Fracture Healing
Core Surgery Lectures

Jaydeep K. Moro  MD FRCSC
St. Joseph’s Healthcare

Fracture Events

- Bone’s lamellar and osteonal structures direct crack propagation in certain predetermined directions
- The lamellar junctions and cement lines of bone are weak, and they crack more easily than the bulk of the material

Fracture Events

- These weak interfaces are oriented so that the cracks travel along and around the bone, rather than directly across it
- Energy that would quickly break a bone is used in forming longitudinal or circumferential cracks that do not cause failure and that can be repaired by remodeling

Fracture Events

- Material strength of bone varies on how its loaded
- Strongest in compression
- Weakest in shear
- Intermediate in tensile failure stresses

Fracture Events

- Tensile stresses lie at 45° to the fibres
- Failure occurs by separating fibres, not breaking thru them
- Torsion causes a spiral # pattern usually at a 45° to the shaft

Fracture Events

- Greater the energy → more # fragments
- Energy propagated thru bone as a stress wave (like a sound wave or an earthquake)
- Greater the magnitude of stress wave → more likely many parts of the bone will reach failure criterion simultaneously
- Velocity of stress wave in bone is ~ 3000 m/s!!!
- Energy required to break a bone is small compared to ADLs

Fracture Events

- ~ 15 Joules of energy to break adult tibia or femoral shaft
- Energy released from a 70 kg male falling to the ground from standing is ~ 500 J
- #s from insignificant falls prevented by energy absorption by eccentric muscle contractions & deformations of surrounding soft tissues
- In the elderly, weaknesses in muscles, ligaments & bone lead to ↑ fracture susceptibility with minimal trauma

Fracture Events

- Soft tissue deformation absorbs energy
Loads applied \( \perp \) compress STs & propagate stress waves up & down the body/limb
- Skin, fat, muscle, clothing, (fur on animals)
- STs brace bones against bending by supporting part of the tensile stresses
- Fascia, ligaments, tendons, joint capsules, contracted muscle

9 Fracture Events
- STs absorb energy as they stretch
- Must be as stiff as bone to be effective
- Thus in high energy #s, ST damage parallels bony injury (high degree of comminution)
- Now # healing impaired as bone relies on the damaged STs for this!!!!!!

10

11 3 Phases of Fracture Healing
- Inflammatory
- Reparative
- Remodelling

12 Inflammatory Phase
- Immobilizes the #
- Pain causes patient to protect the injured part
- Hydrostatic swelling splints the #
- Vasodilation & hyperemia at tissue level
  - Histamines, prostaglandins, cytokines
- Invasion by neutrophils, basophils, phagocytes to clean up necrotic debris

13

14 Inflammatory Phase
- # hematoma organizes into a fibrin network \( \rightarrow \) pathways for cell migration

15 Inflammatory Phase
- Release of sequestered bone matrix protein growth factors
  - Regulate cell migration & differentiation
- Peaks < 48 hours
- Quite diminished 1 week after the #

16

17 Reparative Phase
- Activated within 1\(^{st}\) few days after #
- Persists for several months
- Development of reparative callus tissue
  - In & about the # site
  - Gradually transforms into bone
- Callus may consist of cartilage, fibrous tissue, osteoid, woven bone, and
Reparative Phase

18

1° callus response is direct response of bone to local inflammation

- Regardless of cause of inflammation
  - #, infection, foreign body, neoplasm
- Response independent of mechanical factors
- Response does not continue indefinitely
  - If 1° (provisional) callus fails to unite # ends within weeks → may cease to grow & resorb

19

If 1° callus connects # ends → healing progresses to bridging callus or hard callus

- Hard callus differentiates simultaneously throughout (rather than as an advancing front from the # ends)

20

Calcification of callus dependent on local $O_2$ tension

- Direct bone formation by osteoblasts or
- Endochondral ossification
- Growth of large callus greatly outpaces the ingrowing vessels → endochondral ossific'n
- In small, mechanically stable defect (eg. drill hole) → 1° (intramembranous) woven bone formation

21

Cellular components of callus derive from marrow & periosteum

- Number of osteoblasts & osteocytes at time of # insufficient to meet high anabolic demands of growing callus
- 1° source of callus cells
  - Pluripotential mesenchymal cells, fibroblasts, chondroblasts

22

As callus calcifies & becomes rigid → # becomes internally immobilized

- Clinical exam reveals a solid immobile # site
  - Clinical union

23

Remodeling Phase
Initial calcification remodeled by osteoblasts & osteoclasts → replacement of calcified cartilage & woven bone by lamellar bone

This phase is normal remodelling activity of bone

□ May remain accelerated in # region for several years!!!!!! (replacing each volume several times!)

28 Remodeling Phase in Children

■ More vigourous progression

■ Modeling

□ Independent resorption & formation of bone

■ Remodeling

□ Formation coupled to resorption

■ Results in gradual modification of # region

□ Reaches threshold of optimal shape influenced by mechanical loads

□ Bone remolds to original shape prior to the #

■ Can accept greater degrees of displacement & angulation of #s

29 Primary Bone Healing

■ Requires perfect # fragment apposition & rigid fixation

■ Complete suppression of callus response

■ Healing proceeds via normal osteonal bone remodelling

■ No advantage over callus-mediated (2°) bone healing

30 Primary Bone Healing

■ Progresses very slowly in the adult

■ Intermediate stages are weak

■ Does not progress in an anaerobic environment

31 Variables in Fracture Repair

1 Blood supply

□ Age

□ Season

□ Species

□ Type of marrow

2 Temperature

□ Endocrine & autocrine factors

□ Metabolic bone disorders

33 Blood Supply

□ Afferent supply anastomose amongst themselves

□ 1. medullary system from nutrient artery

□ Supplies the diaphysis

□ 2. metaphyseal system

□ Supplies cancellous bone of metaphysis (proximally & distally)

□ 3. anastomoses within medullary system
In children, separate epiphyseal & metaphyseal systems → merge at physeal closure → adult metaphyseal system

Periosteal system

34 Blood Supply

Nature & severity of # affect blood supply to bone

Min displaced # → small vessels in cortical bone disrupted
- Medullary & periosteal vessels may be sufficiently elastic to remain intact
- Medullary system may be 1° source for healing (callus vascularization)

35 Blood Supply

Greater # displacement → medullary system disruption
- Metaphyseal or periosteal vessels may contribute to vascularization of callus
- "4th afferent system"
  - From adjacent STs (muscle)
  - Muscle flaps greatly enhance # healing

36 Blood Supply

Vasodilation & angiogenesis occur rapidly after #
- Dog model: max reached (6X N!) by 10 days
- Persisted for 4 months
- Distant bone blood flow ↑d & peaked @ 1-3 wks
- Blood vessels crossed # line @ 3 weeks

Humans
- Failure of vessels to cross # site by 10 weeks → possible nonunion (osseous phlebography)

37 Delayed Union

Microangiogram of a 6-week-old canine radius fracture
- Tremendous increase in vascularity and the inability of the capillaries to penetrate the fibrocartilage of this hypertrophic delayed union

38 Blood Supply

ORIF with plates & screws may cause periosteal ischaemia directly beneath the plate
- Does not interfere with regional revascularization
- Reamed IM nail obliterates medullary blood supply
- ↑ demand of metaphyseal, periosteal & ST systems
- Fluted nails allow ingrowth of medullary arteries
- Pharmacological manipulation of blood flow
  - Possibly useful for delayed unions, infected #s
  - Not used clinically

39

40 Fluted IM Reamer

41

42 Age


- #s heal much more vigourously in children than adults
- In elderly, # healing may proceed slowly
  - i.e. time to heal may be perceived as delayed union in a much younger patient
- Slow healing not an inherent cellular problem of aging
  - Osteoblasts from trabecular bone grown in culture show similar metabolic characteristics regardless of age

43 Season
- Variation of circulating metabolites of vitamin D in elderly
  - Higher levels in summer (more sun)
- Seasonal incidence of hip #s
  - More in winter months
- No relation to # healing however

44 Species
- Rodents (rats & rabbits) heal #s rapidly
  - Better model for human children than adults

45 Type of Marrow
- At birth, most bones have red (hemopoietic) marrow
- With age → ↑ yellow (fatty) marrow in appendicular skeleton (limbs)
- Adults have red marrow confined to axial skeleton (spine & pelvis), some in proximal femur
- Red marrow highly osteogenic
  - # heal rapidly in adults (ribs, spine, pelvis) vs. tibial shaft (yellow marrow)

46 Temperature
- "Warm bones" heal more rapidly than "cold bones"
  - Axial skeleton – warm (also red marrow!)
  - Appendicular skeleton – cold (yellow marrow!)
- Mouse model
  - Vertebral #s heal more rapidly if kept at higher temperatures

47 Endocrine & Autocrine Factors
- Cortisone
  - Catabolic → ↓ size of # callus
- Growth hormone
  - ↑ callus volume (only if absent normal endogenous GH)
- PTH & Thyroxine
  - ↑ rate of bone remodelling
- Calcitonin & 24,25-(OH)₂-D₃ significantly ↑ for 1st 6 weeks of # repair
  - Effects on # healing not entirely clear

48 Endocrine & Autocrine Factors
- Other unidentified circulating factors
  - Patients with head injuries vigourously heal #s vs. non-CHI patients
Heterotopic ossification with CHI patients
• Serum from these pts stimulate osteoblasts in culture
• Disturbing bone marrow (reaming IM canal) → liberates factors stimulating bone growth & mineral apposition elsewhere in skeleton

49 Metabolic Bone Disorders
• Rickets or osteomalacia
  □ #s heal normally
  □ Resulting bone tissue has mineral deficit
• Osteoporosis
  □ #s heal normally
  □ Remodeled # site is osteoporotic

50 Mechanical Environment
• Strength or stiffness of any structure depends on
  □ Product of a geometric factor and the strength or stiffness of the material within
• If geometric factor made larger
  □ Can use a weaker material for the same strength (eg. large diameter of weak callus)
  □ Weak callus made 2 – 5X faster than lamellar bone
    ■ Therefore needs to be of larger diameter

51 Fracture Callus
52 Bone loaded in bending by a force F
• Cross-sectional moment of inertia (CSMI)
  □ CSMI = π / 4(R^4 - r^4)
• Section modulus = CSMI / R

53 Geometric Properties of Callus
• External callus may easily reach 2x the section modulus of the intact cortex
• Total callus may have 3x this value
• ∴ Callus needs to only be 1/3 – 1/2 strength of normal cortex

54 Mechanical Environment
• Absolute rigidity at a # site
  □ Stress protection of fixation device → bone resorption
  □ Lack of motion → inhibits callus formation
• # healing benefits from controlled axial loading and micromotion
  □ Exactly how much is not known
    ■ Ribs heal with a lot of motion
    ■ Tibial shaft may not

55 Mechanical Environment
• Devices allowing micromotion
  □ IM nails
    ■ Rather than cortical plates
Titanium composition
- Rather than stainless steel
- As a # heals → more load borne by bone & less by the fixation device

57  Electrical Phenomena in #’s
- When bone is mechanically loaded → stress-generated potentials are produced
  - 2 mechanisms
    - 1. Streaming potentials
      - Interstitial fluids forced thru a calcified matrix by dilation of some regions & compression of others
    - 2. Piezoelectric potentials
      - Deformation of collagen molecules

58  Electrical Phenomena in #’s
- There exists a dynamic resting electrical state of bone (complicated!)
- # site become negatively charged
  - this polarization is related to the cascade of biological events that result in repair

59

60

61  Assessment of # Healing
- May progress for several years
- Healing definition
  - when the bone can tolerate the loads normally experienced in every day activities
- Radiologic Union
  - Sign of bridging callus
- Clinical Union
  - Stiffness across # site on clinical examination

62  Biologic Intervention in # Healing
- In last 50 years, focus has been perfecting the mechanical environment
- Future – modifying biologic environment
  - Stimulation of osteogenesis (osteoinduction)
    - Delayed 1° fixation – ORIF 1 week post-# → may reactivate or amplify healing cascade
  - Electrical stimulation
  - Protein growth factors (osteoinduction)
  - Low frequency ultrasound
  - Osteoconduction
    - Variety of commercial “collagen” matrix grafts

63

64  Conclusion
- Dr. Girdlestone – comments 70 years ago
  - Clinical application of biologic agents
  - Shift in orthopaedics from “carpentry” to “gardening”!!!
Thank you!

References

- Chapman’s CD
- Rockwood & Green
- Miller