ANATOMICAL BASIS OF FRACTURE HEALING: A SCIENTIFIC REVIEW

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Abstract

Background

Fracture healing is a well-orchestrated biological and anatomical process that includes cell growth and multiplication, restoration of blood supply, and continuous remodeling of bone tissue. Successful bone repair depends upon the integrity of osseous tissue, periosteum, blood supply, and mechanical stability. Understanding the anatomical basis of fracture healing is essential for orthopedic management and rehabilitation.

Objective

This study aims to examine the anatomical components and biological processes involved in fracture healing, as well as to highlight their importance in contemporary orthopedic clinical practice.

Methods

A structured narrative review was conducted using standard anatomy and orthopedic textbooks along with peer-reviewed articles indexed in PubMed and related biomedical databases. Relevant literature focusing on bone anatomy, vascular supply, fracture repair, and remodeling mechanisms was analyzed.

Results

Fracture healing occurs in a series of well-defined stages, including the inflammatory phase, reparative phase, and remodeling phase. Multiple anatomical structures—such as the periosteum, endosteum, cortical and cancellous bone, blood vessels, and adjacent soft tissues—play essential roles in this process. At the cellular level, coordinated activity among osteoblasts, osteoclasts, chondrocytes, and mesenchymal stem cells drives tissue repair and regeneration. In addition, both mechanical stability and an intact vascular supply are critical factors that determine successful fracture union.

Conclusion

The anatomical basis of fracture healing involves complex interactions between bone structure, vascular supply, cellular activity, and biomechanical forces. Comprehensive understanding of these mechanisms is fundamental for fracture management, surgical planning, and prevention of delayed union or nonunion.

Keywords: Fracture healing, bone anatomy, periosteum, callus formation, osteogenesis, bone remodeling, orthopedic anatomy

Introduction

Bone is a highly specialized form of connective tissue with an exceptional ability to regenerate. In contrast to many other tissues, it can repair itself without forming scar tissue and is capable of regaining its original structure and function. For this reason, fracture healing is regarded as a distinctive physiological process that results from the interaction of cellular activity, vascular responses, and biomechanical forces. [1]

Fractures are one of the most frequently encountered injuries in orthopedic practice globally. They can occur due to traumatic events, underlying osteoporosis, pathological bone conditions, or repetitive mechanical stress. Effective healing requires sufficient vascular supply, proper stabilization of the fracture site, preservation of the periosteum, and an appropriate biological healing response. [2] When these essential factors are compromised, complications such as delayed union, malunion, or nonunion may develop.

From an anatomical perspective, bone is composed of dense cortical bone and porous cancellous bone, with an external covering of periosteum and an internal lining of endosteum. Both the periosteum and endosteum house osteogenic cells that are crucial for bone repair and remodeling. Furthermore, the surrounding muscles and soft tissues play an important role by providing vascular supply and contributing to mechanical stability throughout the healing process. [3]

Recent progress in orthopedic surgical techniques, biomaterials, and regenerative medicine has greatly enhanced the management of fractures. Despite these advances, a clear understanding of the anatomical and biological principles underlying fracture healing remains essential for both clinicians and researchers.

Aims and Objectives

This study aims to examine the anatomical components and biological processes involved in fracture healing, as well as to highlight their importance in contemporary orthopedic clinical practice.

Materials and Methods

A structured narrative review was carried out using peer-reviewed literature sourced from databases such as PubMed, Scopus, and Google Scholar, in addition to standard textbooks of anatomy, orthopedics, and histology. The search strategy included key terms such as “fracture healing,” “bone anatomy,” “callus formation,” “periosteum,” “bone remodeling,” and “bone vascular supply.”

Only English-language publications from 1990 to 2025 were considered for inclusion. Key foundational texts in anatomy and histology were also reviewed to support the discussion. The collected information was systematically categorized into sections focusing on the anatomical basis, stages of biological healing, and relevant clinical applications. All references were organized and formatted in accordance with the Vancouver citation style.

Results

Anatomy of Bone Relevant to Fracture Healing

Gross Structure of Bone

Bone is broadly divided into two main structural types: cortical (compact) bone and cancellous (trabecular or spongy) bone.

Cortical Bone

Cortical bone forms the dense, outer layer of long bones and is primarily responsible for mechanical strength and structural support. It is organized into osteons (Haversian systems) that are aligned along the long axis of the bone. This arrangement allows cortical bone to effectively resist bending forces as well as torsional (twisting) stresses. [4]

Cancellous Bone

Cancellous bone is made up of a network of trabeculae with interconnecting spaces filled with bone marrow. Compared to cortical bone, it is more metabolically active and has a richer blood supply. Because of this higher vascularity, cancellous bone contributes significantly to faster healing, particularly in fractures involving the metaphyseal regions. [5]

Periosteum

The periosteum is a dense connective tissue layer that covers the outer surface of bone, except at the articular cartilage regions. It is composed of two layers:

1. Outer fibrous layer
2. Inner cambium (osteogenic) layer

The inner cambium layer contains osteoprogenitor cells, which can differentiate into osteoblasts and contribute to new bone formation. The periosteum plays a vital role in fracture repair and callus formation. It is especially important in children, where it is thicker, more active, and more vascular, leading to faster healing. [6]

Endosteum

The endosteum is a thin cellular membrane that lines the medullary cavity of long bones as well as the internal surfaces of trabecular bone. It contains osteogenic cells that participate in bone formation and plays an important role in internal bone remodeling during the fracture healing process.

Blood Supply of Bone

Adequate blood supply is a critical requirement for effective fracture healing.

Nutrient Artery

The nutrient artery enters the bone to supply the medullary cavity and the inner two-thirds of the cortical bone, playing a key role in maintaining the viability of the central bone structures.

Periosteal Arteries

Periosteal vessels are responsible for supplying the outer cortex of the bone. After a fracture, these vessels become especially important as they contribute significantly to the revascularization and repair process.

Metaphyseal and Epiphyseal Vessels

These blood vessels supply the ends of long bones and are particularly well developed in regions rich in cancellous bone. [7]

Any disruption to the vascular network can significantly impair healing and may lead to complications such as delayed union or avascular necrosis.

Bone Cells Involved in Healing

Osteoblasts

Osteoblasts synthesize osteoid and promote mineralization.

Osteoclasts

Osteoclasts resorb necrotic bone and participate in remodeling.

Osteocytes

Osteocytes maintain bone metabolism and act as mechanosensors.

Chondrocytes

Chondrocytes contribute to cartilage formation during endochondral ossification.

Mesenchymal Stem Cells

These pluripotent cells differentiate into osteoblasts and chondroblasts during repair. [8]

Phases of Fracture Healing

Fracture healing progresses through overlapping phases that include inflammation, repair, and remodeling.

Inflammatory Phase

This phase starts immediately after the injury and typically lasts for a few days.

Hematoma Formation

Damage to blood vessels at the fracture site leads to the formation of a hematoma. This clot acts as a temporary fibrin framework that supports the migration of inflammatory cells. [9]

Inflammatory Response

Neutrophils and macrophages infiltrate the area to clear necrotic debris. These cells also release cytokines such as interleukins and tumor necrosis factor-alpha, which help regulate inflammation and stimulate angiogenesis as well as cellular proliferation.

Vascular Changes

New capillaries begin to form, gradually restoring blood supply to the injured region. This revascularization is essential for delivering oxygen, nutrients, and reparative cells required for healing.

Reparative Phase

The reparative phase begins within a few days of injury and may continue for several weeks.

Soft Callus Formation

Granulation tissue is gradually replaced by a fibro-cartilaginous (soft) callus composed mainly of collagen and cartilage. This structure provides early stabilization of the fracture while still allowing limited flexibility. [10]

Hard Callus Formation

As healing progresses, endochondral ossification replaces cartilage with woven bone, forming a hard callus that bridges the fracture site. Osteoblasts actively lay down new bone matrix during this process.

Intramembranous Ossification

This occurs directly beneath the periosteum without a cartilage intermediate, contributing to new bone formation around the fracture. Occurs directly beneath the periosteum without cartilage intermediate.

Endochondral Ossification

This process occurs in areas with relatively low oxygen levels, where cartilage forms first and later is replaced by bone, acting as a temporary support structure. [11]

Remodeling Phase

The remodeling phase may continue for months or even years after the injury.

Conversion of Woven Bone to Lamellar Bone

Immature woven bone is gradually replaced by stronger, more organized lamellar bone, restoring normal bone architecture.

Restoration of Medullary Canal

Osteoclasts resorb excess callus while osteoblasts reconstruct the cortical structure and re-establish the medullary canal.

Wolff’s Law

Bone structure adapts according to the mechanical stresses applied to it. Appropriate loading helps align trabeculae along lines of stress, optimizing strength and function. [12]

Types of Fracture Healing

Primary (Direct) Bone Healing

Primary bone healing occurs when there is absolute stability at the fracture site, typically achieved through rigid internal fixation such as compression plating, with minimal or no interfragmentary movement.

Key features include:

- No formation of visible external callus
- Direct remodeling of bone through osteonal (Haversian) systems

- Requirement for precise anatomical reduction of the fracture fragments[13]

Secondary (Indirect) Bone Healing

Secondary bone healing is the most common pattern of fracture repair and occurs when there is relative stability at the fracture site.

It progresses through several stages:

1. Formation of a hematoma at the fracture site
2. Development of a soft (fibro-cartilaginous) callus
3. Conversion into a hard (bony) callus
4. Ongoing bone remodeling to restore normal structure

This type of healing involves both intramembranous and endochondral ossification processes.

Anatomical Factors Influencing Fracture Healing

Age

Children heal faster because of:

- Thick periosteum
- Rich blood supply
- Greater osteogenic potential

Elderly individuals exhibit delayed healing because of reduced vascularity and osteoporosis. [14]

Blood Supply

Vascular compromise significantly impairs healing. Fractures involving scaphoid neck or femoral neck are prone to avascular necrosis because of limited blood supply.

Fracture Configuration

Transverse fractures generally take longer to heal compared to oblique or spiral fractures because they provide a relatively smaller surface area for bone contact and union. As a result, there is less opportunity for callus formation and stability across the fracture site, which can slow the overall healing process.

Soft Tissue Integrity

Muscles and surrounding tissues provide vascular support. Severe soft tissue damage increases risk of infection and nonunion.

Mechanical Stability

Excessive movement disrupts callus formation, whereas controlled micro motion may stimulate secondary healing.

Clinical Significance

Understanding fracture healing anatomy is fundamental in orthopedic surgery and trauma management.

Fracture Fixation

Internal fixation devices, including plates, screws, and intramedullary nails, are designed to achieve stable fracture fixation while minimizing disruption to the surrounding blood supply. Their primary goal is to maintain proper alignment and mechanical stability of the bone, thereby supporting effective healing while preserving vascular integrity. [15]

Delayed Union and Nonunion

Failure of normal healing progression may occur because of:

- Poor blood supply
- Infection
- Excessive movement
- Nutritional deficiency
- Smoking and systemic disease

Hypertrophic nonunion results from inadequate stability, whereas atrophic nonunion results from poor biological activity. [16]

Bone Grafting

Bone grafts provide:

- Osteogenic cells
- Osteoconductive scaffold
- Osteo inductive growth factors

Autogenous cancellous grafts remain the gold standard in orthopedic reconstruction.

Modern Advances

Recent developments include:

- Bone morphogenetic proteins
- Stem cell therapy
- Tissue engineering
- Biodegradable scaffolds
- 3D-printed implants[17]

These technologies aim to enhance biological repair and reduce complications.

Discussion

Fracture healing is a highly coordinated biological process that involves the integration of anatomy, histology, vascular physiology, and biomechanical principles. The periosteum plays a crucial role in bone regeneration by serving as a rich source of osteogenic precursor cells, highlighting the importance of careful soft tissue handling and preservation during surgical procedures. [18]

Angiogenesis is another essential component of successful fracture repair. Adequate vascular supply ensures proper oxygenation, nutrient delivery, and migration of reparative cells to the fracture site. Interruption of blood flow can compromise healing and may result in delayed union or nonunion. Consequently, modern orthopedic techniques increasingly focus on biological fixation strategies that preserve periosteal blood supply and maintain the fracture hematoma, both of which are vital for optimal bone healing. [19]

Mechanical stability plays a critical role in determining the pattern of fracture healing. Absolute rigidity at the fracture site promotes primary bone healing with direct cortical remodeling, whereas controlled micro motion encourages callus formation characteristic of secondary healing. These biomechanical principles form the foundation of contemporary orthopedic fixation methods. [20]

Several systemic conditions can adversely influence fracture repair by impairing osteogenesis and reducing vascularity. Disorders such as diabetes mellitus, malnutrition, smoking, and osteoporosis are associated with delayed healing and compromised bone regeneration. For this reason, fracture healing should be viewed not only as a localized event but also as a systemic biological process influenced by the patient's overall health status. [21]

Recent developments in regenerative medicine have significantly enhanced the understanding of the molecular mechanisms involved in bone healing. Various growth factors, including bone morphogenetic proteins (BMPs), vascular endothelial growth factor (VEGF), and transforming growth factor-beta (TGF-β), play essential roles in osteoblastic activity, cellular differentiation, and angiogenesis. Emerging approaches involving stem cell therapy and advanced biomaterials hold considerable promise for improving fracture treatment and may transform future orthopedic practice. [22]

Conclusion

Fracture healing is a complex regenerative process that involves the coordinated interaction of anatomical structures, blood supply, cellular responses, and mechanical forces. Successful bone repair depends on the combined contribution of the periosteum, endosteum, cortical bone, cancellous bone, and the surrounding soft tissues.

A thorough knowledge of the anatomical foundations of fracture healing is important for healthcare professionals involved in orthopedic trauma management, reconstructive procedures, and rehabilitation. Maintaining adequate blood supply, achieving stable fixation, and creating an optimal biological environment are key principles for effective fracture treatment and successful bone healing.

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