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Review

Experimental Models of Fracture Consolidation Disorders and Nonunion of Bone Tissue: Modern Approaches, Advantages, Limitations and Prospects of Application

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Abstract

Objective. To analyze current experimental models of fracture union failure and bone nonunion formation, assess their pathogenetic validity, advantages, limitations, and potential applicability in preclinical studies.

Methods. A scoping literature review was conducted, including a systematic search for publications devoted to experimental models of fracture nonunion and nonunion. The literature search was conducted in PubMed, Scopus, and Web of Science using the following keywords and their combinations: fracture nonunion, delayed healing, animal model, and bone healing. The review included original experimental studies on laboratory animals that described the method for modeling fracture nonunion, the animal species, the mechanism of nonunion formation, and the methods for evaluating the results. Clinical studies, abstracts, reports, and publications without experimental modeling were excluded from the analysis. The selected studies were analyzed based on the model type, pathogenetic mechanism, replication features, and limitations of use.

Results. The analysis revealed significant heterogeneity in existing experimental models. Mechanical models based on fixation instability predominantly reproduce hypertrophic nonunion variants and are characterized by high reproducibility. Critical bone defect models are widely used to evaluate biomaterials and regenerative technologies; however, they do not always reflect the pathogenesis of clinical nonunion. Biological models that include periosteal damage, impaired blood supply, or suppression of the osteogenic potential of tissues are more capable of reproducing atrophic forms of consolidation failure. Combined models that integrate mechanical and biological factors demonstrate a higher pathogenetic similarity to clinical nonunion variants but are characterized by greater technical complexity. Systemic and genetic models allow for the study of the influence of metabolic disorders, aging, and molecular mechanisms on reparative osteogenesis. Differences in animal species, observation periods, and nonunion confirmation criteria have been shown to limit the comparability of results between studies.

Conclusions. A universal experimental model capable of fully reproducing all clinical variants of fracture healing failure currently does not exist. The choice of model should be determined by the study objective and the proposed mechanism of bone healing impairment. A promising direction is the standardization of existing approaches and the development of combined models that simultaneously consider mechanical, biological,

and systemic factors. This could improve the reproducibility of experimental studies and facilitate the translation of preclinical data into clinical practice.

Keywords: fracture nonunion, delayed union, hypertrophic nonunion, animal model, fracture healing.

1. Introduction

The incidence of fracture nonunion is estimated to be between 5% and 10%, and this rate may increase as survival rates improve for patients with severe injuries [1]. Fracture nonunion is associated with prolonged pain, limited limb function, repeated surgeries, prolonged rehabilitation periods, and significant socioeconomic burden [2].

Bone fracture healing is a complex, multistage process dependent on the interaction of mechanical stability, local blood supply, cellular osteogenic potential, inflammatory response, and systemic metabolic factors [3]. Disruption of any of these components can lead to delayed consolidation or nonunion, highlighting the need to study the mechanisms of pathological bone healing. Therefore, experimental models are particularly important. The use of appropriate animal models to simulate healing defects is crucial for improving existing treatments and developing new therapies. Models are essential for studying the pathogenesis of nonunion, assessing the role of mechanical and biological factors, and preclinical testing of new treatment methods, including bone grafting materials, growth factors, cell technologies, biomaterials, drugs, and combined regenerative approaches [4].

Experimental orthopedics utilizes models of mechanical instability, critical bone defects, impaired blood supply, periosteal removal, suppression of bone marrow osteogenic potential, soft tissue interposition, drug-induced inhibition of osteogenesis, and combined models of atrophic nonunion. However, each of these models has its own advantages, limitations, and varying degrees of correspondence to clinical patterns of fracture nonunion in humans [5].

However, the literature lacks a unified approach to selecting the optimal experimental model of impaired bone healing. A significant proportion of studies utilize different animal species, anatomical sites, defect creation methods, fixation techniques, observation periods, and nonunion confirmation criteria, which complicates direct comparison of results, reduces experimental reproducibility, and limits the translational value of preclinical data [6].

Furthermore, critical bone defect models are often considered equivalent to fracture nonunion, although the pathogenesis of these conditions is not entirely identical; a critical defect primarily reflects the inability to independently bridge the bone gap, whereas clinical nonunion can be associated not only with defect size but also with mechanical instability, impaired blood supply, infection, and biological insufficiency of the regeneration zone [7,8].

Based on this, experimental models of impaired consolidation can be tentatively classified as mechanical, defective, biological, combined, infectious, and systemic/genetic [9].

This study was conducted in the scoping literature review format with elements of a systematic search.

The aim of this article is to analyze current experimental models of impaired fracture healing and nonunion formation, and to evaluate their pathogenetic validity, advantages, limitations, and applicability in preclinical studies.

2. Materials and Methods

A search of PubMed, Scopus, and Web of Science databases was performed for publications devoted to experimental models of impaired fracture healing and nonunion (2000–2025). Keyword combinations were used: ''fracture nonunion''; ''delayed union''; ''hypertrophic nonunion''; ''animal model''; ''fracture healing''.

Inclusion criteria were:

- experimental preclinical studies devoted to modeling delayed fracture healing or nonunion;
- studies on laboratory animals describing the modeling method;
- primarily modern publications supplemented by classical experimental studies;
- availability of data on the type of model, animal species, and outcome evaluation criteria.

Clinical studies, publications without experimental modeling of consolidation disorders, abstracts, reports, and review articles (except for individual key reviews used to refine the classification of models) were excluded from the analysis.

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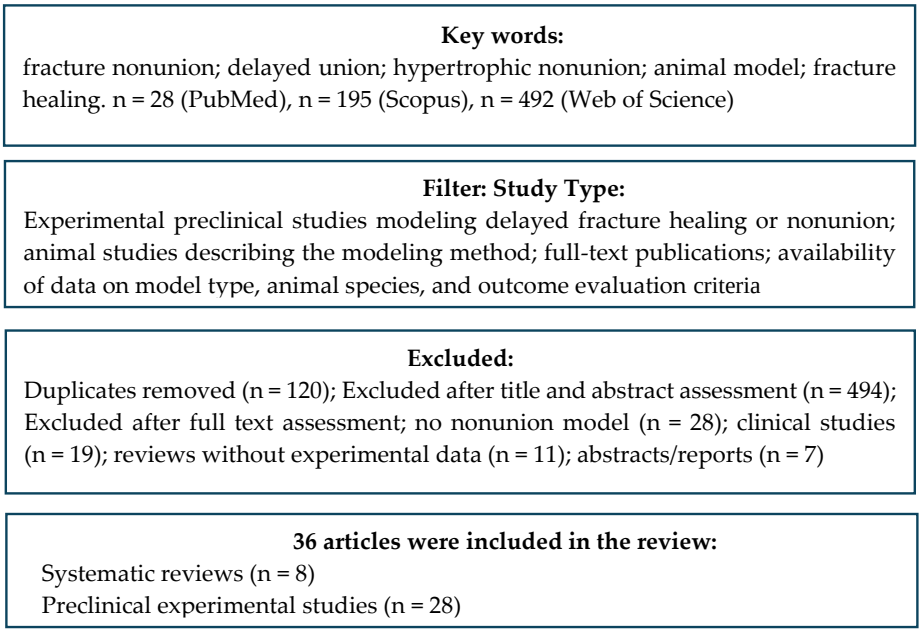

Figure 1 - Algorithm for selecting and including publications in a literature review

The selected publications were sequentially analyzed by title, abstract, and full text, assessing the model used, the mechanism of nonunion formation, animal species, and methods for confirming consolidation failure.

3. Results

Review of Experimental Models. Mechanical Models of Nonunion

Mechanical models simulate hypertrophic nonunion and are used to study the effect of stability on union. Typical examples include intentionally insufficiently rigid fixation or removal of the fixator.

Table 1 - Mechanical Models of Nonunion

Study	Animal / Bone	Modeling Method	Advantages	Limitations
Mølster et al., 1984 [10]	Rat / femur	Rotational instability after osteotomy with varying stiffness of intramedullary fixation	Simple and reproducible model; allows evaluation of the effect of mechanical instability	Does not reproduce vascular and biological impairment; mainly reflects hypertrophic nonunion
Hietaniemi et al., 1995 [11]	Rat / femur	Osteotomy + loosely inserted intramedullary pin →rotational instability	Reproducibly induces delayed union/nonunion; technically relatively simple	Limited representation of atrophic nonunion
Schell et al., 2008 [12]	Sheep / tibia	Comparison of rigid and critically unstable external fixation	Large animal model; high translational relevance; biomechanical assessment possible	High cost and complexity of maintenance
Peters et al., 2010 [13]	Sheep / tibia	Rotationally unstable fixation →delayed healing	Detailed evaluation of callus formation dynamics	Requires prolonged observation and expensive experimental setup

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Table 1 (Continuation) - Mechanical Models of Nonunion

Study	Animal / Bone	Modeling Method	Advantages	Limitations
Claes et al., 2009 [14]	Rat / femur	Reduced fixation stiffness (early dynamization)	Allows assessment of fixation influence on fracture repair	Does not induce stable atrophic nonunion
Schoen et al., 2008 [15]	Rat / femur	Critical-size defect + intramedullary nail	Combines mechanical instability and bone defect; suitable for biomaterial studies	Model is closer to segmental defect than classical fracture nonunion
Garcia et al., 2008 [16]	Mouse / femur	Osteotomy + insufficient fixation stability	High reproducibility; suitable for genetic studies	Small animal size limits surgical manipulation
Tateiwa et al., 2025 [17]	Rat	Alteration of fixation stability at different healing stages	Mimics clinical treatment scenarios for nonunion	Complex design; limited standardizatio

Mechanical models provide useful information about the role of instability, but have limitations: hypertrophic nonunion is less common in humans, and looking exclusively for unstable union may overestimate the importance of the mechanical factor. Furthermore, they do not reproduce the biological aspects of atrophy (periosteal and vascular damage).

Critical Defect Models

Critical defect models (CSDs) create a bone segment that will not heal on its own without a graft or osteogenic factor. These are most commonly segmental defects of the femur or radius of a given length (e.g., 15–20 mm in rabbits). CSD models are useful for testing materials and therapies.

Table 2 - Critical Defect Models

Study	Animal / Bone	Modeling Method	Advantages	Limitations
Zhao et al., 2016 [18]	Rabbit / radius	Standardized critical-size radial defect model for evaluation of bone healing	Simple technique; high reproducibility; suitable for assessment of osteoplastic materials	Rabbit radius is partially unloaded by the ulna →possible overestimation of regenerative capacity
Poser et al., 2014 [19]	Rat / femur	5-mm critical-size femoral defect with plate fixation	Standardized model; useful for evaluation of tissue-engineered constructs	Small animal size limits surgical procedures; does not fully reproduce clinical nonunion
Spicer et al., 2012 [20]	Rat / calvarial bone	Critical-size calvarial defect for testing biomaterials and growth factors	Widely used; highly reproducible; suitable for biomaterial studies	Lack of mechanical loading → poor representation of long-bone healing
Liu et al., 2016 [21]	Rabbit / rib	Determination of critical-size segmental rib defect	Allows standardization of defect size; useful for regenerative studies	Rib model does not reflect biomechanics of long tubular bones
Meng et al., 2019 [22]	Rabbit / segmental defect	Reconstruction of large segmental defects using the Masquelet technique	High clinical relevance; similarity to human reconstructive surgery	Reflects defect reconstruction rather than formation of classical fracture nonunion

Despite their high value for evaluating bone grafting materials and tissue engineering, critical defect models predominantly reproduce the inability to independently fill the bone gap and do not always reflect the pathogenesis of clinical nonunion caused by mechanical instability, infection, or biological insufficiency of the regeneration zone.

Biological models of nonunion

These models directly disrupt regenerative potential. Examples: periosteal coagulation (thermocoagulation) or periosteal excision.

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Table 3 - Biological models of nonunion

Study	Animal / Bone	Modeling Method	Advantages	Limitations
Brownlow et al., 2002 [23]	Rabbit	Atrophic nonunion model; assessment of vascular and metabolic activity within nonunion tissue	Enables investigation of biological characteristics of atrophic nonunion; high pathogenetic relevance	Primarily describes tissue alterations; limited as a reproducible model for nonunion induction
Kaspar et al., 2008 [24]	Rat / femur	Osteotomy + periosteal injury + bone marrow removal + fixation	Reliably reproduces atrophic nonunion; models local suppression of osteogenesis	Technically demanding; highly dependent on standardization of injury extent
Gröngröft et al., 2019 [25]	Mouse / femur	Periosteal cauterization → delayed healing	Allows evaluation of the role of periosteum in reparative osteogenesis; reproducible delayed healing model	More commonly induces delayed union rather than stable nonunion
Wang et al., 2019 [26]	Mouse / femur	Dysfunction of periosteal mesenchymal progenitor cells → impaired regeneration	High molecular and pathogenetic relevance; useful for studying cellular mechanisms of atrophic nonunion	Requires genetic or cellular techniques; difficult to reproduce
Onishi et al., 2020 [27]	Rat / femur	Extensive resection of periosteum and bone marrow	Marked local suppression of osteogenesis; closely mimics atrophic nonunion	High risk of complications and variability; limited reproducibility

Biological models have a greater ability to reproduce atrophic nonunion than mechanical models because they directly affect the osteogenic potential of tissues. However, increased pathogenetic similarity is accompanied by increased complexity of the methodology, increased variability of results, and decreased reproducibility.

Combined Models of Nonunion

Combined models of nonunion combine interventions on several key components of reparative osteogenesis: mechanical stability, periosteal viability, bone marrow osteogenic potential, blood supply, and infection. This approach allows for the reproduction of conditions closer to clinical atrophic nonunion in humans, in which impaired healing is rarely caused by a single mechanism. Most commonly, combined models involve a combination of unstable fixation with periosteal removal, bone marrow damage, segmental defect creation, or local devascularization.

Table 4 - Combined Nonunion Models

Study	Animal / Bone	Modeling Method	Advantages	Limitations
Oni et al., 1995 [28]	Rabbit / tibia	Osteotomy + bone marrow removal + periosteal resection + silicone barrier implantation	Classical atrophic nonunion model; effectively reproduces local suppression of osteogenesis	Technically invasive; silicone barrier creates artificial conditions that may not fully reflect clinical settings
Oetgen et al., 2008 [29]	Mouse / femur	Osteotomy + unstable fixation + periosteal cauterization	Combines mechanical and biological factors; suitable for genetic studies	Small animal size; difficulty in surgical standardization

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Table 4 (Continuation) - Combined Nonunion Models

Study	Animal / Bone	Modeling Method	Advantages	Limitations
Oetgen et al., 2008 [29]	Mouse / femur	Osteotomy + unstable fixation + periosteal cauterization	Combines mechanical and biological factors; suitable for genetic studies	Small animal size; difficulty in surgical standardization
Wu et al., 2021 [30]	Rat / tibia	Unstable fixation + periosteal cauterization	Reproduces combined effects of instability and periosteal damage	Requires precise control of cauterization extent; potential variability in results
Sharun et al., 2021 [8]	Rabbit / radius	10-mm segmental defect + thermal periosteal injury	Larger animal model than mice or rats; suitable for evaluation of regenerative therapies	Rabbit radius is partially unloaded by the ulna; model is closer to segmental defect than classical fracture nonunion
Helbig et al., 2020 [31]	Animal models / segmental defect	Segmental bone defect + infectious component	Reproduces infection-related nonunion; high clinical relevance	High technical complexity; risk of systemic complications; requires strict infection control

Combined models have the greatest pathogenetic similarity to clinical nonunion, as they simultaneously affect mechanical stability, local osteogenic potential, blood supply, and the infectious component. However, this increased clinical relevance is accompanied by greater technical complexity, variability in results, and an increased risk of complications.

Systemic/Genetic Models of Impaired Consolidation

Systemic and genetic models aim to reproduce impaired bone healing by altering the body's overall metabolic state or specific molecular genetic mechanisms. Unlike local mechanical and biological models, these approaches mimic clinical conditions in which impaired consolidation develops as a result of diabetes mellitus, osteoporosis, chronic inflammation, aging, prolonged glucocorticoid use, smoking, nutritional deficiency, or inherited disorders of osteogenesis signaling pathways. Such models are particularly important for studying the pathogenesis of atrophic nonunion and evaluating the effectiveness of orthobiological treatments.

Table 5 - Systemic/genetic models of consolidation disorders

Study	Animal / Model	Modeling Method	Advantages	Limitations
Kayal et al., 2007 [32]	Mouse / diabetic model	Streptozotocin-induced diabetes → impaired angiogenesis and delayed fracture healing	Effectively reproduces the influence of diabetes mellitus on fracture healing; high clinical relevance	Systemic metabolic alterations may affect outcomes beyond bone tissue
Gilley et al., 2009 [33]	Rat / glucocorticoid model	Long-term prednisolone administration → suppression of osteogenesis	Allows modeling of glucocorticoid effects; relevant to clinical immunosuppressive conditions	Risk of systemic complications, weight loss, and increased mortality
Hebb et al., 2018 [34]	Aged mice	Aging → chronic callus inflammation and reduced cellular proliferation	Reflects age-related impairment of bone regeneration; high translational relevance	Requires prolonged observation; high maintenance cost of aged animals
Kolanczyk et al., 2007 [35]	Nf1-deficient mice	NF1/Ras-MAPK pathway disruption → pseudarthrosis-like phenotype	High pathogenetic relevance to congenital pseudarthrosis and neurofibromatosis type 1	Complex genetic model; limited accessibility

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Table 5 (Continuation) - Systemic/genetic models of consolidation disorders

Study	Animal / Model	Modeling Method	Advantages	Limitations
Komatsu et al., 2010 [36]	Mouse / genetic model	Altered Wnt signaling (Lrp5−/−, anti-Dkk1) → impaired bone repair	Useful for investigating molecular mechanisms of osteogenesis	Difficult interpretation; limited clinical reproducibility
Namkung-Matthai et al., 2001 [37]	Rat / osteoporotic model	Ovariectomy → osteoporosis and impaired fracture healing	Reproduces the effect of reduced bone mass on fracture consolidation	Primarily reflects osteoporosis rather than classical fracture nonunion

Despite their high pathogenetic significance, systemic and genetic models primarily reproduce consolidation failure caused by metabolic, age-related, or molecular genetic factors and do not always reflect local mechanical or vascular causes of nonunion. However, these models offer the greatest potential for studying the fundamental mechanisms of reparative osteogenesis and developing targeted therapies.

4. Discussion

Fracture nonunion is a multifactorial process, so no single experimental model can fully reproduce all clinical variants of nonunion. The analysis revealed that published models differ in their underlying pathogenetic mechanism: some reproduce primarily mechanical instability, while others reproduce bone defects, periosteal damage, suppression of osteogenic potential, or systemic regenerative disorders. This diversity of approaches explains why research results are difficult to directly compare.

Mechanical models are most often used to study the role of fixation stability. In the studies of Mølster et al. [10] and Hietaniemi et al. [11], failure of union was achieved through rotational instability after femoral osteotomy in rats. These models clearly demonstrate the importance of mechanical factors, but are more consistent with hypertrophic or fibrous nonunion. A similar approach was used by Schell et al. [12] and Peters et al. [13] in sheep, which increased the translational value of the model, but simultaneously increased the cost and complexity of the experiment.

Critical defect models occupy a special place. Zhao et al. [18] used a rabbit model of a critical radius defect, Poser et al. [19] a rat femur defect, and Spicer et al. [20] a skull defect. These models are convenient for evaluating biomaterials, bone grafting materials, and tissue-engineered constructs. However, they should not be automatically equated with classic fracture nonunion. A critical defect primarily reflects the inability of the bone gap to fill spontaneously, whereas clinical nonunion is often associated with a combination of instability, impaired blood supply, infection, and biological failure.

Biological models are more aimed at reproducing atrophic nonunion. Kaspar et al. [24] used a combination of osteotomy, periosteal injury, and bone marrow removal. Gröngröft et al. [25] used periosteal injury to study delayed healing, and Onishi et al. [27] proposed a model with extensive resection of the periosteum and bone marrow. Such approaches are pathogenetically closer to atrophic nonunion, since they affect the local osteogenic potential of tissues. At the same time, they require more precise surgical standardization, and the results can significantly depend on the extent of periosteal and bone marrow injury.

Combined models appear to be closest to clinical conditions, since impaired consolidation in humans is rarely associated with only one factor. Oni et al. [28] described a rabbit model with osteotomy, bone marrow removal, periosteal excision, and placement of a silicone barrier. Oetgen et al. [29] combined unstable fixation with periosteal thermocoagulation in mice, and Wu et al. [30] used unstable fixation and periosteal coagulation in rats. Sharun et al. [8] proposed a rabbit model with a 10-mm defect and thermal injury to the periosteum. These models better reflect the multifactorial nature of nonunion, but remain technically complex and less convenient for widespread standardization.

Systemic models deserve special attention. Helbig et al. [31] examined models of a segmental defect with an infectious component, which is important for studying infected nonunion. Kayal et al. [32] demonstrated the effect of streptozotocin-induced diabetes on angiogenesis and fracture healing, Gilley et al. [33] used a glucocorticoid model with long-term prednisolone administration, and Hebb et al. [34] analyzed impaired regeneration in aged animals. These models are important because nonunion in clinical

settings often develops against a background of systemic risk factors. However, they do not always reflect the local mechanical and vascular causes of impaired consolidation.

Genetic models allow for a more in-depth study of the molecular mechanisms of osteogenesis disorders. Kolanczyk et al. [35] used Nf1-deficient mice, which is of particular interest for studies related to congenital pseudoarthrosis and impaired NF1/Ras-MAPK signaling. Komatsu et al. [36] studied the effects of impaired Wnt signaling on bone regeneration. Such models have high fundamental value, but require specialized infrastructure and are not always accessible to routine experimental laboratories.

When analyzing the included studies, the lack of uniform criteria for confirming nonunion is noteworthy. Different studies use different observation periods, imaging methods, histological criteria, and biomechanical assessments. This complicates the comparison of results between models and reduces data reproducibility. Therefore, the choice of model should be determined not only by the animal species or the technical feasibility of the surgery, but above all by the purpose of the study: studying mechanical instability, biological failure, infection, systemic factors, or evaluating new regenerative treatments.

Study Limitations

This review has several limitations. The included studies were characterized by significant heterogeneity in terms of animal species, follow-up periods, nonunion confirmation criteria, and outcome assessment methods used. Furthermore, some of the analyzed publications were classical studies, limiting direct comparison with modern experimental approaches. A formal risk assessment of bias was not conducted. The purpose of this review was to systematize existing experimental models and conduct a comparative analysis, rather than to quantify the quality of evidence.

5. Conclusions

Our literature review revealed that existing experimental models of malunion vary significantly in their mechanisms of formation, reproducibility, and degree of correspondence to clinical nonunion patterns. Mechanical models primarily reflect the effects of fixation instability, critical defect models are used primarily to evaluate regenerative technologies, while biological and combined approaches allow for a better reproduction of atrophic malunion patterns. Systemic and genetic models are important for studying the fundamental mechanisms of impaired osteogenesis.

Despite the large number of proposed approaches, a universal experimental model capable of fully reproducing all clinical nonunion variants in humans currently does not exist. Analysis of the included studies also revealed a lack of uniform criteria for confirming nonunion, along with differences in follow-up periods and outcome assessment methods, limiting the comparability of data between studies.

Further development in this area will likely involve not so much the creation of new models as the standardization of existing approaches and the development of combined models that simultaneously consider the mechanical, biological, and systemic factors of impaired bone regeneration. This could improve the reproducibility of experimental studies and facilitate the translation of the obtained results into clinical practice for treating patients with impaired fracture union.

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Сынықтардың консолидациясы бұзылыстарының және сүйек тіндерінің бірікпеуінің эксперименттік модельдері: Заманауи тәсілдер, артықшылықтар, шектеулер және қолданудың келешегі

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Түйіндеме

Шолудың мақсаты: сынықтардың бірігуінің бұзылуы және сүйектердің бірікпеуінің қалыптасуының қазіргі тәжірибелік модельдерін талдау, олардың патогенетикалық жарамдылығын, артықшылықтарын, шектеулерін және клиникаға дейінгі зерттеулердегі әлеуетті қолданылуын бағалау.

Әдістері. Сынықтардың бірікпеу және бірікпеуінің эксперименттік модельдеріне арналған басылымдарды жүйелі түрде іздеуді қамтитын әдебиеттерге шолу жүргізілді. Әдебиеттерді іздеу PubMed, Scopus және Web of Science сайттарында келесі түйін сөздерді пайдаланып жүргізілді: «сынықтардың бірікпеуі», «кешіктірілген консолидация», «жануарлар моделі» және «сүйектің жазылуы». Шолуда сынықтардың бірікпеуін модельдеу әдісін, жануарлар түрін, бірікпеу пайда болу механизмін және нәтижелерді бағалау әдістерін сипаттайтын зертханалық жануарларға арналған түпнұсқа эксперименттік зерттеулер қамтылған. Таңдалған зерттеулер модель түріне, патогенетикалық механизмге, репликация ерекшеліктеріне және пайдалану шектеулеріне негізделіп талданды.

Нәтижелері. Талдау қолданыстағы тәжірибелік модельдерде айтарлықтай гетерогенділікті анықтады. Бекіту тұрақсыздығына негізделген механикалық модельдер негізінен гипертрофиялық бірікпеу нұсқаларын көбейтеді және жоғары қайталануымен сипатталады. Сүйек ақауларының маңызды модельдері биоматериалдар мен регенеративті технологияларды бағалау үшін кеңінен қолданылады. Дегенмен, олар клиникалық бірікпеудің патогенезін әрқашан көрсете бермейді. Периостеальды зақымдануды, қанмен қамтамасыз етудің бұзылуын немесе тіндердің остеогендік әлеуетінің басылуын қамтитын биологиялық модельдер консолидация сәтсіздігінің атрофиялық түрлерін көбейтуге қабілетті. Механикалық және биологиялық факторларды біріктіретін біріктірілген модельдер клиникалық бірікпеудің нұсқаларына жоғары патогенетикалық ұқсастықты көрсетеді. Бірақ техникалық күрделілігінің жоғарылауымен сипатталады. Жүйелік және генетикалық модельдер зат алмасу бұзылулардың, қартаюдың және молекулалық механизмдердің репаративті остеогенезге әсерін зерттеуге мүмкіндік береді. Жануарлар түрлеріндегі, бақылау кезеңдеріндегі және бірікпеуді растау өлшемшарттарындағы айырмашылықтар зерттеулер арасындағы нәтижелердің салыстырмалылығын шектейтіні көрсетілген.

Қорытынды. Қазіргі уақытта сынықтардың жазылу сәтсіздігінің барлық клиникалық нұсқаларын толығымен көбейтуге қабілетті әмбебап эксперименттік модель жоқ. Модельді таңдау зерттеу мақсатымен және сүйек жазылуының бұзылуының ұсынылған механизмімен анықталуы керек. Перспективалық бағыт - қолданыстағы тәсілдерді стандарттау және механикалық, биологиялық және жүйелік факторларды бір уақытта ескеретін біріктірілген модельдерді әзірлеу. Бұл эксперименттік зерттеулердің қайталануын жақсартып, клиникаға дейінгі деректерді клиникалық тәжірибеге аударуды жеңілдетуі мүмкін.

Түйін сөздер: сынықтардың бірікпеуі, кешіктірілген консолидация, гипертрофиялық бірікпеу, жануарлар моделі, сүйектің жазылуы.

Экспериментальные модели нарушения консолидации переломов и несращения костной ткани: Современные подходы, преимущества, ограничения и перспективы применения

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Резюме

Цель обзора: провести анализ современных экспериментальных моделей нарушения консолидации переломов и формирования несращения костной ткани, оценить их патогенетическую обоснованность, преимущества, ограничения и потенциальную применимость в доклинических исследованиях.

Методы. Выполнен обзор литературы с элементами систематизированного поиска публикаций, посвященных экспериментальным моделям нарушения консолидации переломов и несращения костной ткани. Поиск литературы проводился в базах данных PubMed, Scopus и Web of Science с использованием ключевых слов и их комбинаций: «несращение перелома», «замедленная консолидация», «животная модель» и «заживление костей». В обзор включали оригинальные экспериментальные исследования на лабораторных животных с описанием метода моделирования нарушения консолидации, вида животного, механизма формирования несращения и способов оценки результатов. Отобранные работы анализировали по типу модели, патогенетическому механизму, особенностям воспроизведения и ограничениям применения.

Результаты. Проведенный анализ показал значительную неоднородность существующих экспериментальных моделей. Механические модели, основанные на нестабильности фиксации, преимущественно воспроизводят гипертрофические варианты несращения и характеризуются высокой воспроизводимостью. Модели критического костного дефекта широко применяются для оценки биоматериалов и регенеративных технологий, однако не всегда отражают патогенез клинического несращения. Биологические модели, включающие повреждение надкостницы, нарушение кровоснабжения или подавление остеогенного потенциала тканей, обладают большей способностью воспроизводить атрофические формы нарушения консолидации. Комбинированные модели, объединяющие механические и биологические факторы, демонстрируют более высокую патогенетическую близость к клиническим вариантам несращения, но отличаются большей технической сложностью. Системные и генетические модели позволяют изучать влияние метаболических нарушений, старения и молекулярных механизмов на процессы репаративного остеогенеза. Установлено, что различия в используемых видах животных, сроках наблюдения и критериях подтверждения несращения ограничивают сопоставимость результатов между исследованиями.

Выводы. Универсальной экспериментальной модели, способной полностью воспроизвести все клинические варианты нарушения консолидации переломов, в настоящее время не существует. Выбор модели должен определяться целью исследования и предполагаемым механизмом нарушения костного заживления. Перспективным направлением представляется стандартизация существующих подходов и разработка комбинированных моделей, учитывающих одновременно механические, биологические и системные факторы. Это может повысить воспроизводимость экспериментальных исследований и улучшить трансляцию доклинических данных в клиническую практику.

Ключевые слова: несращение перелома, замедленная консолидация, гипертрофическое несращение, животная модель, заживление костей.

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