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Acknowledgements
- TG-117 “Use of MRI Data in Treatment Planning and Stereotactic Procedures – Spatial Accuracy and Quality Control Procedures”
  - Deb Brinkmann, chair
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Outline
- MR in Radiation Treatment Planning (RTP)
- Spatial accuracy of MR images
- Impact of Scanner (strength / configuration)
- Impact of Pulse Sequence / Parameters
- Distortion assessment / QC

MR in RTP

Overview – MR in RTP
- Advances in planning and delivery necessitate **improved target delineation**
  - MR – soft tissue contrast

Overview – MR in RTP
- MR - **Functional / biological information**
  - Further improve target definition / extent
  - Target severity with dose

Khoo, 2006 BJR
Chang, 2006 MedPhys
Overview – MR in RTP

- Image registration
  - To correlate MR-delineated structures to CT

Spatial Accuracy

Spatial Distortions

- Can be ≥ 1cm
- Scanner-Dependent Distortions
  - External Magnetic Field – Inhomogeneity, Environmental Gradients – Nonlinearities, Scale Factor Errors, Eddy Currents
  - RF – Slice Profile
- Patient/Object-Induced Distortions
  - Chemical Shift
  - Magnetic Susceptibility

Spatial Accuracy

- Scanner-dependent distortions
  - Result of:
    - Design compromises
    - Imperfections
    - Drifting / failure of specific components
  - Constant
    - Across multiple imaging sessions
    - Allows for regular testing

Spatial Accuracy

- External magnetic field inhomogeneities:
  - Desire high uniformity over entire volume
    - For linear relationship b/w space & frequency
  - Perfect uniformity not technically feasible
    - Imperfections change resonant frequency
  - Result spatial misregistration

Shimming to improve B0 homogeneity:

- Passive shims (pieces of metal in bore)
  - Installed during initial calibration
- Active shims (superconducting shim circuits)
  - Adjusted at calibration, preventative maintenance
- Resistive shims (linear, non-linear shim circuits)
  - Adjusted during imaging
  - Shim imaging volume vs. whole field
  - Non-linear efficacy - application dependent
Spatial Accuracy

- **External magnetic field inhomogeneities:**
  - Homogeneity maintained over finite spherical volume
  - Vendor specification: DSV (diameter of spherical volume)
  - Imaging outside of DSV subject to distortions
  - Shift depends on strength of applied gradient
  \[ x = \frac{\mu B_0}{\gamma} \]

Spatial Accuracy

- **Environmental Magnetism:**
  - Electromagnetic shielding used in site design
  - Stray magnetism can affect MR acquisition
  - Example:
    - Garbage truck near scanner
    - Iron in truck magnetized
    - Affected B0 homogeneity
    - Result: severe distortion

Spatial Accuracy

- **Gradient Nonlinearities:**
  - Spatial encoding achieved with gradients
    - Linearly mapping position with frequency
  - Deviations from linearity due to:
    - deviations in rise time
    - peak amplitude
    - physical design
  - Deviations \( \uparrow \) with distance from isocenter

Spatial Accuracy

- **Convolutional 2D sequences:**
  - “pin-cushion” or “barrel” effect in-plane
  - “potato chip” effect on image plane
  - “bow-tie” effect on slice thickness

Spatial Accuracy

- **Gradient Nonlinearities:**
  - Example: warping in-plane
  - Example: warping along slice select direction

Environmental Magnetism:

- Electromagnetic shielding used in site design
- Stray magnetism can affect MR acquisition
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  - Affected B0 homogeneity
  - Result: severe distortion

With Garbage Truck

Without Garbage Truck

Example

- detected impact from steel beams for construction placed near MR suite

Importance of QC:

- More subtle effects might not be apparent
- QC procedures needed to catch such errors
  - Example – detected impact from steel beams for construction placed near MR suite

Gradient Nonlinearities:

- Spatial encoding achieved with gradients
  - Linearly mapping position with frequency
- Deviations from linearity due to:
  - deviations in rise time
  - peak amplitude
  - physical design
- Deviations \( \uparrow \) with distance from isocenter
Spatial Accuracy

- **Gradient Nonlinearity Corrections:**
  - Vendors provide in-plane corrections
  - Assume distortion to gradient amplitude is constant
  - Quantitate distortion with phantom
  - Apply to reconstructed images after patient data acquired
  - *Some but not all* vendors provide corrections along slice encoding axis

Spatial Accuracy

- **Eddy Currents:**
  - Generated in conducting materials...
    - Metal dewer, gradient coils, RF coils
  - ... exposed to time varying magnetic field
    - Faraday's law of induction
    - Changing gradient fields
  - Creates perturbing magnetic field
    - Lenz's law
    - Result – spatial distortion
  - Vendors provide some correction method

Spatial Accuracy

- **RF non-uniformity:**
  - RF energy generates a detectable signal
    - Delivered as a pulse (RF pulse)
  - Design criteria for RF waveform
    - Exact shape variable
    - May not be designed to maintain uniform signal
    - Issue for advanced techniques
  - Gradient linearity also impacts slice profile
    - Evaluate RF profile to verify width

Spatial Accuracy

- **Patient/object-induced distortions**
  - Result of:
    - Composition of patient or object
  - Unique:
    - Can vary dramatically b/w patients
    - Must be considered for each imaging situation

Spatial Accuracy

- **Chemical shift** (of the first kind):
  - Produces shift in resonant frequency
    - E.g. 220 Hz decrease for 1.5 T ($\omega_0 = 63.8$ MHz)
  - Misregistration when BW/pixel < chemical shift
  - Manifest along frequency encoding direction
  - Produces banding
    - Banding – only lipid signal shifted for voxels with mixed composition
Spatial Accuracy

**Chemical Shift of the first kind**

- Magnetic Susceptibility:
  - Relates net magnetization to the applied magnetic field
  - Materials in magnetic field become magnetized
  - Creates changes in magnetic field at interfaces
  - Complex, depending on many factors:
    - Susceptibility difference across interface
    - Shape and orientation of the interface with B0
    - Strength and polarity of gradients

**Magnetic Susceptibility**

- Perturbations produce distortion, signal loss
- Relatively small for soft tissues
- Undetectable for many applications
- Difference b/w tissue & air: ~ $9 \times 10^{-6}$
  - Air-tissue interfaces for air cavities
  - External surface of patient

**Impact of Scanner**

- Difference between metal and tissue is large
- E.g., titanium
  - ~ 20 times larger than soft tissue

*Courtesy of Kieran McGee

*Schenk, Med Phys 1996
**Impact of Scanner**

- **Design includes compromises & trade-offs**
  - No single design for all performance specifications
  - Systems optimized to meet subset of applications
- **MR data for use in RTP**
  - Each scanner used should be characterized
- **The physicist needs**
  - Understanding of distortion sources
  - Ability to quantitate image distortion

**Field strength options:**
- **LOW field strength advantages:**
  - Smaller patient-induced distortions
  - Artifacts from metal objects (e.g., brachytherapy)
- **HIGH field strength advantages:**
  - Better signal-to-noise (image quality)
  - Better resolution for metabolites (MRS)

**OPEN magnet:**
- **Advantages**
  - Flexibility in patient positioning
  - Increased patient access
- **Drawbacks**
  - Significant external field inhomogeneities
  - Some scanner-dependent distortions

**NARROW, CYLINDRICAL LONG bore:**
- **Advantages**
  - High performance systems (e.g., cardiac)
  - High resolution imaging (e.g., CNS)
- **Drawbacks**
  - Narrow bore
  - Patient comfort

**WIDE, SHORT bore:**
- **Advantages**
  - Increased magnet aperture
  - Treatment position
  - Relatively claustrophobia
- **Drawbacks**
  - Sacrifice performance, field homogeneity, field strength
  - Decreased homogeneity → increased distortion
**Impact of Sequence**

- **Sensitivity to distortion:**
  - Gradient echo sequences
    - Most sensitive to distortion sources
    - Inhomogeneity effects accumulate throughout acquisition
  - Conventional spin echo sequences
    - 180° refocusing pulse reduces distortion
  - Fast spin echo sequences
    - Least sensitive to off-resonance effects
    - Multiple 180° refocusing pulses and short TEs

- **Advanced acquisition techniques:**
  - Majority rely on “echo planar imaging” or EPI
  - EPI techniques collect a train of echoes
  - Uninterrupted accumulation of phase
  - Very sensitive to field inhomogeneities and eddy current effects
    - PE: severe shifting or compression of objects
    - FE: shearing of object
  - Object induced inhomogeneities
    - Considerable local distortions
    - Distortions ↑ with increasing field strength

**Impact of Sequence Parameters**

- **3D vs. 2D sequences:**
  - For standard rectilinear imaging, spatial distortion due to resonance offsets:
    - Manifest along the frequency encoding axis
    - Phase encoding direction not affected
  - 3D acquisitions use phase encoding along slice encoding direction
    - Less distortion for 3D vs. equivalent 2D acquisitions

- **Bandwidth per pixel:**
  - ↑ BW minimizes resonance offsets
  - Field inhomogeneity, chemical shift, magnetic susceptibility
  - If Δf > BW/pixel, shift will result
  - Magnitude depends on pixel dimensions
  - Trade-off: BW will ↑ SNR
  - \( \text{SNR} \propto (\text{voxel vol.} \times \sqrt{N_y \times NEX / BW}) \)

**BW / pixel for Patient-Induced Distortions:**

- Distortions ↑ with increasing field strength
- Distortions ↑ with decreasing BW/pixel
- \( \Delta f = \gamma B_0 \delta_{ppm} \) (3.5ppm for CS, 9.0ppm for MS)
- \( \# \text{ pixels} = \Delta f / (BW/\text{pixel}) \)
  - (depends on pixel dimensions)

**Impact of Sequence Parameters**

- **Spatial resolution:**
  - Magnitude depends on pixel dimensions
  - Typical pixel resolution .75 – 1.5 mm/pixel
  - Higher resolution reduces physical dimension of shift
    - ↓ FOV will ↑ resolution
  - Trade-off: ↑ resolution will ↓ SNR
    - \( \text{SNR} \propto (\text{voxel vol.} \times \sqrt{N_y \times NEX / BW}) \)

*Note: All graphical elements and diagrams are included inline as part of the text.*
Impact of Sequence Parameters

- **Lipid Suppression:**
  - Lipid signal can be nulled
    - If not clinically relevant
    - To eliminate chemical shift effects
    - Both kinds of chemical shift artifacts
  - Several imaging techniques
    - Spectral saturation
    - Inversion recovery
    - Dixon technique

- **Spectral selective saturation pulses**
  - Uses RF pulse to saturate spins precessing at resonant frequency of fat
  - Affected by poor shimming:
    - Incomplete fat saturation
    - Inadvertent suppression of water

Impact of Sequence Parameters

- **Frequency Encoding Direction:**
  - Resonance offsets manifest along frequency encoding direction
  - Can manipulate to visualize such distortions (in-plane)
    - Repeating scan with reversed gradient
    - Repeating scan swapping frequency & phase
  - Cost – additional scan

Assessment / QC

- **Current Guidance**
  - AAPM and ACR have published acceptance test and QC documents
  - Do not address necessary QC program and image acquisition optimization goals when MRI data used for procedures in which spatial accuracy is critical

Distortion Assessment / QC
Assessment / QC

- ACR Weekly QC protocol
- Geometric accuracy criteria
  - ≤ 2mm over 148mm x 190mm

Courtesy of Kieran McCaw

Assessment / QC

- Works in Progress
- TG-117: Use of MRI Data in Treatment Planning and Stereotactic Procedures – Spatial Accuracy and QC Procedures
  - Review physical bases for spatial accuracy limitations in MRI
  - Provide guidance with examples for reducing or eliminating the effects of distortion
  - Propose QC tests for systems used for applications requiring high spatial accuracy

Assessment / QC

- Step 1: Identify Application Requirements
  - Volumetric coverage (FOV, craniocaudal extent)
  - Spatial resolution (voxel dimensions)
  - Spatial accuracy (tolerance, volume)
  - Bore diameter, RF coils (tx position)
  - MR compatibility of immobilization, applicators
  - Pulse sequence(s) (contrast)

Assessment / QC

- Step 2: Inventory Equipment and Resources
  - Scanner capabilities
    - Identify magnet, gradients, coils, sequences needed to achieve required performance specifications
    - Existing scanner? Upgrades needed? New system?
  - Phantoms for geometric distortion assessment
    - Acceptance / commissioning tests
    - Routine QC
  - Analysis tools (IT support for programming, networking)

Assessment / QC

- Step 3: Quantitate System Performance
  - Baselines (Acceptance / Commissioning)
  - Characterize scanner subsystems
    - External magnetic field (homogeneity)
    - Gradients (linearity, correction algorithms, eddy current compensation...)
    - RF (slice profile)
**Assessment / QC**

**Step 3: Quantitate System Performance**
- Existing tests (ACR, AAPM)
  - Purpose: maintain diagnostic image quality
  - Do not assess spatial fidelity over RTP volumes
  - Can be used with modifications
    - Assess over the desired imaging volume
    - Using application specific imaging parameters

**Step 4: Performance Adequate?**
- Application requirements identified
- System characterized
  - Over volume of interest
- Quantitate System Performance

**Step 5: Establish QC program**
- Measure scanner dependent distortions
  - Phantom of known geometry
  - Verify constancy of spatial fidelity
    - Drifting, failure
    - Environmental magnetism
  - Over the volume of interest

**Application Specific Protocol Optimization**
- Signal suppression techniques
- Gradient echo vs. Spin echo

**Environmental magnetism**
- Drifting, failure

**QC phantom**
- Identify / modify / develop application-specific QC phantom
- Or report unacceptable accuracy
- Modify application? Upgrade scanner? Or report unacceptable accuracy

**Supervising Physician**
- Report Findings to
  - Review feasibility of pursuing application
  - Initiate modification/upgrade & re-evaluate

**Application Upgrade**
- Yes
- No

**FOV, in-plane resolution**
- at least 5 pixels

**MR Data for Treatment Planning**
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Establishing a QC program
- Establish imaging protocol
- Determine testing frequency
- Develop analysis tools
  - Automated evaluation
  - Automated reporting
- Establish procedures when QC fails

Summary
- Spatial fidelity in MR images
  - Source of geometric distortions
  - Impact of scanner characterization
  - Impact of image acquisition parameters
  - Vendor supplied correction methods
- Importance of assessing distortions
  - Over the volume of interest
  - With the same parameters to be used clinically
- Importance of appropriate MR QA program