Fractures classification and healing

1. General Information

Bone tissue is a living tissue composed of an inert part made of 60% hydroxyapatite and 35% type 1 collagen, and cells (osteoclasts, osteoblasts, osteocytes), blood vessels, and nerves for 5%.

This tissue contains, particularly in cancellous bone, the hematopoietic marrow.

Bone tissue, thanks to the properties of its calcified extracellular matrix, ensures three main functions:

- A mechanical function providing support for the body's weight,
- A function of protecting essential organs,
- A metabolic function linked to the ability to store minerals, particularly calcium and phosphate.

Bone tissue is continuously renewed by a remodeling process carried out by two cell types:

- Osteoclasts, which resorb the bone matrix,
- Osteoblasts, which synthesize a new osteoid matrix.

2. Review

Anatomically, there are 3 types of bones:

- Long bones have a diaphysis, 2 metaphyses, and 2 epiphyses
- Short bones (carpus, tarsus, vertebrae) bearing several articular surfaces
- Flat bones (skull, scapula) have no locomotive function

Bones are divided into three parts:

- Diaphysis: the middle, elongated part of the bone, hollow, made of compact tissue surrounding the medullary canal
- Epiphysis: at the ends of the bone, made of spongy tissue, covered with cartilage
- Metaphysis: contains the Growth Cartilage in young individuals, which allows bone growth (not to be confused with a fracture line)

Histologically, there are two main types of bone tissue: compact bone tissue and cancellous bone tissue.

Cancellous bone consists of a network of irregular bony struts or trabeculae separated by communicating spaces containing active marrow or red marrow responsible for the production of stem cells for the cellular elements of the blood. The bony trabeculae are lined with a thin layer of particular connective tissue or endosteum containing both osteoblasts and osteoclasts that ensure bone growth and remodeling.

Compact bone has a highly ordered architecture in the form of columns parallel to the long axis of the bone called haversian systems (or Haversian systems). The bony lamellae produced by osteoblasts are deposited concentrically around large Haversian canals containing blood and lymphatic vessels as well as nerves. These canals communicate with each other as well as with the medullary cavity and the periosteum of the external surface of the diaphysis through transverse canals: Volkmann's canals.

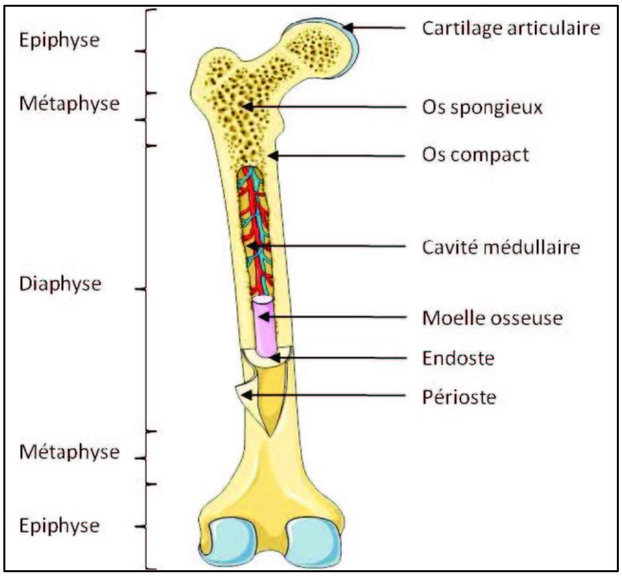


Figure 1: Structure of a long bone. (M. David 2010)

3. Definition of Fracture

A break in the continuity of the bone, ranging from a simple fissure without displacement to a comminuted fracture.

Open fracture = opening of the skin over the fracture site, allowing communication between the bone and the exterior.

4. Etiology of Fractures

4.1. Traumatic Origins

Direct trauma = direct impact (weight or ground). Indirect trauma = torsion, traction (stretching), compression, avulsion.

Contexts:

- Isolated (single bone)
- Polytrauma (combination of injuries, at least one of which is life-threatening)
- Multiple fractures (several limbs)
- Staged trauma (several bones on the same limb)

Trauma to growth zones (conjugation cartilage), (epiphyseal fractures and separations), can disrupt longitudinal growth or lead to bone deviation.

4.2. Pathological Origins

Osteoporosis, osteolytic tumors (osteosarcoma, chondrosarcoma, etc.), chronic renal failure (CRF), primary and secondary hyperparathyroidism, bone cysts.

5. Characteristics of the Fracture (what allows describing the fracture)

5.1 Topography

The bone involved and where on the bone, for example: tibial fracture, femoral fracture, and more precisely its location on the affected bone: diaphyseal fracture (e.g., at the middle third or lower third), metaphyseal or epiphyseal fracture, and in this case the fracture may be articular or extra-articular, apophyseal fracture.

5.2- Degree of Rupture

It is rarely incomplete, affecting only one cortex (e.g., greenstick fracture in young: one cortex is broken, the other is simply bent). It is most often complete, affecting both cortices and separating the fragments.

5.3- Fracture Line(s)

5.3.1 Simple fracture: bi-fragmentary fracture, the line is unique and separates the two fragments, one proximal, the other distal. It can be transverse, horizontal, rarely clean. It can be oblique or spiral: the contact surface between the two separated fragments is larger, but they can slide over each other more easily (unstable fracture).

5.3.2 Complex multi-fragmentary fracture: Defined by several fracture lines. It can be tri-fragmentary (classic example: tibial fracture with a third small "butterfly" fragment), double-level fracture: the two upper and lower lines isolate an intermediate fragment between them, truly multi-fragmentary with 4 or 5 fragments or more (comminuted fracture), the fragments are very numerous and small, surgical reconstruction is impossible.

5.4 Displacement

In which direction or absence of displacement.

- Transverse translation (lateral displacement)
- Longitudinal overlap (one bone is fractured and overrides next to another bone)
- Angular (the fractured bone forms an angle with another bone)
- Rotational (the fractured bone is rotated on itself)

These displacements are governed by muscle action and gravity.

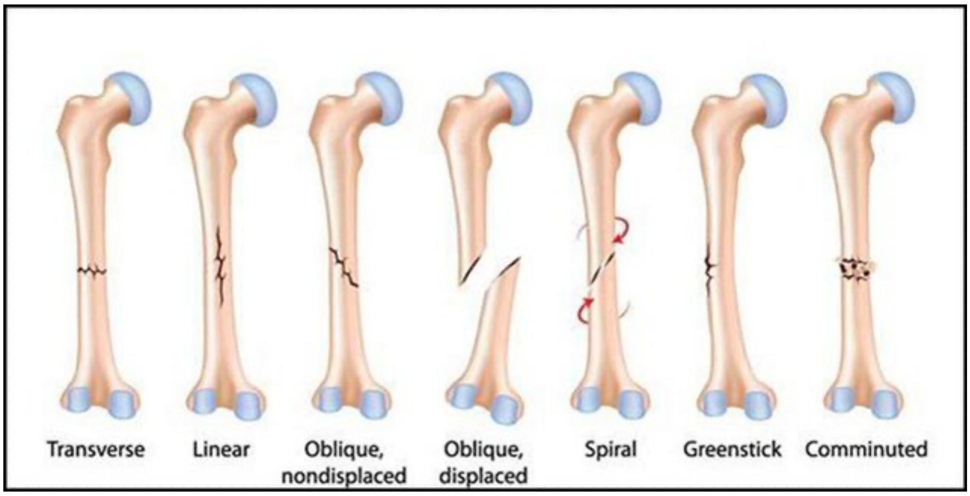


Figure 02: The different types of fractures (Kumara D 2018)

5.5 Skin Condition Near the Fracture

Based on the condition of the skin over the fracture site, we distinguish:

5.5.1 Closed fracture: The skin is intact; no skin lesion is visible.

5.5.2 Open fracture: When the skin is open, the fracture site communicates with the exterior, increasing the risk of infection. Large skin and muscle losses may be visible, posing therapeutic problems for bone coverage.

5.6 Causal Mechanism of the Fracture

- Trauma: fall, avulsion, impact
- Fatigue fractures: result from the repetitive application of moderate forces, which can occur in working animals

- Bone dystrophies: hyperparathyroidism, CRF, essential or aneurysmal bone cysts
- Often malignant bone tumors, e.g., primary or secondary osteosarcoma
- Osteoporosis: Age-related, corticosteroid therapy, Cushing's syndrome

5.7 Associated Lesions

Besides bone trauma, tissues surrounding the fracture site can be injured.

Skin Lesions: The goal in managing open fractures is to prevent any further contamination, avoid additional injury to the bone and surrounding soft tissues, particularly nerve and vascular structures, and promote rapid stabilization. Patients with open fractures have sustained some degree of trauma, sometimes severe. Complete evaluation and stabilization of the patient should be the initial priority.

Fracture stabilization is not the immediate priority, except in cases of major arterial (and possibly venous) hemorrhage. In this case, the priority is to control the bleeding to stabilize the patient, not to repair the fracture first.

Once the patient is stabilized, evaluation and management of the open fracture proceed. Examination gloves must be worn to avoid additional contamination from handling.

The affected limb must be examined to determine:

- The location of the fracture,
- The degree of tissue loss,
- Vascular and nerve integrity.

The degree of tissue loss influences the choice of wound treatment and the type of bone repair. Perfusion is assessed by:

- Palpation of pulses,
- Limb warmth,
- Presence of distal bleeding relative to the fracture.

A complete neurological examination is then performed, with particular attention to:

- Reflexes,
- Response to superficial or deep pain,
- Response to stimulation of specific dermatomes, especially if nerve injury is suspected.

Classification of Open Fractures

The classification of open fractures helps determine:

- The appropriate type of bone repair and soft tissue treatment,
- The risk of complications and functional prognosis.

This classification considers:

- The mechanism of the fracture,
- The energy of the trauma,
- The degree of tissue loss.

A key point: A fracture can be considered open even if the bone no longer protrudes through the skin at the time of examination. Any wound located over a fractured limb must be considered an open fracture and treated as such.

5.7.1 Skin Lesions

- **Type 1 (first degree):** In this case, the bone itself has pierced the skin. The wound is usually 1 cm or less, with little muscle or tissue damage. The trauma is low-energy. Example: fall from a small wall less than 3m. In many cases, the bone is no longer visible at the time of clinical presentation.
- **Type 2 (second degree):** The trauma is more energetic. Example: animal hit by a car at moderate speed (<40 km/h), kick from a hoof. The wound is more than 1 cm and is accompanied by moderate damage to muscles and soft tissues. The skin lesion can be caused by the bone itself but more often results from external forces.
- **Type 3 (third degree):** These fractures result from high-energy trauma, with significant tissue damage and sometimes bone loss. They are usually due to gunshot wounds or road accidents (speed > 60 km/h). They are subdivided into three subtypes:

  - Type 3a: No skin reconstruction needed to cover the bone or close the wound.
  - Type 3b: Skin reconstruction is necessary to cover the bone or close the wound.
  - Type 3c: Presence of an arterial injury requiring vascular repair.
- **Type 4 (fourth degree):** Type 4 open fractures correspond to a complete or nearly complete amputation of the limb. Following total crushing under a heavy vehicle, this would rather indicate the need to complete the already started amputation or to revise a severe traumatic amputation.

NB: Correct typing of the wound is done after surgical debridement in the operating room.

Muscles: Associated muscle injury (disruption, laceration...) promotes their retraction and leads to joint stiffness.

Blood Vessels: Compression, Contusion, Rupture, Tear.

Nerves: Contusion, Rupture, Tear, Compression.

Joints: Rupture of the joint capsule.

All open fractures are considered contaminated. Open wounds older than 8 hours must be presumed infected. Strict aseptic technique is essential at every stage of handling. Avoid any additional injury to soft tissues, vascular, or nerve structures.

Initial Steps:

- On admission, apply a sterile dressing to prevent further contamination (especially nosocomial).
- Once the patient is stabilized, local care can begin.
- Clip from the margins outward to avoid introducing hair into the wound.
- Create wide margins around the site.
- Perform copious lavage with warm physiological saline or Ringer's lactate to prevent hypothermia, especially in fragile or polytrauma patients.

- Diluted 0.05% chlorhexidine can be added, but copious lavage remains the priority ("the solution to pollution is dilution").
- Remove foreign debris and obviously necrotic tissue.
- Tissue viability is assessed by the rule of the 3 P's: Pink (color), Perfusion (bleeding/perfusion), Palpation (consistency).
- Preserve bone fragments attached to soft tissues; small free fragments can be removed, large fragments are generally preserved.
- Perform orthogonal radiographs (lateral and craniocaudal views) including the joint above and the joint below.
- The presence of subcutaneous air near the fracture site often confirms an open fracture, but its absence does not rule out the diagnosis.
- In cases of major trauma, thoracic (and sometimes abdominal or regional) radiographs are recommended.
- Since all open fractures are contaminated, and those older than 8 hours are presumed infected, broad-spectrum, bactericidal, intravenous antibiotic therapy should be initiated as soon as the IV catheter is placed.
- Fractures of long bones (most commonly femoral fractures) can release fat (yellow marrow) that embolizes to the lungs, causing pulmonary embolism with respiratory complications.

5.7.6 Growth Cartilage Injury

Encountered in young animals, a classification was proposed by Harris and Salter.

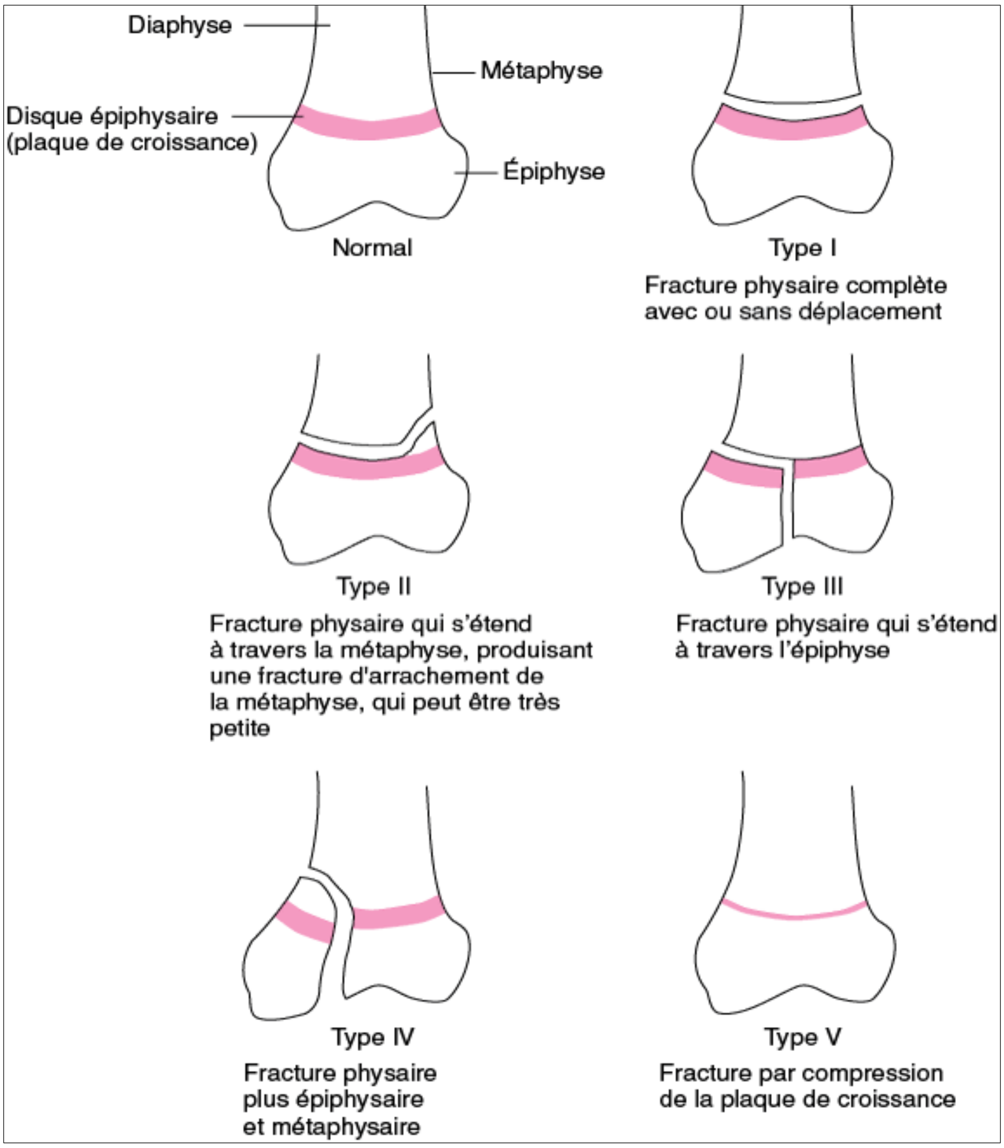


Figure 04: Harris and Salter classification (Russo M et Al 2003)

6. Signs of Fracture

6.1 Functional Signs

Pain is constant since the trauma; it is triggered by limb mobilization. Functional impotence is more or less complete depending on the case.

6.2 Physical Signs

(Examination is performed comparatively with the healthy side). Deformity, edema, ecchymosis (secondary). Pain increases at the fracture site. Abnormal and painful mobility. Possible shortening of the fractured side (compared to the healthy side).

Diagnostic Pitfall: Non-displaced, impacted fracture, with little pain and no clear deformity. This can affect prognosis and complicate treatment (e.g., impacted femoral neck fracture).

7. Main Phases of Bone Healing

7.1 Hematoma and Inflammatory Reaction

Any fracture site is invaded by a hematoma. This hematoma quickly transforms and organizes with the appearance of new vessels from the surrounding healthy tissues. Vascularized fibrous tissue gradually replaces the hematoma. Cell proliferation is already intense 24 hours after the injury. Bone ends are devitalized over several millimeters.

7.2 Proliferation Phase

7.2.1 Connective (Soft) Callus: The fracture site gradually acquires some stability due to the development of this fibrous callus. Mobility decreases; collagen fibers are replaced by mineral salts that are deposited. The fibrovascular tissue undergoes cartilaginous then osseous metaplasia, defining a primary callus. Vascular supply increases oxygen tension, responsible for the transformation of peripheral chondrocytes into osteocytes. Additionally, osteoclasts appear and begin to resorb the devitalized bone ends. Simultaneously, identical activity begins in the medullary region.

7.2.2 Ossification of the Callus (Hard Callus): Bone cells invade the connective callus, and the bony callus begins to appear. There is a periosteal callus that develops peripherally and an endosteal callus that forms in the medullary cavity. The callus models and organizes to form an effective junction between the two fragments, provided the space between them is minimal.

7.2.3 Remodeling Phase: This phase lasts 1 to 4 years. There is peripheral lysis and central densification. Its goal is to adapt the bone segment to mechanical constraints and aims to restore normal morphology.

Stage (Days)	Radiographic Description	Histological Evolution
0 - 5 days	Initial fracture with hemorrhage and soft tissue edema. Formation of a hematoma.	The hematoma provides a temporary framework for healing.
5 - 10 days	The hematoma organizes into a soft (fibrocartilaginous) callus. The fracture line widens. Fracture ends become less distinct. Edema decreases.	Formation of granulation tissue and fibrocartilaginous callus, not visible on X-rays.
10 - 20 days	Mineral deposits from the periosteum and endosteum. The callus begins to mineralize. The fracture line begins to narrow but remains visible. The bony callus does not yet fill the fracture.	The soft callus gradually becomes radiographically visible due to mineral deposits. Active remodeling of bone ends.
20 - 30 days	The fracture line gradually disappears. The bony callus is more homogeneous and fills the fracture site. The callus becomes smoother with better-defined margins.	The callus continues to mineralize, gaining opacity.
40 days (6 weeks)	The fracture line is barely visible or invisible. The bony callus is smaller, better defined, and has opacity close to the original bone.	Advanced bone consolidation.
> 90 days	The bony callus matures and develops trabeculation. The medullary cavity gradually re-establishes. Cortices become clearer. The bone progressively remodels to regain its original shape.	Long-term remodeling phase.

A fracture can be considered radiographically consolidated when the fracture line is no longer visible, the cortex is continuous and uninterrupted, and a bony callus completely bridges the fracture fragments. Removal of fixation devices can be considered when there is radiographic evidence of bridging callus.

8. Causes of Delayed Healing

Different types of factors are distinguished:

- Those related to the animal
- Those related to the fracture
- Those related to the surgical procedure

8.1. Factors Related to the Animal

Two main factors to remember:

- **Osteoporosis:** A degenerative pathology characterized by decalcification, demineralization that weakens the bone trabeculae.
- **Age:** The risk of non-union increases with age.
- Other factors such as anemia, malnutrition, diabetes must be considered.

8.2. Factors Related to the Fracture

- **Location of the fracture:** Healing occurs less well at the diaphyseal level.
- **Degree of comminution (shattering of the bone segment):** The more fragments there are, the less it consolidates.
- **Bone loss** (e.g., open fracture with missing piece).
- **Open fracture:** Contamination with the exterior.
- **Damage to soft tissues** (skin, muscle, periosteum).
- **Associated nerve injury** (fracture + limb paralysis).

8.3 Factors Related to the Surgical Procedure

- **Stability of the fixation** (mobility at the site).
- **Persistence of an inter-fragmentary gap:** If the gap > 5-10 mm, it increases the risk of delayed healing; it is best if it is < 2mm.

There are abnormalities in this consolidation process, such as non-union, which is the absence of consolidation at 6 months, or malunion.

9. Treatment of Fractures

The goal of treatment is to ensure consolidation while maintaining normal morphology (length and axis), preserving the mobility of adjacent joints and the muscle capacity that powers them, while preventing infection. There are two main categories of methods: orthopedic methods and surgical (open) methods, with or without opening the fracture site. Treatment always involves two steps: reduction and immobilization.

9.1. Orthopedic Methods

The basic principle of any closed reduction method is to apply slow, continuous traction on the bone fragment, which can be manipulated to align it with the less maneuverable fragment. It is important that all manipulations are performed while being vigilant about the risks of tearing, perforation, or compression of a major vessel or nerve. Different methods are possible for reducing long bones.

9.1. Indications

- Immobilization of the joints on either side of the fractured bone segment must be possible. Fractured humerus and femur are very poor indications because immobilization of the shoulder and hip is impossible.
- The fracture must be stable after reduction: This is the case for incomplete fractures, or complete simple transverse closed fractures without displacement (except femur and humerus). Orthopedic treatment is contraindicated for splintered, complex, comminuted, beveled, or spiral fractures and fractures at the level of a paired bone segment (radius-ulna, metacarpals, metatarsals).
- Possible for all fractures that do not require anatomical reduction and/or perfect reduction: This excludes articular fractures, which should be treated surgically.
- Skin integrity must be respected: Surgery is required for open fractures.
- Healing duration must be short: One cannot immobilize a dog for 6 months. Caution in young animals regarding fracture disease (bandaging/immobilization) = complete stifle ankylosis -> monitor very closely, checking for muscle retraction. Also, caution with elderly animals.
- The fracture must be recent with no muscle retraction: One can never overcome retraction with orthopedic treatment.
- If the risk of iatrogenic lesions during orthopedic reduction is deemed too high, it is better to opt for osteosynthesis.

9.2. Implementation

General anesthesia is necessary, of course, to ensure analgesia during treatment, but also and especially to achieve the myorelaxation essential for reduction.

Reduction is performed by external manipulation: palpate and try to realign the limb; it is always necessary to suspend the affected limb to realign it by gravity and act by performing extension/counter-extension. Suspending the limb also helps "fatigue" the muscle and thus reduce contraction.

External immobilization (cast, resin, Robert-Jones, etc.) is applied if the reduction is stable. Some rules for their application: immobilize the two adjacent joints, protect underlying tissues, be in a physiological position, check regularly, remove as early as possible.

Caution regarding fracture disease in young animals: the quadriceps retracts (contracture), the dog is unable to flex the stifle. The bandage must be reapplied regularly to stretch the quadriceps (but be careful with the fracture), do not leave for more than 3 weeks. The young heal quickly, but they are also subject to serious complications.

Radiographic control is performed immediately after reduction and immobilization.

Plaster Immobilization: It is practiced less and less because it is a restrictive method and does not guarantee anatomical restitution (lack of perfect stabilization).

- It must always block the joint above and below the fractured diaphysis.
- Plaster promotes the formation of excellent quality bony callus, but prolonged immobilization leads to joint stiffness.

Thomas Splint: Used for treating closed fractures of the metacarpus, radius-ulna, and olecranon, fractures of the tarsus, tibia-fibula, and distal femur for the hind limb.

Orthopedic Surgery (Osteosynthesis)

1. Definition: This is a surgical procedure (open surgery) by which reduction of the bone fragments separated by a fracture is achieved. Care must be taken to avoid converting closed fractures into open fractures (risk of infection + additional trauma).

2. Indications

- Immobilization by a bandage/immobilization device is ineffective: Complete fracture of the femur and humerus, pelvic fracture, certain mandibular fractures.
- Reduction impossible or unstable by external manipulation: Unstable simple fractures, significant displacement, beveled or spiral fractures, multi-splintered fractures, articular fractures, open fractures, old fractures with musculo-tendinous retraction, complicated fractures (non-union, malunion, suppurative osteitis).

3. Basic Rules of Surgery

Perform aseptic surgery (for better healing) with the least possible trauma: this requires perfect knowledge of anatomy and thus surgical approaches. It is important to respect vascularization and muscle insertions, deperiosteze as little as possible, perform careful hemostasis, and limit dead spaces (possible suction drainage).

4. Timing of Intervention

- In the case of a shocked or polytraumatized animal, wait for the restoration of major functions.
- If the animal has thoracic trauma, e.g., hemothorax, pneumothorax... Wait for remission of the problem before intervention (e.g., in case of traumatic myocarditis, postpone anesthesia for 48 to 72 hours).
- In all other cases, intervene as soon as possible: ideally 24 to 48 hours after the trauma.
- If the delay is excessive, there will be difficulties in reduction, increased soft tissue trauma, and interference with the natural processes of bone repair. In a growing animal, fibrous callus forms within 5-6 days; if intervention is delayed, one risks damaging it.

5. Operative Devices

5.1. Anesthetic Protocol: Good quality general anesthesia (analgesia and complete myoresolution).

5.2. Materials:
A "standard" box for soft tissue surgery and a "specific" box for bone surgery are needed.
For bone manipulation and exposure (thus avoiding contamination): bone-holding forceps, bone hooks, Hohmann retractors (to retract soft tissues).
Synthesis materials (implants): nails, pins, plates (mini-plates, T-plates, L-plates), screws (cortical bone, cancellous bone, malleolar, etc.), steel wire, drill, screwdriver.

6. General Techniques

6.1. Approach to the Site

- The fracture is approached according to the general rules of bone surgery.
- Clear incision, large surgical field, incision respecting major vessels, nerves, and large nerve trunks.
- Respect the general structure of muscle and aponeurotic fibers.
- Clean the fracture site with a curette, rinse with physiological saline, remove debris and blood collections.

6.2. Fracture Fixation

6.2.1 Intramedullary Pinning

- It consists of making a hole in the medullary canal; the material is specific: nails, pins, sutures.
- It is done either by a direct or retrograde approach.

- Several types of pinning exist:

A- Simple Intramedullary Pinning:
Stabilization with a single nail. Indications are now reduced to stabilizing oblique fractures on a bone of small diameter. This technique is systematically associated with cerclage wires to prevent rotation.

B- Bundle Intramedullary Pinning:
A variation of the previous one, this technique replaces the single nail with two or more nails of smaller diameter. For the treatment of comminuted fractures, cerclage wires may be associated.

C- Intramedullary Pinning Combined with a Bone Plate:
For greater rigidity, it is possible to add an intramedullary nail to plate stabilization.

6.2.2. Cerclage
Cerclage wires are often used in addition to intramedullary pinning. For ease and safety of tightening, they can be placed with a Loute cerclage wire tightener.

6.2.3. Screws and Plates
The plate is fixed to the bone by at least three screws (6 cortices) on each side of the fracture site. The term "splinting" is sometimes used.

This technique allows early clinical recovery and rapid weight-bearing. Joint mobilization increases circulation, limits edema, promotes bone healing, avoids muscle atrophy and joint ankylosis, as well as immobilization osteoporosis.

Plate osteosynthesis adheres to four principles:

- Anatomical reduction of fracture fragments, especially for articular fractures.
- Stable internal fixation conforming to biomechanical principles.
- Preservation of the vascularization of bone fragments and surrounding soft tissues.
- Early mobilization to avoid fracture disease.

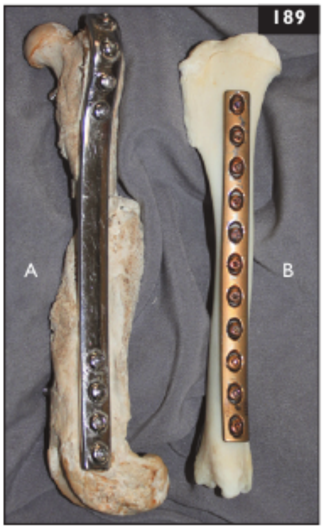


Figure 05: Plates and screws (Lewis D 2015a

A- Indications for Screws and Plates

Indications are virtually unlimited. Plate and screw osteosynthesis can be performed for all types of fractures of long and flat bones (face, scapula, and pelvis) and the axial skeleton (vertebrae).

- **Articular fractures:** This is an absolute indication due to the mandatory anatomical reduction; stabilization can only be perfectly achieved after anatomical reduction and inter-fragmentary compression.
- **Pseudarthrosis (Non-union):** Plates allow compression of the site and very good stability necessary for non-union healing. In this case, it is often combined with a cancellous bone graft.
- **Fractures in poly-fractured animals:** Plate osteosynthesis allows early weight-bearing in cases of fractures of multiple limbs. Prolonged recumbency is thus avoided.

B- Contraindications for Screws and Plates

- **Relative:**
    - Poor general condition of the animal, excessive edema, infected wounds.
    - Financial considerations. This osteosynthesis technique is more expensive than simple intramedullary pinning. However, recovery is early, and there are few or no dressings and post-operative care compared to intramedullary pins and external fixators.
- **Absolute:**
    - Bridging of growth plates by screwing or plate placement must not be performed.
    - Untreated open fractures cannot be treated with plate osteosynthesis.

C- Indications for Screwing
The technique seems simple but requires time, equipment, and skill. The type of screw must be chosen correctly (cortical bone, cancellous bone). Then, the length and diameter must be chosen correctly. One must first drill with a bit appropriate to the screw size; if the screw is inserted directly, there is a risk of breaking the bone.

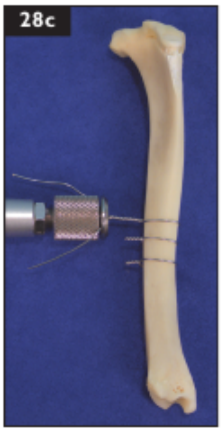


Figure 07: Cerclage technique using a Loute wire tightener (Lewis D 2015b)

Management of Bone Fragments (Spicules):

- Small, vascularized spicule: preserve.
- Small, devascularized spicule: remove.
- Larger spicule, deeply embedded: preserve UNLESS it compromises the stability of the fixation.

In all cases, muscle insertions are respected.
A vascularized spicule actively participates in healing. A devascularized spicule can participate in healing passively by acting as a sort of scaffold. However, caution is needed: if germs develop in the site, a sequestrum may form with a risk of osteomyelitis. Therefore, devascularized spicules are never preserved in the case of an open fracture (thus contaminated).

LATE COMPLICATIONS OF FRACTURES

Multiple factors affect fracture healing, including vascular status, alignment and stability of fragments, and the patient's general health status.

- **Delayed Union:** Slower healing than expected, but the bone eventually heals. Generally considered delayed if bridging callus is not evident within 6 to 8 weeks.

- **Non-union:** Cessation of healing before complete union. Diagnosed after several months without progression. Fracture edges remain sharp and well-defined. Several types exist:
    - **Hypertrophic non-union:** Due to chronic instability. Presence of inactive, organized new bone at the fragment ends, which may become rounded (elephant foot) or interlocking.
    - **Atrophic non-union:** Due to chronic separation of fragments. Absence of callus formation. Fragment ends are thin and tapered (bone resorption). Common in small dogs.
    - **Dystrophic non-union:** Caused by loss of vascularization to one fragment. The affected end remains sharp, well-defined, and pointed. If vascularization is only decreased, the end may be rounded and sclerotic.
- **Malunion:** Fractures that have healed but with abnormal bone geometry (angulation, rotation, shortening). May lead to functional impairment.
- **Sequestrum:** A necrotic bone fragment following loss of vascularization. Appears as a sclerotic, well-defined piece of bone not incorporated into the callus. May be surrounded by a layer of sclerotic bone (involucrum) and associated with a draining tract (cloaca). A complication of osteomyelitis.
- **Synostosis:** Fusion of a bone fragment with an adjacent bone, leading to loss of movement.
- **Joint Stiffness:** Resulting either from prolonged immobilization or from articular fractures.
    - Intra-articular adhesions can develop following hemarthrosis related to an articular fracture. In some cases, bone fragments can act as blocks and limit range of motion.
    - Muscle adhesions can limit movement. For example, adhesion of the quadriceps to a femoral diaphyseal callus can limit knee flexion.
- **Cortical Bone Necrosis:** This complication is seen especially after chronic bone infection, due to vascular disconnection caused by trauma or sepsis.

Amputation Surgery

1. General Information

The subject of "Limb Amputations" pertains to surgical techniques. It is a rigorous technique whose rules and principles must be perfectly understood. This is major surgery that must be fully mastered to achieve the best possible stump. The term stump refers to the distal part of an amputated limb; the bone must be cut shorter than the tissues surrounding the bone. This allows the muscles and skin, among other tissues, to cover the end of the bone.

2. Definition

Amputation is the removal of a body extremity following trauma or a surgical act. In surgery, it serves to limit the incurable spread of serious conditions, for example, gangrene and tumors.

It can be applied preventively to avoid the appearance of other pathologies (e.g., *Blastomyces dermatitidis* synthesizes toxins responsible for degenerative heart and kidney diseases in dogs). And therapeutically for complicated comminuted fractures, chronic complications following previous treatments (osteomyelitis), appendicular neoplasia (osteosarcoma), extensive trauma, chronic non-healing wounds, or peripheral neuropathies (e.g., brachial plexus rupture), severe third-degree burns, localized gangrenous processes (*Clostridium perfringens*).

Certain amputations are necessary due to the owner's financial constraints. However, surgeons are encouraged to exhaust all options before amputating a limb. Unfortunately, causes of amputation of tumoral origin are common; osteosarcomas are the most frequently encountered in dogs and are most often found in the upper part of the femur, with rapid progression and early metastases.

Amputation is the section of a limb through the continuity of a bone, while disarticulation is the section of a limb at a joint.

Figure 08: Necrosis of the forelimb in a bitch (author)

Figure 09: Polyostotic bone tumor of the forearm in a dog (author)

3. Preoperative Care

Preoperative antibiotic therapy, e.g., cefazolin [22 mg/kg IV], should be administered systematically at induction and every 90 minutes during the operation. However, as routine amputations are classified as clean procedures, postoperative antiseptic management should be considered before continuing antibiotics. In most cases, unless there is pyoderma surrounding the incision site, antibiotics are not necessary postoperatively.

Perioperative analgesics are necessary. Additional IV and oral analgesics should be administered during the postoperative period for 10 to 14 days depending on the animal's comfort level. Injectable opioids (e.g., morphine, methadone, fentanyl) can be administered immediately after surgery. NSAIDs, auxiliary analgesics, and anxiolytics are systematically provided for home care.

4. Determining the Amputation Level

- The issue does not arise for traumatic amputation; one must simply remember general principles, notably to preserve as much bone, skin, and limb as possible.
- For tumoral amputation, the rules are also known: one must be far from the tumor, at least 5 cm above, and even more to be truly distant from it.
- For ischemic, diabetic, and even infectious amputations, the amputation level is more difficult to determine. Quite often, the decision on the level is made intraoperatively and depends particularly on the local condition of tissue coloration, muscle bleeding, and infiltration of inflammatory and infectious exudate.

5. Surgical Technique

- Any mode of anesthesia can be used: general anesthesia, spinal anesthesia, and local or locoregional anesthesia via distal nerve block. Use of potent analgesics (opioids if possible).
- Tourniquet and Esmarch bandage: There is a golden rule: one must never exsanguinate the limb in cases of septic amputation or tumoral amputation, to avoid disseminating infection or neoplasia. Unless there are extensive skin lesions on the limb, it is not recommended to place a tourniquet and Esmarch bandage.

6. General Protocol

Phase 1: Skin incision and dissection, allowing exposure of muscle masses, as well as vessels and nerves.

Phase 2: Identification and section of neurovascular branches; veins and arteries are ligated relatively high relative to the amputation level (proximal and distal) and sectioned in the middle; same for nerves after their local anesthesia.

Phase 3: Muscle section and limb resection: to expose and then free the limb.

Phase 4: Muscle and skin sutures: muscles are sutured together in groups of two or three at their ends with absorbable suture, followed by the skin.

6.1. For the Thoracic Limb

6.1.1. Humeral Section

This is the operative method that allows leaving the maximum amount of living tissue in place. The skin incision is made at the level of the distal third of the humerus. The section involves the median, ulnar, and radial nerves. The bone section is made at the proximal third of the humerus.

6.1.2. Humeral Disarticulation

The entire humerus is removed; the excision is therefore wide while leaving the scapula in place to protect the thorax. The incision is made below the level of the joint. The nerves sectioned are the median, musculocutaneous, radial, and axillary.

6.2. The Pelvic Limb

6.2.1. Coxofemoral Disarticulation: Although it allows the highest amputation without bone section, it has the disadvantages of being less aesthetic and no longer providing protection to the male genital organs, unlike the humeral section.

- Lateral and medial skin incision from the stifle fold to the ischial tuberosity, and section of the femoral and sciatic nerves.

6.2.2. Femoral Section: Skin incision (lateral and medial) from the stifle fold to the ischial tuberosity, extending down to the distal third of the thigh. Section of the femoral nerves, section of the femur in its proximal third.

7. Intraoperative Measures

7.1. Regarding the Skin:

Keep as much skin as possible, even that of doubtful viability, to be able to cover the longest possible stump. Any viable skin must be preserved until the final skin closure of the amputation stump.

Handle the skin with minimal trauma, especially the skin that will cover the stump; avoid repeated traction and aggressive instruments.

7.2. Regarding Connective Tissue and Muscles:

Act as for an open fracture; excise all devitalized tissue or tissue destined for necrosis and avoid subcutaneous and muscular undermining.

Keep as much muscle as possible and use them to cover the amputation stump.

7.3. Regarding Vessels and Nerves:

It is preferable to ligate vessels separately, but they can be ligated "in a bundle" during distal amputations like the carpus, provided a double ligature with strong suture is placed.

Nerves must be individualized separately and sectioned as high as possible to avoid their healing into a neuroma (a tumor made up of more or less abnormal nerve fibers).

One should grasp the nerve end with strong forceps, exert downward traction on it, and then section it. A ligature can be placed on the sectioned end.

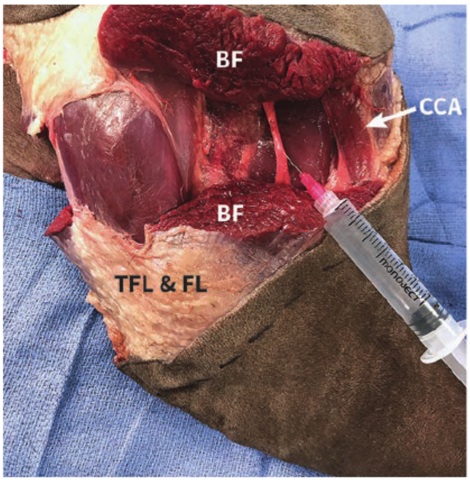


Figure 10: Local anesthetic for perineural injection (Howard J 2021) BF: tensor fasciae latae muscle CCA: caudal crural adductor muscle

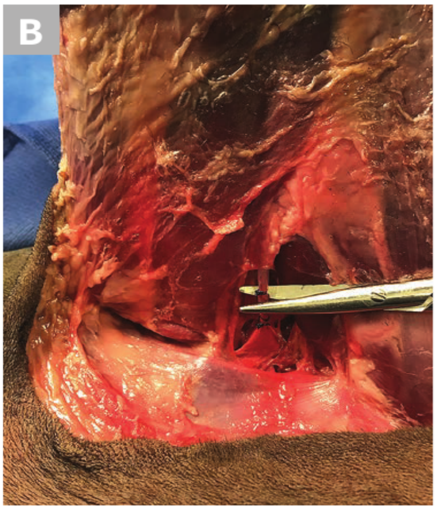


Figure 11: Section of the femoral nerve with scissors (Howard J 2021)

Large arteries and veins should always be ligated with a transfixing suture and 2 circumferential sutures.

7.4. Regarding the Bone:

Bone section is performed either with a Gigli saw, a simple saw, or an oscillating saw (powered saw). The cut bone end must be properly smoothed, filed, ensuring abrasion of bony prominences.

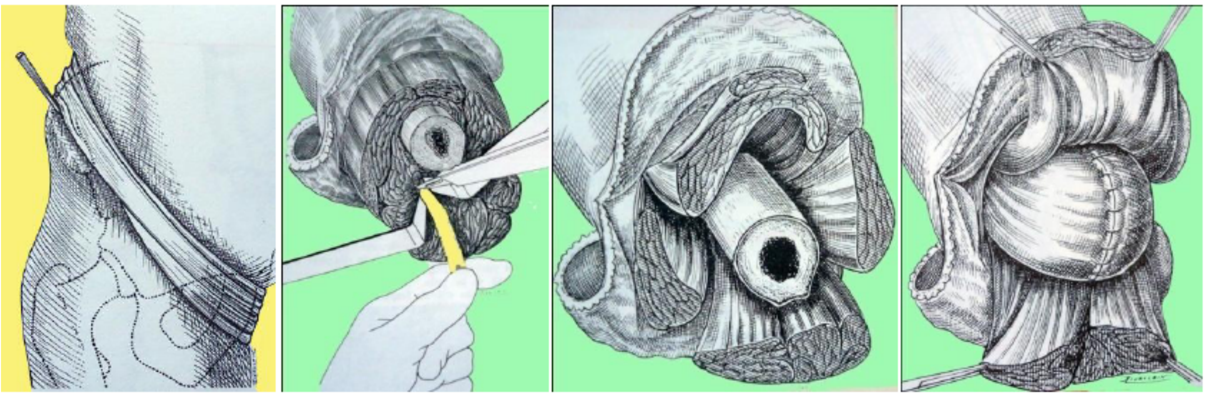
The periosteum is left free without suturing to the bone.

7.5. Regarding Stump Closure:

- Drainage is not mandatory, especially if the tourniquet was released with prior hemostasis control.

- Closure can be direct and involves muscle suture with aponeurosis suture and skin suture. (Suture diameter 4-0 to 3-0).
- In the case of "septic" amputation, closure will only be done with a few approximation stitches or even left open as in gas gangrene.

Placement during thigh amputation or hip disarticulation (a), very high nerve section (b), muscle release for stump (c), and stump closure with muscle padding (myoplasty) (d).



(a) (b) (c) (d)

Figure 12: General principles of amputation (Kihal M 2018)

8. Complications of Amputation Stumps are Numerous

8.1. Skin Problems:

Poor healing is common, mainly related to poor stump closure.
Secondary lesions are also frequent. These include skin erosions with superinfection such as dermatitis or folliculitis and chronic ulcerations.

8.2. Bone Problems:

- The appearance of secondary exostosis at the cut bone end can occur.
- In young animals, resumed growth of the cut bone is possible.
- Osteitis of the cut bone end is also possible.