

Imaging Bone Marrow

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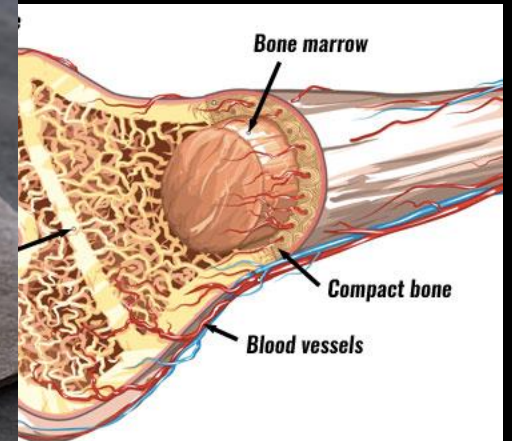
ACR Education Center: MSK Specialized Topics



MARROW- Normal Anatomy

- 3 primary components

Osseous matrix, trabeculae of

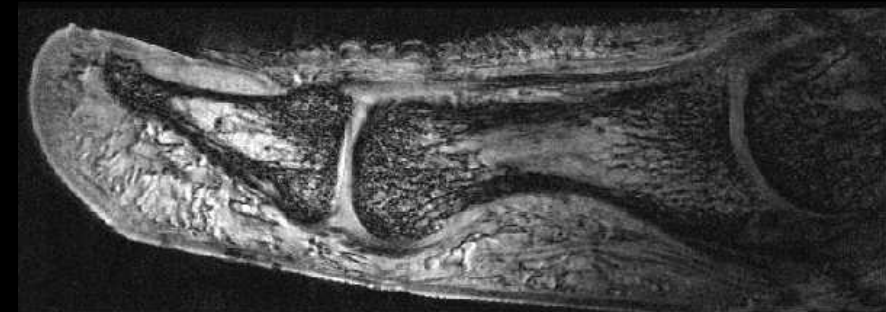


osseous matrix, containing RBC's,

WBC's, platelet precursors

– Yellow marrow

- Hematopoietically inactive-> fat cells

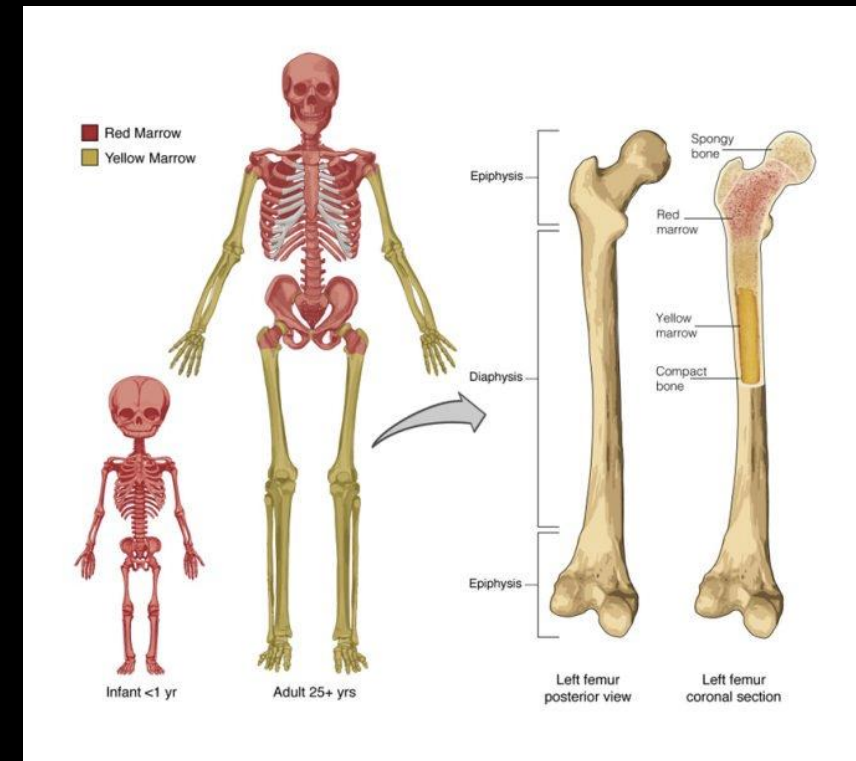
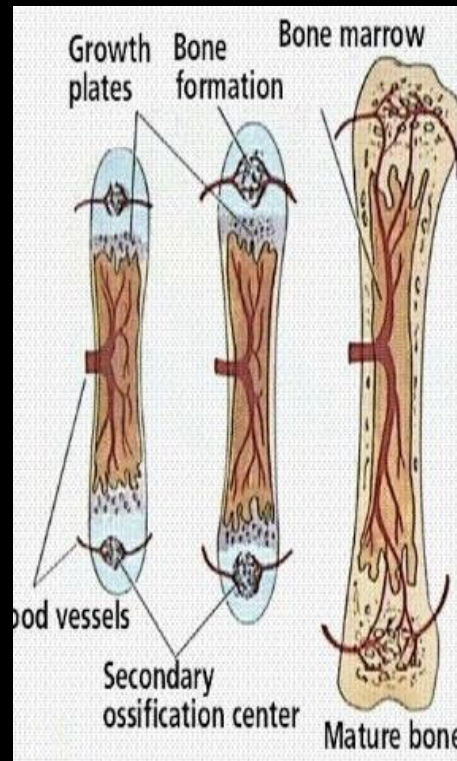


MARROW- Normal Anatomy

Red marrow composition changes with age- important for understanding MRI appearance!

Infants and young children

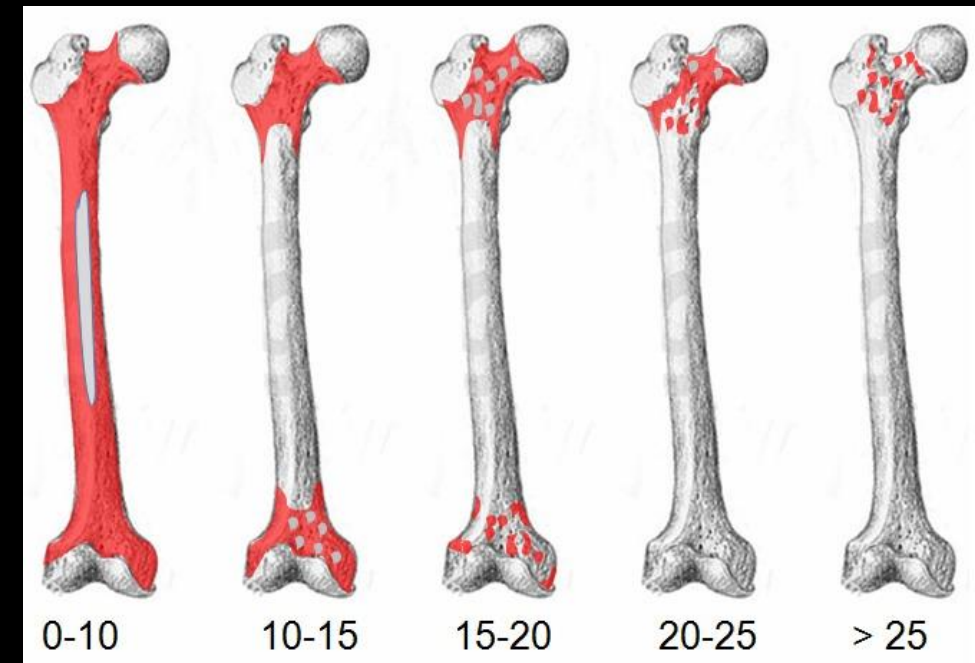
- 40% water
- 40% fat
- 20% protein
- By age 70
 - 60% fat
 - 30% water
 - 10% protein



Yellow marrow- 80% fat, 15% water, 5% protein

MARROW- Distribution

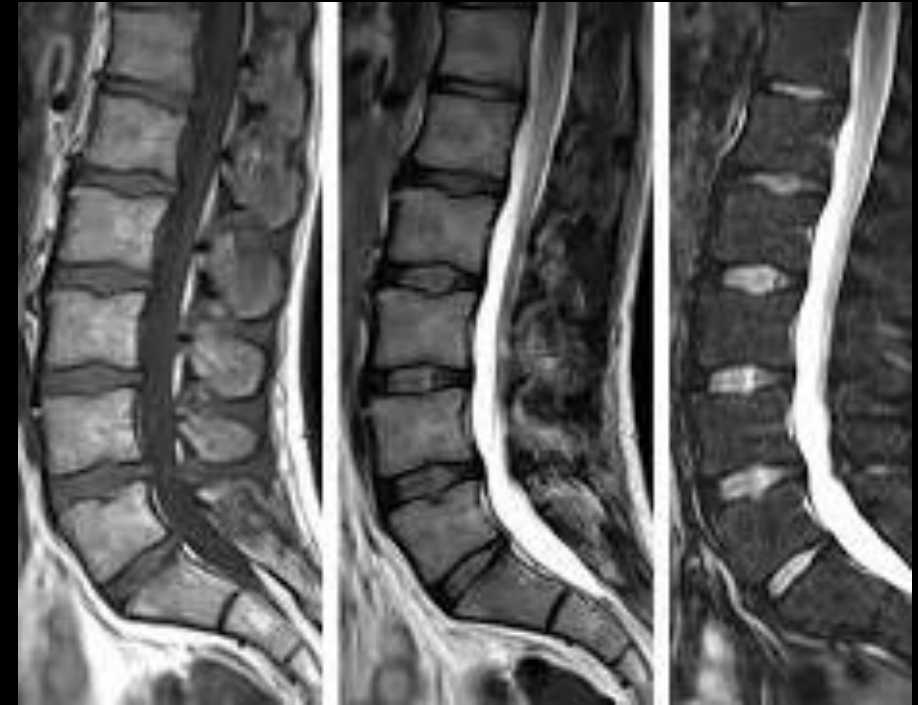
- Shortly after birth, orderly and predictable conversion of hematopoietic to fatty marrow
 - Infancy- red marrow throughout except epiphysis and apophyses (Cartilaginous epiphysis/apophyses = muscle on T1)
 - Adult- reached by middle of third decade
 - Appendicular (peripheral) → axial (central)
 - Long bones— diaphysis → distal metaphysis → proximal metaphysis



MARROW- MRI appearance

- **Pulse sequence selection**

- Fluid sensitive sequences-> STIR, FSE T2 fat suppressed
- T1 nonfat suppressed
- Chemical-Shift (in/out phase)
- +/- IV contrast– ALL edema enhances



- **Marrow composition- cellularity, protein, water and fat**

In phase



Out of phase

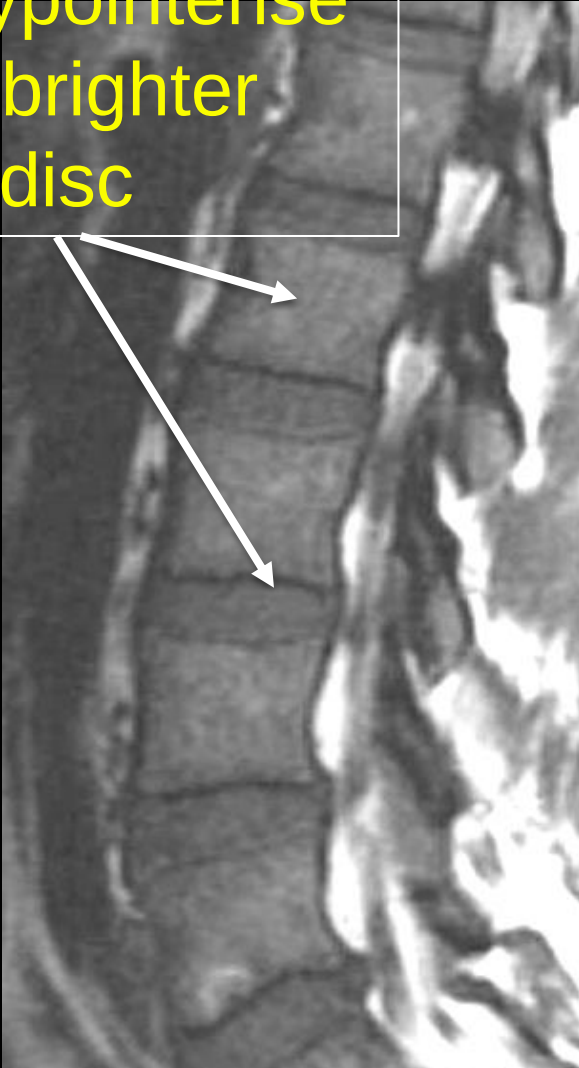
Chemical shift MRI

- Detection of small quantities of fat within a lesion (e.g., differentiation of hemangioma from malignancy)
- Simply repeat an FFE sequence with double the TE, out of phase to fat
- Differentiation of hematopoietic marrow from marrow replacing processes, ie BENIGN vs MALIGNANT
 - Hematopoietic marrow- equal parts lipid and water
 - Should drop in signal on out of phase images
 - Malignant lesions: fat replaced
 - Should not drop

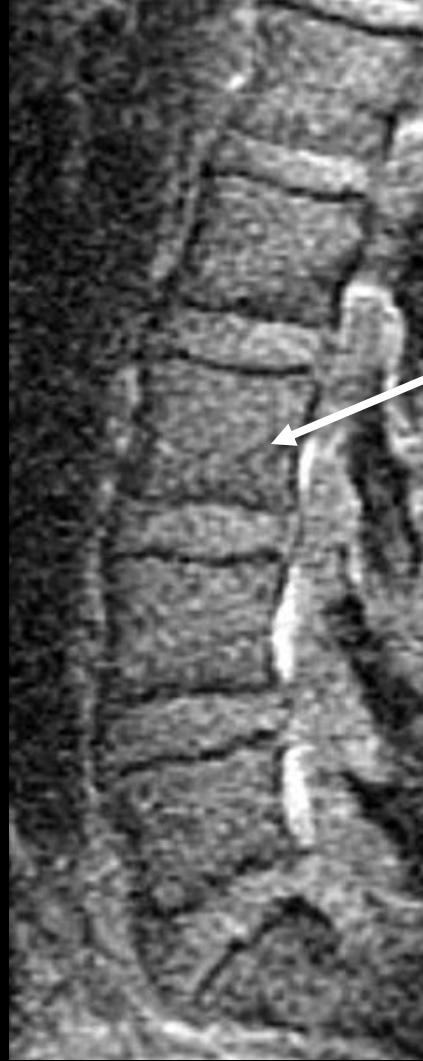
Zajick DC Jr, Morrison WB, Schweitzer ME, Parellada JA, Carrino JA. Benign and malignant processes: normal values and differentiation with chemical shift MR imaging in vertebral marrow. Radiology. 2005 Nov;237(2):590-6.

Chemical Shift

T1 hypointense
BUT brighter
than disc



T1 Non-fatsat



In -phase



Out-of-phase

Chemical Shift



T1 hypointense,
darker than disc

T1 Nonfat sat



In-phase



No
drop

FAT!!

Out-of-phase

Opposed Phase / Chemical Shift Imaging

Out of phase

Fatty marrow: fat $\gg$ H₂O

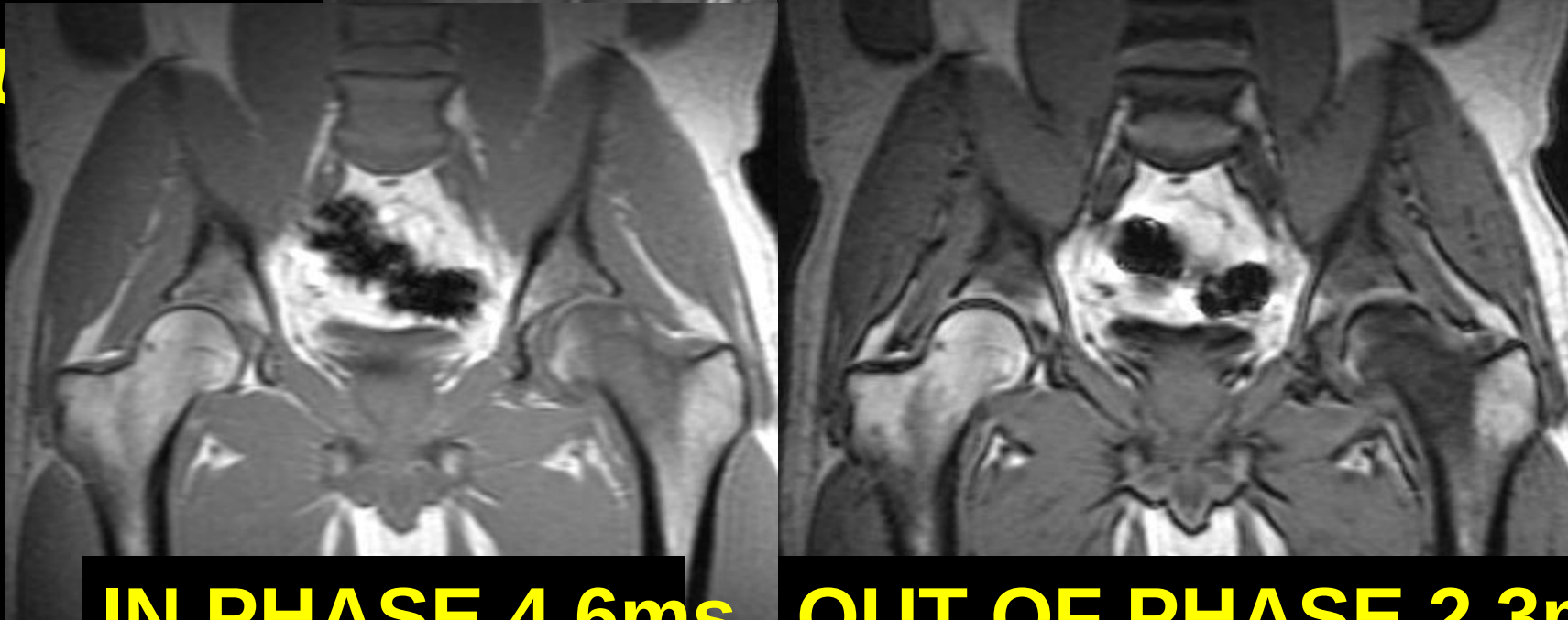
no change/min decrease

Red marrow & BME: H₂O = fat

marked decrease

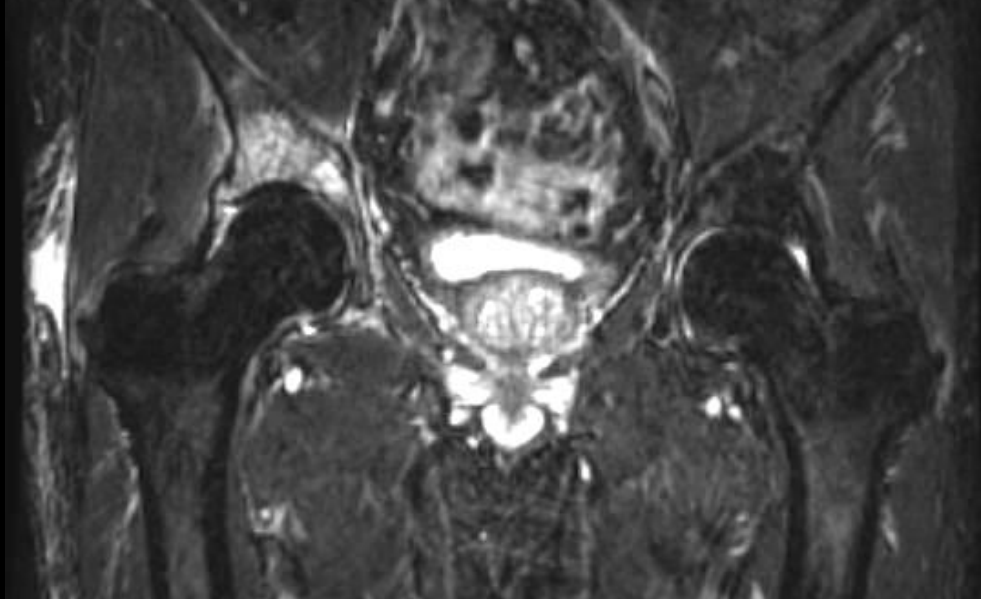
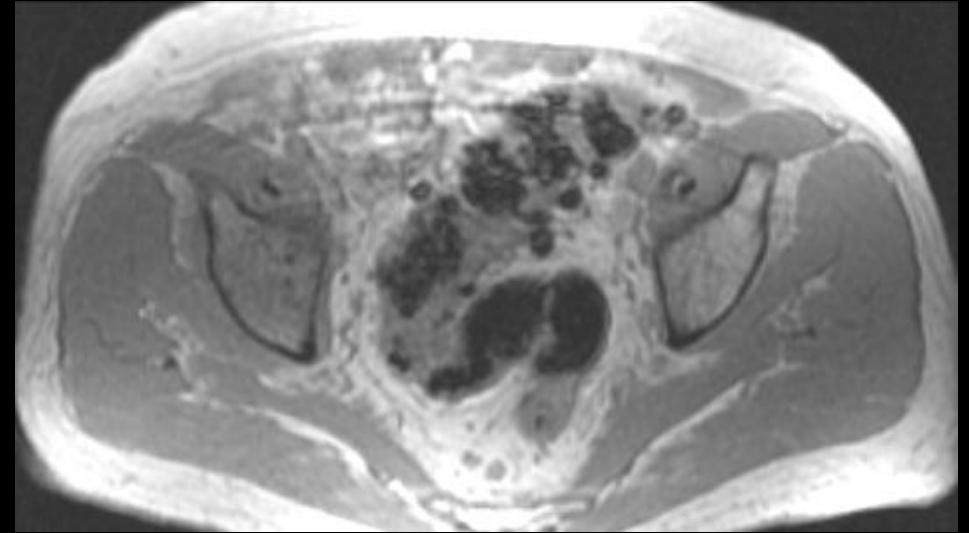
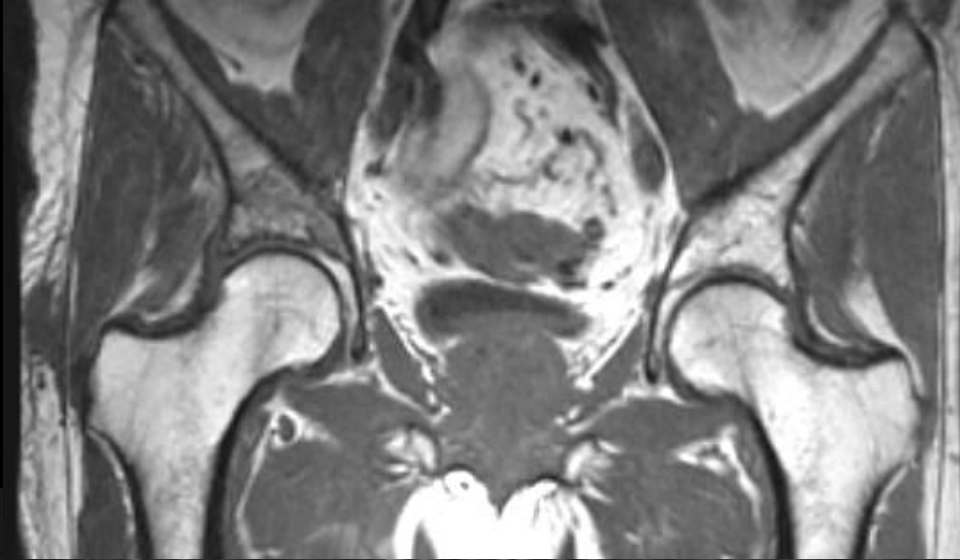
Mets: H₂O, no fat

no change



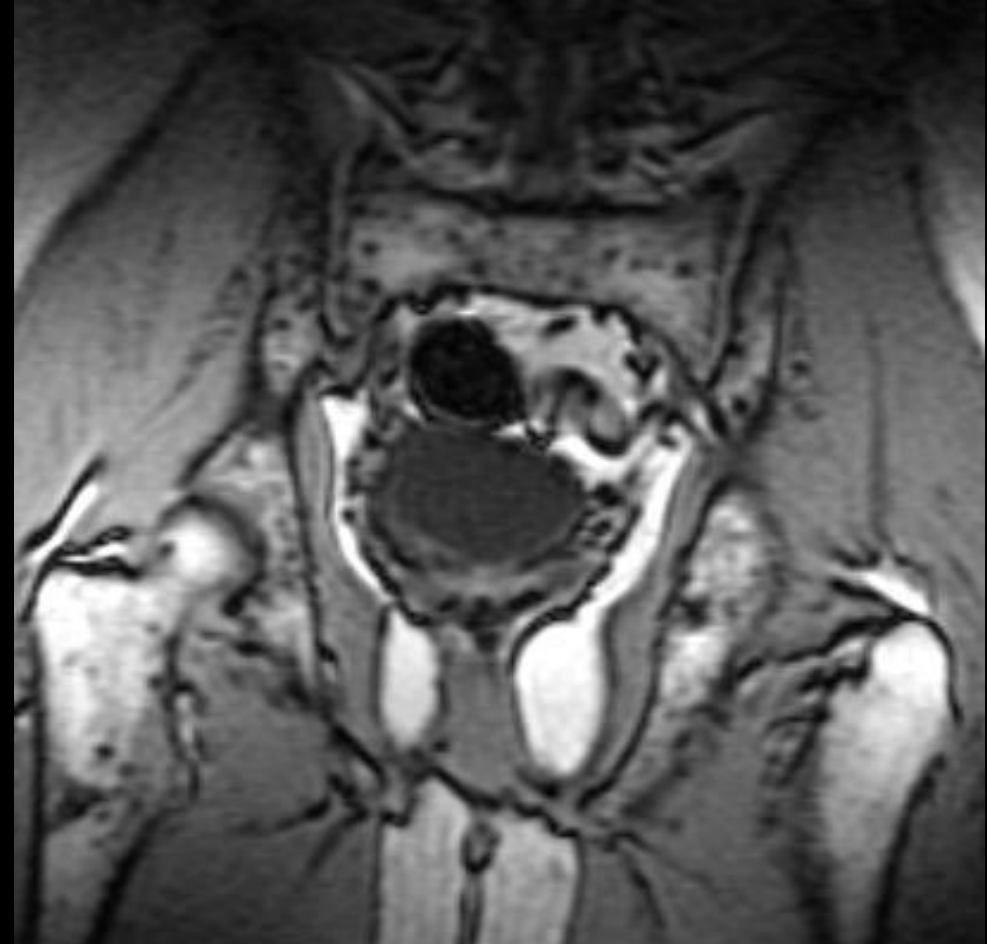
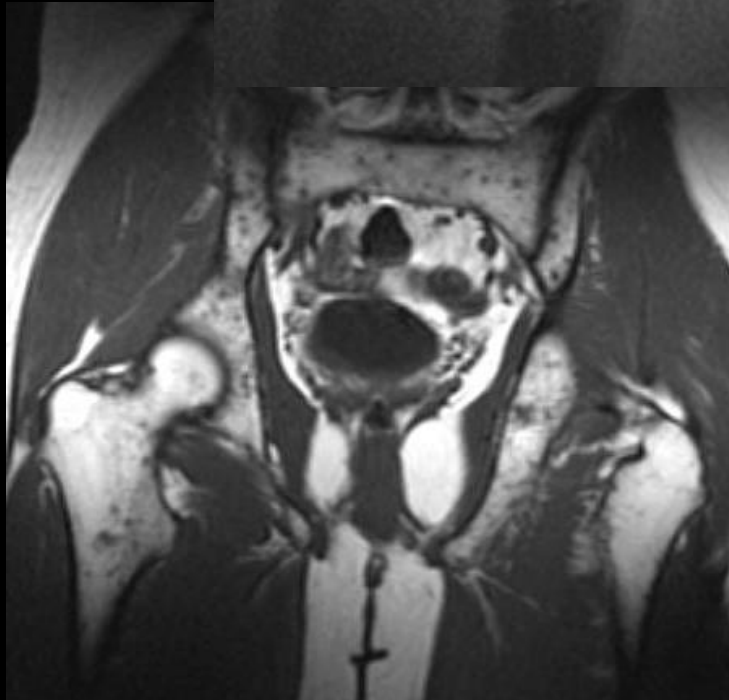
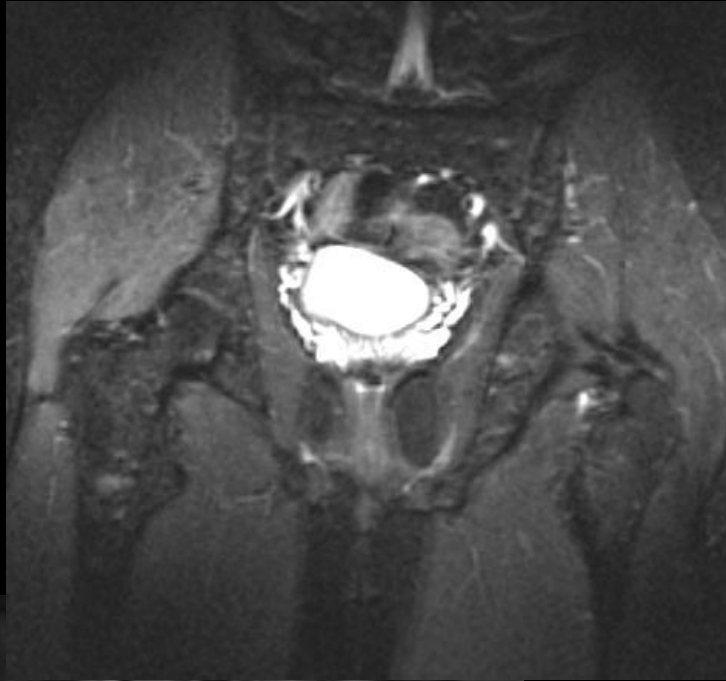
IN PHASE 4.6ms - OUT OF PHASE 2.3ms

Opposed Phase Imaging: Fracture

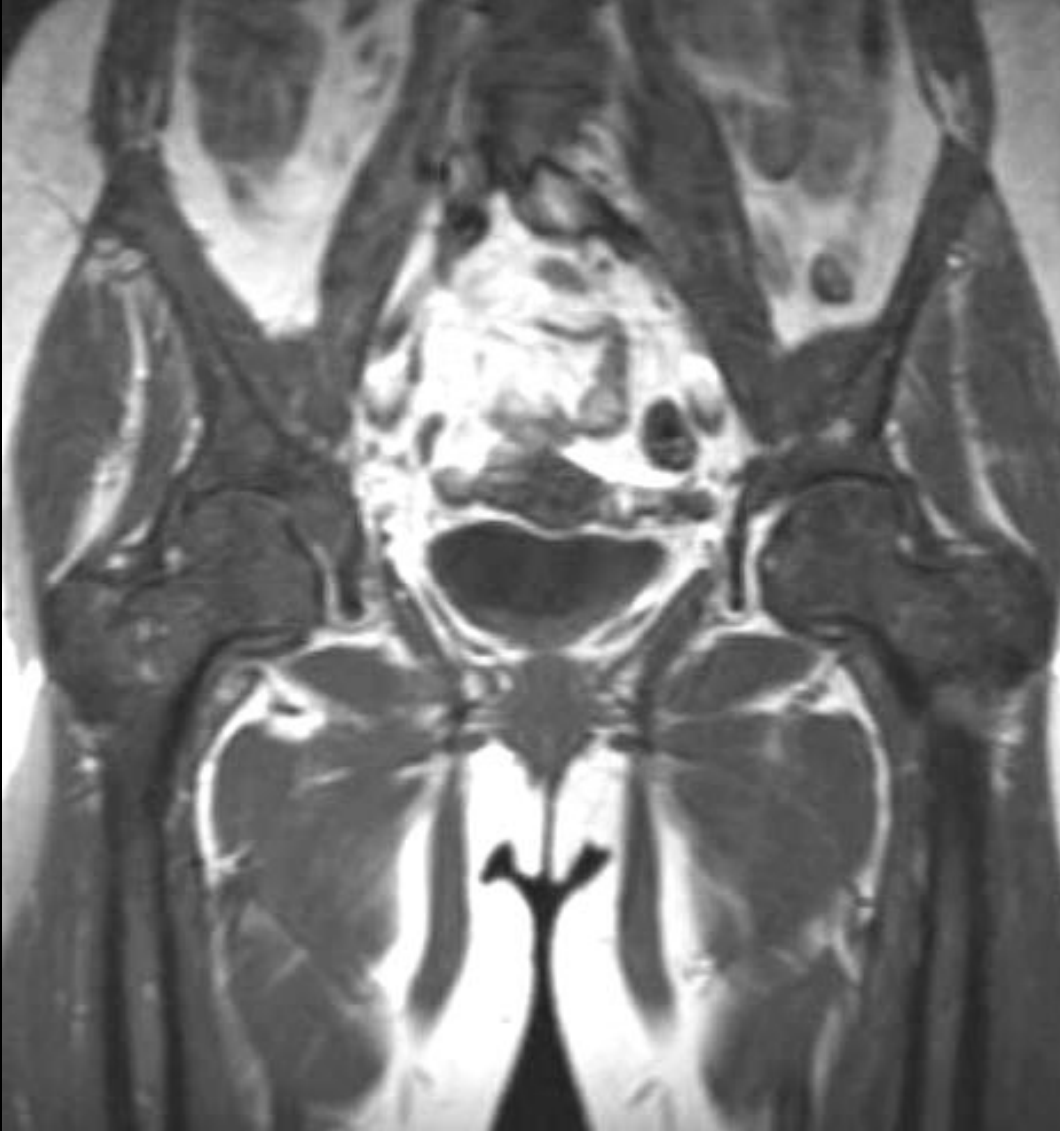


Signal drops out-of-phase

Opposed Phase Imaging: Aplastic Anemia



Little drop in signal on out-of-phase



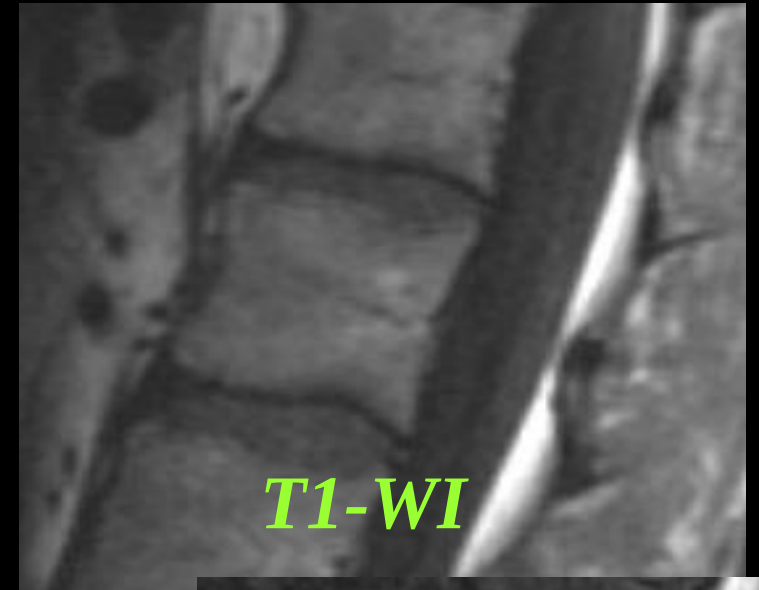
T1 Marrow

- Should be hyperintense to muscle***
- Should be fat in the epiphyses.***

Breast mets - diffuse

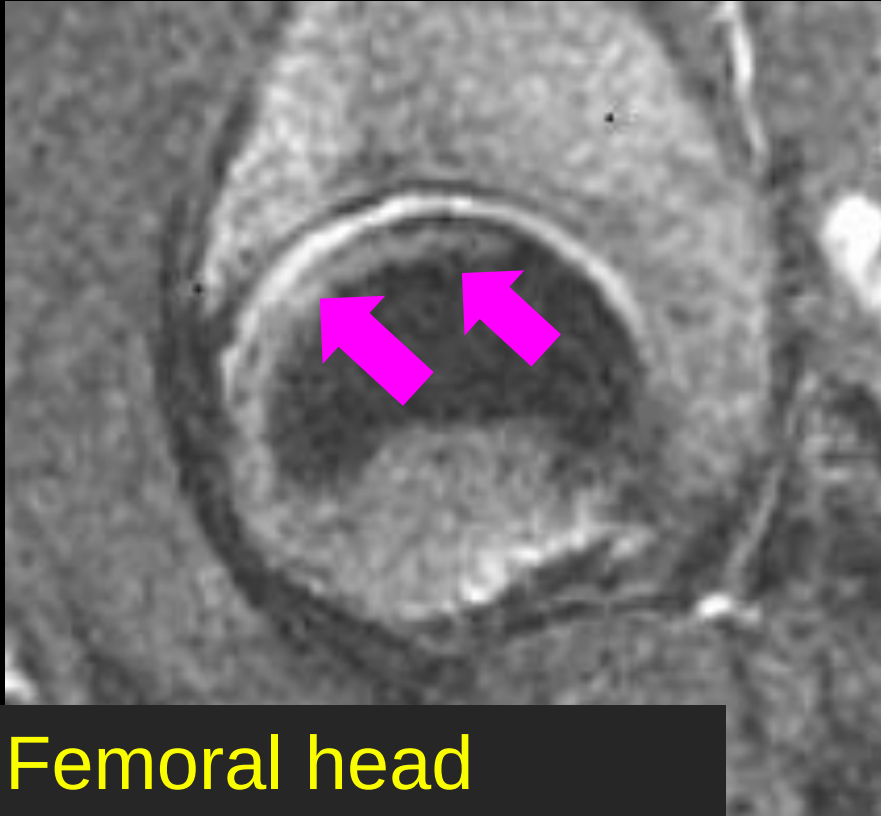
MARROW: Normal MR Imaging

- **Red (Hematopoietic)**
 - T1-- Equal or slightly hyperintense to muscle and disc
 - After the neonate period, SI (signal intensity) LOWER than normal muscle= PATHOLOGY
 - T2 fat suppressed– intermediate signal similar to muscle
 - Most marrow pathology demonstrates relatively high SI
- **Yellow (Fatty)**
 - Follows subcutaneous fat on all sequences



Normal marrow variants

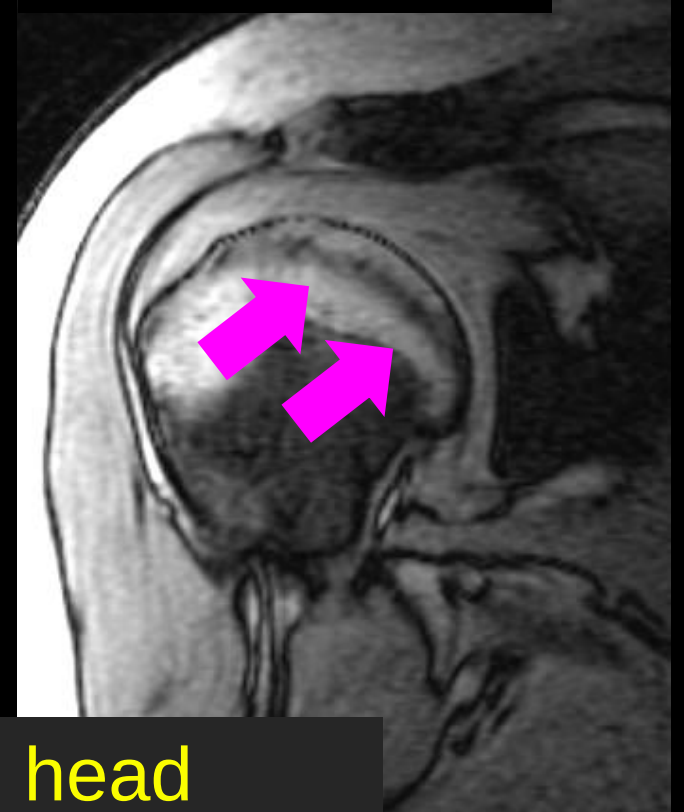
T2 Fatsat



In-phase



Out-of-phase



Islands of red marrow can be seen within the subchondral region of prox humeri and femoral heads in healthy adults!

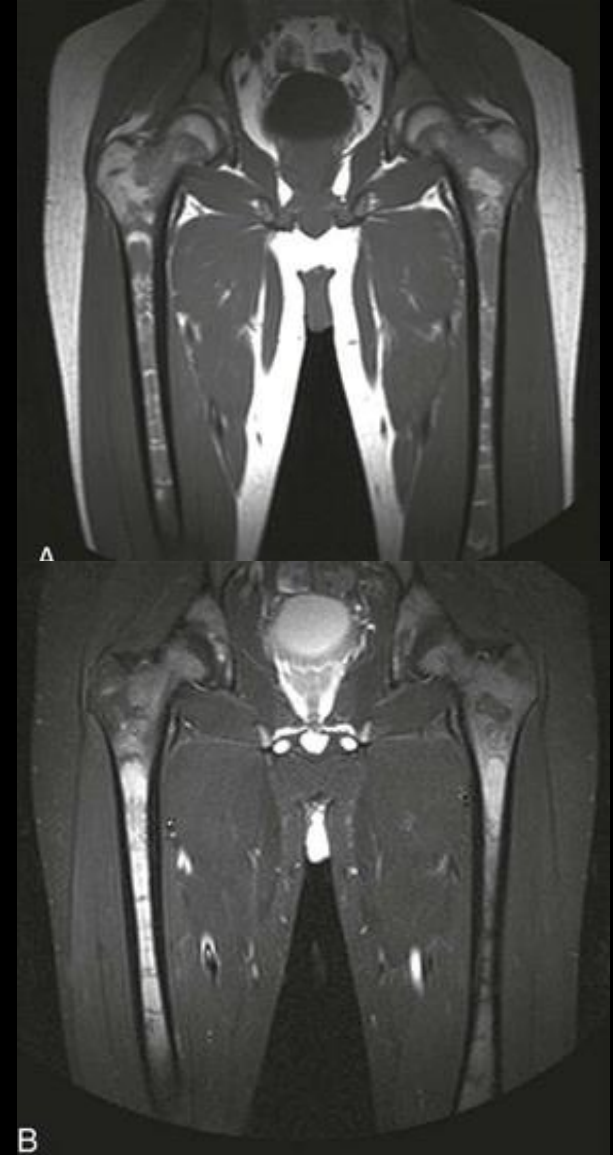
Abnormal Marrow Signal

- Functional vs Non-functional
 - Abnormalities associated with marrow production
 - Marrow Reconversion (Hyperplasia)
 - Replacement Disorders
 - Depletion Disorders
 - Reticulum Disorders
 - Abnormalities NOT associated with marrow production
 - Marrow Edema/Marrow Edema-like



Marrow Reconversion

- Reconversion of fatty marrow to red marrow due to increased demand
- Occurs in a pattern reverse of normal physiologic marrow conversion
 - Vertebrae and pelvis → long bones
 - Proximal metaphysis → distal metaphysis → diaphysis

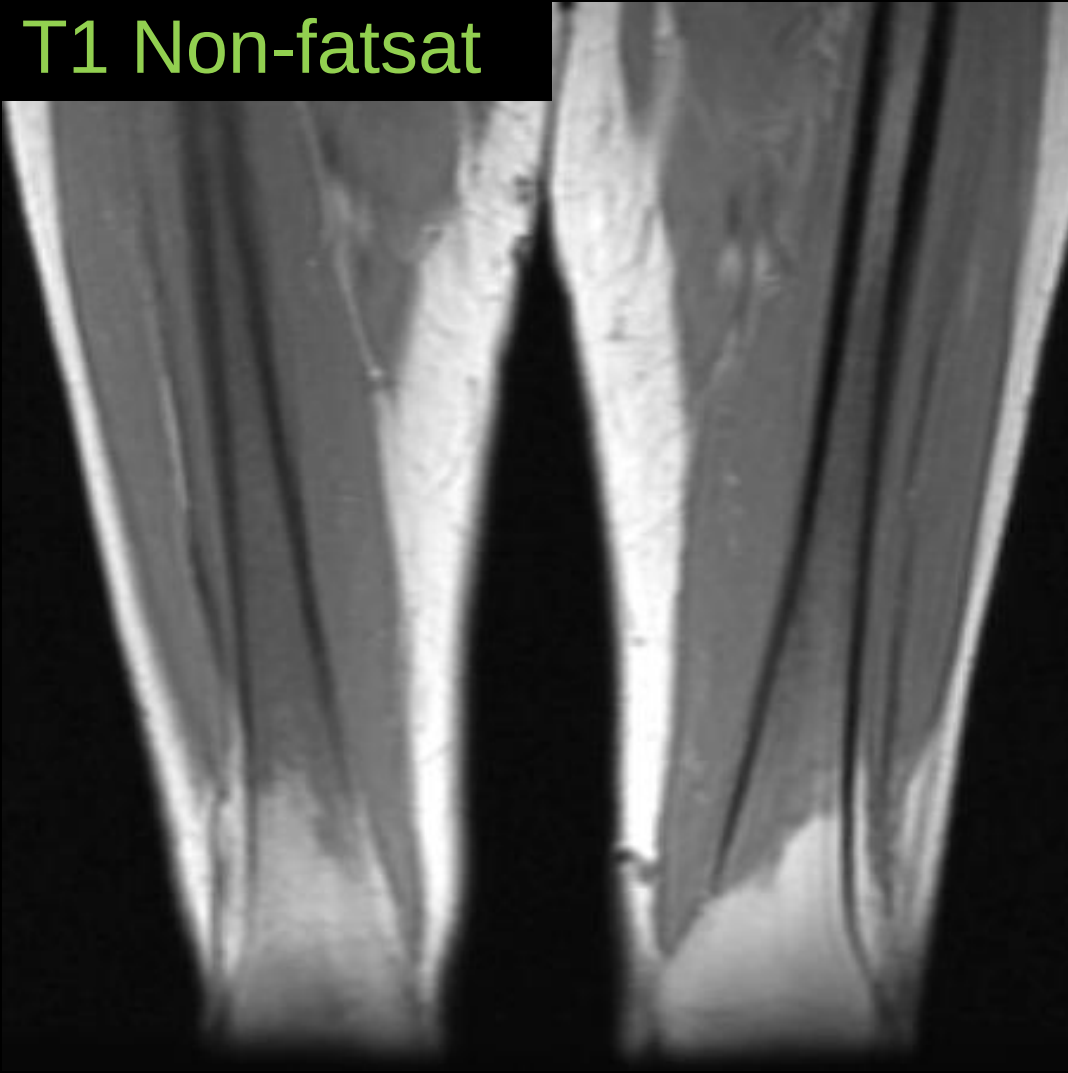


Marrow Reconversion

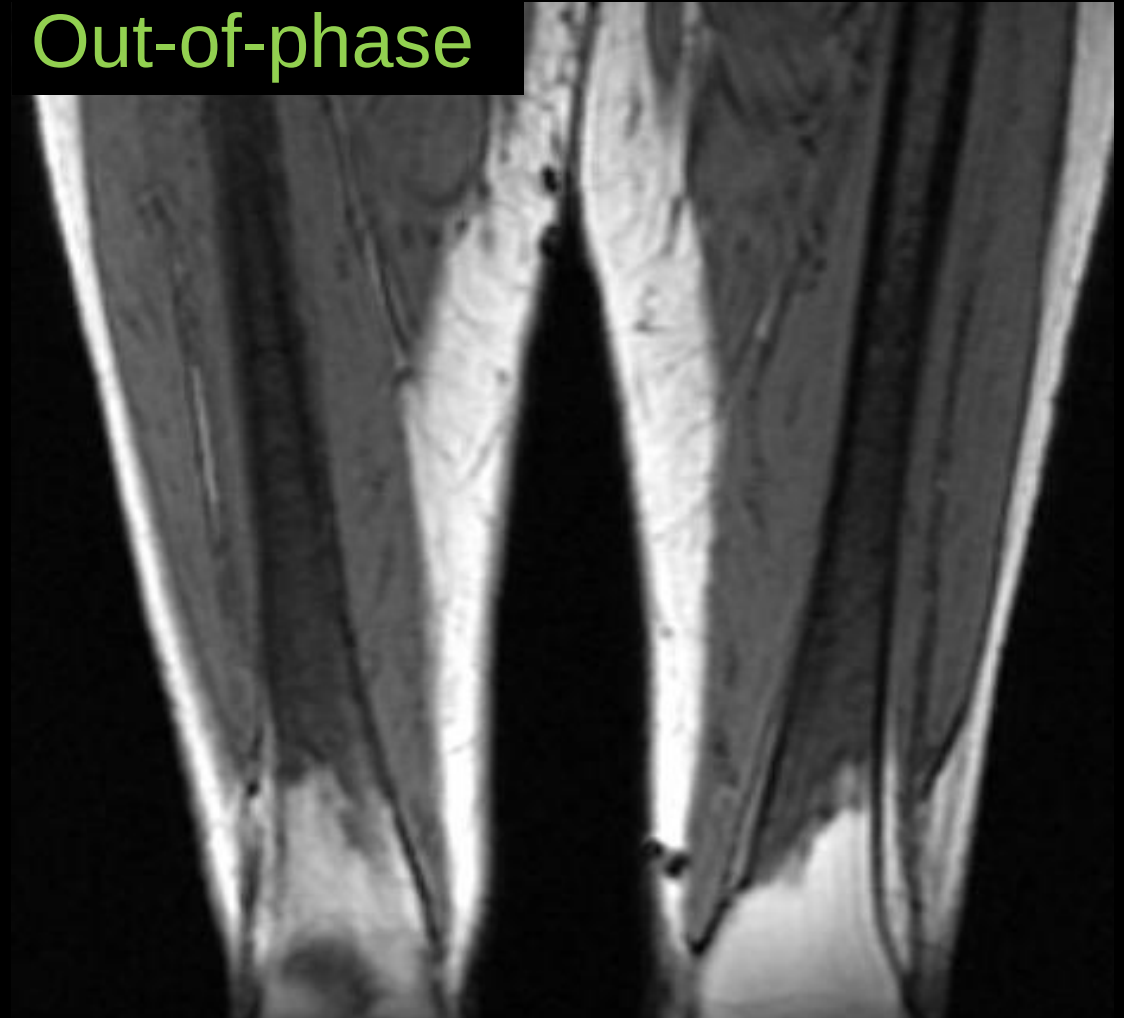
- Increased oxygen demand
 - Endurance athletes, cigarette smokers, esp obese females
- Severe chronic anemia
 - Sickle Cell, Thalassemia, Spherocytosis
- Treatment with granulocyte-macrophage colony stimulating factors (GM-CSF) during chemotherapy

Marrow Reconversion

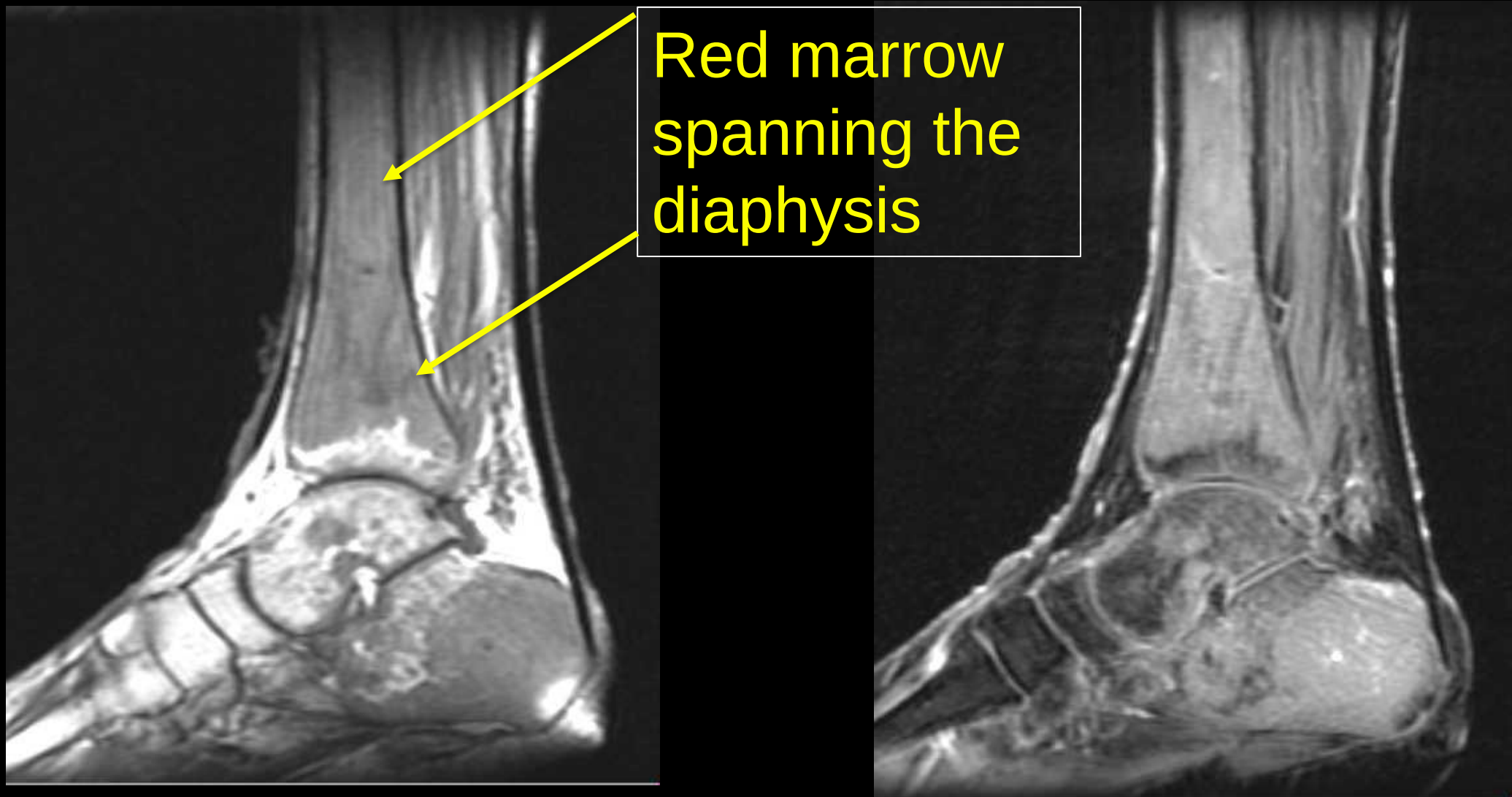
T1 Non-fatsat



Out-of-phase



Reconverted Marrow



Hx of Sickle Cell Disease

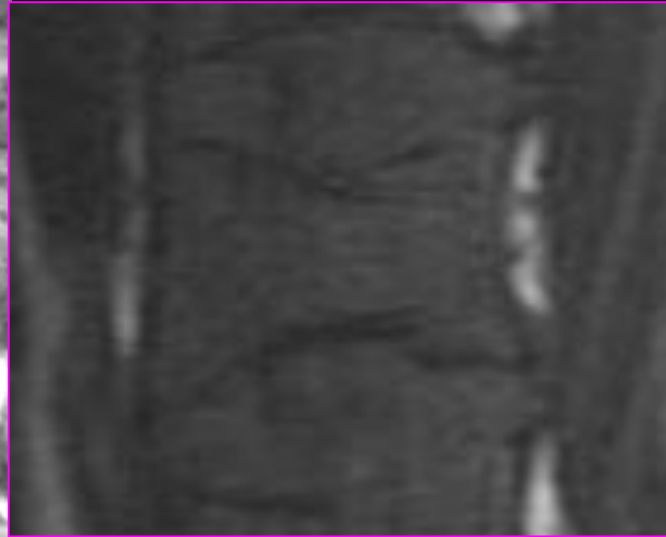
Hx of SCD

Marrow Reconversion



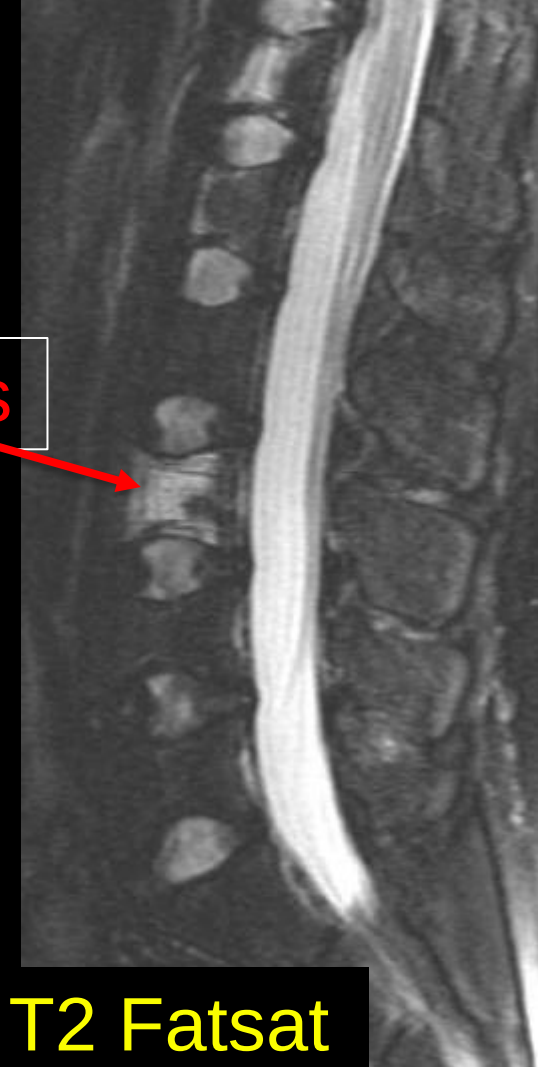
T1

Low T1 c/w disc



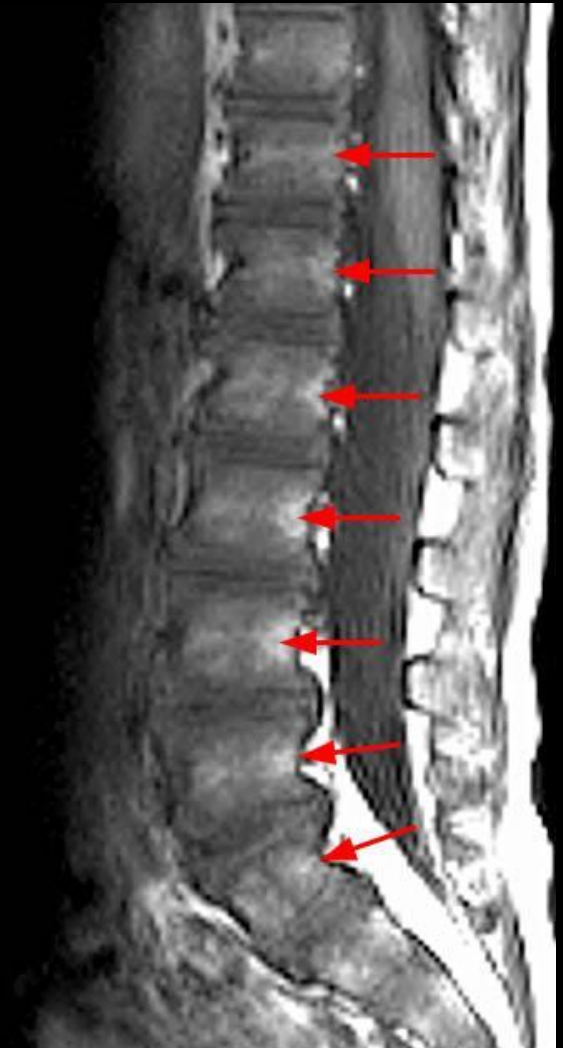
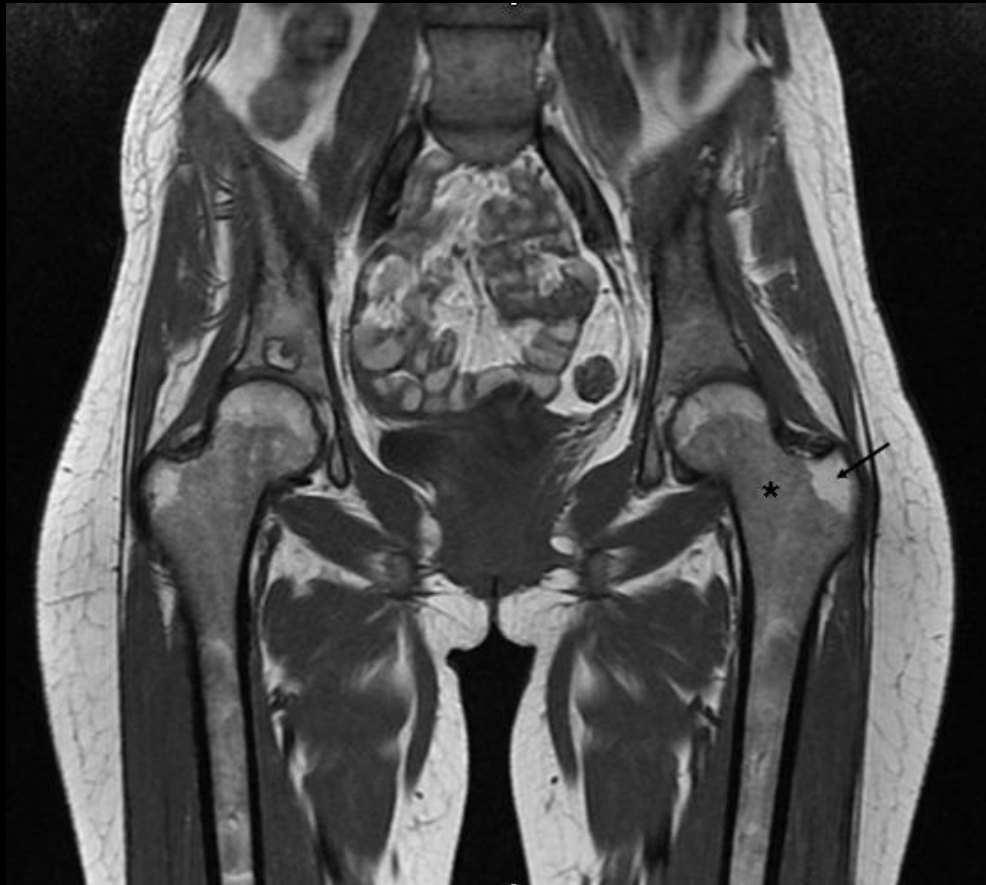
Central endplate depression- "H-shaped" vertebra

Infarcts



T2 Fatsat

Marrow Reconversion: Chronic Smoker



S/p treatment with GM-CSF

(Granulocyte macrophage Colony Stimulating Factor)

History necessary for dx!

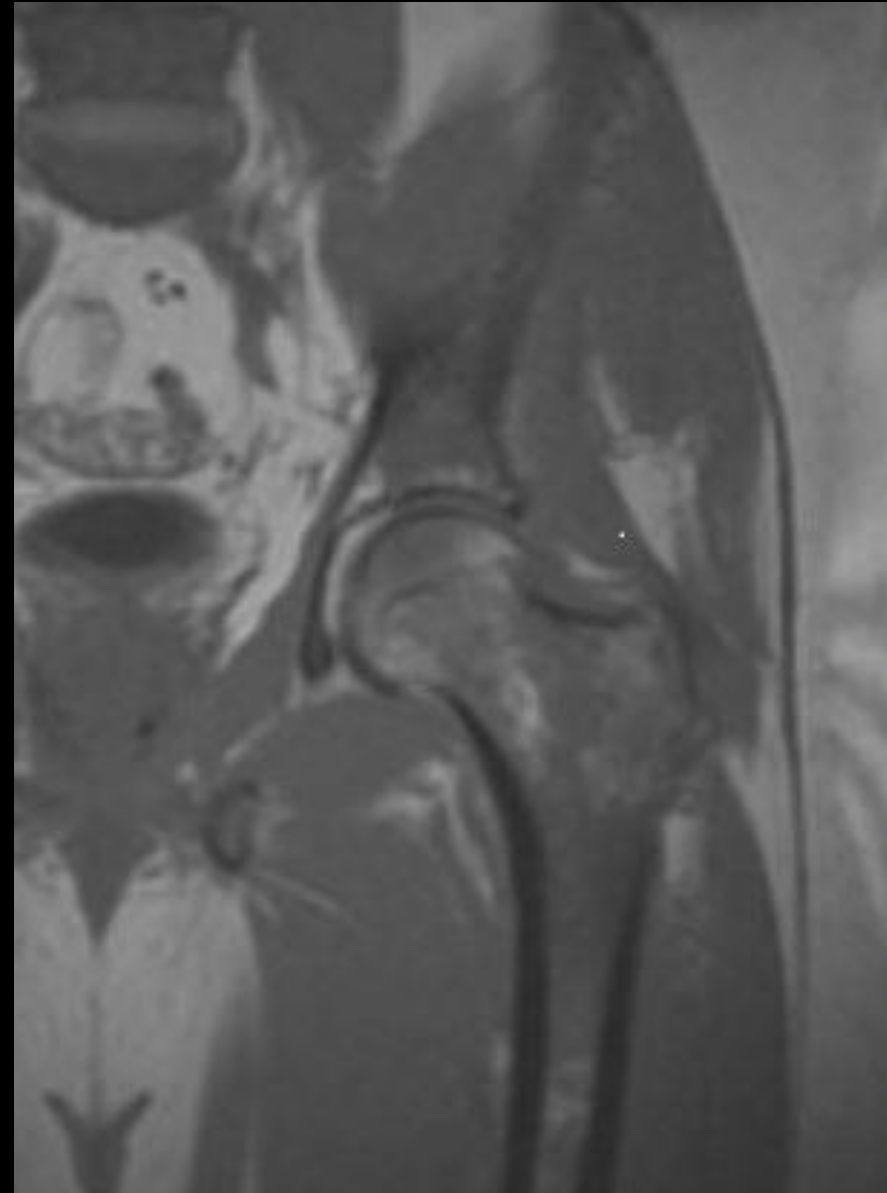
?? Recurrent/Met dz

-alteration in marrow signal
related to therapy usu.

coincides with elevations in
peripheral WBC

-median of 16 days btwn
initiation of therapy and
marrow changes

-clinical presentation



Marrow Replacement Disorders

- Proliferation of abnormal cells
- Neoplastic
 - Leukemia, lymphoma, multiple myeloma, mets
 - Mets-localize in red marrow due to richer blood supply
 - Vertebrae > pelvis > proximal femoral metaphysis > skull
- Can have similar imaging appearance to pathologic reconversion marrow



Diffuse low signal T1



CLL



Lymphoma

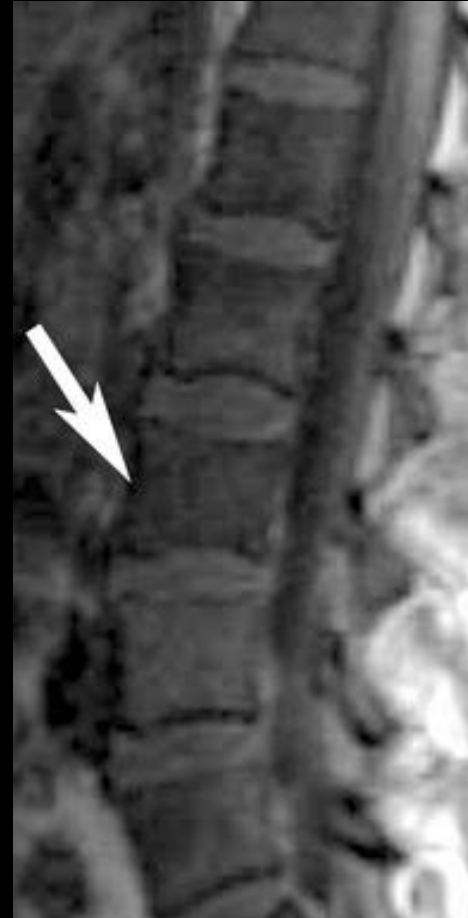
Marrow darker than adjacent disc- T1



T1WI



T2WI-FS



In-phase

No drop on out of phase



Out-of-phase

Discrete and
confluent areas of
marrow signal abnl

Metastatic Disease



T1



T2 Fat-sat

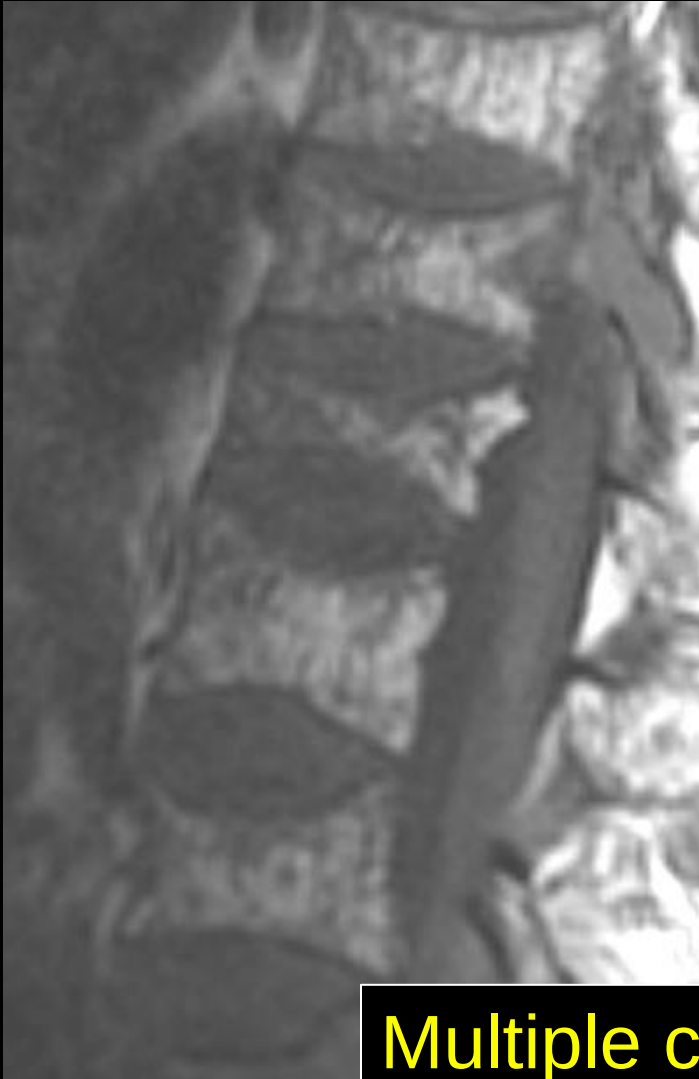


In-phase



Out-of-phase

Multiple Myeloma



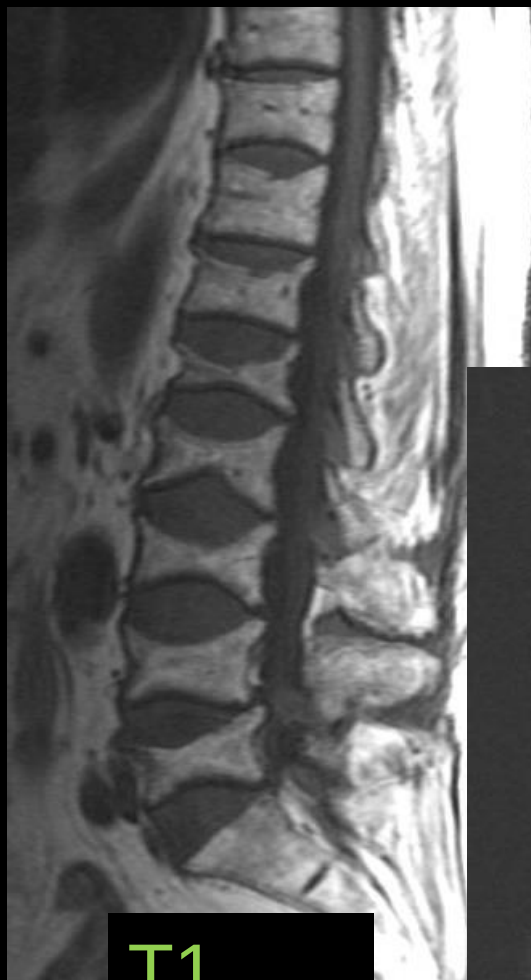
MRI imaging appearance:

- Normal
- Variegated (salt-and-pepper)
- Focal pattern
- Diffuse pattern

Stabler et al.– normal and salt-and-pepper marrow appearance associated with Stage 1 dz, focal and diffuse marrow changes suggest more advanced dz

Multiple compression fxs with salt and pepper appearance of the marrow

Multiple Myeloma



T1

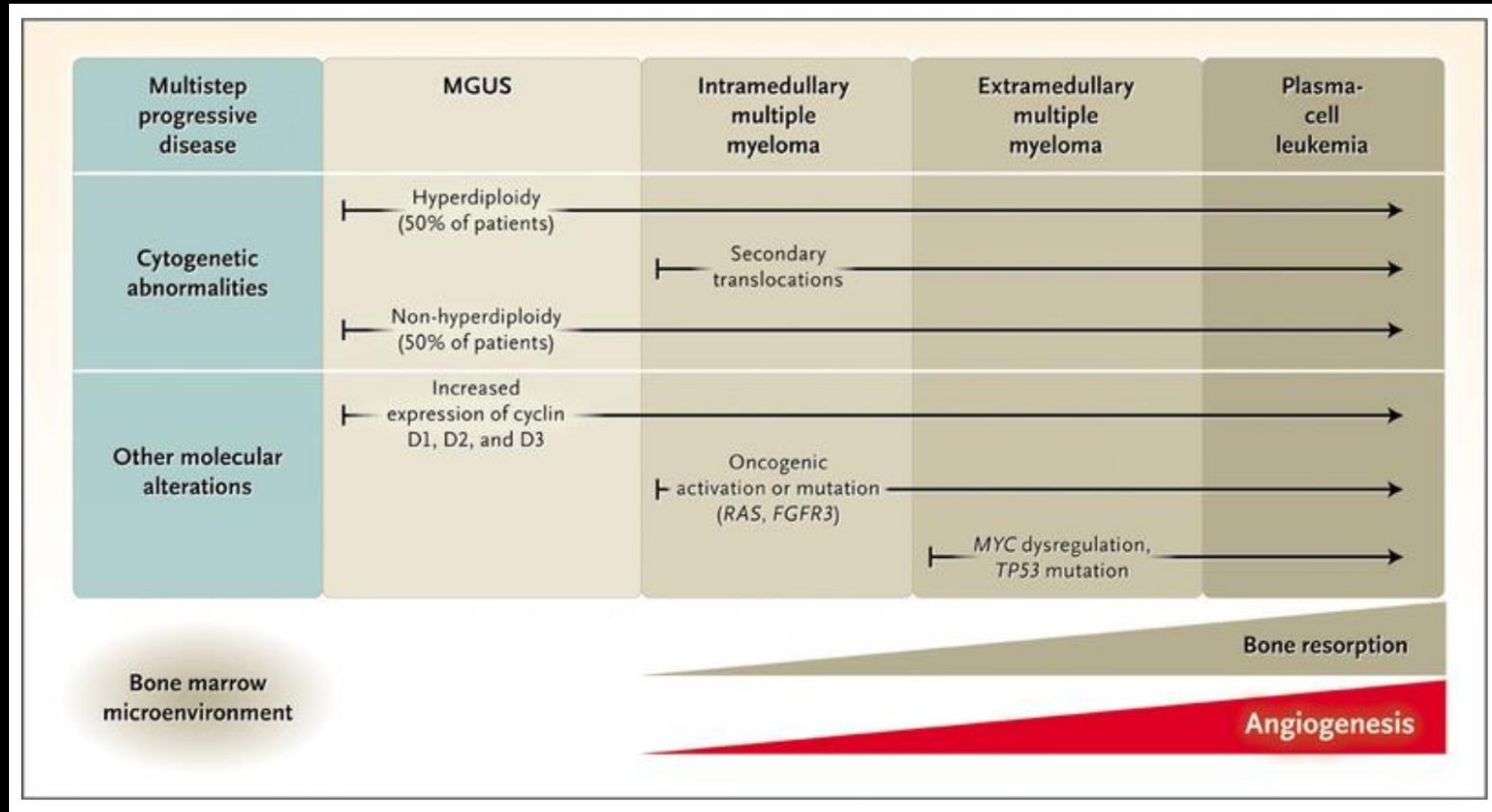
Normal fat
preservation



T1

Diffuse
low signal

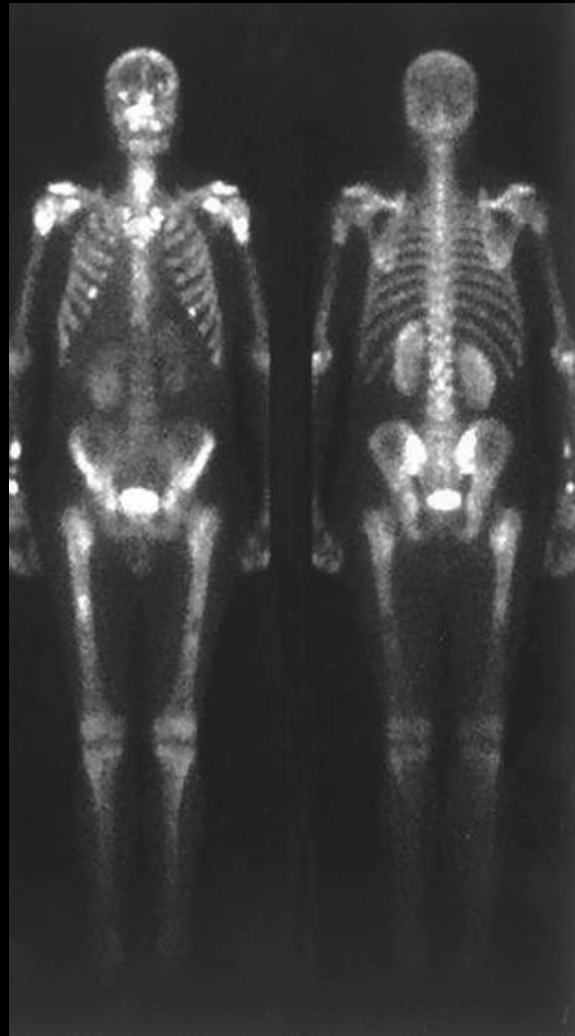
Imaging for Myeloma Staging and Treatment Response



Imaging for Myeloma Staging and Treatment Response



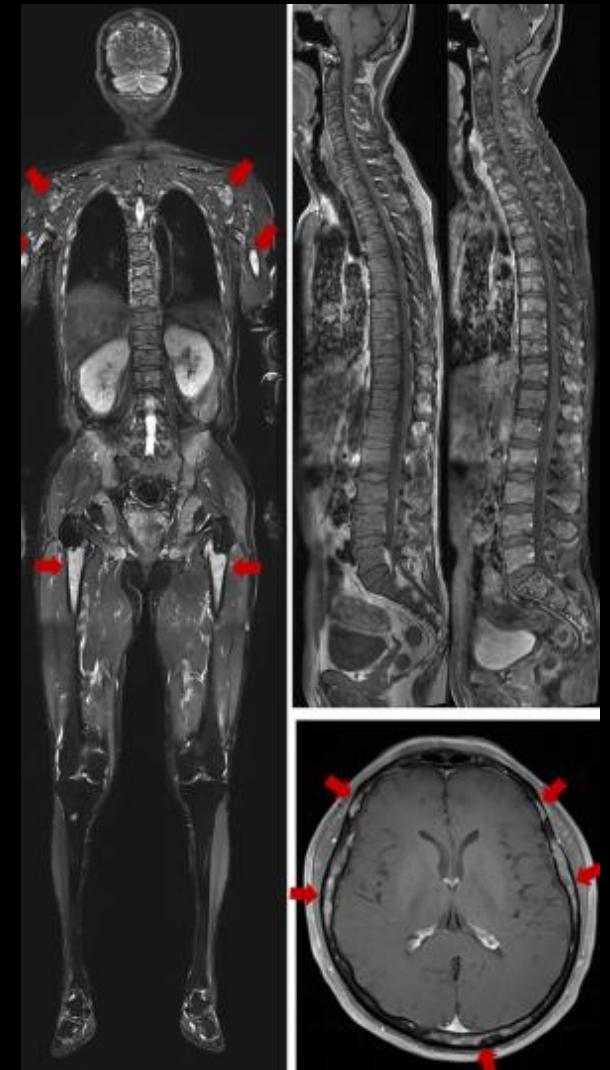
X-ray Skeletal Survey
(50% trabecular bone loss)



Scintigraphy



Low Dose Whole Body CT
(5% trabecular bone loss)



Whole Body MRI
(optimal sensitivity)

Marrow Depletion Disorders

- Loss of normal red marrow
- Viral infections, TORCH, pharmaceuticals, chemotherapy and XRT, aplastic anemia, idiopathic



S/p Left hemipelvis XRT

Increase in fatty marrow post XRT best appreciated in areas that nl contain a predominance of red marrow, ie. pelvis and spine



Look for radiation portal

S/p XRT



T1



T2 fatsat



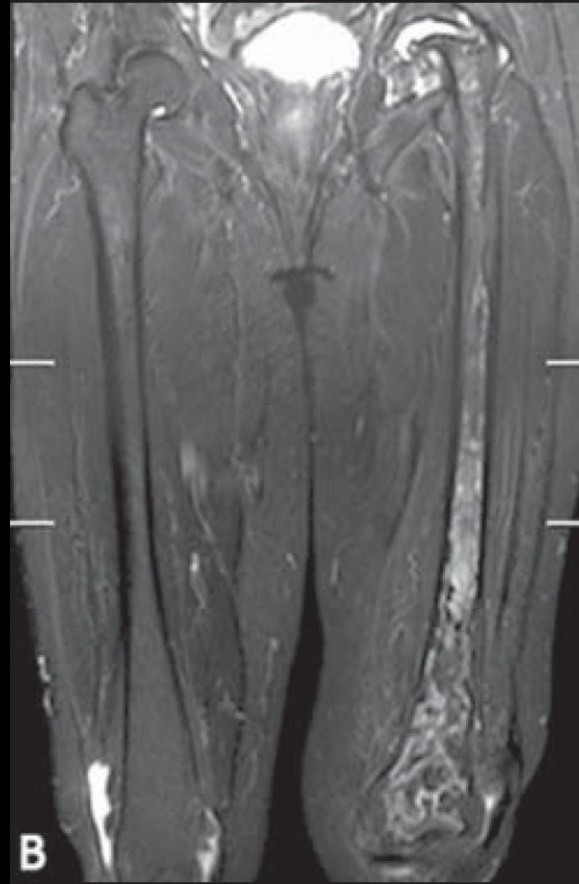
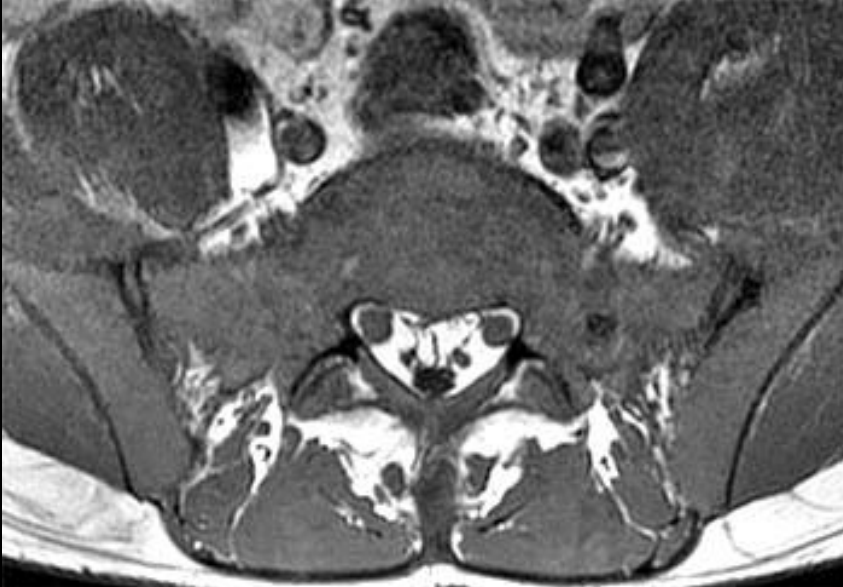
In-phase



Out-of-phase

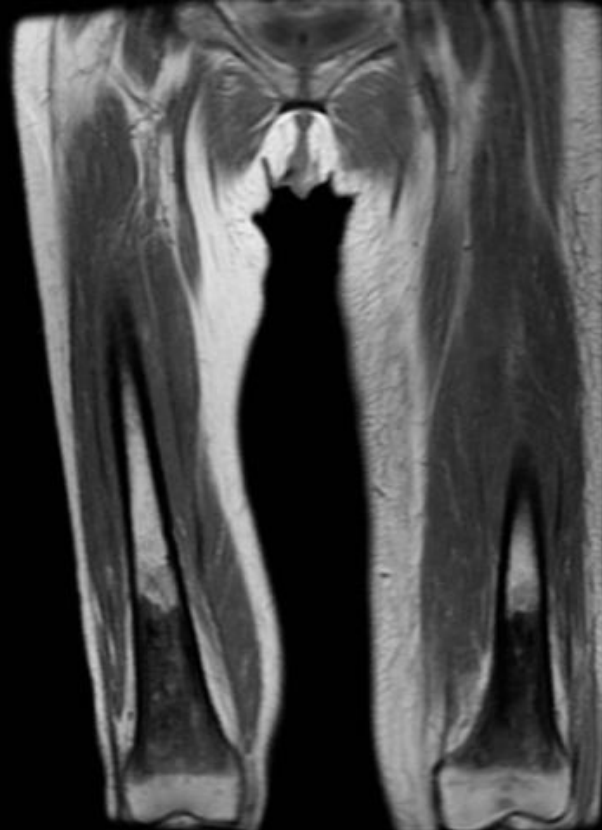
Disorders of Reticulum

- Replacement of normal marrow cells by fibrotic tissue
- Etiologies:
 - Myelofibrosis, Lysosomal Storage disorders (Gaucher's)



Erdheim-Chester

- Non-Langerhans-Cell Histiocytic Neoplasm



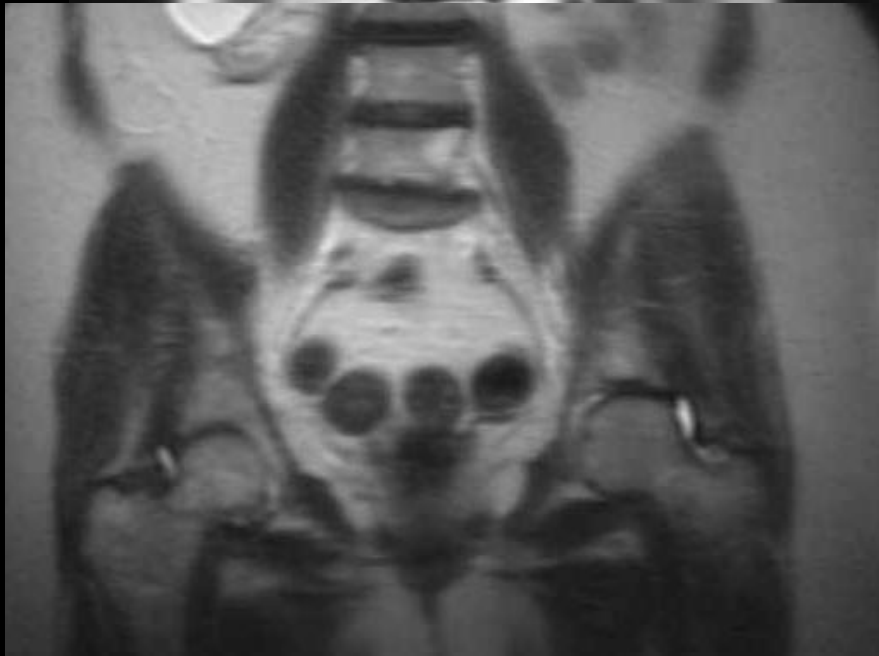
Fast Field Echo (FFE)

- Useful for large FOV survey



SSFSE

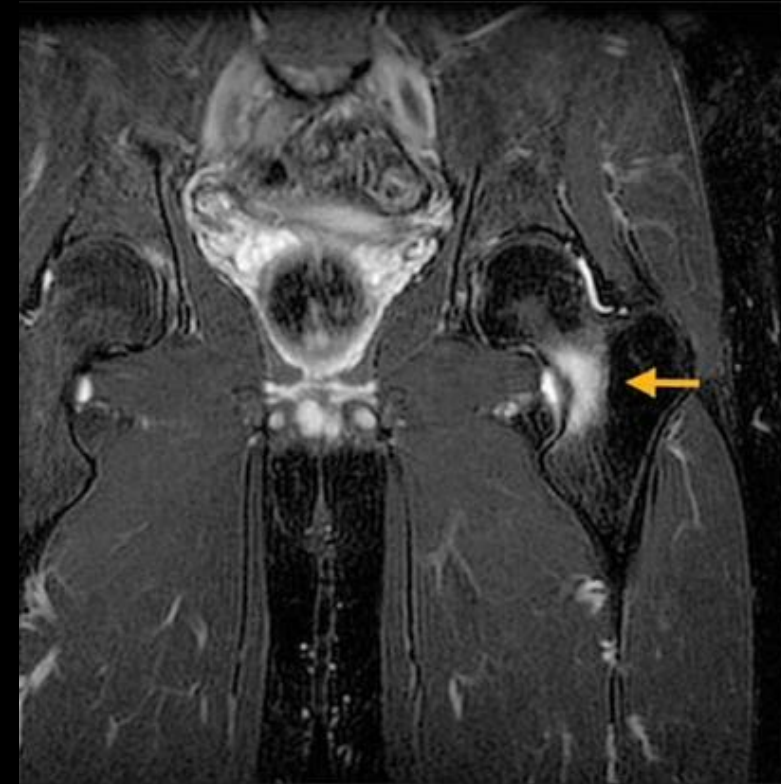
- T2w, fat bright
- Limited for marrow pathology



Myeloma

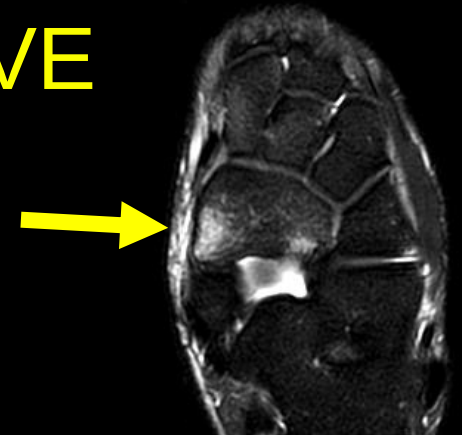
Bone Marrow Edema (BME, BME like signal)

- Nonspecific response by living osseous infrastructure
- Patho-physiology (ECF)
 - hypervascularity & hyperperfusion (hyperemia)
 - inflammatory infiltrate → resorption
 - granulation (fibrovascular) tissue
 - Adaptive/Reactive → biomechanical (Wolfs Law)
- Signal varies with amount of extracellular H₂O
- Enhancement with contrast irrespective of etiology



BONE MARROW EDEMA DDX

- ARTIFACTUAL
- TRAUMATIC
 - Acute
 - Repetitive
- BIOMECHANICAL
- CONGENITAL/
DEVELOPMENTAL
- VASCULAR
- NEOPLASTIC
- INFLAMMATORY
- NEUROPATHIC
- DEGENERATIVE
- IATROGENIC
- IDIOPATHIC
- ADJACENT
EXTRINSIC ST DZ

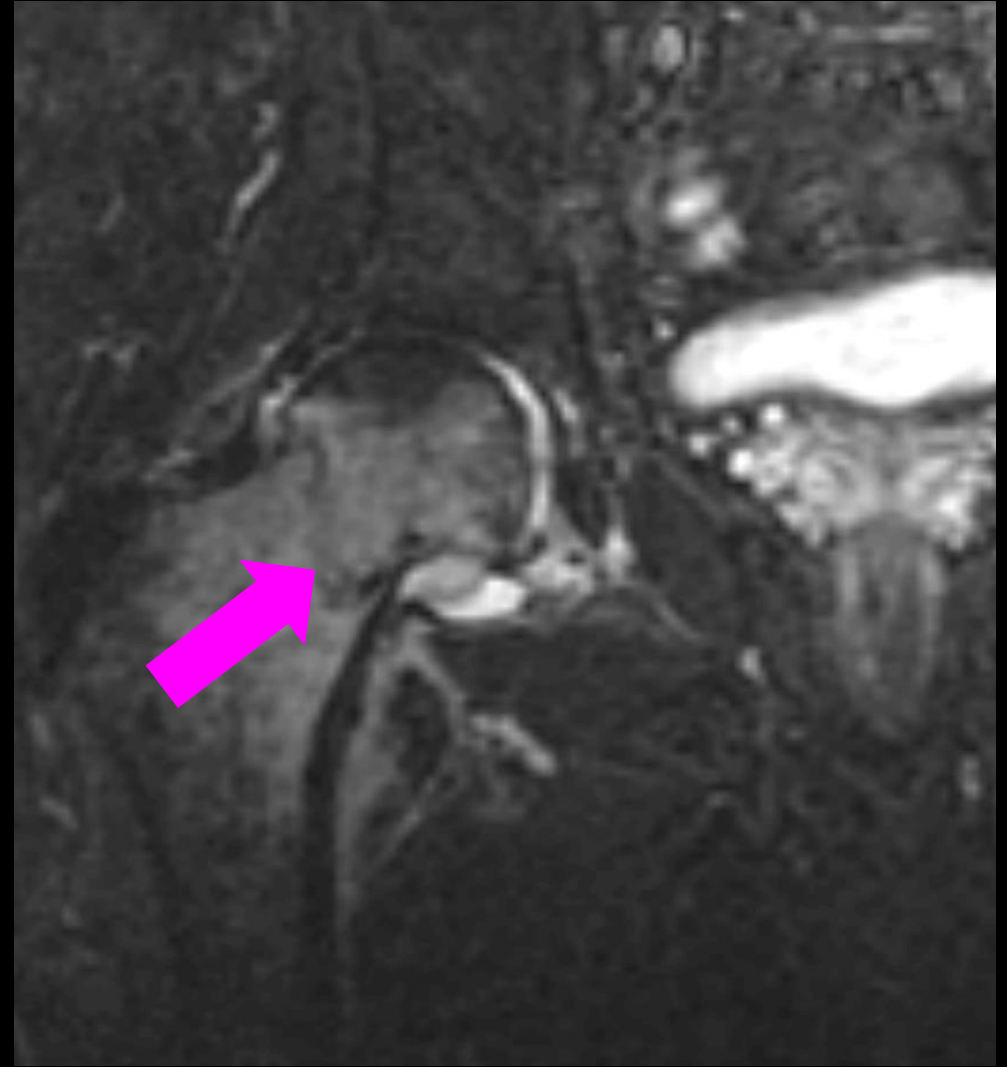


TRAUMA

- Typical locations
- History
- Associated soft tissue injuries
- “Fireworks” pattern
- Occult to radiography
- MRI offers exquisite sensitivity and reproducible patterns



Femoral Neck Occult FX



s/p fall with hip pain



Runner with persistent
medial foot pain

Occult 1st MT stress
Fracture



Osseous Contusion

- “BONE BRUISE”

- Mi

- no

- Pa

- of

- Of

- im

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Bone bruise vs. non-displaced fracture on MRI: a novel grading system for predicting return-to-play

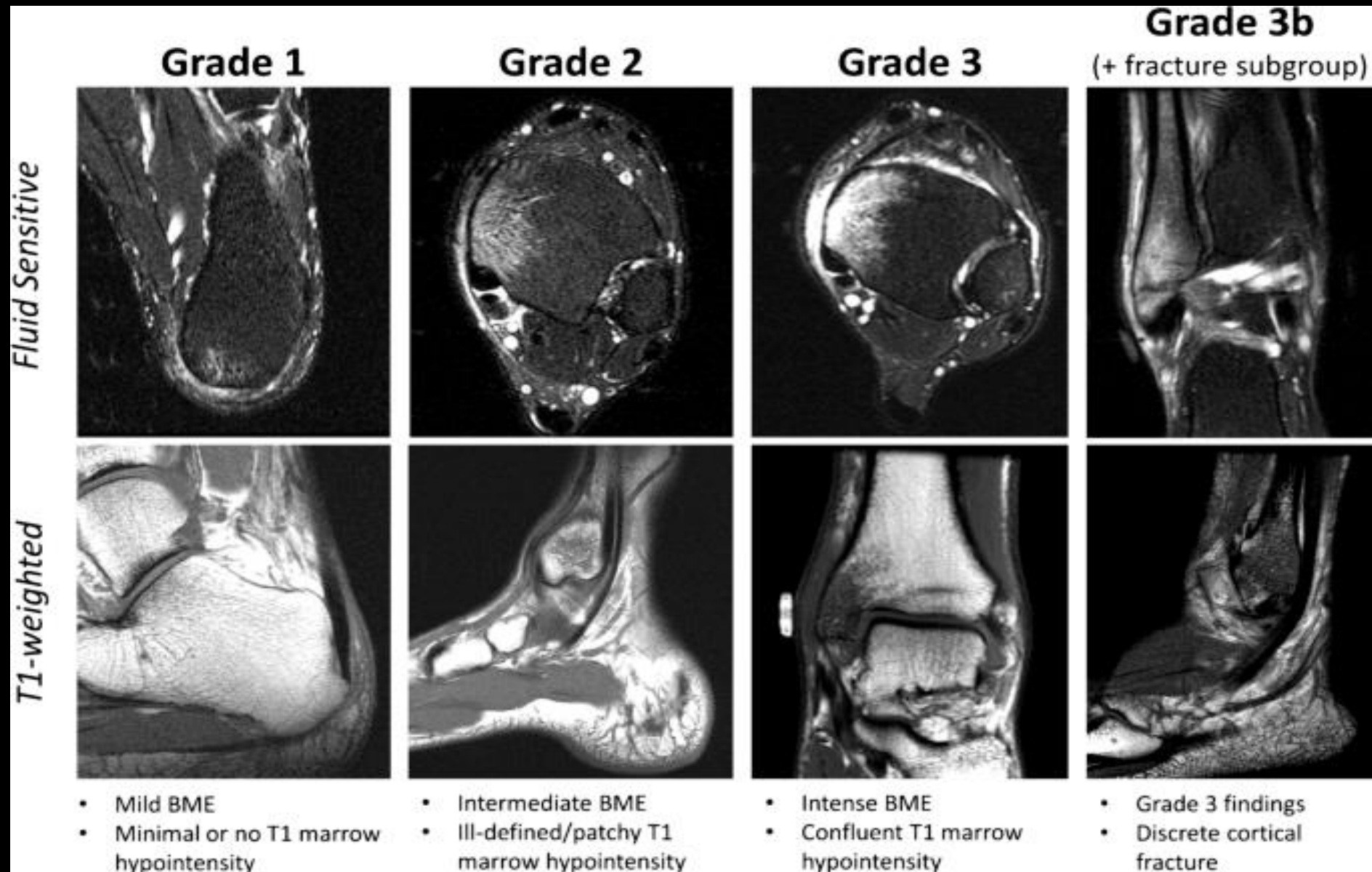
Scientific Article | Published: 23 November 2023

Volume 53, pages 947–955, (2024) [Cite this article](#)

[Jeffrey A. Belair](#) , [Jin Jung](#), [Vishal Desai](#), [William B. Morrison](#), [Peter F. DeLuca](#) & [Adam C. Zoga](#)

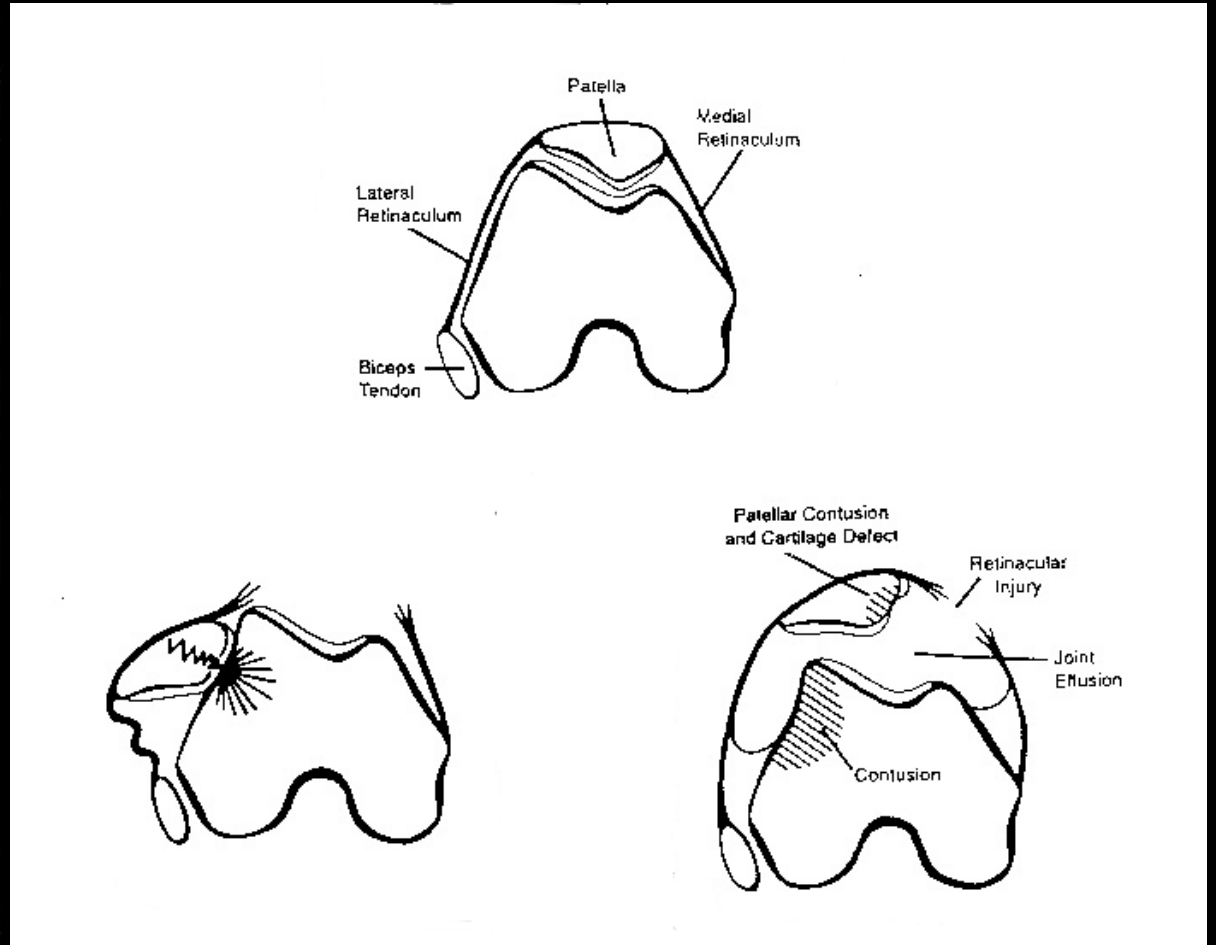
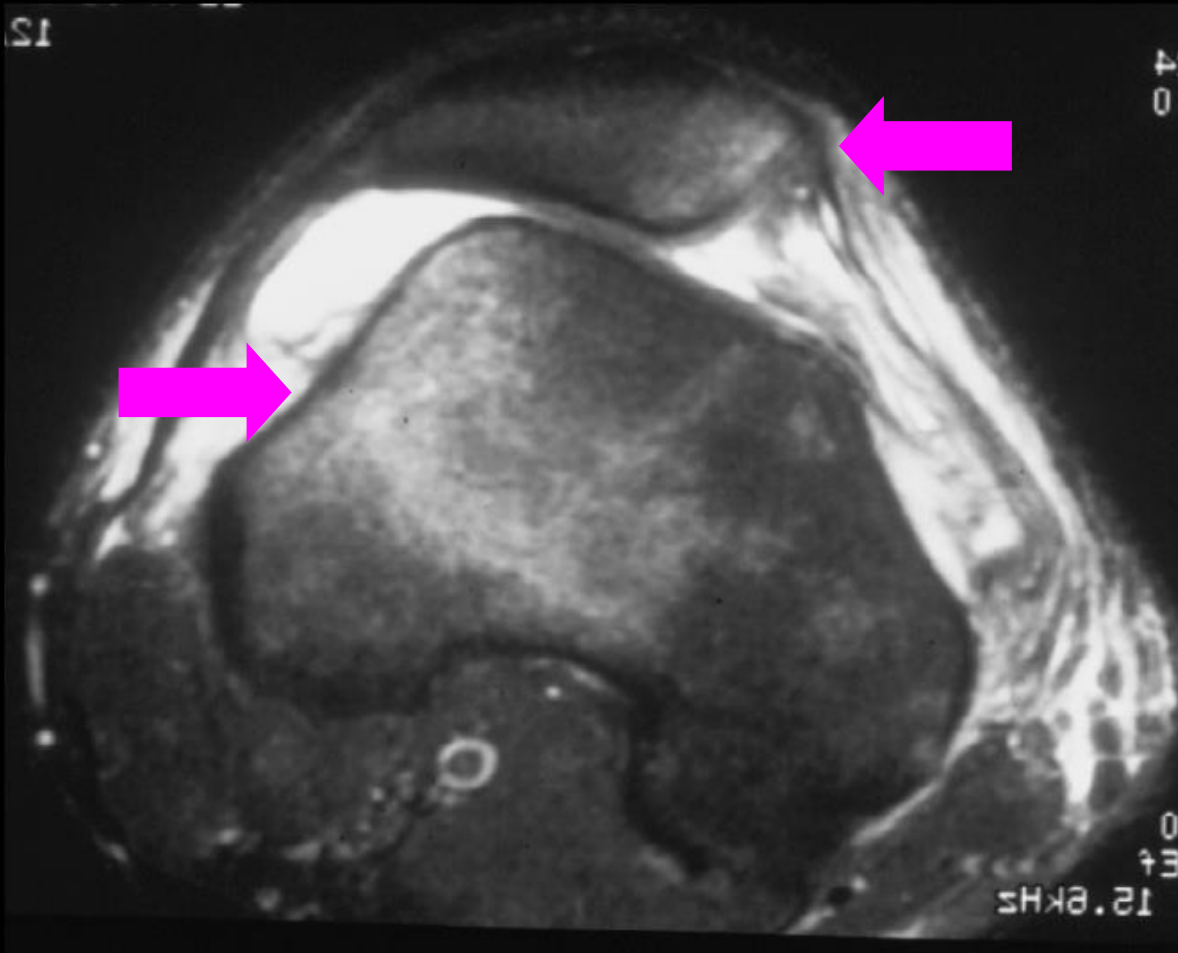
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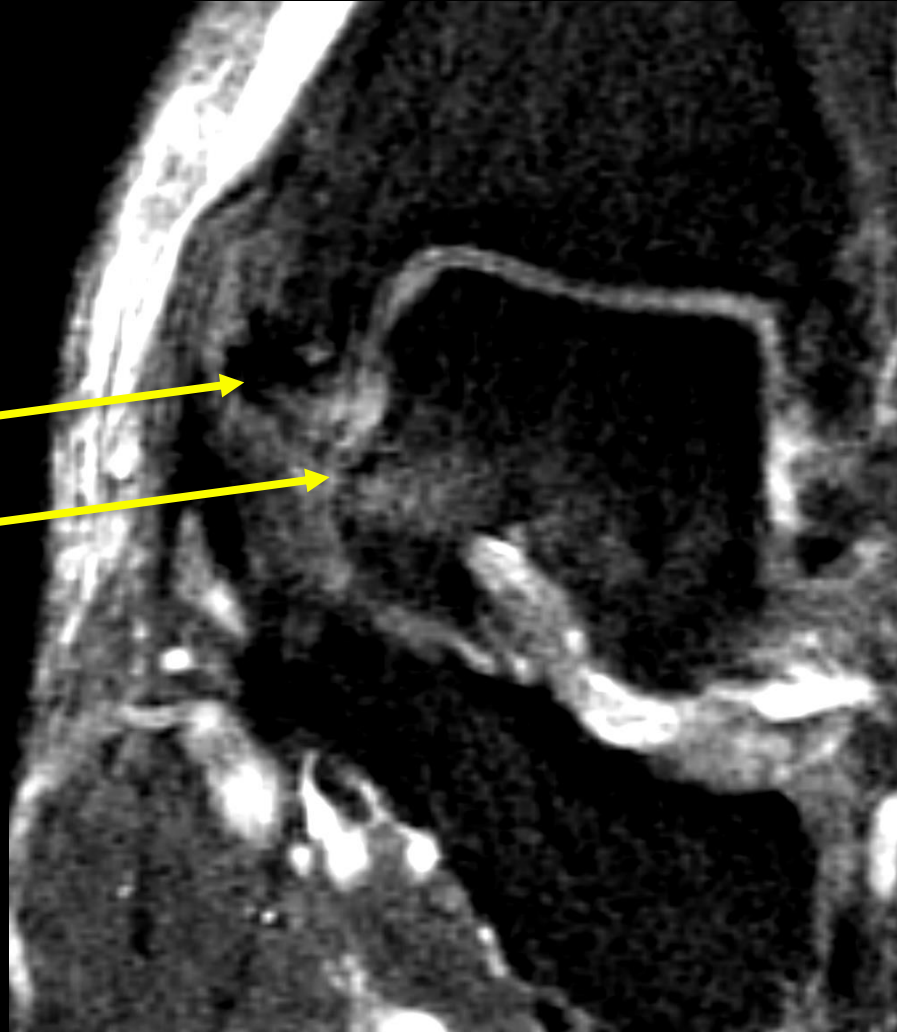
Globular T2 BME with T1 hypointensity had same RTP as true fracture

Recent Transient Lateral Patellar Dislocation



Ankle inversion injury

“kissing”
contusions MM
and medial
talus from
impaction
medially due to
tensile failure
laterally

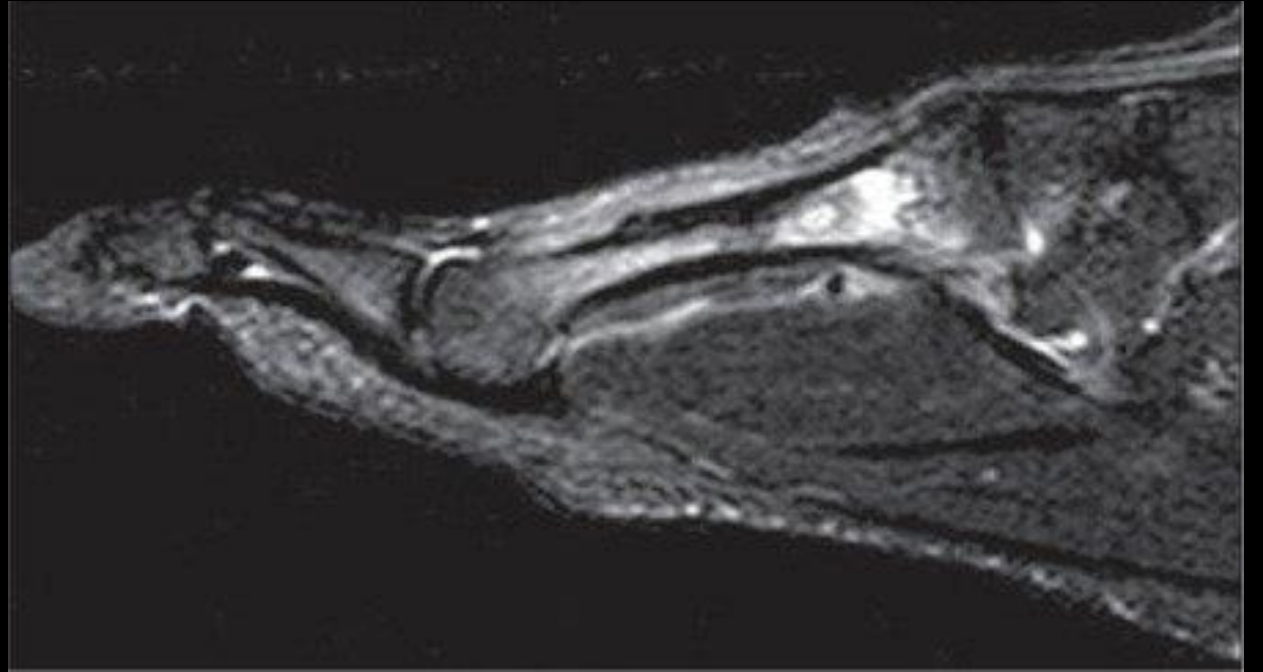
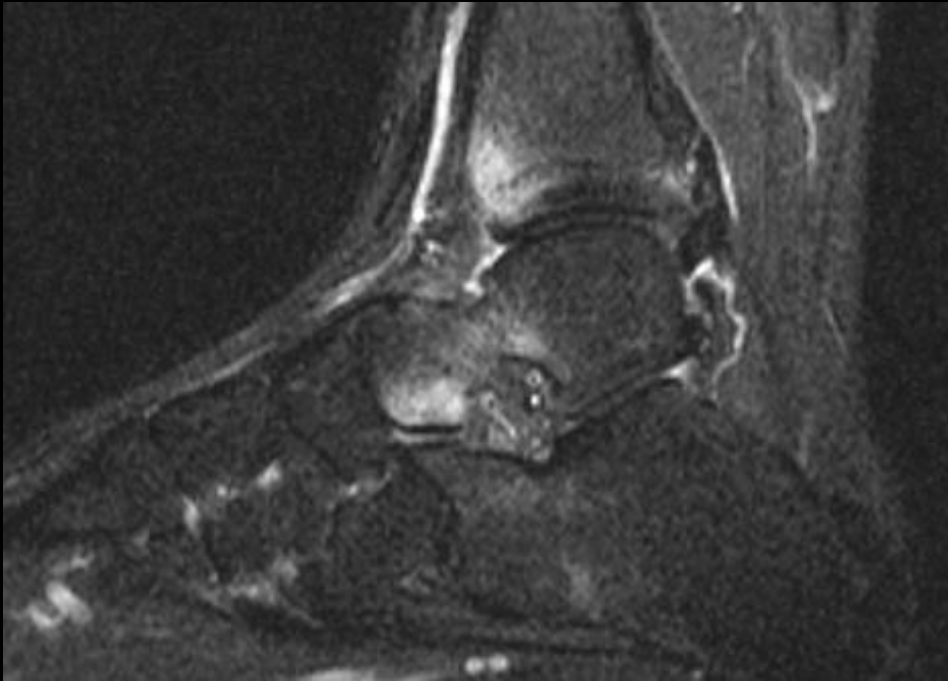


BIOMECHANICAL

- Stress: Injury to *normal bone* related to repetitive, excessive forces.
 - Can be microtrabecular early
 - Can progress to true fracture through cortex
 - AKA fatigue fracture
- Insufficiency: Normal stresses on *abnormal bone* causing osseous injury
 - Osteoporosis
 - Malignancy
 - Infection



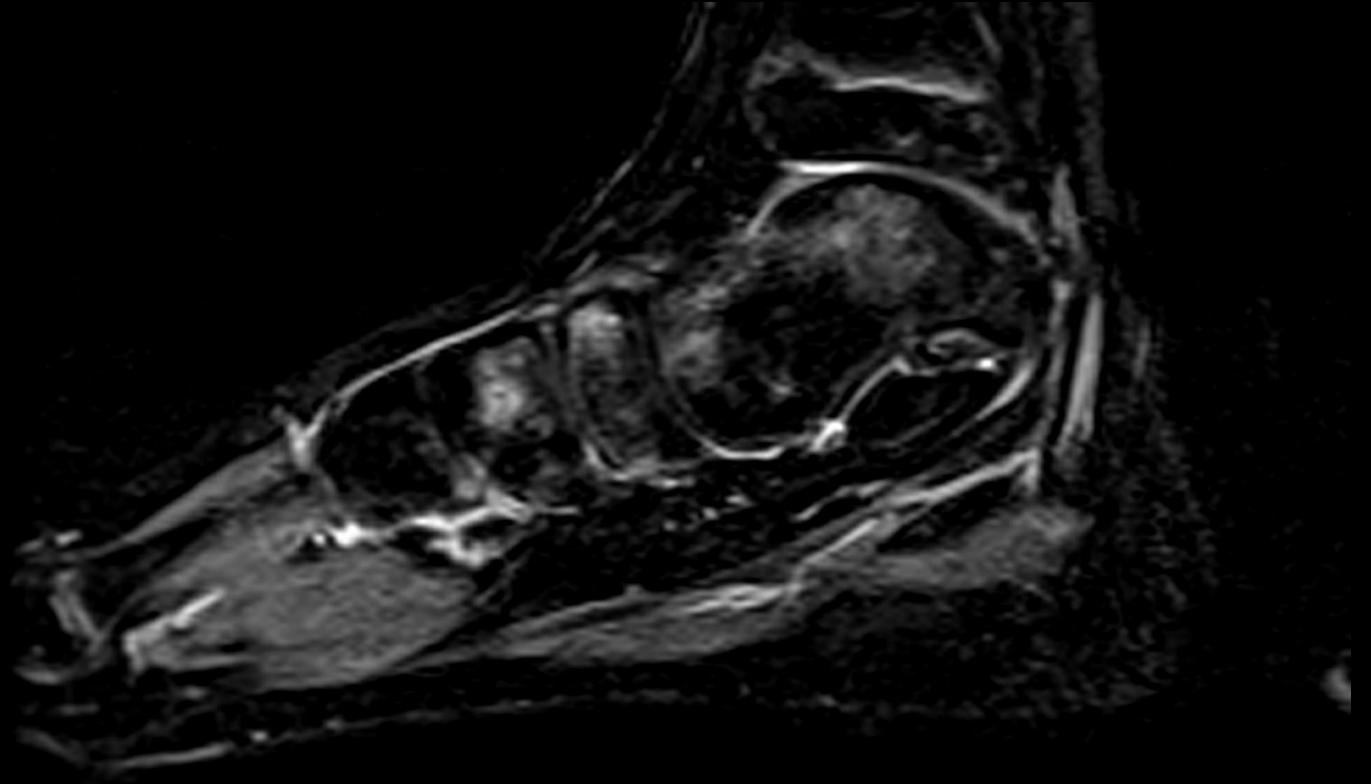
Overuse Related BME



Ballerina

Disuse BME-Diffuse

- BME without fracture or symptoms
- Patterns of BME- patchy, subcortical, or subenthesisial



H/o recent boot immobilization

Post immobilization BME: Patchy

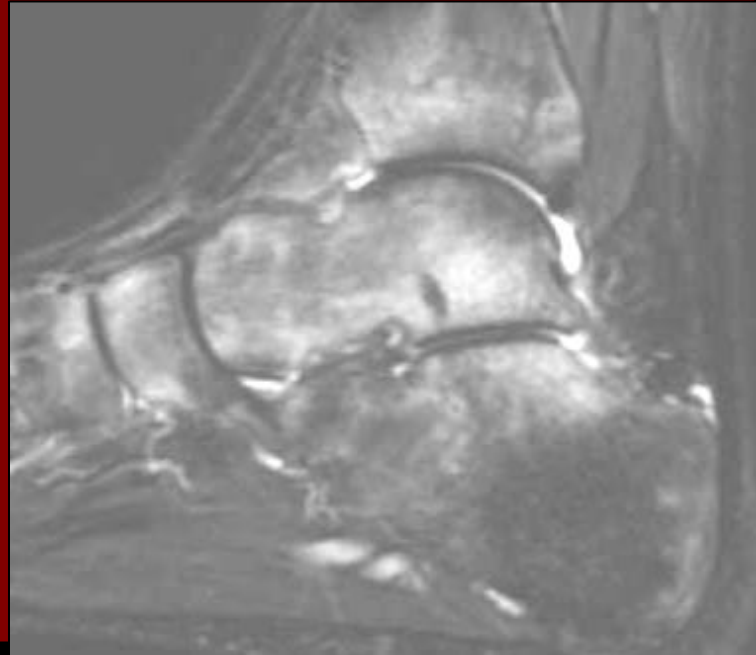


Hx of recent cast immobilization

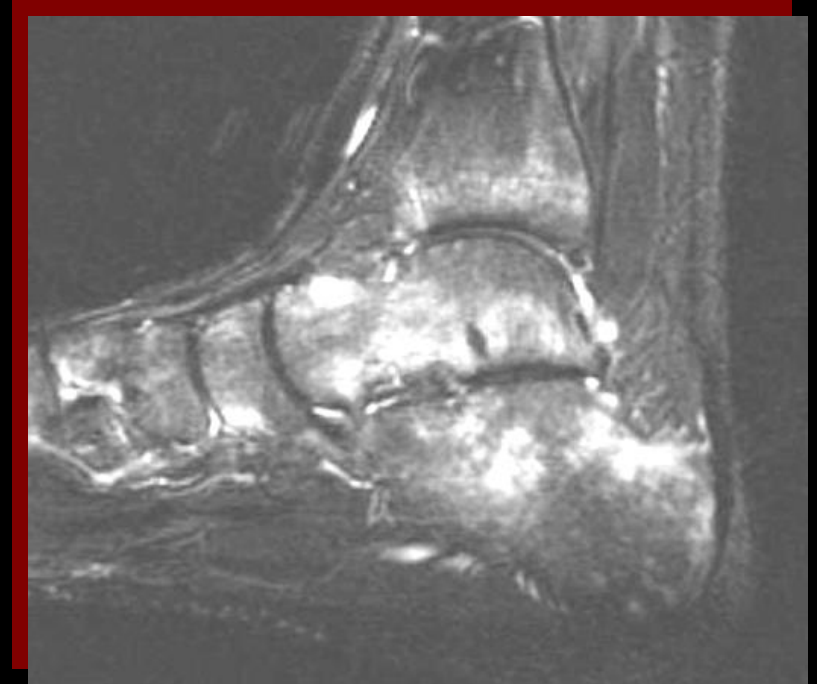
Evolution of Disuse BME



At time of cast removal



1 month post cast removal



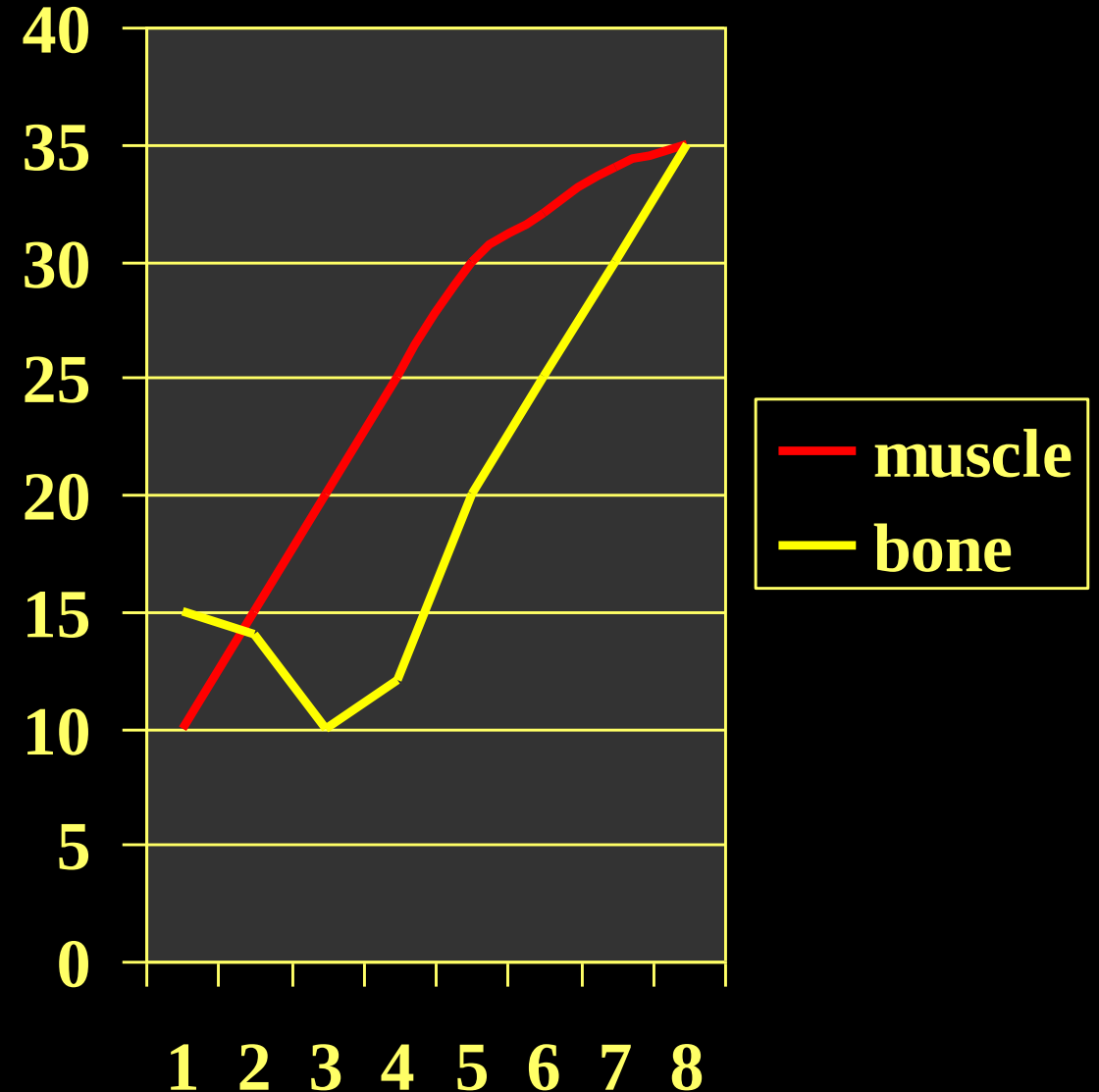
4 month post cast removal

Distal fibula fracture, immobilized for 10 wks, persistent lateral ankle pain

Etiology of Stress Fracture

- During early phase of a new activity, muscle steadily increases strength
- Bone must undergo a phase of osteoclastic resorption first

“AT RISK PERIOD”



Fatigue Fxs:

Predisposing Conditions

- **Anatomic/Biomechanical**
 - Broad Pelvis
 - Femoral anteversion
 - Genu valgus
 - Tibial Torsion
 - Foot Pronation
 - Limb Length discrepancy
 - Muscle imbalances
- **Training Errors**
 - change in intensity, speed or distance
 - insufficient stretching or rest
- **Equipment**
 - inadequate or inappropriate

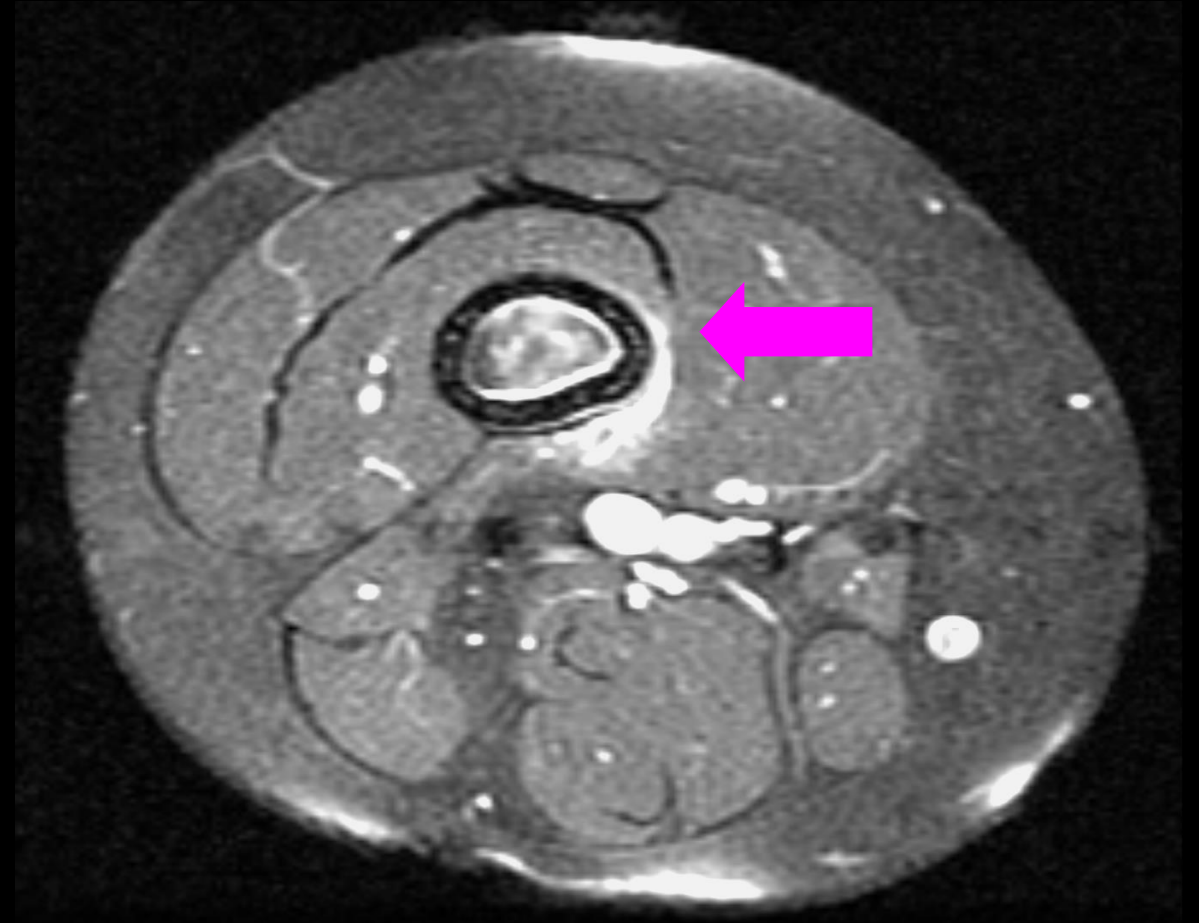


Stress and insufficiency fractures occur in predictable locations

Soccer player with thigh pain

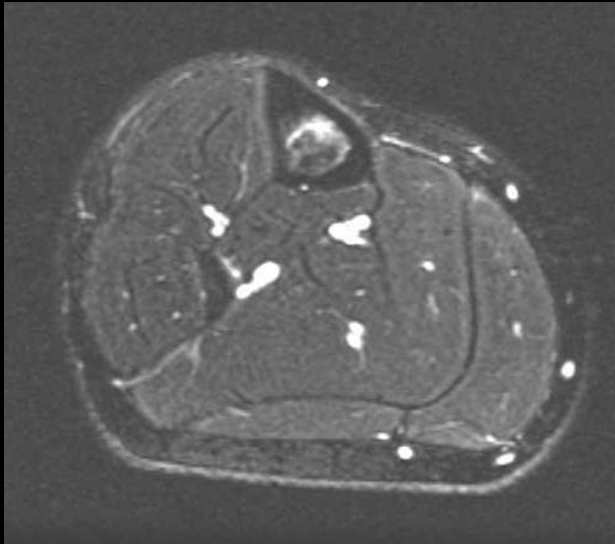
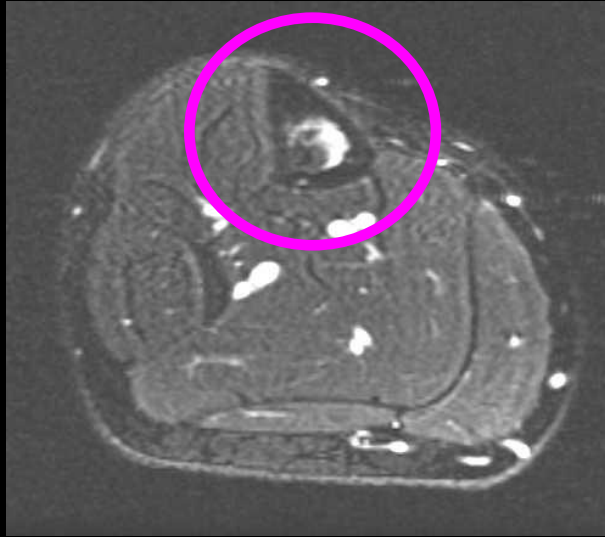


Stress Response / Thigh Splints



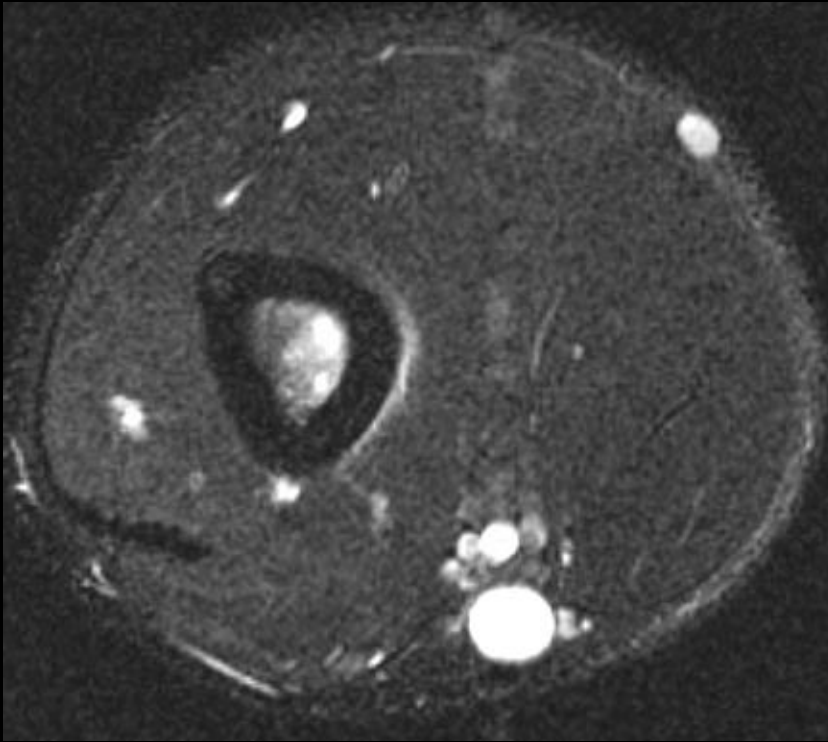
No discrete fracture line!

Medial Tibial Stress Syndrome, ie Shin Splints



Runner with shin pain

Humeral Stress Injury



Pitcher with elbow pain

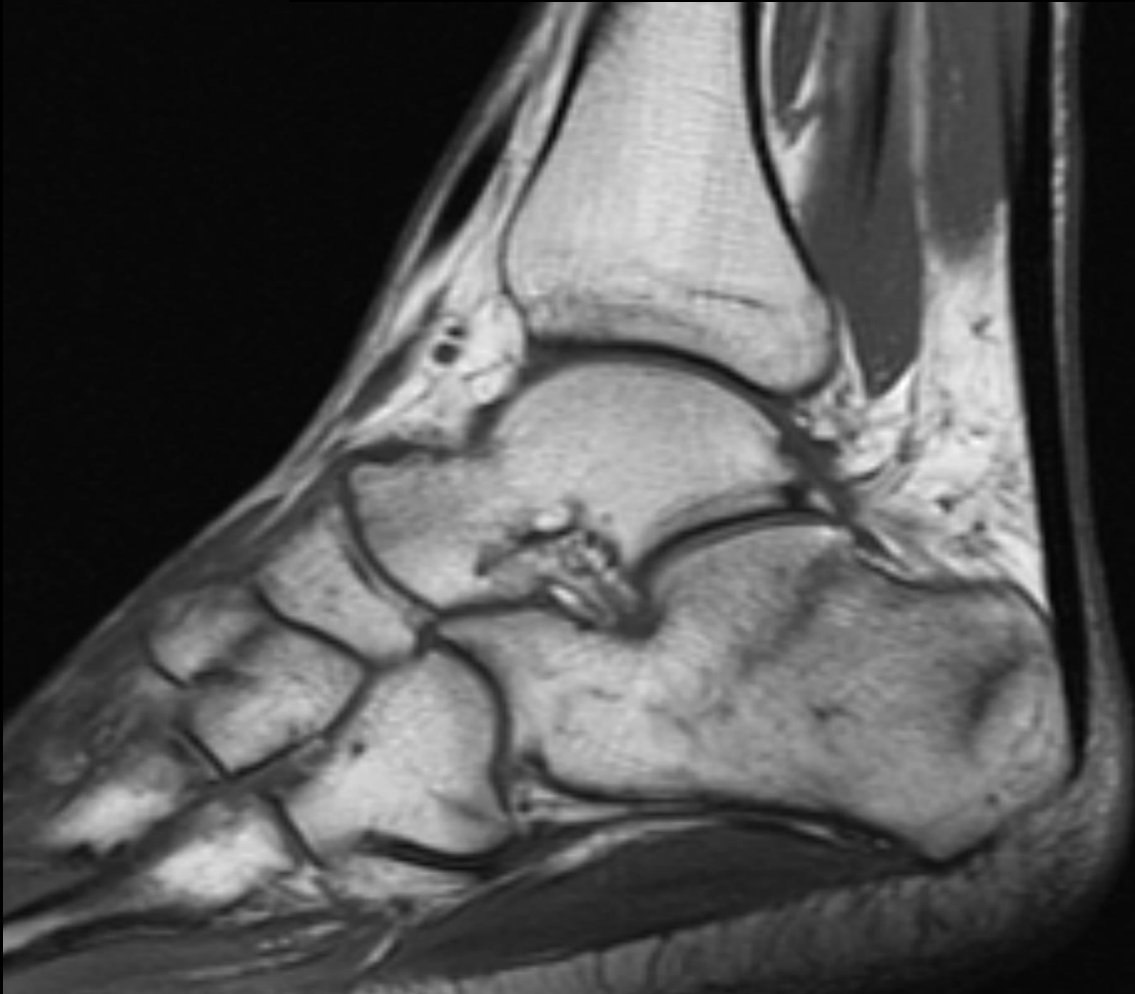


Fibula Stress Fracture: why??



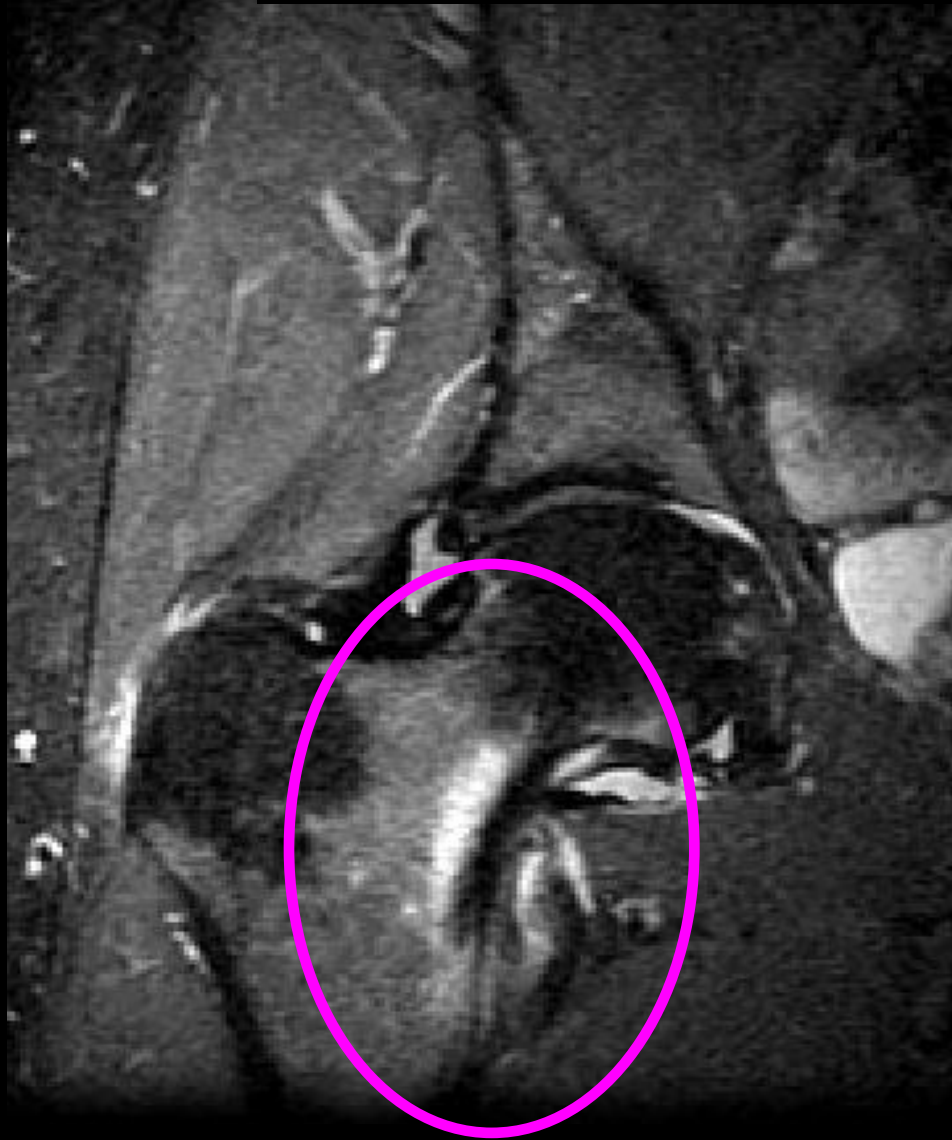
Runner with lateral ankle pain

Calcaneus Stress Fractures



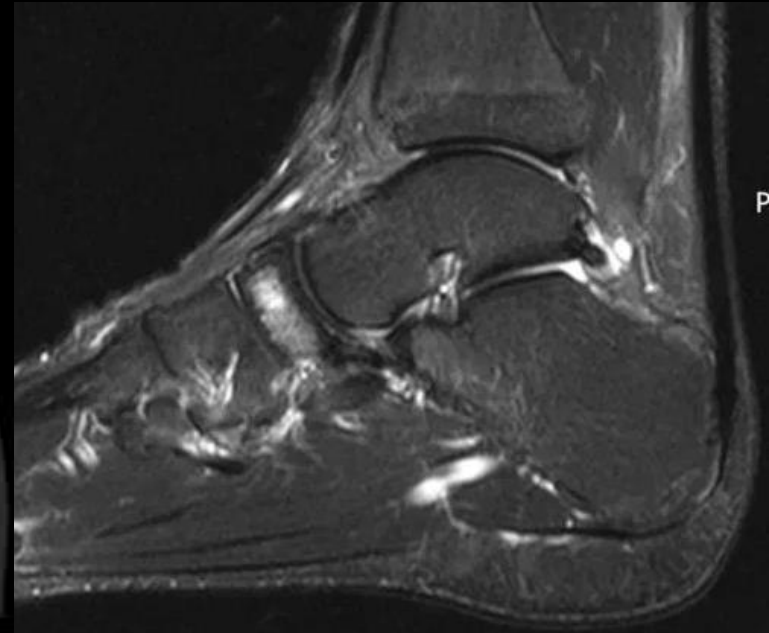
Military recruit with heel pain

Femoral Neck Stress Fracture

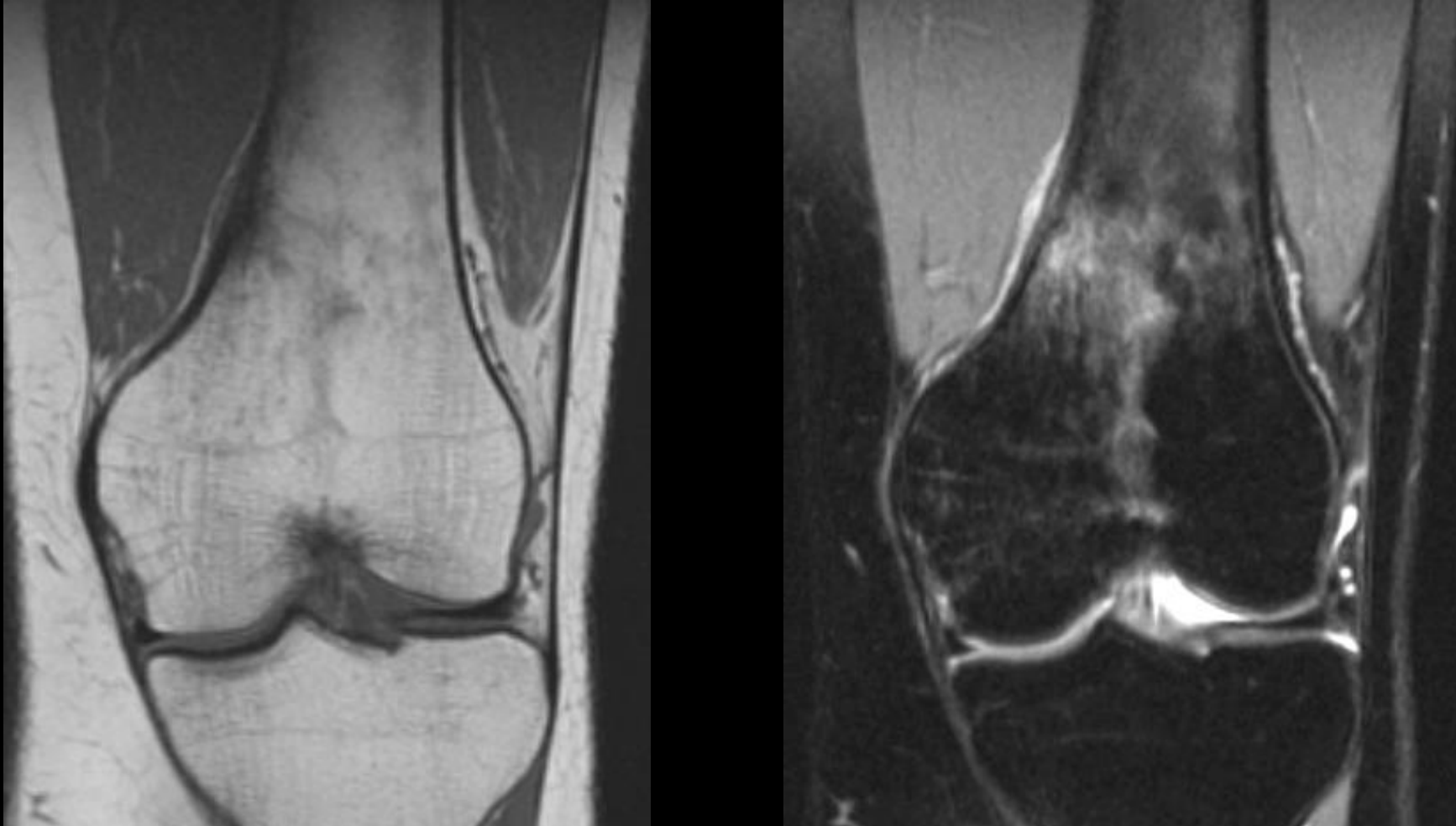


High-Risk Stress Fractures

- High risk for progression to complete fx, delayed union/non-union
- Aggressive treatment, poss surgical intervention
- Locations:
 - Femoral neck
 - Patella
 - Anterior cortex of tibia
 - Medial malleolus
 - Talus
 - Tarsal Navicular
 - Great toe sesamoids
 - 5th Metatarsal

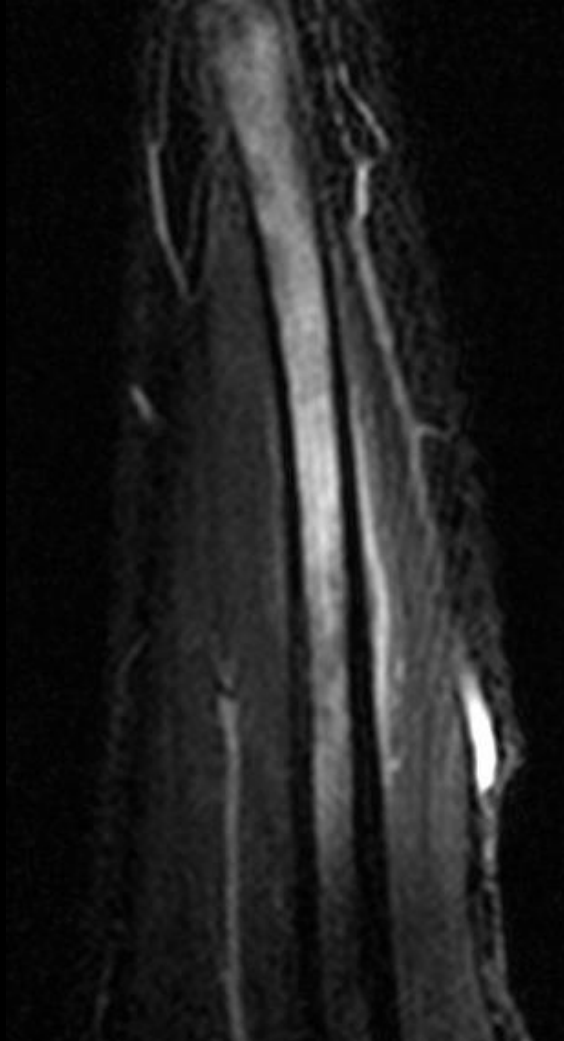


Stress Fractures- less common locations

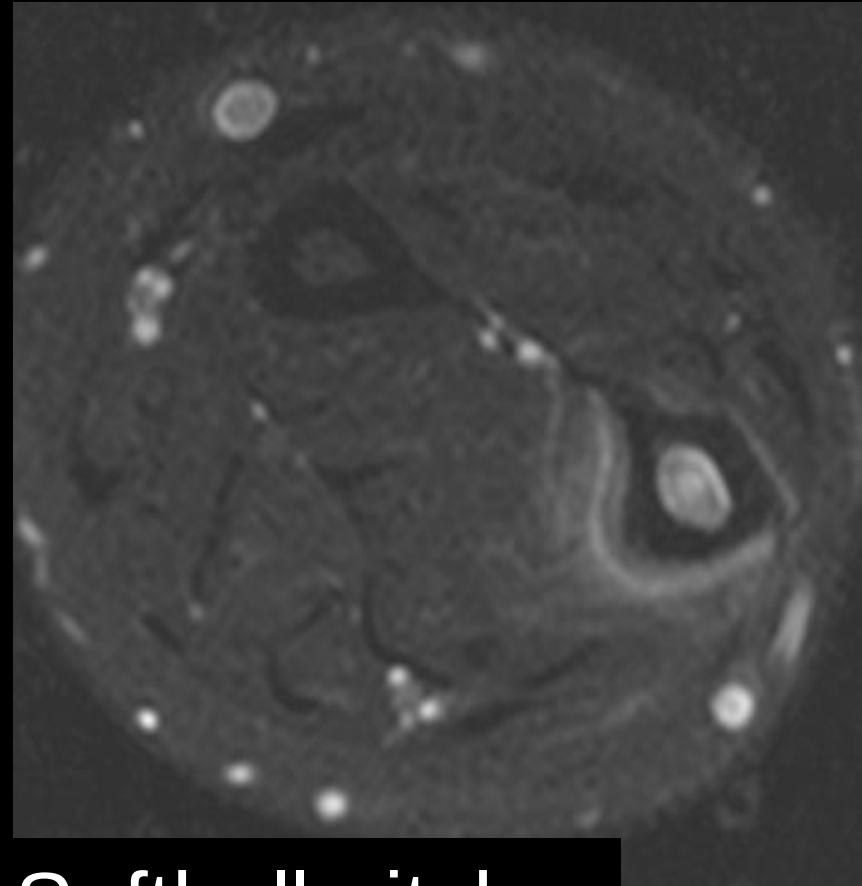


Atypical locations: periostitis may be mistaken for tumor

Ulna Stress Injury



Extensive BME and periostitis



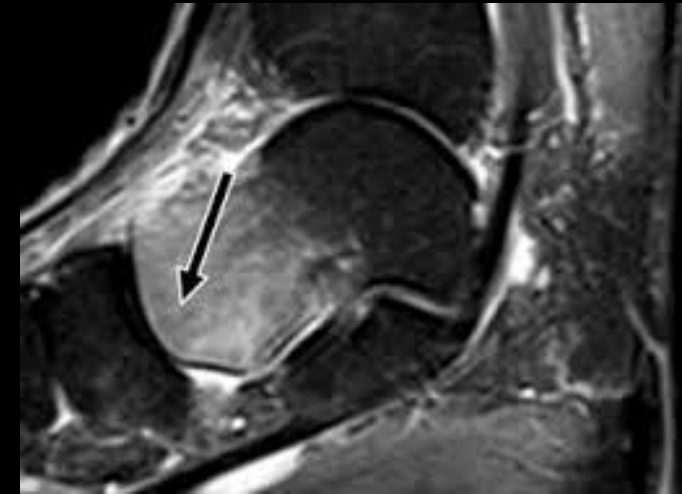
Softball pitcher

Stress Fx Sites and Commonly Related Sports

- Acromion
 - Weight lifting
- Femur
 - Running, ballet, jumping sports
- Fibula
 - Distance running, aerobics, ballet
- Humerus/olecranon
 - Throwing/raquet sports
- Medial malleolus
 - Jumping sports, distance running
- Metatarsals
 - Distance running, marching, ballet
- Patella
 - Hurdling, jumping sports, running
- Pars interarticularis
 - Gymnastics, diving, ballet, volleyball
- Ribs
 - Throwing sports, rowing
- Sacrum
 - Distance running
- Sesamoids
 - Distance running, ballet, jumping sports
- Tarsals
 - Running/sprinting, ballet, jumping sports
- Tibia
 - Distance running, jumping sports, ballet
- Ulna
 - Fast-pitch softball, racquet sports, gymnastics

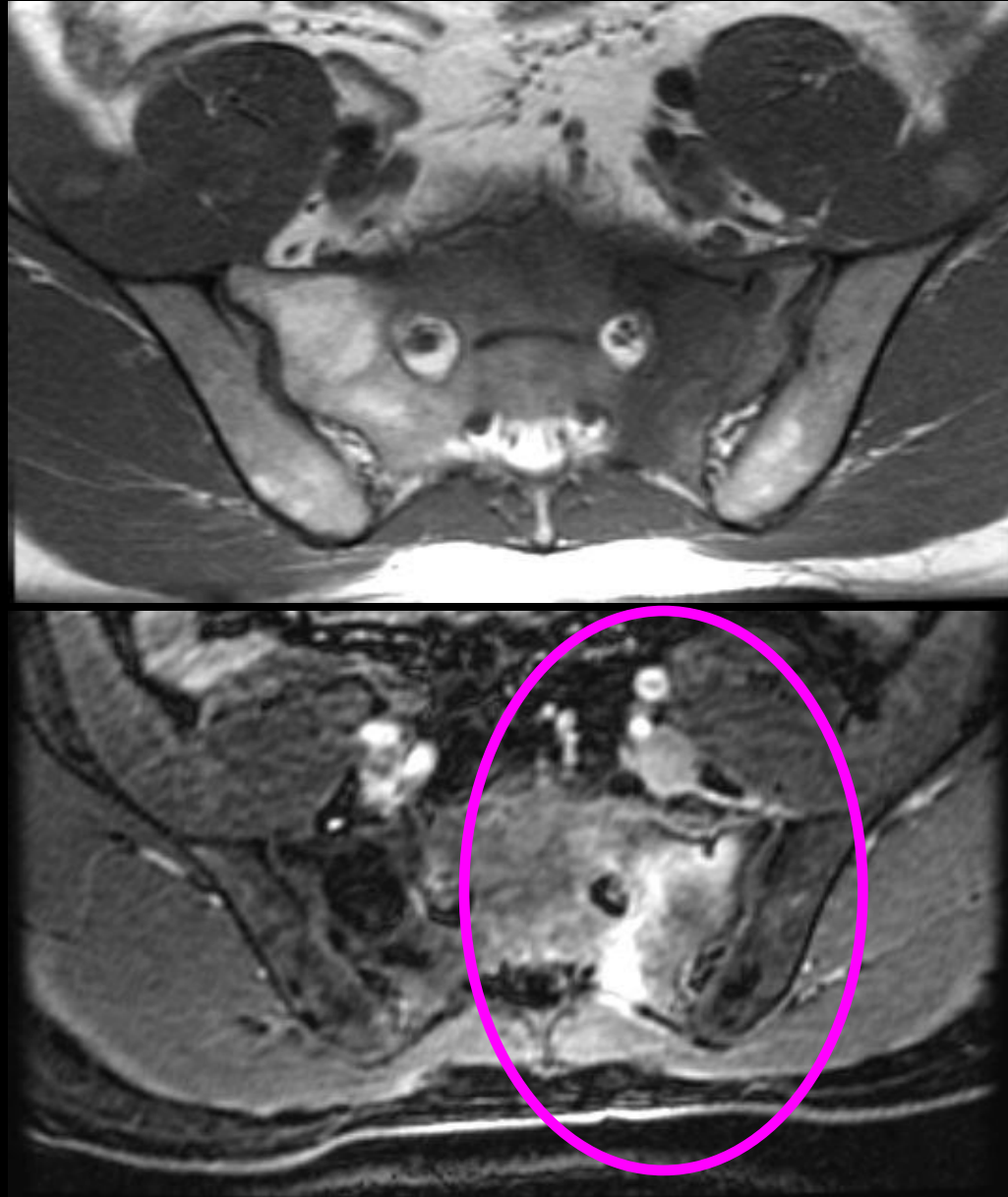
Insufficiency Fxs: Predisposing Conditions

- Osteoporosis (any cause)
 - post menopausal
 - steroid induced
- Osteomalacia & Rickets
 - Renal Failure
- Rheumatoid Arthritis
- Diabetes Mellitus
- Post Radiotherapy
- Post lower extremity Fx (disuse osteoporosis)
- Surgery (arthroplasty)
- Paget Disease
- Osteogenesis Imperfecta
- Osteopetrosis
- Hyperparathyroidism (Renal Failure)

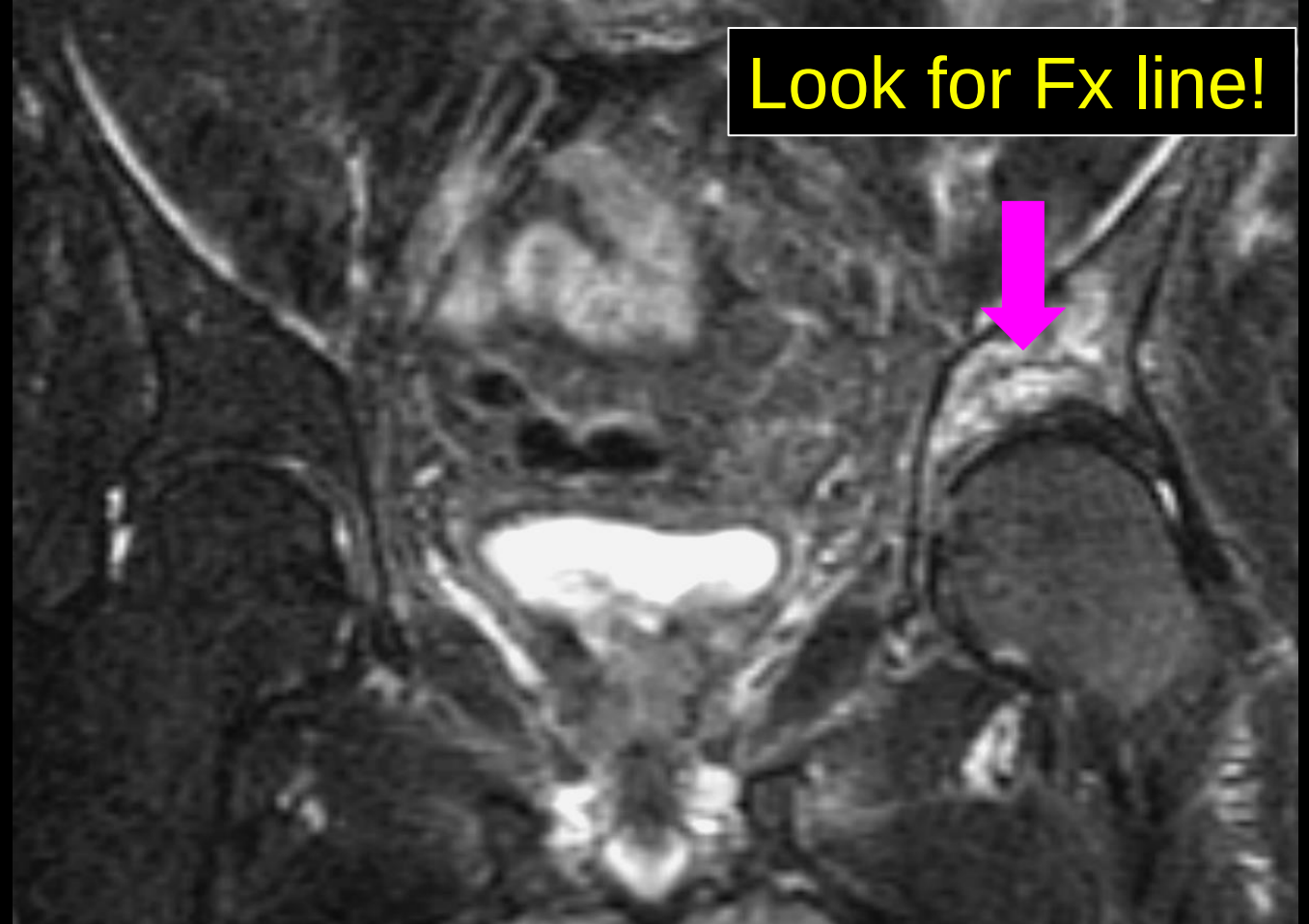
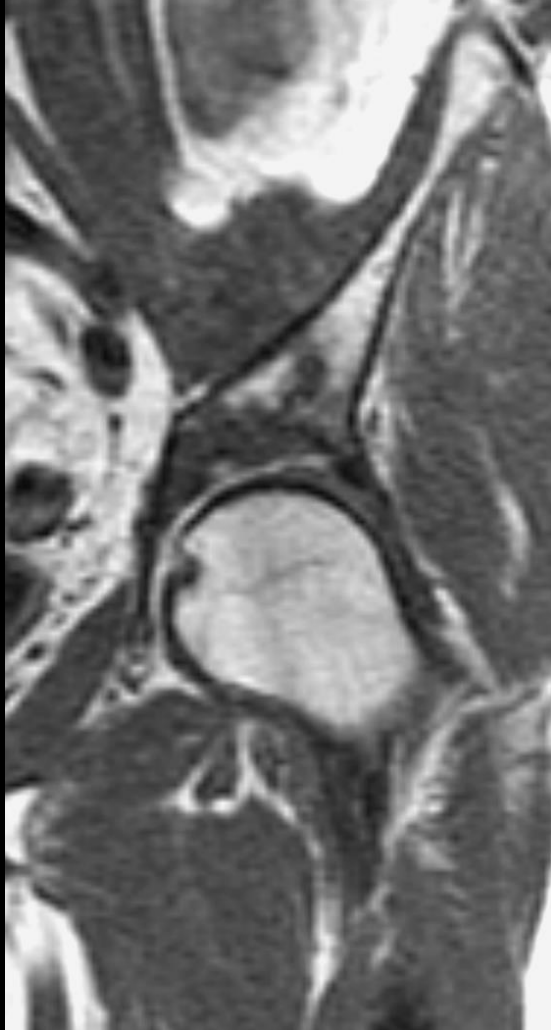


Sacral Insufficiency Fracture

Lumbar Spine MRI:
LLE Pain



Supra-acetabular Insufficiency Fracture



Hx of breast cancer with hip pain

Subchondral Insufficiency Fractures of the Knee (SIFK, SONK, SPONK)

- Sudden onset of severe knee pain
- Upper middle aged and elderly but active
- Wt-bearing surface of MFC most common
- Associated with meniscus tear (MM root tear)
- Subchondral fatigue fracture in osteoporotic bone
- Osteoarthritic sclerosis may be protective
- May progress to frank osteonecrosis or resolve



Subchondral Insufficiency Fracture

BME extends to intercondylar notch



60 year old female post meniscus repair



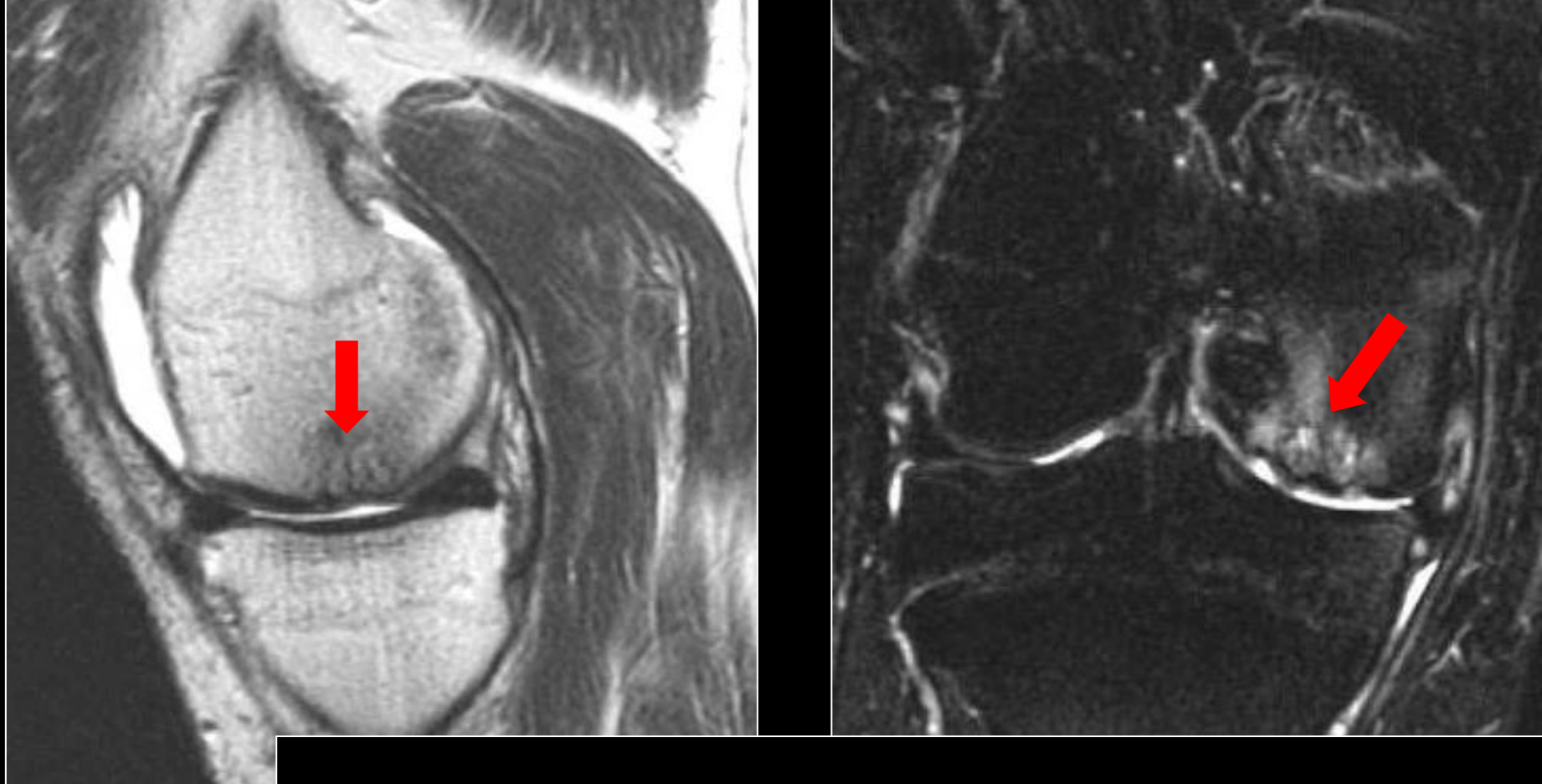
Crescentic Lesion



Can MRI predict the outcome of SONK?

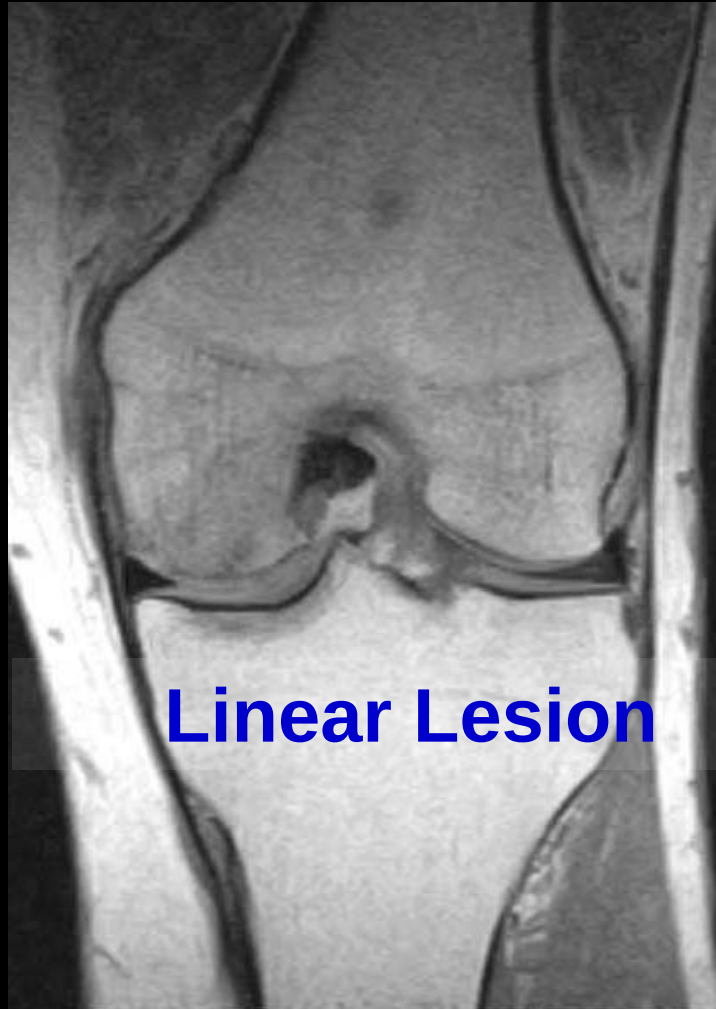
Gil HC, Levine SM, Zoga AC. MRI findings in the subchondral bone marrow: a discussion of conditions including transient osteoporosis, transient bone marrow edema syndrome, SONK, and shifting bone marrow edema of the knee. *Semin Musculoskelet Radiol.* 2006 Sep;10(3):177-86.

24 Month Follow-up



Progression to osteonecrosis

Initial MRI examination:



10 Month Follow-up

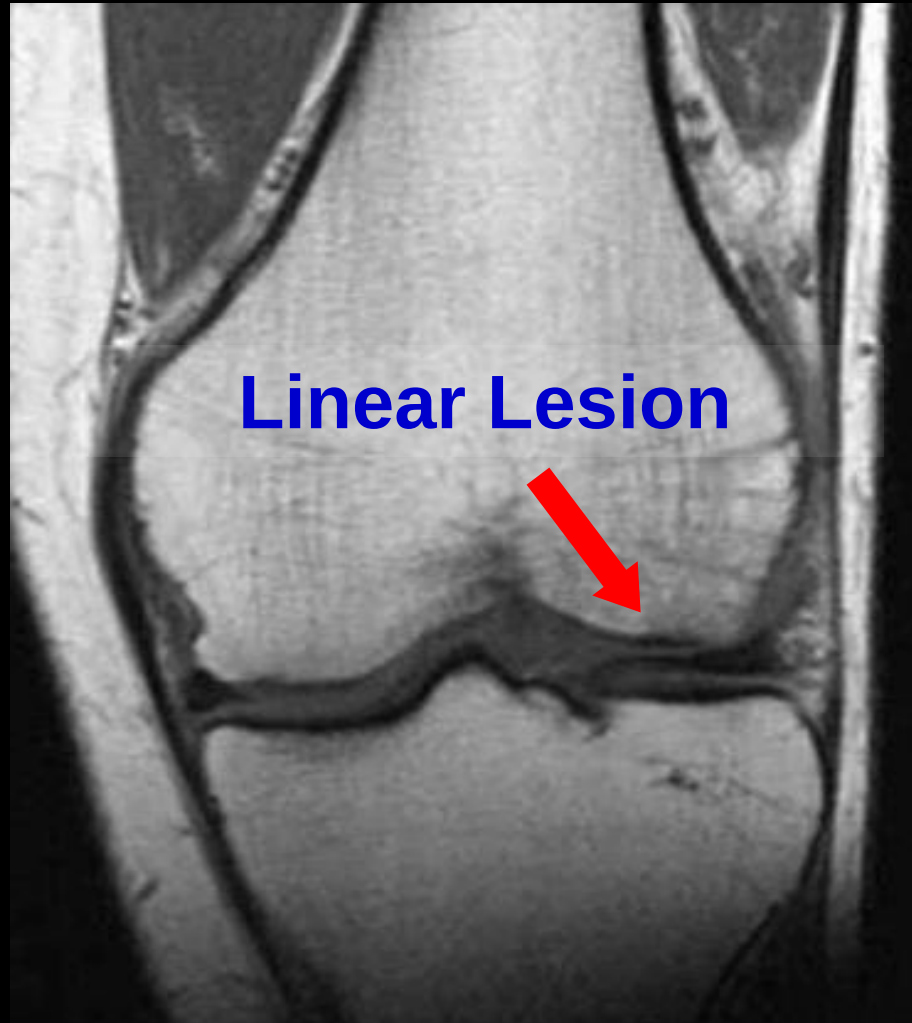


Resolution

Initial presentation



5 Month Follow-up

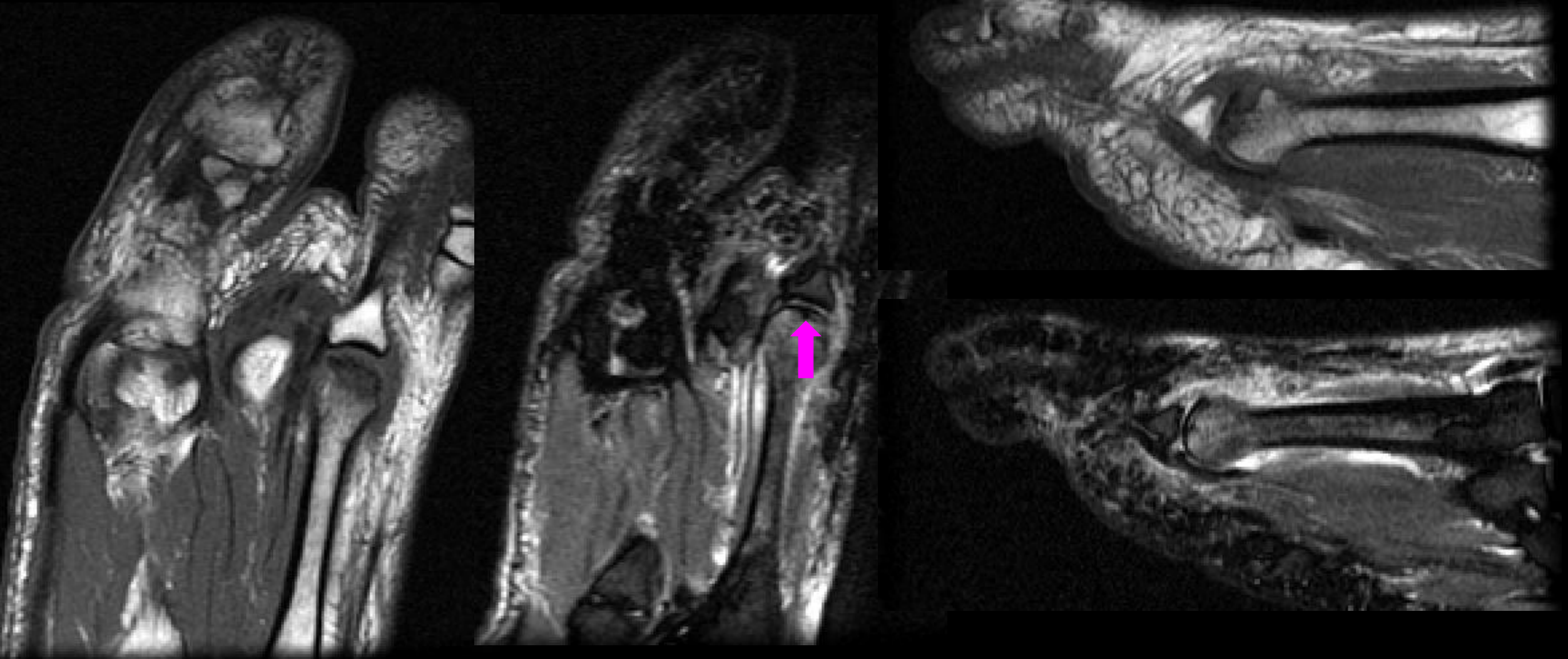


11 Month Follow-up (6 months later)



Resolution

Metatarsal Subchondral Insufficiency Fracture



Subchondral fractures from abnormal biomechanics



Clavicular osteolysis



Talar head



Osteitis pubis



Femoral Head

CONGENITAL/DEVELOPMENTAL: Tarsal Coalitions

- < 1% incidence
- Talocalcaneal and calcaneonavicular 90%
- 50% bilateral
- Failure of differentiation and segmentation of primitive mesenchyme
- Painful pes planus

Medial TC (middle subtalar) joint coalition



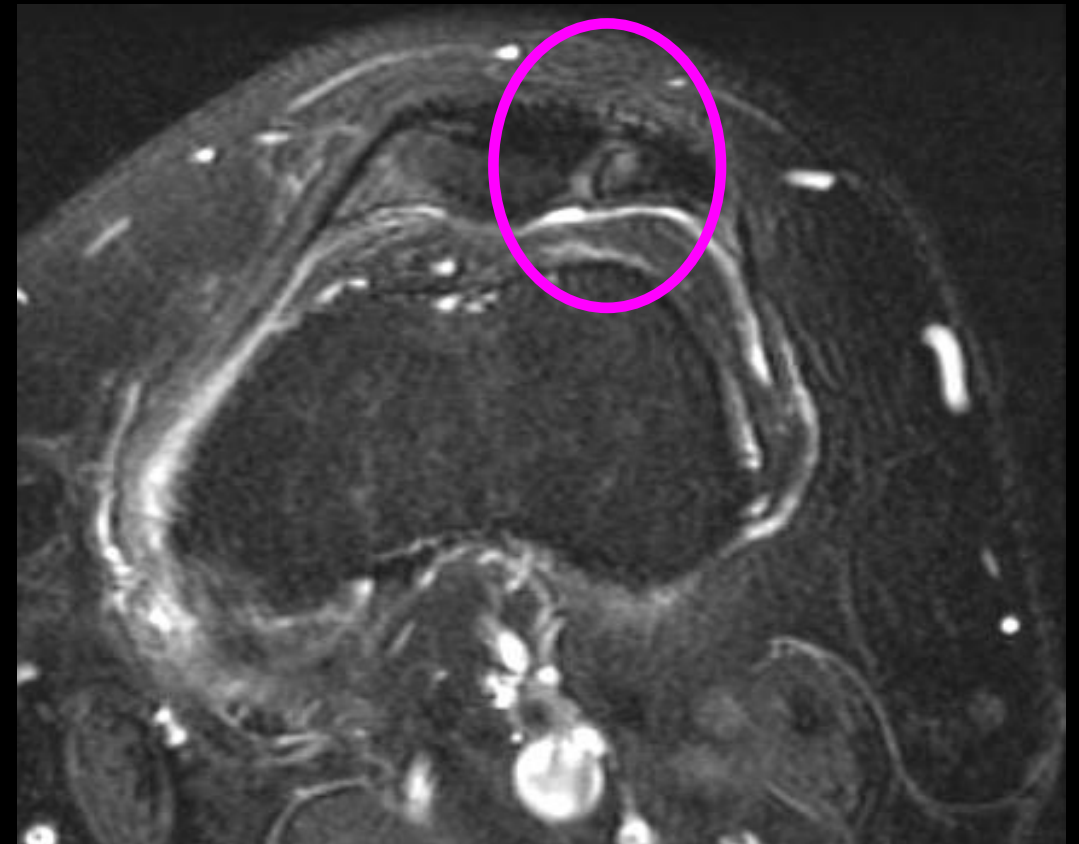
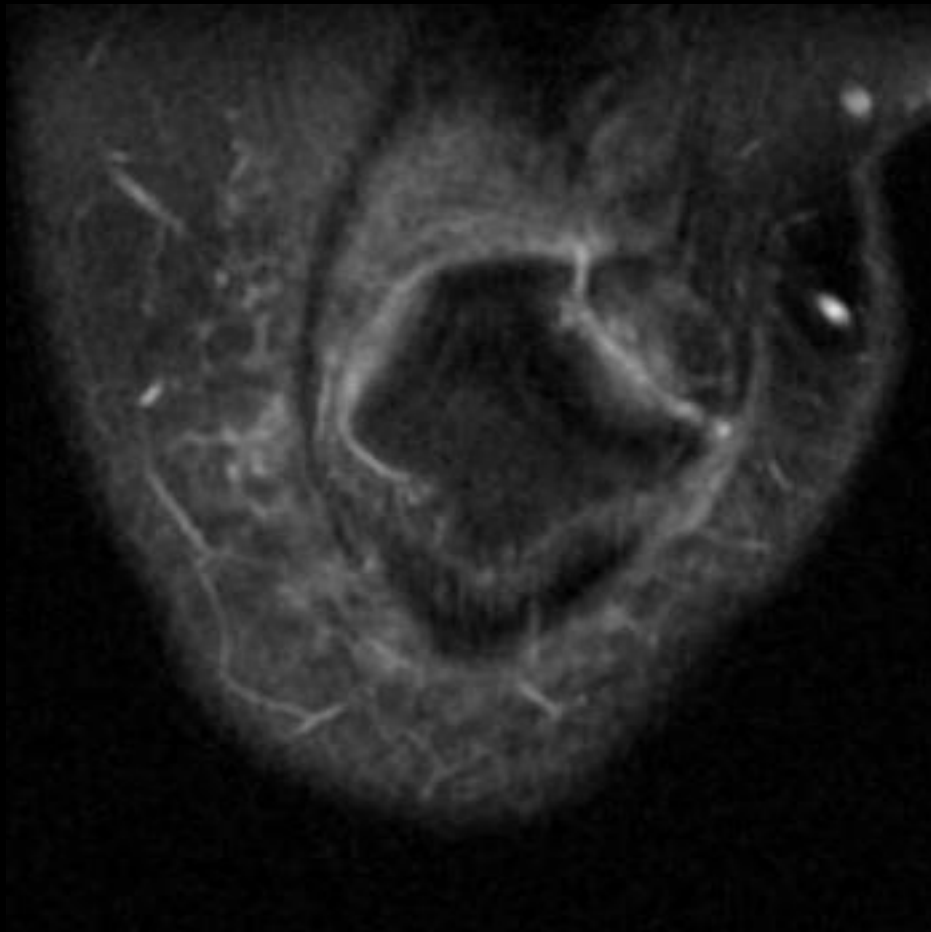
“Drunken Waiter” sign

CONGENITAL/DEVELOPMENTAL

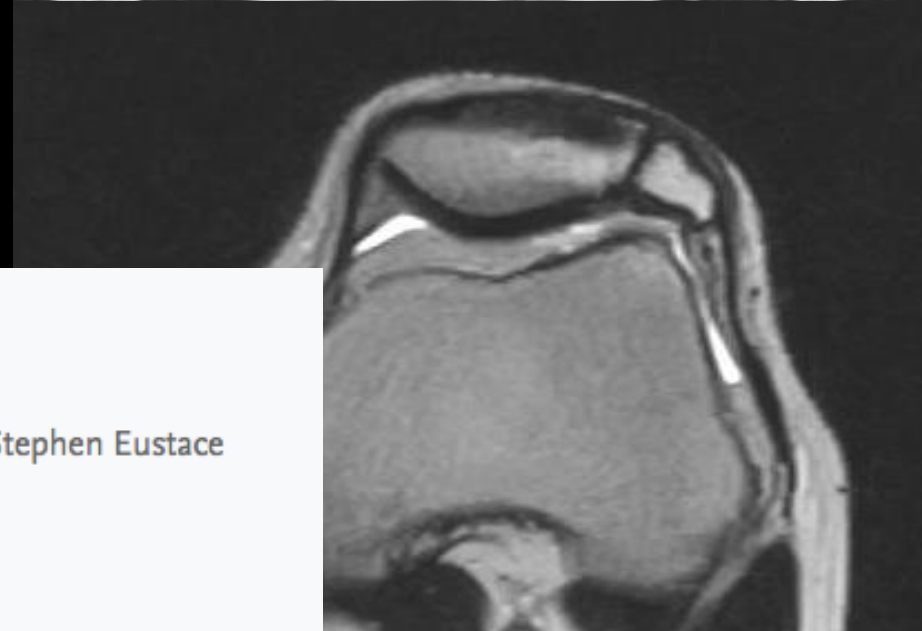
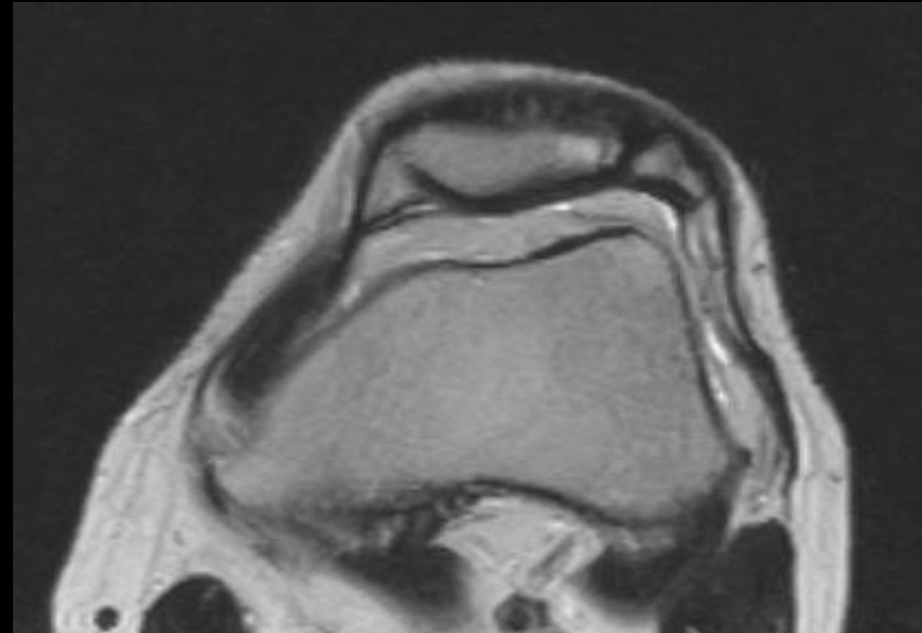
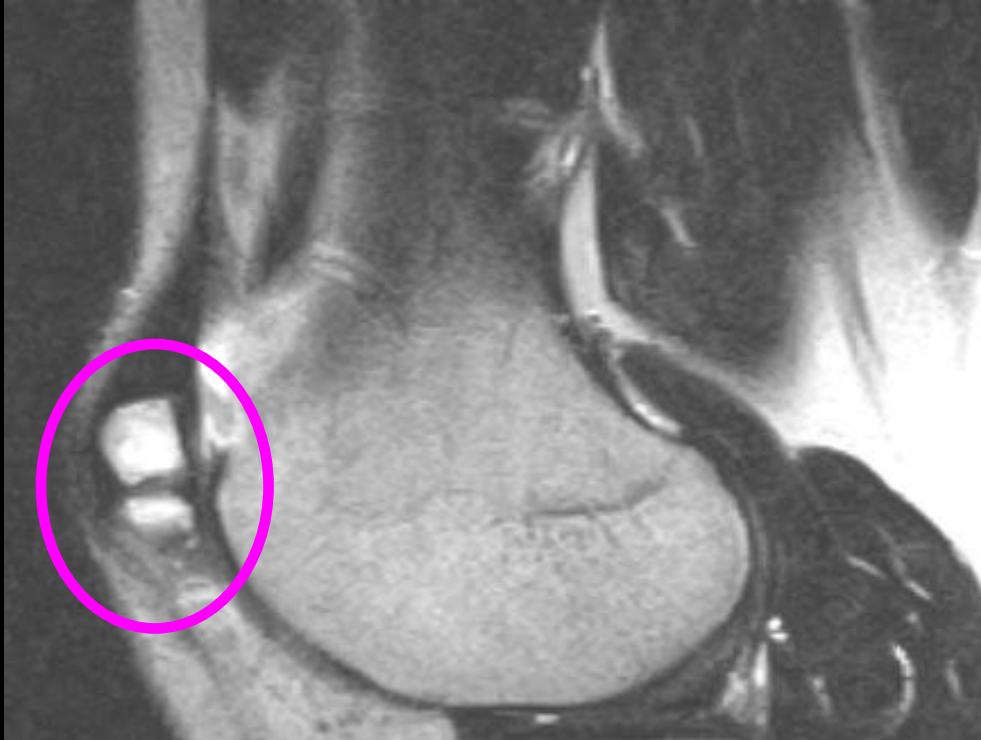
- Chronic Chondroosseous Disruption
 - Bipartite patella
 - Dorsal defect of the patella
 - Os subfibulare of the ankle
- Developmental Synchondrosis
 - Os Navicularis
 - Os Acromiale

May predispose to premature DJD

Bipartite Patella



Bipartite Patella



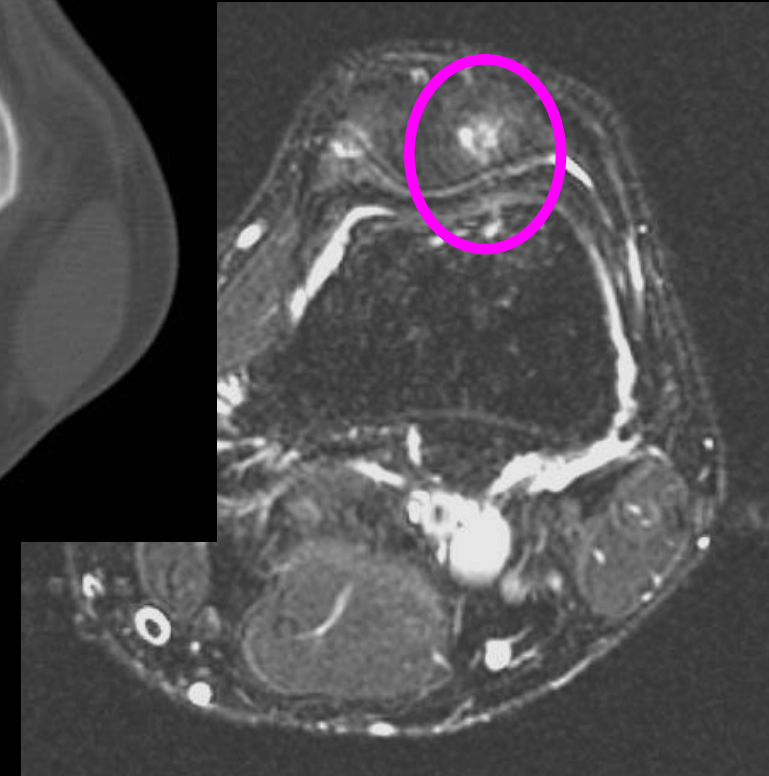
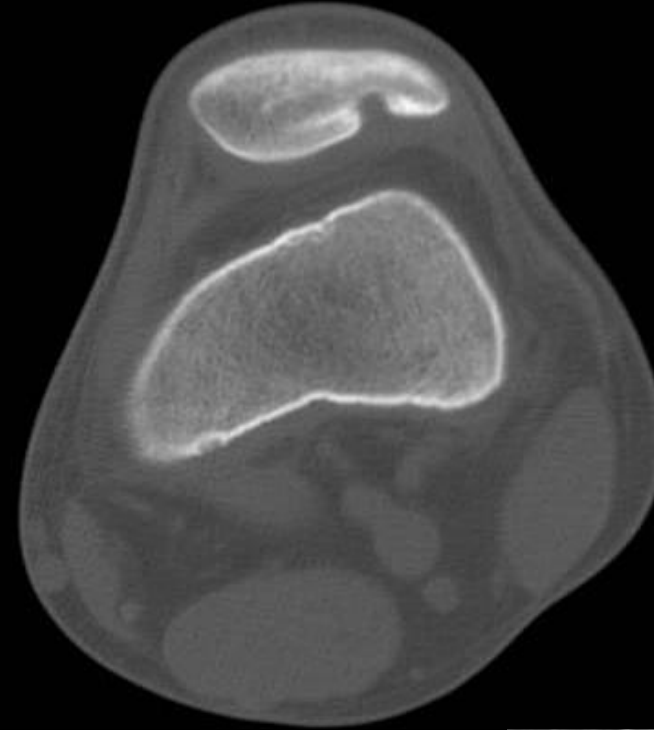
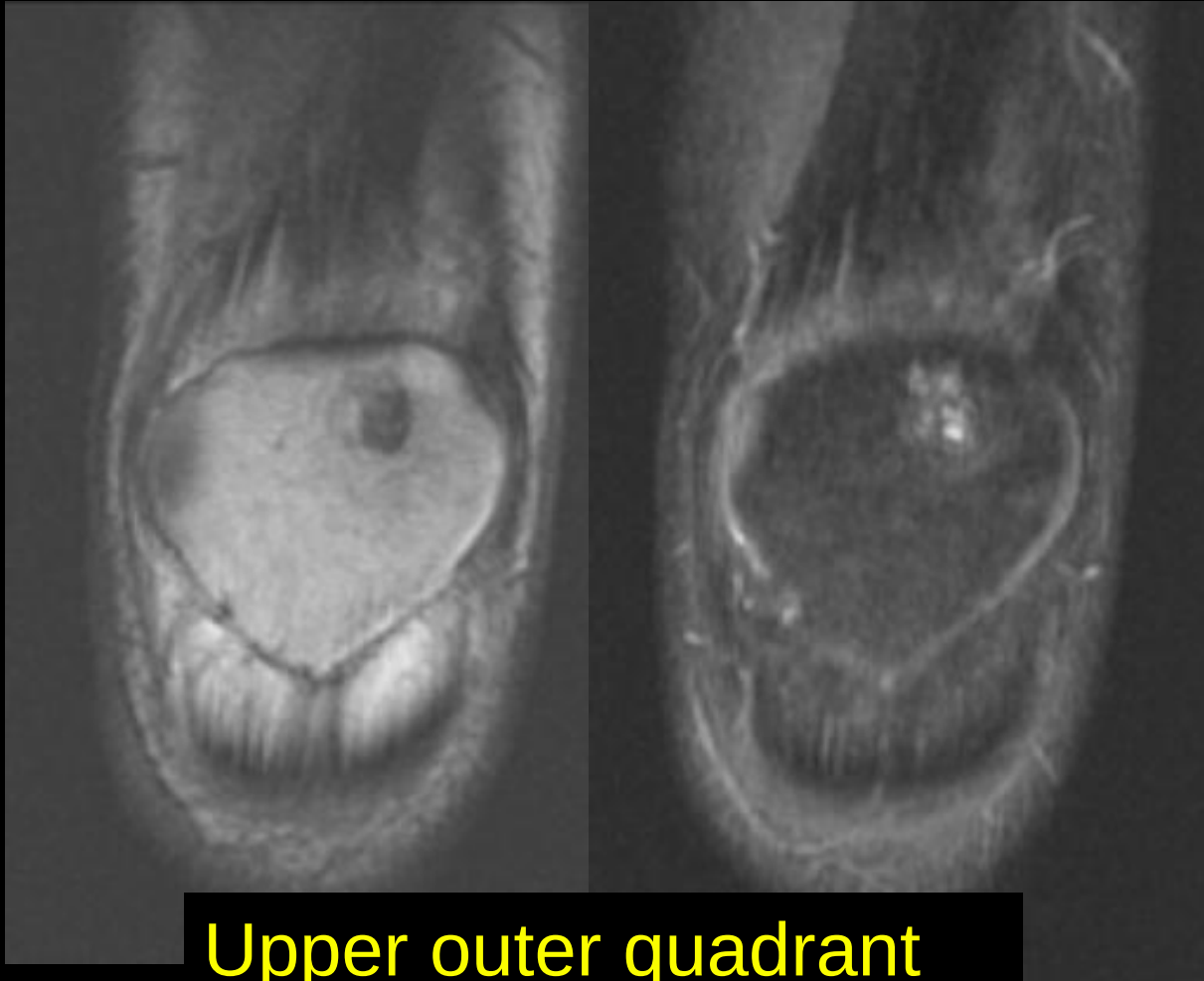
MRI findings in bipartite patella

Eoin C. Kavanagh*, Adam Zoga, Imran Omar, Stephanie Ford, Mark Schweitzer, Stephen Eustace

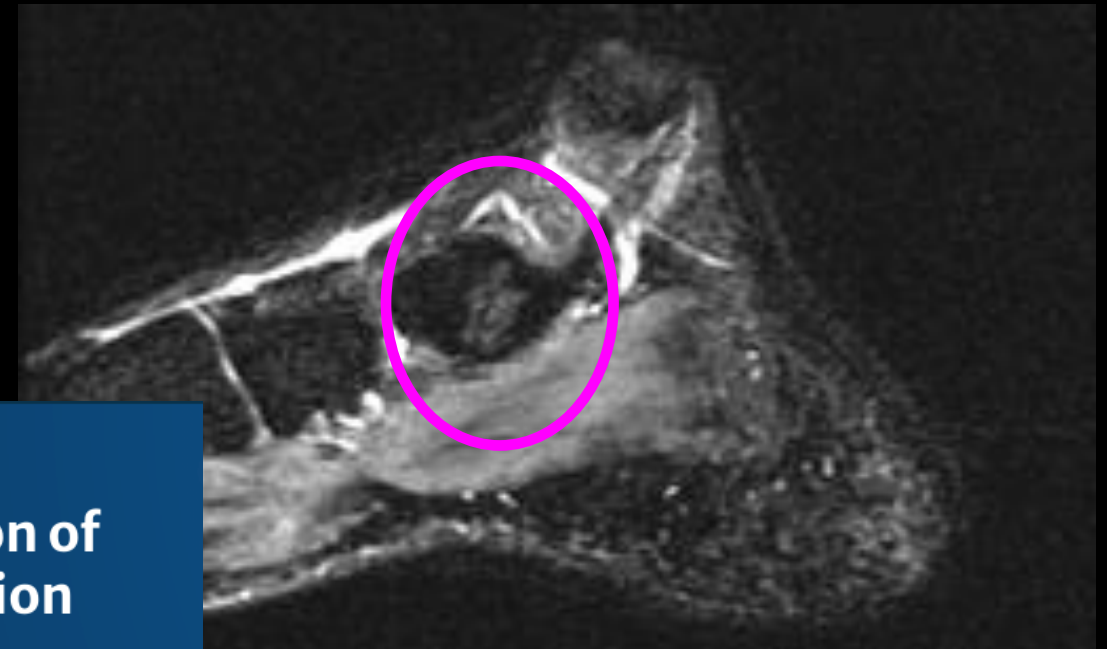
*Corresponding author for this work

Radiology

Dorsal Defect of the Patella



Type 2 os navicularis



[Home](#) > [Skeletal Radiology](#) > [Article](#)

Painful type II os naviculare: introduction of a standardized, reproducible classification system

Scientific Article | Published: 19 June 2020

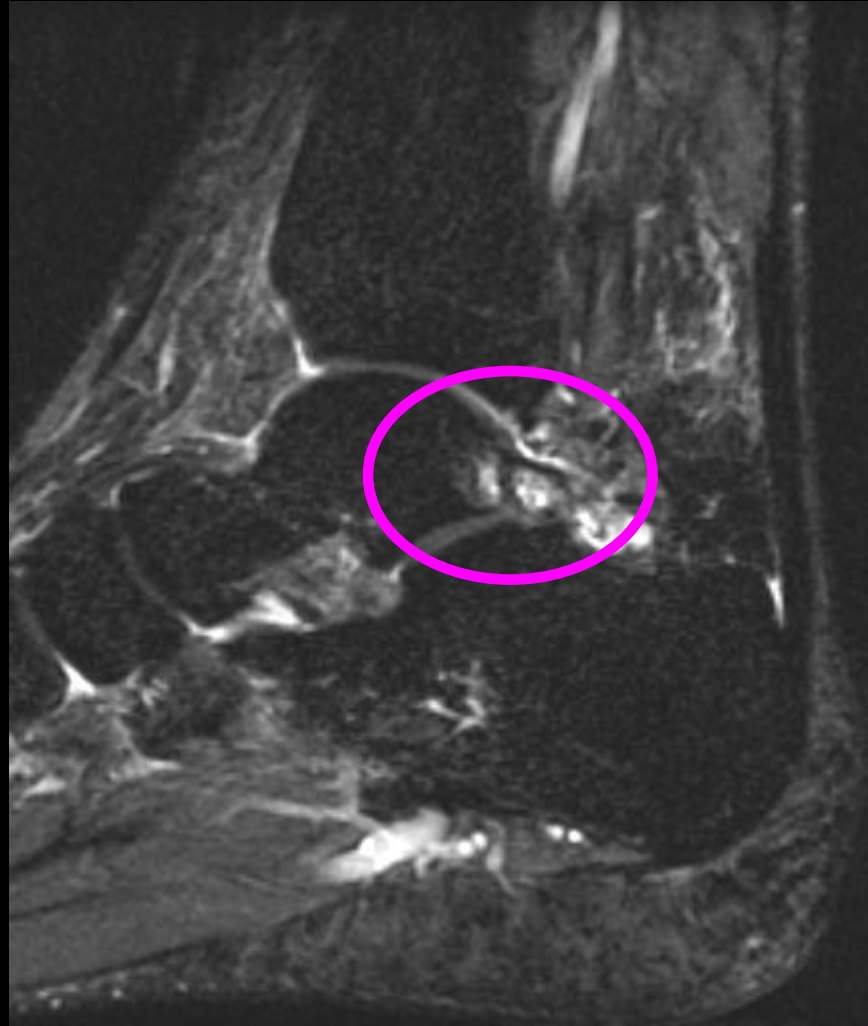
Volume 49, pages 1977–1985, (2020) [Cite this article](#)

[Sarah I. Kamel](#), [Jeffrey A. Belair](#) ✉, [Tarek M. Hegazi](#), [Ethan J. Halpern](#), [Vishal Desai](#), [William B. Morrison](#)
& [Adam C. Zoga](#)

Little Leaguer's Elbow



Os trigonum syndrome / posterior impingement



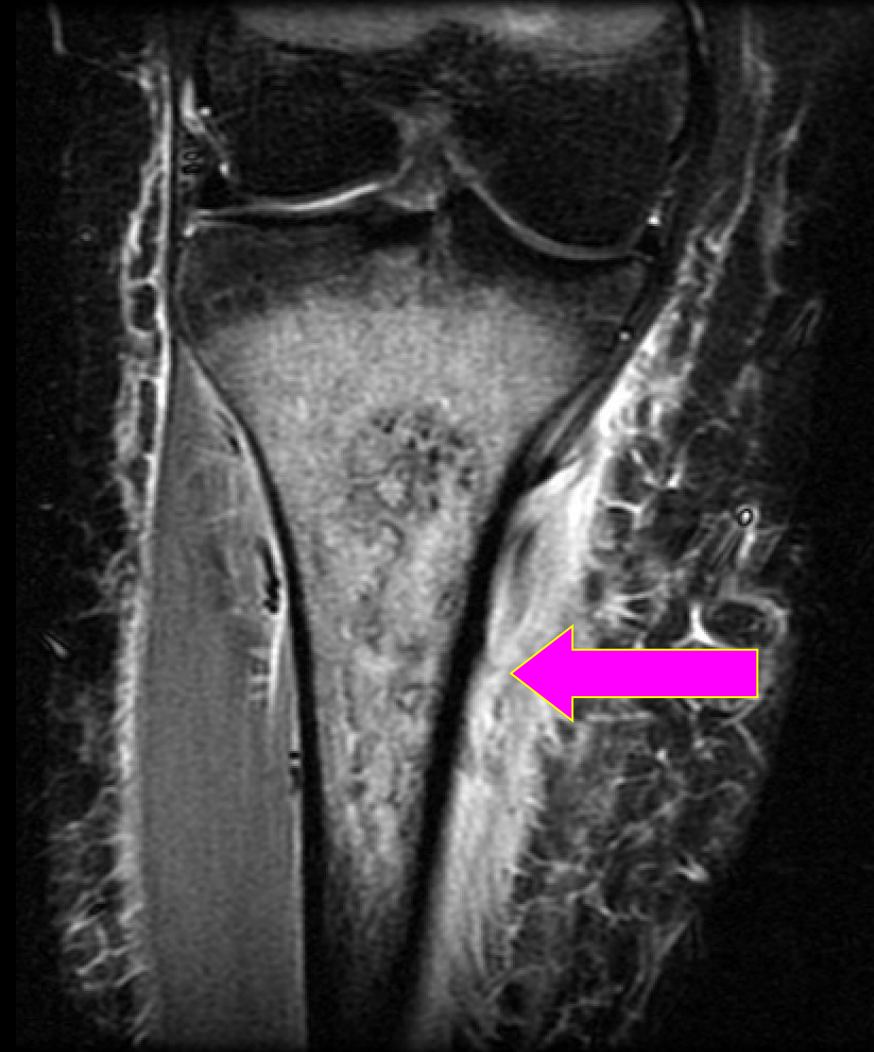
VASCULAR: Osteonecrosis

- Vascular insufficiency--?? Reversible (Transient Osteoporosis)
- Broad Categories– PLASTIC RAGS
 - Most common- STARS
 - Steroids
 - Traumatic
 - Alcohol abuse
 - Radiation
 - Systemic, ie Sickle Cell Dz
- Terminology- AVN (juxtaarticular), bone infarct (metaphyseal/diaphyseal)→ “osteonecrosis” all encompassing

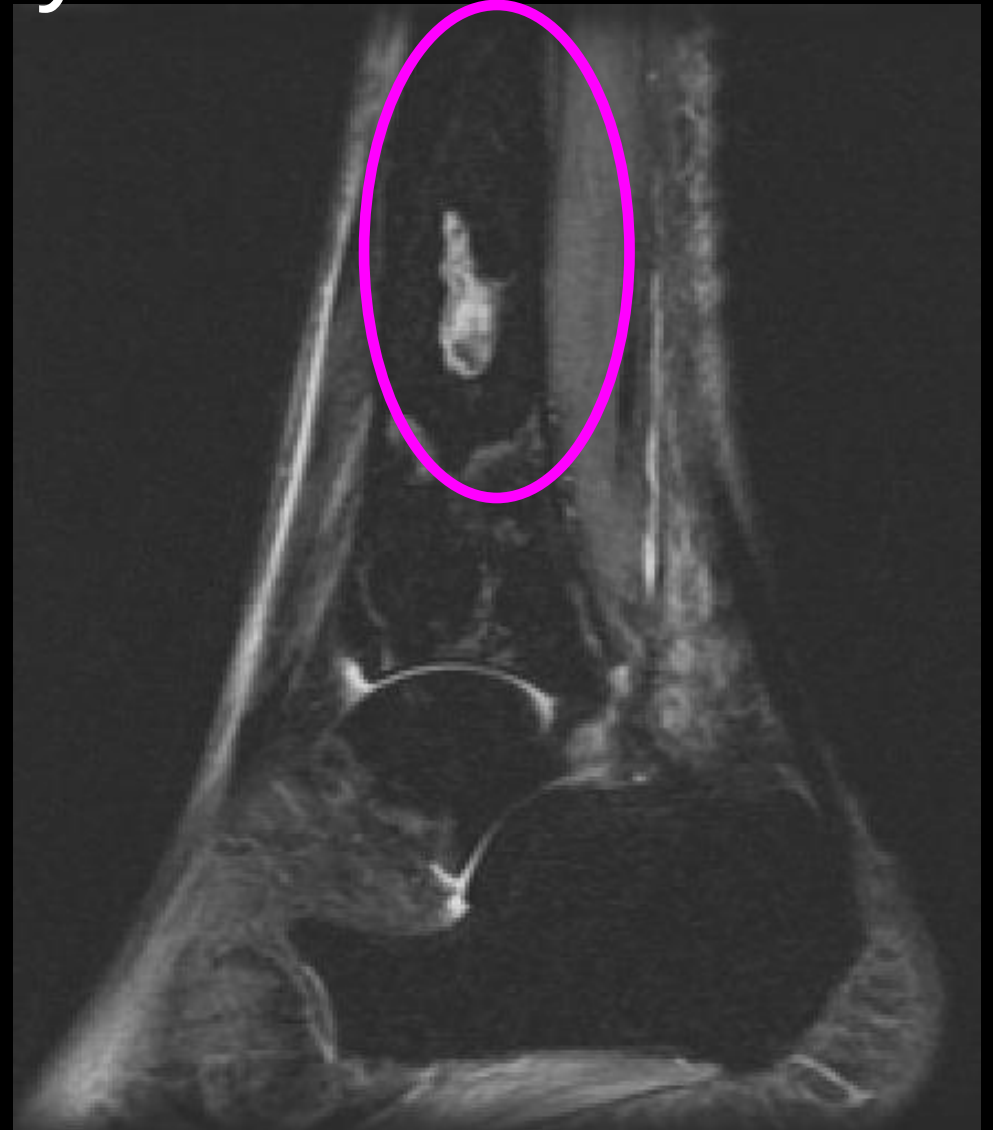
Sickle Cell Anemia: Acute Infarct



Marrow reconversion



Mature Medullary Infarct

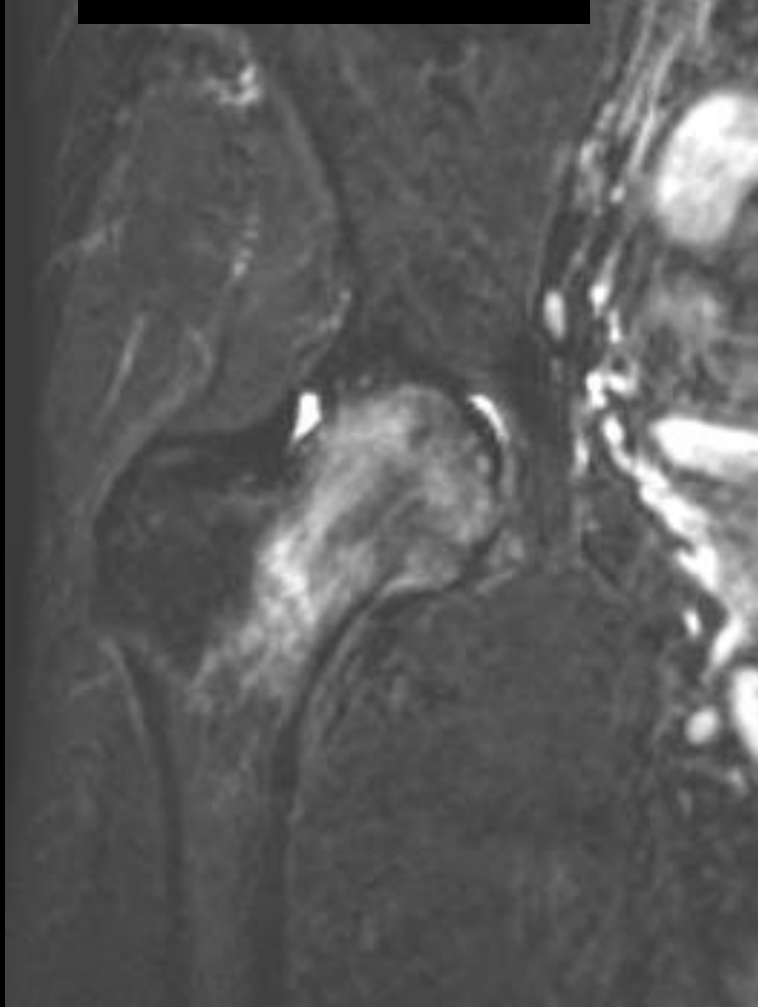


Osteonecrosis

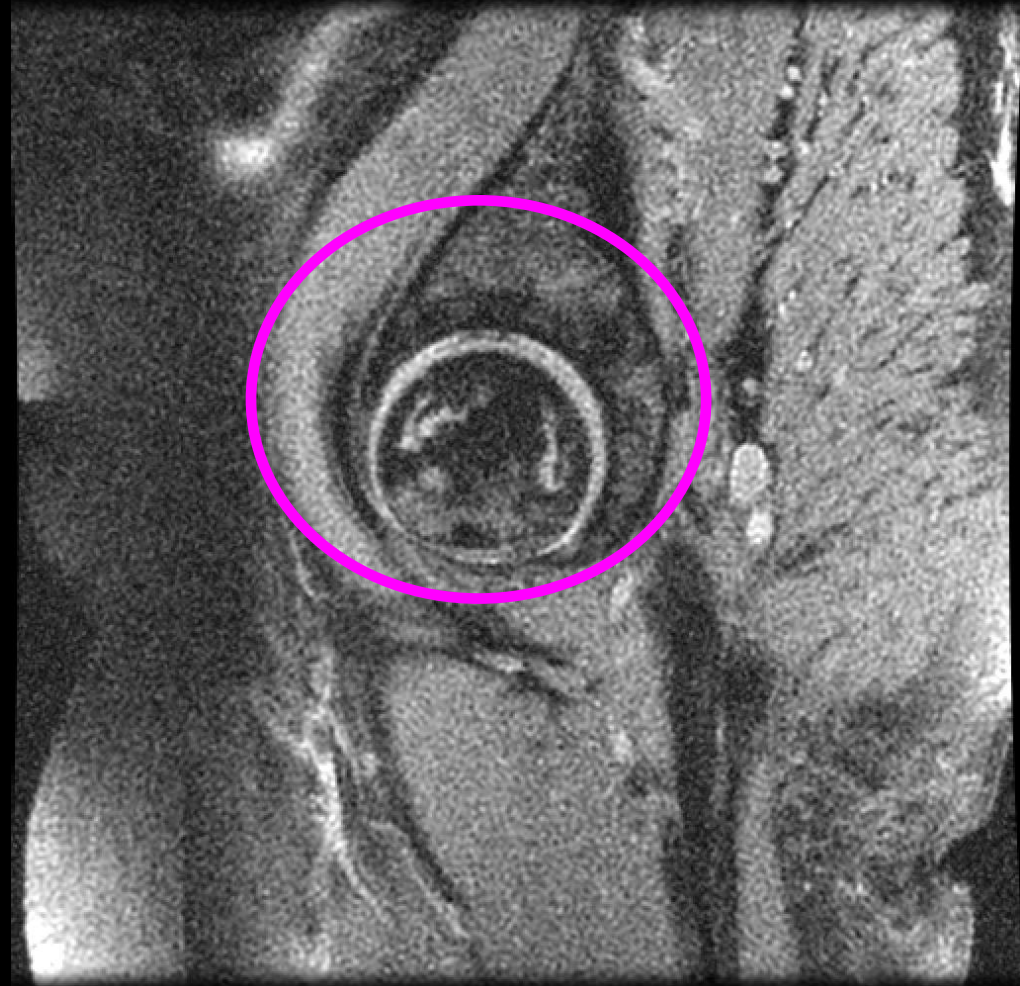
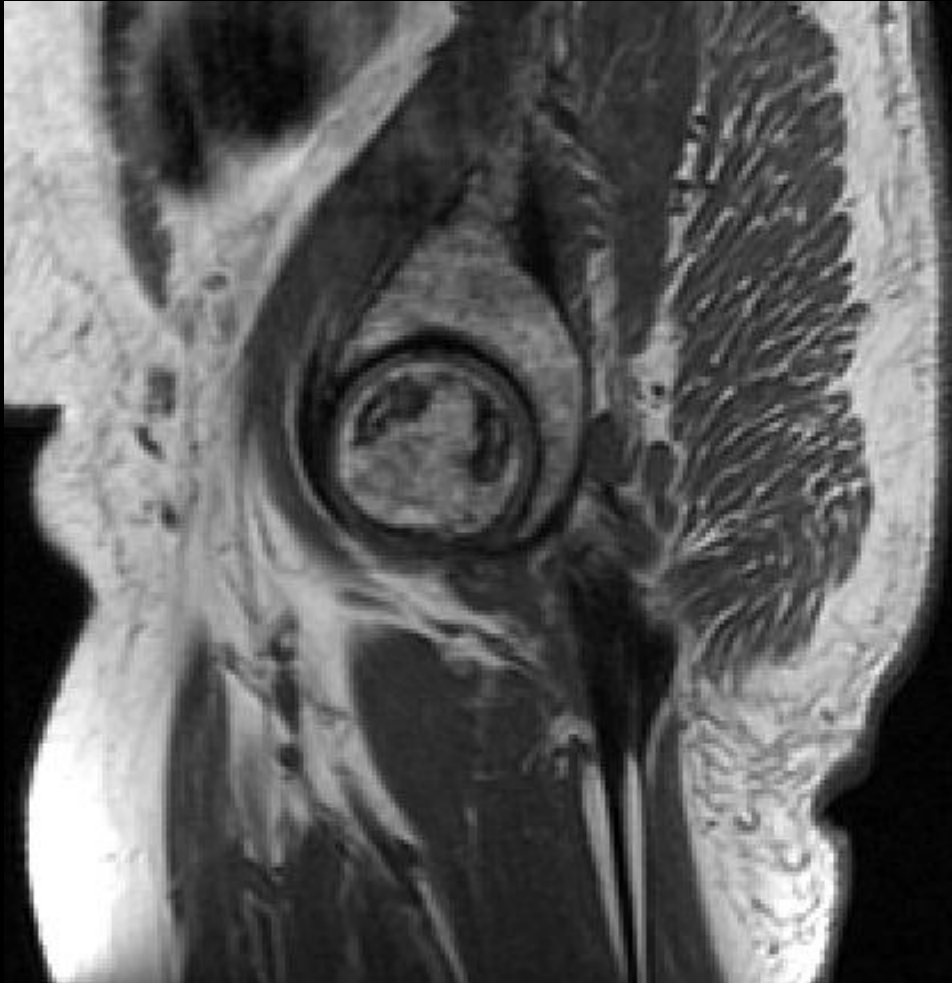
- Femoral head very common location- 75%
- MRI Imaging
 - BME- early
 - Pain improvement usu. parallels the resolution of BME
 - Double line sign (specific)
 - Ring of T1 hypointensity and T2 hyperintensity
- Report % articular surface involvement, articular collapse, OA

Active/Acute AVN

Diffuse BME



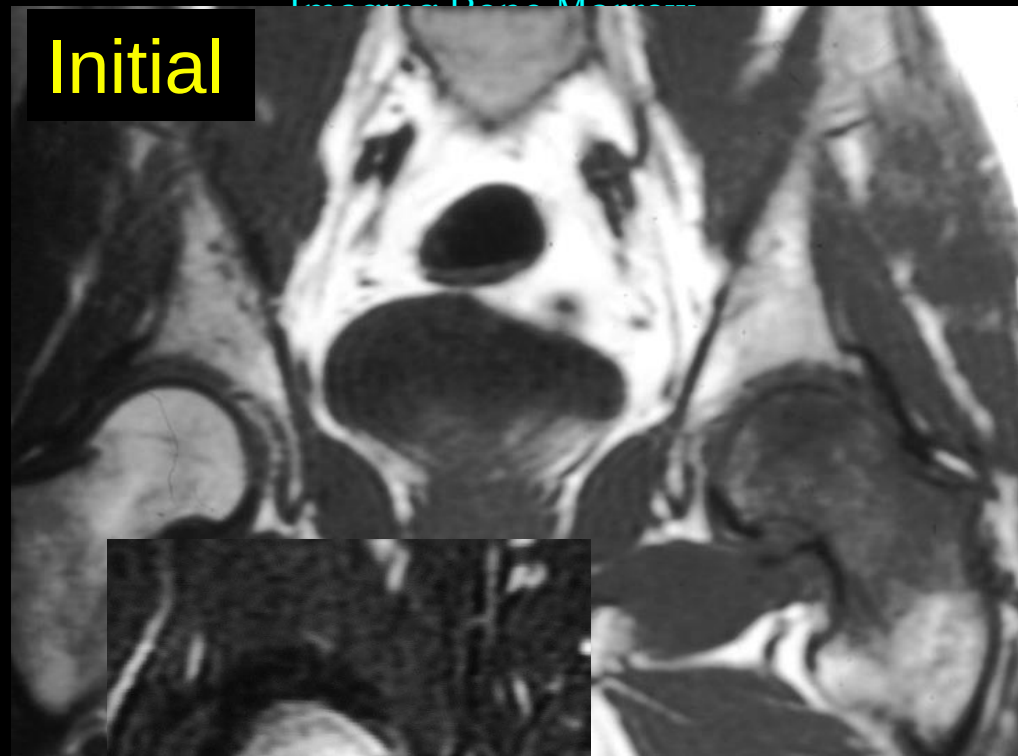
Late: Chronic AVN



Subchondral Insufficiency Fracture Femoral Head / “Transient Osteoporosis of the Hip”

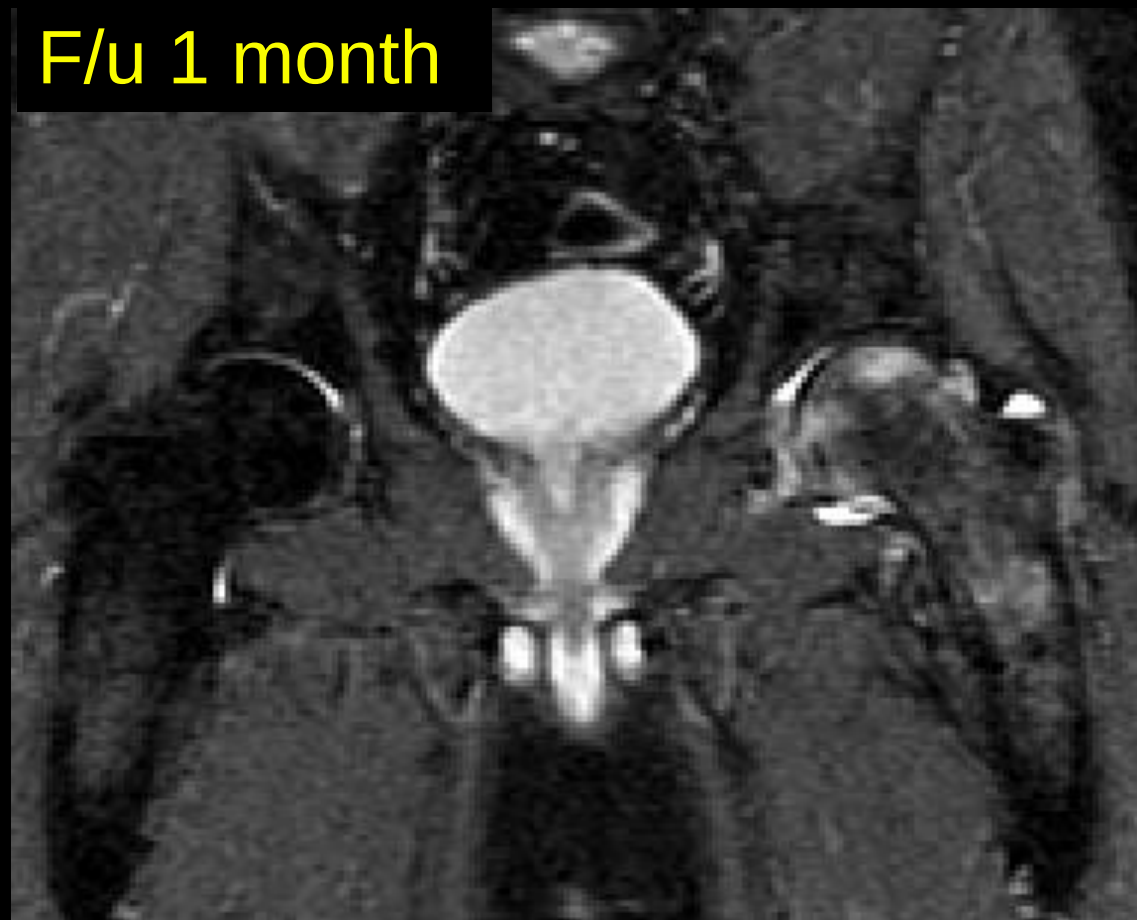
- BME without clear demarcations-- no FX line or geographic region of signal alteration
- Accompanying STS, effusion
- Resolution over time (6-12 wks)
- Marrow signal reconstitution
- May represent salvaged AVN

Initial



Atraumatic spontaneous
onset of hip pain

F/u 1 month



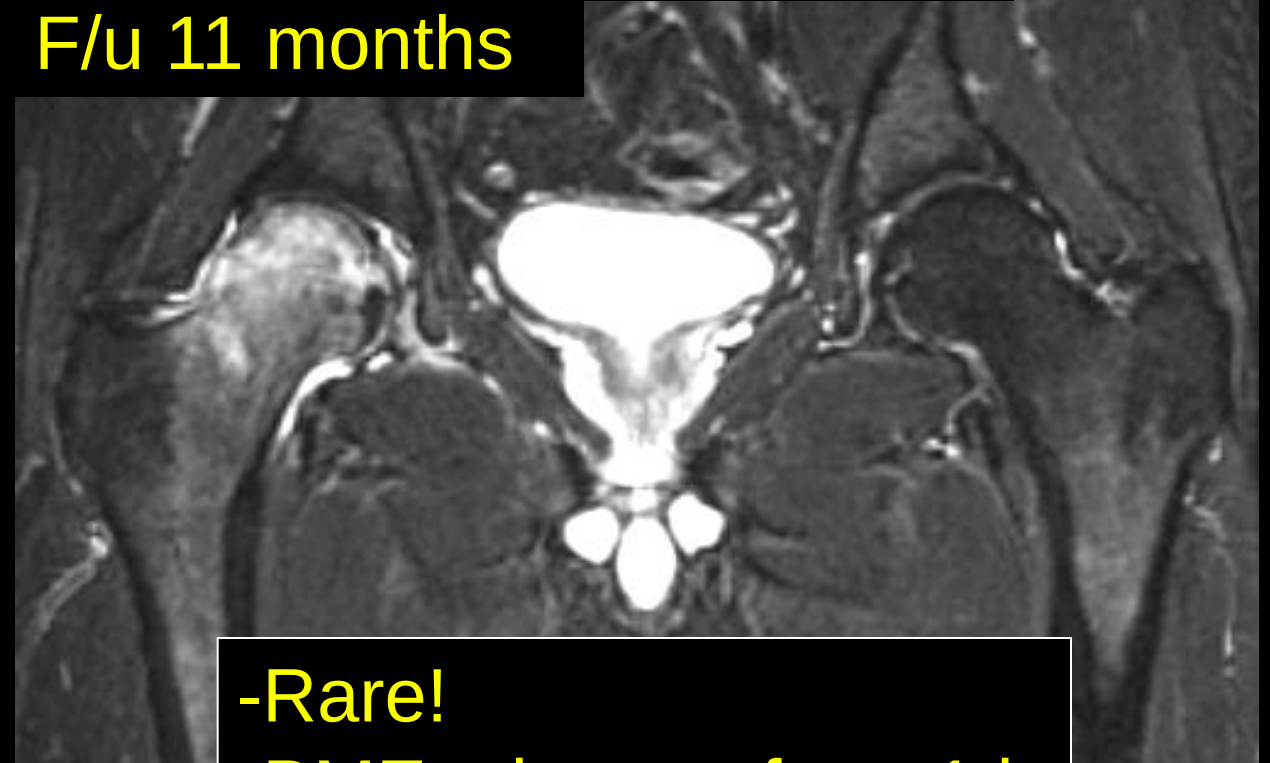
Regional Migratory Osteoporosis, aka Shifting Bone Marrow Edema

Initial



- sudden onset of pain
- migrating arthralgia of lower limb, middle-age males
- usu. self-limited

F/u 11 months



- Rare!
- BME migrates from 1 jt to another or shifts within a single jt

Degenerative Subchondral BME

Osteoarthritis / Chondrosis

- Cartilage loss -> jt space narrowing
- Bone marrow “lesions” (BML)
 - Histological- bone marrow necrosis, trabecular abnl, bone marrow fibrosis, bone marrow edema
 - BM lesions strongly associated with pain!
- “Smoldering fire” pattern
- Osteophytes
- Effusions/ Synovitis

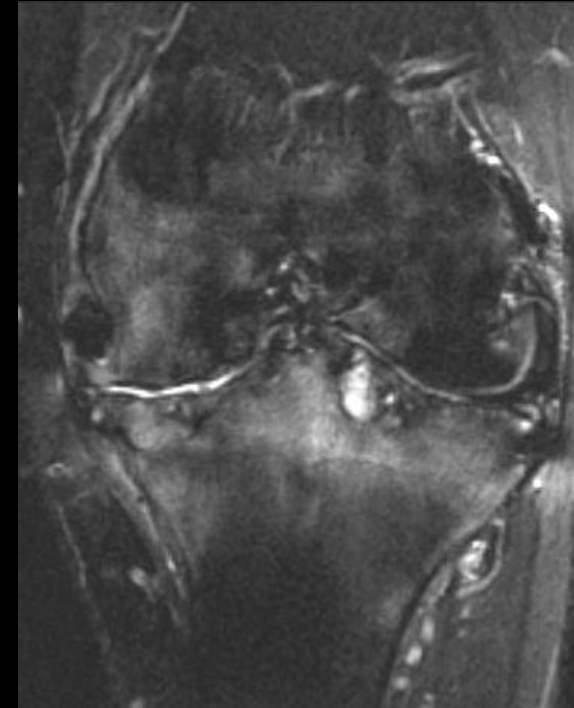
Felson DT, Chaisson CE, Hill CL, Totterman SM, Gale ME, Skinner KM, Kazis L, Gale DR. The association of bone marrow lesions with pain in knee osteoarthritis. Ann Intern Med. 2001 Apr 3;134(7):541-9.

Osteoarthritis and extensive BME

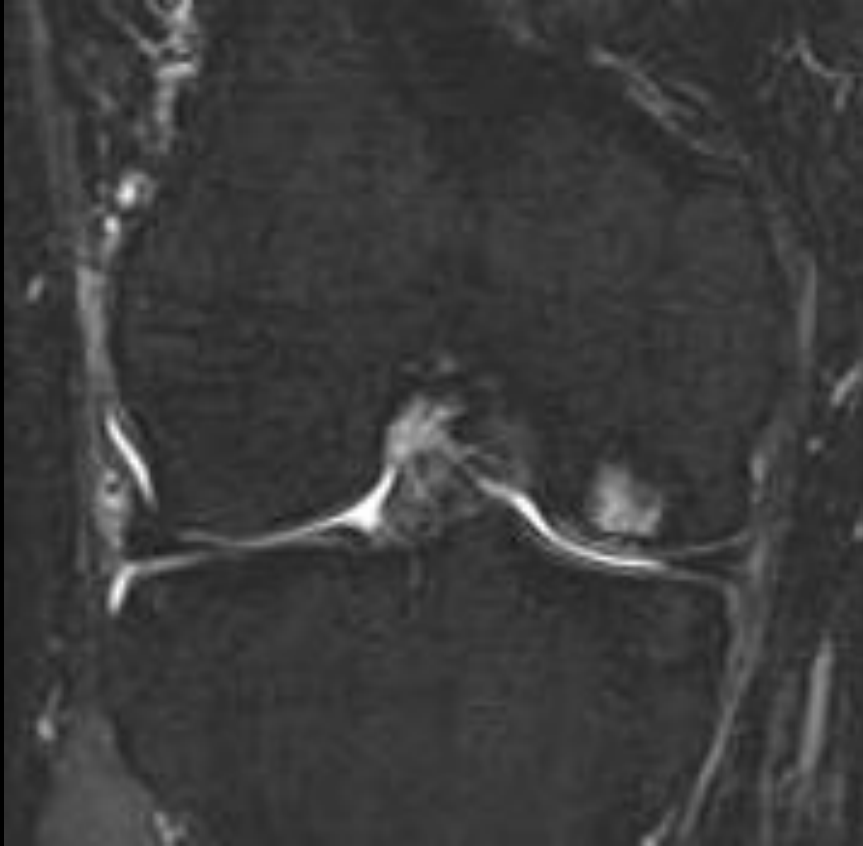


Scher C, Craig, J and Nelson F. Bone marrow edema in the knee in osteoarthritis and associated with total knee arthroplasty within a three-year follow-up. Skeletal Radiol 2008; 37:609-617.

- Subjects with BME more likely to have TKA
 - Global BME- 13x more likely to have TKA
 - Global BME=marrow edema femoral/tibial condyle
- Meniscal tears, cartilage loss NOT associated with need for TKA



Chondral Injury

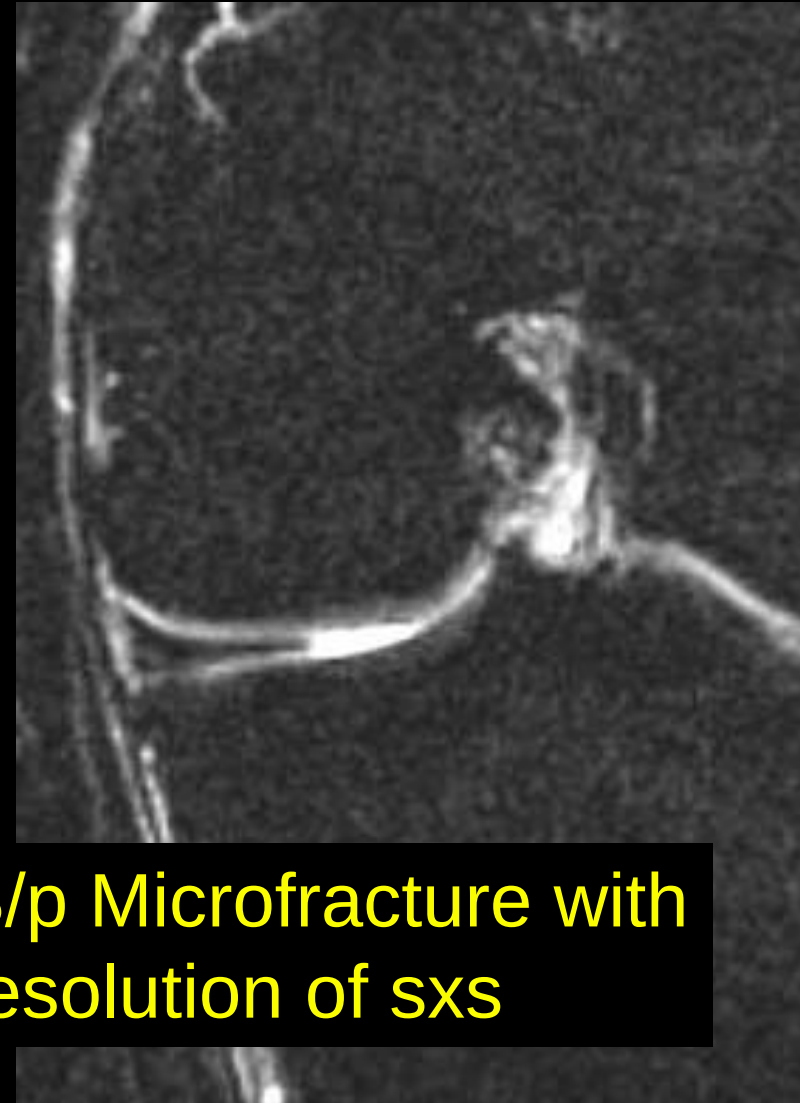


- Focal subchondral BME is common on MR images of treatable, cartilage defects in the knee
- BME finding may prove to be an important clue to assist in the detection of these traumatic chondral lesions
- “Roaring fire” pattern

Subchondral BME can resolve



Pro Basketball player
with medial pain

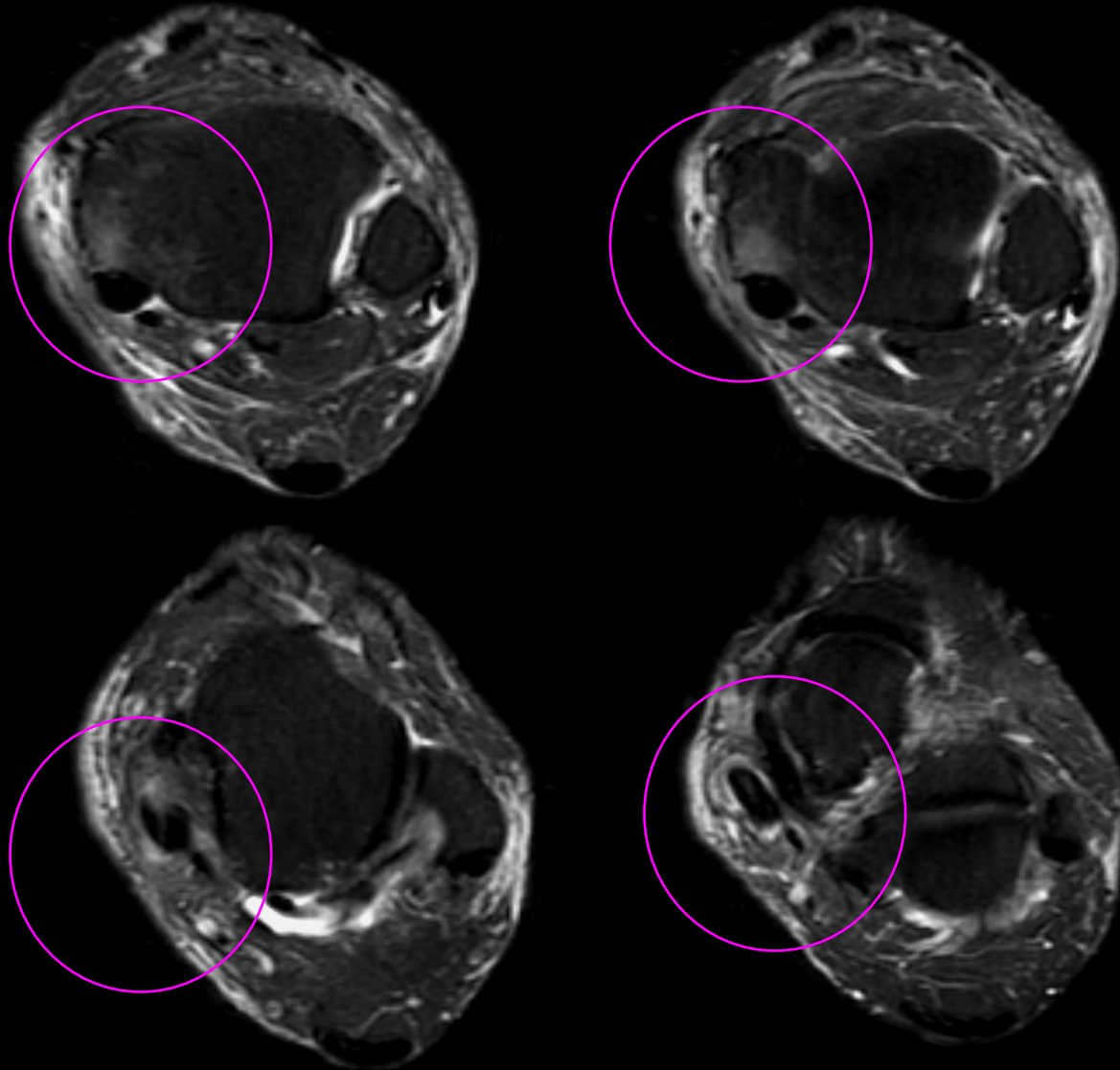


S/p Microfracture with
resolution of sx's

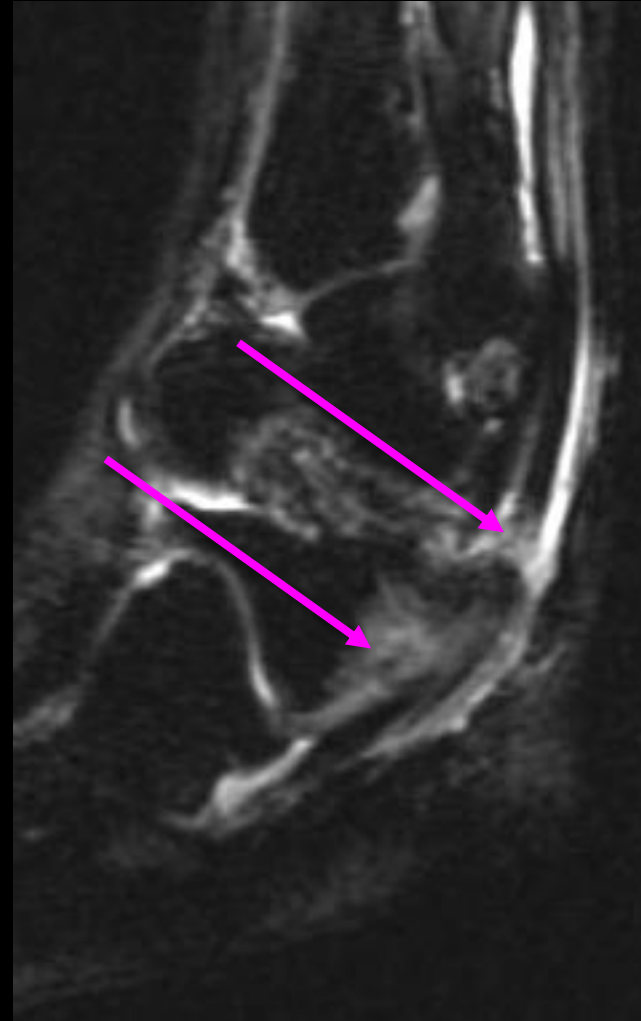
Subtendinous Bone Marrow Edema

- Response to tendon abnormality
 - Mechanical (friction)
 - Hyperemia of the overlying tendon sheath
- Most common locations in LE
 - Tibialis Posterior Tendinopathy → posterior med malleolus
 - Peroneal tendon tear / instability → lateral fibula
- High association with location of sx

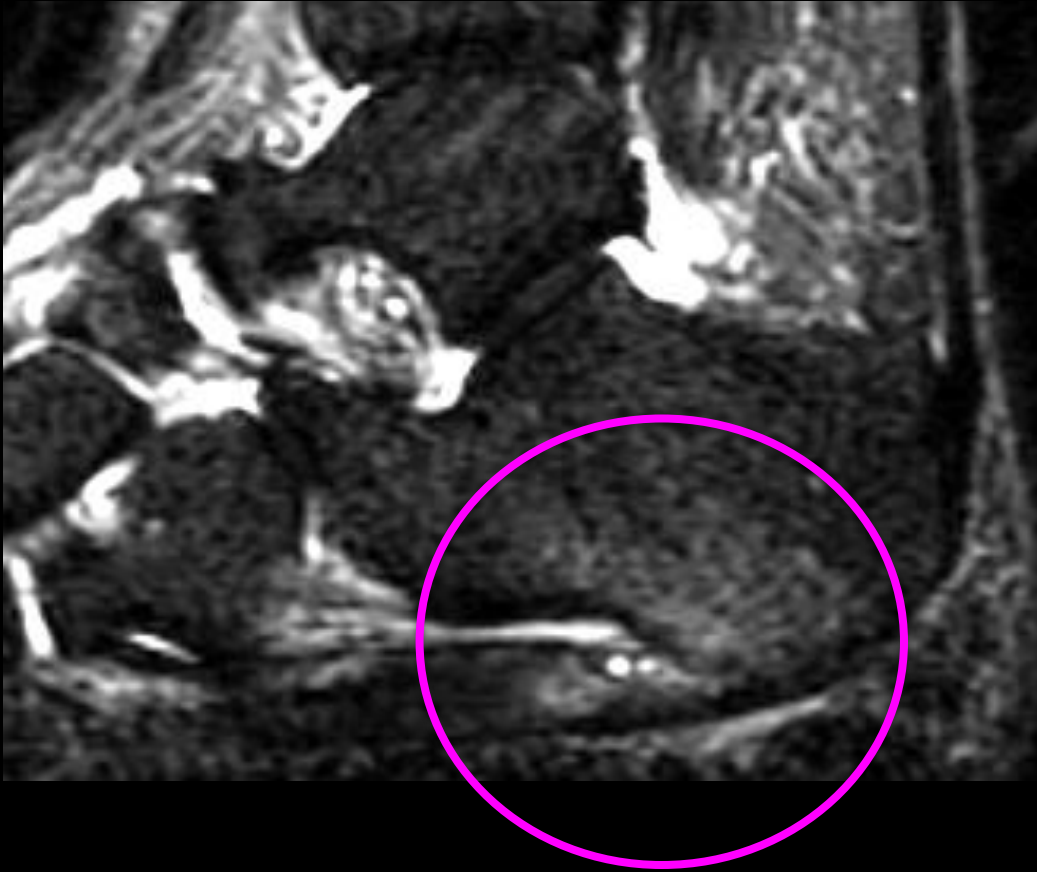
Subtendinous BME at PTT



Peroneal Tendinopathy



Enthesial BME: Plantar Fasciitis



Bone Marrow Take Homes

- MRI- maximizes sensitivity for bone marrow processes with pattern reproduction
- Bone marrow abnormalities occur in many clinical settings, so use other imaging findings and clinical info to explain bone marrow edema
- Reporting normal/variant bone marrow patterns as pathology leads to unnecessary imaging and intervention



QUESTIONS?