University of Michigan
Medical School

MRI for Radiation Therapy Planning (2)

Yue Cao, Ph.D.
Departments of Radiation Oncology, Radiology and Biomedical Engineering
University of Michigan

Panel: J. Balter, E. Paulson, R Cormack

University of Michigan
Medical School

Acknowledgments

Radiation Oncology

- James Balter, Ph.D.
- Avraham Eisbruch, MD
- Mary Feng, M.D.
- Felix Feng, MD
- Theodore S. Lawrence, MD, Ph.D
- Randall Ten Haken, Ph.D.
- Christina I. Tsien, MD
- Hesheng Wang, Ph.D.
- Shu-hui Hsu, Ph.D.
- Ke Huang, Ph.D.

Biomedical Engineering

- Doug Noll, Ph.D.

MRI simulation staff

- Jeremy French

Siemens Medical Systems

- Steven Shea, Ph.D.

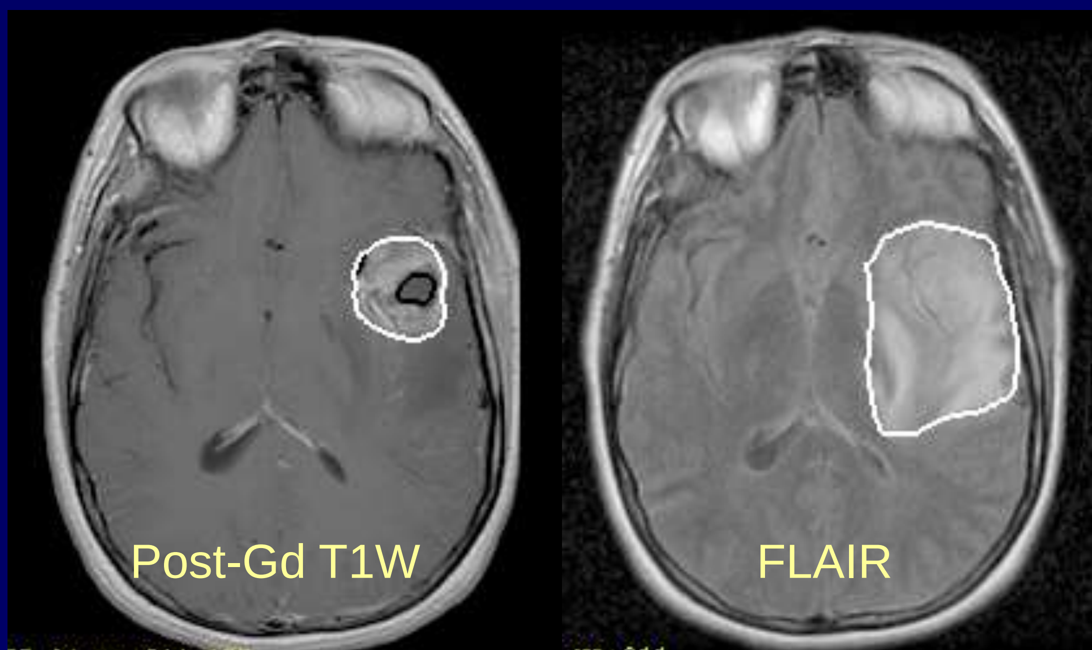
NIH grants

- RO1 NS064973 (Cao)
- RO1 CA132834 (Cao)
- RO1 EB016079 (Balter)

University of Michigan Medical School

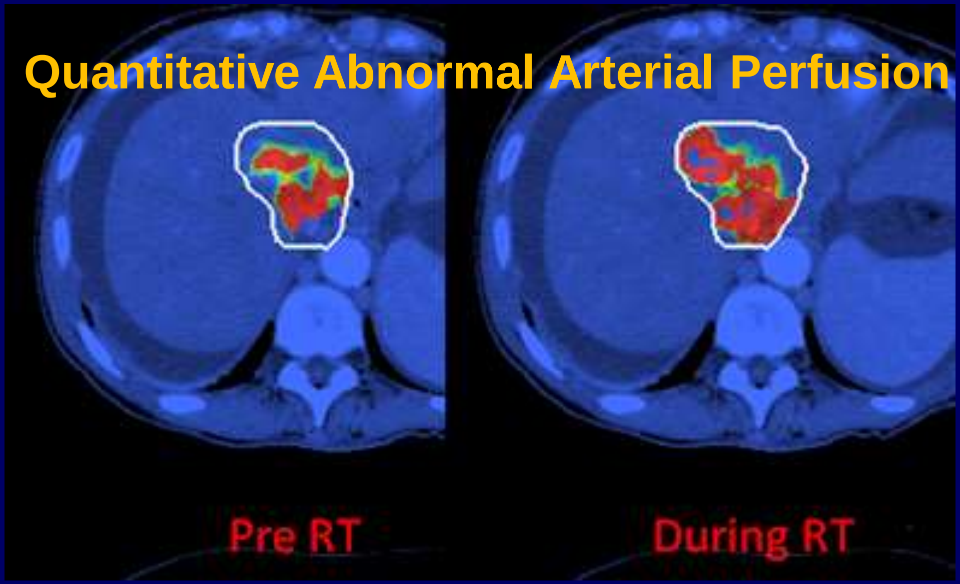
MRI for RT Planning: why

- Superior soft tissue contrast
- Tumor and OAR delineation



MRI for RT Planning: why

- Superior multi-soft tissue contrasts
- Physiological and metabolic imaging
- Tumor and OAR delineation
- Boost target (active tumor) definition



Wang, AAPM 2013

Integration of MRI in RT

- Target and/or Boost volume definition
- OAR delineation and organ function assessment
- Treatment Planning
- Motion management
- On-board Tx verification
- Early Tx response assessment
  – to image active residual tumor
  – to assess normal tissue/organ function reserve

MRI Simulator

- MRI scanner is designed for diagnosis
- Challenges for use as a RT simulator:
  - System-level geometric accuracy
  - Patient-induced spatial distortion
  - Electron density (synthetic CT)
  - IGRT support
  - RF coil configuration optimization
  - Sequence optimization for RT planning
  - Etc.

Geometric Accuracy

- System-level geometric characterization
  - Specs requirement in RFP
  - Site characterization during acceptance
  - Establish system QA procedures
- Patient-level characterization, correction and QA/QC
  - Patient by patient characterization
  - Patient-specific QA/QC (cannot be done by phantoms)
  - Distortion correction procedure

University of Michigan Medical School

Why does a patient induce geometric distortion?

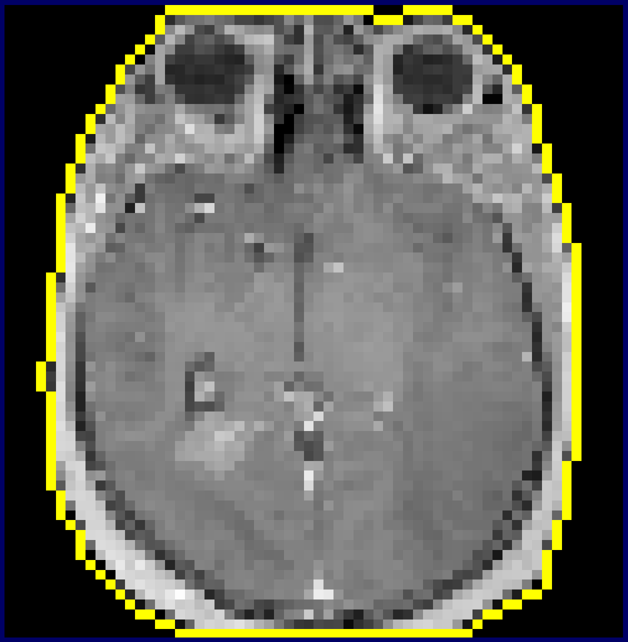
- Tissue magnetic susceptibility

	air	water	blood	bone	fat	Au
χ (10^{-6} cm^3/mol)	0.36*	-8.9**	-8.8 - -9.1* (O_2:55-96%)	-11.3***	-8.4	-28

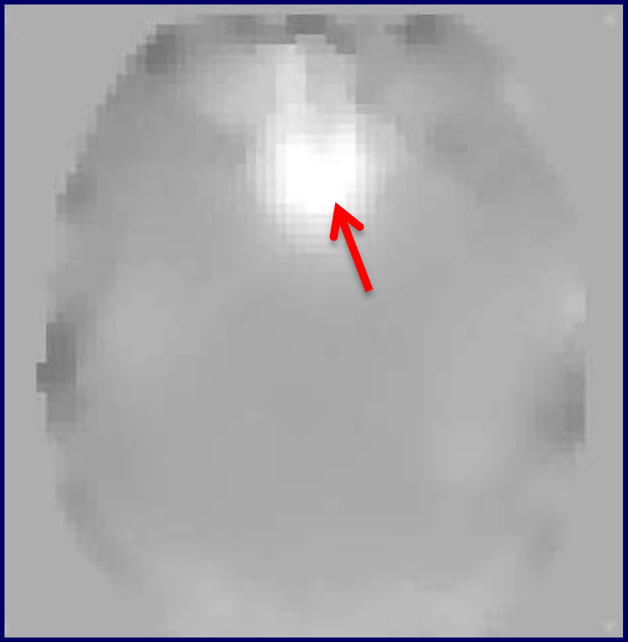
- Inhomogeneous $\Delta\chi \rightarrow \Delta B_0$
- Inhomogeneous human anatomy
  – Air-tissue/blood/bone, bone-tissue/fat
  – Metal (paramagnetic or diamagnetic)
- High external field $\rightarrow$ large ΔB_0

* Vignaud, MRM 2005; **CRC Handbook 1991;***Hopkins, MRM 1997

Inhomogeneous anatomy



anatomy

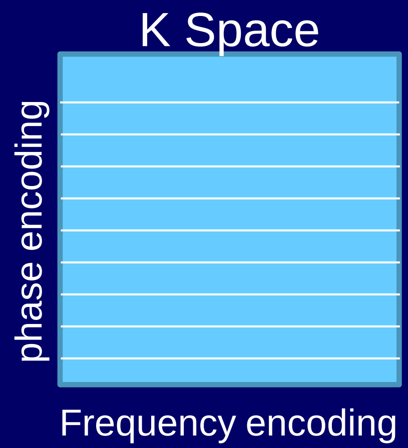


ΔB_0

Wang, Balter, Cao PMB 2013

University of Michigan
Medical School

Geometric distortion



- Conventional K-space acquisition
- 2D acquisition
  - Frequency encoding and slice selection
- 3D acquisition
  - FE: $\omega_x=\gamma(xG_x)$ → $\omega_x'=\gamma(\Delta B_0(x)+xGx)$

→ Shift $\Delta x = \frac{\Delta B_0}{BW_f} \Delta V_x$

Pixel size in mm/pixel

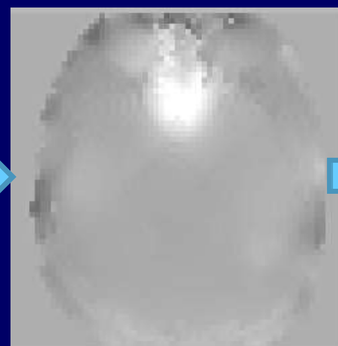
Frequency Encoding G
bandwidth in Hz/pixel

  - Mapping individual patient ΔB_0

University of Michigan
Medical School

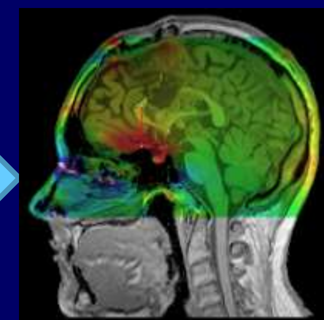
Patient-level Distortion Correction and QA

Acquire wrapped phase different maps by 2 gradient echoes



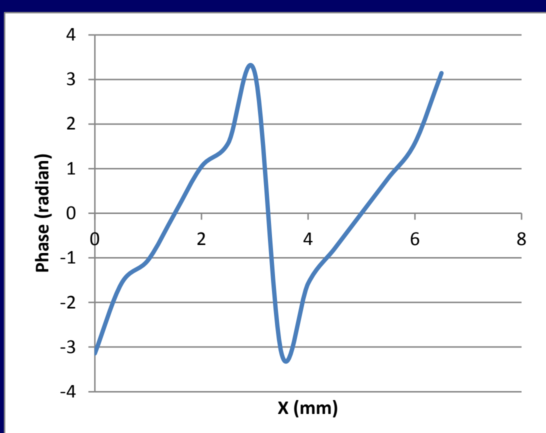
Unwrap and convert to the field map

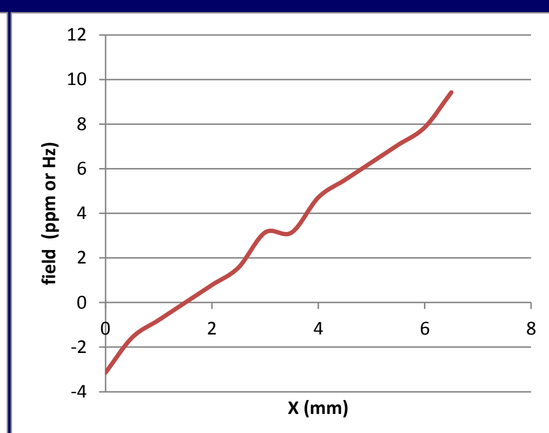
Correct gradient non-linearity



Assess whether a distortion correction is needed for images

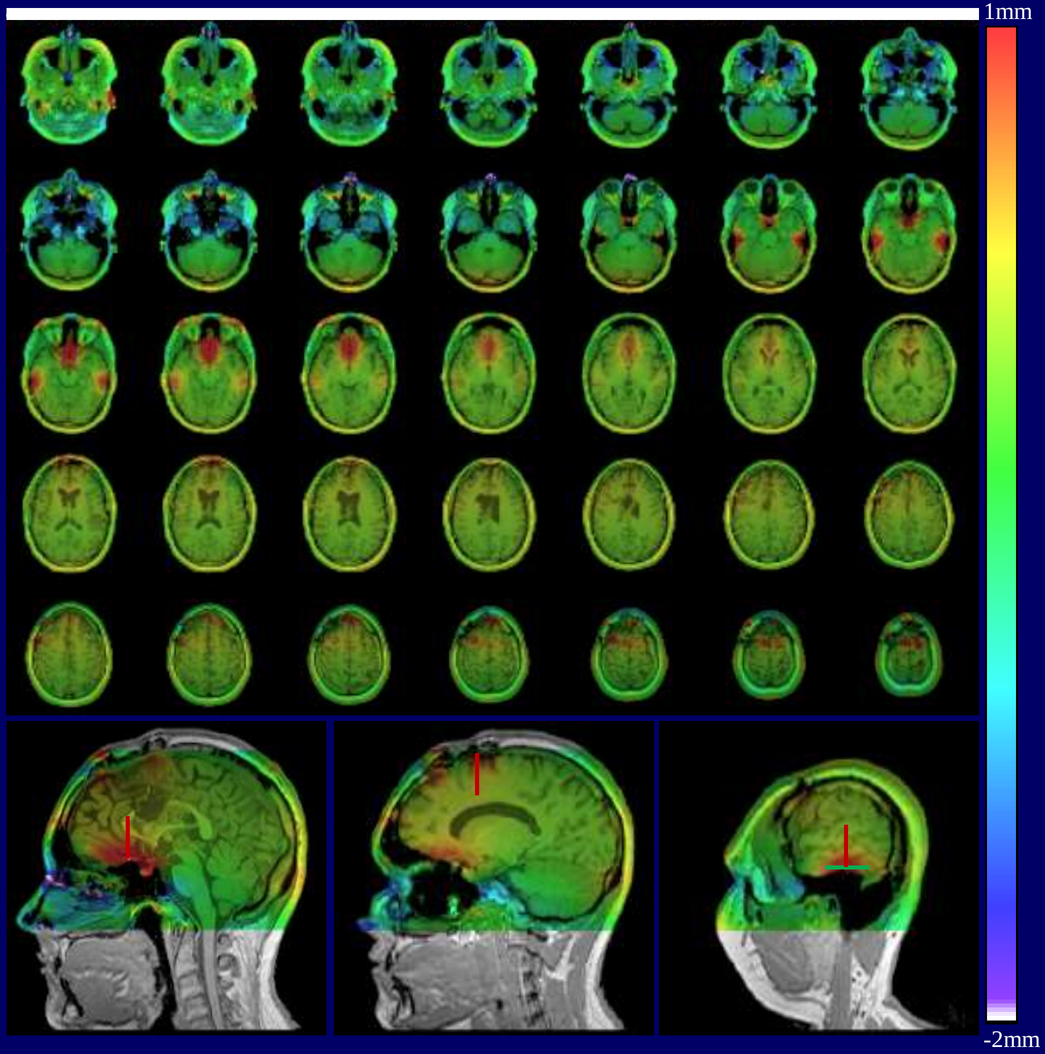
Correct distortion
Or stop





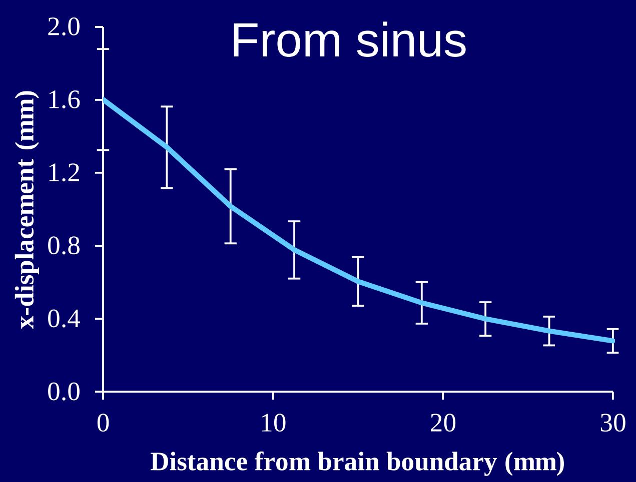
Distortion map

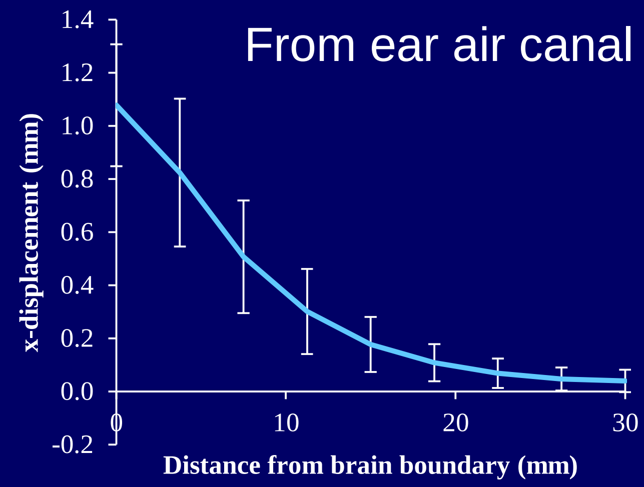
3d T1-weighted images (mprage)with BWf=180 Hz/pixel

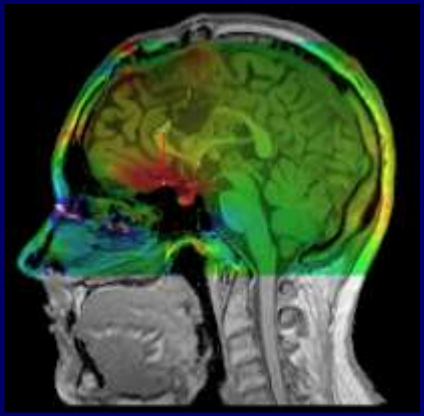


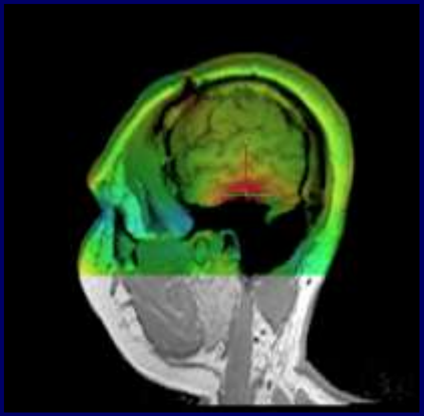
Wang, Balter, Cao PMB 2013

Distortion from air boundary (n=19)



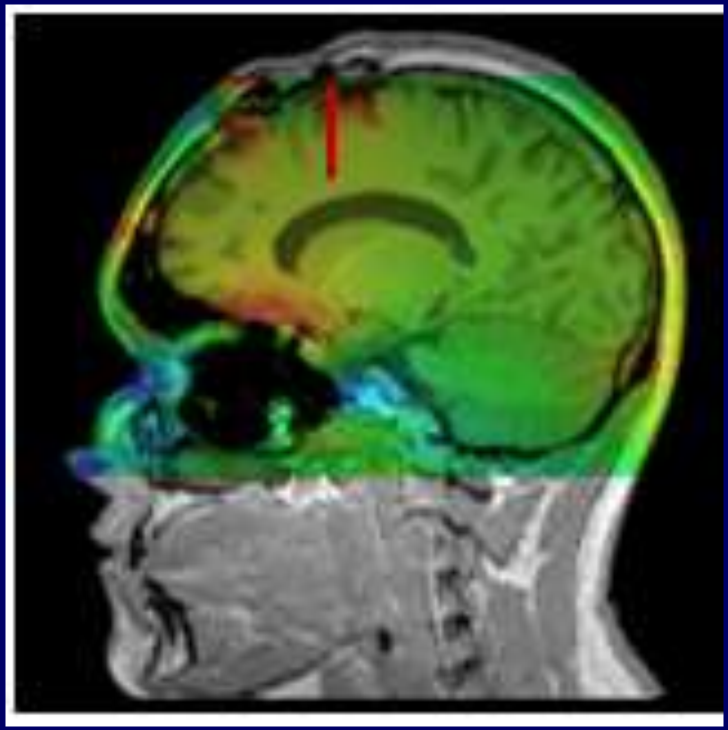


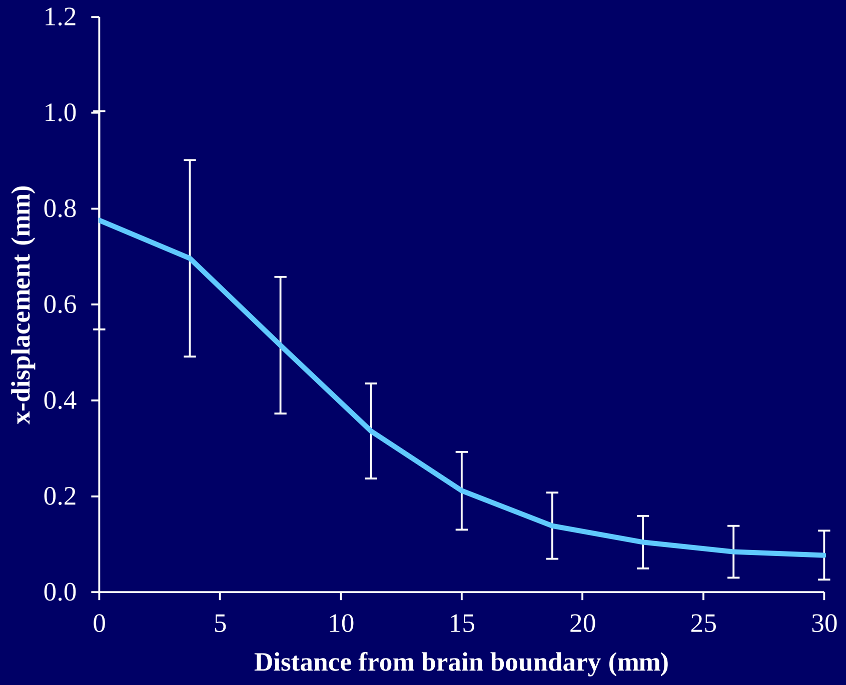




Wang, Balter, Cao PMB 2013

Distortion from metal

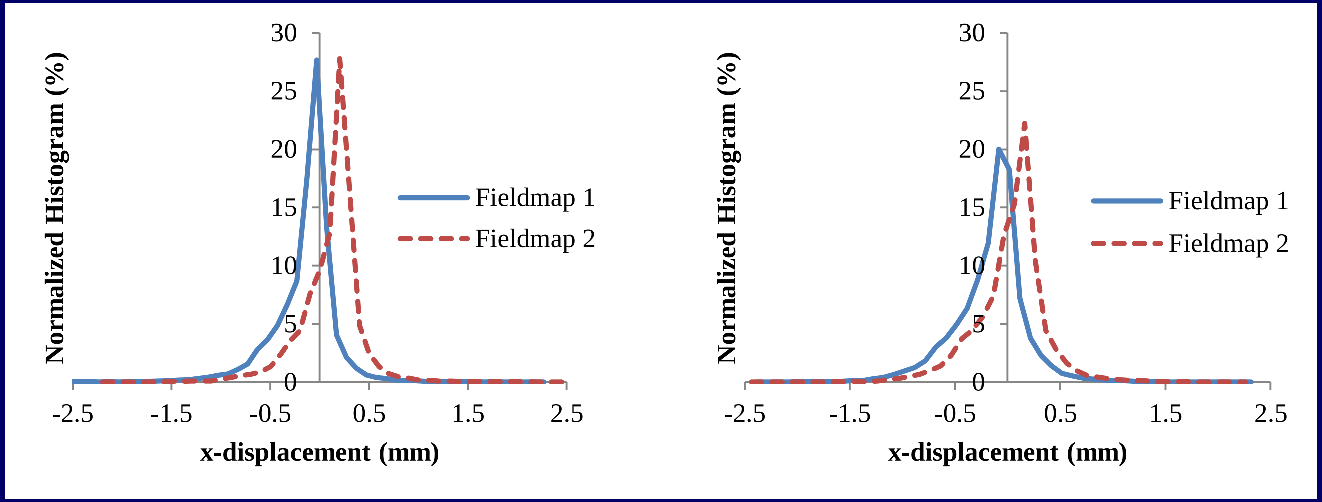




Perturbation in ΔB_0 map due to object movement

- Uniform water phantom
  - ΔB_0 map (0 min) vs ΔB_0 map (15 min) after moving a water phantom into the scanner bore
- Human subject
  - Does ΔB_0 map change over scanning time?
  - If yes, what does it impact on geometric accuracy of the images?

How stable is the field map of the head at 3T?



- ΔB_0 maps acquired twice at the beginning and end of the imaging session (~40 min a part)
- Systematic shifts (<0.33 ppm or 0.3 mm) were observed in 16 of 17 patients
- Systematic shift is small and does not cause local distortion

University of Michigan
Medical School

Chemical Shift: water and fat

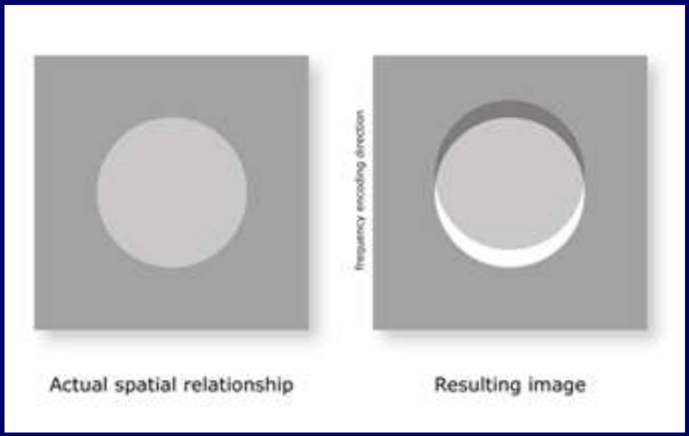
- Difference between resonance frequencies of water and fat
  - 3.5 ppm
  - 1.5T: 224 Hz; 3T: 448 Hz
- Mismapping in frequency encoding and slice selection directions

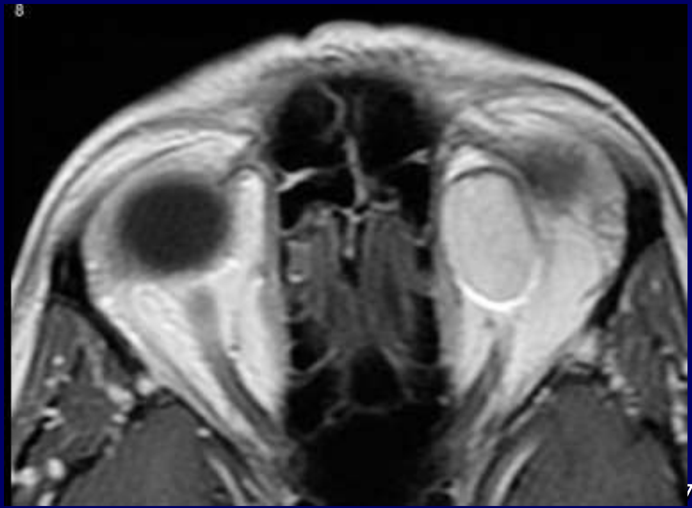
  At 3T,

  if BW_f=200Hx/1mm →2.24 mm

  if BW_f=800Hx/1mm →0.56 mm

Spin echo sequence



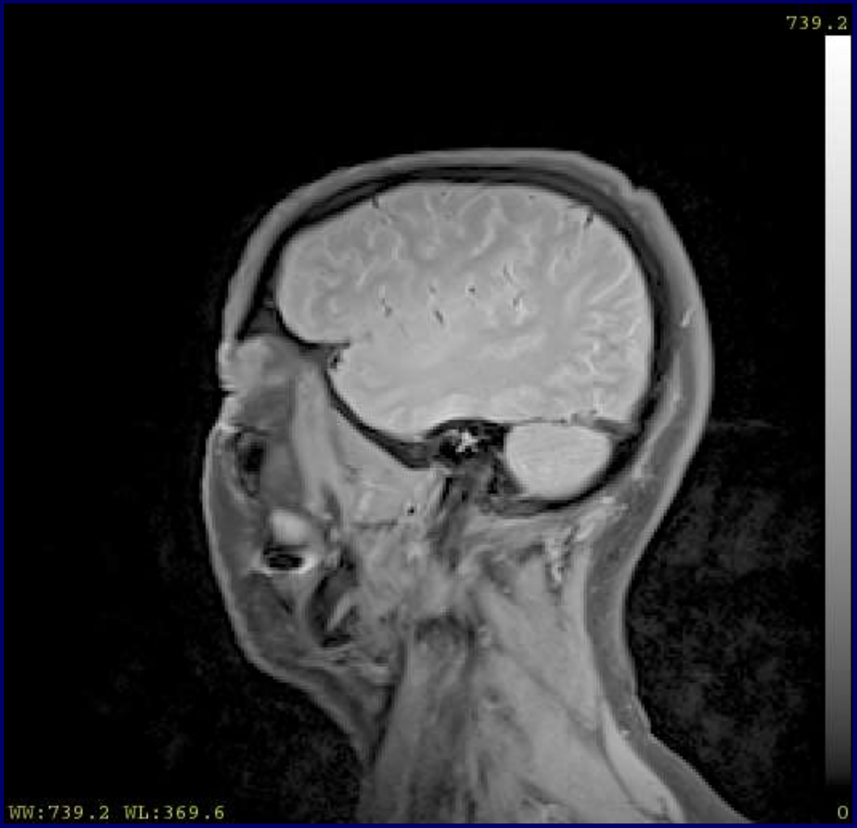


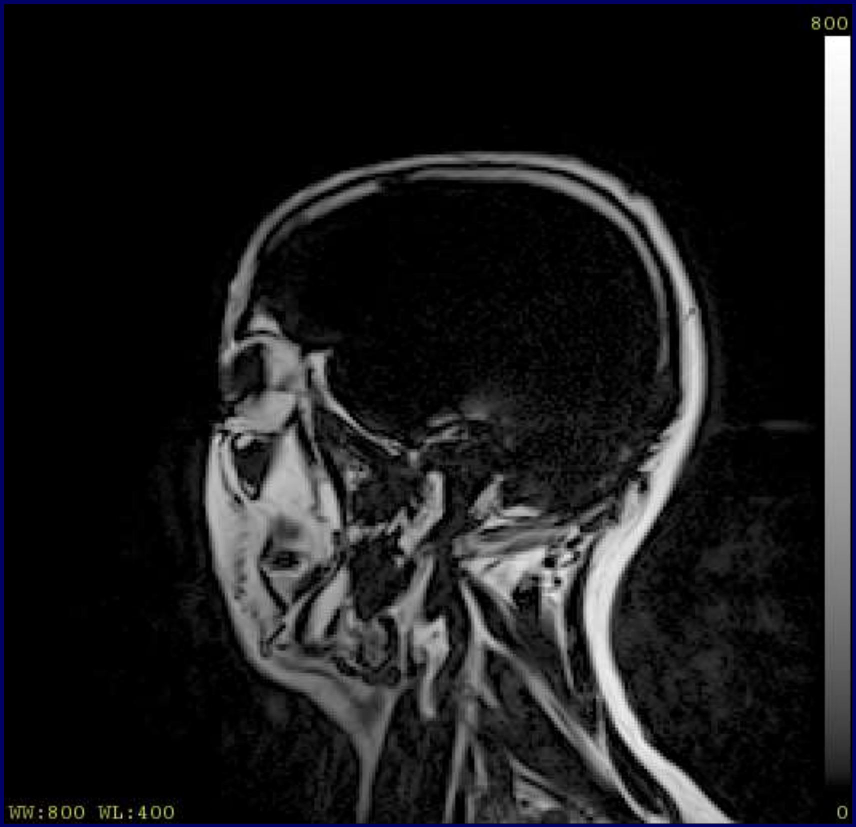
Chemical Shift of Water and Fat

Gradient echo: dark boundary due to Water and fat signals out of phase

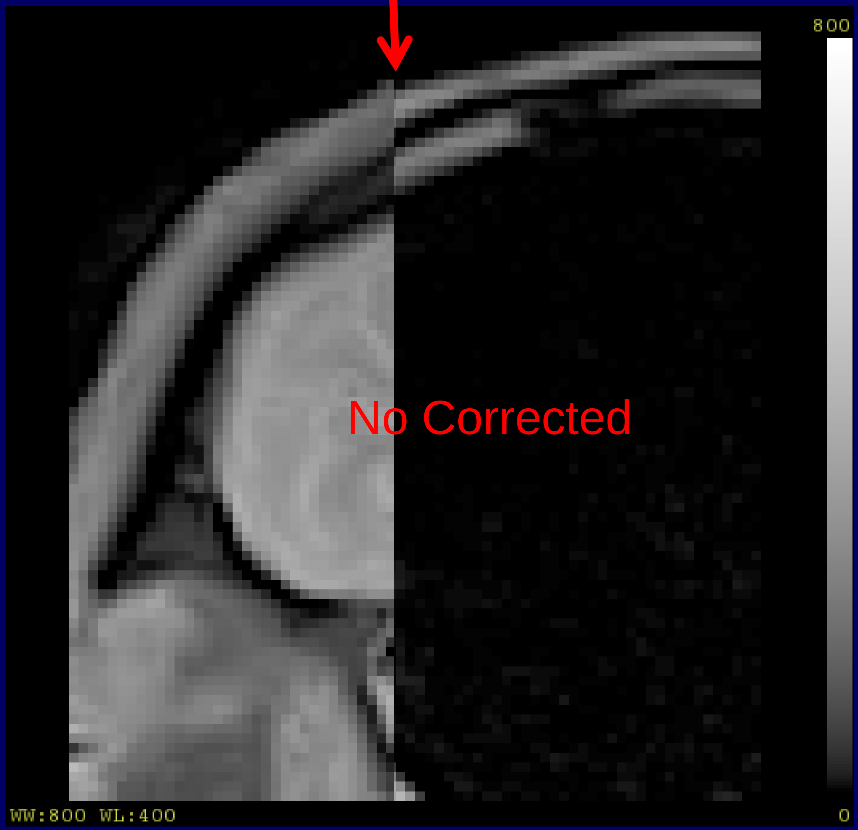
- TEs for Water and fat out- and in-phase at 3T
- In-phase: N x 2.3 ms
- Out-phase: N x 3.45 ms

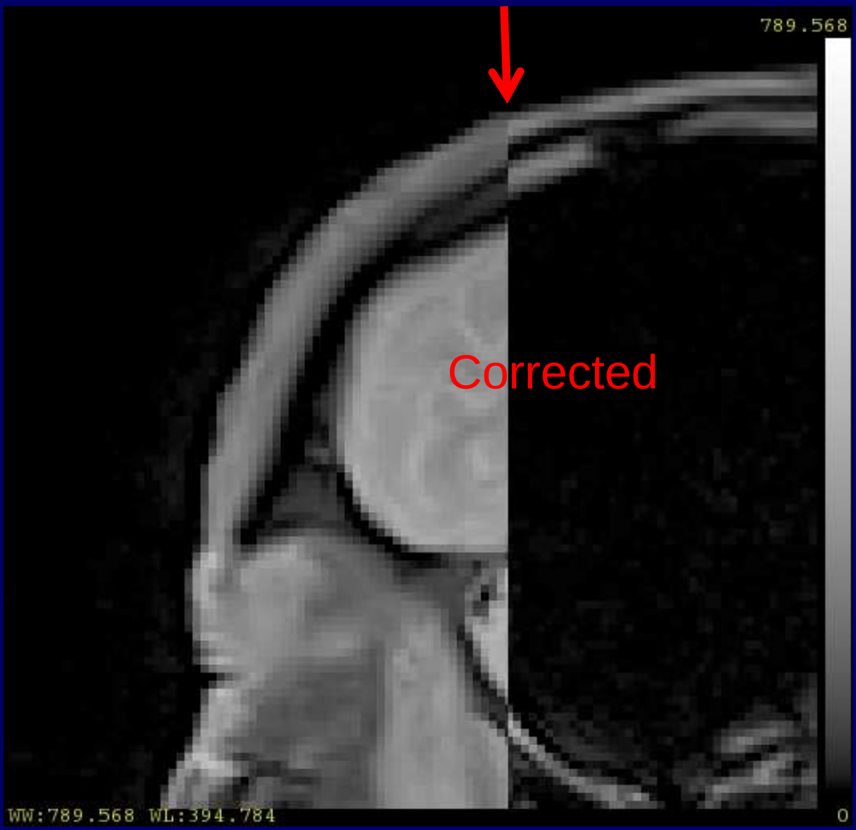
Dixon Method to separate water and fat signals





Shift correction of fat to water





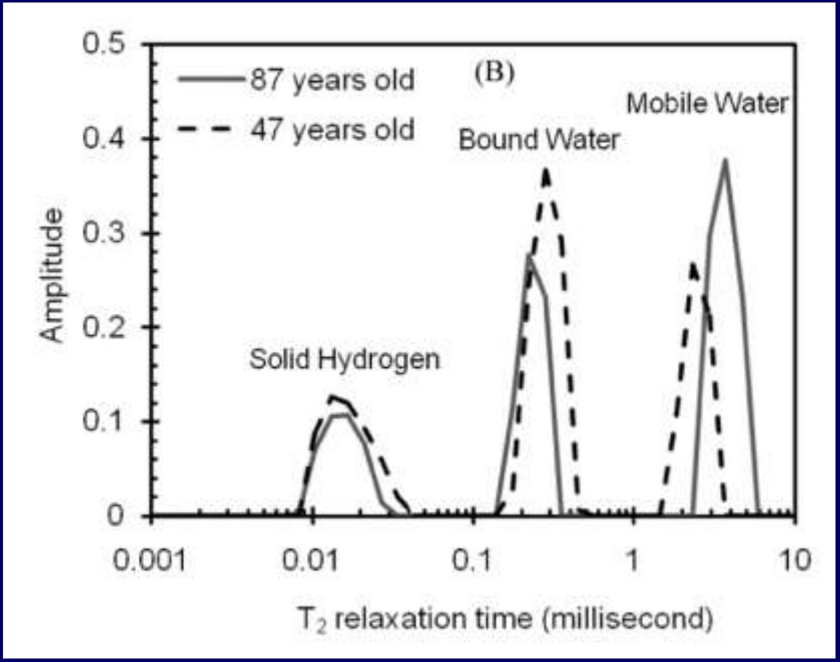
Fat rotates 431Hz slower than water at our scanner
Frequency encoding direction bandwidth: 405 Hz/pixel, 1.17 mm/pixel

How can you get electron density from MRI?

- MR-CT alignment → conventional approach
- Manual segmentation and density assignment (Chen et al in 1990s)
- Atlas-based density insertion → registration of individual MRI to atlas of CT/MRI (e.g., Balter ICCR 2010)
- Utilization of multi-contrast MRI, including ultrashort TE (TE<0.1 ms) images, to synthesize "CT" and "DRR"
  - Subtraction of images acquired by UTE and non-UTE
  - Tissue pattern learning, classification and/or segmentation and assigning each classified/segmented voxel "density" properties
- Hybrid approach

What are sources of MR signals from cortical bone?

- Proton spins from water
  - Free water in microscopic pores
    long T2*/T2 (T2*: 2-4 ms)
    pore volume fraction (a few percent)
  - Bound water in the extracellular matrix
    short T2* (T2*: 0.379-0.191 ms; T1: 186-102 ms)
- Ca hydroxyapatite
  T2*: 0.01-0.02 ms
- Fat from bone marrow



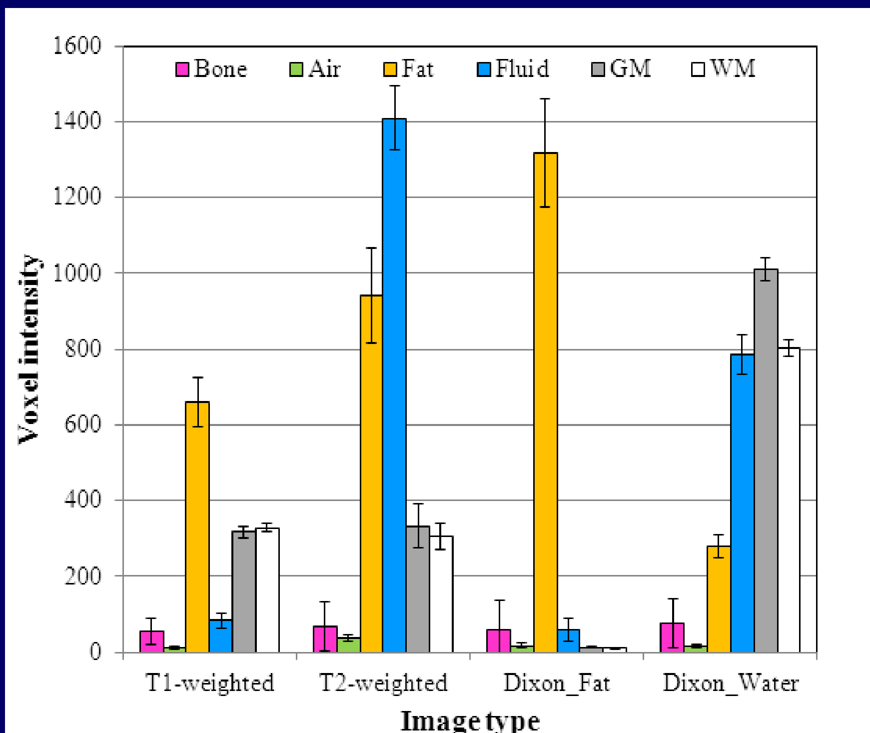
Spectral analysis of multiple T*2/T2s in femurs (Nyman, Bone 2008)

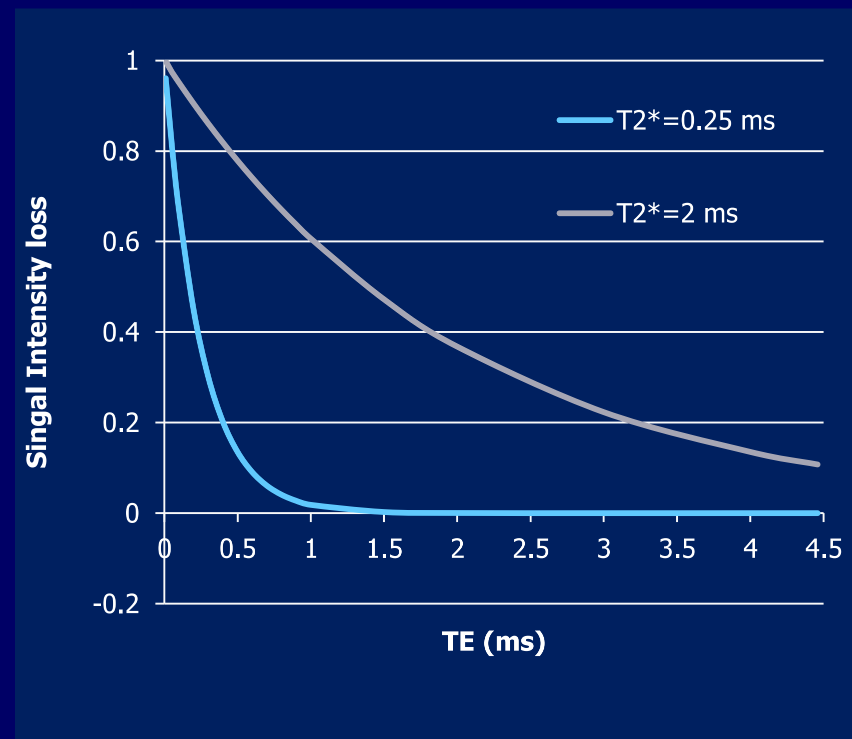
Nyman 2008, Kokabi 2011

University of Michigan Medical School

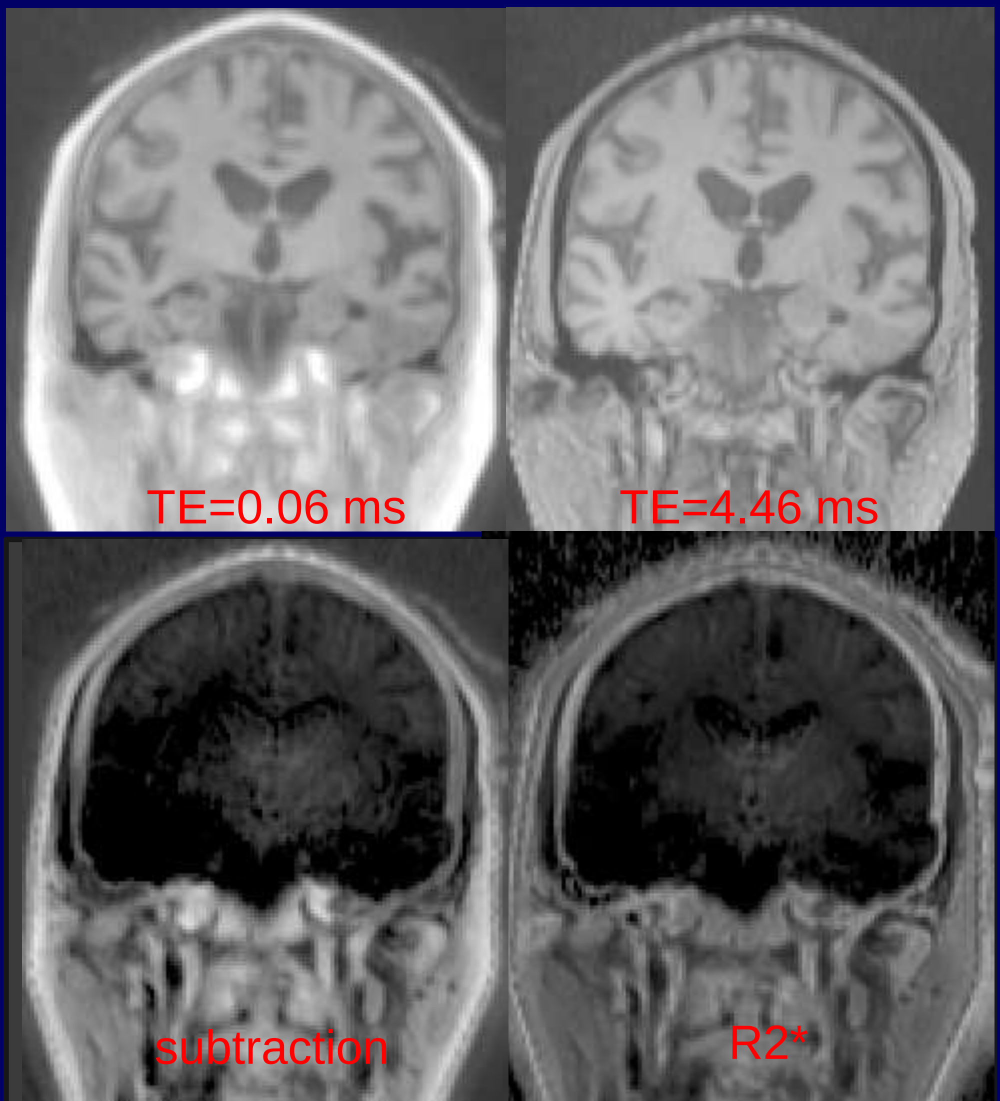
Can you differentiate air from bone without UTE images?

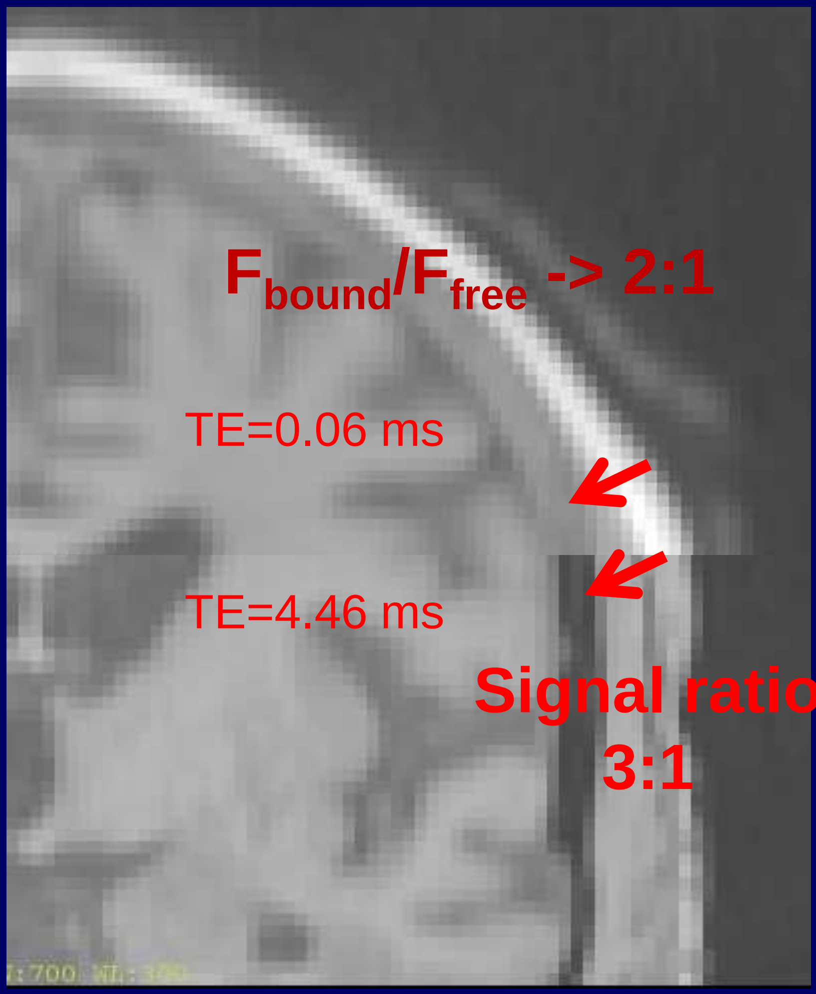
Cortical bone in the head
By Hsu, Balter, Cao AAPM 2012





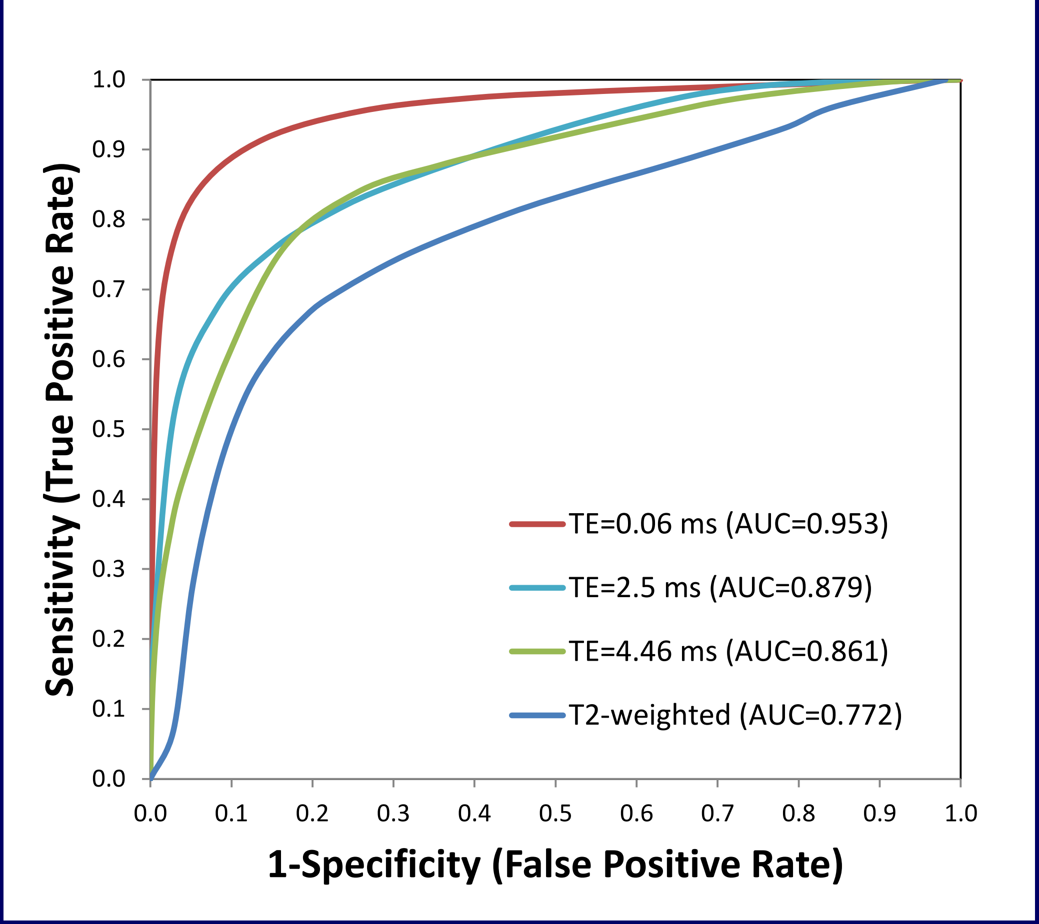
UTE image


TE=0.06 ms
TE=4.46 ms
subtraction
R2*


F_{bound}/F_{free} -> 2:1
TE=0.06 ms
TE=4.46 ms
Signal ratio
3:1

Separate air from bone by MRI

- Tested MRI
  - UTEI, TE=0.06 ms
  - T1WI: TE=2.5 ms
  - 2nd T1WI: TE=4.5 ms
  - T2WI: TE= 80-120 ms
- ROC analysis
- CT as truth
  - Air: HU <-400
  - Bone: HU > 200

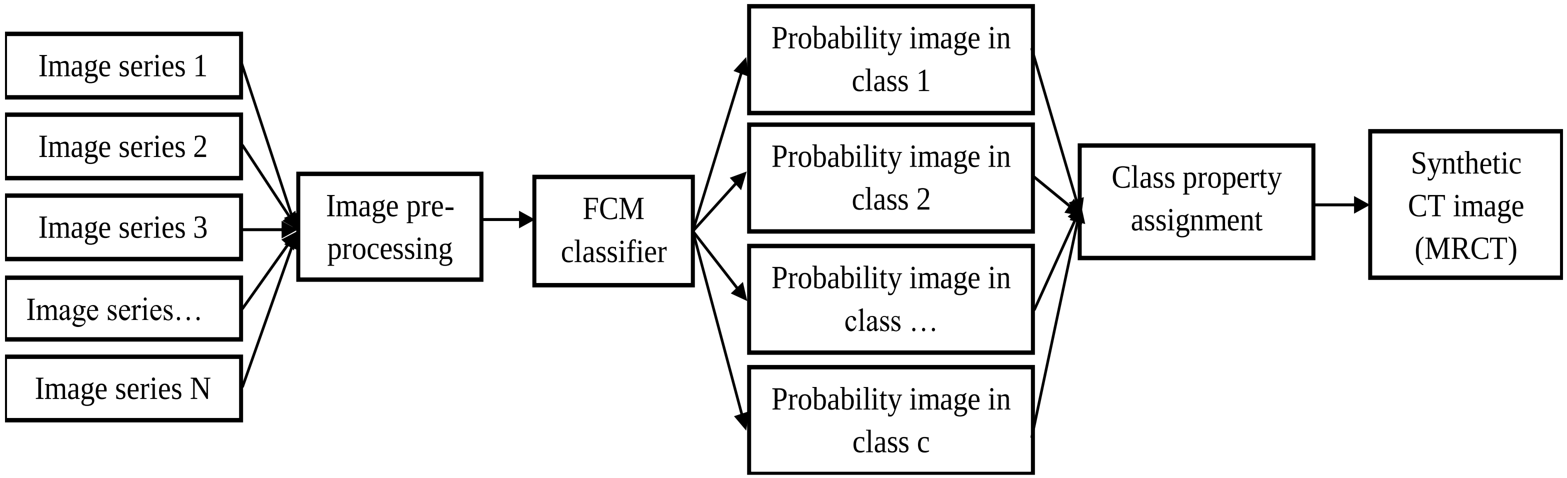


Hsu, Balter, Cao AAPM 2013

Synthetic CT: Multispectral modeling

- MRI signals provide various sources of contrast
- By combining the information from multiple scans of the same tissue, we classify different tissue types
- Assigning properties to these classified tissues permits generation of attenuation maps, as well as synthetic CT scans

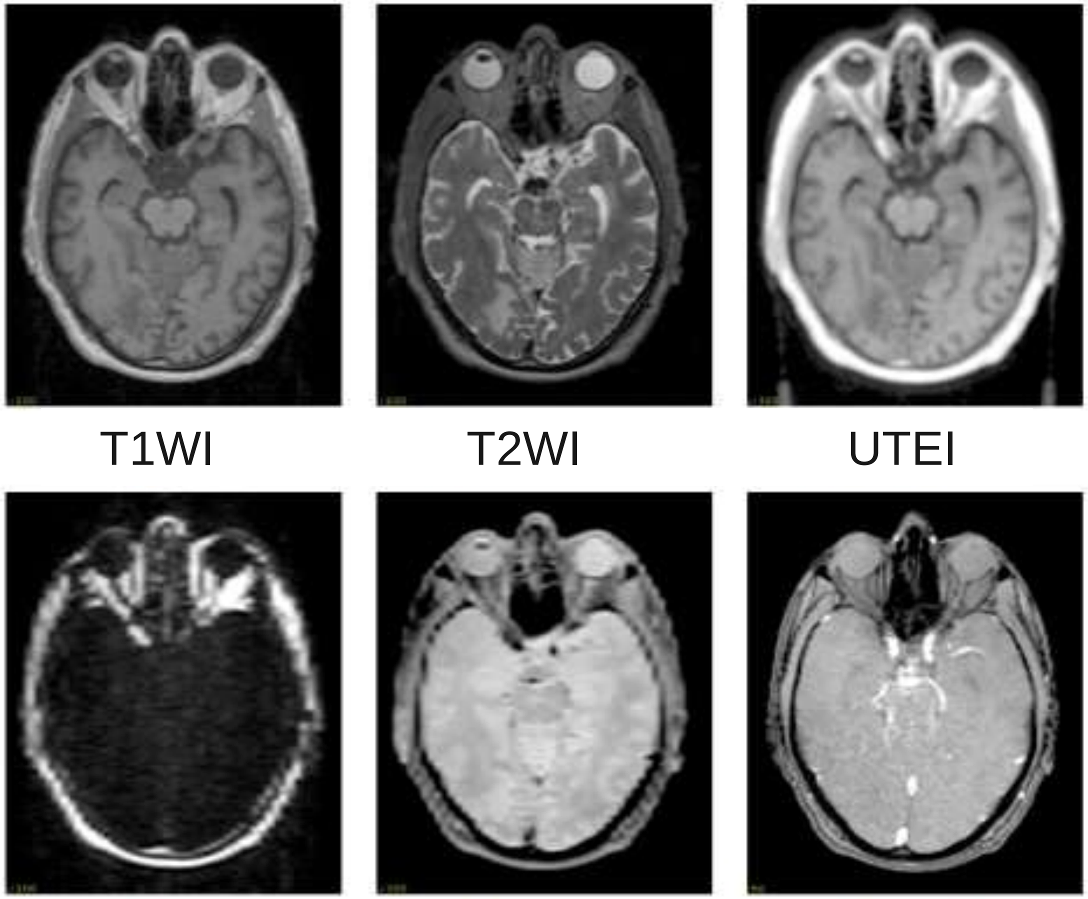
Synthetic CT process



UM protocol and coil setup

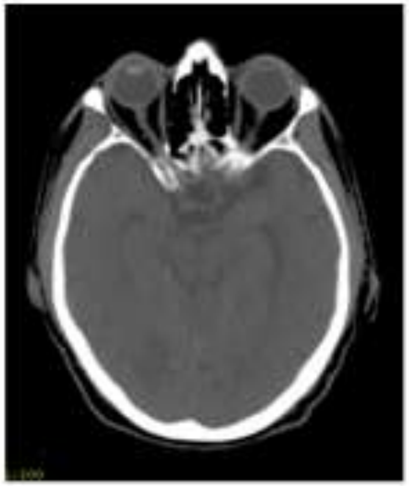
- 3T Skyra
- Protocol
  - Localizer
  - TOF white vessel
  - T1W-MPRAGE
  - UTE (TE=0.06 ms)
  - T2W-SPACE
  - Dixon (fat and water)
  - Total time 12.5 min
- Coils
  - Body18 + large flexible coil
- indexed flat table top insert
- Patient in Tx position and w mask

Input MRI



T1WI T2WI UTEI

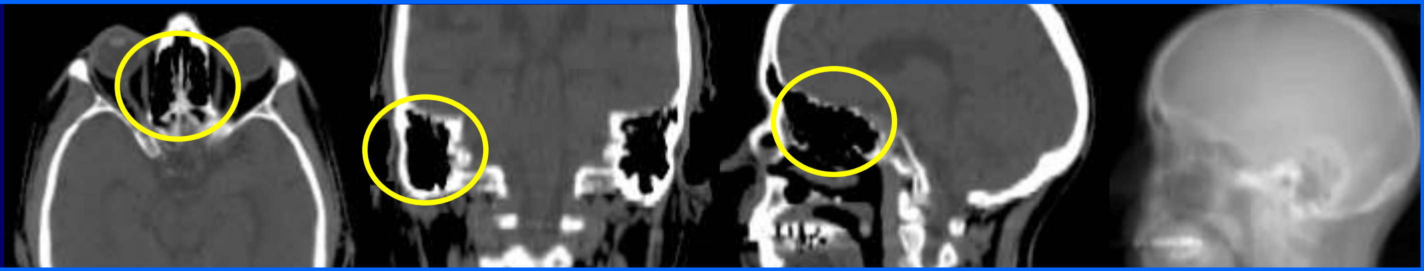
Fat water Vessel



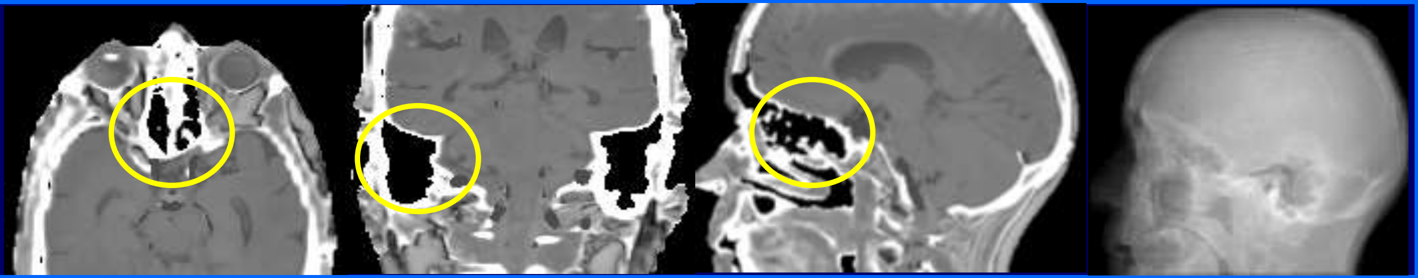
CT

Synthetic CT and DRR

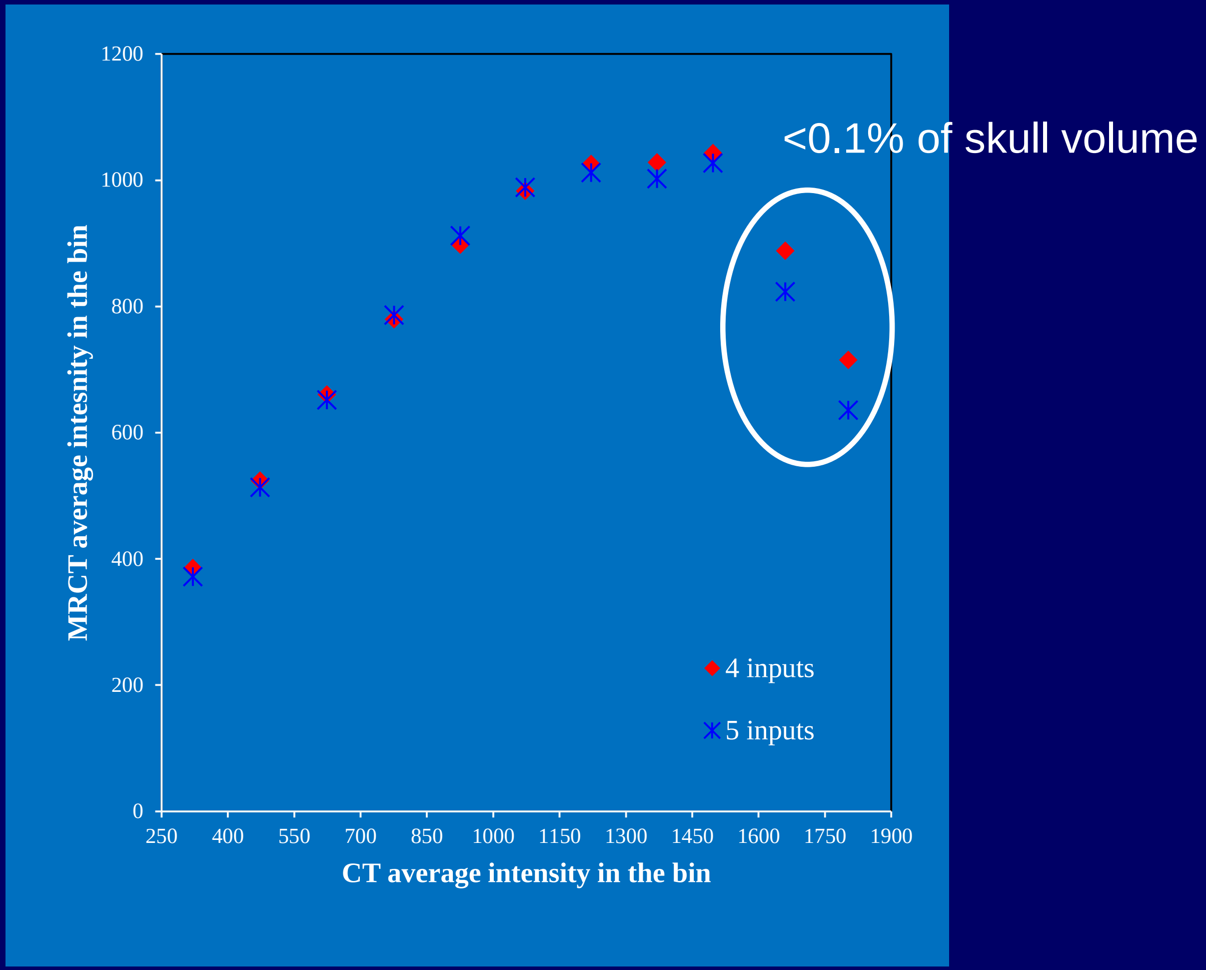
CT



Synthetic CT
Threshold: 100
Sensitivity: 75%
Specificity: 98%



Intensities in bone: Synthetic vs actual CT



9-field focal brain treatment plan

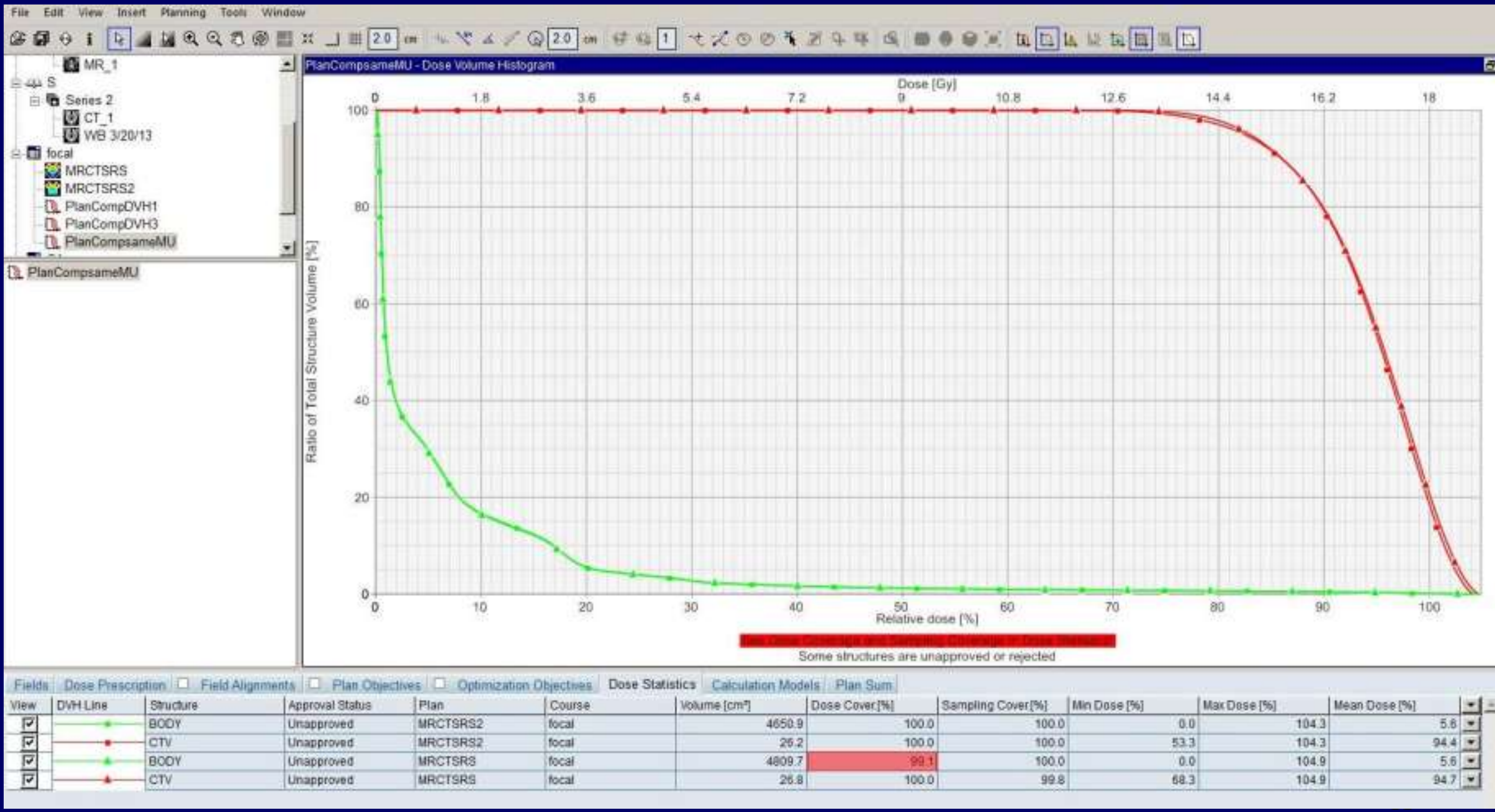
University of Michigan
Medical School

Fields | Dose Prescription | Field Alignments | Plan Objectives | Optimization Objectives | Dose Statistics | Calculation Models | Plan Sum

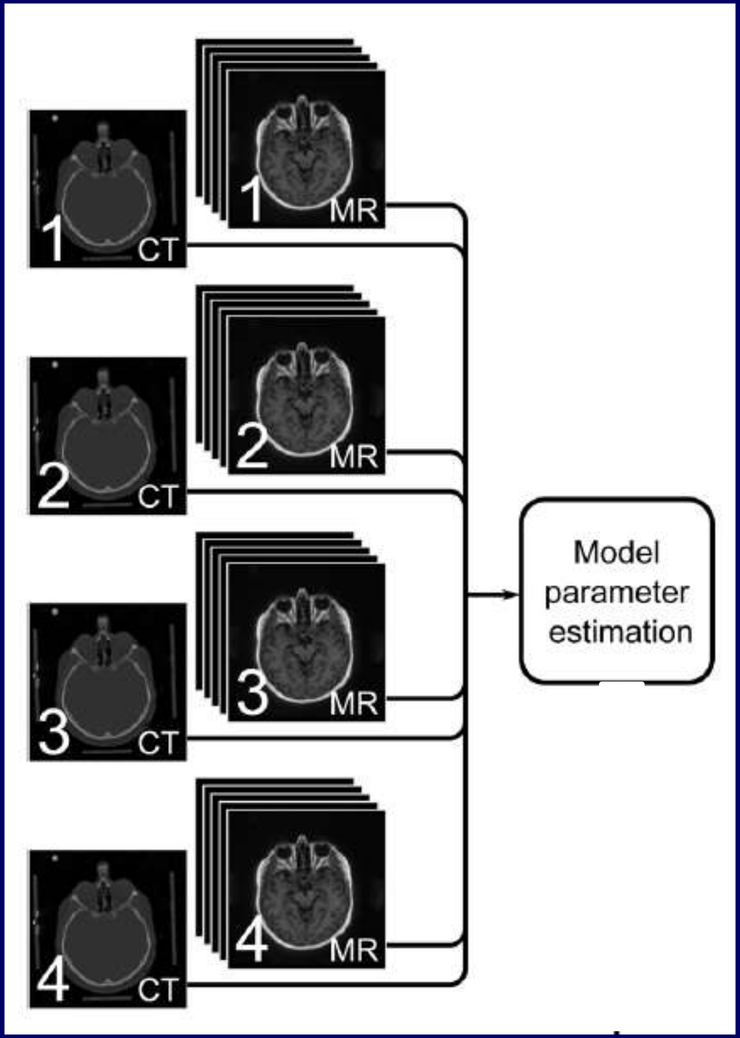
Group	Field ID	Technique	Machine/Energy	MLC	Field Weight	Scale	Gantry Rtn [deg]	Coll Rtn [deg]	Couch Rtn [deg]	Wedge	Field X [cm]	X1 [cm]	X2 [cm]	Field Y [cm]	Y1 [cm]	Y2 [cm]	X [cm]	Y [cm]	Z [cm]	SSD [cm]	MU	Ref. D [Gy]
✓	Field 1	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	160.0	0.0	0.0	None	4.9	+2.4	+2.5	3.9	+2.2	+1.7	0.51	-5.52	-6.06	89.0	315	3.725
✓	Field 2	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	130.0	0.0	0.0	None	4.8	+2.4	+2.5	3.9	+2.2	+1.7	0.51	-5.52	-6.06	90.8	287	3.246
✓	Field 3	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	100.0	0.0	0.0	None	4.8	+2.4	+2.4	3.9	+2.2	+1.7	0.51	-5.52	-6.06	92.8	263	2.835
✓	Field 4	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	70.0	0.0	0.0	None	4.7	+2.4	+2.3	3.9	+2.2	+1.7	0.51	-5.52	-6.06	93.2	260	2.773
✓	Field 5	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	140.0	0.0	45.0	None	4.9	+2.2	+2.7	3.9	+2.2	+1.7	0.51	-5.52	-6.06	89.4	309	3.590
✓	Field 6	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	90.0	0.0	90.0	None	4.7	+2.4	+2.3	4.4	+2.2	+2.2	0.51	-5.52	-6.06	90.2	294	3.371
✓	Field 7	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	30.0	0.0	45.0	None	4.2	+2.2	+2.0	4.4	+2.2	+2.2	0.51	-5.52	-6.06	91.5	280	3.090
✓	Field 8	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	120.0	0.0	90.0	None	4.8	+2.3	+2.5	4.4	+2.2	+2.2	0.51	-5.52	-6.06	89.4	304	3.552
✓	Field 9	STATIC-I	UM-EX1 - 6X	Static	0.111	Varian IEC	50.0	0.0	0.0	None	4.4	+2.2	+2.2	3.9	+2.2	+1.7	0.51	-5.52	-6.06	92.8	263	2.820

University of Michigan
Medical School

9-field plan: DVHs from same fields and MUs calculated on CT and MRCT

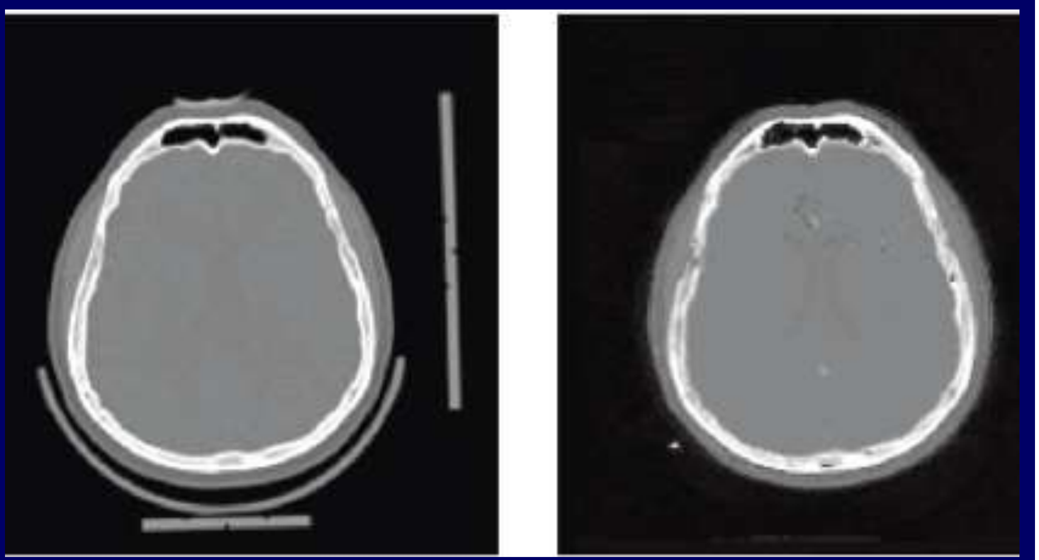


Relationship between Intensities of CT and MRI (Johansson 2011)

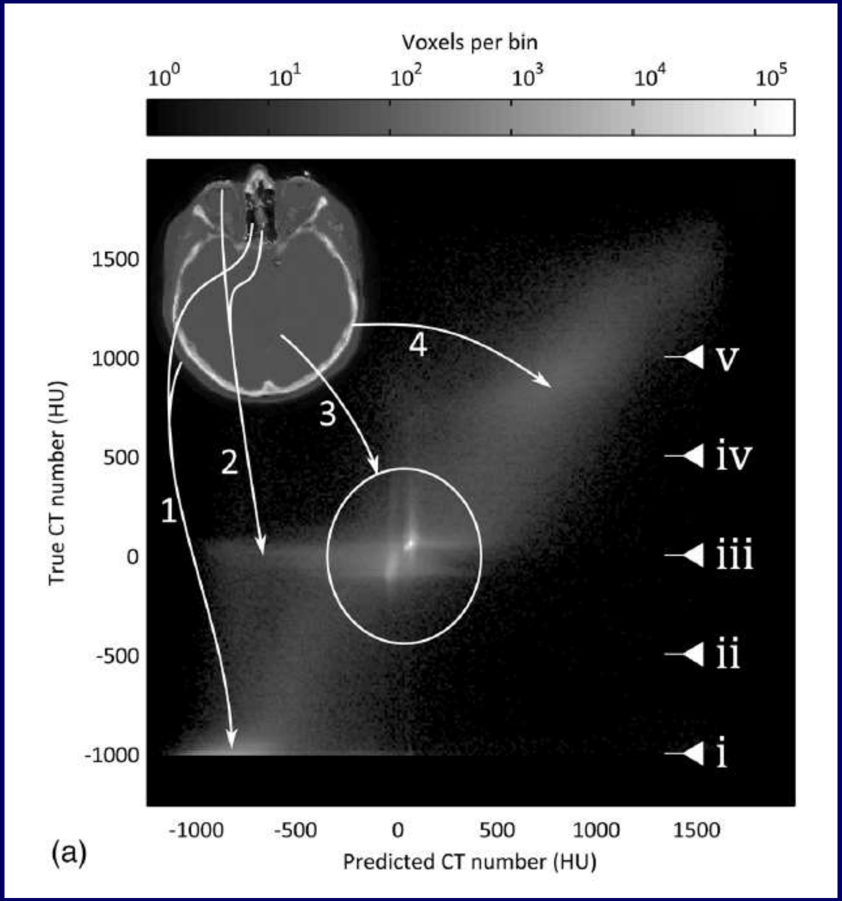


- Inputs
  - Dual echo UTE sequence (TEs=0.07/3.75 ms)
  - T2 weighted images
  - 4 subjects
- Fit them by a GMR model
- Apply to a MRI dataset without CT to create “CT”

GMR Model



CT Synthesized CT



Johansson 2011

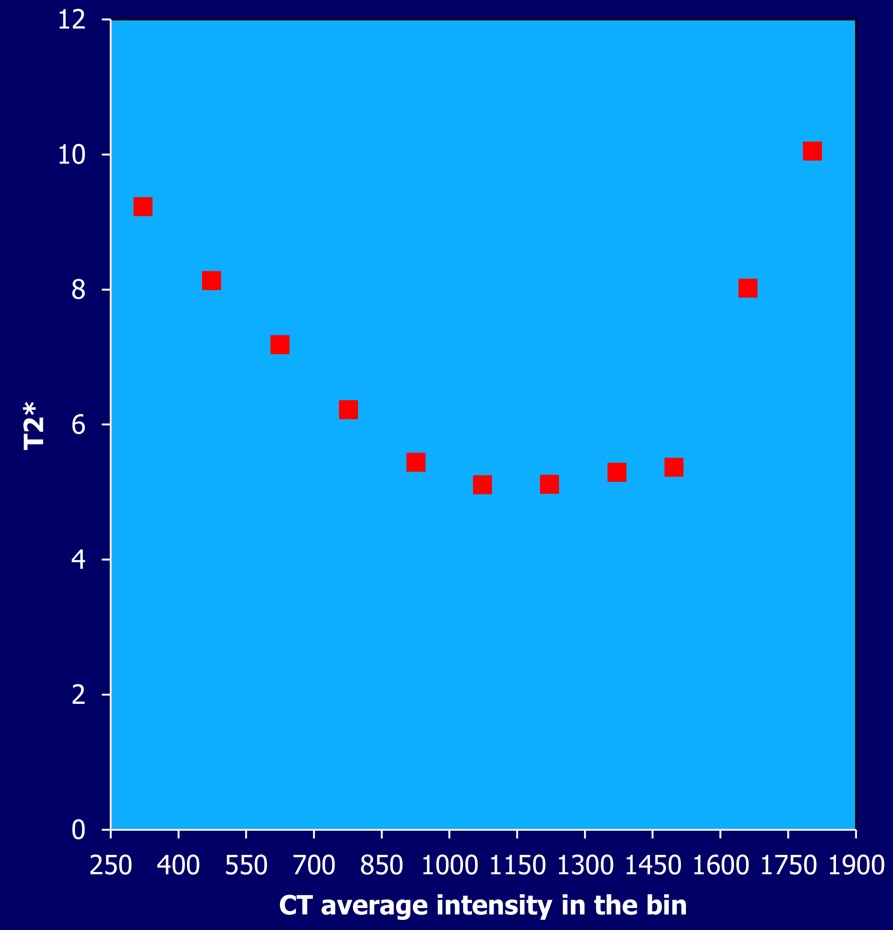
How to evaluate synthesized "CT" or "DRR"

- Voxel-to-voxel comparison of intensities between "CT" and CT (or "DRR" to DRR
- Considering attempted uses
  - Radiation dose plans created from "CT" vs CT
  - Image guidance consequences using "DRR" vs DRR
- Other criteria?

Challenges outside of head

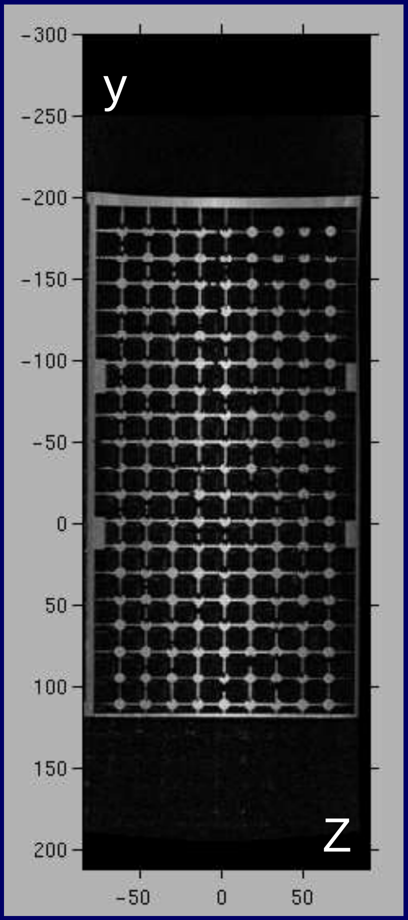
University of Michigan Medical School

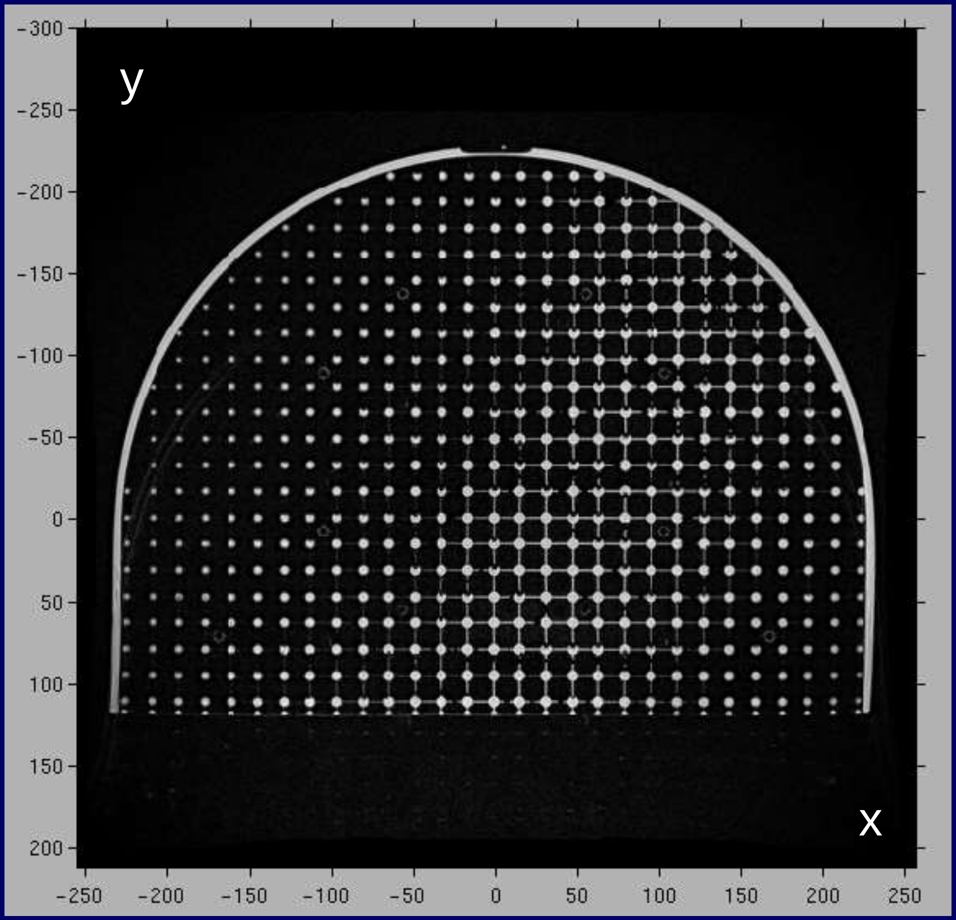
- Organ motion
- Presence of other materials
  - Iron, large fat fractions, cartilage,…
- Large B1 field inhomogeneity
- Variable air pockets
- UTE sequence

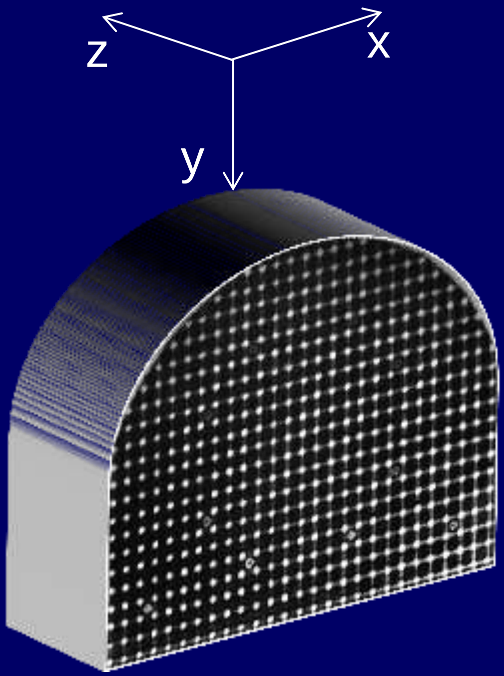


12
10
8
6
4
2
0
T2*
250 400 550 700 850 1000 1150 1300 1450 1600 1750 1900
CT average intensity in the bin

Geometric phantom: System level characterization





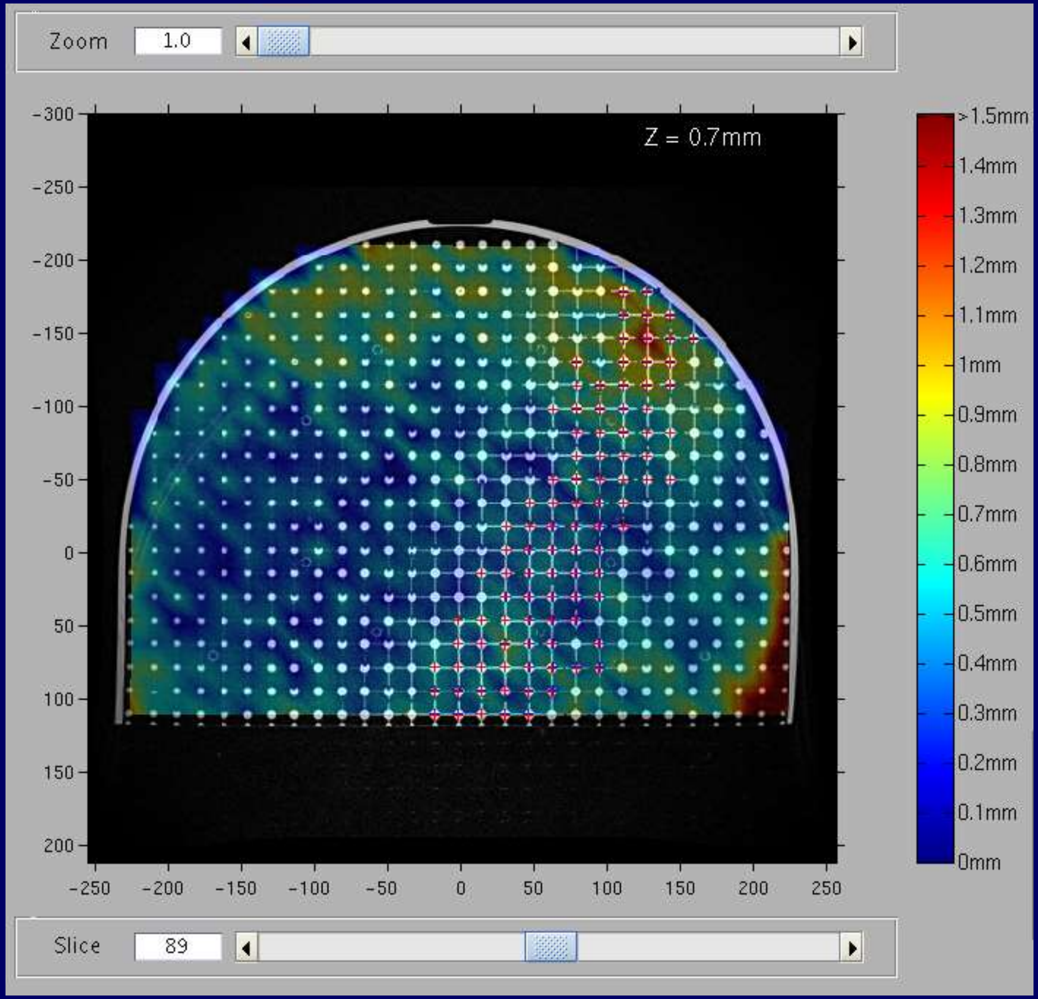


- X: 29 Columns; Y: 21 rows; Z: 9 Sheets
- Center to center 16 mm

Automated Search Algorithm

- To determine the center of all globes

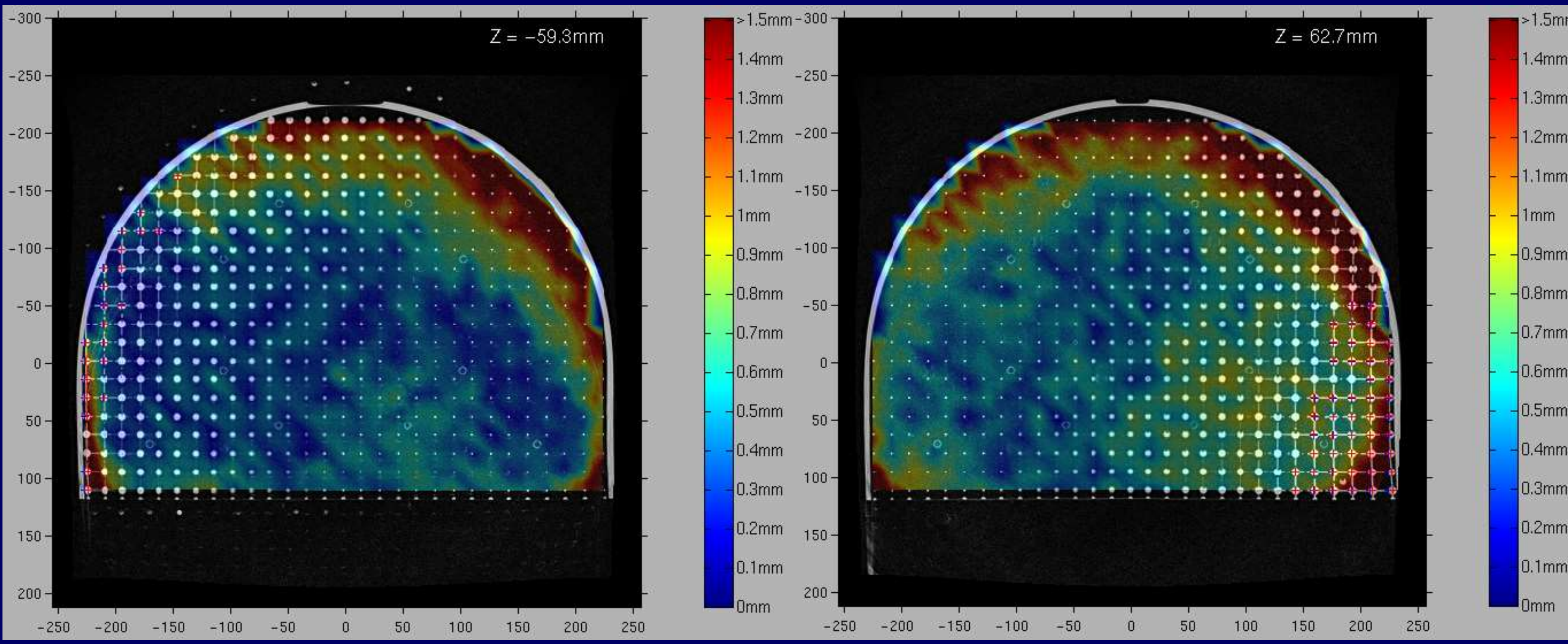
Isocenter plane



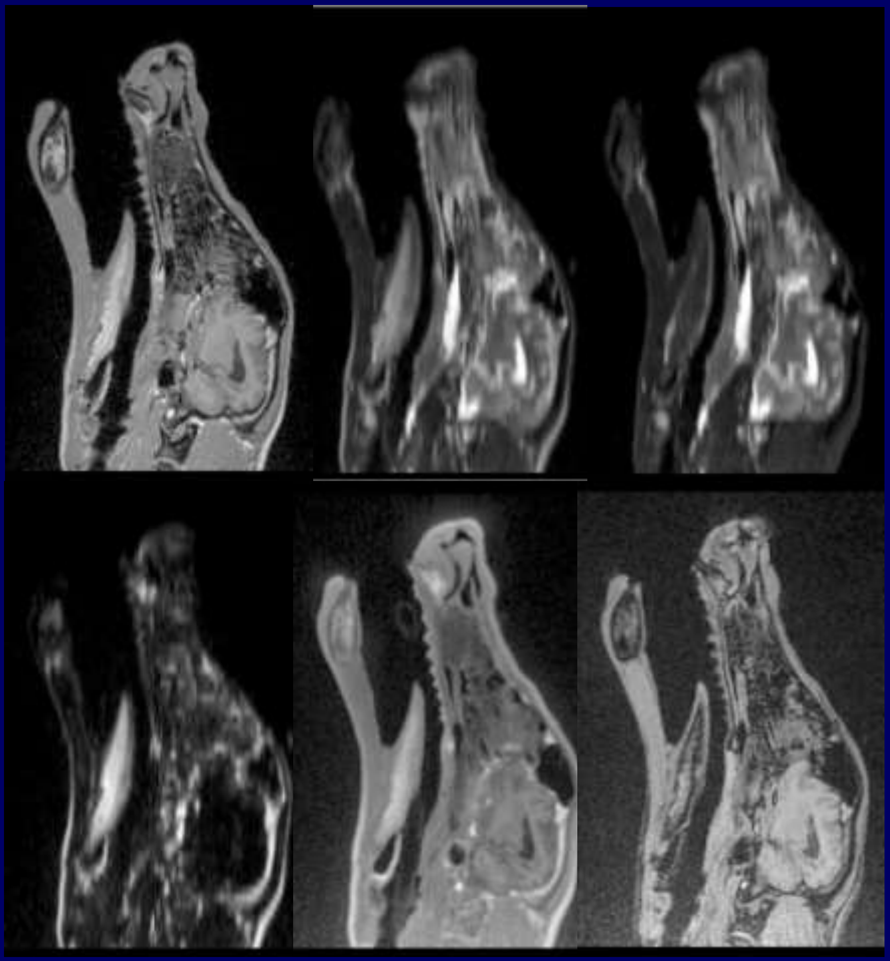
Off Isocenter

Z = -59.3 mm

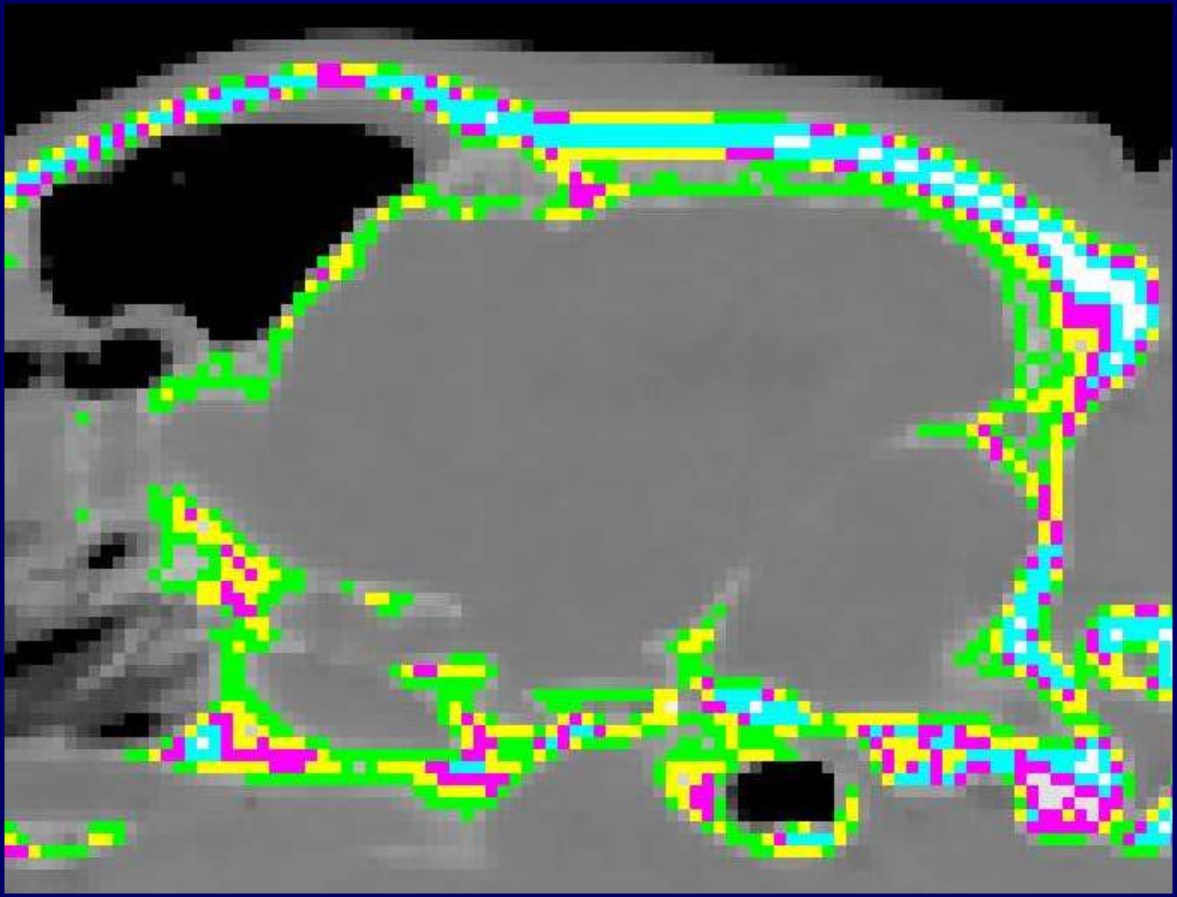
Z = 60.7 mm



Animal MRI Scans

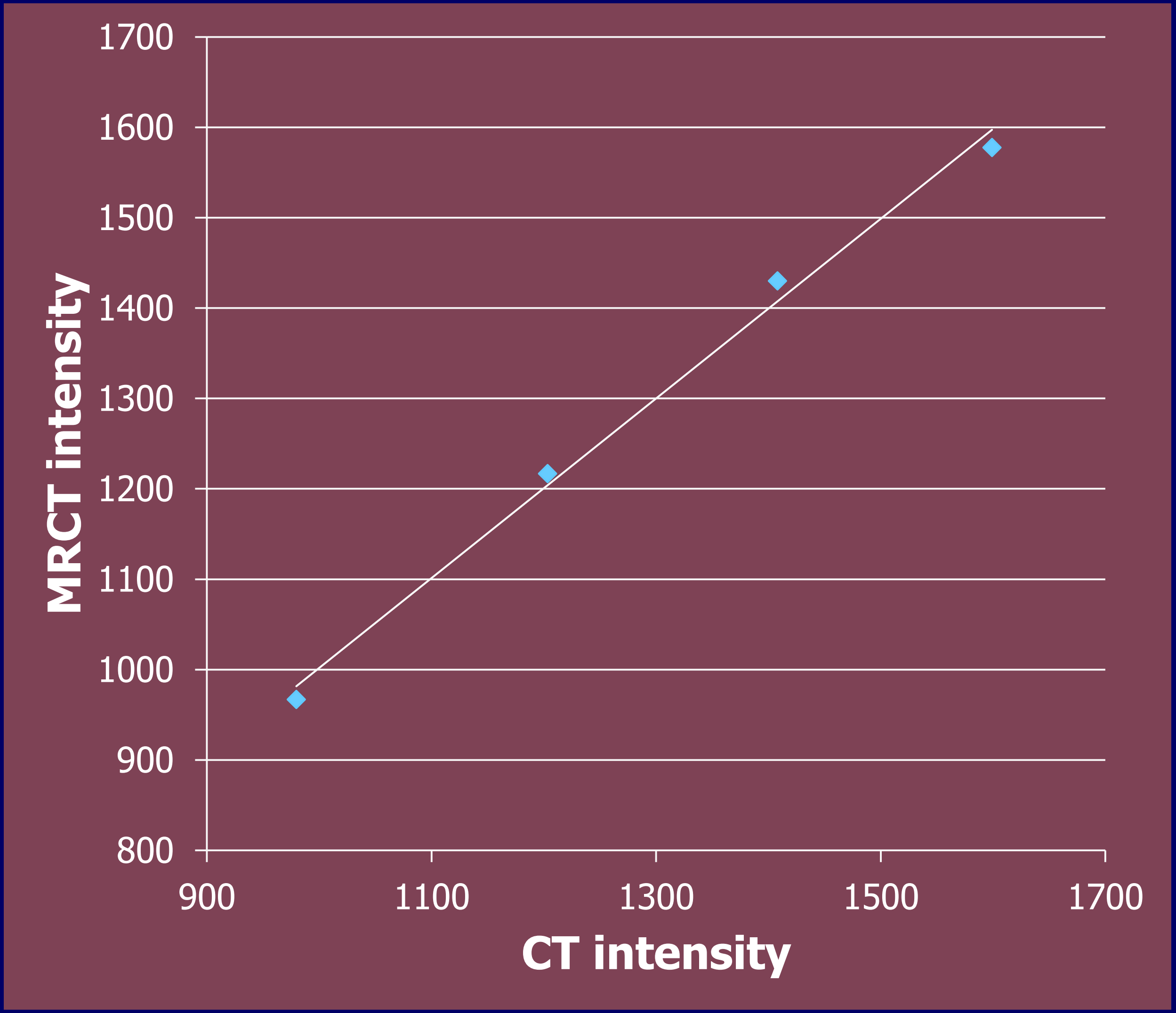


CT



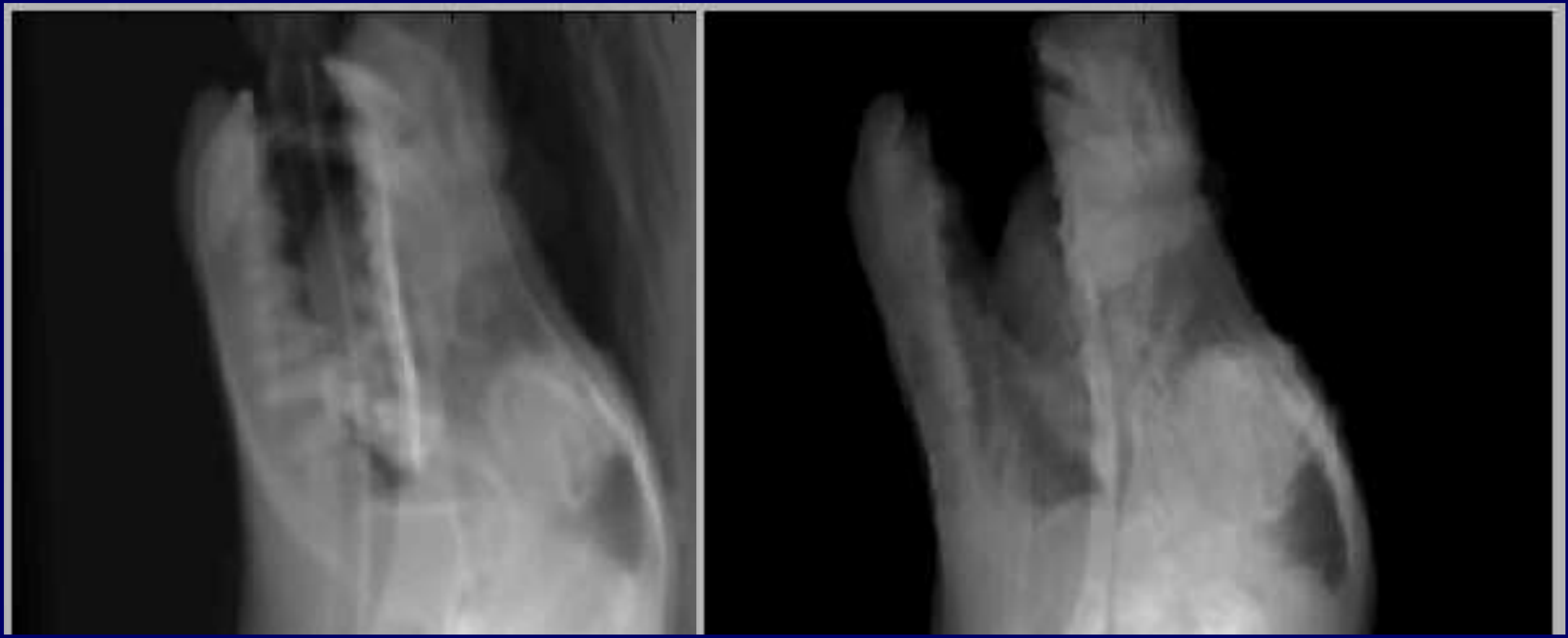
300 (green), 700 (yellow), 1000 (pink), and 1300 (blue) Hounsfield Units

MRCT vs CT



1700
1600
1500
1400
1300
1200
1100
1000
900
800
MRCT intensity
900
1100
1300
1500
1700
CT intensity

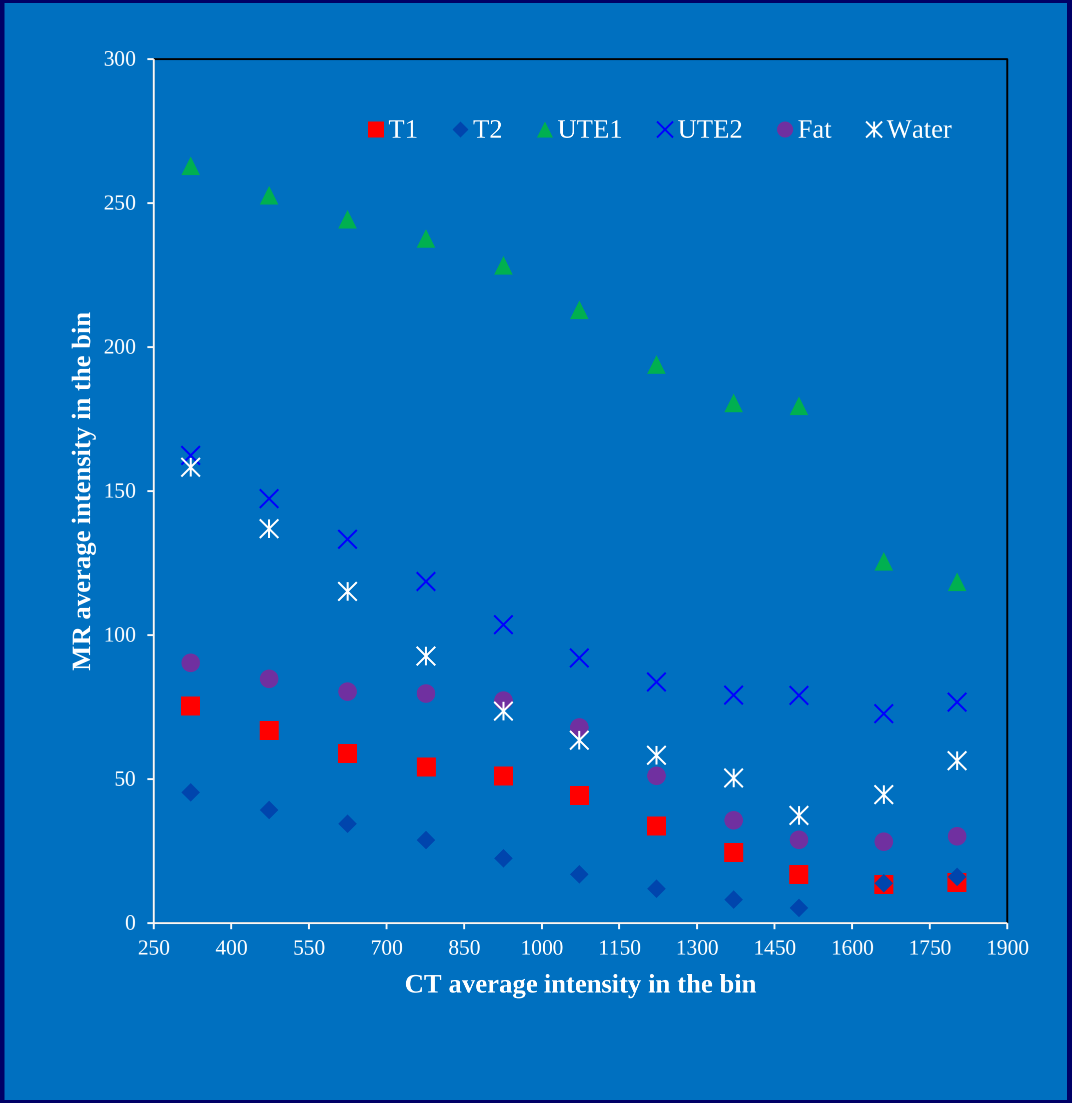
Digitally reconstructed Radiographs



CT

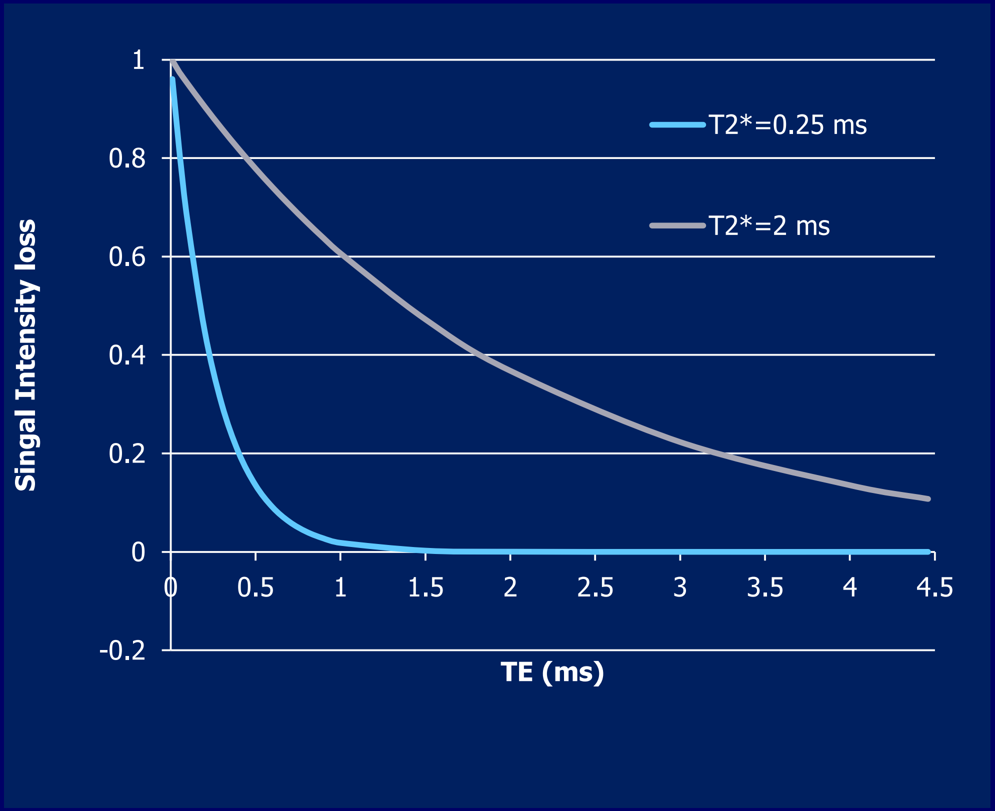
MRCT

MRI



T1
T2
UTE1
UTE2
Fat
Water
MR average intensity in the bin
300
250
200
150
100
50
0
250
400
550
700
850
1000
1150
1300
1450
1600
1750
1900
CT average intensity in the bin

University of Michigan
Medical School

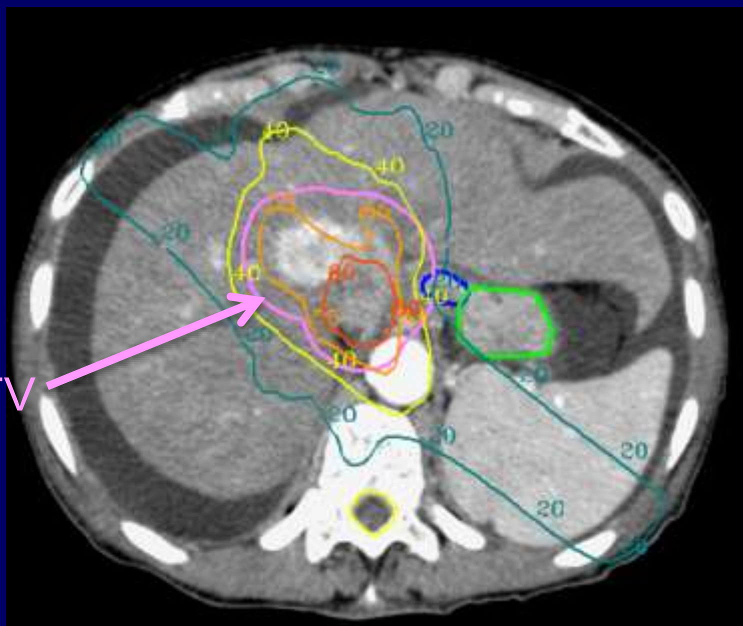


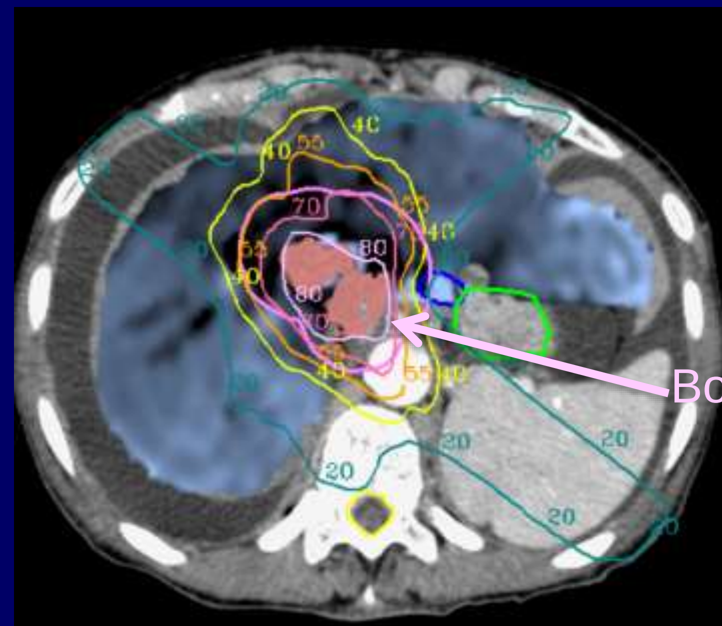
First volunteer MRCT (UTE, no CT)

University of Michigan
Medical School

Targeting active tumor based upon physiological response

PTV





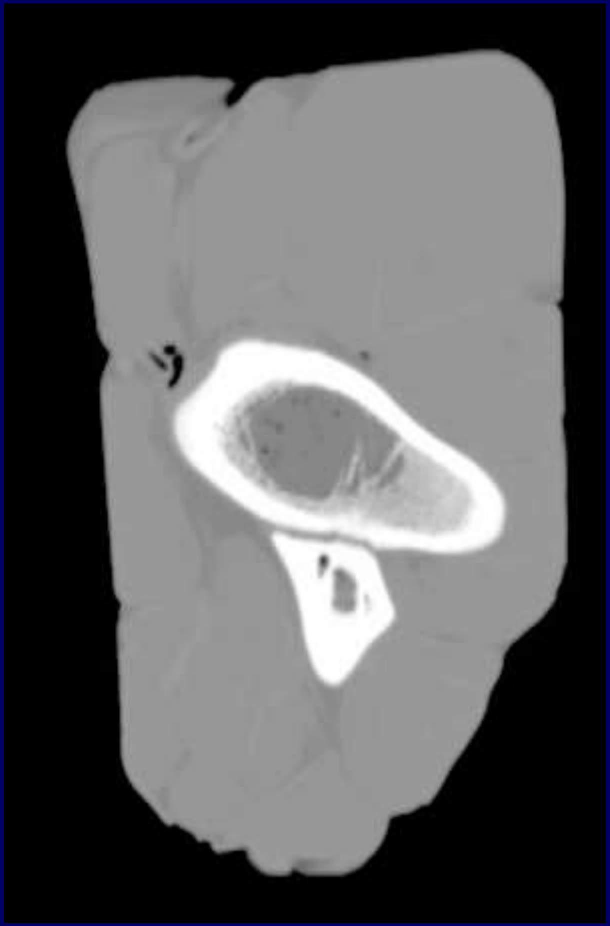
Boost target

Standard course
55 Gy (5 Fx)
NTCP:10%

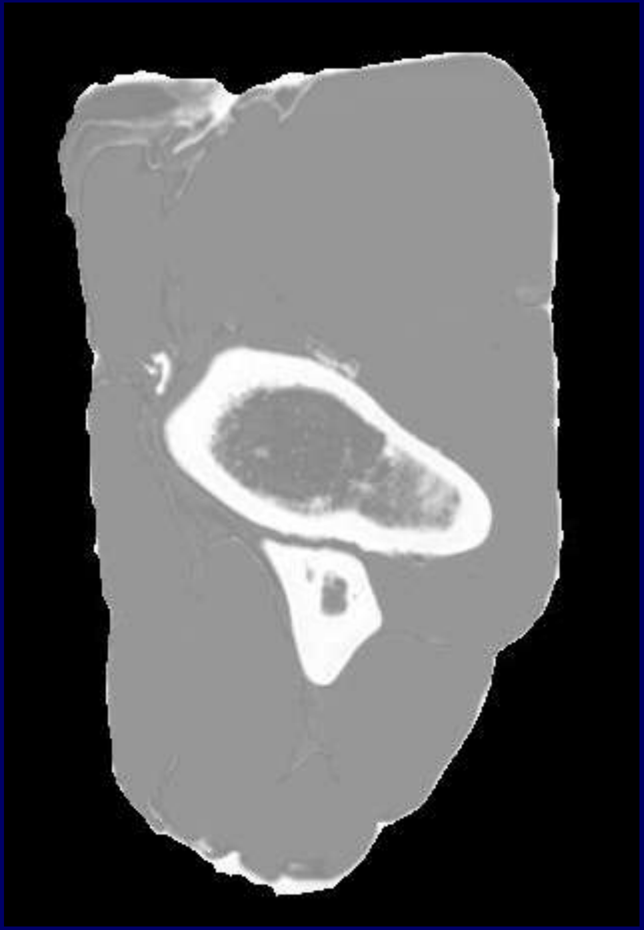
Adaptive course
80 Gy (5 Fx)
NTCP: 10%

M. Matuszak, M. Feng, 2013

Biological Sample (no UTE)



CT



MRCT