MR image processing, registration, and planning for intracranial radiotherapy

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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

Why MRI?

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

MR for RT is trendy, but it is not new

T1 weighted MRI with contrast
CT with contrast
**Common MR-based TPS workflows**

**Stereotactic frame**

**Advantages**
- Classic SRS workflow
- Patient well-immobilized
- Possible to use CT to QA the MR
- Possible to do inhomogeneity corrections

**Disadvantages**
- No easy way to check for distortion
- No inhomogeneity correction
- MR pulse sequence limitations

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**MR with frame alone**

**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**

**Advantages**
- Patient well-immobilized
- Possible to use CT to QA the MR
- Possible to do inhomogeneity corrections

**Disadvantages**
- CT scan dose
- Imaging workflow time
MR without frame / CT with frame

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

DTI tractography along trigeminal nerve
Hodaie et al., Plos One, 7(3), 2012

Common MR-based TPS workflow
Frameless

Useful CNS Pulse Sequences

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

FLAIR: Fluid Attenuated Inversion Recovery
STIR: Short-Tau Inversion Recovery
Inversion pulse applied before excitation pulse, "zeros 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)

T2 SPACE image showing good visualization of CSF structures

FLAIR image of tumor and surrounding inflammation

Steady-state sequences (CISS/SPACE)

CISS: Constructive interference in steady state
SPACE: Sampling perfection with application-optimized contrasts by using different flip-angle evolutions
Use RF-pulses to refocus echoes and maintain a steady-state net magnetization
Creates bright CSF signal
Good for visualizing fine structures in CSF

T2 SPACE image showing good visualization of CSF structures

Volumetric interpolated sequences (VIBE)

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

VIBE image of a pituitary microadenoma

Specialized sequences: FGATIR

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

FGATIR image used for an OCD treatment


Volumetric interpolated sequences (VIBE)

Specialized sequences: FGATIR

A couple of useful tricks (there are others)

<table>
<thead>
<tr>
<th>Scans compared</th>
<th>% studies w ≥ 1 new lesion</th>
<th>95% CI</th>
<th>Range of # new lesions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan 1:2</td>
<td>35.3%</td>
<td>22.4%–49.9%</td>
<td>1–10</td>
</tr>
<tr>
<td>Scan 2:3</td>
<td>21.8%</td>
<td>11.3%–35.3%</td>
<td>1–9</td>
</tr>
<tr>
<td>Scan 1:3</td>
<td>43.1%</td>
<td>29.3%–57.8%</td>
<td>1–14</td>
</tr>
</tbody>
</table>

Contrast timing can be important!

M. Kushnirsky et al., JNS 124, 2016.
Use MIPs to help distinguish tumors and vessels

Images courtesy of University of Virginia

MR for intracranial radiotherapy

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QA specific to MR for intracranial radiotherapy

Emerging MR applications for intracranial RT

Procedural uncertainty = \[
\sqrt{(\text{Biology})^2 + (\text{Imaging})^2 + (\text{Beam Delivery})^2}
\]

You can’t localize targets perfectly

<table>
<thead>
<tr>
<th>Modality</th>
<th>Radial Deviation (mean ± STD) (mm)</th>
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<tbody>
<tr>
<td>CT</td>
<td>0.4±0.2</td>
</tr>
<tr>
<td>*MR (T1-weighted)</td>
<td>1.4±0.3</td>
</tr>
<tr>
<td>*MR (T2-weighted)</td>
<td>1.4±0.5</td>
</tr>
<tr>
<td>PET</td>
<td>1.1±0.5</td>
</tr>
<tr>
<td>†SPECT</td>
<td>1.6±0.5</td>
</tr>
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</table>

<table>
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<tr>
<th>Localization of known stereotactic targets with various modalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT, *MR (T1-weighted), *MR (T2-weighted), PET, †SPECT</td>
</tr>
</tbody>
</table>

Radiotherapy doesn’t require beautiful images

It requires anatomy to be located where it appears

…and images are not necessarily reality!

Motion artifact

Metal artifact

Chemical shift artifact


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**QA for MR geometric distortion**

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!

**Biology is not always predictable**

Radiation necrosis

Pre-SRS

16 months post


**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.

H+ diffusion CSF

H+ diffusion white matter

H+ diffusion tumor

Diffusion-weighted (DWI) imaging

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ADC map brain with brain metastasis

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

- 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)

Depicted is a T2* time curves graph with a shaded area representing rCBV.

Graphs inspired by a presentation by Max Wintermark.


Recurrent metastatic tumors are more "leaky" due to faulty BBB
PSR values are lower in recurrences than for radiation necrosis


Proportion MR Spectroscopy (1H MRS)

Choline, Lipid/Lactate, NAA, Normal, Cr

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

Radiomics

- MR-thermometry
  - Uses the MR to measure relative temperature
  - Useful for thermal therapies

H. Itakura et al., Science translational medicine (7), 2015

De Sennesville et al., Eur Radiol 17:2401, 2007

What about alternative ablative therapies?

\[ \Delta T = \frac{\Delta \phi}{\gamma B_0^2 TE} \]

- \( \Delta \phi \) = PRF change coefficient  (0.01 ppm/°C)
- \( \gamma \) = gyromagnetic ratio (42.58 MHz/T)
- \( B_0 \) = main magnetic field (T)
- \( TE \) = echo time (s)
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 HU’s

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