

## Magnetic Resonance Imaging 2.0

David R Pickens, PhD

Department of Radiology and Radiological Sciences  
Vanderbilt University Medical Center  
Nashville, Tennessee



Disclosures for DRP: None



### Outline

- The medical physicist's future role in clinical MRI
- Measurements and metrics
  - Current
  - Improved and focused testing
- New clinical technologies
  - Challenges and new requirements
- Clinical integration
  - Regulatory requirements and training needs
  - Automating routine QC and improving system performance
  - Expanding interactions with technologists and radiologists



### The Current Role of the Qualified Medical Physicist in MR Imaging

- Quality assurance for imaging systems
  - On-going quality evaluation
- Certification, accreditation, regulatory compliance
  - ACR, IAC, TJC testing
- Image quality and artifact evaluation
- Training/education
  - Residents, med phys students, technologists, radiologists
- Advisors for purchase, installation, and upgrades
- Pulse sequence optimization and development
- Patient and personnel safety



### The Expanded Role of the Clinical Medical Physicist in MR Imaging

- Continue doing our current work, *but...*
- Integration of the medical physicist into the imaging team
  - Provide ongoing and continuous advice for using new systems safely and effectively
  - Provide ongoing recommendations on analysis of advanced quantitative datasets
  - Provide new ways to ensure image quality with advanced automated quality assurance testing and reporting
  - Provide improved ways of ensuring optimized performance across multiple systems
  - Provide awareness of evolving standards and performance requirements



### Characterization of Advanced Systems Performance



## Traditional MRI System Testing

- Magnet, gradient, and RF subsystem tests
- Signal-to-noise ratio (system)
- Percent image uniformity (system)
- High contrast spatial resolution (system)
- Low contrast detectability (system)
- Percent signal ghosting (system)



ACR QA Phantom

Acceptance Testing and Quality Assurance Procedures for Magnetic Resonance Imaging Facilities. AAPM Report 100; 2010



## Metrics for Advanced Systems

- Current methods provide base-line performance check
  - limited with respect to new technologies
- Evolving systems require new techniques for determination of
  - Signal-to-noise ratios
  - Uniformity
  - Geometric distortion
  - Stability over time
  - Repeatability
- Metrics for hybrid imaging systems
- Methods required for quantitative MRI



## Expanded MR System Evaluation in the Clinic

- Dictated by complex acquisition paradigms with quantitative results
  - fMRI
  - DCE-MRI
  - DWI and DTI
  - Cardiac
  - Interventional
  - Ultrafast imaging
  - Spectroscopy: proton and other metabolites
- Dictated by new hardware capabilities
  - Treatment systems with high intensity ultrasound
  - Ultrahigh field imaging
  - Multi-channel parallel (receive) imaging
  - B1 shimming
  - Multi-channel RF excitation
- Dictated by the need for consistent information across systems



## Issues in Advanced Quantitative MR Imaging

- Imaging accuracy
  - How much variance in rescanning same phantom on same system
- Imaging reproducibility
  - How much variance between different systems
- Imaging bias
  - Are phantom results from one vendor's system matched to another
- Patient accuracy
  - How much variation with repeated scans on same patient with no physiological changes



Jackson EF, et al. Trans. Onc. (2009) 2, 211-215

## Important Measurements in Expanding Uses of Parallel imaging

- Noise between coil elements in parallel imaging: spatially heterogeneous noise propagation
  - Directly affects SNR in images
  - Problem with major differences in coil noise
  - Problem with correlated noise in multiple coils
  - Described with noise covariance matrix in receive channels
- SNR depends on acceleration factor R
  - g-factor (geometry factor  $\geq 1$ ) for both SENSE and GRAPPA accounts for noise variation affecting SNR
  - $SNR_R = SNR_g / (g \cdot \sqrt{R})$



Dietrich O, et al. JMRI 26:375-385 (2007)  
Hansen MS and Kellman P. JMRI (2014)

## SNR in Parallel Imaging

- ACR method is applicable systems exhibiting Rician noise distributions
- Parallel systems' noise is not Rician; conventional measurements of SNR are not accurate
- Noise distributed in spatially varying ways
- Difficult to compare image quality for different protocols or different systems
- Correction measures from manufacturers alter the noise characteristics



Spherical phantoms  
–17 cm and –26 cm

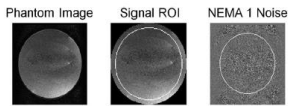


### Advanced SNR Measurement for Parallel Imaging

- NEMA method 1 using spherical phantom
- Signal and noise found from image pairs
  - ROI from average of two 5 minute apart images gives signal
  - Noise image comes from subtraction of two images
  - SD is the noise corrected for non-Gaussian distribution

$$SD = \left[ \frac{\sum_{i=1}^n \sum_{j=1}^{m_i} (R(i,j) - \bar{R})^2}{\sum_{i=1}^n (m_i) - 1} \right]^{1/2}$$

R bar = average of ROI  
R(i,j) = individual pixel  
n, m are pixel row and column




Phantom Image    Signal ROI    NEMA 1 Noise

Goerner FL and Clarke GD. Med. Phys. 38(9), 2011.

### Uniformity Measurements in Parallel Imaging

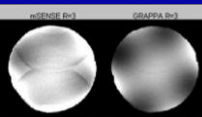
- Spatially dependent sensitivities due to geometries and sensitivities of RF coils
- Correction methods improve intensity uniformity and SNR
- Modified NEMA method 2: gray scale uniformity map
- Works with various parallel imaging approaches
- Most consistent for describing decreased uniformity with increasing R (acceleration factor)
- Spherical phantom 17.8 cm diameter, EPI acquisition




Goerner FL et.al. Med. Phys. 40(8), 2013

### Advanced Measurement of Uniformity for Parallel Imaging

- Pixels binned into 5 assigned gray level representations (A – E) based on comparison to mean, S<sub>i</sub> in a 75% ROI
- Each pixel value, I, assigned to bins
  - A → I ≤ Sx0.8, B → Sx0.8 < I ≤ Sx0.9, C → Sx0.9 < I ≤ 1.1
  - D → Sx1.1 < I ≤ Sx1.2, E → Sx1.2 ≤ I
- Grouped into G0 (bin C), G1 (B+D), G2 (A+E)
- Groups contain number of pixels within 10% of mean, between 10% and 20%, and > or < 20% of mean
- Percent image uniformity from number of pixels in each group:
  - UN2 = 100(1 - (0.5 · G1 + G2))



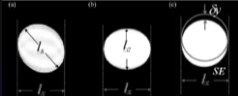


mSENSE Bin1    GRAPPA Bin1



Goerner FL et.al. Med. Phys. 40(8), 2013

### Other Advanced MRI System Tests


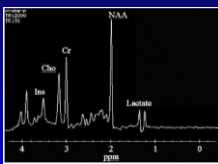

- Ultrafast imaging (EPI)
  - EPI ghosting (N/2 or Nyquist ghosts)
    - Spherical homogeneous phantom
    - Zeroth-order or first-order phase shifts
    - Calculation of ghosting ratio
      - Not to exceed 3% for single shot spin-echo EPI
  - Geometric distortion
    - Spherical homogeneous phantom
    - Distortion measured in frequency encoding direction
    - Measurements of shear, compression or dilation, and image shift
  - Stability
    - Acquire phantom data over extended time
    - Signal, ghosting intensity, ghosting ratio
    - Compute coefficient of variation for signal intensity (<0.25% for 1.5T when fMRI changes are 1-4%)

Acceptance Testing and Quality Assurance Procedures for Magnetic Resonance Imaging Facilities. AAPM Report 100; 2010

### MR Spectroscopy Tests: Testing for Routine Clinical Use

- VOI location accuracy
  - Prescribed and imaged VOI should be +/- 1.0 mm
- Spectral quality tests
  - Tissue mimicking phantom
    - Check water suppression
    - Check eddy current correction, if available
    - Check fitting of Lorentzian peaks to spectral peaks
    - Check global water peak FWHM (<7 Hz)
    - Check SNR of spectrum (phantom specific)

Acceptance Testing and Quality Assurance Procedures for Magnetic Resonance Imaging Facilities. AAPM Report 100; 2010

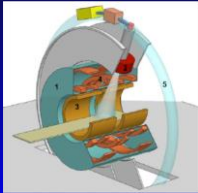
### Clinical Physics and New Technologies




### Emerging MRI Systems Configurations: New Areas of Medical Physics Involvement

- Dedicated MRI systems
- Increasing field strengths
  - 3 T systems
  - ≥ 7 T ultrahigh field systems
- Higher performance gradients
- Increasing RF performance
  - High field power deposition
  - New RF transmitting methods
- Hybrid Systems
  - PET/MR
  - SPECT/MR
- Therapeutic/interventional/surgical systems
  - MRgHFUS
  - MRI-LINAC

UMC Utrecht, The Netherlands  
6MV LINAC  
1.5T magnet  
Simultaneous operation




Raaymakers BW, et al.  
PMB 54(2009) N229-N237




### Measurement of Ultrahigh Field System Characteristics

- Importance of magnetic field measurements at high and ultrahigh fields
  - Fringe fields
  - Static gradients
- New concerns about RF levels
  - Power deposition/SAR
  - RF uniformity
- Acoustic noise concerns
- New tools required

METROlab™ Three-axis Hall magnetometer. Calibrated to 14T







### Importance of SAR Measurements

- SAR increases ~quadratically with field strength
- Vendor estimation methods proprietary and often overestimate SAR in current systems
- Poor estimation can restrict pulse sequences
- Scanner SAR values not useful for RF exposure testing for implanted devices, peripheral areas, or interventional
- Independent monitoring and simulation systems needed for safety and clinical applications
- Proposed RF dosimeters to measure average SAR independent of vendor

Johns Hopkins RF dosimeter



Qian D et al. Med Phys 40 (12) December 2013



### Parallel RF Transmission Systems

- Very important at ultrahigh fields
  - Coil performance a function of object being imaged
  - Different sessions, different results
- Different parallel transmission methods
  - Beam steering approaches (RF shimming)
  - Full temporal independence between array waveforms—analogue to parallel receive
- Parallel transmission
  - Needs sequential calibration
  - Power deposition must be controlled locally over entire sample
  - More difficult requirements for safety validation and control
  - Potentially severe consequences

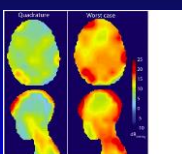



Figure 4: Comparison between the local SAR deposition caused by quadrature excitation and the worst case RF deposition in a closed head array.


D. O. Brunner, ISMRM 2011 Workshop on High Fields. www.ismrm.org, accessed 11-Oct-2013



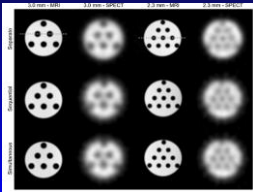
### Hybrid Imaging Systems

- PET/MRI, SPECT/MRI (pre-clinical)
  - Currently available; expensive
  - More widespread in the future
  - New area of expertise for most MR-oriented medical physicists

PET/MRI System




healthcare.siemens.com  
Accessed 14-Nov-2013



Resolution phantoms that function for both modalities  
Flood field correction need for SPECT  
Careful evaluation of shim settings need for MRI  
SNR affected by SPECT components

Hamaura MJ et al. Phys. Med. Biol. 55 (2010) 1563-1575

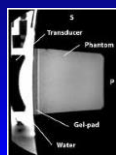
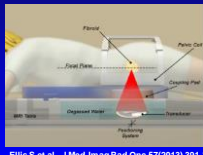


### MR Guided High Intensity Focused Ultrasound (MRgHIFU)


- High power focused ultrasound for treatment in MR imaging field
- MR system monitors treatment location, temperature of the treated area
- Specialized phantoms for testing thermal recording capability, treatment, and for imaging
- Used for uterine leiomyomas, bone metastases, brain tumors in clinical trials
- Future applications in prostate, liver, and breast

Soft tissue phantom

Partanen et al. In CP1113: 8<sup>th</sup> Internat. Symp. On Therapeutic Ultras. 2009. Ed. by S. Ebbini; AIP.

Ellis S et al. J Med Imag Rad Onc 57(2013) 391-399



## New Pulse Sequences and Acquisition Methods

- Non-Cartesian acquisitions for dynamic and real-time imaging with parallel coils systems
- Improved spatial accuracy for MRI-based treatment planning
- New quantitative acquisition methods
- Bio-marker and hyper-polarized gas imaging
- Multi-array transmit/receive systems
- MR spectroscopic imaging at ultrahigh fields
- Incorporation of realtime interventional capabilities

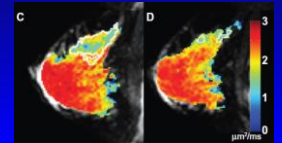


## Quantitative MRI

- Quantitative values from MR acquisitions
  - Disease staging
  - Pharmaceutical efficacy
  - Therapy treatment planning
- Higher performance needed than qualitative imaging
- Highly specialized phantoms needed
- Standardization and calibration required
- Significant physics support necessary

DW-MRI: breast cancer patient undergoing neoadjuvant therapy. White area in C: pretreatment. White area in D: post-treatment.

Abramson RG, et.al. Breast Cancer: Targets and Therapy 2012;4:139-154.



## The MR Medical Physicist in the Clinic

## Regulatory Issues of Ultrahigh Field MRI

- International Electrotechnical Commission (IEC)
  - Static field exposure varies by nation
    - UK maximum exposure is 2T
    - Australia maximum is 5T
  - “dose limits” reduce acceptable exposure time/day
- International Commission on Non-ionizing Radiation Protection (ICNIRP)
  - Guidelines recommend flux density of 2T peak
  - Time varying electrical and magnetic fields (1Hz to 100kHz)
- Effect of EU Physical Agents Directive 2013/35/EU on exposure to electromagnetic fields.
- FDA in the U.S. defines significant risk with MRI systems
  - 8 T or greater: adults, children, infants > 1 month
  - 4 T: infants 1 month old or less (neonates)
- Various issues are likely to concern the medical physicist in new installations of ultrahigh field systems



## Safety and Comfort Issues: Concerns at Ultrahigh Fields

- Sources of patient discomfort
  - Noise at high fields
  - Bio-effects from high field systems (electric and static fields)
- Sources of concern for staff
  - Long term exposure to high fields and static gradients
  - Concerns with stressful environment
  - Concerns with intra-room noise
- Implanted device concerns: patients and staff
- Medical physicist responsible for understanding the ultrahigh field environment and addressing concerns of patients and staff



## Occupational Measurements: Responsibility of the Medical Physicist

- Static field measurements
- Time-varying gradient fields
  - Search coil or 3 axis coil system for vector measurement
  - Integrator for magnetic flux density
- Dosimeters for staff
  - Hall effect sensors, induction coils, integrators
  - Dose metrics
    - Peak static field
    - TWA (time-weighted average) static field
    - Field-time product and instantaneous and peak dB/dt



## Education and Training For the MR Medical Physicist

- Monitoring systems and software
  - RF modeling and monitoring
  - Sound levels, RF levels, and static field gradients
  - SAR simulation programs
- New pulse sequences and equipment for use with multi-channel RF
- Complex, specialized phantoms
  - Dynamic phantoms
  - Phantoms for assessing therapeutic/interventional systems
  - Phantoms for quantitative measurements



## Automated Quality Assurance and Protocol Maintenance

- Use available technologies and informatics tools
  - DICOM information
  - Automatic transmission of images to QC workstation
  - Automatic detection of new QC study
- Use of software pipelines
  - Automatic population of QC database for each system
  - Automatic processing of phantom image data
  - Automatic report generation and long term metrics
  - Web access and neural net systems for QC exceptions and notifications
- Specialized phantoms
  - Work closely with technologists
  - Use jigs to enable quick scans
- Database maintenance of protocols for uniformity of image production across multiple systems and sites



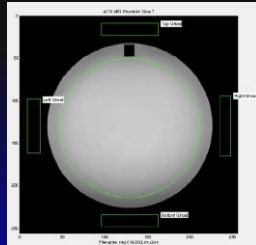
## Automatic Analysis of ACR Phantom

Table 2. Percent Integral Uniformity

Percent Integral Uniformity	\$2.25
Specification Minimum	\$2.00

Table 4. Percent-Signal Ghosting

Percent-Signal Ghosting	0.0020693
ACR Maximum	0.025
Pass-Fail	Pass



Commercially available software; conventional analyses  
Full report generation without interaction

Table 1. Imaging Information

Institution	Vanderbilt Medical Center
System	VX300
Magnetic Field Strength	3
Protocol	T1-w/ax CLEAR
DICOM Slice Thickness(mm)	5
SOP Instance UID	1.2.840.77000.11.17047.5.0.5484.20130170640-0000127
Slice Location	60
Echo Time	20
Repetition Time	400.0000



## Advanced Automatic Assessment of Patient Images

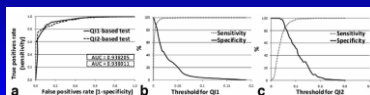
- Produce quality metrics from clinical images automatically
- Use for on-going QC locally
- Use for inter-facility QC evaluation
  - Important in multicenter trials
  - Important in large facilities with multiple systems performing the same exams
- Provide reproducibility/stability information
- Independent of MR system and software
- Important for quantitative analysis of images



## Automatic Analysis of Patient-Related Artifacts

- Edge artifacts
  - Chemical shift
  - Ringing
  - Motion ghosting
- Flow artifacts
- Aliasing from positioning problems
- Artifacts propagate into the air background
- Alter the noise distributions in affected areas in 3D imaging
- Two quality metrics from background
  - Artifactual voxel detection –  $QI_1$
  - Noise distribution analysis –  $QI_2$
- Methodology demonstrates patient image quality determination automatically in multicenter trial environment

ROC performance of automated artifact analysis



Mortamet B et al., Mag Res Med, 62:365-372(2009)



## In Summary

- New technology hard to understand
  - The physicist is the educational resource
- New pulse sequences difficult to use properly
  - The medical physicist will be the valued consultant for best image quality
- Automated analysis of advanced quantitative images
  - Black boxes to most users; the physicist will be the expert consultant
- Automated quality assurance programs
  - The physicist will be the administrator for these to ensure best system performance
- Full member of the clinical imaging team, interacting daily with technologists and radiologists



**Source Material**

1. Acceptance Testing and Quality Assurance Procedures for Magnetic Resonance Imaging Facilities. AAPM Report 100; 2010
2. Jackson EF, et.al. *Trans. Onc.* (2009) 2, 211-215
3. Dietrich O, et.al. *JMRI* 26:375-385 (2007)
4. Hansen MS and Kellman P. *JMRI* (2014)
5. Goerner FL and Clarke GD. *Med. Phys.* 38(9), 2011
6. Goerner FL et.al. *Med. Phys.* 40(8), 2013
7. Raaymakers BW, et.al. *PMB* 54(2009) N229-N237
8. Qian D et.al. *Med Phys* 40 (12) December 2013
9. D. O. Brunner. ISMRM 2011 Workshop on High Fields. [www.ismrm.org](http://www.ismrm.org), accessed 11-Oct-2013
10. Hamaura MJ et al. *Phys. Med. Biol.* 55 (2010) 1563-1575
11. Partanen et al. In CP1113: 8<sup>th</sup> Internat. Symp. On Therapeutic Ultras. 2009. Ed. By E. S. Ebbini; AIP.
12. Ellis S et al. *J Med Imag Rad Onc* 57(2013) 391-399
13. Abramson RG, et.al. *Breast Cancer: Targets and Therapy* 2012;4 139-154.
14. Mortamet B et.al. *Mag Res Med.* 62:365-372(2009)

