Evolution of Radiology: An Introduction for Non-Radiologists

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”

TOPICS
- Radiographs
- CT
- X-rays (EMS)
- Nuclear Med
- Ultrasound
- MRI
- Physics
- Coils
- Magnets
- Safety
- WOW

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How We Make Radiographs

Light rays bounce off my hand and into my camera. We call the image:
- “Light-Ray”
- “Photograph”

How We Make Shadows

“Shadow-graph”

Everywhere hand blocks the light is dark… Everywhere hand doesn’t block the light is illuminated.

Now, if we hang photographic film on wall we get…

“Negative-graph”

Everywhere hand blocks light the film is not exposed and stays white… Everywhere hand doesn’t block the light the film gets exposed and turns dark.
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**How We Make Radiographs**

- X-ray Tube
- X-ray Detectors
- Terminology: X-rays: Rays that pass thru the patient. The image is called a "radiograph".

**20th Century: Images = Film**

- Radiographs
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- Nuclear Med
- Ultrasound
- MRA
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- WOW
- X-ray Detectors
- Processed in the dark room
- Developer
- Film
- Allowed to dry
- Radiologist
- Primary
- Specialist
- Outside
- File room
- Lost/Damaged

**21st Century: Images = Film**

- X-ray Detectors
- Digital Imaging
- PACS
- Picture Archive & Communication System
- Computer
- Server
- Loaded to the network
- Primary
- Specialist
- Outside
- Electronic Images
- Patient's chart
- Lost/Damaged

**21st Century: Digital Imaging**

- Toshiba
- Siemens
- General Electric
- GE
- Phillips
- Siemens
- Toshiba
- Wonder!

**Old Terms Still Used**

- "Film": What I tend to call radiographs
- "Wet read": Look at the film STAT
- Refers to when we would look at films right out of the developing solution, before they had time to dry.
- "Dial a telephone"
- "Ring tones"

**Radiographs are Limited**

- Radiographs can detect only four densities of tissue:
  - Metal (white)
  - Bones (light gray)
  - Soft Tissues (dark gray)
  - Air (black)

- All soft tissues look the same on radiographs:
  - Muscles
  - Tendons
  - Vessels
  - Nerves
  - Organs/Body
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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”

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

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

Need Multiple Views

For Joints: Need 3 Views!

Tomography: Small Step Forward

To overcome flat 2D nature of radiographs...
- Structures in the Focal Plane → are in focus.
- Structures out of focal plane are blurred out.
- At best, we got blurry pictures.
- Long exposures = high radiation.

CT: Giant Leap Forward

CT: Computed Tomography (Tomo [Gr]: part, slice)
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.
Hounsfield & EMI Brain Scanner

1972: Godfrey Hounsfield, a British electrical engineer at EMI Laboratories, developed EMI Brain Scanner.
- Finally, could see through the skull into the brain!
- “Hounsfield Units” is the scale we use to measure CT density.

EMI: “Electric and Musical Industries”

www.sciencemuseum.org.uk

CT = Rotating X-rays

Computed AXIAL Tomography

Axial Plane:
- Top to Bottom
- Base of skull
- Arch of C1
- Body of C2

Computed VOLUME Tomography

Thin, continuous slices = Solid volume of data
Can reformat data:
- Any 2-D plane
- Coronal, Sagittal, Oblique
- Even in 3-D!

Multi-Planar Reformat

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

Why CT is So Great

Hospitals have CT scanners in the ER
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**CT Usage Increasing in ERs**

Computed Tomography Use Among Children Presenting to Emergency Departments With Abdominal Pain

**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
  - Knees: Menisci, Ligaments, Cartilage
  - Shoulder: Rotator Cuff, Labrum
  - Spine: Disks, Spinal Cord

**Evolution of Radiology**

**BIGGEST PROBLEM WITH CT**

High radiation dose

- We are exposed to low levels of radiation every day, “Background Radiation”
  - Earth: naturally occurring radionuclides
  - Atmosphere: Radon-222 (from U-238)
  - 2nd leading cause of lung cancer after smoking
  - Space: cosmic rays
  - Airline crews are more exposed to cosmic rays, doubling their background exposure.

Ave background dose ≈ 2.4mSv/year

**Radiation from Diagnostic Imaging**

- Average background dose ≈ 2.4mSv/year
- Chest Radiograph ≈ 0.06mSv
- 1 week of background radiation
- Chest CT ≈ 7.0mSv
- 3 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 detectable and may be nonexistent.”

**What are X-rays?**

- X-rays are not naturally occurring
- Produced by X-ray tubes
- Used for diagnostic imaging
- Radiographs
- Tomography
- CT
- Fluoroscopy (radiographs in real-time)
- Used for radiation therapy
- Treating tumors
- 1000s of magnitude higher radiation dose than in diagnostic imaging

X-rays part of Electromagnetic Spectrum

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Electromagnetic Spectrum

**TOPICS**
- Radiographs
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- X-rays (EMS)
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- MR (EMS)
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![Iguazu Falls, Brazil-Argentina Border](image1)

WOW

The Way Energy Moves Throughout the Universe

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Visible Light

Non-Ionizing Radiation
- No Free Radicals
- Doesn't Damage DNA

Ionizing Radiation
- Detach Electrons
- Atoms ionized
- "Free Radicals"
- Damage DNA

“SUPERMAN IS ABLE TO FOCUS ON OBJECTS FAR BEYOND THE RANGE OF NORMAL HUMAN SIGHT. HIS EYES CAN PERCEIVE VIRTUALLY THE ENTIRE ELECTROMAGNETIC SPECTRUM, ENABLING HIM TO SEE THROUGH MOST SOLID OBJECTS.”

To Perceive Energy
- Detector sensitive to energy frequency
- Energy able to reach the detector

"X-ray Vision Specs" even if they could detect X-rays they still wouldn't work...

There are no naturally occurring X-rays out there to detect!

**Evolution of Radiology**

MRI
Ultrasound
Nuclear Med
CT
Radiographs
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Ways we can Perceive Light

- **Transmission**
  - Light transmitted thru lamp
  - X-rays transmitted thru pt
  - Radiographs
  - Tomography, CT
  - Fluoroscopy
  - Shows STRUCTURE

- **Emission**
  - Energy emitted from light saber
  - Energy emitted from patient
  - EKG (Heart's natural electricity)
  - Thermography
  - Nuclear Medicine (injected radiisotope)
  - Shows FUNCTION

Thermography

- Images patient’s naturally emitted heat energy.
- Widely agreed to be of NO diagnostic value.

Nuclear Medicine

- Developed after World War II
- Research on nuclear bomb byproducts
- Fission Uranium-235 → Iodine-131
- Naturally occurring Iodine not radioactive
- Iodine-131 is HIGHLY radioactive
  - Emits β-particles
  - Much more damaging than γ-rays
  - Accumulate in and destroys Thyroid tissue
  - Nuclear Reactor Fallout ➔ Hypothyroid
- Take iodine pills to block I-131 from Thyroid
- Useful for treating Thyroid Cancer

Iodine

- Naturally occurring element
- Rare on Earth (47th abundant)
- Rare in Humans (<0.05%)
- Taken up by Thyroid Gland
- Made into Thyroid Hormone

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### Nuclear Medicine

#### TOPICS
- Radiographs
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**Nuclear Medicine**

> Developed more agents to accumulate in specific tissues, emit low-energy γ-rays.

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**Nuclear Medicine: Bone Scan**

- Was used a lot before CT & MR
- Shows bone pathology earlier than radiographs
- Nowadays, seldom used for focal lesions

We use MR for:
- Focal bone pain not seen on radiographs
- Infections (osteomyelitis)
- Imaging primary bone tumors

We still use Nuc Med Bone Scans for:
- Looking for bone metastases in entire body
- Breast Cancer
- Prostate Cancer

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**Nuclear Medicine: PET/CT**

- Most recent innovation in Nuc Med
- PET: Positron Emission Tomography

- Uses agents with very short half-lives
- Flurine-18 (100 min)
- Oxygen-15 (2 minutes)
- Made onsite with cyclotron
- Agents taken up by tumors, metastases
- Well shows abnormal FUNCTION

Combined with CT (Computed Tomography)
- Well shows underlying ANATOMY
- Used for staging cancer patients

#### Ultrasound

**Ways we can Perceive Light**

- Emission
- Transmission
- Reflection
- "Sound Navigation And Ranging"

- Developed after World War II
- Based upon SONAR
- Sound wave sent out
- If sound hits an object
- Measure time for the reflected echo to return
- Multiply the time by speed of sound
- Works best in water
- Water transmits sound well

**Evolution of Radiology**
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**Sonography**

Uses radio waves (Not X-rays, γ-rays)

- Non-Ionizing Radiation
- Ionizing Radiation

- Medical imaging techniques that use sound waves (ultrasound) to create images.

- Useful for:
  - Tissues that contain/surrounded by water
  - Abdominal organs
    - Gall bladder (Gall Stones)
    - Kidneys (Kidney Stones)
  - Blood vessels
    - Blood clots (DVT: Deep Venous Thrombosis)
  - Imaging without Ionizing Radiation
    - Pelvic organs
      - Uterus, Ovaries
      - Testes
    - Babies (Newborn)
    - Babies… before birth

**Sonography Useful for...**

Tissues that contain/surrounded by water
- Abdominal organs
- Gall bladder (Gall Stones)
- Kidneys (Kidney Stones)
- Blood vessels
- Blood clots (DVT: Deep Venous Thrombosis)

Imaging without Ionizing Radiation
- Pelvic organs
- Uterus, Ovaries
- Testes
- Babies (Newborn)
- Babies… before birth

**Obstetric Ultrasound**

Marty age -5 months

**Next... MRI**

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

**MRI: Giant Leap Sideways**

**MRI Scanner: 2 Components**

- THE MAGNET

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### MRI Scanner: 2 Components

- **THE COIL:** Jobs
  - Radio Frequency Transmitter
  - Radio Frequency Receiver

### How MR Scanner Works

**Magnet**
- Aligns spins of protons in hydrogen nuclei
- Aligns in direction of magnetic field, B_0

**Coil**
- Sends RF pulse to flip spinning protons
- After RF pulse is off, protons realign to B_0
- As protons realign, resonate RF energy
- Measures strength of resonant RF echo
- At a specific “Replication Time”, T_R

Steps 1&2 repeated many times / image slice

### 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):**
    - Subcutaneous fat
    - Fatty yellow bone marrow
  - **Dense Stuff (with few Hydrogen protons):**
    - Cortical bone
    - Ligaments, tendons
    - Meniscus

### T1 Recovery Curve (T_R~500ms)

- **Fat:**
- **Fluid:**
- **Dense Stuff:**

- **Time to Echo T_E (ms)**

### T2 Decay Curve (T_R~2,000ms)

- **Fat:**
- **Fluid:**
- **Dense Stuff:**

- **Time to Echo T_E (ms)**

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**Fat-Sat T2 Decay Curve (T_R~2,000ms)**

- Magnetic field divides body into slices
- Each slice is subdivided into “voxels”
  - voxel: 3D pixel
  - voxel size = 2D pixel size X slice thickness
- Coils measure signal in each voxel
- Computer maps this onto 2D slices
  - High signal: White (“Bright”)
  - Intermediate signal: Gray (“Iso-intense”)
  - Low signal: Black (“Dark”)

**Comparing Sequences**

- Knee, same mid-sagittal slice
- “Proton Density” Poor separation fat from fluid
- PD-weighted image (T_R long, T_E short)
  - Fluid: Intense
  - Fat: Intermediate
  - Dense Stuff: Low

**T2 Decay Curve (T_R~2,000ms)**

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

**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

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Seeing in 4-Dimensions

TOPICS
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Seeing in 4-Dimensions

Radiographs are flat projections
- Only give information in 2-D
- Need 2+ projections to fully see patient

CT is a stack of slices
- Images the patient in 3-D

MR is a stack of slices... and more
- Not only shows tissues in 3-D
- It shows the composition of the tissues
  - T1: How Fatty, T2: How Wet
- MR shows more than just 3-D

Seeing in 5-Dimensions!

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Seeing in 5-Dimensions!

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

Limitations of MRI

Knee Coil

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Knee Coil for the Ankle

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Foot Coil

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

Don’t order MSK MR before getting Radiographs!
**MR Scans are Long**

- MR scans take 30-60 min
- 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.

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**Scanners**

- A CT scanner... is a doughnut
- 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
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**“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.

Diagnostic 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.

---

**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...

---

**New 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!

Marty age 14

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**Wide Bore 1.5T, also Short Bore**

Wide bore + short bore = less “closed in” feeling

Marty age 14
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MR scanner is a tube

**Claustrophobia**

- Don't make patients claustrophobic
- Things I've seen clinicians write:
  - I told my patient he was trauamic an MR scan is
  - I told my patient it's like laying inside a COFFIN
  - I told my patient it's like laying in a SEWER PIPE

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

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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.

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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

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If your patient is still anxious

- Can take something mild as an outpatient
  - Valium (Diazepam)
  - Alivan (Lorazepam)
  - Cocktail? (not all 3)
  - Patient should not drive!
- General anesthesia can be arranged
  - (It rarely comes to that)

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The Big Problem with MRI

**It’s a Big Magnet**
**It’s Always On**

- It’s not that simple...
- Can’t we just frlick a switch and turn it off?
- 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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Why is it Always On?

- It's a Big Magnet
- It's a Big Magnet
- It's Always On

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Occasionally Replenish Cryogens

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

Things Stuck in Magnets: Floor Buffer

Things Stuck in Magnets: Gas Tank

Things Stuck in Magnets: ICU Bed
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Things Stuck in Magnets: Chair

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Warning Signs

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Metal Objects May Become Airborne

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MRI Safety in China

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MRI Safety in China

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Limit Access to MR Suite

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A True Tragedy

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MRI Safety

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No Implanted Electronics

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No Implanted Electronics
- No pacemakers
- No cochlea implants
- No neuro-stimulators

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

New UW Screening Sheet

Need to have Multiple Views
- Waters View: Bullet projecting next to the orbit
- AP View: Bullet nowhere near the eye

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”
Evolution of Radiology: An Introduction for Non-Radiologists

Evolution of Radiology

This Patient is NOT MR Compatible

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

History?

“Stabbing Chest Pain”

Evolution of Radiology

Thought Experiment: Magnetic Attraction

TOPICS
Radiographs
CT
X-rays (EMS)
Nuclear Med
Ultrasound
MR
Physics
Coils
Magnets
Safety
WOW

Glass of Water
Like bullet in eye
Magnetic attraction ≤ Weight paperclip + glass + Jell-O

Like bullet in brain
Magnetic attraction ≥ Weight paperclip + glass + Jell-O

Iron Cup

Evolution of Radiology

Metal Inside Patients

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

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

Imaging Issues

Evolution of Radiology

Metal Example: Femoral Rod

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

Patient has unexplained knee pain.

Evolution of Radiology

Metal Example: Interference Screws

ACL graft intact

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

ACL graft intact
Evolution of Radiology: An Introduction for Non-Radiologists

What to Order When (WOW): MSK
- Should always start with radiographs
  - Least expensive study
  - May show the answer
  - Needed for planning other studies
- CT
  - In ER for fracture detection (spine)
  - For surgical planning of known fractures
  - To assess degree of surgical fusion
- MRI
  - Joints: Tears, internal derangement
  - Spine: Disk bulges, cord compression
  - Bones: Occult fractures, infection, tumors...

Putting it all together: Case example
41 yo F
- Neck pain
- Numbness/tingling
- Radiating down both arms
- Down to the fingers
- Spares the thumbs
- Radiculopathy
- C7, C8

What to order first?
- Radiographs... of what?
- Cervical spine

Putting it all together: Case example
Surgery
- Remove bulging C5-C6 & C6-C7 disks
- Fuse vertebral bodies of C5 to C6 & C6 to C7
Did well for nearly two years...

Putting it all together: Case example

WOW: Practical Considerations

<table>
<thead>
<tr>
<th>TOPICS</th>
<th>Radiographs</th>
<th>Charge ($)</th>
<th>Time (min)</th>
<th>Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>$154</td>
<td>&lt; 1 sec.</td>
<td>~0.06 mSv (1 week background)</td>
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<tr>
<td>C5 &amp; C6</td>
<td>$2,400</td>
<td>30-60 min</td>
<td>NONE</td>
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<tr>
<td>C1</td>
<td>$1,200</td>
<td>~30 min</td>
<td>~7.0 mSv (3 years background)</td>
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<td>Nuclear Med</td>
<td>$1,200</td>
<td>700</td>
<td>NONE</td>
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<tr>
<td>Ultrasound</td>
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<td>~30 min</td>
<td>~3.5 mSv (1.5 years background)</td>
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<tr>
<td>MR</td>
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<td>~30 min</td>
<td>~18 mSv (18 years background)</td>
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<tr>
<td>US</td>
<td>$1,500</td>
<td>4hr post inject</td>
<td>7 mSv (whole body)</td>
<td></td>
</tr>
</tbody>
</table>

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