External Skeletal Fixation in Small Animal Fracture Repair

Russell Yeadon

Vets Now Referrals, Swindon
Sponsor this evening
INTRODUCTION

Fracture planning

• Relies on understanding of different mechanisms of bone healing
• Prediction of predominant mode of bone healing for any given fracture determines:
  – rate of bone healing
  – degree of stability required
• Management plan can then be determined
Why use an ESF?
Plan

• Quick review of bone biology
  – Direct healing
  – Indirect healing

• External Skeletal Fixation
  – Major types, configurations and mechanics
  – Application techniques

• Examples of different applications
Bone biology

- Normal
- Transverse
- Oblique
- Spiral
- Comminuted
- Segmental
- Avulsed
- Impacted
- Torus
- Greenstick
Stages of fracture healing

Inflammation → Repair → Remodeling
Mechanisms of bone formation

3 main types of bone formation – different involvement in different types of bone healing:

1. Cutting cones
2. Intramembranous bone formation
3. Endochondral bone formation
1. Cutting cones

- Cutting cones traverse fracture site
- Primarily a mechanism to remodel bone
- Osteoclasts at the front of the cutting cone remove bone
- Trailing osteoblasts lay down new bone
- Re-establish Haversian system
Haversian System

- Osteon with central Haversian canal containing
  - cells
  - vessels
  - nerves
- Volkmann’s canal
  - connects osteons
2. Intramembranous (periosteal) bone formation

- Mechanism by which long bone grows in width
- Osteoblasts differentiate directly from pre-osteoblasts (periosteum and endosteum) and lay down seams of osteoid
- Does NOT involve cartilage precursor / matrix
3. Endochondral bone formation

- Mechanism by which long bone grows in **length**
- Osteoblasts line a cartilage precursor
- Chondrocytes hypertrophy, degenerate and calcify (low oxygen tension)
- Vascular invasion of cartilage occurs followed by ossification (increasing oxygen tension)
Bone healing

- 2 main subtypes, each with different involvement of the 3 bone formation methods

Primary (direct) healing

Secondary (indirect) healing
Primary (direct) bone healing

Orthopaedic carpentry
Primary (direct) bone healing

• Two subtypes
  A. Contact healing  
    (no gap)
  B. Gap healing  
    (<200-500μm gap)

• Both require absolute stability (<2% inter-fragmentary strain)
Definition

• Inter-fragmentary strain
  – Defined as the % deformation of the fracture gap

\[ \text{Strain (\( \varepsilon \))} = \left[ \frac{\text{Distance of deformation}}{\text{original fracture gap}} \right] \times 100 \]
A. Contact healing

- Bone ends in direct contact
- Re-establishes cortical **lamellar** bone structure
  - Cutting cones cross fracture line
  - Leave osteon “ pegs” crossing fracture line
  - Haversian system re-established
- Resorption and formation occur simultaneously
  - rate ~50μm per day
  - slow process (months-years)
- Begins immediately when local conditions appropriate (contact and stability)
B. Gap healing

- Fracture gap <200-500µm
- Gap fills with haematoma / loose connective tissue
- <2 weeks after fracture, vascular supply re-established
- Gap fills directly with woven bone
  - intramembranous ossification – direct recruitment / differentiation of osteoblasts
  - i.e. no cartilaginous anlage
- Woven bone gradually \(\rightarrow\) lamellar bone by cutting cones (remodelling)
Traditional AO principles

1. Rigid internal fixation
2. Accurate anatomic reduction
3. Atraumatic operative technique
4. Early mobilization

- Aimed at maximizing primary bone healing
- Permits load sharing between implants and reconstructed bone column
AO1. Rigid internal fixation

- Most fractures that have full open reduction should have rigid internal fixation
AO2. Anatomic reduction

- Important in articular fractures
- Avoid callus formation
AO3. Atraumatic operative technique

- Necessary for successful management of all fractures (and surgery in general)
- Halsted’s principles
  a) gentle handling of tissue
  b) aseptic technique
  c) sharp anatomic dissection of tissue
  d) careful hemostasis
  e) obliteration of dead space
  f) avoidance of tension
Limitations to direct bone healing

• Requires minimal / no fracture gap
  – Accurate reduction ± compression

• Requires absolute stability (<2% strain)
  – Rigid fixation (internal)

• Slow to achieve maximum strength
  – Durable fixation
  – Susceptible to failure for many months
  – Problematic if implant removal required
Is accurate anatomical reconstruction possible here?
Is bulky internal fixation desirable here?
Anatomic reduction

• Not necessary for all long bone fracture repair
• Cost/benefit ratio of reconstructing all the fragments
• Must preserve the neuro-vascular supply to bone and surrounding soft tissue
Anatomic reduction

• Load sharing between reconstructed bone column and implants
Indirect bone healing
Orthopaedic gardening
Indirect healing

1. Inflammation

- Haematoma
- Inflammatory cells cleanse fracture site of necrotic debris, bacteria, etc
- Vascular thrombosis $\rightarrow$ bony necrosis at edges of fracture
  - Increases fracture gap $\rightarrow$ decreases relative strain...
- Increased capillary permeability
- Release of inflammatory, angiogenic and osteoinductive factors
- Early granulation
Indirect healing

2. Soft callus formation

- **Endochondral ossification** when inter-fragmentary strain <10%
  - Chondrocytes $\rightarrow$ type II collagen matrix (cartilage callus)
- **Intramembranous ossification** (periosteal callus)
- Soft callus starts to stabilise fracture,
  - ↑ instability $\rightarrow$ bigger callus
Indirect bone healing

3. Hard callus

- **Endochondral ossification** progresses as inter-fragmentary strain reduced to ~2%
  - cartilage callus converts to woven bone
- **Intramembranous ossification** progresses throughout periosteal callus
Indirect bone healing

4. Remodelling

• Cutting cones cross fracture site
  – remodel woven bone callus
  – re-establish lamellar bone cortices
• Intramedullary canal re-established
• Responds to Wolff’s law (remodels in response to mechanical stimuli)
Biologic fracture management

- Atraumatic surgical technique top priority
- Preserve vitality of bones and soft tissue
  - Neurovascular supply
  - Periosteum
  - Endosteum
- Preserve fracture haematoma
  - chemical mediators
  - early soft callus
Many inflammatory, angiogenic and osteoinductive factors expressed early in healing process.

<table>
<thead>
<tr>
<th>Member of the TGF-β superfamily</th>
<th>Time of expression</th>
<th>Specific responses in vivo and in vitro</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDF-8</td>
<td>Restricted to day 1(^{20})</td>
<td>Potential function as a negative regulator of skeletal muscle growth(^{20})</td>
</tr>
<tr>
<td>BMP-2</td>
<td>Days 1–21(^{10,20}) (the earliest gene to be induced and second elevation during osteogenesis)</td>
<td>Recruitment of mesenchymal cells</td>
</tr>
<tr>
<td>BMP-3, -8</td>
<td>Days 14–21(^{20}) (restricted expression during osteogenesis)</td>
<td>Temporal data suggest a role in the regulation of osteogenesis</td>
</tr>
<tr>
<td>BMP-4</td>
<td>Days 14–21(^{20})</td>
<td>Involvement in the formation of callus at a very early stage in the healing process</td>
</tr>
<tr>
<td>BMP-7</td>
<td>Days 14–21(^{20})</td>
<td>In vitro: BMP-3 and -4 stimulate the migration of human blood monocytes(^{63})</td>
</tr>
<tr>
<td>GDF-10, BMP-5, -6</td>
<td>Days 3–21(^{20})</td>
<td>Regulatory role in both types of ossification</td>
</tr>
<tr>
<td>GDF-5, 1</td>
<td>Day 7 (maximal) to day 14(^{20}) (restricted expression during chondrogenic phase)</td>
<td>In vitro: stimulation of relative mature osteoblasts(^{19})</td>
</tr>
<tr>
<td>GDF-3, GDF-6, 9</td>
<td>No detectable levels within the fracture callus(^{20})</td>
<td>Regulatory role in both types of ossification</td>
</tr>
<tr>
<td>TGF-β1, -β2, -β3</td>
<td>Days 1–21(^{20})</td>
<td>GDF-5 an exclusive involvement in chondrogenesis is suggested</td>
</tr>
<tr>
<td></td>
<td>Days 3–14(^{20})</td>
<td>Stimulation of mesenchymal aggregation and induction of angiogenesis through chemotaxis of endothelial cells and degradation of matrix proteins</td>
</tr>
<tr>
<td></td>
<td>Days 3–21(^{20})</td>
<td>GDF-6 may be expressed only in articular cartilage(^{20}) and with GDF-5, 7 more efficiently induce cartilage and tendon-like structures in vivo(^{28})</td>
</tr>
</tbody>
</table>

\(^{9}\) see: Transient increased expression in the surrounding soft tissues from day 6 to day 9

\(^{10}\) see: Through out fracture healing

\(^{19}\) see: Regulatory role in both types of ossification

\(^{20}\) see: Stimulation of mesenchymal aggregation and induction of angiogenesis through chemotaxis of endothelial cells and degradation of matrix proteins
Biologic fracture management

AO principles
• Rigid internal fixation
• Accurate anatomic reduction
• Atraumatic operative technique
• Early mobilization

Biologic principles
• Adequate fixation
• Accurate bone axial / length orientation
• Atraumatic operative technique
• Early mobilization

• Not new concept
• Reprioritizes AO principles
Biologic fracture management

• Optimise secondary (indirect) bone healing
  – Requires less rigid stabilisation
    • Callus development → additional stabilisation
  – No load sharing by bone column initially – need strong stabilisation
  – BUT faster than primary (direct) healing so need less durable stabilisation
Biologic fracture management

- Interlocking nail
- Plate / screws (bridging plate)
Biologic fracture management

- ESF
- ESF + IM pin
Fracture forces – a reminder

- Tension
- Axial compression
- Rotation
- Bending
EXTERNAL SKELETAL FIXATION

An Introduction
Plan

• Quick review of bone biology
  – Direct healing
  – Indirect healing

• External Skeletal Fixation
  – Major types, configurations and mechanics
  – Application techniques

• Examples of different applications
• Transcutaneous fixation pins inserted into bone
  – connected by external rods, bars, or columns
Advantages of ESF

• Rigidity versatile depending on construct
• No implants at fracture site
• Applied closed or through minimal approach
  – no disturbance of soft tissues
• Versatile construction for varying anatomy / fracture configuration
• Can be combined with other fixation methods
• No residual implants (removed at fracture union)
Types of ESF

- Linear
- Ring
- Acrylic / freeform
- [Pinless]
Linear ESF
ESF Components

- Fixation pins/wires
- Connecting bars/rods
- Connecting clamps
- Special components
Fixation pins / wires

- Smooth
- Threaded
  - End
  - Central
  - Positive profile
  - Negative profile
- Half pin
- Full pin
- Wires
- ALL penetrate BOTH cortices of the bone
Connecting bars

- Stainless steel
- Aluminum
- Titanium
- Carbon fiber
Clamps

• Single
  – Pin to rod
• Double
  – Rod to rod
• Acrylic / resin boluses

Kirschner-Ehmer

Imex SK

Securos

Meynard

Synthes
IMEX SK External Fixation System

- Accepts varied fixation pin diameter (including positive profile pins)
- Can be assembled and disassembled independent of frame construct
Type I

Type 1A
• Unilateral uniplanar

Type 1B
• Unilateral biplanar

Least rigid frame types
Type II

- Bilateral uniplanar
- Full pins
- May include additional half pins
- Limited to use below elbow / stifle
- More rigid than type 1
Type III

- Bilateral biplanar
- I + II = III
- Most rigid linear frame
Increasing ESF rigidity

- Type III: 182 kg
- Type II: 140 kg
- Type Ib: 66 kg
- Type I (double connecting bar): 45 kg
- Type I: 25 kg

LOAD 1 cm-10 kg

DEFLECTION .21 CM/CM
Increasing ESF rigidity

- Double bar / clamp
- Increase pin / bar diameter
  - Aim for 20-25% bone diameter for fixation pin
- Reduce bone-bar distance
- Pin distribution
  - >1cm from fracture site
  - Even spread across proximal and distal fragments
- Number of pins (up to 4 per fragment)
Increasing ESF rigidity

- Tie-in IM Pin
Increasing ESF rigidity

• Application of “struts” to join frame components
Special components
Fixation Pins

• Weakest link is the bone-pin interface
Fixation Pins: Design

Positive Profile Pins

• Superior stiffness and axial extraction characteristics (site dependent)
• Pre-drill (0.1mm < pin core diameter)
• Low insertion speed (<150rpm)
Fixation Pins: Design

Negative Profile Pins:
- **Ellis Pins**
- Thread-shaft interface is stress riser
- Stress riser effect mitigated if interface is positioned in medullary canal

Partially threaded Steinmann pin
Ellis pin
Fixation Pins: Design

Tapered thread run-out pins (IMEX “Duraface”)
• 55% stiffer than equivalent diameter +ve profile pins
Fixation Pins: Application

- Pre-drilling pilot hole →
  - ↓ mechanical damage
  - ↓ heat generation

Ring sequestrum

Bone necrosis occurs @ 56° for 10 secs
DRILL BIT

Twist channel in drill bit ➔ escape of debris while drilling ➔ minimizing frictional heat – **high RPM**

FIXATION PIN

No escape channel for debris – **low RPM**
Fixation Pins: Application

- Fixation pin < 30% bone diameter
- Beveled tip of half pins should completely penetrate far cortex
Fixation Pins: Application

- Small / stab incisions
- Not through traumatic / surgical wounds
- Space pins appropriately
- Distance bars / clamps from skin
  - Post-op swelling
  - Joint movement (esp elbow and hock)
- “Safe corridors”
  - Neurovascular bundles
  - Large muscle masses
Circular / ring ESF
Gavriil A Ilizarov, MD

- Graduated from medical school in 1944
- Staff surgeon at Hospital for War Invalids, Western Siberia
- Faced with consequences (nonunion fractures, bone defects and osteomyelitis) of WWII
cESF

- Lack of facilities, equipment and antibiotics
cESF

- Ilizarov Method revolutionized
  - limb lengthening
  - deformity correction
  - bone transport
  - soft tissue expansion
  - cranio-facial reconstruction
  - fracture management
cESF

- Small diameter fixation wires
- One wire either side of each ring
- Wires tensioned to improve stiffness (depending on ring / patient size)
Fixation Elements: Wires

• 1.6 and 1.0mm diameter wires
• Single lip cutting point
• Stopper or olive wires
Wire placement

• Minimal soft tissue penetration
• Perpendicular wire placement
• Wires flat against rings
  – Above
  – Below
  – Washer spacers / bolts / posts
• Wire tensioning
Supporting Elements: Rings

• High strength tempered aluminum alloy
• Full, 5/8, 1/3 ring arches
• Assorted other shapes
Supporting Elements: Rings

Ring diameter is single most important variable affecting biomechanics of cESF

- Selection based on patient dimensions
- Minimum ring diameter
  - Must leave 1-2cm clearance between soft tissues & rings
Connecting Elements

- Linear motors
- Threaded rods
Assembly Elements

• Fixation bolts
• Washers
• Hinges
cESF advantages

• Small fragment stabilisation
  – Juxta-articular fractures
• Versatile
• Self-dynamising
  – Controlled axial micromotion
  – Excellent resistance to bending and rotation forces
• Minimal soft tissue disruption
  – Especially if applied closed
Fracture Management

Rigid
Micromotion

AXIAL MICROMOVEMENT AND TIBIAL FRACTURES

Micromovement mode (n=38)
Rigid mode (n=35)

Log Stiffness (Nm degree)

Weeks After Fracture 13.4 18.1
cESF application

- “Far-near-near-far” fixation
- Two ring blocks separated by linear motors
Post-op management

• Minimize skin-pin movement
• Prevent self-trauma from wire tips / sharp ends
• Radiography <q6-8 weeks
• Periodic checking apparatus tightness
Distraction osteogenesis

- Law of Tension Stress
  - slow steady tension stimulates cellular proliferation
  - terminates when cells occupy their genetic space constraints
- Abbott 1939
- Ilizarov 1954
Distraction osteogenesis

- Intramembranous bone formation
- Endochondral bone formation

Similarities with fracture healing & embryonic bone development
Distraction osteogenesis
Bone transport

- Large bone defects
- Segment of bone is transported
  - regenerate bone forms in its wake
Hybrid ESF
Hybrid ESF

• Combines circular and linear components
• Uses threaded pins & transfixation wires
Hybrid ESF

Advantages:
• Quicker / simpler to apply
• Increased versatility
• Anatomical sites where full rings impractical
  – Femur
  – Humerus
  – Near joints

Disadvantage:
• Lose some benefits of axial micromotion from cESF (depending on construct)
Linear-Circular Hybrid Constructs

1A

1B

i/m pin tie-in
hESF application
Acrylic / freeform ESF
Acrylic / epoxy resin ESF

Mix PMMA powder / solvent – fill tubing in semi-liquid phase prior to curing
Acrylic ESF: Advantages

- Pins any diameter
- Pins in almost any orientation
- Largely radiolucent
- Minimal distance between connecting column and bone
- Lightweight
- Limited inventory
- Cheap
Acrylic ESF: Disadvantages

- Difficult to maintain reduction if used for primary fixation
- Heat during polymerization (curing)
- Fumes are noxious, toxic and teratogenic
- Difficult to make adjustments
- Technical errors (bubbles, gaps, etc.)
“Pinless” ESF
Extreme biologic ESF

- Pinless ESF – does not penetrate periosteum – minimal vascular compromise or potential for tracking infection
- Current system (Synthes) too large for small animal applications
- [Reported for mandibular fractures of cattle]
ESF application and management

A few key points
Carpentry vs gardening
ESF Application

• Hanging limb prep?
• Fluoroscopy?
• Proximal and distal pins inserted first to re-establish limb axis and length
Destabilization

• 6w typically recommended
• Better to remove frame components than fixation pins

• Destabilization <4 weeks:
  – ↑ callus, ↓ mechanical strength

• Destabilization at 6 weeks:
  – no ↑ callus, but ↑ mechanical strength

• Destabilization at 12 weeks:
  – no ↑ callus or mechanical strength
Aftercare

- Bandaging
- Cleaning???
- Antibiotics???
Pin tract discharge

- Bone resorption
- Pin loosening
- Soft tissue liquefaction
- Local bacterial infection
Case selection

• Will fracture healing occur before the ESF fails?
  – All ESFs will have some complication if left in situ long enough
  – Fracture biology
  – Patient signalment

• Is ESF mechanically appropriate?

• Additional considerations (owner factors, lifestyle, fixator management, personal experience / preference)

Internal fixation often more appropriate
How do we choose ESF configuration?

• BIOMECHANICS and BIOLOGY
• Fracture type, location, configuration
• Patient age, weight, and activity
• Other injuries
• Surgeon skill, experience, and equipment
Plan

• Quick review of bone biology
  – Direct healing
  – Indirect healing
• External Skeletal Fixation
  – Major types, configurations and mechanics
  – Application techniques
• Examples of different applications
Long bone fractures
Comminuted humeral fracture - ESF
Radius / ulna
Radius / ulna
Femur
Femur
Tibia
Tibia
Tibia
Tibia
Other fracture applications
Mandibular fractures
Tarso-metatarsal luxation
(Plantar ligament intact)
Tarso-metatarsal luxation
Tarso-metatarsal luxation
Tarso-metatarsal luxation
MT/MC Fractures
MT/MC Fractures
Surgical technique

• Dorsal approach
• K-wires directed retrograde through the fracture/luxation
  – exit MT bones at dorsal aspect of distal articular surfaces
  – driven distally until pin tip barely visible at fracture site
• Fractures/luxations reduced
• K-wires driven proximally into the MT
  – up to or through the TMT joints
Surgical technique

• One or two pins placed transversely across bases of the MT or distal row of tarsal bones

• Pin ends contoured over dorsal MT

• Epoxy resin compressed over ends of K-wires to anchor frame
  – wooden tongue depressors used to space bolus away from skin
    • allow for post operative swelling
    • prevent thermal injury during curing
Pelvic ESF
Pelvic ESF

“No other type of fracture lends itself to iatrogenic trauma with so little to show for surgical interference as does the fractured pelvis” (Whittick, 1974)

“With a little thought, patience and practice, the KE splint may successfully be used for the repair of pelvic fractures” (Knowles, 1949)
How does ESF management of pelvic fractures compare to conventional plate/screws?

- Mechanical Factors
  Application of EF to ilial fracture is superior to plate/screws in terms of yield and failure and is of comparable stiffness.
Hip luxation

- Coxo-femoral luxation: customized hinge units mounted from frame → pin driven into the proximal femur
Spinal application
Non-fracture applications
Hock instability
Stifle Disruption
Stifle Disruption
Limb deformity management
Can get complicated...
Pedal Arch Wire Scaffold (PAWS)
Neurogenic injury subsequent to sensory neuropathy (trophic ulceration)
PAWS used to protect foot during renervation
Take home messages - ESF

- Choice of fixation technique based on understanding of specific fracture biology and mechanics
  - Careful case selection
  - Preservation of biologic potential essential
- Extremely versatile
- Familiarity with range of implants / ESF systems (and respective properties) important
Questions