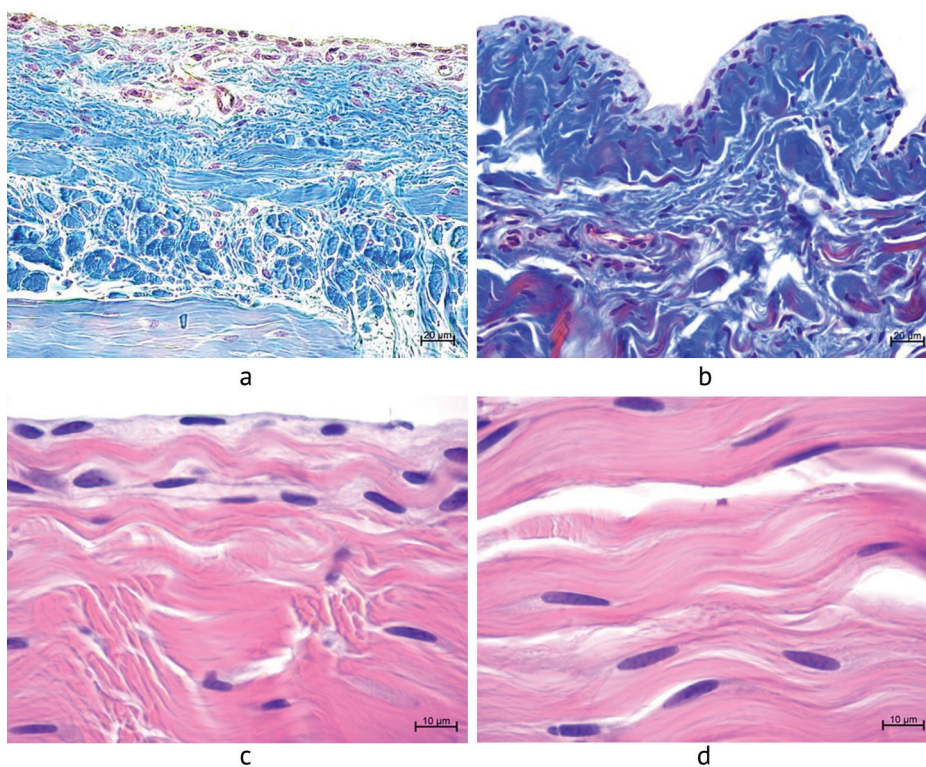


Fig. 2 Synovial membrane of the contralateral carpal joint of a lamb:

(a) 120 days of the experiment (the animals were 5.5 months old), general appearance; (b) 365 days of the experiment (the animals were 13.5 months old), general appearance, folded surface; (c, d) 365 days of the experiment (the animals were 13.5 months old), fibroblast-like synoviocytes of the lining layer (c), fibroblasts, fibrocytes in the subsynovial layer (d). Paraffin sections, stained with Masson's three-color method (a, b), hematoxylin and eosin (c, d). Magnification $\times 400$ (a, b), $\times 1000$ (c, d)

Table 1

Semi-quantitative and quantitative characteristics of the synovial membrane of the carpal joint

Parameter		Thickness of the lining layer (mcm)	Synoviocyte density	Synovitis score
		Me ($p_{25};p_{75}$)	[min-max]	Me ($p_{25};p_{75}$)
Control	120 days	36.73 (28.54;37.42) [23.18–41.16]	179.11 (130.26;203.53) [113.97–219.81]	0 (0;1)
	365 days	23.63 (20.19;28.04) [13.71–32.78] $p^{120-365} = 0.0326$	97.69 (89.55;146.54) [73.27–179.11] $p^{120-365} = 0.0009$	1 (0;1)
Experiment	120 days	42.65 (30.72;48.51) [25.86–52.42] $p^{c-e} = 0.0002$	219.81 (203.53;269.66) [187.25–284.94] $p^{c-e} = 0.0009$	3 (3;4)
	365 days	25.74 (22.43;28.57) [20.32–34.07] $p^{c-e} = 0.1301$ $p^{120-365} = 0.0001$	138.41 (113.97;162.82) [97.69–187.25] $p^{c-e} = 0.0141$ $p^{120-365} = 0.0011$	1 (0;1)

Note: The Mann – Whitney test was used; the differences were statistically significant at $p < 0.05$, p^{c-e} — comparison of control and experiment, $p^{120-365}$ — comparison of experimental term

Morphological characteristics of the synovial membrane of the carpal joint of the experimental limb

After 120 days of the experiment, a statistically significant ($p < 0.05$) increase in the thickness of the lining layer and the numerical density of synovial cells (Table 1), located in two to three layers (Fig. 3 a) were seen in the synovial membrane of the experimental joint relative to the control (Table 1). The proportion of macrophage-type synoviocytes increased (more than 50 % in the field of view). Such cells had an eccentrically located nucleus, cytoplasmic outgrowths, and foamy cytoplasm with granular inclusions (Fig. 3 b). In the upper collagen-elastic layer, cellularity was increased, and an inflammatory infiltrate of focal and diffuse distribution was revealed (Fig. 3 c) that consisted mainly of lymphocytes, plasma cells, and histiocytes. In some cases, the formation of synovial villi was noted (Fig. 3 d).

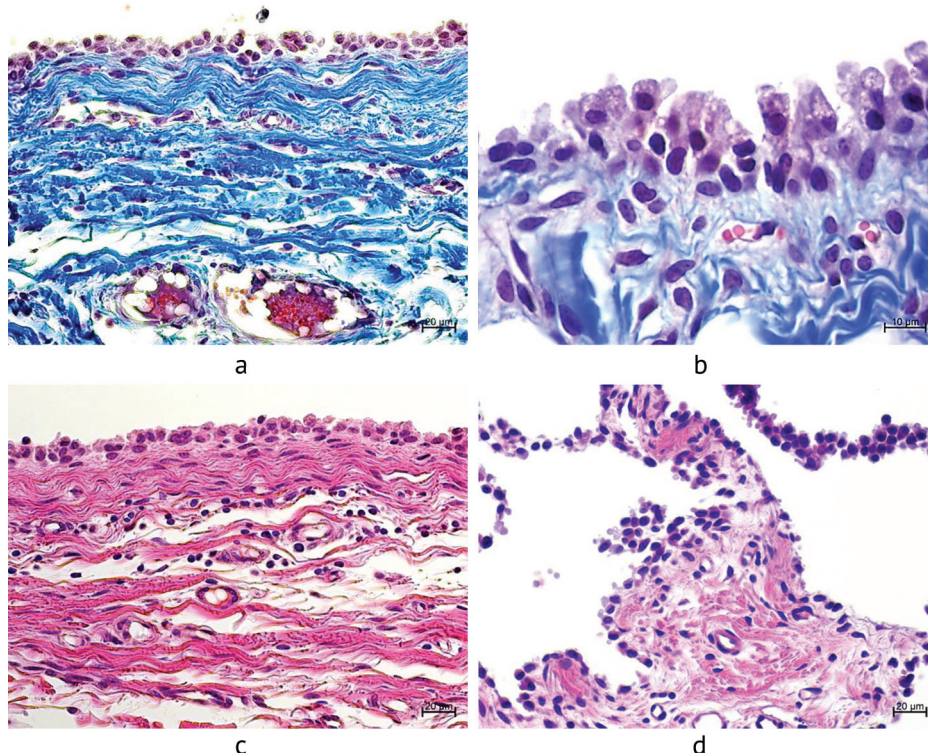


Fig. 3 Synovial membrane of the carpal joint of a lamb in the experiment time-point of 120 days: (a) lining and collagen-elastic layers; (b) macrophage-type synoviocytes; (c) diffuse and perivascular inflammatory infiltrate; (d) formation of synovial villi. Paraffin sections, stained with Masson's three-color method (a, b), hematoxylin and eosin (c, d). Magnification $\times 400$ (a, c, d), $\times 1000$ (b)

Semi-quantitative assessment of the synovial membrane according to Krenn et al. [18] revealed mild synovitis (Table 1).

After 365 days of the experiment, synoviocytes in the lining layer were arranged in one to three layers in most cases (Fig. 4 a); synovial cells had characteristics of the macrophage and fibroblast types (Fig. 4 b); a tendency towards a decrease in the proportion of macrophage-type cells (about 30 % in the field of view) compared to the previous period of the experiment and a decrease in the values of the thickness of the lining layer and the numerical density of synoviocytes were noted. Compared with the controls, the differences in the parameter "thickness of the lining layer" were statistically insignificant ($p > 0.05$), the values of the numerical density were statistically significantly ($p < 0.05$) higher (Table 1). Over a large area, the synovial membrane had a folded surface (Fig. 4 c). In the upper collagen-elastic layer, cellularity in most cases was normal, and inflammatory infiltrate was not detected.

Semi-quantitative assessment of the synovial membrane showed no synovitis (Table 1).

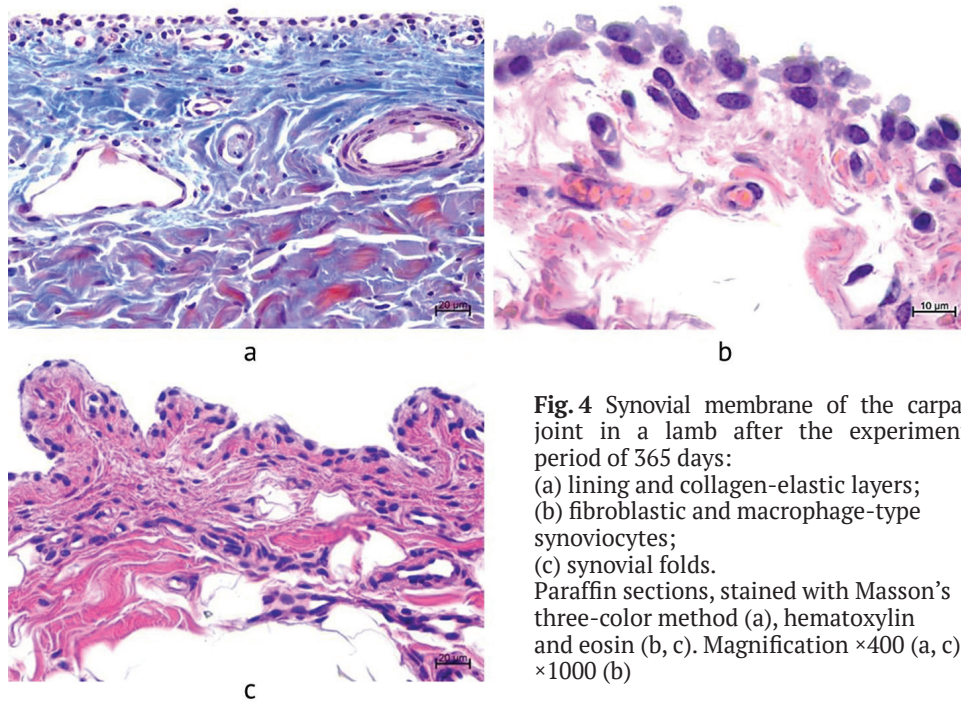


Fig. 4 Synovial membrane of the carpal joint in a lamb after the experiment period of 365 days:
(a) lining and collagen-elastic layers;
(b) fibroblastic and macrophage-type synoviocytes;
(c) synovial folds.
Paraffin sections, stained with Masson's three-color method (a), hematoxylin and eosin (b, c). Magnification $\times 400$ (a, c), $\times 1000$ (b)

DISCUSSION

The synovial membrane plays a key regulatory role in determining the composition of the synovial fluid and differs from other barrier membranes in its unique architecture. The intima (lining inner layer) of the human synovial membrane normally contains approximately 90 % fibroblast-like and 10 % macrophage-like synoviocytes. The collagen-elastic layer (subintima) consists of elastic and collagen fibers (collagen types I, III, IV, V, and VI), laminin, fibronectin, and proteoglycans. It also contains fibroblasts and macrophages, sympathetic and sensory nerves, blood and lymphatic vessels [19, 20].

For extrapolating experimental data to clinical settings, sheep are the most suitable animal model for studying the musculoskeletal system, as they are close to humans in terms of joint morphology, weight, and bone size [21, 22, 23]. There are a few publications in the literature on the structure of the synovial membrane of the sheep knee joint at different ages [24, 25]. Despite a growing understanding of the role of the synovial membrane in joint pathology, quantitative data on the structure and function of this tissue remain incomplete.

This study provides the first data on the structural reorganization of the synovial membrane of the sheep carpal joint at different ages. At 5.5 and 13.5 months of age, fibroblastic synoviocytes predominated in the synovial lining layer, and histological signs of synovitis were not detected. It was established that as the animals continued growing, the topography of the intimal layer changed from a smooth surface at 5.5 months to a folded surface at 13.5 months. Histomorphometric measurements revealed a decrease in the thickness of the intimal layer and the numerical density of synoviocytes, while light-optical measurements revealed an increase in the proportion of the fibrous component in the intimal layer.

In a number of experimental and clinical studies, signs of synovitis were detected during osteosynthesis of the limb segment adjacent to the joint [26] and after joint arthroplasty [27, 28]. In an experiment on adult dogs, tibial bone defect was managed using a combination of Ilizarov non-free bone grafting and the Masquelet method and signs of synovitis in the knee joint were

detected in 70 % of cases one month after removal of the apparatus [26]. Sugimura et al. report that the severity of synovitis reaches a peak six months after total knee arthroplasty and reduces after one to two years [28].

In this study, after 120 days of the experiment, the assessment according to Krenn et al. [18] showed mild synovitis in all animals. Structural changes in the synovial membrane were expressed by hyperplasia (due to thickening of the lining layer), an increase in the numerical density of synoviocytes and an increased number of macrophage-like synoviocytes (more than 50 % in the field of view), the formation of synovial villi, and the presence of lymphohistiocytic infiltrate of focal and diffuse types.

It is known that both types of synovial cells, macrophages and fibroblasts, perform various pro- and anti-inflammatory functions and can both prevent inflammation by forming an anti-inflammatory barrier that promotes the constant clearance of danger signals coming from the synovial fluid and accumulating due to mechanical stress, and contribute to synovial inflammation [29, 30]. Macrophage-type synoviocytes participate in phagocytosis, produce proteolytic enzymes that damage cartilage, and pro-inflammatory mediators, enhancing the immune response and activating fibroblast-like synovial cells. After activation, fibroblast-like synoviocytes secrete proinflammatory cytokines (TNF- α , IL-1 β and IL-6) and, through the expression of cadherin-11, CD44 and matrix metalloproteases, acquire migratory and invasive properties, forming synovial pannus [20, 31, 32].

Non-bioresorbable fixators used in osteosynthesis of intra-articular fractures can cause a number of complications, such as infection, persistent pain (most often due to synovitis), and arthritis. Titanium fixators (screws and plates) are widely used for osteosynthesis of fractures and in maxillofacial oncology due to their biocompatibility and favorable mechanical properties, which closely match bone elasticity [33, 34].

Under the experimental conditions studied, structural changes in the synovial membrane were reversible during osteosynthesis of an intra-articular metaepiphyseal fracture of the distal radius using titanium screws. By the end of the experiment, after 365 days, no histological signs of synovitis were detected. Fibroblast-like synoviocytes predominated in the synovial membrane, elevated synoviocyte density values persisted, and the thickness of the synovial membrane lining was comparable to that of the control.

CONCLUSION

Osteosynthesis of intra-articular metaepiphyseal fractures of the distal articular end of the radius in lambs using titanium screws provoke mild synovitis after 120 days of the experiment. This synovitis was characterized by thickening of the lining layer, an increase in the numerical density of synoviocytes and in the number of macrophage synoviocytes, and the presence of a lymphohistiocytic infiltrate. By the end of the experiment, the synovial membrane inflammation reversed, and histological signs of synovitis were absent.

Conflict of interest Not declared.

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Ethical statement The study was conducted in accordance with the principles of the European Convention ETS No. 123 for the Protection of Vertebrate Animals used for Experimental and other Scientific Purposes (with the appendix of 15.06.2006, Strasbourg) and the rules of good laboratory practice (GOST 33044-2014, GOST 33215-2014, GOST 34088-2017, PS SanPiN 3.3686-21). Protocol of the institutional committee dates to 29.11.2024 No. 1 (76).

REFERENCES

1. Suleimenov BSh, Rustemova KR. Aspects of the treatment of fractures of the distal metaepiphysis of the radial bone in adults and children. *Astana medical journal*. 2020;104(2):53-63. (In Russ.)
2. Makogonov IV, Tarasov AN. Back to the question of forearm fractures in children: tradition and contemporary view (literature review). *Medical Alliance*. 2025;13(2):53-58. doi: 10.36422/23076348-2025-13-2-53-58. (In Russ.)
3. Deng H, Zhao Z, Xiong Z, et al. Clinical characteristics of 1124 children with epiphyseal fractures. *BMC Musculoskelet Disord*. 2023;24(1):598. doi: 10.1186/s12891-023-06728-9.
4. Bergkvist A, Lundqvist E, Pantzar-Castilla E. Distal radius fractures in children aged 5-12 years: a Swedish nationwide register-based study of 25 777 patients. *BMC Musculoskelet Disord*. 2023;24(1):560. doi: 10.1186/s12891-023-06680-8.
5. Proshchenko YN, Pozdeeva NA. Tactics of treatment in children with intraarticular fractures of the distal humerus. *Traumatology and Orthopedics of Russia*. 2012;18(4):82-86. (In Russ.) doi: 10.21823/2311-2905-2012-4-82-86.
6. Semenov SV, Malakhov OA, Sharpar' VD, et al. The use of a titanium elastic nail (ten) for the treatment of the radial neck fracture in children. *Pediatric surgery*. 2015;19(5):38-40. (In Russ.)
7. Korobeinikov AA, Aranovich AM, Popkov DA. Ilizarov method in the treatment of children with periarticular fractures. *Genij Ortopedii*. 2021;4(27):418-423. doi: 10.18019/1028-4427-2021-27-4-418-423.
8. Jozsa G, Kassai T, Varga M. Preliminary experience with bioabsorbable intramedullary nails for paediatric forearm fractures: results of mini-series. *Genij Ortopedii*. 2023;29(6):640-644. doi: 10.18019/1028-4427-2023-29-6-640-644.
9. Lascombes P, Journeau P, Popkov DA. Resorbable implants in paediatric orthopaedics and traumatology. *Genij Ortopedii*. 2023;29(6):629-634. doi: 10.18019/1028-4427-2023-29-6-629-634.
10. Gerasimenko MA, Koren MN, Tretiak SI, Zhuk YV. Minimally invasive methods OF surgical treatment FOR injuries OF The upper limb In children. *Russian Sklifosovsky Journal "Emergency Medical Care"*. 2014;(3):22-24.
11. Vissarionov SV, Bolshakov GA. Comparative analysis of the results of surgical treatment of children with unstable fractures of the distal radius. *Pediatric Traumatology, Orthopaedics and Reconstructive Surgery*. 2025;13(3):237-246. (In Russ.) doi: 10.17816/PTORS676873.
12. Syurabibil AH, Munajat I, Mohd EF, et al. Displaced Physeal and Metaphyseal Fractures of Distal Radius in Children. Can Wire Fixation Achieve Better Outcome at Skeletal Maturity than Cast Alone? *Malays Orthop J*. 2020;14(2):28-38. doi: 10.5704/MOJ.2007.008.
13. Merkulov VN, Dorohin AI, Buhtin KM. *Pediatric traumatology*. Mironov SP. (ed.) Moscow: GJeOTAR-Media, 2019:256. (In Russ.)
14. Agadzhanlyan VV, Tuzovsky AA. To the question of the treatment of fractures of the tibia condyles. *Polytrauma*. 2022;(2):67-77. (In Russ.) doi: 10.24412/1819-1495-2022-2-67-77.
15. Persiani P, Martini L, Calogero V, et al. Analysis of the risk of a secondary displacement in conservatively treated paediatric distal radius metaphyseal fractures. A multicentric study. *Clin Ter*. 2022;173(1):84-87. doi: 10.7417/CT.2022.2397.
16. Aitchison AH, Allen NB, O'Neill CN, et al. Synovial Fluid Immune Cell Composition Following Intraarticular Fracture May Contribute to Posttraumatic Osteoarthritis. *Int J Mol Sci*. 2024;25(22):12037. doi: 10.3390/ijms252212037.
17. Cepela DJ, Tartaglione JP, Dooley TP, Patel PN. Classifications In Brief: Salter-Harris Classification of Pediatric Physeal Fractures. *Clin Orthop Relat Res*. 2016;474(11):2531-2537. doi: 10.1007/s11999-016-4891-3.
18. Krenn V, Morawietz L, Burmester GR, et al. Synovitis score: discrimination between chronic low-grade and high-grade synovitis. *Histopathology*. 2006;49(4):358-364. doi: 10.1111/j.1365-2559.2006.02508.x.
19. Stefani RM, Halder SS, Estell EG, et al. A Functional Tissue-Engineered Synovium Model to Study Osteoarthritis Progression and Treatment. *Tissue Eng Part A*. 2019;25(7-8):538-553. doi: 10.1089/ten.TEA.2018.0142.
20. Dydykina IS, Arutyunova EV, Kovalenko PS, et al. Synovitis in osteoarthritis: the current state of the problem. *Modern Rheumatology Journal*. 2021;15(2):120-125. (In Russ.) doi: 10.14412/1996-7012-2021-2-120-125.
21. Turner AS. Experiences with sheep as an animal model for shoulder surgery: strengths and shortcomings. *J Shoulder Elbow Surg*. 2007;16(5 Suppl):S158-S163. doi: 10.1016/j.jse.2007.03.002.
22. Sartoretto SC, Uzeda MJ, Miguel FB et al. Sheep as an experimental model for biomaterial implant evaluation. *Acta Orthop Bras*. 2016;24(5):262-266. doi: 10.1590/1413-785220162405161949.
23. Banstola A, Reynolds JNJ. The Sheep as a Large Animal Model for the Investigation and Treatment of Human Disorders. *Biology (Basel)*. 2022;11(9):1251. doi: 10.3390/biology11091251.
24. Eitner A, Pester J, Nietzsche S, et al. The innervation of synovium of human osteoarthritic joints in comparison with normal rat and sheep synovium. *Osteoarthritis Cartilage*. 2013;21(9):1383-1391. doi: 10.1016/j.joca.2013.06.018.
25. Solbak N, Achari Y, Chung M, et al. Normal sheep synovium has similar appearances and constitutive expression of inflammatory cytokines within and between knee joints: a baseline histological and molecular analysis. *Connect Tissue Res*. 2014;55(2):156-163. doi: 10.3109/03008207.2014.880427.
26. Stupina TA, Diuriagina OV, Mokhovikov DS, et al. Histomorphometric changes in the synovial membrane of the knee joint in combined use of the Ilizarov non-free bone plasty and the Masquelet technique (experimental study). *Genij Ortopedii*. 2021;27(2):249-253. doi: 10.18019/1028-4427-2021-27-2-249-253.
27. Kurien T, Kerslake RW, Graven-Nielsen T, et al. Chronic postoperative pain after total knee arthroplasty: The potential contributions of synovitis, pain sensitization and pain catastrophizing-An explorative study. *Eur J Pain*. 2022;26(9):1979-1989. doi: 10.1002/ejp.2018.
28. Sugimura N, Aso K, Wada H, et al. Temporal changes in synovitis and chronic pain after total knee arthroplasty: A two-year longitudinal study. *Journal of Joint Surgery and Research*. 2025;3(2):96-102. doi: 10.1016/j.jjoir.2025.04.002.
29. Knab K, Chambers D, Krönke G. Synovial Macrophage and Fibroblast Heterogeneity in Joint Homeostasis and Inflammation. *Front Med (Lausanne)*. 2022;9:862161. doi: 10.3389/fmed.2022.862161.
30. Khmelevskaya A, Houtman M, Buerki K, et al. OP0230 synovial fibroblasts, macrophages and dendritic cells form an inflammatory niche in rheumatoid arthritis, but not in psoriatic arthritis synovium. *Annals of the Rheumatic Diseases*. 2025;84(1):191-192. doi: 10.1016/j.ard.2025.05.241.

31. Bai LK, Su YZ, Wang XX, et al. Synovial Macrophages: Past Life, Current Situation, and Application in Inflammatory Arthritis. *Front Immunol.* 2022;13:905356. doi: 10.3389/fimmu.2022.905356.
32. Thangadurai M, Sethuraman S, Subramanian A. A 2D inflammatory co-culture model for investigating synovial fibroblast and macrophage interactions in rheumatoid arthritis. *Sci Rep.* 2025;15(1):30105. doi: 10.1038/s41598-025-16007-3.
33. Riviş M, Roi C, Roi A, et al. The Implications of Titanium Alloys Applied in Maxillofacial Osteosynthesis. *Appl Sci.* 2020;10(9):3203. doi: 10.3390/app10093203,
34. Barber CC, Burnham M, Ojameruaye O, McKee MD. A systematic review of the use of titanium versus stainless steel implants for fracture fixation. *OTA Int.* 2021;4(3):e138. doi: 10.1097/OI9.0000000000000138.

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