MR Data for Treatment Planning: Spatial Accuracy Issues, Protocol Optimization, and Applications (Preview of TG117 Report)

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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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  - Ed Jackson
  - R. Jason Stafford
  - Steve Goetsch

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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**

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MR in RTP

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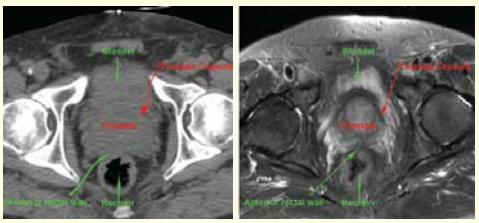
Overview – MR in RTP

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



Khoo, 2006 BJR

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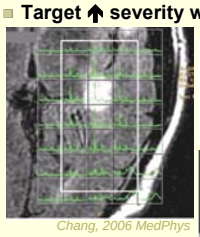
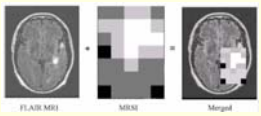
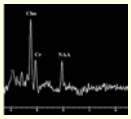
Overview – MR in RTP

- MR - **Functional / biological information**
  - Further improve target definition / extent
  - Target ↑ severity with ↑ dose



Chang, 2006 MedPhys





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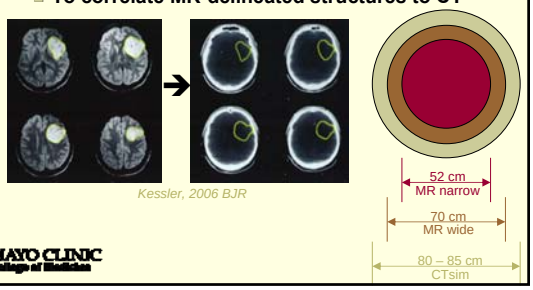
Overview – MR in RTP

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



Kessler, 2006 BJR

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Overview – MR in RTP

- **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**

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Spatial Accuracy

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Spatial Accuracy

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

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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**

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Spatial Accuracy

- **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**

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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**

$$x = \frac{\omega/\gamma - B_0}{G_x}$$

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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**

With Garbage Truck

Without Garbage Truck

Courtesy of Kiaran McGee

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Spatial Accuracy

- **Environmental Magnetism:**
- **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**

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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 ↑ with distance from isocenter**

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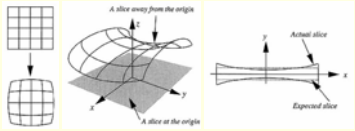
Spatial Accuracy

- **Gradient Nonlinearities:**
- **Conventional 2D sequences:**
  - **"pin-cushion" or "barrel" effect in-plane**
  - **"potato chip" effect on image plane**
  - **"bow-tie" effect on slice thickness**



Sumanaweera, Neurosurg 1994

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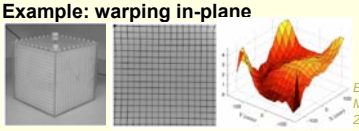
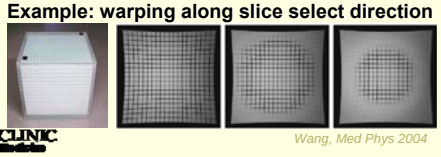
Spatial Accuracy

- **Gradient Nonlinearities**
  - **Example: warping in-plane**



Baldwin, Med Phys 2007

  - **Example: warping along slice select direction**



Wang, Med Phys 2004

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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

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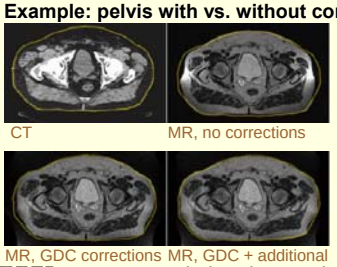
Spatial Accuracy

- **Gradient Nonlinearities**
  - Example: pelvis with vs. without corrections



CT | MR, no corrections

MR, GDC corrections | MR, GDC + additional point-by-point corrections

Chen, Med Phys 2006

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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

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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

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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

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Spatial Accuracy

- **Chemical shift** (of the first kind):
- Produces shift in resonant frequency
  - E.g. 220 Hz decrease for 1.5 T (ω_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

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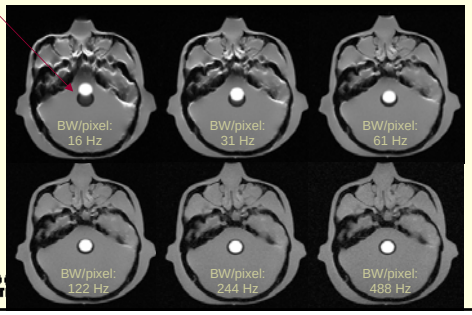
Spatial Accuracy

Chemical Shift of the first kind



Spatial Accuracy

- **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

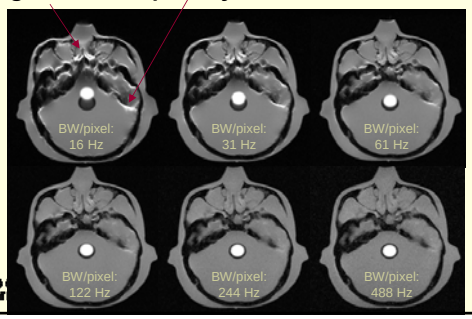
Spatial Accuracy

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

*Schenk, Med Phys 1996

Spatial Accuracy

Magnetic Susceptibility



Spatial Accuracy

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

Courtesy of Kiaran McGee

*Schenk, Med Phys 1996

Impact of Scanner

Impact of Scanner

- Design includes compromises & trade-offs
  - No single design for all performance spec's
  - 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

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Impact of Scanner

- **Field strength options**:
  - **0.2 - 1.0 T** ("Open", permanent or resistive magnet)
  - **1.5, 3.0 T** (Cylindrical bore, superconducting magnet)
- LOW field strength advantages:
  - ↓ patient-induced distortions
  - ↓ artifacts from metal objects (e.g. brachytherapy)
- HIGH field strength advantages:
  - ↑ signal-to-noise (image quality)
  - ↑ resolution for metabolites (MRS)

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Impact of Scanner

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

www.gehealthcare.com
GE 0.7T OpenSpeed

www.medgear.org
Phillips 1.0T Panorama
MR simulator

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Impact of Scanner

- **NARROW, CYLINDRICAL LONG bore**:
  - High performance systems (e.g. cardiac)
  - High resolution imaging (e.g. CNS)
- Advantages
  - Increased field homogeneity
  - ↓ scanner-dependent distortions
- Drawbacks
  - Narrow bore
  - ↓ patient comfort

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Impact of Scanner

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

www.medical.siemens.com
Siemens 1.5T Espree
Wide / short bore

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Impact of Sequence

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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

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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

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Impact of Sequence

- **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

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*Mansfield, Br J Radiol 1978

Impact of Sequence Parameters

- **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
  - SNR ∝ (voxel vol. × √ Ny × NEX / BW)

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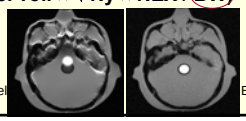
BW/pixel: 16 Hz

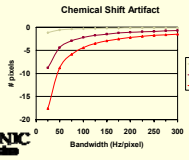


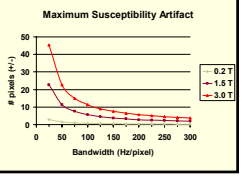
BW/pixel: 488 Hz

Impact of Sequence Parameters

- **BW / pixel for Patient-Induced Distortions:**
  - Distortions ↑ with increasing field strength
  - Distortions ↑ with decreasing BW/pixel
  - $\Delta f = \gamma \cdot B_0 \cdot \partial_{ppm}$, (3.5ppm for CS, 9.0ppm* for MS)
  - **# pixels = Δf / (BW/pixel)** (depends on pixel dimensions)

*Schenk, Med Phys 1996





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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
  - SNR ∝ (voxel vol. × √ Ny × NEX / BW)

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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

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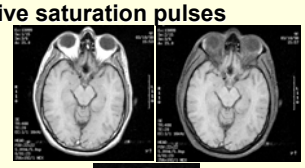
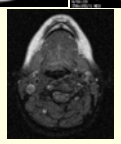
Impact of Sequence Parameters

- **Lipid Suppression:**
- Spectrally selective saturation pulses
  - Uses RF pulse to saturate spins precessing at resonant freq-uency of fat
  - Affected by poor shimming:
    - Incomplete fat saturation
    - Inadvertent suppression of water





Courtesy of Kiaran McGee

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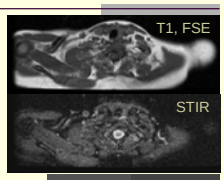
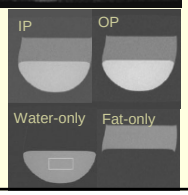
Impact of Sequence

- **Lipid Suppression:**
- Inversion recovery techniques (STIR)
- Dixon technique
  - Requires multiple data acquisitions (two TE)
  - Lipid & tissue signals in and 180° out of phase
  - Add / subtract for lipid- and tissue-only images





J Ma, JMRI 2006

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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

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Distortion Assessment / QC

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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

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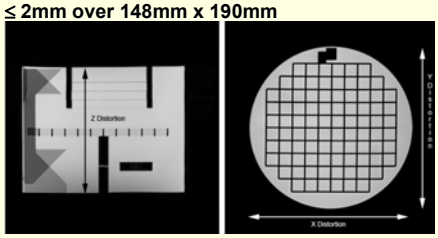
Assessment / QC

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



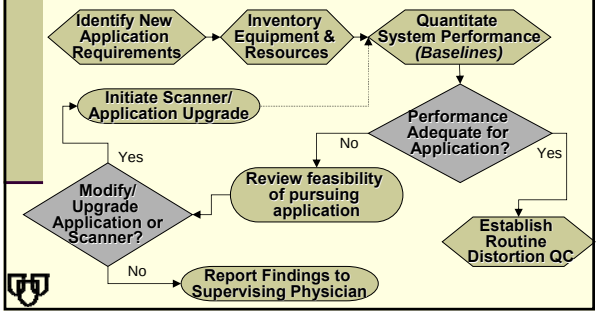
Courtesy of Kiaran McGee

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

- **Assessment/QC for new application**



Assessment / QC

- **Step 1: Identify Application Requirements**
- **Volumetric coverage** (FOV, cranio-caudal 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**

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Assessment / QC

- **Step 3: Quantitate System Performance**
- **Application Specific Protocol Optimization**
  - **2D vs. 3D**
  - **FOV, in-plane resolution**
  - **Gradient echo vs. Spin echo**
  - **Signal suppression techniques**

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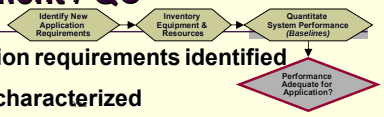
Assessment / QC



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

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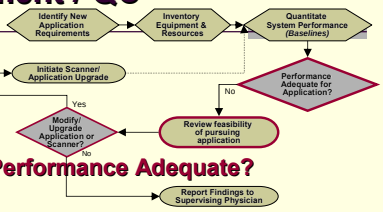
Assessment / QC



- **Step 4: Performance Adequate?**
  - **If not:**
    - **Modify application? Upgrade scanner?**
      - Initiate modification/upgrade & re-evaluate
    - **Or report unacceptable accuracy**

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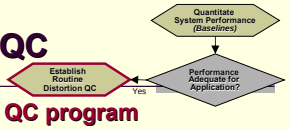
Assessment / QC



- **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**

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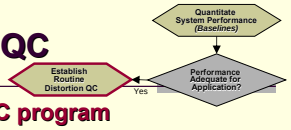
Assessment / QC



- **Establishing a QC program**
- **Distortion phantom for routine QC**
  - **Define the QC phantom requirements**
    - **Volume to test over**
    - **Fiducial spacing**
    - **Fiducial resolution** (in-plane ≥ 5 pixels)
    - **Dimension compatibility** (RF coil, stereotactic frames, immobilization)
  - **Identify / modify / develop application-specific QC phantom**

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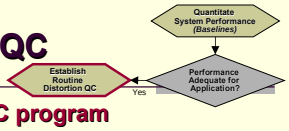
Assessment / QC



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

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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

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