MRI Driven Radiotherapy Treatment Planning

Minsong Cao, PhD

Department of Radiation Oncology

UCLA

Advantages of Magnetic Resonance Imaging (MRI)

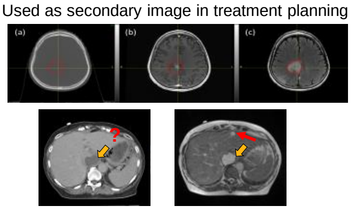
- Superior soft tissue contrast
- Functional and physiological imaging
- Real time dynamic imaging
- No radiation imaging dose

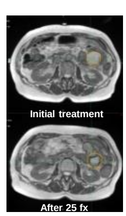
→

- ❑ Target/OAR delineation
- ❑ Treatment setup and verification
- ❑ Assessment of treatment response and adaptive treatment planning
- ❑ Motion management

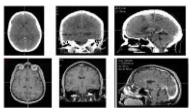
MRI in RT planning

Used as secondary image in treatment planning



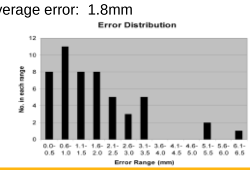


Uncertainty in rigid image registration



CT/MRI images of the same patient sent to 45 institutions for image registration

Average error: 1.8mm

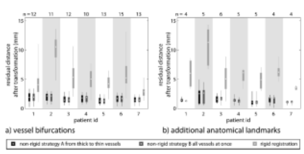


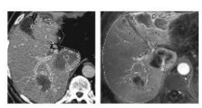
Results of a Multi-Institutional Benchmark Test for Cranial CT/MR Image Registration

Kenneth Ulin, Ph.D.[1], Marcia M. Urie, Ph.D.[1], and Joel M. Cherlow, M.D., Ph.D.[2]
[1]Quality Assurance Review Center, Providence, RI 02903, USA
[2]Long Beach Memorial Medical Center, Long Beach, CA 90801, USA

Int J Radiat Oncol Biol Phys. 2010; 77(5):

Uncertainty in deformable image registration





Additional planning margin is needed to account for the uncertainties in image registration

Vasquez Osorio et al. Med Phy V39(5), 2012

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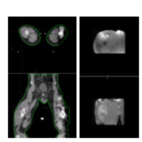
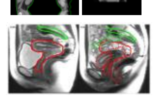
Other Challenges of using diagnostic MRI

- Diagnostic MRI is often imaged at:
  - different position than RT treatment simulation
  - limited field of view (FOV)
  - different organ filling
  - different respiration phase
- Insurance often reimburses for only one simulation





Lim et al. IJROBP. V79(2) 2011

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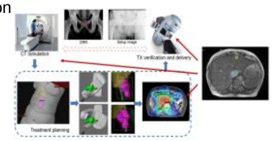
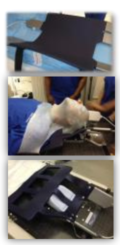
MRI driven treatment planning

- What CT brings to us for treatment planning?
  - Patient imaged in treatment position
  - Non obstructive imaging
  - High spatial integrity
  - Information for dose calculation
  - Treatment setup reference images



MRI imaging in treatment position

- Most commercial MRI scanners have smaller bore size than large bore CT
- MRI coil integrated with immobilization device
- Immobilization device:
  - MRI safe (i.e. Carbon fiber not MR safe)
  - Minimize image artifact and magnetic susceptibility
- Coil attenuation consideration if used for treatment delivery guidance



Challenge – Spatial integrity

- MRI image distortion
  - Gradient non-linearity
  - Field inhomogeneity
  - Chemical shifts
  - Magnetic susceptibility

Scanner dependent (Gradient non-linearity)
Sequence dependent (Field inhomogeneity, Chemical shifts, Magnetic susceptibility)

System dependent
Patient dependent

Geometric distortion – System dependent

- Field inhomogeneity $\Delta x_{\text{field}} = \frac{\Delta B_0(x,y,z)}{G_{\text{read}}}$
  - Inversely proportional to gradient strength
  - Compensated through shim coils
- Gradient nonlinearity $\Delta x_{\text{grad}} = \frac{x * \Delta G_{\text{read}}}{G_{\text{read}}}$
  - Usually the dominant factor
  - Gradient strength falls off at periphery of FOV => increased distortion at periphery

➡ Increase with increasing **FOV** and **B_0**; Decrease with **gradient field strength**
Can be assessed and corrected using geometric phantom

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Weygand et al. IJROBP. V95(4) 2016

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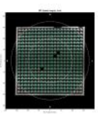
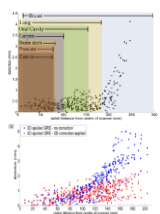
Distortion – Assessment and correction



B_0= 0.35T



B_0= 1.5T

Walker. Australasian Phys and Eng Sci in Med 37(1) 2014

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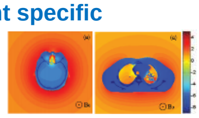
Geometric distortion – Patient specific

- Magnetic susceptibility $\Delta x = \Delta\chi \frac{B_0}{G_{\text{read}}}$
  - Proportional to magnet strength B_0
  - Determined by the susceptibility difference between tissues
  - Most pronounced at air-tissue interface
  - Patient dependent and difficult to assess and correct



Anatomical site	Structure	Max distortion (ppm)	Mean distortion (ppm)	Range of distortion (ppm)	0.5 T (5 mT/m) Max distortion (mm)	0.5 T (5 mT/m) Mean distortion (mm)	0.5 T (5 mT/m) Range of distortion (mm)	3.0 T (5 mT/m) Max distortion (mm)	3.0 T (5 mT/m) Mean distortion (mm)	3.0 T (5 mT/m) Range of distortion (mm)
Brain	Body	3.48	0.43	9.36	0.55	0.04	0.94	3.29	0.26	5.62
	Bone	3.36	0.25	6.37	0.34	0.03	0.64	2.02	0.15	3.82
	Air cavities	5.66	0.92	9.98	0.57	0.09	1.00	3.40	0.55	5.98
Lung	Body	2.99	0.41	5.37	0.30	0.04	0.54	1.79	0.25	3.22
	Bone	4.96	0.64	7.71	0.50	0.06	0.77	2.98	0.38	4.63
	Lung	5.56	0.71	8.85	0.56	0.07	0.89	3.34	0.43	5.31
Prostate (no air pockets)	Body	3.98	0.54	6.42	0.40	0.05	0.64	2.39	0.32	3.85
	Bone	2.48	0.41	3.03	0.25	0.04	0.30	1.49	0.25	1.82
Pelvis (air pockets)	Body	3.91	0.46	5.91	0.39	0.05	0.59	2.35	0.28	3.55
	Bone	2.54	0.47	4.02	0.25	0.05	0.40	1.52	0.28	2.41
	Air pockets	4.85	0.68	7.27	0.49	0.07	0.73	2.91	0.41	4.36

Stanescu et. al. Med Phys. V39 (12), 2012

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Geometric distortion – Planning Margin

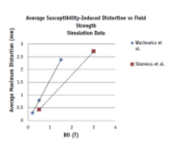
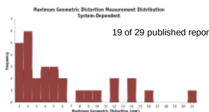
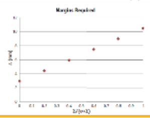


Fig. 3. Variation of maximum geometric distortion as a function of field strength for data reported by Stanescu et al (53) and Wachowicz et al (66). Because 3 field strengths were simulated by Wachowicz et al (66), a linear relationship between geometric distortion and field strength can be inferred.

Weygand et al. IJROBP. V95(4) 2016



19 of 29 published reports are >2mm

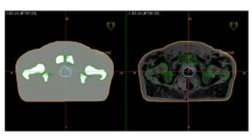


$$\Delta = 2.5\Sigma + 0.7\sigma$$

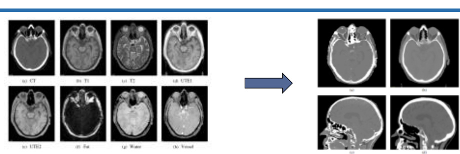
Fig. 4. Required margin (Δ) as a function of the proportion of the systematic component of geometric distortion (Σ) to total geometric distortion ($\Sigma + \sigma$, where σ is the random component of geometric distortion). Here, $\Sigma/(\Sigma + \sigma) = 1$ implies that the distortion is purely systematic and, consequently, requires a very large margin.

Challenge - Dose calculation

- MRI does not provide information of electron densities of tissues which is required for heterogeneity correction
- Solutions:
  - Bulk density assignment
  - Atlas based segmentation
  - Direct voxel-vise conversion (Pseudo-CT or synthetic, substitute-CT)



Jonsson et al. Rad Onc 2010, 5:62



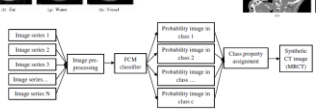


Figure 3. Overall scheme of using multiple MRI volumes to generate MRCT.

Hsu et al. PBM 58(23) 2013

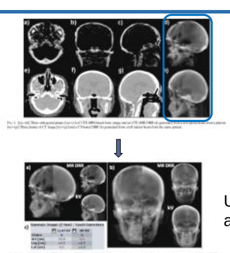
Study	Site	Planning technique	Method	Dose calculation difference	Reference
Chen et al	Prostate (n=15)	IMRT	Bulk assign (bone)	2% (target coverage)	IJROBP V60(2) 2004
Honsson et al	HN, prostate, brain, lung (n=40)		Bulk assign (bone + air)	D95<1% (PTV) MU difference < 1.6%	Rad Onc V5:52 2010
Chin et al	HN (n=7)	IMRT	Bulk assign (bone + air)	<5% (target coverage)	JACMP V15(5) 2014
Korsholm et al	HN (n=18) prostate (n=21) Pelvic (n=8)	VMAT	Bulk assign (bone + air)	1.5% PTV 4.2% OAR	IJROBP V9(16) 2014
Prior et al	Prancreas (n=5) Prostate (n=5)	IMRT	Bulk assign (per ICRU46)	<3% for PTV 5% for OAR	PMB V61. 2016
Dowling et al	Prostate (n=39)	3D	Atlas based	2% (point dose)	IJROBP V83(1)2012
Jonsson et al	Brain (n=5)	3D	Synthetic CT	<1% for D90 and 97% gamma passing	Rad and Onco 108 (2013)
Korhonen et al	Prostate (n=10)	IMRT/VMAT	Synthetic CT	0.8% PTV; 94% gamma passing	Med. Phys. 41 (1) 2014
Zheng et al	Brain (n=10)		Synthetic CT	99% gamma passing	IJROBP V93(3) 2015
Paradis et al	Brain (n=12)	VMAT	Synthetic CT	1% maximum	IJROBP V93(5) 2015

Challenge –Treatment setup reference

- Image guidance for patient treatment setup is primarily x-ray based
- Heavily relies on bony anatomy
- General MRI images do not have bony anatomy information


Reference image


Setup image



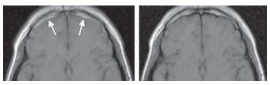
Ultrashort TE (UTE) image for bony anatomy reference image

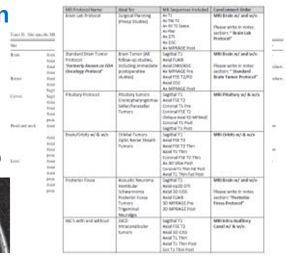
Yang, Cao et al. Med. Phys. 43 (1), 2016

MRI sequence selection

- MRI pulse sequence impacts the appearance of tissues on the MRI image
- Understand MR image artifacts

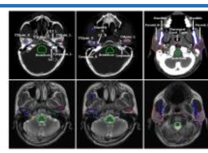
(Morelli et al. V31(3).2011. RadioGraphics)





MR Protocol Name	Ideal for	MR Sequences Included	Care/Connect Order
Brain Lab Protocol	Surgical Planning (Preop Studies)	Ax T1 Ax TSE T2 Ax 3D T2 Space Ax Flair Ax DTI Ax DSC Ax MPRAGE Post	MRI Brain w/ and w/o Please write in notes section: " Brain Lab Protocol"
Standard Brain Tumor Protocol *"Formerly known as FDA Oncology Protocol"*	Brain Tumor (All follow-up studies, including immediate postoperative studies)	Sagittal T1 Axial FLAIR Axial DWI/ADC Ax MPRAGE Pre Axial FSE T2/PD Axial DSC Ax MPRAGE Post	MRI Brain w/ and w/o Please write in notes section: " Standard Brain Tumor Protocol"
Pituitary Protocol	Pituitary tumors Craniopharyngiomas Sellar/Parasellar Tumors	Sagittal T1 Axial FSE T2 Coronal T1 Pre Coronal FSE T2 Oblique Axial 3D MPRAGE Coronal T1 Post Sagittal T1 Post	MRI Pituitary w/ & w/o
Brain/Orbits w/ & w/o	Orbital Tumors Optic Nerve Sheath Tumors	Sagittal T1 Axial FSE T2 Axial FSE T2 Thin Axial T1 Thin Coronal FSE T2 Thin Ax 3D Vibe Post Coronal T1 Thin Fat Post Axial T1 Thin Fat Post	MRI Orbits w/ & w/o
Posterior Fossa	Acoustic Neuroma Vestibular Schwannoma Posterior Fossa Tumors Trigeminal Neuralgia	Sagittal T1 Axial ep2D DTI Axial 3D CISS Axial FLAIR 3D MPRAGE Pre 3D MPRAGE Post	MRI Brain w/ and w/o Please write in notes section: "Posterior Fossa Protocol"
IAC's with and without	SSCD Intracanalicular tumors	Sagittal T1 Axial FSE T2 Axial 3D CISS Axial T1 Thin Axial T1 Thin Post Cor T1 Thin Post	MRI Intra-Auditory Canal w/ & w/o

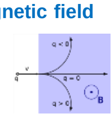
Contouring on MRI



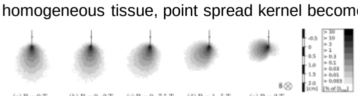
- Useful references:
  - MRI section anatomy
  - MRI contour guidelines and atlas
    - Lim et al. Consensus Guidelines on Cervix Cancer. IJROBP. V79(2) 2011
    - Sun et a. Contour atlas for HN. Rad Onc V110, p390. 2014
    - MRI Prostate Anatomy Atlas: http://www.prostadoodle.com/
    - MRI Brain Atlas: http://headneckbrainspine.com/Brain-MRI.php
    - MRI axial cross sectional anatomy: https://mrimaster.com/index.5.html

Considerations for MR guided treatment system – Impact of magnetic field

Lorentz force:



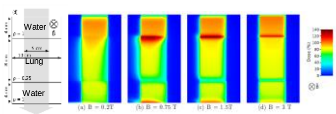
In homogeneous tissue, point spread kernel becomes asymmetric



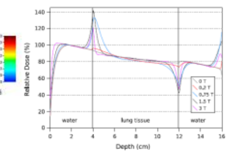
Raaijmakers et al. PMB. 53 (2008)

Impact of magnetic field on dose distribution

- Significant dose increase at tissue-air boundaries due to secondary electrons returned back by the Lorentz force



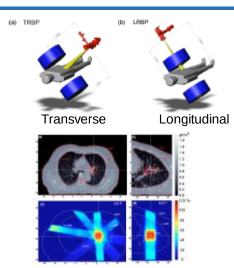
Electron return effect (ERE)

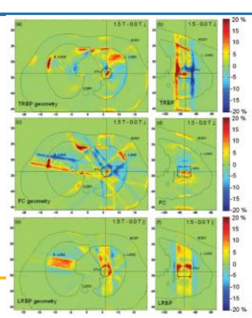


Raaijmakers et al. PMB. 53 (2008)

Treatment Planning Considerations for ERE

- The ERE can be characterized by Monte Carlo simulation
- Treatment planning system should incorporate MC simulation to account for the ERE
  - Dose calculation
  - Dose optimization





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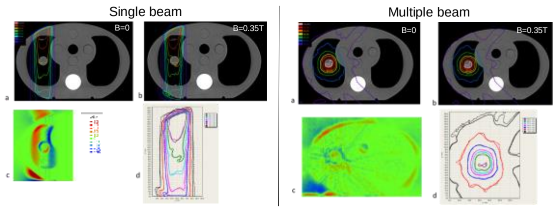
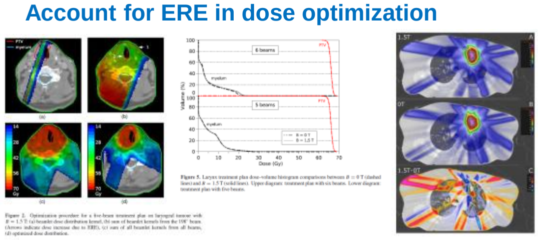
Account for ERE - Low magnetic field



Account for ERE in dose optimization



Raaijmaker et al. PMB 52. 2007

Menten et al. Rad Onc 119. p461 2016

Other practical considerations for planning

- Data transfer and management
- Adaptive treatment planning
- Motion management
  - Respiration motion
  - Peristaltic motion
- Functional imaging for treatment planning

Considerations for implementation of MRI driven treatment planning

- Imaging with coil and immobilization devices
- Spatial integrity / Geometric accuracy
- Imaging protocols/ sequences selection
- Information for dose calculation
- Reference image for treatment setup

(the five items above: MRI only RT)

- Dose distortion due to magnetic field → MRI guided delivery

Summary

- MRI offers superior soft-tissue contrast for target delineation and patient setup
- Special efforts are needed to address issues such as geometric distortion, lack of electron density info and dose distortion due to magnetic field
- A rigorous QA program is essential for MR driven planning
- Personnel and staff training is also important