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Evaluation of the effect of osteosynthesis wires on the structural reorganization of metaepiphyseal cartilage (an experimental and morphological study)

A.A. Korobeinikov, T.A. Stupina✉, O.V. Dyuryagina, M.A. Stepanov, N.I. Antonov

Ilizarov National Medical Research Centre for Traumatology and Orthopedics, Kurgan, Russian Federation

Corresponding author:Tatyana A. Stupina, StupinaSTA@mail.ru

Abstract

Introduction Premature arrest of bone growth is the most common complication of bone fractures at the growth plate level.

The **purpose** of the work was to evaluate the structural reorganization of metaepiphyseal cartilage following its direct injury with metal and biodegradable wires in an experiment.

Materials and methods The metaepiphyseal cartilage of the distal femur of 18 lambs of both sexes was studied. The age of the animals at the beginning of the study was (43.92 ± 0.8) days, by 60 and 120 days (102.63 ± 0.82) and (161.1 ± 0.9) days, respectively. The animals underwent transphyseal insertion of wires/pins: series 1 — Kirschner wires, series 2 — titanium wires, series 3 — poly-L-lactic acid pins. The duration of the experiment was 60 and 120 days. Clinical and radiographic studies were carried out. Histomorphometry was performed using an AxioScope.A1 microscope and Zenblue software (CarlZeissMicroImagingGmbH, Germany).

Results Reactive changes in the growth plate at the interface with the wire were manifested by proliferation of chondrocytes in the zone of proliferating cartilage and in the reserve zone; the minimally expressed changes were noted in series 2, the most pronounced were in series 1. By the end of the experiment, at the interface with the wire in series 1, blood vessels penetrated into the metaepiphyseal cartilage; in series 3 the amount of the fibrous component was increased, which indicates further formation of "bone bridges" and "fibrous bridges," respectively. In undamaged areas of the growth plate in all series, the zonal structure was preserved. By the end of the experiment, increased values of the thickness of the metaepiphyseal cartilage were noted (1.2 times higher than the control), differences between series were a tendency; in series 2 and 3 the ratio of metaepiphyseal cartilage zones was comparable to the control; in series 1 the proportion of the proliferating cartilage zone was increased by 4 %.

Discussion The main problem with growth plate injuries is the formation of bone tissue or fibrosis, which affects the growing process. Currently, the question of choosing a treatment tactic for growth plate injury depending on the size of the "bone bridges" is debatable. Relevant are future comparative studies of the regeneration of metaepiphyseal cartilage defects after the use of fixators made from different materials.

Conclusion Histomorphometric characteristics of the growth zone reliably showed that the insertion of wires, regardless of their material, was not accompanied by inhibition of the bone-forming function of the distal metaepiphyseal cartilage of the femur.

Keywords: growth plate, metal and biodegradable fixators, histology, morphometry

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INTRODUCTION

The bone growth zone (physis, epiphyseal plate, growth plate, metaepiphyseal cartilage) is a highly specialized cartilaginous tissue located between the epiphysis and metaphysis at the proximal and distal ends of long bones. Longitudinal bone growth occurs due to the processes of enchodral ossification in the epiphyseal plate [1, 2]. Metaepiphyseal cartilage has a zonal structure. Different authors distinguish from three (reserve, proliferative, hypertrophic) to six zones; all classifications are based on the proliferative and biosynthetic activity of chondrocytes and the degree of their differentiation. The epiphyseal plate is monopolar, since bone formation runs in one direction [1, 3].

Treatment of injuries (mechanical, infectious, iatrogenic, malignant) to the growth plate is a difficult task due to avascular nature of the metaepiphyseal cartilage [2, 4, 5, 6].

Mechanical injuries to the growth plate are common and account for 15 to 30 % of all bone injuries in children; they are more frequent in boys; the peak of injuries is the age of 11–14 years [7, 8]. The main complication of treatment of the epiphyseal plate injury is premature closure of growth plates, formation of bone bridges, resulting in limb deformation and limb length discrepancy [7, 8, 9]. Deformities of the lower limb account for 43.7 % of all orthopedic disorders in children, of which 21.4 % are changes in the knee joint [10].

To treat growth plate injury, both conservative and surgical methods are used [7, 11, 12, 13]. In the surgical method of treatment, fractures passing through the growth zone are fixed using either metal or biodegradable bone fixators [14, 15, 16, 17].

One of the current areas of pediatric traumatology is the assessment of the state of the growth plate when using various surgical techniques for correcting pathological conditions associated with dysfunction. In the available literature there are no comparative experimental and histological studies on the effect of non-biodegradable and biodegradable wires on the structure of metaepiphyseal cartilage.

Purpose: to evaluate the structural reorganization of metaepiphyseal cartilage following direct injury with metal and biodegradable wires in an experiment.

MATERIALS AND METHODS

The object studied was the metaepiphyseal cartilage of the distal femur in 18 lambs of both sexes after transphyseal insertion of pin fixators. The duration of the experiment was 60 and 120 days after surgery.

The age of the animals at the beginning of the study was (43.92 ± 0.8) days, by 60 and 120 days (102.63 ± 0.82) and (161.1 ± 0.9) days, respectively. The body weight of the lambs on the day of surgery was (14.0 ± 3) kg, on days 60 and 120 it was (21.92 ± 0.85) and (28.92 ± 2.4) kg, respectively.

Exclusion criteria: diseases of the musculoskeletal system.

Animals are divided into 3 series. In series 1 (n = 6), a stainless steel wire, d = 1.5 mm (CITO, Russia), was transphyseally inserted; in series 2 (n = 6), it was a straight elastic intramedullary nail made of titanium, d = 1.5 mm (Rotor Med LLC, Russia); in series 3 (n = 6) a biodegradable pin made of poly-L-lactic acid, d = 1.5 mm (Inion OTPS TM, Finland) was used.

Each animal underwent transphyseal insertion of one fixator through the distal growth plate of the femur of the right pelvic limb. In series 1 and 2, the insertion of the wire/nail was carried out transcutaneously using an osteosynthesis drill. The wire/nail was inserted dorsoventrally in the lateral-medial direction at an angle to the longitudinal axis of the bone of 30–35° through the metaphysis, physis and epiphysis of the bone, without penetrating into the cavity of the knee joint. After X-ray confirmation of the correct insertion of the fixator, its outer part was bitten off with pliers at the level of the cortical plate and hidden under the skin. If necessary, 1–2 interrupted Vicryl tm Plus 3–0 sutures (Ethicon, Johnson & Johnson International, USA) were made on the skin at the injection site.

Animals in series 3 underwent a skin incision in the projection of the pin passage. Next, a canal for pin insertion was formed antegrade using a Kirschner wire, and the direction of the wire was chosen so that the angle of intersection with the growth plate was 30–35° in the frontal plane. The wire passed to the subchondral layer of the bone. A biodegradable 1.5-mm pin was installed in a reusable contact applicator, with the help of which it was inserted into the formed canal to the entire depth of the latter. The excessive end of the pin was bitten off with pliers, and the skin was sutured with interrupted sutures Vicryl tm Plus 3–0 (Ethicon, Johnson & Johnson International, USA).

To prevent the development of inflammatory processes, all animals were prescribed an analgesic anti-inflammatory drug (i/m ketoprofen 50 mg, 0.5 ml) and an antimicrobial agent (i/m ceftriaxone 1.0, 7–10 mg/kg). The surgical wound was treated with a solution of hydrogen peroxide 3 % and furatsilin 1:5000, daily for the first 10 days after surgery, then twice a week. The sutures were removed after 10–14 days.

In all experimental series, the wires and pins remained in situ the entire observation period. Animals were euthanized after premedication with a solution of diphenhydramine 1 % (0.02 mg/kg) and Rometar 2 % (1 mg/kg), followed by the administration of a lethal dose of barbiturates.

Animal care, operations, manipulations and procedures were carried out in accordance with regulatory documents: GOST R 33044-2014. Principles of good laboratory practice; PS SanPiN 3.3686-21 Sanitary and epidemiological requirements for the prevention of infectious diseases; GOST 33215-2014 Guide to the maintenance and care of laboratory animals. Rules for equipping premises and organizing procedures; GOST 34088-2017 Guide to the maintenance and care of laboratory animals. Rules for keeping and caring for farm animals.

For histomorphometric examination, fragments of the distal articular end of the femur were fixed in a 10 % solution of neutral formalin, then washed in running water and decalcified in a mixture of equal volumes of hydrochloric and formic acid solutions, dehydrated in ethyl alcohol, and embedded in paraffin. To obtain objective information about the qualitative and quantitative characteristics of the object being studied, histological sections of adequate orientation and thickness were used [18]. Histological preparations (longitudinal sections along the axis of the femur) with a thickness of 5.00 μm were prepared on an HM 450 Thermo Scientific microtome (USA) and stained with hematoxylin and eosin using the three-color method according to Masson. Light-optical examination and digitization were carried out using an AxioScope.A1 microscope equipped with an AxioCam digital camera (Carl Zeiss MicroImaging GmbH, Germany).

Histological characteristics of the metaepiphyseal cartilage considered its zones, the identification of zones in the direction from the epiphysis to the diaphysis: the zone of resting cartilage (reserve or border zone); zone of proliferating cartilage; zone of vesicular (hypertrophied) cartilage; zone of calcified cartilage [1].

Zenblue software (Carl Zeiss MicroImaging GmbH, Germany) was used for histomorphometry. The thickness of the metaepiphyseal cartilage (hmet.car, μm) was determined as the distance between its upper and lower borders with an interval of about 20 μm, 20 measurements were taken from each case, the percentage of its zones. As a control, the metaepiphyseal cartilage of the distal femur of the contralateral limb was morphometrically measured. The width of the defect zone was determined by taking 30 measurements in each case.

Data analysis was carried out using descriptive statistics methods. Samples were checked for normal distribution of values using the Kolmogorov test. The measure of central tendency is presented as the arithmetic mean and error of the arithmetic mean (M ± m); for samples where the normality hypothesis was rejected, the data are presented as median and quartiles (Me (*p*25–*p*75)). Hypotheses about differences between the compared groups were tested with a normal distribution using the Student's t test, with an asymmetric distribution using the Wilcoxon test; differences were considered significant at $p < 0.05$ (AtteStat program, version 9.3.1).

RESULTS

The lambs of all experimental series had the weight-bearing function of the affected pelvic limb from the following day after surgery until the end of the experiment. Upon examination and palpation, no changes were found in the area of the distal metaphysis of the femur. The function of the knee joint (full flexion and extension) was completely preserved in all experimental animals at all stages of observation. There were no restrictions of mobility in the knee joints.

At the stages of the study, the bone tissue in the area of implantation in the animals of all series had a uniform structure. The contour of the epiphyseal plate was clearly visible. There were no visible areas of closure of the growth plate in the areas adjacent to the implants (Fig. 1).

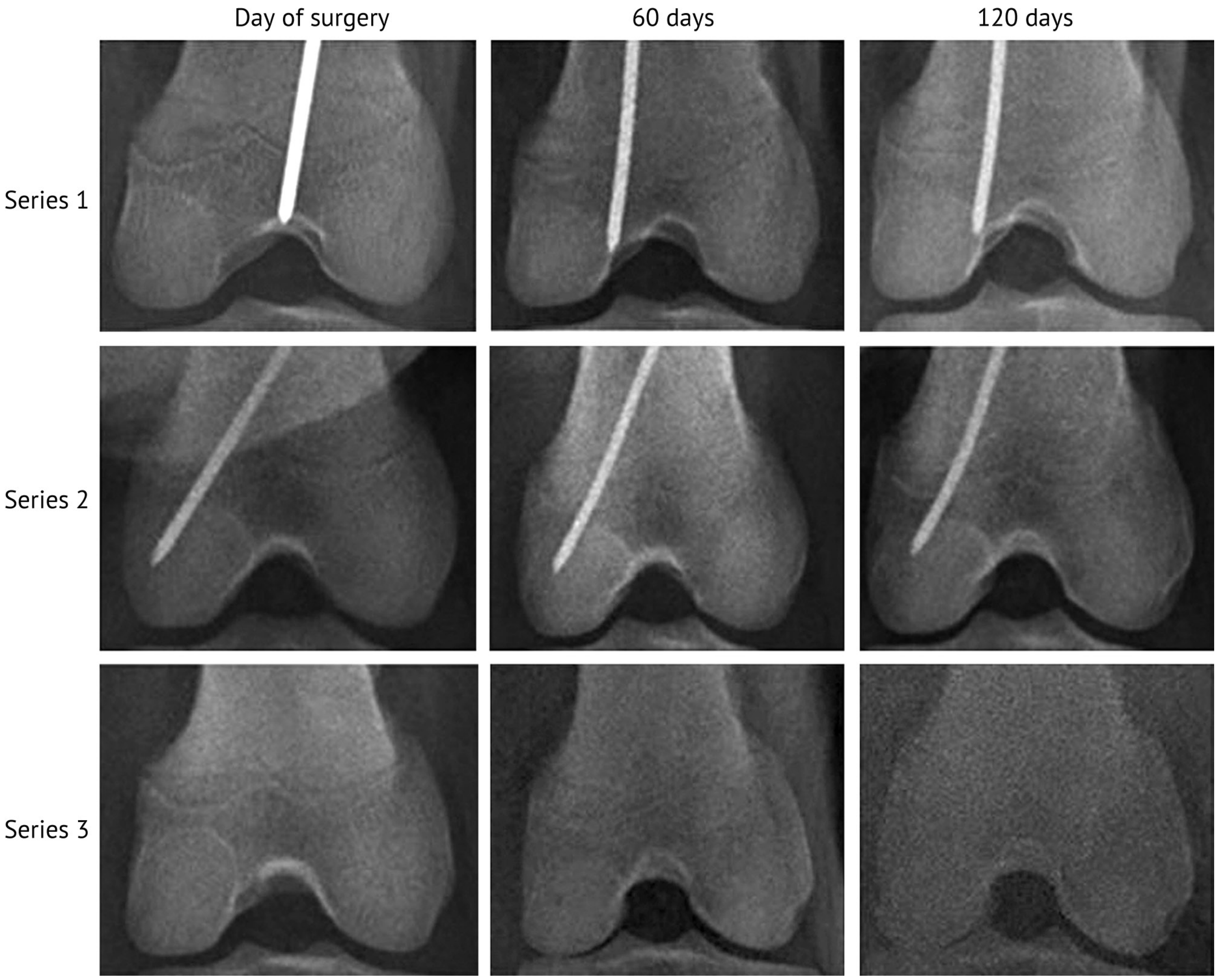


Fig. 1 Radiographic images of wires/pins in the femoral metaphyses at the time-points of the experiment

In the control limb, the metaepiphyseal cartilage of the distal femur maintained a zonal structure throughout the experiment. Its zones were clearly defined: the border (reserve) zone with the epiphysis; zone of proliferating cartilage, proliferating chondrocytes were arranged in columns; the zone of vesicular cartilage, represented by hypertrophied chondrocytes; the zone of calcified cartilage adjacent to the endochondral bone of the diaphysis (Fig. 2).

The thickness of the metaepiphyseal cartilage decreased by an average of 18 % with the growth of lambs (from 3.5 to 5.5 months) (Table 1). The decrease in this parameter was due to a pronounced decrease in the thickness of the reserve zone (Fig. 2, Fig. 5).

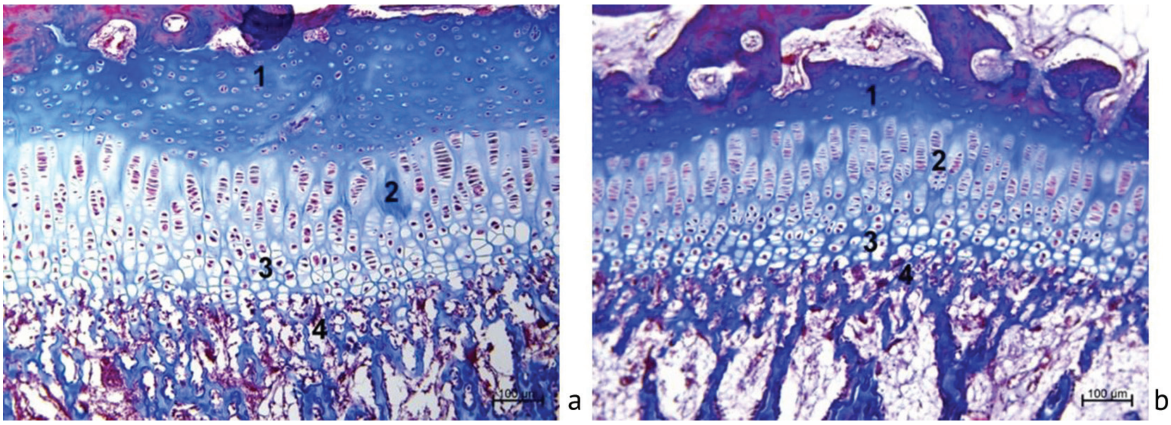


Fig. 2 Metaepiphyseal cartilage of the distal femur of the contralateral limb (control): *a* — age 3.5 months; *b* — age 5.5 months; 1 — reserve zone; 2 — zone of proliferating cartilage; 3 — zone of vesicular cartilage; 4 — zone of calcified cartilage. Paraffin section, stained with the three-color method according to Masson. Magnification ×100

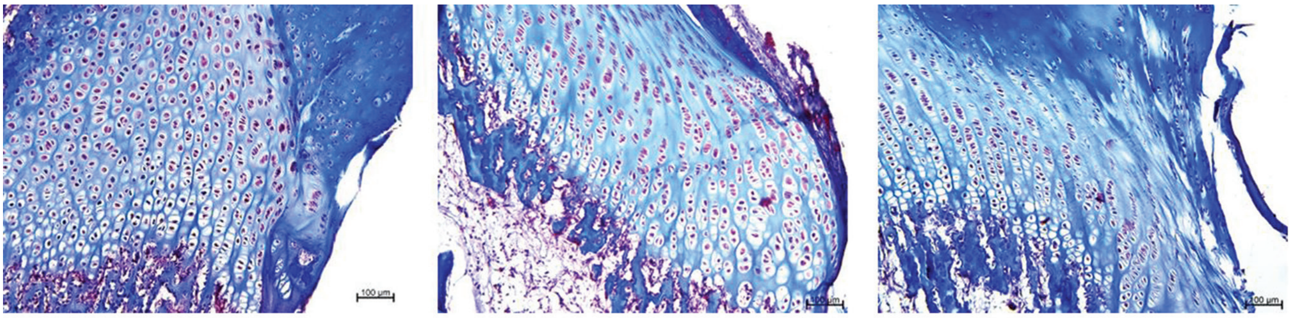
Table 1

Thickness of the metaepiphyseal cartilage of the distal femur at the stages of the experiment
Me (Q1; Q3)

Параметр / Серия		$h_{met.car.}$, мкм
Control	60 days	607.59 (574.25; 644.41)
	120 days	493.08 (446.92; 546.37) p^{60-120} = 0.001
Series 1	60 days	797.58 (765.21; 838.95) p^{c-s1} = 0.0001
	120 days	592.32 (457.59;649.36) p^{c-s1} = 0.0188
Series 2	60 days	732.32 (636.66; 773.02) p^{c-s2} = 0.003 p^{s1-s2} = 0.004
	120 days	621.11 (518.31; 780.71) p^{c-s2} = 0.0001 p^{s1-s2} = 0.0541
Series 3	60 days	680.89 (626.01; 708.92) p^{c-s3} = 0.0111 p^{s3-s1} = 0.0001 p^{s3-s2} = 0.0578
	120 days	589.01 (522.13; 632.07) p^{c-s3} = 0.009 p^{s3-s1} = 0.0598 p^{s3-s2} = 0.0532

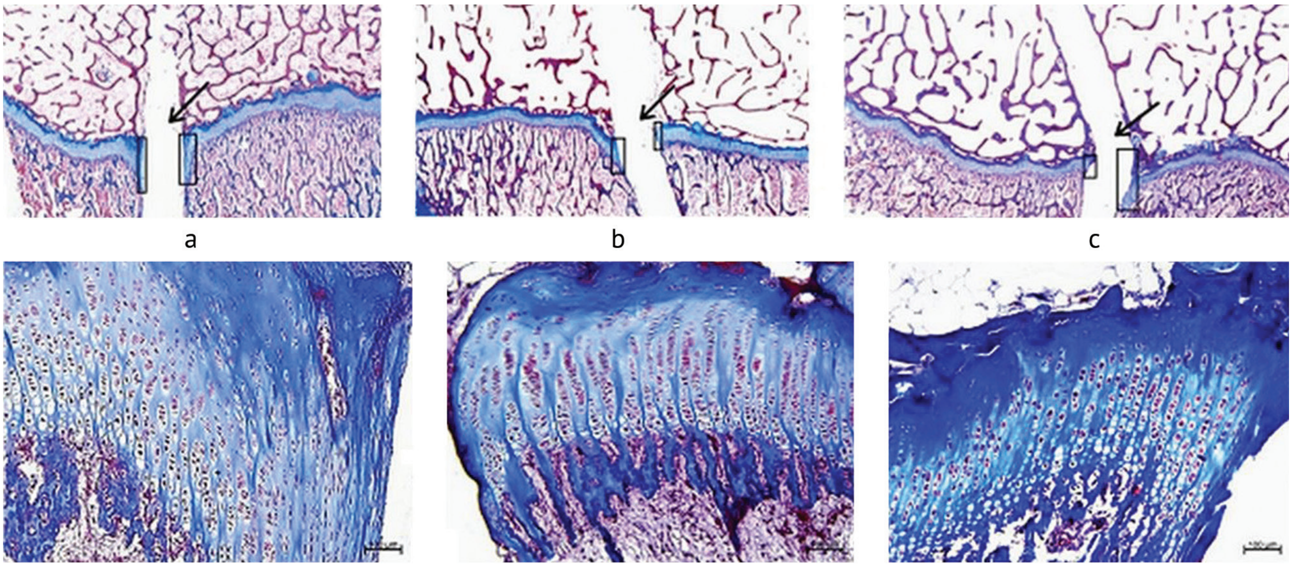
Note: Wilcoxon test was used, differences were statistically significant at p < 0,05, p^{60-12} — comparison of control at the stages, p^{c-s1} — comparison of control and series 1, p^{c-s2} — comparison of control and series 2, p^{s1-s2} — comparison of series 1 and series 2, p^{c-s3} — comparison of control and series 3, p^{s3-s1} — comparison of series 3 and series 1, p^{s3-s2} — comparison of series 3 and series 2.

In the experimental series throughout the study, reactive changes in the metaepiphyseal cartilage at the border with the wire were manifested by the proliferation of chondrocytes (Fig. 3, 4) both in the zone of proliferating cartilage and in the reserve zone, more intensely expressed in series 1. By the end of the experiment, at the border with the wire in all series, functionally active chondrocytes shaped in columns were noted. In series 1, in all animals, the penetration of vessels from the border zone into the zone of proliferating cartilage was seen (Fig. 4 d). In series 3, an increase in the proportion of the fibrous component was noted in the defect zone (Fig. 4 f).



a b c

Fig. 3 Reactive changes in the metaepiphyseal cartilage of the distal femur at the border with the wire: *a* — series 1; *b* — series 2; *c* — series 3. Experiment duration: 60 days. Fragments of paraffin sections. Magnification ×100. Staining with three-color method according to Masson



d e f

Fig. 4 Reactive changes in the metaepiphyseal cartilage of the distal femur at the border with the wire: *a, d* — series 1; *b, e* — series 2; *c, f* — series 3. The experiment lasted 120 days. The defect area (wire location) is indicated by an arrow. The extent of the zone of chondrocyte proliferation at the border with the wire is shown by a frame. Histotopograms (*a, b, c*). Fragments of paraffin sections. Magnification ×100 (*d, e, f*). Staining with three-color method according to Masson

After 60 and 120 days of the experiment, the width of the defect zone (wire tract) in the metaepiphyseal cartilage (M ± m) was (1404.74 ± 32.58) μm in series 1 and (1491.77 ± 15.37) μm respectively; (1448.41 ± 22.21) μm and (1459.35 ± 13.81) μm in series 2, respectively; and in series 3 (1618.08 ± 36.42) μm and (1639.01 ± 18.47) μm, respectively. There were no significant differences between the experimental periods ($p > 0.05$); the differences between series 1 and 2 were statistically insignificant ($p = 0.655$), the differences between series 1 and series 3 were at the trend level ($p = 0.0546$), between series 2 and series 3 were significant ($p = 0.0373$).

In the undamaged areas of the metaepiphyseal cartilage, the zonal structure was maintained throughout the experiment; an increase in the proliferative and biosynthetic activity of cartilage cells was noted in the zone of proliferating cartilage and in the border zone. In the border zone and epiphysis, newly formed areas of cartilage were present, represented by isogenic groups and separately located chondrocytes with a formed interterritorial matrix (Fig. 5).

Histomorphometrically, the most pronounced increase in the thickness of the metaepiphyseal cartilage of the distal femur was revealed during the experiment of 60 days in series 1 relative to the control, the differences with series 2 and 3 were statistically significant (Table 1). By the end of the experiment, statistically significant high values of this parameter relative to the control were in all series, the differences between series were at the level of a tendency (Table 1).

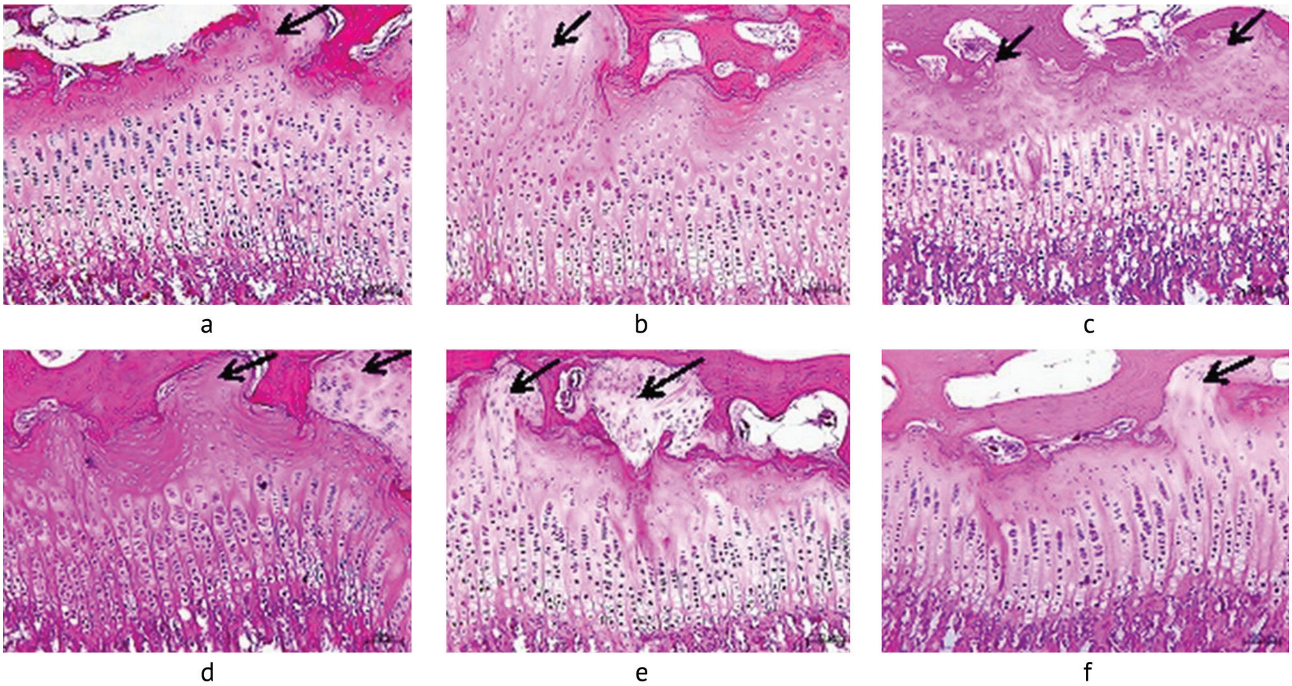


Fig. 5 Metaepiphyseal cartilage of the distal femur: *a, d* — series 1; *b, e* — series 2; *c, f* — series 3. Experiment duration: 60 days (*a, b, c*), 120 days (*d, e, f*). Newly formed areas of cartilage (arrow). Paraffin section, stained with hematoxylin and eosin. Magnification ×100

In the control limb during the growth of lambs, the percentage ratio of the zones of metaepiphyseal cartilage of the distal femur at the age of 3.5 and 5.5 months was 35:29:21:15 and 24:37:24:16 (reserve zone: zone of proliferating cartilage: zone hypertrophied chondrocytes: zone of calcified cartilage), accordingly; there was a pronounced (more than 5 %) decrease in the proportion of the reserve zone and an increase in the proportion of the zone of proliferating chondrocytes.

In experimental series after 60 days compared to the control, the change in the proportion of the reserve zone and zone of proliferating cartilage was more pronounced. Thus, the portion of the reserve zone in series 2 and 3 was reduced by 13 and 9 %, respectively, and in series 1 it was increased by 3 %. The proportion of the proliferating cartilage zone in all series was increased: in series 1 and 3 by 5 %, in series 2 by 15 %. After 120 days of the experiment in series 2 and 3, the ratio of metaepiphyseal cartilage zones was comparable to the control; in series 1 the portion of the zone of proliferating cartilage increased by 4 % (Fig. 6).

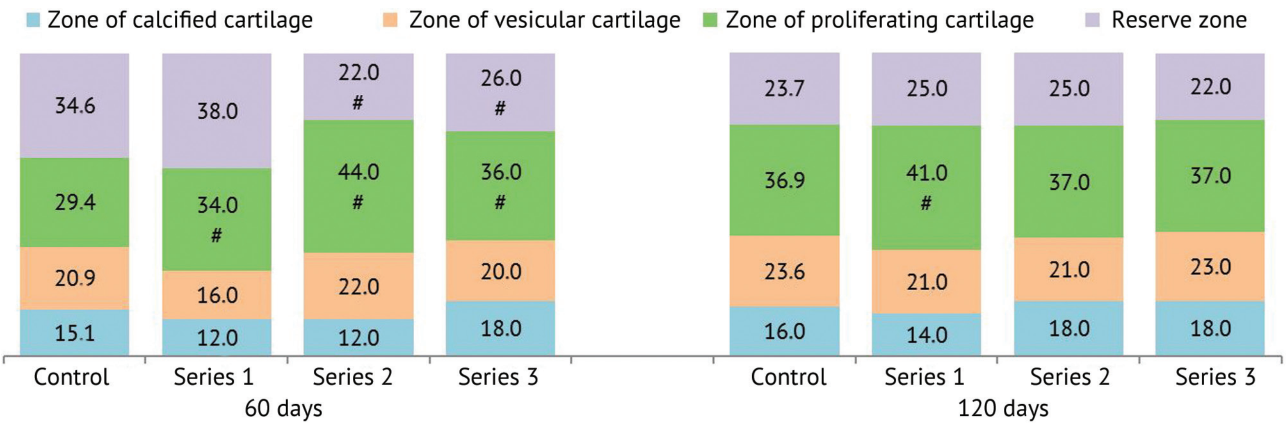


Fig. 6 Diagram showing the percentage of the zones in the metaepiphyseal cartilage of the distal femur at the stages of the experiment; # — significant differences with control at $p < 0.05$

DISCUSSION

The main function of the metaepiphyseal plate is bone growth in length due to balanced proliferation and elimination of chondrocytes [19, 20].

This function is provided by the structural features of the metaepiphyseal plate. The border or reserve zone is in contact with the epiphysis and is characterized by a predominance of intercellular substance in relation to the cells. Cartilage cells in this zone do not proliferate under normal conditions. It is assumed that the cells of this zone are a kind of stem cells that maintain a stable number of cells in the proliferative zone. In the zone of proliferating cartilage, cells are actively dividing. The growth of metaepiphyseal cartilage occurs due to an increase in the number of chondrocytes and the volume of the intercellular substance in this zone. In the zone of hypertrophied cartilage, chondrocytes lose the ability to divide, but retain high metabolic activity that results in a significant increase in size. In the zone of calcified cartilage, the death of chondrocytes and calcification of the matrix occurs, which serves as an ossification framework for osteoblasts [1, 19].

Due to the fact that the epiphyseal plate is an active, dynamic zone of growing bone, it is sensitive to the effects of various exogenous and endogenous factors.

The development of post-traumatic growth deficiency in children is based on two mechanisms: formation of “bone bridges” after vascularization and invasion of osteoblasts; ischemic necrosis of the epiphyseal cartilage due to trauma [15].

In our study, in the experimental series with direct injury to the growth plate of the distal femur with a wire/pin, signs of ischemic necrosis were not found. By the end of the experiment, the values of the width of the metaepiphyseal cartilage defect zone in series 1 and 2 were comparable, the differences between series were not statistically significant ($p > 0.05$); in series 3 the values were significantly higher, which is due to the conditions of pin insertion.

In all series, reactive changes in the form of proliferation of chondrocytes in the border (reserve) zone and the zone of proliferating cartilage were detected in areas of the metaepiphyseal cartilage at the border with the implant. The minimally expressed reactive changes in chondrocytes were noted in series 2, the most pronounced in series 1. In the latter series, by the end of the experiment, at the border with the wire, the penetration of blood vessels into the metaepiphyseal cartilage was revealed, which is prognostically unfavorable for the restoration of the growth zone. The vessels in the metaepiphyseal cartilage on the bone side are a source of osteoblasts that form “bone bridges.” In series 3, by the end of the experiment, in the areas of the metaepiphyseal cartilage adjacent to the pin, an increase in the proportion of the fibrous component was noted, which may indicate the subsequent formation of the so-called “fibrous bridge”.

The obtained histomorphometric characteristics of undamaged areas of the growth zone indicated that the insertion of implants, regardless of their material, was not accompanied by inhibition of the bone-forming function of the distal metaepiphyseal cartilage of the femur. This is confirmed by maintaining during the experiment for 120 days statistically significant increased values of the thickness of the metaepiphyseal cartilage (1.2 times higher than the control), the differences between the series showed only a tendency. The increase in this parameter occurred due to an increase in the proliferative and biosynthetic activity of cartilage cells in the zone of proliferating cartilage and in the border zone.

The works of a number of authors show that the proportions of zones in the metaepiphyseal cartilage are different for each species of mammal (rat, rabbit, pig, calf) [1, 21, 22]. Data on the relationship between the zones of metaepiphyseal cartilage in lambs at different age periods have not been found in the available literature.

In our study, the ratio of zones of metaepiphyseal cartilage in the distal femur was determined for the first time in lambs during growth (at the ages of 3.5 and 5.5 months). The most significant changes in the thickness of the reserve zone (decrease) and the zone of proliferating cartilage (increase) were revealed.

Celarek et al in an experiment on sheep found that at the age of 3.5 months, the most vulnerable zone under mechanical stress is the zone of proliferating cartilage, in which microscopic cracks were identified [23].

It is known that the main factors for the normal growth of metaepiphyseal cartilage are vascular support and the unimpaired function of the proliferating cartilage zone [2, 15, 24].

The main problem with growth plate injuries is the formation of bone tissue (bone bridge) and/or fibrosis (fibrous bridge), which hinders growth and may lead to angular deformities or limb length discrepancy [25, 26, 27].

The effectiveness of surgical removal of bone bridges from the epiphyseal plate is debatable, and the data in the world literature are contradictory. Thus, Peterson reports that the function of the growth plate that underwent surgery may vary from 0 to 200 % relative to the similar zone of the healthy limb [28]. That is, the function of the metaepiphyseal cartilage can be completely arrested or significantly increased.

Surgical methods for treating growth plate injuries are of unconditional interest, but require additional detailed research and analysis [11]. Until now, the choice of tactics for treating growth plate injuries depending on the size of the bone bridges has been debatable. According to some authors, the surgical treatment method is used when the bone bridge occupies more than 33 % of the growth plate; according to others, when the bone bridge occupies more than 50 % [26, 29, 30, 31].

Therefore, comparative experimental and morphological studies of the regeneration of metaepiphyseal cartilage defects after the use of wires/pins made of different materials are relevant in the future.

CONCLUSION

The revealed structural changes in the metaepiphyseal cartilage in the experimental series are characteristic of the reparative phase. At the border with the wires, active proliferative and biosynthetic activity of chondrocytes was observed, more intensely expressed in series 1.

Histomorphometric characteristics of intact areas of the growth plate showed that the insertion of wires, regardless of their material, was not accompanied by inhibition of the bone-forming function of the distal metaepiphyseal cartilage of the femur. In the experimental series, compared to the control limb, the change in the proportion of the reserve zone and the zone of proliferating cartilage was more pronounced. By the end of the experiment, the ratio of metaepiphyseal cartilage zones was comparable to the control in series 2 and 3; in series 1, the proportion of the proliferating cartilage zone increased by 4 %.

Conflict of interest *None.*

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REFERENCES

1. Zavarukhin VI, Morenko ES, Sviridov MK, Govorov AV. Embryonic development and the structure of the growth plate. Pediatric Traumatology, *Orthopaedics and Reconstructive Surgery*. 2015;3(2):61-65. (In Russ.) doi: 10.17816/PTORS3261-65
2. Wang X, Li Z, Wang C, et al. Enlightenment of Growth Plate Regeneration Based on Cartilage Repair Theory: A Review. *Front Bioeng Biotechnol*. 2021;9:654087. doi: 10.3389/fbioe.2021.654087
3. Kazemi M, Williams JL. Properties of Cartilage-Subchondral Bone Junctions: A Narrative Review with Specific Focus on the Growth Plate. *Cartilage*. 2021;13(2_suppl):16S-33S. doi: 10.1177/1947603520924776
4. Takeuchi A, Yamamoto N, Hayashi K, et al. Growth of epiphysis after epiphyseal-preservation surgery for childhood osteosarcoma around the knee joint. *BMC Musculoskelet Disord*. 2018;19(1):185. doi: 10.1186/s12891-018-2109-4
5. Qi L, Jiang Y, Wang Y, et al. The use of the pediatric physeal slide-traction plate in the treatment of neer-horwitz grade IV proximal humeral fractures in children: A case report and literature review. *Front Surg*. 2022;9:960541. doi: 10.3389/fsurg.2022.960541
6. Tiffany AS, Harley BAC. Growing Pains: The Need for Engineered Platforms to Study Growth Plate Biology. *Adv Healthc Mater*. 2022;11(19):e2200471. doi: 10.1002/adhm.202200471
7. Dover C, Kiely N. Growth plate injuries and management. *Orthopaedics and Trauma*. 2015;29(4): 261-267. doi: 10.1016/j.mporth.2015.04.002
8. Sananta P, Lesmana A, Alwy Sugiarto M. Growth plate injury in children: Review of literature on PubMed. *J Public Health Res*. 2022;11(3):22799036221104155. doi: 10.1177/22799036221104155
9. Levine RH, Thomas A, Nezwek TA, et al. Salter-Harris Fracture. In: *StatPearls* [Internet]. Treasure Island (FL): StatPearls Publ.; 2024. Available from: https://www.ncbi.nlm.nih.gov/books/NBK430688/. Accessed May 17, 2024.
10. Brovin DA, Trofimova TN, Kenis VM, Braylov SA. Diffusion-tensor magnetic resonance imaging of the growth plates: substantiation of the method and evaluation of its reproducibility. *Diagnostic radiology and radiotherapy*. 2022;13(3):67-76. (In Russ.) doi: 10.22328/2079-5343-2022-13-3-67-76
11. Sokolovskij OA, Serdjuchenko SN, Brodko GA, Demencov AB. Growth plate surgery: history and prospects. *Medical news*. 2011;7:C.31-35. (In Russ.)
12. Korobeinikov AA, Aranovich AM, Popkov DA. Ilizarov method in the treatment of children with periarticular fractures. *Genij Ortopedii*. 2021;27(4):418-423. doi: 10.18019/1028-4427-2021-27-4-418-423
13. Miyamura S, Tanaka H, Oka K, et al. Physeal bar resection using a patient-specific guide with intramedullary endoscopic assistance for partial physeal arrest of the distal radius. *Arch Orthop Trauma Surg*. 2018;138(8):1179-1188. doi: 10.1007/s00402-018-2985-y
14. 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
15. Hajdu S, Schwendenwein E, Kaltenecker G, et al. The effect of drilling and screw fixation of the growth plate--an experimental study in rabbits. *J Orthop Res*. 2011;29(12):1834-1839. doi: 10.1002/jor.21463
16. Sheikh Z, Najeeb S, Khurshid Z, et al. Biodegradable Materials for Bone Repair and Tissue Engineering Applications. *Materials* (Basel). 2015;8(9):5744-5794. doi: 10.3390/ma8095273
17. Fan XL, Wang J, Zhang DH, et al. Antegrade intramedullary fixation for adolescent fifth metacarpal neck fracture and its impact on epiphyseal growth. *BMC Musculoskelet Disord*. 2021;22(1):546. doi: 10.1186/s12891-021-04436-w
18. Shhudlo MM, Varsegova TN, Stupina TA, et al. The problem of the Holmes effect in quantitative telepathology (methodological aspects). *News of the Chelyabinsk Scientific Center*. 2003;(1):120-124. (In Russ.)
19. Ağırdil Y. The growth plate: a physiologic overview. *EFORT Open Rev*. 2020;5(8):498-507. doi: 10.1302/2058-5241.5.190088
20. Fernández-Iglesias Á, Fuente R, Gil-Peña H, et al. The Formation of the Epiphyseal Bone Plate Occurs via Combined Endochondral and Intramembranous-Like Ossification. *Int J Mol Sci*. 2021;22(2):900. doi: 10.3390/ijms22020900
21. Villemure I, Stokes IA. Growth plate mechanics and mechanobiology. A survey of present understanding. *J Biomech*. 2009;42(12):1793-803. doi: 10.1016/j.jbiomech.2009.05.021
22. D'Andrea CR, Alfraihat A, Singh A, et al. Part 2. Review and meta-analysis of studies on modulation of longitudinal bone growth and growth plate activity: A micro-scale perspective. *J Orthop Res*. 2021;39(5):919-928. doi: 10.1002/jor.24992
23. Celarek A, Fischerauer SF, Weinberg AM, Tschegg EK. Fracture patterns of the growth plate and surrounding bone in the ovine knee joint at different ages. *J Mech Behav Biomed Mater*. 2014;29:286-294. doi: 10.1016/j.jmbbm.2013.09.010
24. Chung R, Xian CJ. Recent research on the growth plate: Mechanisms for growth plate injury repair and potential cell-based therapies for regeneration. *J Mol Endocrinol*. 2014;53(1):T45-T61. doi: 10.1530/JME-14-0062
25. Shaw N, Erickson C, Bryant SJ, et al. Regenerative Medicine Approaches for the Treatment of Pediatric Physeal Injuries. *Tissue Eng Part B Rev*. 2018;24(2):85-97. doi: 10.1089/ten.TEB.2017.0274.
26. Yu Y, Fischenich KM, Schoonraad SA, et al. A 3D printed mimetic composite for the treatment of growth plate injuries in a rabbit model. *NPJ Regen Med*. 2022;7(1):60. doi: 10.1038/s41536-022-00256-1
27. Guo R, Zhuang H, Chen X, et al. Tissue engineering in growth plate cartilage regeneration: Mechanisms to therapeutic strategies. *J Tissue Eng*. 2023; 14:20417314231187956. doi: 10.1177/20417314231187956
28. Peterson HA. Partial growth plate arrest and its treatment. *J Pediatr Orthop*. 1984;4(2):246-258. doi: 10.1097/01241398-198403000-00015
29. Khoshhal KI, Kiefer GN. Physeal bridge resection. *J Am Acad Orthop Surg*. 2005;13(1):47-58. doi: 10.5435/00124635-200501000-00007

30. Moreta J, Abril JC, Miranda C. Arthroscopy- assisted resection-interposition of post-traumatic central physeal bridges. *Rev Esp Cir Ortop Traumatol*. 2013;57(5):333-339. (In Span.) doi: 10.1016/j.recot.2013.07.004
31. Ladenhauf HN, Jones KJ, Potter HG, et al. Understanding the undulating pattern of the distal femoral growth plate: Implications for surgical procedures involving the pediatric knee: A descriptive MRI study. *Knee*. 2020;27(2):315-323. doi: 10.1016/j.knee.2020.02.003

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Information about the authors:

Anatoly A. Korobeinikov — Candidate of Medical Sciences, Head of Laboratory, koroban@list.ru, https://orcid.org/0009-0005-0326-8285;

Tatyana A. Stupina — Doctor of Biological Sciences, Leading Researcher, StupinaSTA@mail.ru, https://orcid.org/0000-0003-3434-0372;

Olga V. Dyuryagina — Candidate of Veterinary Sciences, Head of Laboratory, diuriagina@mail.ru, https://orcid.org/0000-0001-9974-2204;

Mikhail A. Stepanov — Candidate of Veterinary Sciences, veterinarian, m-stepanov@mail.ru;

Nikolai I. Antonov — Candidate of Biological Sciences, Senior Researcher, aniv-niko@mail.ru, https://orcid.org/0000-0002-8627-2749