MR image processing, registration, and planning for intracranial ~~radiotherapy~~ *Radiosurgery*

David Schlesinger, Ph.D.

Lars Leksell Gamma Knife Center
University of Virginia

University of Virginia Health System

Department of Radiation Oncology

Conflicts of Interest

None

Session Educational objectives

1. Review important differences in objectives between diagnostic and therapeutic MR
2. Review quality assurance considerations critical to accurate and precise treatment delivery based on MR targeting.
3. Discuss recent advances in the use of MR imaging to evaluate treatment efficacy
4. Highlight novel therapeutic techniques made possible by advanced MR pulse sequences such as MR thermometry and MR

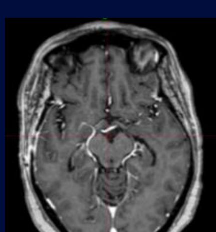
MR for intracranial radiotherapy

Goals of MR for therapy vs diagnostic imaging

QA specific to MR for intracranial radiotherapy

Emerging MR applications for intracranial RT

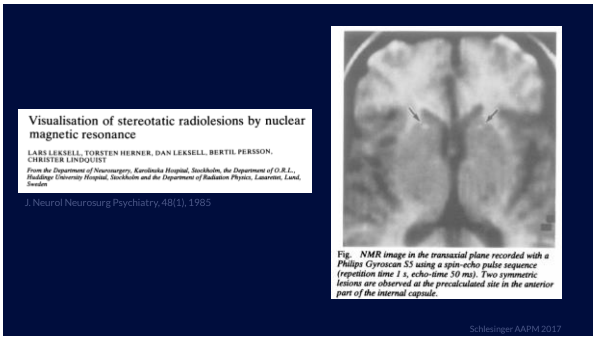
Why MRI?



T1-weighted MRI with contrast

CT with contrast

MR for RT is trendy, but it is not new


Visualisation of stereotatic radiolesions by nuclear magnetic resonance
LARS LEKSELL, TORSTEN HERNER, DAN LEKSELL, BERTIL PERSSON, CHRISTER LINDQUIST
From the Department of Neurosurgery, Karolinska Hospital, Stockholm, the Department of O.R.L., Huddinge University Hospital, Stockholm and the Department of Radiation Physics, Lasarettet, Lund, Sweden
J. Neurol Neurosurg Psychiatry, 48(1), 1985
Fig. NMR image in the transaxial plane recorded with a Philips Gyroscan S5 using a spin-echo pulse sequence (repetition time 1 s, echo-time 50 ms). Two symmetric lesions are observed at the precalculated site in the anterior part of the internal capsule.
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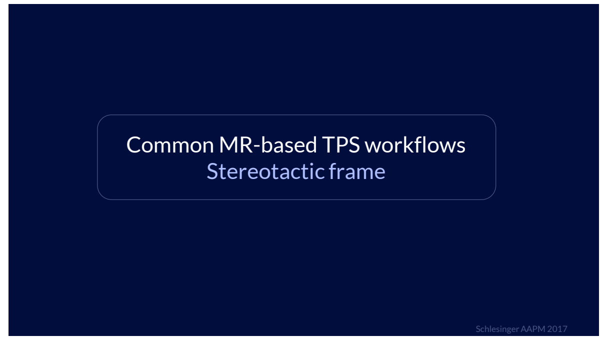
Common MR-based TPS workflows
Stereotactic frame
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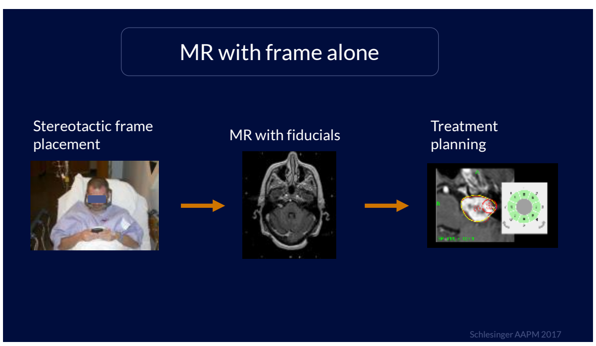
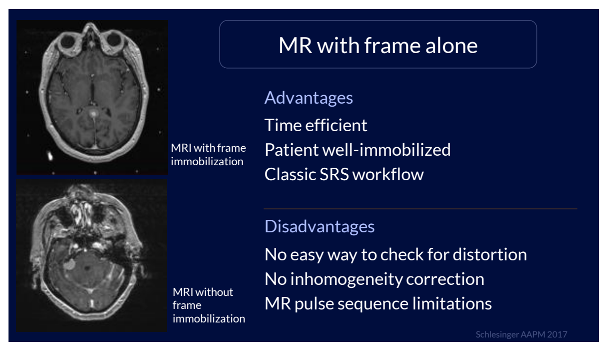

MR with frame alone
Stereotactic frame placement
MR with fiducials
Treatment planning
Schlesinger AAPM 2017


MR with frame alone
MRI with frame immobilization
MRI without frame immobilization
Advantages
Time efficient
Patient well-immobilized
Classic SRS workflow
Disadvantages
No easy way to check for distortion
No inhomogeneity correction
MR pulse sequence limitations
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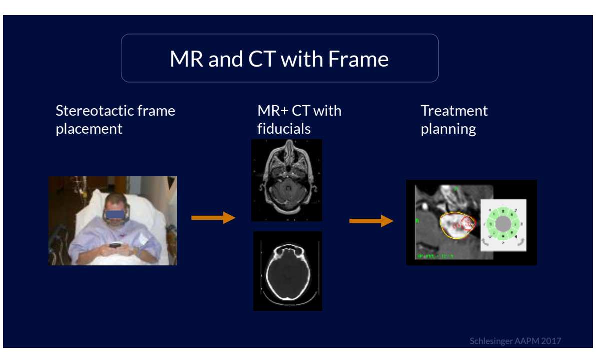
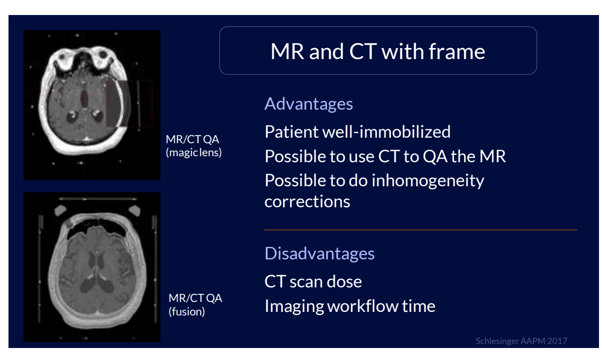

MR and CT with Frame
Stereotactic frame placement
MR+ CT with fiducials
Treatment planning
Schlesinger AAPM 2017


MR and CT with frame
MR/CT QA (magic lens)
MR/CT QA (fusion)
Advantages
Patient well-immobilized
Possible to use CT to QA the MR
Possible to do inhomogeneity corrections
Disadvantages
CT scan dose
Imaging workflow time
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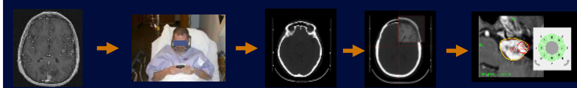
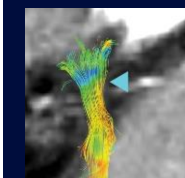
MR without frame / CT with frame

MR (no fiducials) → Stereotactic frame placement → CT with fiducials → Coregistration → Treatment planning



MR without frame / CT with frame



DTI tractography along trigeminal nerve

Hodaie et al., Plos One, 7(3), 2012

Advantages

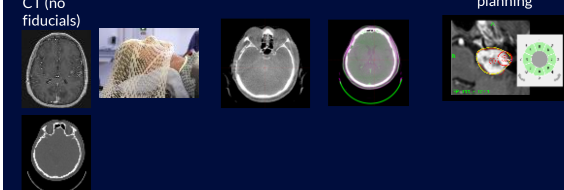
- Possible to use CT to QA the MR
- Possible to do inhomogeneity corrections
- Advanced MR sequences possible

Disadvantages

- CT scan dose
- Imaging workflow time
- MR motion artifact

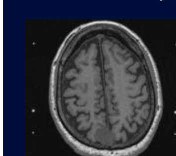
Common MR-based TPS workflow
Frameless

MR and/or CT (no fiducials) | Mask | CBCT | Coregistration | Treatment planning



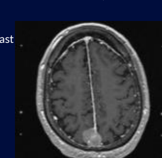
Useful CNS Pulse Sequences

3D T1-weighted volumetric sequences (usually Gradient Echo)



Pre-contrast T1

Post-contrast T1



Workhorse sequences for intracranial radiosurgery
Pre-contrast helpful for identifying hemorrhage
Post-contrast helpful for identifying tumors

Images courtesy of University of Virginia

Inversion-recovery sequences (FLAIR / STIR)

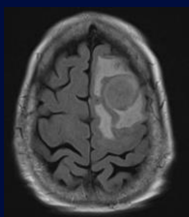


Image courtesy of University of Virginia

FLAIR image of tumor and surrounding inflammation

FLAIR: Fluid Attenuated Inversion Recovery

STIR: Short-Tau Inversion Recovery

Inversion pulse applied before excitation pulse "zeroes out" signals from particular tissues

Inversion time (TI) set to cancel out CSF (FLAIR) or fat (STIR) signal

Permits enhanced visualization of brain inflammation (FLAIR), or surgical packing (STIR)

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Steady-state sequences (CISS/SPACE)

T2 SPACE image showing good visualization of CSF structures

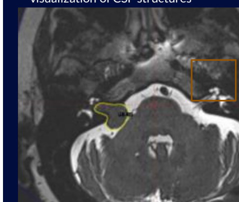

Image courtesy of University of Virginia

CISS: Constructive interference in steady state

SPACE: Sampling perfection with application-optimized constrasts by using different flip-angle evolutions

Use RF-pulses to refocus echos and maintain a steady-state net magnetization

Creates bright CSF signal

Good for visualizing fine structures in CSF

Useful source: S. Stuckey, et al., AJNR 18, 1996

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Volumetric interpolated sequences (VIBE)

VIBE image of a pituitary microadenoma

Image courtesy of University of Virginia

VIBE: Volumetric Interpolated Brain Examination*

Gradient-echo sequence using asymmetric k-space sampling and zero-filling in the slab-select direction

Optimized for fast acquisition times

Contrast depends more on tissue and less on pulse-sequence timing (i.e. inversion time)

Useful for sellar-region tumors

*Developed from a similar sequence: Volumetric Interpolated Breath-hold Examination

Useful source: S. Wetzel, et al., AJNR 23, 2002

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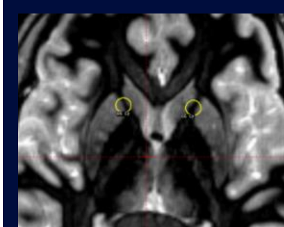
Specialized sequences: FGATIR



FGATIR image used for an OCD treatment

Image courtesy of University of Virginia

FGATIR: Fast gray matter acquisition T1 inversion recovery

Similar in idea to FLAIR/STIR, but nullifies white matter signal

Allows better visualization of deep grey matter structures

Useful for functional indications and obsessive-compulsive disorder

Useful source: A. Sudhyadhom, et al., Neuroimage 47, 2009.

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A couple of useful tricks (there are others)

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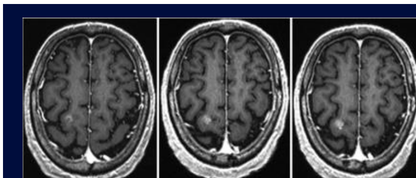
Contrast timing can be important!



Scan 1: time of injection
Scan 2: ~10 min delay
Scan 3: ~15 min delay

Scans compared	% studies w ≥ 1 new lesion	95% CI	Range of # new lesions
Scan 1:2	35.3%	22.4%-49.9%	1-10
Scan 2:3	21.6%	11.3%-35.3%	1-9
Scan 1:3	43.1%	29.3%-57.8%	1-14

M. Kushnirsky et al., JNS 124, 2016

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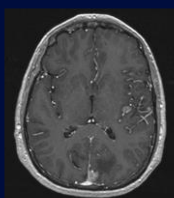
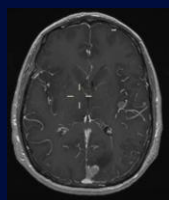
Use MIPs to help distinguish tumors and vessels


T1 post-contrast


MIP 5.0mm slab

Images courtesy of University of Virginia

MR for intracranial radiotherapy

Goals of MR for therapy vs diagnostic imaging

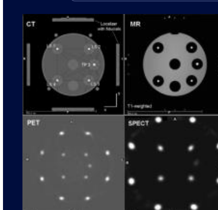
QA specific to MR for intracranial radiotherapy

Emerging MR applications for intracranial RT

Procedural uncertainty =

$$\sqrt{(\text{Biology})^2+(\text{Imaging})^2+\cancel{(\text{Beam Delivery})^2}}$$

You can't localize targets perfectly



Modality	Radial Deviation (mean ± STD) (mm)
CT	0.4±0.2
*MR (T1-weighted)	1.4±0.3
*MR (T2-weighted)	1.4±0.5
†PET	1.1±0.5
‡SPECT	1.6±0.5

*Siemens Magnetom Symphony, †Siemens CTI ECAT EXACT HR, ‡Siemens MULTISPECT 3

Localization of known stereotactic targets with various modalities

C.P. Karger, P. Hipp, M. Henze, G. Echner, et al., Phys Med Biol 48, 2003.

…and images are not necessarily reality!

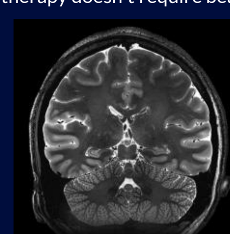

Motion artifact


Metal artifact


Chemical shift artifact

L. J. Erasmus, et al.,SA Journal of Radiology 8/2004
M.J. Graves, et al., J. of Magnetic Resonance Imaging 38, 2013.

Radiotherapy doesn't require beautiful images



It requires anatomy to be located where it appears

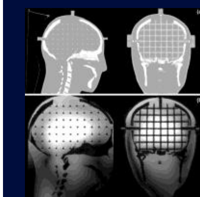
MR for intracranial radiotherapy

Goals of MR for therapy vs diagnostic imaging

QA specific to MR for intracranial radiotherapy

Emerging MR applications for intracranial RT

QA for MR geometric distortion



I Compter, et al., MAGMA 29(3), 2016.

- Use a phantom with markers at known positions or a regular grid.
- CT can be used as a geometric gold standard.
- Doesn't find all sources of distortion!

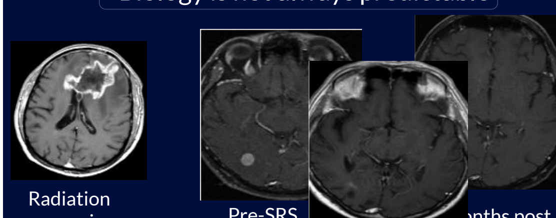
MR for intracranial radiotherapy

Goals of MR for therapy vs diagnostic imaging

QA specific to MR for intracranial radiotherapy

Emerging MR applications for intracranial RT

Biology is not always predictable



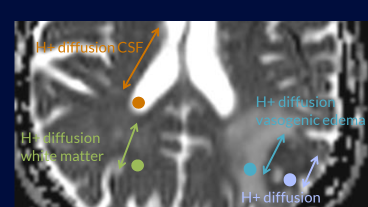
R. Shah, et al, RadioGraphics 32(5), 2012

Happening now!

~~The future~~: Image the biology

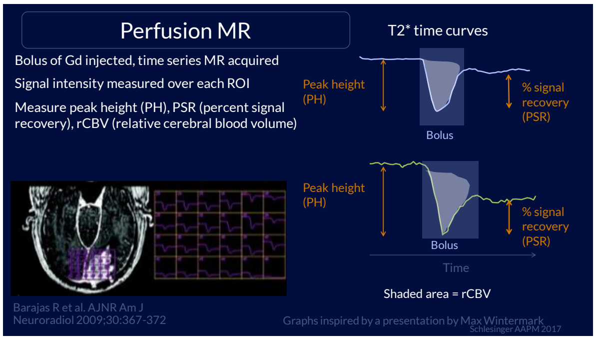
Diffusion-weighted (DWI) imaging

- Indirectly measures the "cellularity" of tissue
- CSF has fewer cells, less restrictive to diffusing H+
- Actively growing tumors have many cells, more restrictive to diffusion.
- Often expressed in terms of an apparent diffusion coefficient (ADC)



ADC map brain with brain metastasis

Slide adapted from a presentation by Max Wintermark. Images courtesy UVA.


Perfusion MR
T2* time curves
Bolus of Gd injected, time series MR acquired
Signal intensity measured over each ROI
Measure peak height (PH), PSR (percent signal recovery), rCBV (relative cerebral blood volume)
Peak height (PH)
% signal recovery (PSR)
Bolus
Peak height (PH)
% signal recovery (PSR)
Bolus
Time
Shaded area = rCBV
Barajas R et al. AJNR Am J Neuroradiol 2009;30:367-372
Graphs inspired by a presentation by Max Wintermark
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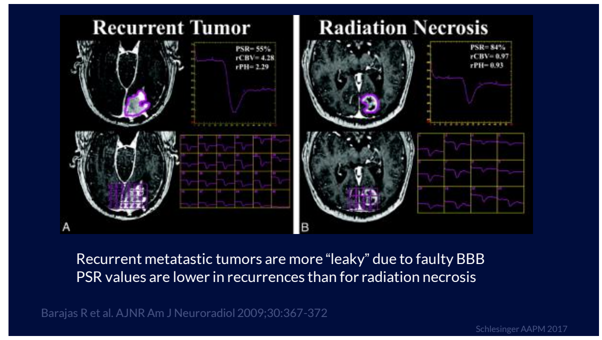
Recurrent Tumor
Radiation Necrosis
A
B
Recurrent metatastic tumors are more "leaky" due to faulty BBB
PSR values are lower in recurrences than for radiation necrosis
Barajas R et al. AJNR Am J Neuroradiol 2009;30:367-372
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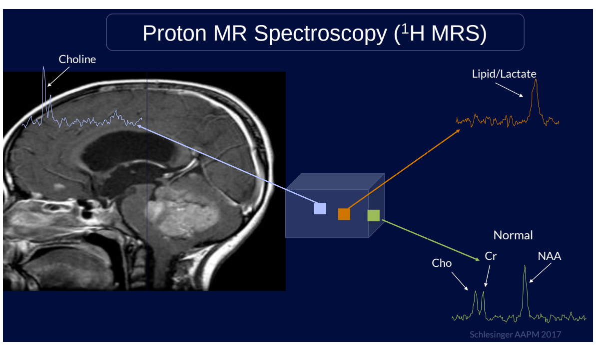
Proton MR Spectroscopy (^{1}H MRS)
Choline
Lipid/Lactate
Normal
Cho
Cr
NAA
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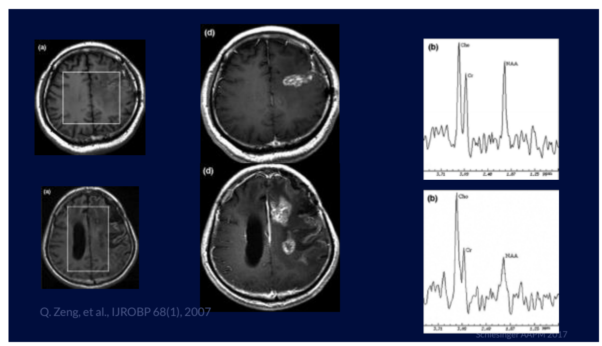
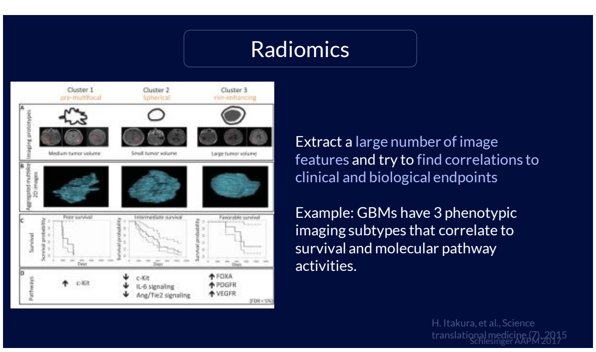

Q. Zeng, et al., IJROBP 68(1), 2007


Radiomics
Extract a large number of image features and try to find correlations to clinical and biological endpoints
Example: GBMs have 3 phenotypic imaging subtypes that correlate to survival and molecular pathway activities.
H. Itakura, et al., Science translational medicine (7), 2015
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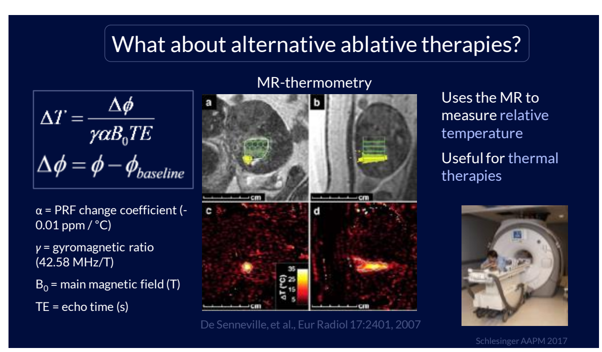
What about alternative ablative therapies?
MR-thermometry
$\Delta T = \frac{\Delta\phi}{\gamma\alpha B_0 TE}$
$\Delta\phi = \phi - \phi_{baseline}$
α = PRF change coefficient (-0.01 ppm / °C)
γ = gyromagnetic ratio (42.58 MHz/T)
B_0 = main magnetic field (T)
TE = echo time (s)
Uses the MR to measure relative temperature
Useful for thermal therapies
De Senneville, et al., Eur Radiol 17:2401, 2007
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Conclusions

- MR has long been an integral part of intracranial radiotherapy (especially SRS)
- Provides important anatomical and biological information
- It is critical to understand potential sources of uncertainty

Things I haven't talked about

- MR simulators
- MR Linacs
- Methods for creating "artificial CTs" and estimating HUs

The use of MRI in RT is only likely to increase!