Ballistic Orthopaedic Injuries

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Objectives

- **Understand Ballistics**
- **Differentiate High-velocity and Low-velocity Injuries**
- **Understand Management Principles**
- **Understand Operative Indications**
- **Examine Controversies and Future Directions**

Ballistic Orthopedic Injuries

- **Greater than 81,000 non-fatal firearm injuries per year in US**
  - **Data: CDC 2017**

- **There are 223+ Million firearms in the United States**
  - **77+ Million Handguns**
  - **66+ Million Shotguns**
  - **76+ Million Rifles**
  - **3+ Million Assault-type weapons**

WISQARS Database.
www.cdc.gov/wisqars/facts.html

Ballistic Orthopedic Injuries

- **Often associated with orthopedic complications**
  - **Fracture**
  - **Compartment syndrome**
  - **Nerve injury**
  - **Vascular injury**
  - **Infection**
  - **Soft tissue damage**
  - **Lead toxicity**

Understanding Ballistics - Wounding Potential

- **Damage comes from energy transfer from ballistic object to tissues**

$$\textbf{Bullet Kinetic Energy} = \frac{mass\ x\ velocity^2}{2}$$

Wounding Potential

- **2 ways to increase wound potential of a weapon**
  1. **Give the bullet more energy**
  2. **Improve the efficiency of energy transfer**

Wounding Potential - Ballistics and Tissue Damage

- **Increasing bullet mass -> Linear increase in energy -> Greater Tissue Damage**
- **Increasing bullet velocity -> Exponential increase in energy -> GREATER TISSUE DAMAGE**
- ***Velocity has bigger impact on energy than mass***

Wounding Potential - Ballistics Terminology

- **Muzzle Velocity = Velocity of the bullet as it exits the weapon**
  - **Determined by amount of gun powder and length of barrel**

- **Ballistic Coefficient = Effect of air resistance on the bullet's velocity**
  - **Determined by the bullet's shape**

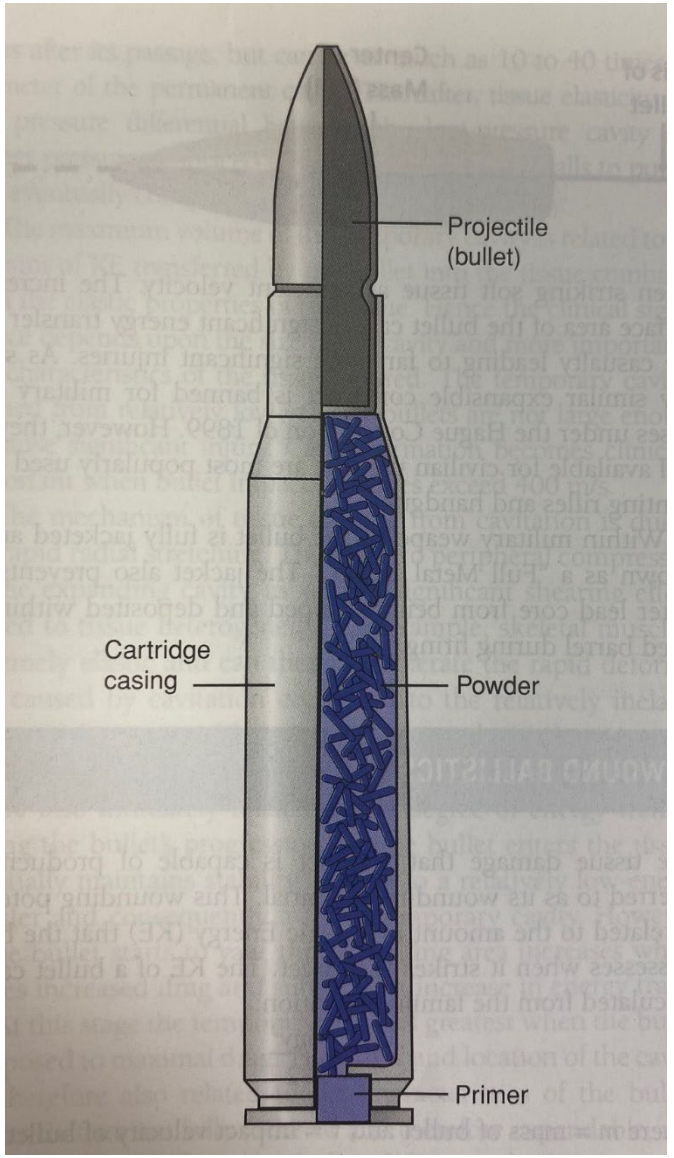
Wounding Potential - Velocity

- **Firearms are best described as High or Low Velocity**
  - **Way of describing their wounding potential**

- ***High Velocity* = Muzzle velocities usually > 2000 ft/s (600 m/s)**
- ***Low Velocity* = Muzzle velocities usually < 2000 ft/s (600 m/s)**

Getting Bullets Up to Speed

- **Pulling trigger releases firing pin which strikes primer**
- **Primer ignites powder**
- **Gas and heat in confined tube produces pressure to eject bullet**
- **The longer the gun barrel, the more time gas and heat have to accelerate the bullet**



Ramasamy, McMenemy, Stinner, Clasper. Gunshot and Wartime Injuries. In. Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA Wolters Kluwer Health, Inc; 2019. Figure 14-11

Examples of High and Low Velocity Weapons

HIGH VELOCITY

M16 Rifle
(2970 ft/s)

Remington Model 700
(2650 ft/s)

XVR 0.460 Magnum
(2660 ft/s)

LOW VELOCITY

.22 Long Rifle
(1070 ft/s)

Glock Gen 5 G17
(1230 ft/s)

Remington 870 Shotgun
(1550 ft/s)

Wounding Potential - Kinetic Energy Comparison

Low-Velocity Firearms

Weapon	Bullet Weight (g)	Velocity (ft/s)	Velocity (m/s)	Kinetic Energy (ft-lb)
0.22 Long Rifle	2.6	1200	663	128
0.38 Pistol	6.2	880	268	163
0.45 Pistol	14.9	850	259	369

High-Velocity Firearms

Weapon	Bullet Weight (g)	Velocity (ft/s)	Velocity (m/s)	Kinetic Energy (ft-lb)
0.22 Savage	4.5	2750	838	1175
30/06 Springfield	9.7	2750	838	2519
5.56-mm M-16	3.6	3250	991	1290

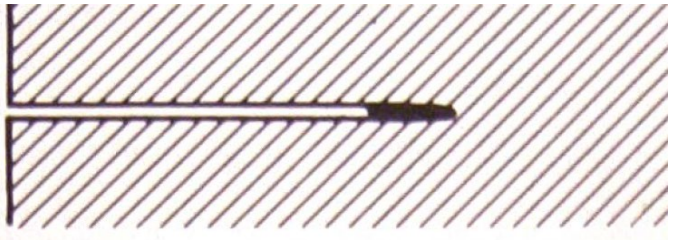
Wounding Potential - Caliber

- **Bullet caliber describes its diameter**
- **Indirectly suggests amount of lead (mass)**
- **“0.22” fires a 0.223 in. diameter bullet**
- **“9mm handgun” fires a 9mm diameter bullet = same as a “0.38”**
  - **Most popular handgun round in US**

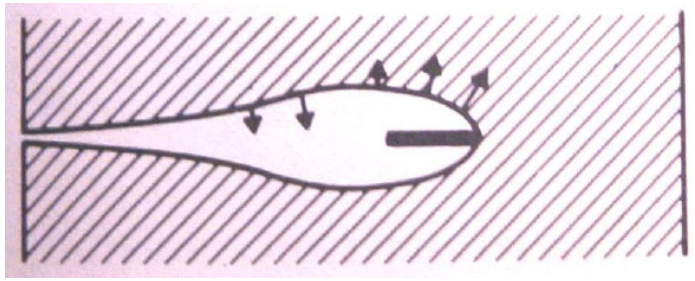
www.parentsagainstgunviolence.com

Wounding Potential: Deformation and Tumbling

- **Bullets create wounds by**
  1. **Creating a permanent cavity by directly cutting thru tissues**
     - **Same wound that would be produced by a spear or arrow head of the same diameter**



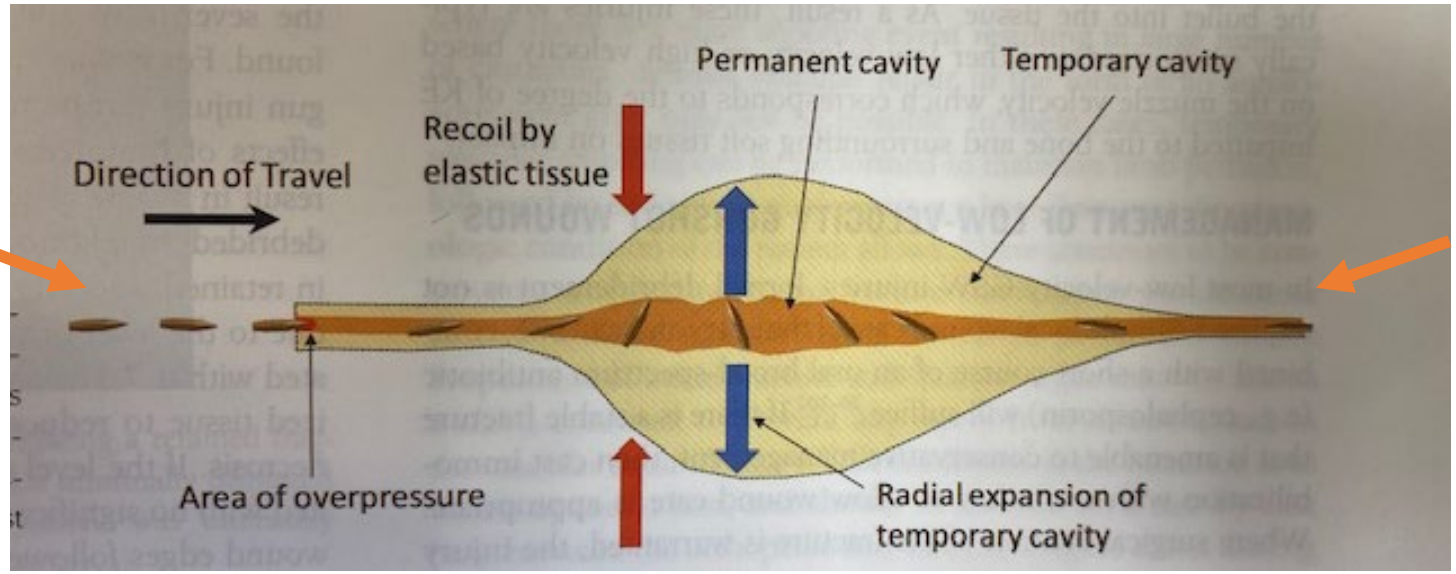
  2. **Creating a temporary cavity or "cavitation"**
     - **Created by turbulent flow in wake of bullet**
     - **Increased by fragmentation, tumbling, or deforming the bullet**



Wounding Potential: Deformation and Tumbling

- **Ways to increase energy transfer to tissues**
  - **Increase velocity of bullets**
  - **Make bullets easy to deform, tumble, or fragment**

Conical shape of bullet during flight decreases effect of drag to maintain muzzle velocity



Deformation, fragmentation, and tumbling in tissues increases energy transfer before bullet exit

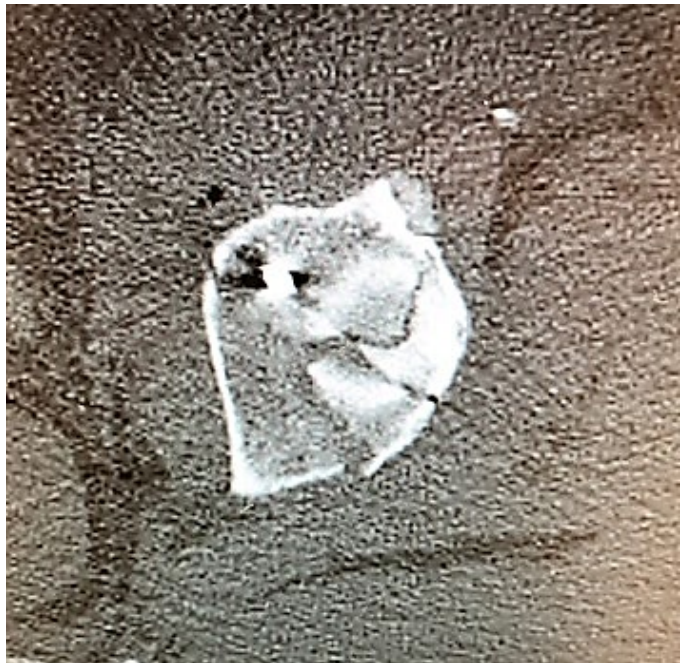
Ramasamy, McMenemy, Stinner, Clasper. Gunshot and Wartime Injuries. In. Tornetta P, Ricci WM, eds. Rockwood and Green's Fractures in Adults, 9e. Philadelphia, PA Wolters Kluwer Health, Inc; 2019. Figure 14-14.

Wounding Potential - Cavitation

- **Path of destruction larger than the bullet profile**
- **Temporary cavity collapses and reforms repeatedly with diminishing amplitude**
- **Greater tissue damage to inelastic structures**
- **This means vessels and nerves never in contact with direct path of bullet can be injured**

Wounding Potential - “Hollow Point”

- **Also called “Soft Point”**
- **Designed to expand surface area on contact**



Intraarticular ballistic “hollow point” round demonstrates “expansion” following impact after removal

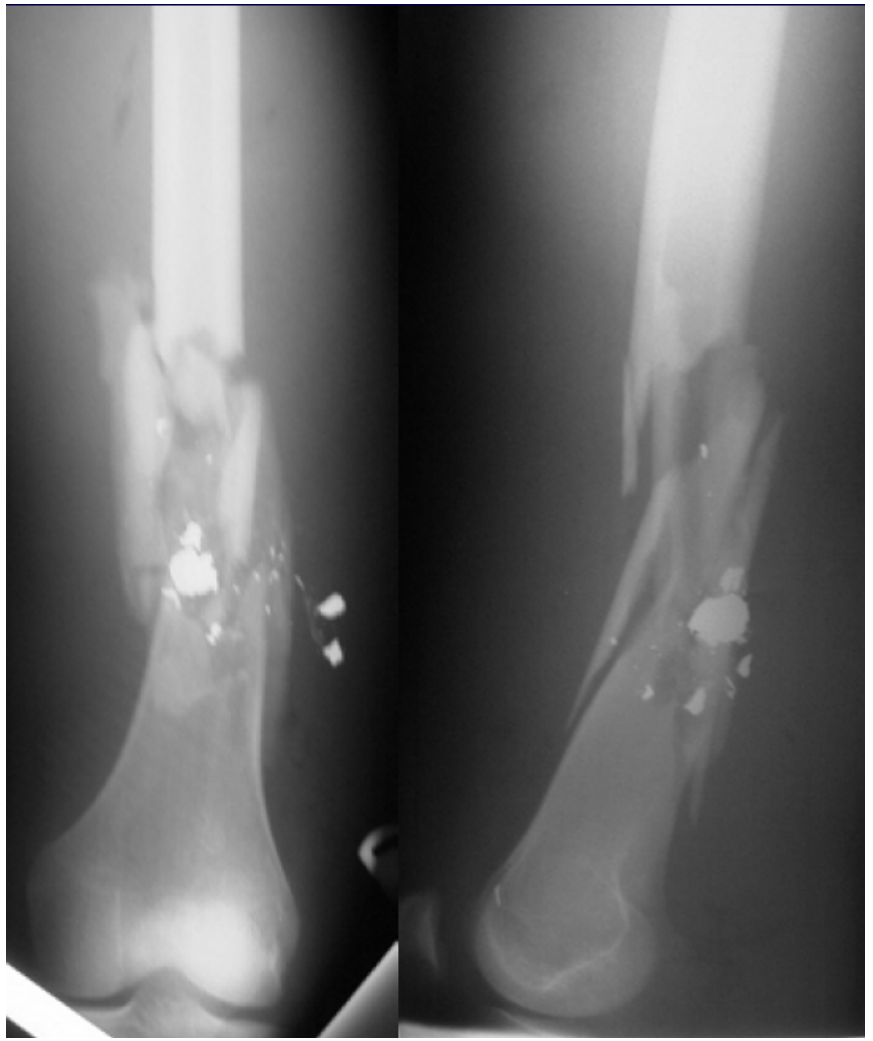
Wounding Potential - Slowing Bullets Down

- **Bullets that do not deform, fragment or tumble during path through tissues will create less damage**

- **Increasing the surface area "presented" to tissues during travel increases energy transfer from bullet to tissues**

Wounding Potential - Ballistics Effect on Tissues

- Skin and Muscle
  - Relatively elastic – tolerate stretching effect of cavitation
- Bone
  - Exerts significant retarding effect on projectiles
  - Results in considerable energy transfer
    - Extensive fragmentation/deformation of projectiles
    - Comminution
    - Bone fragments can become secondary missiles

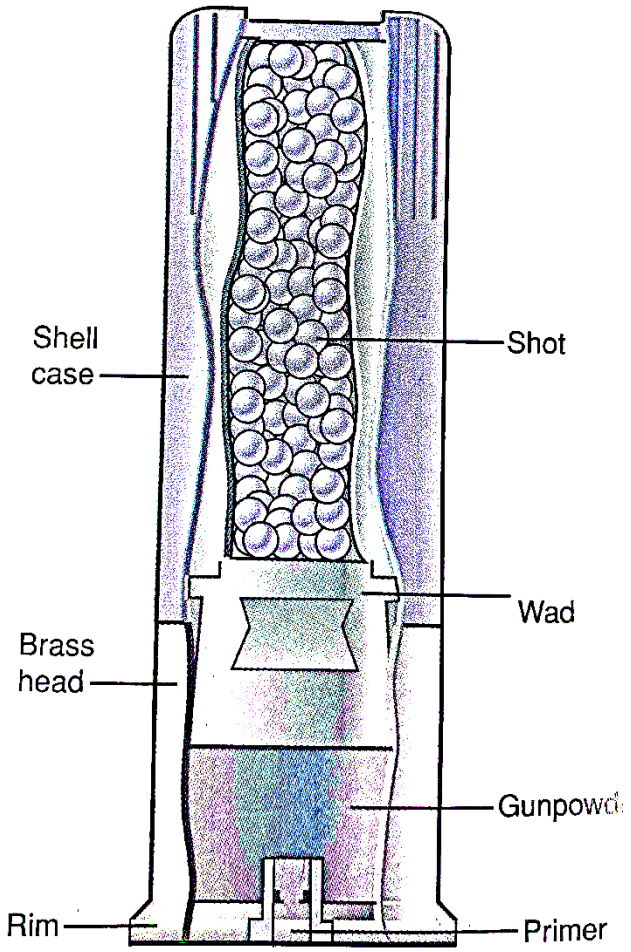


Wounding Potential - Ballistics Effect on Tissues

- **Nerves and Vessels**
  - **Often fixed anatomically - vulnerable to distortion from cavitation**
  - **Intimal damage in vessels and axonal damage in nerves even if macroscopically intact**
  - **Can result in functional failure remote distances from path of bullet**

Wounding Potential Special Case - Shotguns

- **Massive wounding potential at close range despite lower muzzle velocity**
  - **Fire higher mass of metal projectile(s)**
  - **Present spherical profile to air and tissues**
  - **Slow down quickly once fired**
- **Fires numerous pellets contained within a “shot” or a single, solid “slug”**
- **The “wad” separates the shot from the powder, and prevents gas from blowing through the shot rather than propelling the shot out of the shotgun.**



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Wounding Potential Kinetic Energy of Shotgun Blasts

High Velocity Firearms

Weapon	Bullet Weight (g)	Velocity (ft/s)	Velocity (m/s)	Kinetic Energy (ft-lb)
0.22 Savage	4.5	2750	838	1175
30/06 Springfield	9.7	2750	838	2519
5.56-mm M-16	3.6	3250	991	1290

Shotguns

Gauge	Shell Type	Shot Weight (g)	Velocity (ft/s)	Velocity (m/s)	Kinetic Energy (ft-lb)
12	2 ¾-in.	38	1330	405	2145
16	2 ¾-in.	35	1295	395	2033
20	2 ¾-in.	28	1220	372	1626

Wounding Potential Special Case - Shotguns

Medial side concentrated close-range entry with charred skin edges

Larger lateral side exit wound

- **Most severe wounds come from within 10-15 yards**
- **Concentration of shot makes entire load function as a unit**
- **Destroys everything in its path**

Ballistic Injuries
Clinical Management

ED Management

- **ATLS Management – Control hemorrhage**
- **Inspection**
  - **Entrance and exit wounds, charred skin edges, holes in clothing**
  - **Remember: the clothing can be in the wound, driven into bone etc.**
- **Pulse examination**
  - **Intimal damage is common even in macroscopically intact arteries**
  - **Be aware for expanding hematoma**
- **Plain radiographs of injured areas**
- **Angiography**
  - **Only when indicated by discrepancy of pulses**

Low-Velocity Extremity Fractures

- **Low-velocity, non-contaminated wounds in stable/non-op fractures**
  - **Most recommend superficial wound lavage in ED in lieu of formal debridement**
  - **IV or brief course of oral antibiotics equivalent – 1st gen. cephalosporin**
  - **14/794 (1.8%) infection rate in pooled meta-analysis with oral or IV antibiotics**

Sathiyakumar, CORR, 2015.

Low-Velocity Extremity Fractures

- **Low-velocity, non-contaminated wounds in unstable/operative fractures**
  - **IV antibiotics for surgical prophylaxis**
  - **“Semi-conservative” treatment with superficial debridement/lavage at time of fracture fixation equivalent to extensive debridement**

Low-Velocity Joint Injuries

- **Universal agreement for extensive debridement, especially if retained intra-articular foreign bodies**
  - **Tornetta et al. – 42% incidence meniscal damage, 15% chondral injury in radiographically normal knees after penetrating joint injury**
- **Intra-articular debris may lead to septic arthritis**
- **Systemic Lead Toxicity**

Tornetta, J Orthop Trauma, 1997

Systemic Lead Toxicity

- **Any retained ballistic fragments anywhere in body**
- **Greater risk with greater fragmentation, greater lead load, and intraarticular location**
  - **Synovial fluid acts as lead solvent**
- **Confirmed with serum lead level > 5-10 µg/dL**
  - **Monitor levels q3 months for 1 year from injury**
- **Chronic fatigue, anemia, headaches, neuropathy, abdominal pain, encephalopathy occur with lead levels > 24 µg/dL**

Apte, J Trauma Acute Care Surg, 2019

Low-Velocity Pelvic and Hip-Girdle Fractures

- **Warrant special consideration because of possible GI tract contamination**
- **Broad spectrum antibiotics for 48-72h indicated**
- **Extra-articular pelvic/hip fractures do not require debridement even if contaminant intestinal spillage**
- **Intra-articular pelvic/hip fractures require formal debridement**

Rehman, J Trauma, 2011

High-Velocity Extremity Fractures

- **Analogous to open fractures**
  - **High-velocity weapons and close range shotgun wound cause massive tissue destruction**
- **Require extensive debridement, broad spectrum antibiotics**
  - **Infection rate >40% in pooled studies**
  - **Infection rate 80% in wounds closed primarily**
    - **Importance of delayed closure**

Sathiyakumar, CORR, 2015.

Soft Tissue and Bone Defects

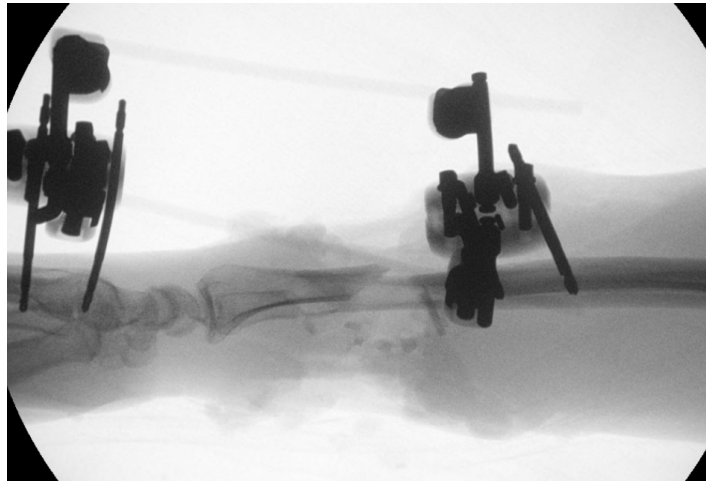
- **More common in high-velocity or shotgun injuries**
- **Serial debridement should be performed until clean wound bed**
- **Wounds can be covered with negative-pressure dressings or antibiotic pouches**
- **Segmental bone defects can be treated with induced membrane or bone transport techniques**

Patient 1: Identifies the problem of high velocity injuries – bone and soft tissue defects

- **43 year old female**
- **Shot off ATV by known assailant with AR-15 assault rifle**

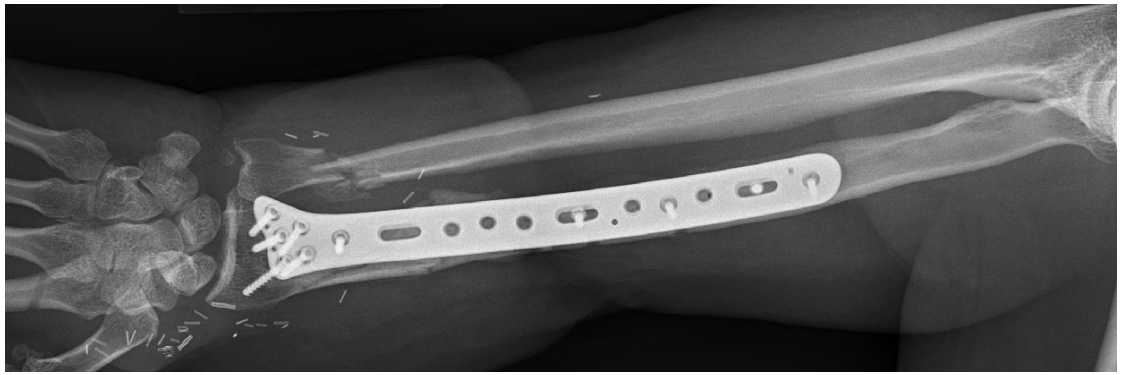
Patient 1 - Bone and Soft tissue defects

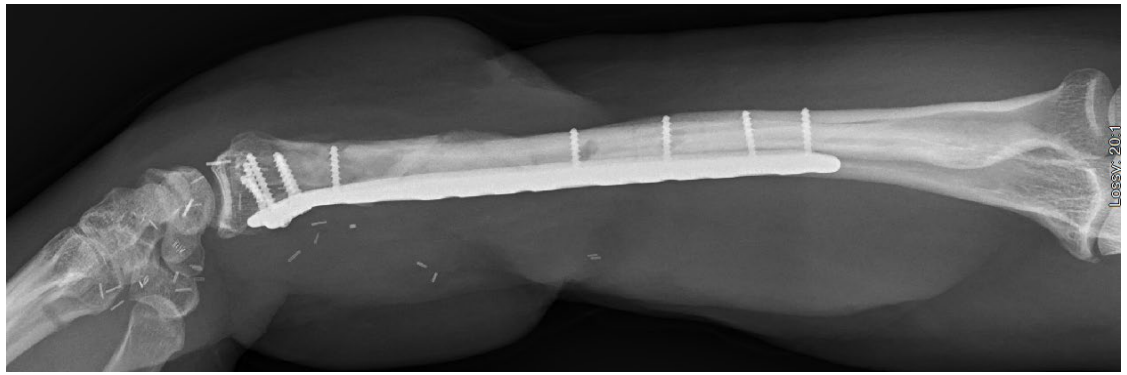
- **OR emergently**
- **Debridement – sepsis control**
- **Wrist spanning external fixation**
  - **Length for defect management**



Patient 1 - Bone and Soft tissue defects

- **Serial debridements - prepare a clean viable bed**
- **Staged internal fixation – maintain anatomy to promote functional upper extremity rehabilitation**
- **Bone defect - Induced membrane technique**
- **Soft Tissue Defect management - ALT free flap coverage**
- **Delayed tendon reconstructions: EPL, EIP, EDC, FDS**





Associated Neurologic Injuries

- **Peripheral nerve injuries are common - 40% in GSW to hand**
- **Rarely is nerve completely severed (neurotmesis)**
- **Most common is conduction block (neuropraxia) from transient ischemia or concussive effects from cavitation**

Neurologic Injury Management

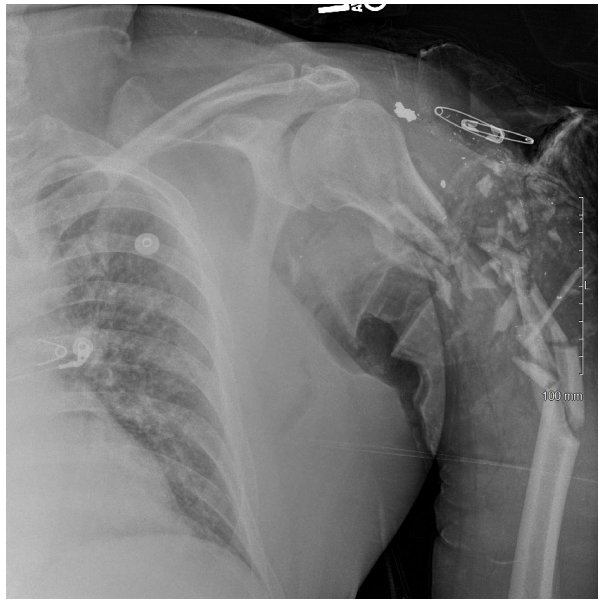
- **Early observation of nerve injury is reasonable – 70-90% recovery rate**
  - **Follow for signs of exam improvement**
  - **An early electrodiagnostic study may offer good baseline – allows time for Wallerian degeneration to show on study**
  - **A 3-month electrodiagnostic study then can establish a trend**

Neurologic Injury – Failure of Observation

- **Nerves not showing clinical or electrodiagnostic improvement by 3 months are more likely to be ruptured or trapped in callus or scar**
- **Consider exploration at that time**

Patient 2 – Ballistic injury with nerve injury

- **50 yr. old male**
- **12g shotgun misfired into axilla while cleaning**
- **ED: Absent axillary nerve function**

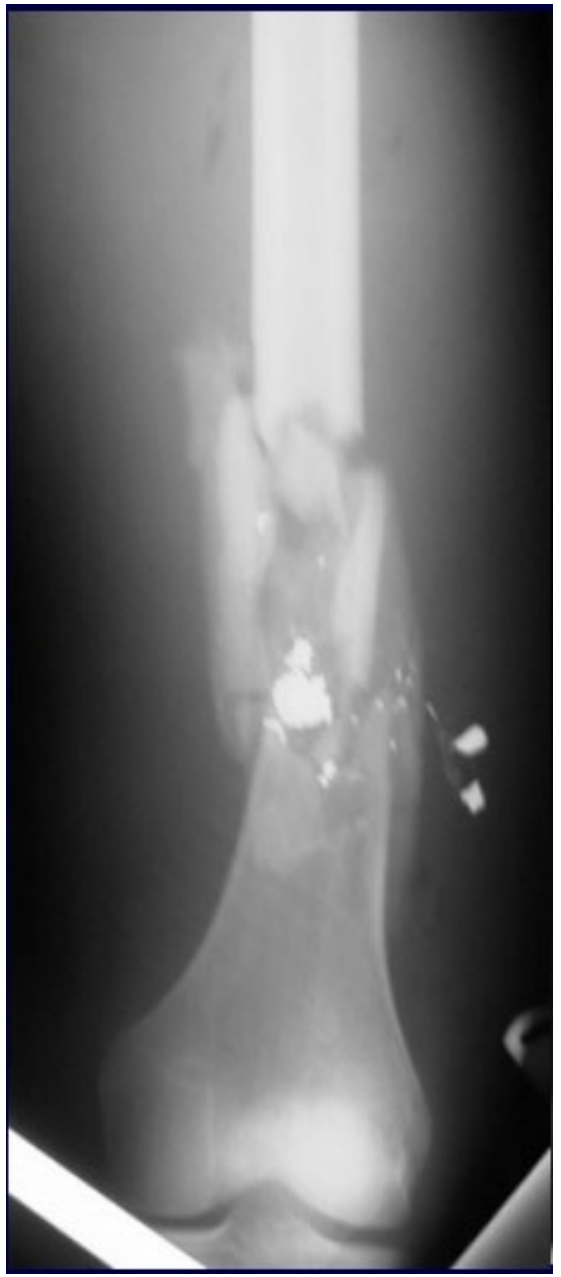


Patient 2 – Ballistic injury with nerve injury

- **Emergent debridement in OR**
- **Serial debridements**
- **Latissimus pedicled flap**
- **Intrameduallary fixation plus PMMA and plate fixation**
- **Delayed osteosynthesis (not pictured)**

Low-Velocity Injuries

- **Bullet fragmentation**
- **Fracture comminution**
- **Less soft tissue injury**
- **Often heal quickly**
  - **Undisturbed soft tissues**
  - **Comminution acts like bone graft**

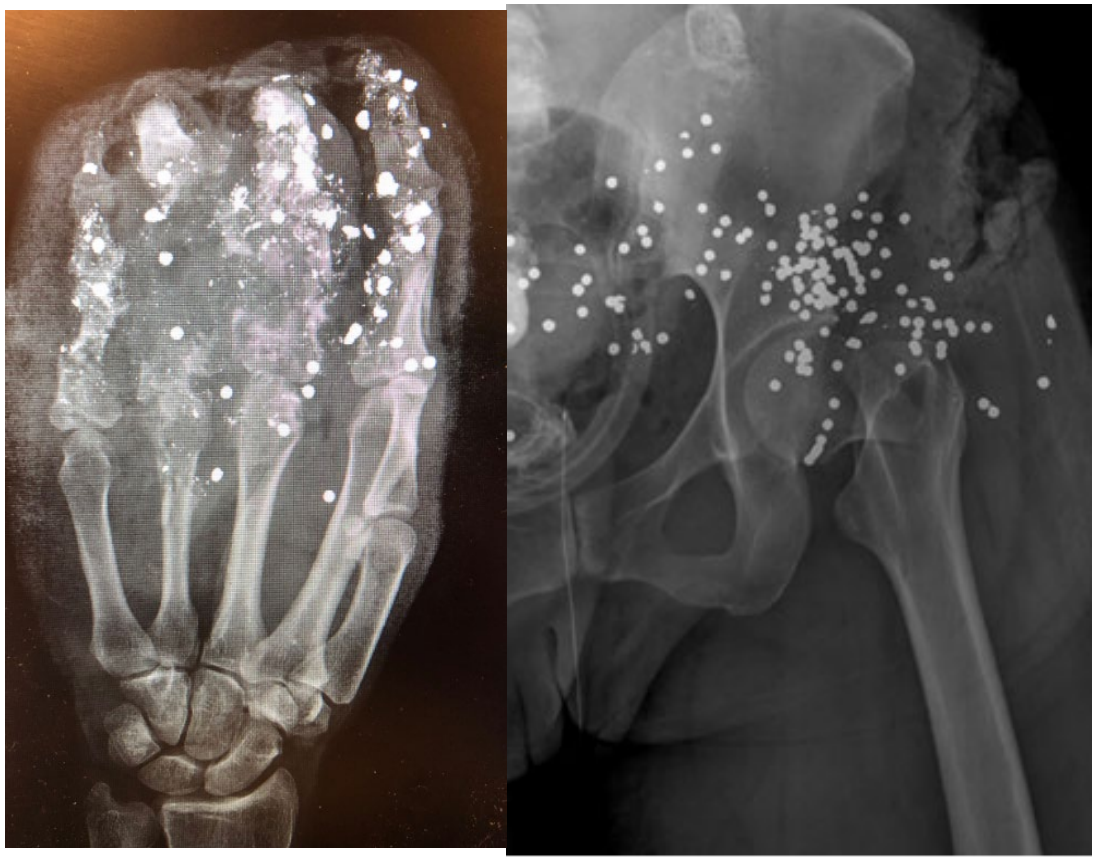


High-Velocity Injuries

- **Bullet fragmentation**
- **Fracture comminution**
- **Significant soft tissue injury**
  - **May be highly contaminated**

Shotgun Injuries

- **Slugs or pellets**
- **Comminution**
- **Massive soft tissue injury and contamination if close range**
- **Beware wadding as source of contamination – must be found and removed**

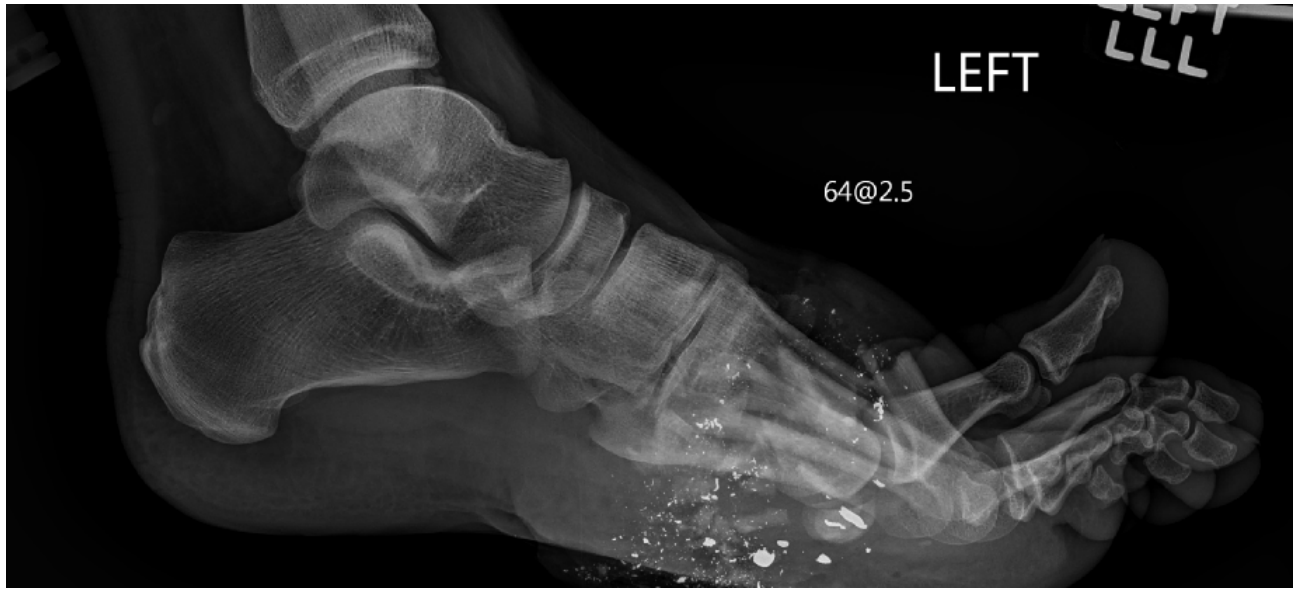


Shotgun Wadding

- **May be missed on plain radiographs**
- **Scrutinize CTs for appearance of shotgun wadding or clothing**

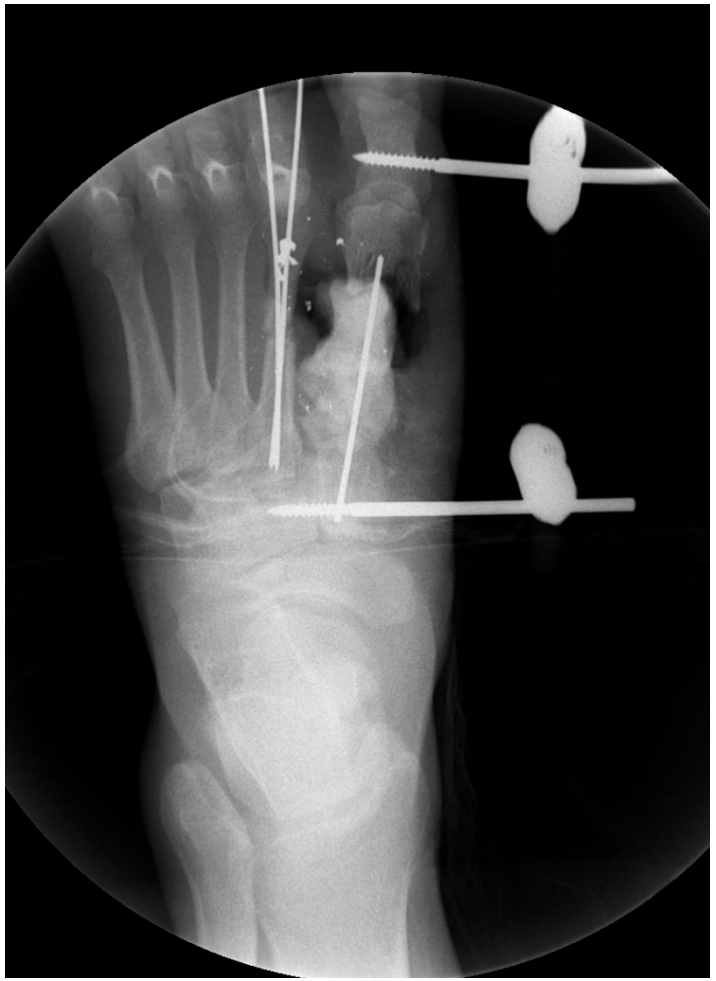
Patient 3 - A Shotgun injury

- **25yr. old male**
- **Walking thru house with loaded shotgun**
- **Accidental discharge into his own foot**



Patient 3 - A Shotgun injury

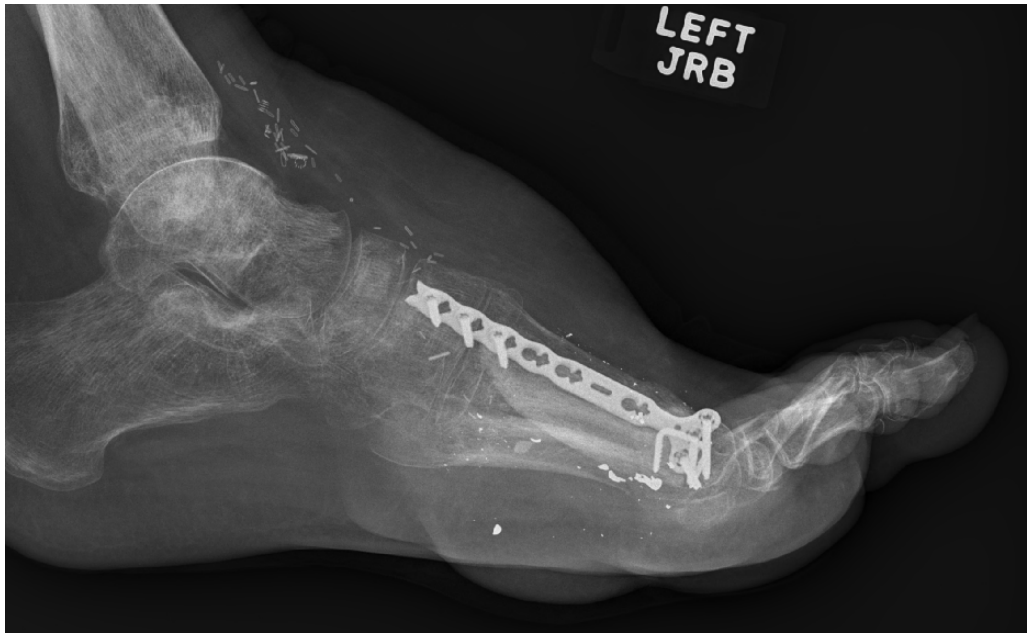
- **Urgent debridement – removal of wadding**
- **Spanning ex fix, percutaneous pinning to maintain length**
- **Antibiotic cement spacer to prepare soft tissue**
  - **Infection treatment**
  - **Bone defect management**



Clinical photo courtesy Dr. Andrew Carlone

Patient 3 - A Shotgun injury

- **Free flap wound coverage**
- **Induced membrane technique**
- **Iliac crest tricortical bone graft**



Associated Vascular Injuries

- **Relatively common**
  - **~15% of upper extremity penetrating injuries**
- **Includes laceration (direct bullet path) and intimal injuries (wider cavitation defects)**
- **Mandates dedicated and careful vascular examination**
- **Must workup any asymmetry or exam abnormality**

Vascular Injury Management

- **Patients with hard signs (absent pulses, pulsatile bleeding, bruit, thrill, expanding hematoma) → OR for revascularization**
  - **Intraoperative Angiography for localization**
- **Patients with abnormal exam and ABI <0.9 → Angiography**
- **Patients with abnormal exam and ABI >0.9 → Serial Examinations**
  - **ABI >0.90 has 99% negative predictive value for arterial injury**
- **Early prophylactic fasciotomy indicated if prolonged ischemia**
  - **4 to 6 hours of cold ischemic time mandatory**
  - **Warm ischemia (no pulses with decreased perfusion highly recommended for fasciotomy but if not close monitoring**

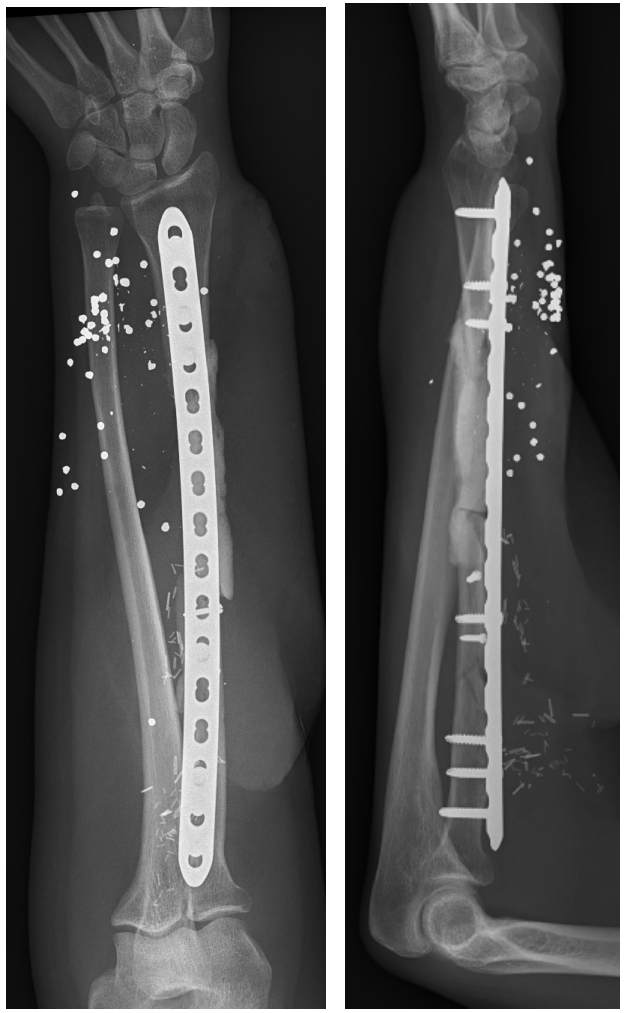
Johansen, J Trauma, 1991

Patient 4 – Vascular and nerve injury

- 29 year old female
- Shotgun blast from 4-5 ft by a carjacker
- Radial artery transection – perfused hand
- Median and radial nerve transections
- OR emergently
- Need a planned approach with required expertise to handle all injuries

Patient 4 - Vascular and nerve injury

- **Radial artery ligation, hand remains warm and well perfused**
- **Serial debridements –till clean and viable**
- **Intact ulna provides skeletal stability till fixation possible**
- **Open treatment radial shaft**
- **Antibiotic cement spacer**
- **Sural nerve cable graft for 11 cm median n. defect**
- **Free flap coverage**



Patient 4 - Vascular and nerve injury

E.D.

Fixation

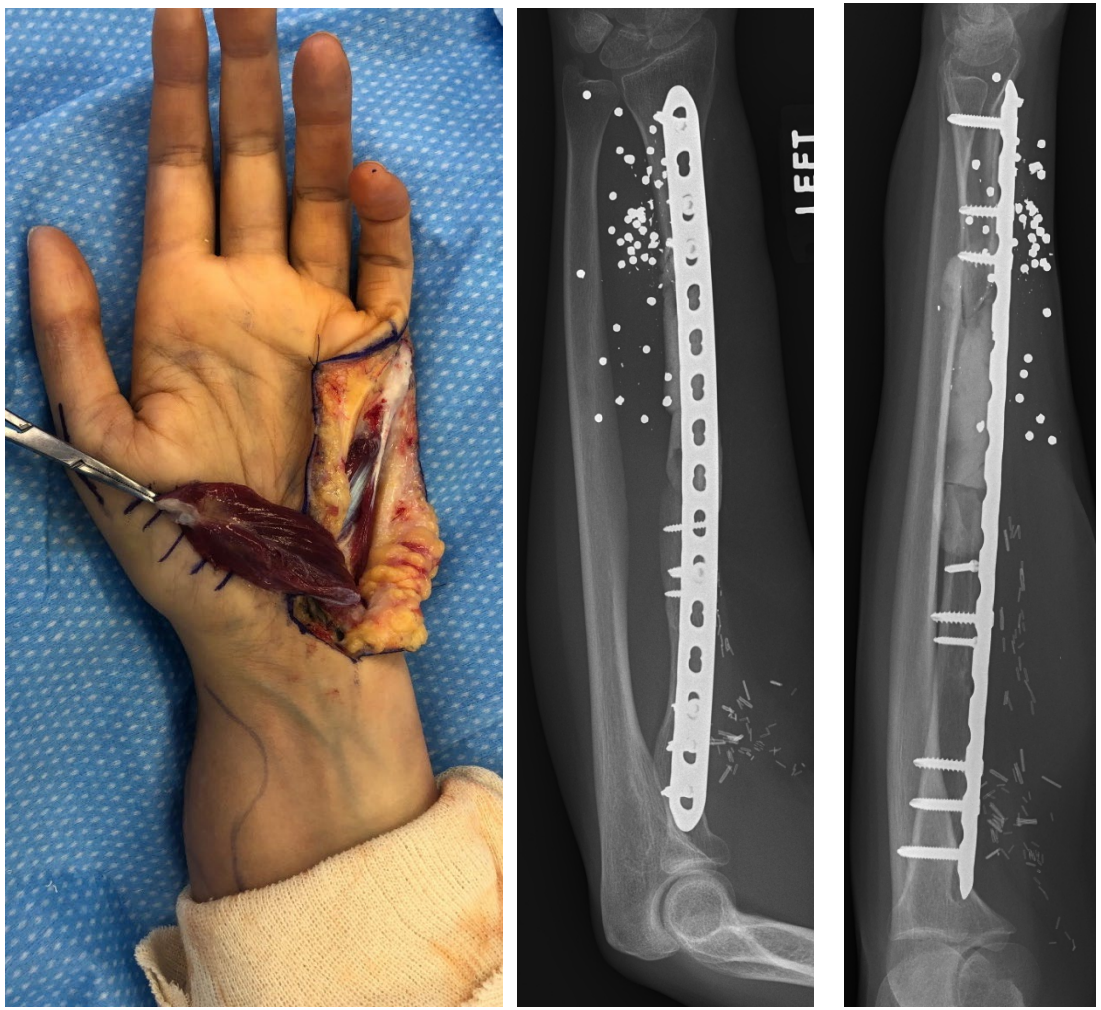
Coverage

Serial debridements to create clean wound viable bed

Clinical photos courtesy Dr. Eric Moghadamian and Dr. Brian Muffly

Patient 4 - Vascular and nerve injury

- **Median nerve never recovered function**
  - **Opponensplasty 14 months post-injury**
- **Antibiotic spacer retained but can be replaced by bone graft**
- **Near-complete function restored to hand**



Clinical photo courtesy Dr. Chelsea Wallace

Misnomers of Management

- **Bullets are not free of contamination**
  - **Bullets coated with S. aureus still grow in culture after firing – Wolf et al, J Trauma, 1978**
  - **Shotgun wadding or clothing fragments may be associated with significant contamination**
  - **Ballistic fractures to pelvis/hip girdle may be exposed to additional contaminant from coincident bowel injury**

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Future Directions

- **Treatment costs of ballistic fractures rising faster than medical care inflation rate by factor of 300%**
- **High quality research needed to develop evidence based guidelines for debridement and antibiotic use practices**

Hakanson, Orthopedics, 1994

Summary

- **Low-velocity = Treatment similar to closed fractures**
  - **Short course of IV or PO antibiotics**
  - **Debridement rarely, can be determined on case-by-case basis, superficial debridement equivalent to extensive**
- **High-velocity and close range shotgun injuries require urgent debridement and open fracture management principles**
- **Debridement mandated by intraarticular path**
  - **Risks for septic arthrosis and systemic lead toxicity**

Summary Continued

- **Patients with high retained lead load must have lab monitoring for lead levels for up to 1 year**
- **Associated vascular and nerve injuries are common**
  - **Careful examination on presentation**
  - **Hard signs vascular injury → Emergent OR exploration**
  - **Abnormal exam and ABI < 0.9 → Angiography**
  - **Abnormal exam and ABI > 0.9 → Serial Examinations**

Key References

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