Evolution of Radiology: Focus on MSK MRI

**Nov 8th, 1895: The Birth of Radiology**
- 11/8/95 Wilhelm Conrad Röntgen produces “X-rays”
- 12/28/95 Röntgen presents: “On a New Kind of Rays”
- 2/11/96 Jones publishes: “The Discovery of a Bullet Lost in the Wrist by Means of the Roentgen Rays”

**X-rays as Diagnostic Tool**

Can see:
- Bones
- Fractures
- Joint width, surfaces
- Arthritis
- Osteophytes
- Erosions

Can’t see:
- Inside skull
- Can’t see the brain
- Inside joints
- Can’t see tears
- Ligaments, Tendons
- Menisci, Cartilage

Radiographs: 2D projection of 3D patient
- Radiographs flatten everything
- Can’t tell what’s in front, what’s behind
- With radiographs: NEED MULTIPLE VIEWS!
  - “One view = No views”

**Need Multiple Views**

Small finger
- Not a subtle fracture
- Fragment overlap each other so perfectly on PA view, are undetectable

**CT: Giant Leap Forward**

CAT: Computed Axial Tomography
- 1917 Johann Radon, Austrian mathematician, proved image of a 3D object could be reconstructed from an infinite number of 2D projection images of the object.
- Had to await the advent of mainframe computers in the 1970’s.

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Hounsfield & EMI Brain Scanner
1972: Godfrey Hounsfield, a British electrical engineer at EMI Laboratories, developed EMI Brain Scanners.
- “Hounsfield Units” is the scale we use to measure CT density.
- EMI: “Electric and Musical Industries”

Why CT is So Great
- Can see the brain
  - Strokes, bleeds, tumors
- Can see organs (lungs, liver, bowel)
  - Tumors, trauma, acute/chronic diseases
- Can see fractures otherwise missed
  - Cervical spine, pelvis
- And now with ultra-fast, multi-slice...
  - Can scan the heart in a single beat!
  - Can see coronary arteries, pulmonary emboli

Hospitals have CT scanners in the ER

CT Usage Increasing in ERs
Computed Tomography Use Among Children Presenting to Emergency Departments With Abdominal Pain

Biggest Problem with CT
- High radiation dose

We are exposed to low levels of radiation every day, “Background Radiation”
- Earth: naturally occurring radionuclides
- Uranium-238, potassium-40
- Radon

- Atmosphere: Radon-222 (from U-238)
- 2nd leading cause of lung cancer after smoking
- Space: cosmic rays
- Airline crews, who spend a lot of time in the upper atmosphere, receive 2x typical background dose.

Ave background dose ≈ 2.4mSv/year

Radiation from Diagnostic Imaging
Ave background dose ≈ 2.4mSv/year
- Chest Radiograph ≈ 0.06mSv
  - 1 week of background radiation
- Chest CT ≈ 7.0mSv
  - 53 YEARS of background radiation

How much radiation is too much?
"Risks of medical imaging at effective doses below 50 mSv for single procedures or 100 mSv for multiple procedures over short time periods are too low to be medically detectable and may be nonexistent."

Other Problems with CT
- Usually requires IV contrast
  - 1% patients are allergic to CT contrast
  - Can affect renal function

- Costs more than radiographs
  - Knee radiographs (4 views): $154
  - Knee CT (no contrast): $1,200

Can’t see structures inside joints
- Knee: Menisci, Ligaments, Cartilage
- Shoulder: Rotator Cuff, Labrum
- Spine: Disks, Spinal Cord
**MRI: Giant Leap Sideways**

MRI doesn’t rely on X-rays to see projected shadows of patients
- Unlike radiographs, tomography, CT
- MRI sees tissues based upon sub-atomic characteristics
  - Proton nucleus of Hydrogen
  - “NMR”
  - “Nuclear Magnetic Resonance”
  - “No More Radiologists”
- MRI
  - “Magnetic Resonance Imaging”

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**MRI Scanner: 2 Components**

**THE MAGNET**

- Aligns spins of protons in hydrogen nuclei
- Align in direction of magnetic field, \( B_0 \)

**THE COIL: 6 Jobs**

1. Sends RF pulse to flip spinning protons
2. Measures strength of resonant RF echo
   - At a specific time, \( T_E \), “Echo Time”
   - At a specific “Repetition Time”, \( T_R \)

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**Key to MRI**

Specific tissue types have specific resonant echoes (\( T1, T2 \)) depending upon specified \( T_R & T_E \)
- Fluid (Hydrogen protons in \( H_2O \))
  - Cysts
  - Joint effusions
  - Edema (in soft tissues, in bone marrow)
- Fat (Hydrogen protons in fat)
  - Sub-cutaneous fat
  - Fatty yellow bone marrow
- Dense Stuff (with few Hydrogen protons)
  - Cortical bone
  - Ligaments, tendons, Menisci

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**T1 Recovery Curve (\( T_R \approx 500ms \))**

- Fat: High
- Fluid: Low
- Dense Stuff: Low

**Steps**
1. Sends RF pulse to flip spinning protons
2. As protons realign, resonate RF energy
3. Measures strength of resonant RF echo
   - At a specific “Repetition Time”, \( T_R \)

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**How MR Scanner Works**

- Aligns spins of protons in hydrogen nuclei
- Align in direction of magnetic field, \( B_0 \)

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The Evolution of Radiology

**Focus on Musculoskeletal MRI**

**Radiographs**

CT
MR
Signal
Sequences
Coils
Magnets
Safety
Hardware

**T2 Decay Curve**

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>80ms</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Low</td>
</tr>
</tbody>
</table>

**2T-weighted image**

- Fluid: Intermediate (T₂: long, T₁: long)
- Fat: Intermediate
- Dense Stuff: Low

To increase separation of fluid from fat, can apply Fat-Suppression (“Fat-Saturation”)

**Fat-Sat T2 Decay Curve**

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**How We Make MR Images**

Magnetic field divides body into slices
Each slice is subdivided into “voxels”
- voxel: 3D pixel
- voxel size = 2D pixel size X slice thickness

Computer maps this onto 2D slices

- High signal: White (“Bright”)
- Intermediate signal: Gray (“Iso-Intense”)
- Low signal: Black (“Dark”)

**Comparing Sequences**

Fluid: Low
Fat: Low
Fat: High

**T2 Decay Curve**

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**“Proton Density”**

Poor separation of fat from fluid

PD-weighted image

- Fluid: Intermediate
- Fat: Intermediate
- Dense Stuff: Low

Great separation of Dense Stuff from fluid & fat

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Comparing Sequences

**T1**
- Dense Stuff: Low
- Cyst: Fluid: Low
- Menisci: DENSE: Stuff: LOW
- Fat: High

**T2fs**
- Dense Stuff: Low
- Cyst: Fluid: Inter
- Menisci: DENSE: Stuff: Low
- Fat: Inter

**PD**
- Dense Stuff: Low
- Cyst: Fluid: High
- Menisci: DENSE: Stuff: Low
- Fat: Low

MRI: Need Multiple Sequences

- **T1** shows Fat best
  - Most normal anatomy surrounded by fat
  - In essence, T1 shows anatomy best
- **T2** shows Fluid best
  - Most pathology contains fluid (edema)
  - In essence, T2 shows pathology best
  - Fat-suppression makes fluid more conspicuous
- **PD** shows Dense Stuff best
  - Good for meniscal and tendon tears
  - Used mostly for MRI of joint pain

Limitations of MRI

- **Limited Field of View (FOV)**
  - Image resolution related to voxel size
  - Smaller FOV = smaller voxels
  - Smaller voxels = higher resolution
  - To maximize resolution, try to limit FOV
- **Can only image inside the coil**
  - Requires an assortment of different coils for different body parts

Knee Coil

Knee Coil for the Ankle

Foot Coil

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- Elbow Coil
- Wrist Coil
- 2 Part Torso Coil
- Many Coils are Needed

MRI Scans are Expensive:
- Coils are expensive: >$25,000 EACH!
- Scanners are expensive: >$2,000,000
- Specialty trained technologists are expensive
- MR scans take 30-60 minutes
  - Run several sequences in several planes
  - Can scan only a limited number of patients per day
  - Have to charge a lot per scan
- Knee Radiographs (4 views): $154
- Knee CT (no contrast): $1,200
- Knee MR (no contrast): $2,400

MR Scans are Long:
- Patient's need to lie still... like a statue... for the entire time.
- If the patient is ill the day of the scan and can't stop coughing or sneezing, should reschedule.
- Patients who can't lie flat, severe heart failure (CHF), can't get MRI.

Don't order MSK MR before getting Radiographs!
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Scanners

Radiographs
CT
MR
Signal Sequences
Coils
Magnets
Safety
Hardware

A CT scanner... is a doughnut.

Radiographs
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An MR scanner... is a cannoli.

MR Scanner is a Tube

They don’t build tubes to torture patients. Tubular design is needed to achieve the high magnetic fields inherent to MRI. This is a 1.5 T magnet.

Tesla: Measure Magnetic Field Strength

Earth’s magnetic field:
30 µT (3×10⁻⁵ T)

Typical refrigerator magnet:
3 mT (3×10⁻³ T)

High Field MRI scanner:
1.5 – 3 T
1,000 times the strength refrigerator magnet
100,000 times the Earth’s magnetic field

“Open” MRI = Low Field

Favored by commercial stand-alone MRI sites

Our MRI scanner is open on all four sides, that’s a major advantage for large people who find a tunnel too confining, for children who might become frightened inside a tunnel, and for anyone with a touch of claustrophobia.

“Open” MRI = Low Field

Favored by commercial stand-alone MRI sites

Typical open MR: 0.1–0.3T

1/10th strength of a high field scanner...

1/10th image resolution of a high field scanner.

Costs 1/10th the price to buy low field scanner...

They charge the same price as a high field scan.

Diagnosis value of low field MR is inferior to that of high field MR.
UW Experience with Open MR

0.7 T “Mid Field”
- This is highest field open scanner made
- Our accuracy: Knee
  - In 1.5 T MR: ≈ 95% ☺
  - In this scanner: 75% ☺
  - Same UW radiologists
  - Same UW protocols

Diagnostic value of low field MR is inferior to that of high field MR.

UW Experience with Open MR

Our surgeons refused to schedule patients in our open scanner.
- Ran it only 2 days/week
- Primarily: Obese patients
- As bad as this scanner was, it did a particularly poor job with...
  - Obese patients.
- Got rid of it for a 3 T ☺!

My Recommendations

For yourself or your patients:
- Don’t use open low field scanners
- Always want to use at least a 1.5 T scanner
- Go to a 3 T if available!

What about obese patients?
- Patients who don’t fit in the standard 1.5 T?
- We now have an alternative to low field open scanners for the “Wisconsin-sized” patient...

Wide Bore 1.5T

It’s still a tube...
But it’s a much wider tube

Same size opening as a CT scanner
Table can hold up to 500 lbs!
MR scanner is just a tube

- Nothing happens inside the tube
  - Nothing moves
  - Nothing crushes
  - Open at both ends
  - Plenty of air
  - No radiation
  - No X-rays
  - No flashing lights

*If it didn't make any noise you wouldn't even know anything was happening.*

MR scanners make lots of noise

- We protect the patient’s ears
  - Ear plugs
  - Headphones
    - Can play radio station
    - or CD
    - or patient’s iPod

- Our goal is to make patient relaxed
  - We get our best pictures of people sleeping

Can take something mild as an outpatient

- Valium (Diazepam)
- Ativan (Lorazepam)
- Cocktail? (not all 3)
- Patient should not drive!

If patient is really problematic

- We can provide conscience sedation at hospital
  - Not at outpatient facility

If patient is really really problematic

- General anesthesia can be arranged
  - (It rarely comes to that)

The Big Problem with MRI

- It’s a Big Magnet
- It’s Always On

Occasionally Replenish Cryogens

Isn’t it an electromagnet?

- Can’t we just flick a switch and turn it off?
- It’s not that simple...
- Yes, it’s an electromagnet.
- Yes, it works by passing current through wire

To achieve 1.5T, need to pass A LOT of current through wire

- Requires low resistance wire...
- ...super-conducting wire
- Super-conducting materials operate at CRYOGENIC TEMPERATURES!
- Can’t turn off magnet with venting cryogens.
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MRI Safety

Everyone in the entire medical center needs to respect MRI safety
Can’t bring into the scanner room anything that is:
- Ferromagnetic
- Electronic that is not certified MRI compatible.

Safety Videos

www.patiencys.com/mri

Things Stuck in Magnets: Floor Buffer

www.MRImetalDetector.com

Things Stuck in Magnets: Gas Tank

www.simplyphysics.com

Things Stuck in Magnets: ICU Bed

www.MRImetalDetector.com

Things Stuck in Magnets: Chair

www.simplyphysics.com
Limit Access to MR Suite

MRI Safety

No Implanted Electronics

A True Tragedy

Freak MRI Accident Kills Westchester Boy

6-year-old boy undergoing an MRI exam at a Westchester hospital died after the machine’s powerful 10-ton magnet turned an oxygen canister into a missile that smashed his skull, officials said yesterday.

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### Metal Inside Patients

**Safety Issues**
- Metal that can’t move is not a safety issue
- Fillings in the teeth
- Orthopedic hardware
- Need to worry about metal that CAN move
  - Metal in/around eyes
  - Welding equipment
  - Grinding equipment
  - Fire guns w/o protection
  - People who’ve been shot
  - Old aneurysm clips

### New UW Screening Sheet

**Radiographs**
- CT
- MR
- Signal Sequences
- Coils
- Magnets
- Safety Hardware

**CT**
- Radiographs
- CT
- MR
- Signal Sequences
- Coils
- Magnets
- Safety Hardware

**MR**
- Radiographs
- CT
- MR
- Signal Sequences
- Coils
- Magnets
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**Safety**
- Radiographs
- CT
- MR
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- Coils
- Magnets
- Safety Hardware

**Hardware**
- Radiographs
- CT
- MR
- Signal Sequences
- Coils
- Magnets
- Safety Hardware

### An actual case...

We’re screening the patient to see if he’s MR compatible. We ask the patient if he has any metal in his body. He replies, “…yeah… I think I was shot in the head once.”

**Is this patient MR compatible?**

Maybe yes, maybe no.

We get a skull radiograph...

What do you say now?

“One view = no views”

### Need to have Multiple Views

- **Waters View**
  - Bullet projecting next to the orbit
- **AP View**
  - Bullet nowhere near the eye

### This Patient is NOT MR Compatible

Don’t want this knife blade to move from its current position.

**History?**

“Stabbing Chest Pain”
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Metal Inside Patients

Radiographs
CT
MR
Signal Sequences
Coils
Magnets
Safety Hardware

Safety Issues
- No implanted electronics
- No metal that can move

Imaging Issues
- Metal can affect the magnetic field
- "Susceptibility artifact"
- May limit diagnostic value of the scan...
- But often the scans come out just fine.
- As long as the patient is MR safe, we’re willing to try.
- If we can’t get useful images, cancel all charges.

Metal Example: Femoral Rod

Radiographs
CT
MR
Signal Sequences
Coils
Magnets
Safety Hardware

Patient with lots of metal
Is it unsafe to put this patient in the magnet?
Of course not!

Fracture!
Even in retrospect this fracture cannot be seen on the radiograph.

Metal Example: Interference Screws

Radiographs
CT
MR
Signal Sequences
Coils
Magnets
Safety Hardware

T2fs Coronal
artefact

T2fs Sagittal
artefact

ACL graft intact

PD Sagittal

ACL graft intact

Any questions about anything?

Radiographs
CT
MR
Signal Sequences
Coils
Magnets
Safety Hardware

Should always start with radiographs
- Least expensive study
- May show the answer
- Needed for planning other studies

CT (MSK)
- Used in ER for fracture detection (spine)
- Used for surgical planning of known fractures
- Best ordered by treating specialist

MRI
- Used for tears, occult fractures, infections, ...
- Best ordered by treating specialist

What to Order When (WOW)