MRI for Radiation Therapy Planning

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MRI for RT Planning: why

- Superior soft tissue contrast
- Tumor and OAR delineation

Post-Gd T1W

FLAIR
MRI for RT Planning: why

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

Quantitative Abnormal Arterial Perfusion

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
Why does a patient induce geometric distortion?

- **Tissue magnetic susceptibility**

<table>
<thead>
<tr>
<th></th>
<th>air</th>
<th>water</th>
<th>blood</th>
<th>bone</th>
<th>fat</th>
<th>Au</th>
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</thead>
<tbody>
<tr>
<td>$\chi$ ($10^{-6}$ cm$^3$/mol)</td>
<td>0.36*</td>
<td>-8.9**</td>
<td>-8.8 - -9.1* (O2:55-96%)</td>
<td>-11.3***</td>
<td>-8.4</td>
<td>-28</td>
</tr>
</tbody>
</table>

- **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** $\Delta B_0$

Inhomogeneous anatomy

anatomy

$\Delta B_0$

Wang, Balter, Cao PMB 2013
Geometric distortion

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

\[ \Delta x = \frac{\Delta B_0}{BW_f} \Delta V_x \]

- Mapping individual patient \( \Delta B_0 \)

Pixel size in mm/pixel

Frequency Encoding G bandwidth in Hz/pixel
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)

From sinus

From ear air canal

Wang, Balter, Cao PMB 2013
Distortion from metal

- Graph showing the relationship between distance from brain boundary (mm) and x-displacement (mm).

- The graph indicates a decrease in x-displacement as the distance from the brain boundary increases.
Perturbation in $\Delta B_0$ map due to object movement

- **Uniform water phantom**
  - $\Delta B_0$ map (0 min) vs $\Delta B_0$ map (15 min) after moving a water phantom into the scanner bore

- **Human subject**
  - Does $\Delta B_0$ 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?

- $\Delta B_0$ maps acquired twice at the beginning and end of the imaging session (~40 min apart)
- 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
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 $BW_f=200\text{Hz}/\text{mm} \rightarrow 2.24 \text{ mm}$
  - if $BW_f=800\text{Hz}/\text{mm} \rightarrow 0.56 \text{ mm}$
Chemical Shift of Water and Fat

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

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

Nyman 2008, Kokabi 2011

Spectral analysis of multiple T*2/T2s in femurs (Nyman, Bone 2008)
Can you differentiate air from bone without UTE images?

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

Subtraction

R2*

F_{\text{bound}}/F_{\text{free}} \rightarrow 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

Image series 1
Image series 2
Image series 3
Image series N

Image pre-processing → FCM classifier → Probability image in class 1
Probability image in class 2
Probability image in class …
Probability image in class c

Class property assignment → Synthetic CT image (MRCT)
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

<0.1% of skull volume

MRCT average intensity in the bin vs CT average intensity in the bin

4 inputs
5 inputs
9-field focal brain treatment plan

![9-field focal brain treatment plan diagram]
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

- Organ motion
- Presence of other materials
  - Iron, large fat fractions, cartilage, ...
- Large B1 field inhomogeneity
- Variable air pockets
- UTE sequence
The graph shows the relationship between CT average intensity in the bin and T2* values. The x-axis represents the CT average intensity in the bin, while the y-axis represents T2*. The data points are plotted as red squares, indicating a downward trend as the CT average intensity increases.
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

\[ Z = -59.3 \text{ mm} \]

\[ Z = 60.7 \text{ mm} \]
Animal MRI Scans

T1W  T2W  Water

fat  UTE1  UTE2
300 (green), 700 (yellow), 1000 (pink), and 1300 (blue) Hounsfield Units
MRCT vs CT
Digitally reconstructed Radiographs

CT

MRCT
MRI

MR average intensity in the bin vs. CT average intensity in the bin:
- T1
- T2
- UTE1
- UTE2
- Fat
- Water

Legend:
- Red square: T1
- Blue diamond: T2
- Green triangle: UTE1
- Purple cross: UTE2
- Pink circle: Fat
- Black cross: Water

X-axis: CT average intensity in the bin
Y-axis: MR average intensity in the bin
Signal Intensity loss vs. TE (ms)

- T2* = 0.25 ms
- T2* = 2 ms
First volunteer MRCT (UTE, no CT)
Targeting active tumor based upon physiological response

- 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)