

Optimizing MR Imaging Practices: The Physicist as a Consultant

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PD, T1, T2, TE, TR, Flip Angle, Echo Train Length, Bandwidth, FOV, Slice thickness, matrix size, phase sampling ratio, inversion recovery time, saturation band, gradient echo, spin echo, fast spin echo, EPI, cardiac gating, respiratory gating, phase encode ordering, steady state, linear coil, quadrature coil, phased array coil, parallel imaging. This is just a partial list of the tissue characteristics and operator choices that can affect Magnetic Resonance Image appearance. With such a wide range of parameters, MRI, all by itself, is more complicated, *and more flexible*, than all other imaging modalities combined. With few exceptions, most technologists learn how to operate their \$1.5 million scanner by simply pushing buttons. They have little understanding of how to optimize sequences for contrast, SNR and/or resolution. Further, the American College of Radiology now requires a daily, weekly and yearly quality control program to be supervised by a qualified medical physicist or MRI scientist. Experience with such programs has shown that maintaining such complicated equipment at peak operating levels can be more involved than periodic preventive maintenance visits from a service engineer. In this presentation, three categories of consulting opportunities shall be discussed, 1) ACR accreditation submission, 2) Supervising a quality control program and 3) Protocol optimization.

1. ACR Accreditation Submission

All ACR accredited MRI facilities must submit example clinical images (Brain, C-Spine, L-Spine and Knee) as well as T1 and T2 weighted images of the ACR Phantom once every three years. Roughly one third of all sites fail their initial submission and they do so because they have not paid proper attention to the ACR's requirements in terms of image resolution and filming procedures. Although the medical physicist is not expected to evaluate the diagnostic quality of clinical images, we can certainly make sure that all of the technical requirements are met and that the phantom images meet the minimum requirements.

The following statistics regarding the ACR accreditation program were provided by Jeff Hayden of the ACR:

	Total Applied	Total Accredited	Currently Accredited
Facilities	3739	3097	2836
Units	4996	3822	3325

Pass Rates during Initial cycle

	First Attempt	Second Attempt	Third Attempt
1997	44%	75%	71%
1998	43%	70%	83%
1999	38%	73%	86%
2000	48%	79%	83%
2001	60%	84%	89%
2002	68%	96%	99%

Pass Rates during Renewal cycle

	First Attempt	Second Attempt	Third Attempt
2000	53%	91%	
2001	56%	85%	
2002	67%	95%	

Initial Pass Rates by body part and phantom

	11/01	6/02
Brain	64%	85%
C-Spine	43%	59%
L-Spine	60%	81%
Knee	69%	92%
Phantom	83.3%	83.9%

Every site applying for ACR accreditation receives a detailed set of instructions explaining what material to submit, filming requirements and recommended spatial resolution. An overview can be found at http://www.acr.org/departments/stand_accred/accreditation/mri_accred_overview.html Although the spatial resolutions are only *recommended*, there is no good reason why every clinical scanner can't meet those requirements, even low field scanners. Of course, low field scanners will require a greater number of averages resulting in longer scan times, but that is the penalty that one pays for using a low field scanner.

Preparing an accreditation submission is a lot of work and many technologists can feel overwhelmed by the process. It *is* the role of the technologist to put the material together, but it should be the role of the physicist to make sure it is done correctly. Prior to submission, the physicist should check every film and make all of the phantom measurements. Many sites also prefer to have the physicist acquire the phantom images as well. On the next page I have provided an example data sheet that I fill out when reviewing a site's C-SPINE images. Similar data forms would be used with the other body parts.

As a justification for using the services of a physicist, let's look at the costs involved. The basic accreditation fee is \$1900. Reapplication for deficiency is \$500 to \$1000. Reapplication also requires additional technologist time and delays receiving the accreditation certificate. With proper physicist involvement, the first attempt pass rates will be much higher and will result in avoiding the additional time and costs of reapplication.

Clinical Imaging Checklist – C-SPINE

Requirements

1. Sagittal short TR/short TE with Dark CSF (T1 weighting)
 - a. Homogeneous signal intensity of cord
 - b. CSF hypointense to the core/nerve roots so cord/nerve roots are clearly defined
 - c. Good contrast between disk and CSF
 - d. Fat is not so intense so that it masks fat/muscle planes anatomical structures
2. Sagittal long TR/long TE (T2 weighting) or T2*W with bright CSF
 - a. CSF hyperintense to cord/nerve roots so that cord margins clearly defined
 - b. CSF hypo- or isointense with white matter
 - c. Homogeneous signal intensity of cord
3. Axial long TR/long TE (T2 weighting) or T2*W with bright CSF
 - a. CSF hyperintense relative to cord/nerve roots which are well defined
 - b. Good contrast between disk and CSF
4. Sagittal coverage for foramen magnum to T1 & laterally through neural foramina
5. Axial coverage from C3 to T1, including one slice through each disk space
6. Slice thickness \leq 3mm
7. Slice Gap \leq 1mm
8. Max pixel dimension \leq 1.0 mm

	Sag T1s	Sag T2/T2*	Axial T2/T2*	Other
Plane:	Sagittal	Sagittal	Axial	<input type="checkbox"/>
Seq Type (SE, FSE, FLAIR, etc):	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
TR:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
TE:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
BW:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
*ETL:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
*TI:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
FOV (freq.):	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Freq. Matrix:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Calculated Pixel size (freq)				
*PSR:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
FOV (PE):				
Full FOV PE Matrix:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Calculated Effective PE Matrix				
Calculated Pixel size (PE)				
Calculated Pixel Area				
Thick:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Skip:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
NSA (NEX):	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Total # of slices:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Scan Time:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Total # of slices	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Pt. info filmed:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Seq. Info filmed:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Slice location filmed:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

* Enter if applicable.

ETL: Echo Train Length TI: Inversion Time
 PSR: Phase Sampling ratio (*i.e.* Rectangular FOV)

It takes roughly 2 hours to review all of the clinical images in a submission and fill out the above data sheets. With practice, making the phantom measurements in both the ACR protocol and site protocol images should be take about 45 minutes, a little faster on a well tuned high field scanner and a little longer on a low field scanner that has low SNR and homogeneity problems. The time is well spent. I have yet to do this type of pre-review without finding problems that *may* have caused a site to fail one or more body parts.

One last piece of advice regarding *acquiring the phantom images*. The ACR requires a single slice sagittal localizer and 4 sets of axial images. Before you acquire **any** axial images, acquire a coronal localizer as well. All too often, the phantom is slightly twisted which will cause problems with the low contrast resolution measurements. If you take the time to make sure the phantom is level head to foot and straight left to right, then acquiring the images should take roughly half an hour.

2. Supervising a QC Program

According to the ACR:

“A qualified medical physicist/MR scientist **should** have the responsibility for overseeing the equipment quality control program and for monitoring performance upon installation and routinely thereafter. Although facilities are **not required** to have the services of a qualified medical physicist/MR scientist at this time, it is strongly recommended.”

The fact that this is only strongly recommended and not required is due primarily to the lack of physicists qualified to supervise an MRI QC program. Of course, that’s what the AAPM is trying to rectify with courses such as this. Unfortunately, a few hours of CE is not going to make one qualified but it’s a start.

The ACR provides each accredited facility with an MRI Quality Control Manual which they published in the summer of 2001. The manual is divided into three main sections that define the role of the Physician, Technologists and Medical Physicist/MRI scientist. Other than a few minor typographical errors I consider it a very well written manual and those involved should be applauded for their efforts. (Copies can be ordered from the ACR and I strongly recommend it for those wishing to provide physics services to MRI facilities.) This manual defines two roles for the physicist, supervising the Daily/Weekly QC program and yearly QC testing of the scanner hardware. It is not my purpose here to repeat what is in the manual but to highlight some of the key features of the QC program, to present examples of why these tests are important and to point out pitfalls to avoid.

Daily/Weekly QC

Most manufacturers have the technologists run a QC program that consists of some sort of daily SNR measurement and little else. The QC program as outlined in the ACR manual consists of 11 observations or measurements obtained using the ACR phantom:

1. Is the table OK? Does it move up and down, in and out? Any obvious damage?
2. Is the console OK? Does the computer boot? Is auto-archive enabled?
3. Center frequency? Has there been a large shift which might be caused by metal in the scanner?
4. Transmitter Gain or Attenuation? This will vary from manufacturer to manufacturer. GE has TG, R1 and R2.
- 5-7. Phantom geometry. Sagittal localizer length (Z axis) should be 148 ± 2 , A/P (Y axis) and L/R (Z axis) should both be 190 ± 2 .
- 8-9. High contrast resolution (L/R and A/P) should be ≤ 1.0 mm.

10. Low contrast detectability – pick a single slice to monitor that has around 6 spokes visible. It will be a different slice depending upon the field strength and the imaging sequence.
11. Are there any obvious artifacts?

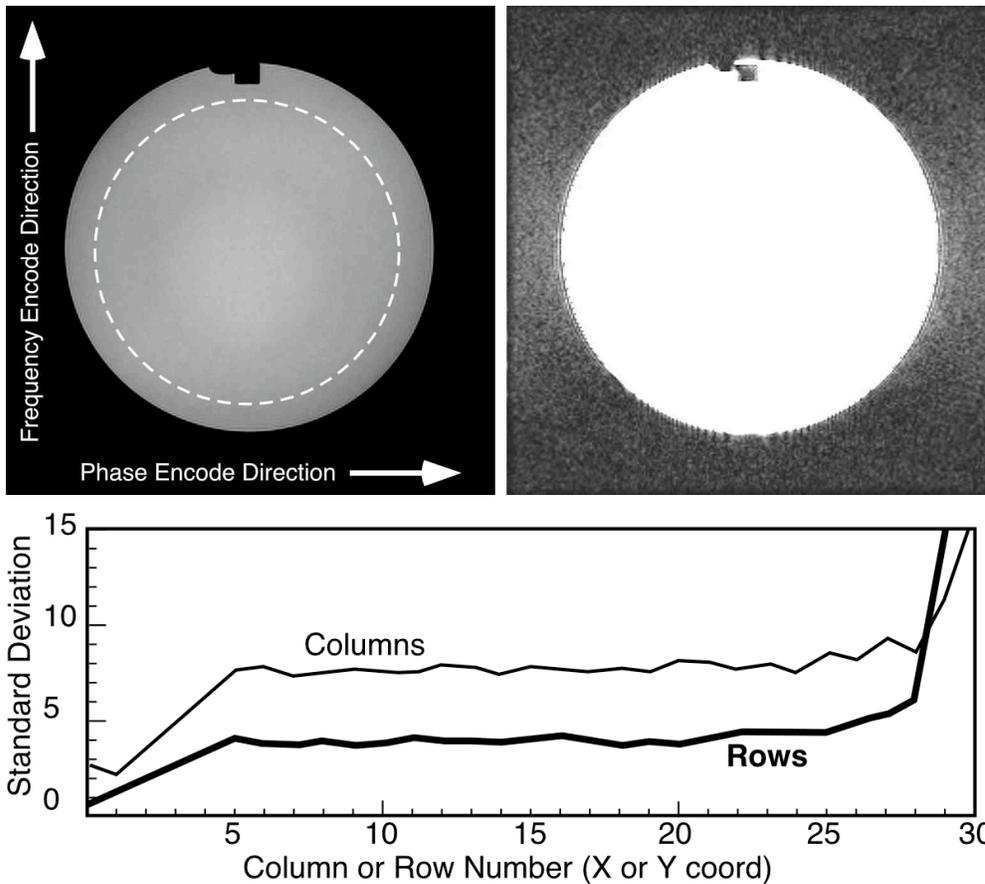
Note that there is no SNR measurement in the ACR program. The high and low contrast resolution measurements give a purely subjective measure of scanner performance with very little ability to detect gradual changes in scanner performance. Difference in the low contrast detection could be due to phantom positioning changes. Initially, the ACR stated that these measurements should be done on a daily basis but due to pressure from outside parties changed that to weekly. This was done over the objection of all members of the ACR MR physics board members. So the current state of affairs is that a site will do *at a minimum* the manufacture's daily SNR measurement and the ACR's tests on a weekly basis.

That is *not* what every site I supervise does. Before I describe the programs that I implement, I'd like to take a moment and discuss the rationale for performing *daily* QA measurements. The first goal of *any* QC is to ensure that the equipment is capable of performing diagnostic imaging *right now*. From that point of view, the tests outlined in the ACR's manual are adequate. However, there is also the desire to ensure that the scanner is working at *its* optimal level, not just meeting some minimal standard. A good QC program should also detect small changes and/or trends that may predict a future problem. For both of these goals, a more objective quantifiable value (or values) is needed. Possible choices include mean signal, std. dev. of noise, SNR, ghosting and/or signal uniformity. No matter what metric is chosen, there is always going to be some normal variation. By making the measurement on a weekly basis, it may take several months to collect enough data to spot a negative trend while daily measurements will show such a trend much faster. I'll show examples of just such trends below.

When choosing an imaging sequence to use for daily QA, one could use a simple spin echo sequence such as used in the ACR T1 protocol. However, that may not be a sequence that the site ever uses in practice. Since we want to verify that the site's system is working up to par, I prefer to choose a sequence that the site actually uses on a daily basis. I recommend using the ACR's sagittal localizer to start with and then use the site's own head T1 protocol with just a few modifications. The sequence should use a FOV of 25cm, a 256x256 matrix and a 5 skip 5 slice spacing. These parameters are necessary to make the high and low contrast measurements relevant. In addition to the ACR's tests, I have the technologist measure the mean signal and background noise (frequency encode direction) in slice #7, the 'flood' image. This then replaces the manufacturer's SNR measurement. Further, while the technologist is making the above measurements I ask them to run their T2 weighted sequence assuming that it is some sort of Fast or Turbo Spin Echo. These types of sequences are the most likely to exhibit ghosting problems. I ask the technologist to measure the mean signal in the phantom, the mean signal in the 'air' in both the frequency and phase encode directions as well as the standard deviation of the 'air' in the frequency encode direction. From this we calculate a % ghosting value and T2 SNR. All sites using superconducting magnets (most do) should record cryogen levels on a daily basis.

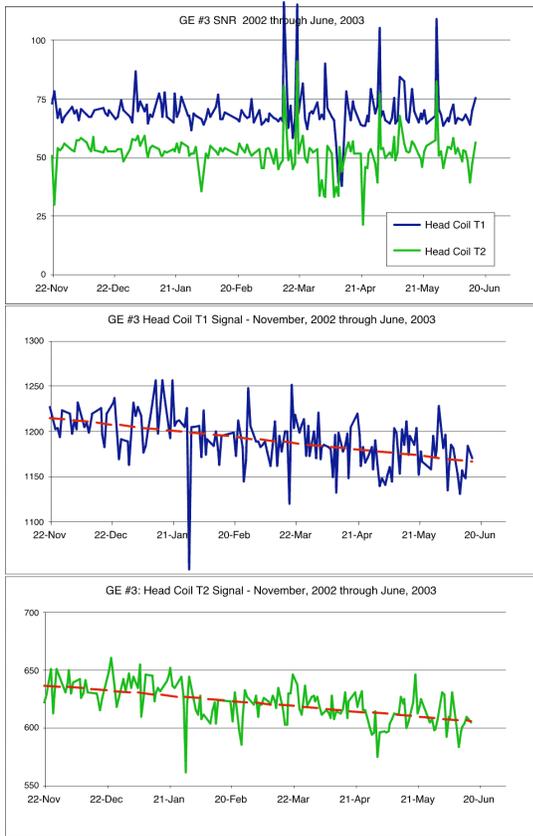
When making measurements it's very important that you teach the tech exactly where to make the signal and noise measurements. One must always stay away from edges, both edges of the phantom and edges of the image. The images below demonstrate two of the most common pitfalls. When looking at the image on the left, without the labeling it is impossible to tell which is the phase encode and which is the frequency encode direction. One must always make the background noise measurement in the frequency encode direction. Close examination of the image on the right shows a narrow band of reduced signal all the way around the image. The edges represent the high frequency information in the MR signal. Most manufacturers over sample the signal from the scanner and then apply a filter. This reduced signal represents the roll-off from the filter. From the graph we see that this roll-off region extends for about 5 pixels. When measuring the background noise and/or ghosting, if the ROI extends into that region, the values obtained will be too low. This wouldn't be disastrous if the technologists made the measurement the same way each time. Unfortunately, they are more likely to move around from

day to day. Since the standard deviation of the noise is in the denominator of the signal to noise ratio, it can result in fairly large fluctuations in the calculated number.



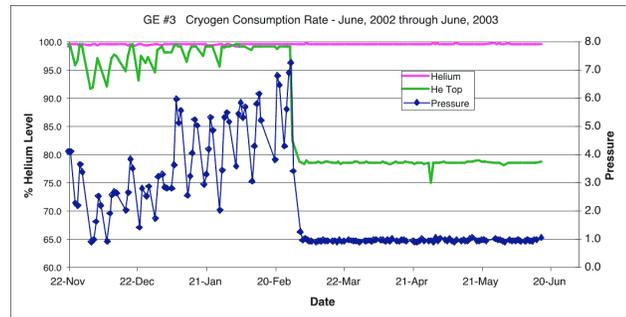
An additional problem with making noise measurements is truncation. The image data is always in integer form. When using the ROI tools on some consoles, they will only report the standard deviation rounded to the nearest integer. Assume for a moment that the signal in the phantom has a mean of 400. A true noise standard deviation of either 3.6 or 4.4 will both be reported as 4. The calculated SNR will be 100 when in fact it could be anywhere between 91 and 111. When evaluating QC data, it is often better to look at the signal mean instead of SNR, assuming, of course, that the RF receiver gain remains constant.

It is important that the physicist review the QC data on a regular basis. Even though the technologist may have been told what the 'action limits' are, i.e. when measured values fall outside of normal ranges some action should be taken, they may simply ignore it. Additionally, it's a good idea to make sure the technologist is actually making the measurements or is making it correctly. I recently visited a site for their yearly QC check. I had been reviewing their data on a monthly basis and everything had looked fine. When I ran the daily QA, I made an A/P measurement of 194 mm (spec is 190 ± 2). I chose QA images at random from the previous month and on everyone I measured 194 yet the values entered in the data sheets for the last 6 months had all been exactly 190. The technologist ran the scans but never made the measurements.

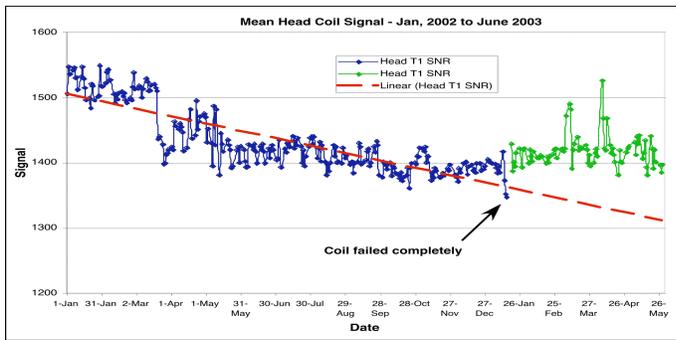


These graphs plot the data obtained from a newly installed GE OpenSpeed system. Note the wide variation in the SNR values. Much of this was caused by placing the ROI too close to the edge of the image as described above. It's very difficult to discern any particular trend in the SNR data. However, there is a clear downward trend in the mean signal data, roughly 1% per month. At the time of this writing, we hadn't diagnosed the cause of this trend. Hopefully, we'll have an answer to present in San Diego.

Another interesting set of data is that of the Helium level and pressure seen below.



The service engineer did some major work on the cold head in early March. Again, at the time of this writing, I'm not sure what was done. I'll try and let you know in San Diego.



As a final example of the predictive value of a daily QA program, we see a long term downward trend of the mean signal of a head coil in a 1.5 T scanner. On January 15th the signal reached an all time low and totally failed later that day.

Yearly System Checkout

One of the most important services that an MRI Scientist/Medical Physicist can provide is the yearly top to bottom checkout of each MR scanner. The yearly system evaluation looks at magnetic field homogeneity, slice position accuracy, RF coil performance, inter-slice RF interference and soft copy displays (monitors). During the last twelve months I have performed this evaluation on 18 scanners and in the process found problems with:

- | | | |
|--------------------------------|----------------------|------------------|
| 4 CTL coils | 1 Anterior neck coil | 3 Knee PA coils |
| 1 Flexible Body PA coil | 2 Shoulder PA coils | 1 TMJ coil |
| 3 Neurovascular PA coils | 1 Cardiac PA coil | 1 extremity coil |
| 2 Peripheral Vascular PA coils | 1 Display monitor | |

In addition I identified 3 power injectors overdue for calibration, 4 scan rooms with the RF shielding tabs broken off their doors and two severe geometric distortion. Due to recent

concerns with safety issues I recently obtained a Gauss meter to map the fringe fields to define the safe zones. So far I have identified 3 scanners where the 5 gauss line extends out into the nearby hallway. At one of those sites I mapped out a 40 square foot area *outside of the building* where the field ranged from 5 to 18 gauss. That region was a grass field behind the building and normally has no traffic but it was immediately fenced off to prevent any possibility of problems.

The ACR manual provides a good description of how to perform the system evaluation. One issue missing from that description of RF coil evaluation is what to do about phased array coils. The vast majority of RF coil problems center around the full or partial failure of one channel of a multi-channel phased array coil. It is absolutely critical that the uncombined images from each channel be looked at individually. Unfortunately, it is difficult to predict what type of numbers you will obtain when looking at the individual images. Every coil is different. CTL coils from two different manufacturers can behave very differently. Most phased array coils consist of an even number of channels and there is usually some sort of symmetry present. I will present example images of coils that have failed and those that are working properly.

3. Protocol Optimization

A large percentage of MRI operators can be described as button pushers. They follow a cookbook procedure set up by their applications specialist. When a site receives hardware or software upgrades they will often need assistance in adapting their old protocols to take full advantage of their new capabilities. When a new technique is published, the literature may contain a reasonable description of scan parameters but all of the terminology will be specific to one manufacturer. A site with a different manufacturer's equipment may need help in adapting the protocol to the capabilities of their equipment. Unfortunately, this often requires many years of hands-on MRI experience, something that an MRI scientist has but most medical physicists don't. I will present a few very common techniques that almost everybody can benefit from and can be easily implemented on most scanners.