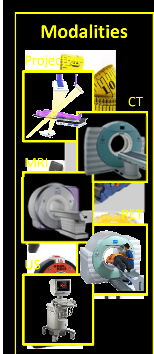
THE DEPARTMENT OF BIOMEDICAL ENGINEERING

ACT1
Image Acquisition:
Turning People into ~~Numbers~~ Matrices

Jeff Siewerdsen, Ph.D.
Department of Biomedical Engineering
Johns Hopkins University

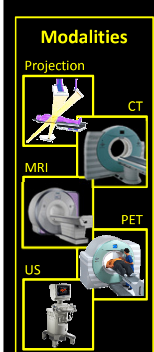
Johns Hopkins University
Schools of Medicine and Engineering



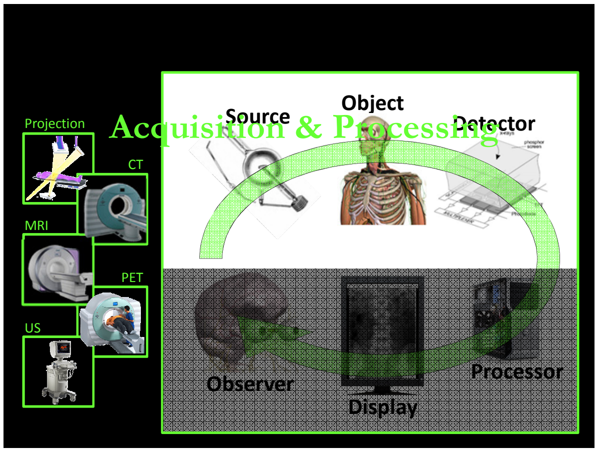
A medical imaging system is a machine that transforms people into numbers.

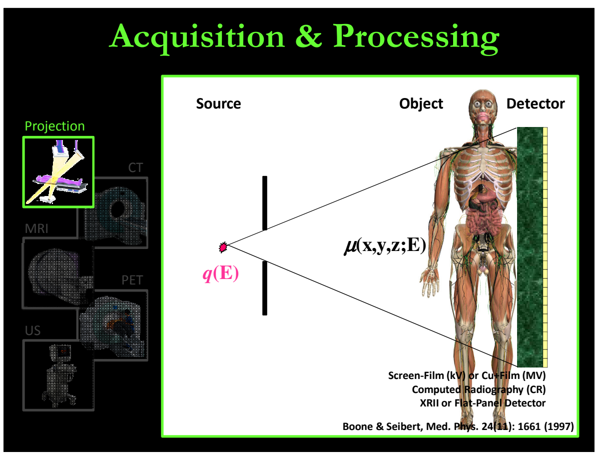
*... performs a **measurement**.*

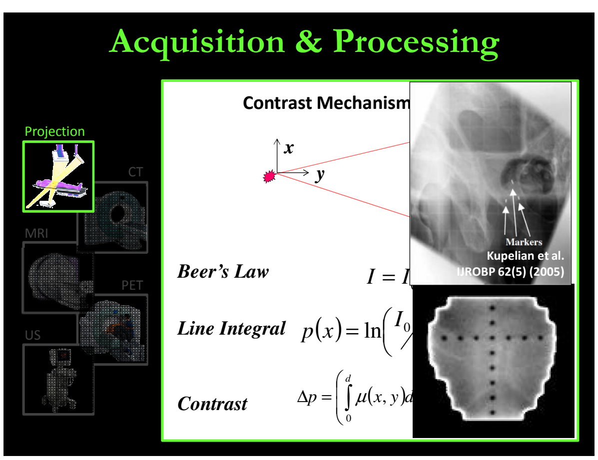
Overview

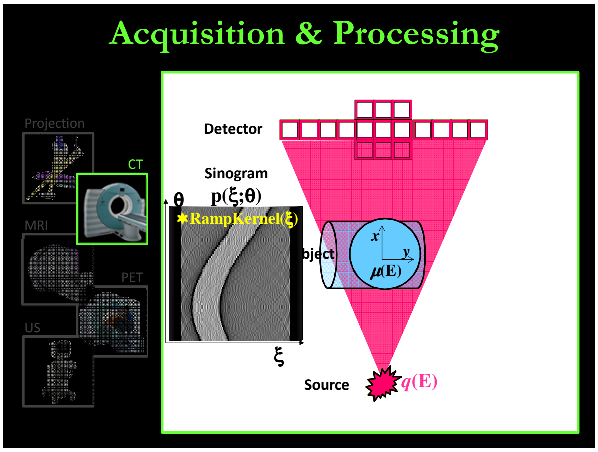


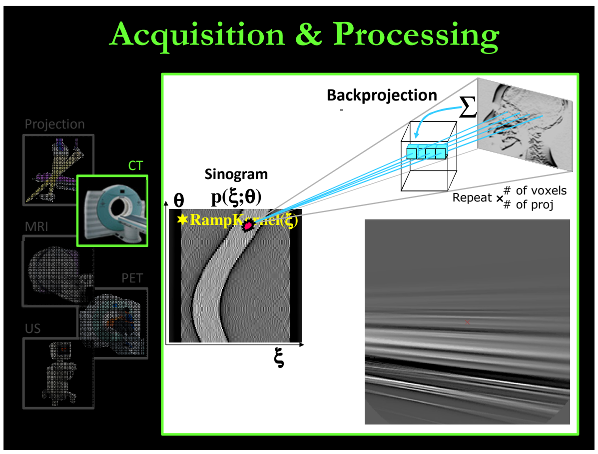
Acquisition & Processing	Image Quality Characteristics	Role in IGRT / ART
Physical Principles	Spatial Resolution	Real-Time
Contrast Mechanism(s)	Contrast Resolution	Near-Real-Time
Physical Configuration	Temporal Resolution	Offline
Processing & Reconstruction		

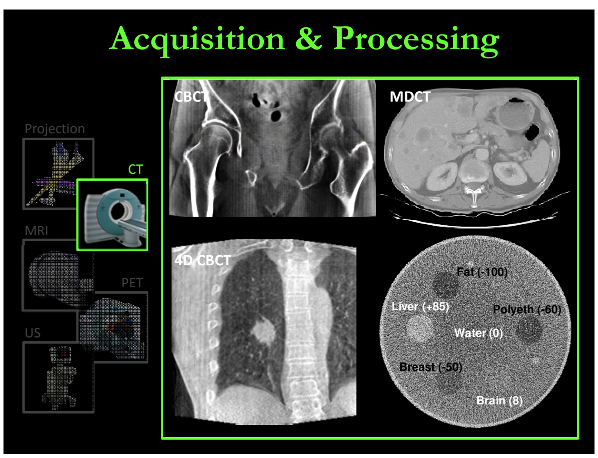

Acquisition & Processing
Projection
CT
MRI
PET
US
Source
Object
Detector
Observer
Display
Processor

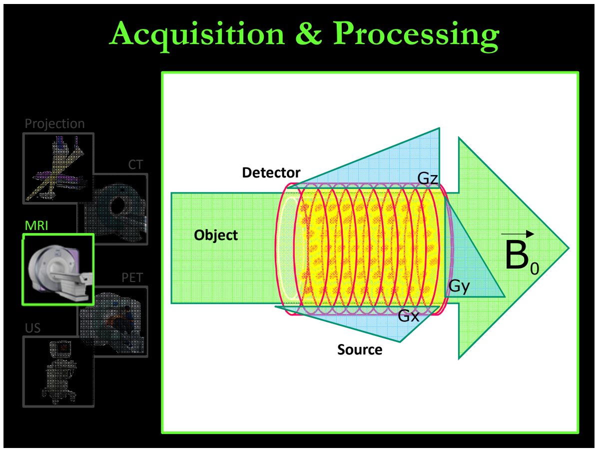

Acquisition & Processing
Projection
CT
MRI
PET
US
Source
Object
Detector
μ(x,y,z;E)
q(E)
Screen-Film (kV) or Cu+Film (MV)
Computed Radiography (CR)
XRII or Flat-Panel Detector
Boone & Seibert, Med. Phys. 24(11): 1661 (1997)


Acquisition & Processing
Projection
CT
MRI
PET
US
Contrast Mechanism
x
y
Markers
Kupelian et al.
IJROBP 62(5) (2005)
Beer's Law
Line Integral
Contrast

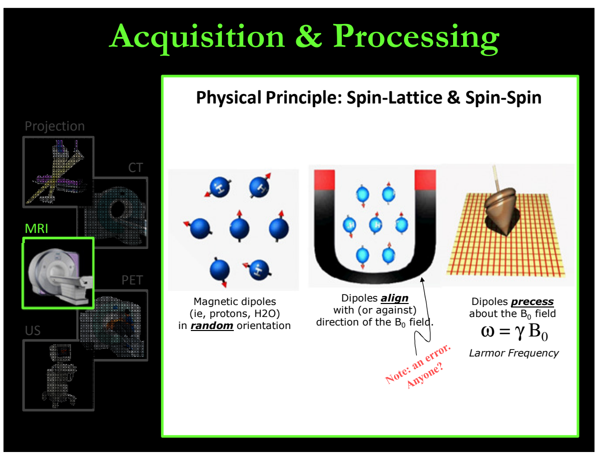

Acquisition & Processing
Projection
CT
MRI
PET
US
Detector
Sinogram
p(ξ;θ)
θ
✶RampKernel(ξ)
ξ
bject
x
y
μ(E)
Source
q(E)


Acquisition & Processing
Projection
CT
MRI
PET
US
Backprojection
Σ
Sinogram
p(ξ;θ)
θ
ξ
Repeat × # of voxels
# of proj

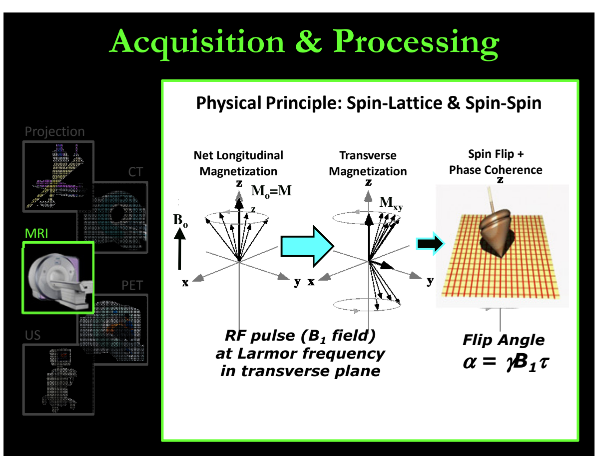

Acquisition & Processing
Projection
CT
MRI
PET
US
CBCT
MDCT
4D CBCT
Fat (-100)
Liver (+85)
Polyeth (-60)
Water (0)
Breast (-50)
Brain (8)



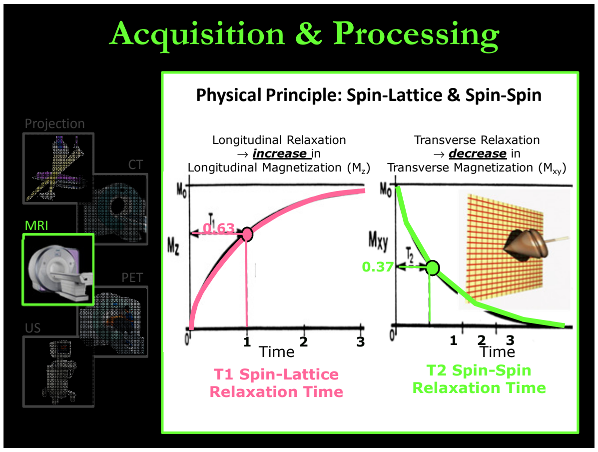
Acquisition & Processing
Projection
CT
MRI
PET
US
Detector
Object
Gz
Gy
Gx
Source
$\vec{B}_0$

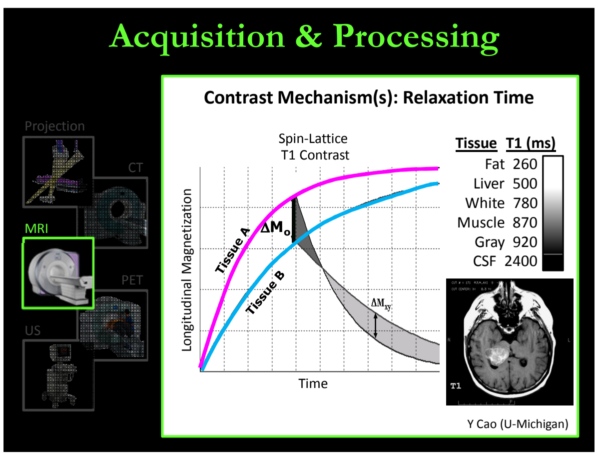


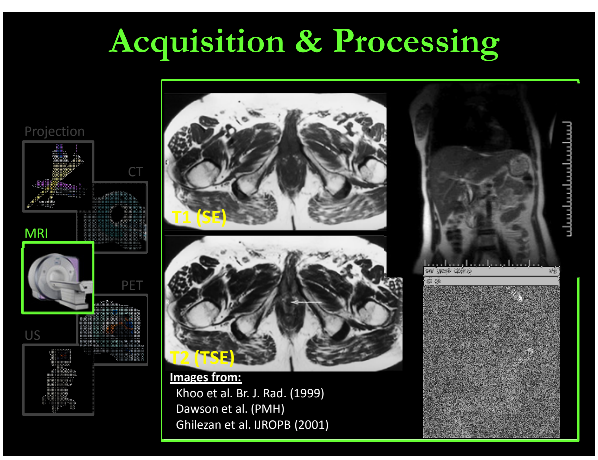
Acquisition & Processing
Projection
CT
MRI
PET
US
Physical Principle: Spin-Lattice & Spin-Spin
Magnetic dipoles (ie, protons, H2O) in random orientation
Dipoles align with (or against) direction of the B_0 field.
Dipoles precess about the B_0 field
$\omega = \gamma B_0$
Larmor Frequency
Note: an error. Anyone?

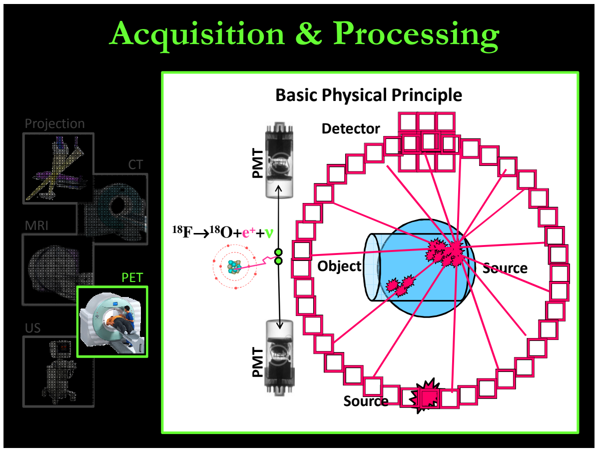


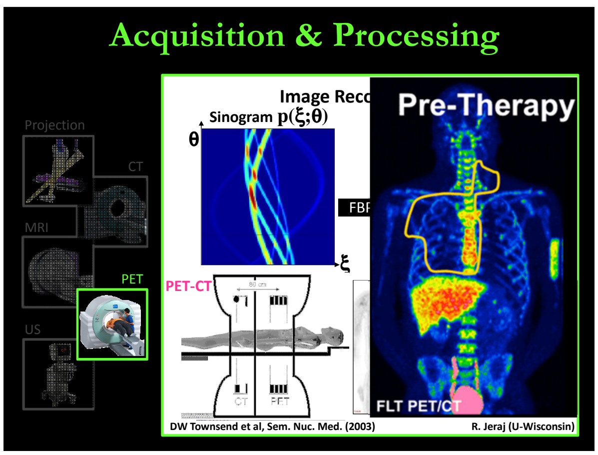
Acquisition & Processing
Projection
CT
MRI
PET
US
Physical Principle: Spin-Lattice & Spin-Spin
Net Longitudinal Magnetization
Transverse Magnetization
Spin Flip + Phase Coherence
B_0
$M_0=M$
M_{xy}
z
x
y
RF pulse (B_1 field) at Larmor frequency in transverse plane
Flip Angle
$\alpha = \gamma B_1 \tau$

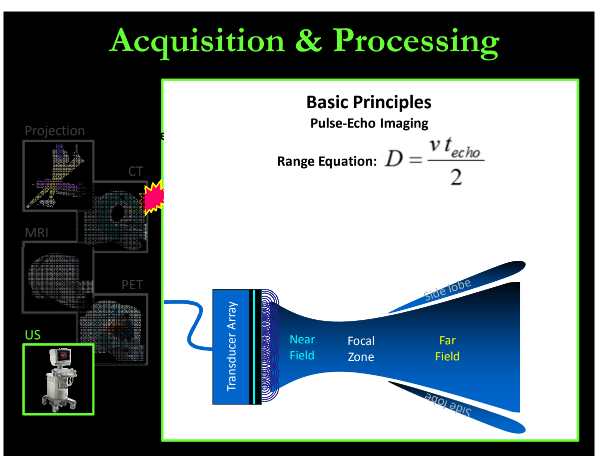

Acquisition & Processing
Physical Principle: Spin-Lattice & Spin-Spin
Projection
CT
MRI
PET
US
Longitudinal Relaxation
→ increase in
Longitudinal Magnetization (Mz)
Transverse Relaxation
→ decrease in
Transverse Magnetization (Mxy)
0.63
0.37
Time
T1 Spin-Lattice
Relaxation Time
T2 Spin-Spin
Relaxation Time


Acquisition & Processing
Contrast Mechanism(s): Relaxation Time
Projection
CT
MRI
PET
US
Spin-Lattice
T1 Contrast
Longitudinal Magnetization
Tissue A
Tissue B
Time
Tissue T1 (ms)
Fat 260
Liver 500
White 780
Muscle 870
Gray 920
CSF 2400
Y Cao (U-Michigan)

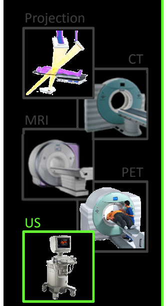

Acquisition & Processing
Projection
CT
MRI
PET
US
T1 (SE)
T2 (TSE)
Images from:
Khoo et al. Br. J. Rad. (1999)
Dawson et al. (PMH)
Ghilezan et al. IJROPB (2001)


Acquisition & Processing
Projection
CT
MRI
PET
US
Basic Physical Principle
Detector
PMT
$^{18}F \rightarrow {}^{18}O + e^{+} + \nu$
Object
Source
PMT
Source


Acquisition & Processing
Projection
CT
MRI
PET
US
Image Reco
Sinogram p(ξ;θ)
θ
ξ
FBP
PET-CT
Pre-Therapy
FLT PET/CT
DW Townsend et al, Sem. Nuc. Med. (2003)
R. Jeraj (U-Wisconsin)


Acquisition & Processing
Projection
CT
MRI
PET
US
Basic Principles
Pulse-Echo Imaging
Range Equation: $D = \frac{v\, t_{echo}}{2}$
Transducer Array
Near Field
Focal Zone
Far Field
Side lobe
Side lobe

Acquisition & Processing



Basic Principles

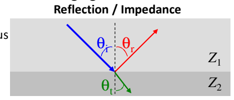
Pulse-Echo Imaging

Velocity of sound

$$v = \sqrt{\frac{B}{\rho}}$$

B ← Bulk modulus; ρ ← Density

Reflection / Impedance



Material:	v (m/s):	Z (Mrayls):	R (soft tissue):
Air	330	0.0004	1.00
Lung	600	0.18	0.79
Fat	1460	1.34	0.07
Water	1480	1.48	0.02
Soft tissue	1540	1.54	0
Liver	1555	1.65	0.03
Blood	1560	1.65	0.03
Kidney	1565	1.63	0.03
Muscle	1600	1.71	0.05
Bone	4080	7.80	0.67

Reflectivity

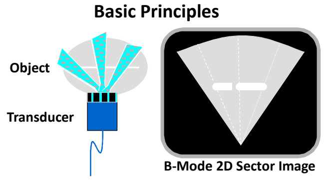
$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

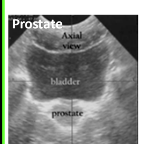
Acoustic Impedance

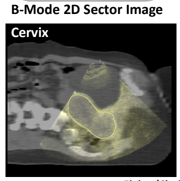
$$Z = \rho v$$

Acquisition & Processing

Basic Principles







W. Tome (U-Wisconsin)

Elekta (Clarity™)

Contrast is higher in CT than x-ray projections, because:

- 0% 1. CT uses a higher dose.
- 0% 2. CT uses contrast agents.
- 0% 3. CT uses lower-energy x-rays.
- 0% 4. CT has lower noise.
- 0% 5. Because:

$$\bar{\mu}_1 - \bar{\mu}_2 > \int \mu(x,y,z)dy\Big|_{x1} - \int \mu(x,y,z)dy\Big|_{x2}$$

10

Contrast is higher in CT than x-ray projections, because:

1. CT uses a higher dose.
2. CT uses contrast agents.
3. CT uses lower-energy x-rays.
4. CT has lower noise.
5. **Because:**

$$\bar{\mu}_1 - \bar{\mu}_2 > \int \mu(x,y,z)dy\Big|_{x1} - \int \mu(x,y,z)dy\Big|_{x2}$$

Imaging Performance

Modalities

CT

Accuracy (Quantitation)

Extent to which the measured value equals the 'true' value
Vital to longitudinal imaging, QI:

- Monitoring (SUV → remission)
- Diagnosis (BMD → osteoporosis)
- Tx planning (μ → dose calculation)

Precision (i.e., "Resolution")

Min interval in {DIM} for which two stimuli can be distinguished

{ $\vec{x}$ / *the measured property* / t }

Spatial Resolution
→ lp/mm… PSF, LSF, ESF… MTF
(≠ pixel size!)

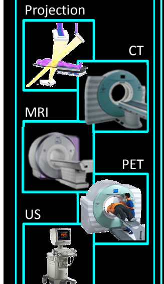
Contrast Resolution
→ contrast… noise… CNR (SDNR)
(≠ a display parameter)

Temporal Resolution
→ speed… temporal MTF (≠ fps)

cuiusmodi "Resolution"

Modalities

Projection, CT, MRI, PET, US



Spatial Resolution

$$MTF(f_r) = FT\left\{\begin{matrix} RT[PSF(x,y)] \\ LSF(x) \\ \frac{\partial}{\partial x}[ESF(x)] \end{matrix}\right\}$$

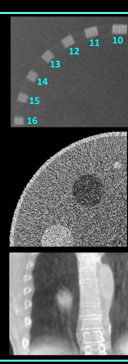
Contrast Resolution

$$SDNR = 2\frac{\bar{\mu}_1 - \bar{\mu}_2}{(\sigma_1 + \sigma_2)}$$

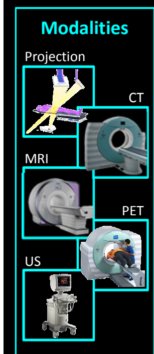
Temporal Resolution

Direct analogue to spatial resolution
(with 1-sided causal response)

$$MTF(f_t) = FT\left\{\begin{matrix} IRF(t) \\ \frac{\partial}{\partial t}[ERF(t)] \end{matrix}\right\}$$

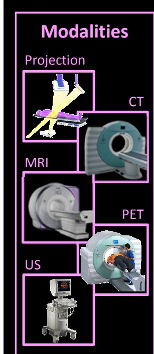


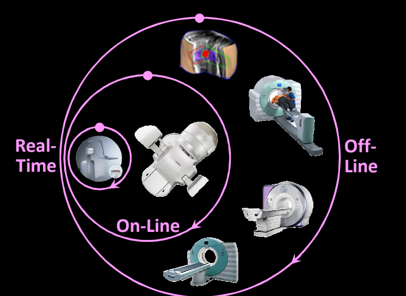
Imaging Performance



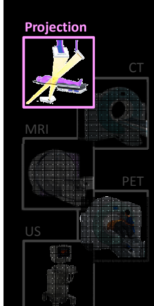
Modalities	Quantitative Accuracy	Spatial Resolution	Contrast Resolution	Temporal Resolution
Projection	-	+++ (but 2D)	---	--- Rad ++ Fluor
CT	++ MDCT - CBCT	++	+	- 3D + 4D
MRI	-	+	+++	--- 3D + Cine
PET	+	-	++	- 3D + 4D
US	+	++	+	+++

Role in IGRT / ART



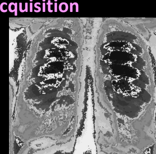


Role in IGRT / ART



Temporal Scales of Acquisition

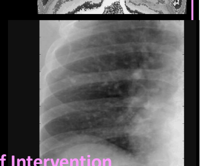
Radiography
~Instantaneous (exposure time: 10 ms)
… but <u>static</u>



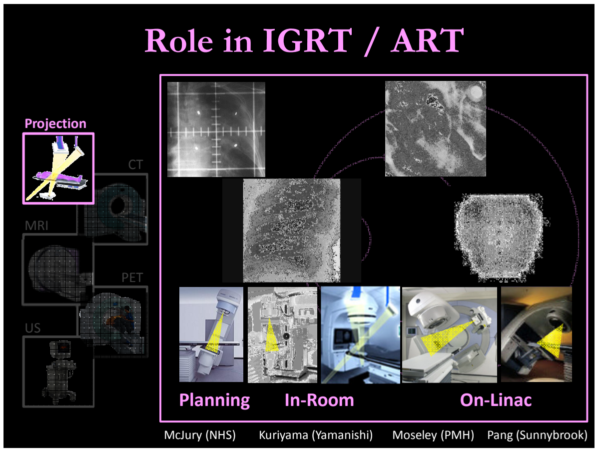
Fluoroscopy
Real time / dynamic
1 fps… 5 fps… 30-60 fps

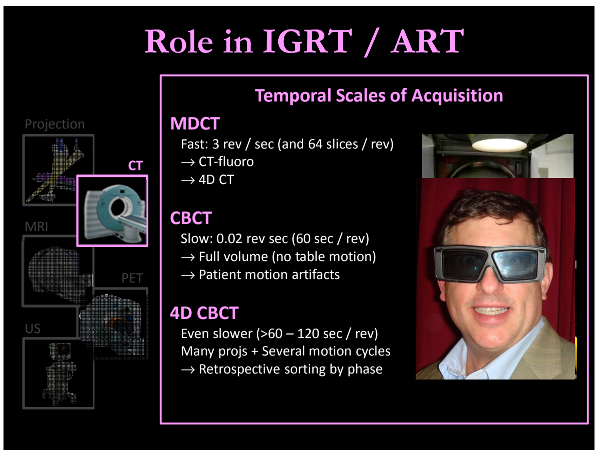
Speed governed by:
- Frame rate of the detector

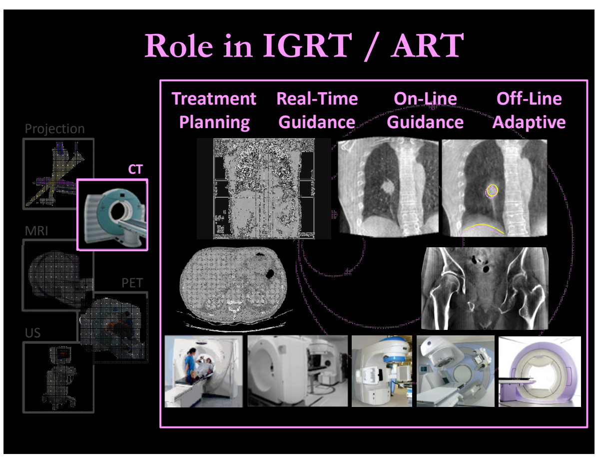
also:
- Exposure rate (mA)
- Detector gain (e.g., high-gain XRII)
- Spatial resolution requirement

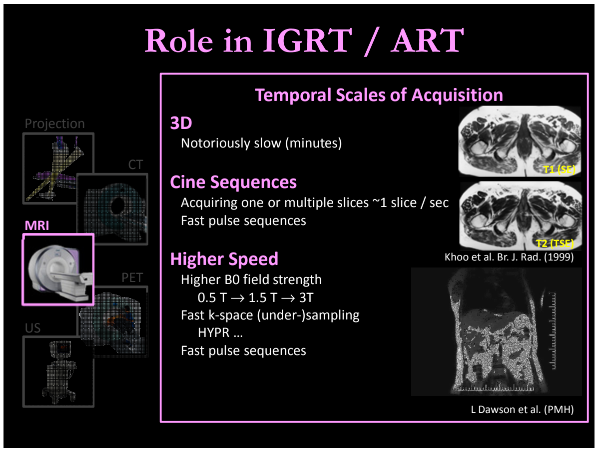


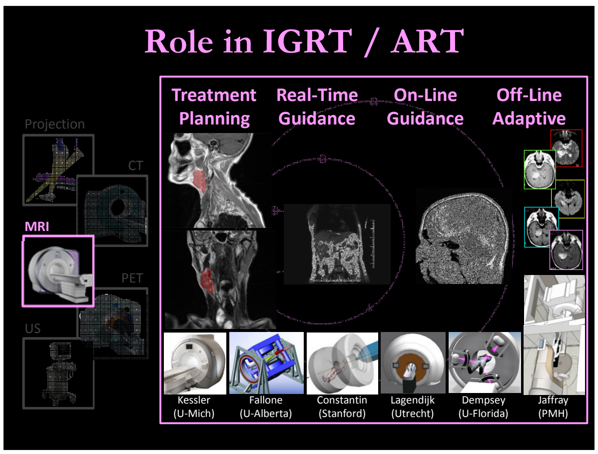
Temporal Scales of Intervention

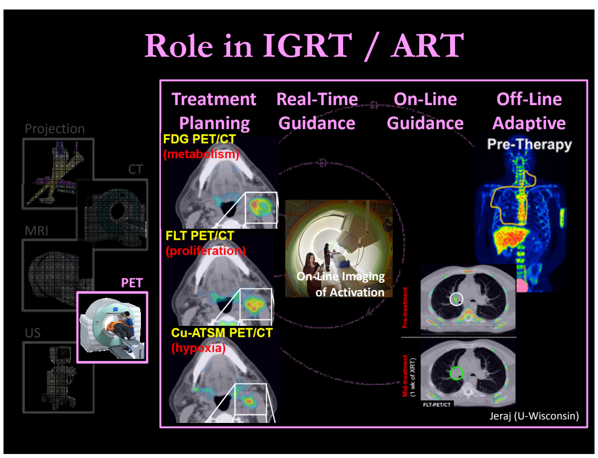

Role in IGRT / ART
Projection
CT
MRI
PET
US
Planning
In-Room
On-Linac
McJury (NHS)
Kuriyama (Yamanishi)
Moseley (PMH)
Pang (Sunnybrook)


Role in IGRT / ART
Projection
CT
MRI
PET
US
Temporal Scales of Acquisition
MDCT
Fast: 3 rev / sec (and 64 slices / rev)
→ CT-fluoro
→ 4D CT
CBCT
Slow: 0.02 rev sec (60 sec / rev)
→ Full volume (no table motion)
→ Patient motion artifacts
4D CBCT
Even slower (>60 – 120 sec / rev)
Many projs + Several motion cycles
→ Retrospective sorting by phase

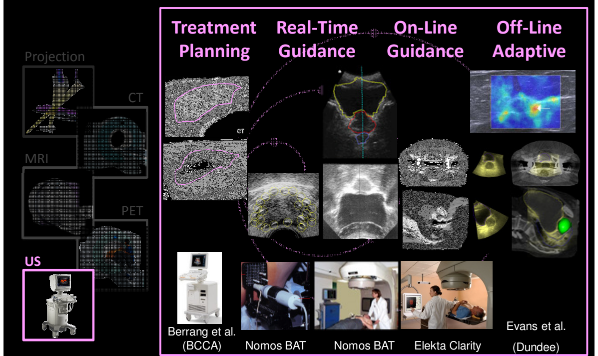

Role in IGRT / ART
Projection
CT
MRI
PET
US
Treatment Planning
Real-Time Guidance
On-Line Guidance
Off-Line Adaptive


Role in IGRT / ART
Projection
CT
MRI
PET
US
Temporal Scales of Acquisition
3D
Notoriously slow (minutes)
Cine Sequences
Acquiring one or multiple slices ~1 slice / sec
Fast pulse sequences
Higher Speed
Higher B0 field strength
0.5 T → 1.5 T → 3T
Fast k-space (under-)sampling
HYPR ...
Fast pulse sequences
T1 (SE)
T2 (TSE)
Khoo et al. Br. J. Rad. (1999)
L Dawson et al. (PMH)


Role in IGRT / ART
Projection
CT
MRI
PET
US
Treatment Planning
Real-Time Guidance
On-Line Guidance
Off-Line Adaptive
Kessler (U-Mich)
Fallone (U-Alberta)
Constantin (Stanford)
Lagendijk (Utrecht)
Dempsey (U-Florida)
Jaffray (PMH)


Role in IGRT / ART
Projection
CT
MRI
PET
US
Treatment Planning
Real-Time Guidance
On-Line Guidance
Off-Line Adaptive
FDG PET/CT
(metabolism)
FLT PET/CT
(proliferation)
Cu-ATSM PET/CT
(hypoxia)
On-Line Imaging of Activation
Pre-Therapy
Jeraj (U-Wisconsin)

Role in IGRT / ART



Which of the following imaging modalities has the highest temporal resolution?

0% 1. Ultrasound
0% 2. MV portal imaging
0% 3. MDCT
0% 4. MRI
0% 5. PET

10

Which of the following imaging modalities has the highest temporal resolution?

1. **Ultrasound**
2. MV portal imaging
3. MDCT
4. MRI
5. PET

Reference: *The Essential Physics of Medical Imaging,* Jerrold T. Bushberg et al. (Lippincott & Williams, 2002).

Which of the following modalities is used exclusively "offline" (outside the treatment room and on a timescale much greater than the fractionation schedule)?

- 0% 1. MDCT
- 0% 2. MRI
- 0% 3. Nuclear Medicine
- 0% 4. All of the above
- 0% 5. None of the above.

10

Which of the following modalities is used exclusively "offline" (outside the treatment room and on a timescale much greater than the fractionation schedule)?

1. MDCT
2. MRI
3. Nuclear Medicine
4. All of the above
5. **None of the above.**

...*diation Therapy*, edited by D. J. ...or and Francis, New York, 2011).

… Acts II and III

Which of the following describes the performance of an imaging system to discriminate soft tissues?

0% 1. Spatial resolution
0% 2. Integral dose
0% 3. Field of view
0% 4. Contrast resolution
0% 5. Temporal resolution

10

Which of the following describes the performance of an imaging system to discriminate soft tissues?

1. Spatial resolution
2. Integral dose
3. Field of view
4. **Contrast resolution**
5. Temporal resolution

Reference: *The Essential Physics of Medical Imaging,* Jerrold T. Bushberg et al. (Lippincott & Williams, 2002).

Pop-Quiz #1

QuestionTextHere…

- 0% 1. asdf
- 0% 2. asdf
- 0% 3. asdf
- 0% 4. asfd
- 0% 5. asdf

10

Pop-Quiz #1

QuestionTextHere…

1. asdf
2. asdf
3. asdf
4. asfd
5. asdf

Reference: *Image-Guided Radiation Therapy*
Edited by D. J. Bourland (Taylor and Francis, New York, 2011)

Pop-Quiz #2

QuestionTextHere…

- 0% 1. asdf
- 0% 2. asdf
- 0% 3. asdf
- 0% 4. asfd
- 0% 5. asdf

10

Pop-Quiz #2

QuestionTextHere…

1. asdf
2. asdf
3. asdf
4. asfd
5. asdf

Reference: *Image-Guided Radiation Therapy*
Edited by D. J. Bourland (Taylor and Francis, New York, 2011)

Pop-Quiz #3

QuestionTextHere…

0% 1. asdf
0% 2. asdf
0% 3. asdf
0% 4. asfd
0% 5. asdf

10

Pop-Quiz #3

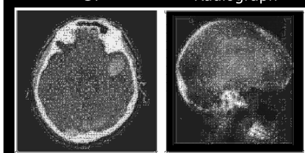
QuestionTextHere…

1. asdf
2. asdf
3. asdf
4. asfd
5. asdf

Reference: *Image-Guided Radiation Therapy*
Edited by D. J. Bourland (Taylor and Francis, New York, 2011)

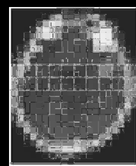
Contrast

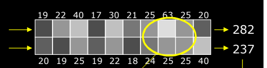
CT Radiograph



$$\text{Contrast} = \frac{I_1 - I_2}{(I_1 + I_2)/2}$$

Why $C_{CT} >> C_{rad}$?





$$C_{CT} = \frac{63-25}{(63+25)/2} = 86\%$$

$$C_{rad} = \frac{282-237}{(282+237)/2} = 17\%$$

The main image quality advantage of CT over radiography is:

0% 1. Spatial resolution
0% 2. Contrast resolution
0% 3. Temporal resolution
0% 4. Speed
0% 5. Reimbursement

10

The main image quality advantage of CT over radiography is:

1. Spatial resolution
2. **Contrast resolution**
3. Temporal resolution
4. Speed
5. Reimbursement

Reference:
The Essential Physics of Medical Imaging
Bushberg et al.

Dr. Tork complains that he cannot see the trabecular bone details in a CT image. A reasonable course of action is to:

0% 1. Acquire a radiograph.
0% 2. Administer contrast agent.
0% 3. Re-scan at higher mAs.
0% 4. Re-reconstruct with a different filter.
0% 5. Display on a bigger monitor.

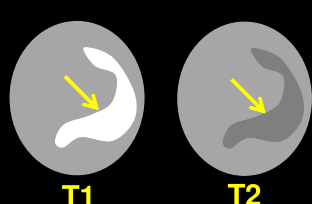
10

Dr. Tork complains that he cannot see the trabecular bone details in a CT image. A reasonable course of action is to:

1. Acquire a radiograph.
2. Administer contrast agent.
3. Re-scan at higher mAs.
4. **Re-reconstruct with a different filter.**
5. Display on a bigger monitor.

The material marked by the yellow arrow is probably:

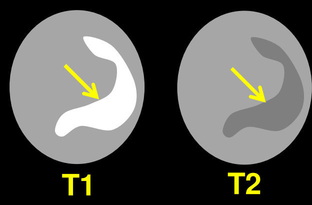
0% 1. Water
0% 2. Fat
0% 3. Bone
0% 4. Gd
0% 5. Cancer



10

The material marked by the yellow arrow is probably:

1. Water
2. **Fat**
3. Bone
4. Gd
5. Cancer



Fundamentals of MRI
William G. Bradley, MD PhD FACR

This is not a pipe. It is…

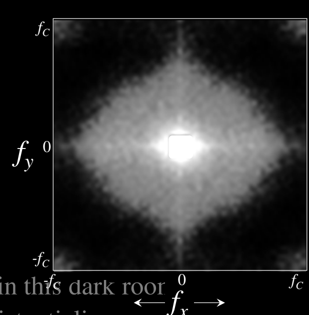
0%
0%
0%
0%
0%

1. whatever you want it to be.
2. in French, so I don't know.
3. an image of a pipe.
4. Too nice outside to be in this dark room discussing existentialism.

10

This is not a pipe. It is…

1. whatever you want it to be.
2. in French, so I don't know.
3. **an image of a pipe.**
4. Too nice outside to be in this dark room discussing existentialism.

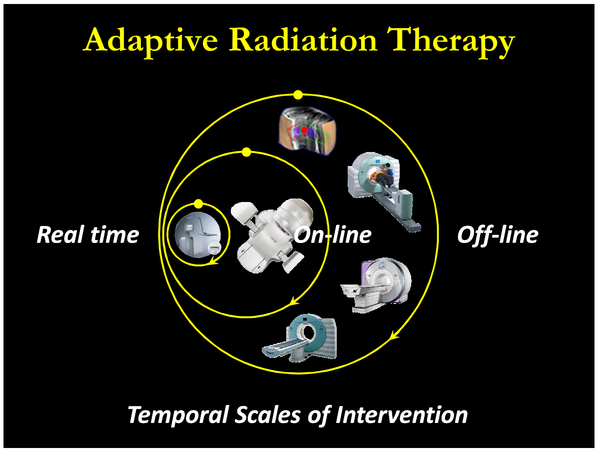


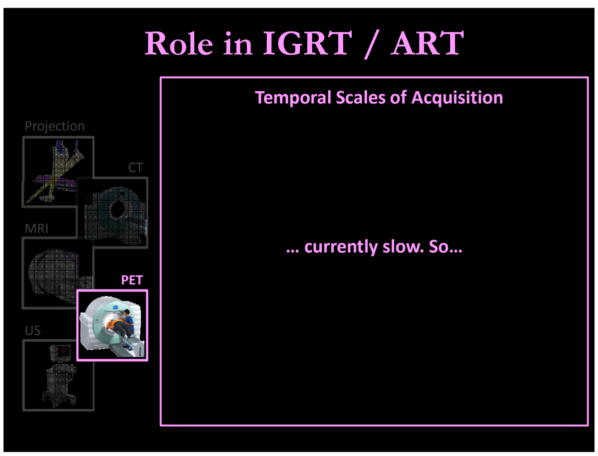
<u>Jeff – Jan-Jakob bridge</u>

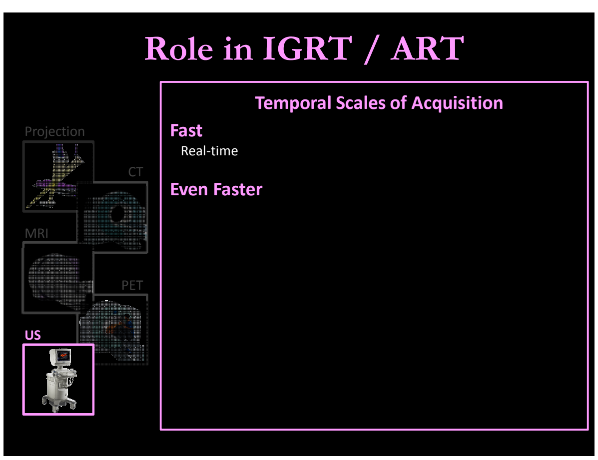
Pose a set of unanswered questions:

we have all these images, things moving, … how are we going to make sense of it and respond (adapt) to this information in treatment delivers?

bridge


Adaptive Radiation Therapy
Real time
On-line
Off-line
Temporal Scales of Intervention


Role in IGRT / ART
Projection
CT
MRI
PET
US
Temporal Scales of Acquisition
… currently slow. So…


Role in IGRT / ART
Projection
CT
MRI
PET
US
Temporal Scales of Acquisition
Fast
Real-time
Even Faster