Range of Results from over 534 ACR-mandated Annual MRI Performance Evaluations on over 204 Magnets from 8 Vendors Spanning a 10-year Period

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**** 78% of all MRI scanners have Image Quality problems. *****

***** 25% of all Multi-Channel RF coils have at least one bad channel. *****

BACKGROUND

All MRI centers accredited by the ACR are required to have Yearly Performance Evaluations. Some have questioned the value of these tests, believing that vendor provided servicing is adequate. Between August 2001 and October 2011, 534 full system evaluations were performed on 204 different magnets from 8 different vendors. Problems ranging from minor to serious were found during 78% of these evaluations. The yearly performance evaluations included tests of following system attributes: 1) Magnet Homogeneity 2) Gradient calibration 3) SNR of every single channel of every RF coil 4) Ghosting 5) Image uniformity 6) High and Low contrast resolution 7) Slice position accuracy 8) Soft and hard copy displays 9) Table positioning 10) Site safety issues including 5 gauss line determination and 10) Technologist QC program. Most vendors only provide rudimentary tools for SNR and geometric analysis and little or no tools for magnet homogeneity testing. Custom software was developed (IDL) for automatic analysis of ACR phantom geometry, uniformity, ghosting and SNR. This software was extended for automated SNR analysis of all types of RF coils regardless of # of channels, phantom used or coil geometry. Software was also developed for 3D Magnetic Field Homogeneity mapping using phase difference methods on 3D GRE sequences.

Types of Magnets Tested and # of Problems Found

Vendor	Field	System Count	# Of Tests	# of times problem(s) found	% of times problem(s) found
Biosound Esaote	0.25	2	3	2	66.7%
GE/ONI	1.50	2	2	2	100.0%
General Electric	0.20	2	5	5	100.0%
	0.35	5	13	10	76.9%
	0.70	4	22	20	90.9%
	1.50	57	195	154	79.0%
	3.00	4	15	12	80.0%
Hitachi	0.30	13	19	15	78.9%
Philips	1.50	20	35	25	71.4%
	3.00	7	19	15	78.9%
Picker/Marconi	0.23	7	17	14	82.4%
	1.00	5	8	8	100.0%
	1.50	11	28	23	82.1%
Siemens	0.19	2	1	1	100.0%
	0.23	2	5	2	40.0%
	1.00	2	2	1	50.0%
	1.50	30	83	60	72.3%
	3.00	17	32	24	75.0%
Toshiba	0.35	8	21	19	90.5%
	1.50	4	9	5	55.6%
	Totals:	204	534	417	78.1%

This table lists the number of magnets and their field strength that were tested from each vendor. An initial system performance evaluation or acceptance test requires 10 to 14 hours. Data analysis and report generation takes an additional 5 to 8 hours. Both times vary depending on the number of coils present, the number of channels per coil and the magnet vendor. Subsequent visits usually take about 25% less time.

The following pages will describe in detail how each test was performed and the rationale for methods used.

The single most important lesson from these years of testing: It is absolutely imperative that every channel of every phased array coil be examined. Relying on the composite images alone will invariably result in missed problems.

RF Coil Testing

When measuring SNR as part of a continuing QA program the most important considerations are consistency and reproducibility. SNR values depend upon many factors including:

1) Voxel volume (x, y & z size) - Linear dependence.
2) Receiver BW - square root dependence
3) Number of averages - square root dependence
4) Number of channels - roughly square root dependence

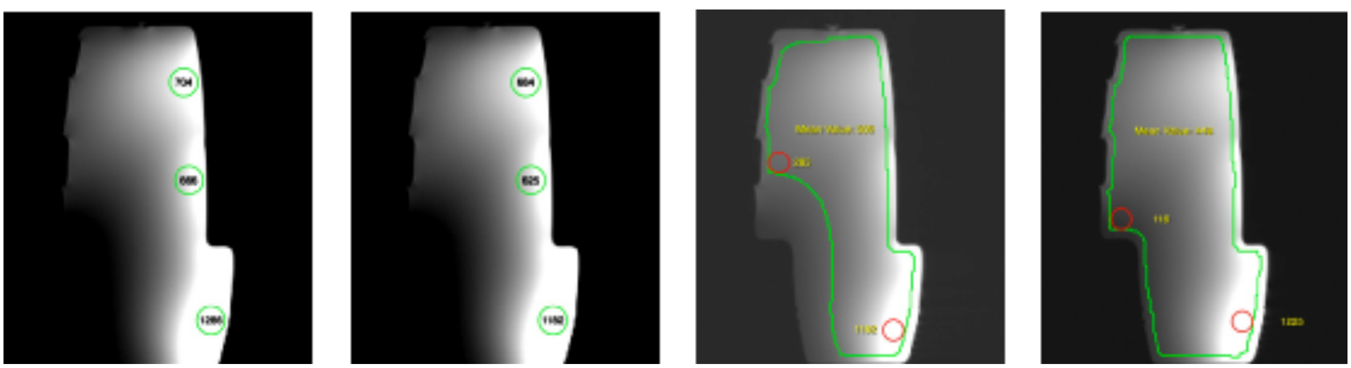
In addition to these ‘quantifiable’ factors, the measured SNR value depends on the choice of phantom, coil geometry and how the Signal and Noise values are measured. Furthermore, most vendors also use image processing such as noise filtering, distortion correction and adaptive channel combination. Whenever possible, this post-processing was disabled.

All of the testing was performed using Spin Echo sequence with a TR/TE of 300/20 and a slice thickness of 3 mm at high fields and 5 mm at low fields. The FOVs were chosen to be at least twice the diameter of the phantom in the phase encode direction to mimimize wrap around of any ghosting. If this was not possible then the maximum allowed FOV was used and in some cases anti-aliasing (No Phase Wrap) was used (with 2 NSA).

Each scan was run twice. This allows calculating the SNR value two different ways, measuring the noise as the standard seviation in the background air, (referred to as the ‘Air’ method), or as the standard deviation of the residual inside the phantom after subtracting the two images (referred to as the NEMA method).

Measuring the Signal

Calculating an SNR value requires two values, the mean signal value and the standard deviation (S.D.) of the noise. The ACR’s QC manual recommends using a circle that contains 80% of the phantom for volume coils but for other coils it recommends positioning a small circular ROI on top of the region of highest signal. Small changes in the positioning can result in substantially different results and there is no way you can expect to exactly repeat the measurement on the next visit. Additionally, multi-channel phased array coils will have local maximums corresponding to each coil and a single ‘peak’ signal value won’t take those into proper consideration. (See below - left 2 images.)

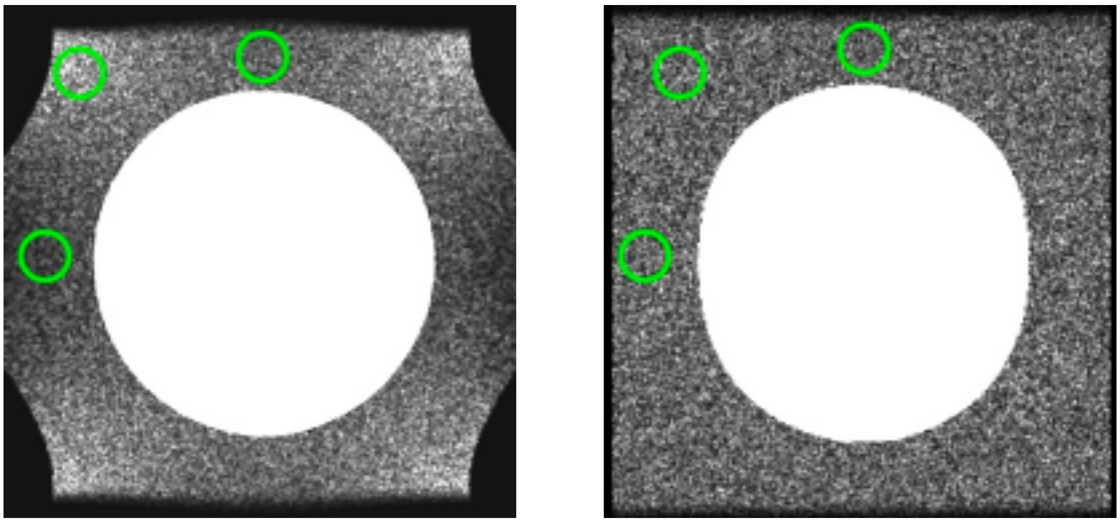


In order to provide consistent, reliable measurement of the signal mean, regardless of phantom geometry or coil performance, software was developed that takes a user defined threshold to determine an ROI that is moved four pixels in from the phantom edges. In addition, it determines the minimum and maximum values within the ROI. The two images above on the right show the results obtained with a threshold of 10% and 3%. The software also measures the S.D. of the background outside of the phantom and the S.D. inside the ROI applied to the subtracted images.

Measuring the Noise

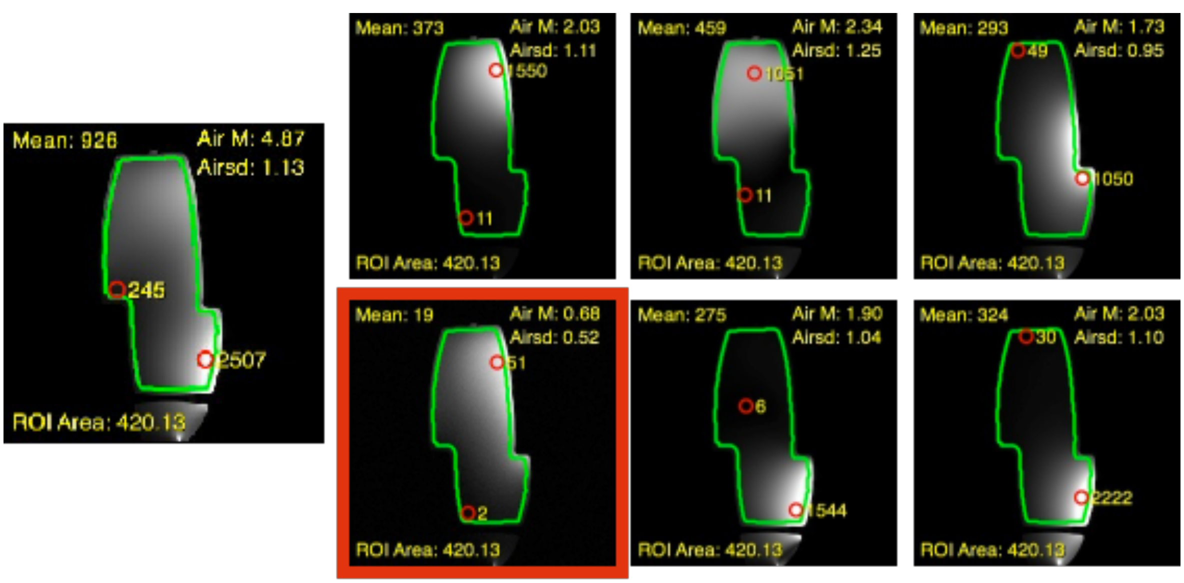
Between the Signal and the Noise, the Noise value is by far the more important because it is in the denominator. Small changes in the noise make large changes in the SNR value. For this reason, whenever possible, FOVs that are at least twice as large as the phantom were used to give a large area to measure the noise over. Thin slices (3 mm) were used to reduce the SNR value (higher relative noise levels.) The previously mentioned software automatically measures the background noise outside of the phantom. Algorithms were also developed to reject signal from ghosting.

The underlying assumption in SNR measurements is that the background noise is random and spatially invariant. (Rayleigh distribution in the air and Gaussian in the NEMA subtractions.) In order for this to be true, it is imperative that no post processing be applied. The three most common problems are smoothing, geometric distortion correction and adaptive combination of phased array images. (More on that below.) Distortion correction is a major problem with most open and/or short bore magnets. Here is an example from a GE Openspeed with and without correction. While the phantom in the left hand image is circular, where should the noise be measured?



Multi-channel or Phased Array Coils

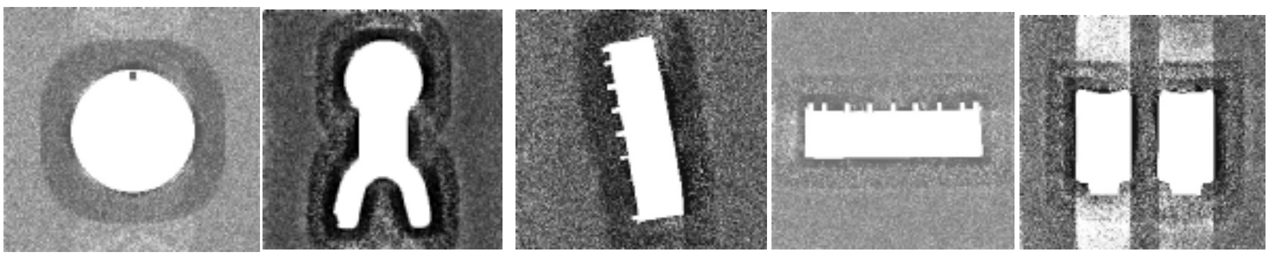
When looking at phased array (PA) coils, it is often difficult to tell if there is anything wrong by only looking at the final composite image. Often, there is a lot of overlap between channels which can mask a problem with one channel. Most vendors provide some method of obtaining ‘uncombined or intermediate images’. With Siemens and GE scanners it is simple to do. With Philips and Toshiba, there is a long and tedious process, but it is doable.



The composite image, above, is from an 8 channel CTL spine coil. Casual examination may or may not identify a region of slightly lower signal near the center of the phantom. This coil has two channels at each of three positions, superior, middle and inferior. One of the 'middle' channels has a mean value of 19 as opposed to 275-459 for the other five. Interestingly, the vendor's own test software does not look at the individual channels, just the mean signal above each coil position in the composite. The vendor's specs are set so low that this coil easily passed! After showing them the uncombined images, they agreed to replace it.

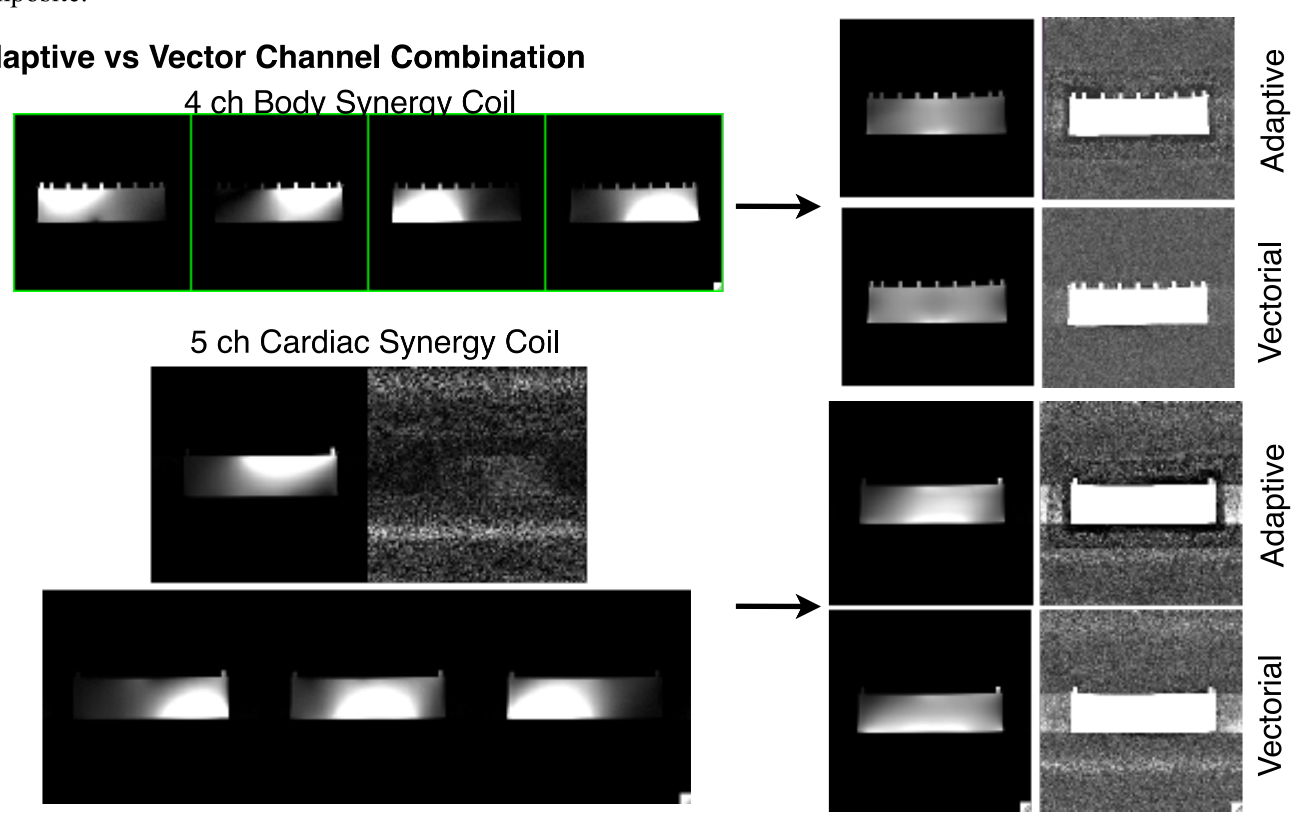
Adaptive Channel Combination

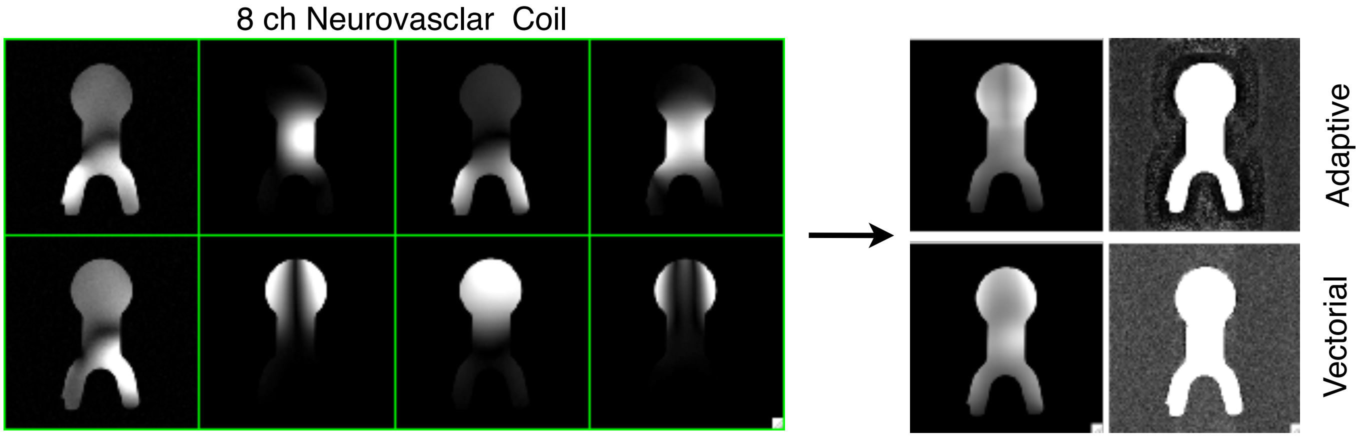
Phased array coils produce one image per channel which then must be combined to make the final or composite image. The simplest way of doing this is by using vector combination, square root of the sum of the squares. However, most vendors use a more sophisticated algorithm known as Adaptive Combination which improves local SNR and reduces artifacts but makes it very hard to measure background noise because the noise is no longer spatially invariant. (See below)



When uncombined images are saved on Siemens systems, adaptive combination is turned off and all SNR measurements are straight forward. On Philips' systems, the adaptive combination cannot be turned off which has led to substantial year to year variability in SNR values. It was this variability that motivated the implementation of the NEMA method. Under ideal circumstances the NEMA and Air methods should return the same SNR value. (This includes compensating for the differences in Rayleigh and Gaussian statistics...not important here.) However, if there is any ghosting, as seen in the last image on the right above, then the NEMA method is not reliable either. While it is not possible to force the Philips scanners to use the Vector combination method, since the uncombined images are already part of the processing, it was possible to use those images to create a vector composite.

Adaptive vs Vector Channel Combination





The above images clearly show the difference in the background noise between Adaptive and Vectorial combination. The interesting thing to note is that the vectorial composites have better uniformity than the adaptives, for the Body Synergy coil, 70% vs 51% and for the NVA coil, 73% vs 37%. However, the performance of these algorithms may not work will with uniform phantoms. (It is certainly a question worth exploring!) The cardiac coil shows another example how it is difficult to tell if there is a problem unless you look at each channel, then it's easy!

RF Coil Testing Results

Single Channel Coils			
Description	Count	Problems	% prob
Body	216	9	4.2%
Body Flex	62	8	12.9%
Body & Spine	24	5	20.8%
CP/GP Flex	145	17	11.7%
Endorectal	5	0	0.0%
Extremity	67	8	11.9%
Head Neck	1	1	100.0%
Head QD	185	16	8.6%
Knee/Foot	48	9	18.8%
Knee QD	78	5	6.4%
Loop	6	1	16.7%
MultiPurpose	9	6	66.7%
Neck	53	7	13.2%
Shoulder	36	2	5.6%
Spine	30	6	20.0%
Wrist	39	2	5.1%
Totals:	1004	102	10.2%

2 Channel Coils			
Description	Count	Problems	% prob
3" Dual (TMJ)	22	6	27.3%
Body Flex	87	10	11.5%
Breast	6	1	16.7%
CTL	18	2	11.1%
Extremity	4	1	25.0%
Flex	41	1	2.4%
Knee	27	4	14.8%
Neck	34	4	11.8%
Shoulder	19	2	10.5%
TMJ	34	1	2.9%
Wrist	6	1	16.7%
Totals:	298	33	11.1%

3 Channel Coils			
Description	Count	Problems	% prob
CTL	3	3	100.0%
Foot	10	3	30.0%
Head/Neck	8	2	25.0%
Knee	2	1	50.0%
Knee/Foot	2	2	100.0%
NVA	1	1	100.0%
Shoulder	28	15	53.6%
Wrist	7	6	85.7%
Totals:	61	33	54.1%

4 Channel Coils			
Description	Count	Problems	% prob
Body	50	12	24.0%
Breast	28	9	32.1%
Cardiac	18	5	27.8%
Carotid	1	1	100.0%
CTL	47	11	23.4%
Extremity	16	3	18.8%
Flex	22	1	4.5%
Head	56	12	21.4%
Knee	13	10	76.9%
NVA	43	17	39.5%
Pelvic	6	0	0.0%
PVA	11	9	81.8%
Shoulder	186	28	15.1%
Torso	72	28	38.9%
Wrist	39	11	28.2%
Totals:	608	157	25.8%

5 Channel Coils			
Description	Count	Problems	% prob
Cardiac	13	3	23.1%
CTL	23	5	21.7%
Totals:	36	8	22.2%

6 Channel Coils			
Description	Count	Problems	% prob
Body	5	1	20.0%
Cardiac	6	2	33.3%
Carotid	1	1	100.0%
CTL	59	29	49.2%
Head	5	1	20.0%
Knee	2	1	50.0%
Neck	11	2	18.2%
Torso	10	3	30.0%
Totals:	99	40	40.4%

7 Channel Coils			
Description	Count	Problems	% prob
Breast	30	4	13.3%

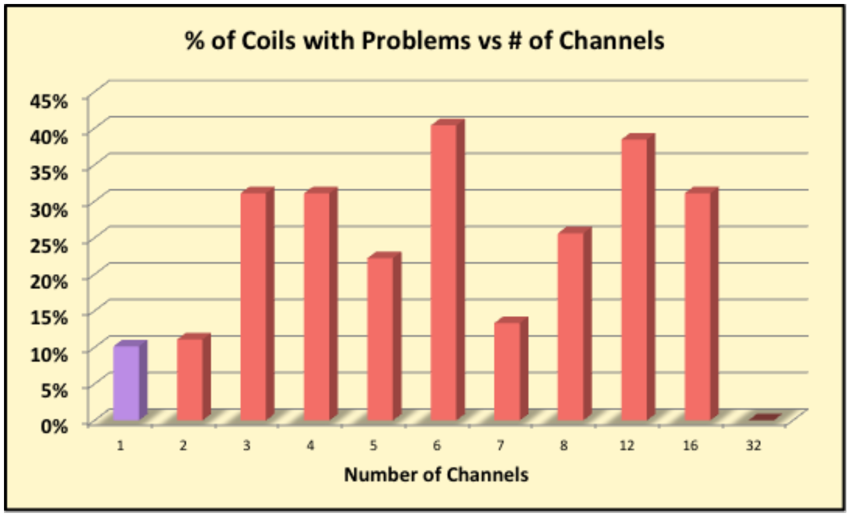
8 Channel Coils			
Description	Count	Problems	% prob
Body	31	12	38.7%
Breast	14	7	50.0%
Carotid	1	0	0.0%
CTL	63	24	38.1%
Foot	17	1	5.9%
Head	56	2	3.6%
Knee	58	6	10.3%
NVA	40	24	60.0%
Shoulder	10	3	30.0%
Wrist	30	3	10.0%
Totals:	320	82	25.6%

12 Channel Coils			
Description	Count	Problems	% prob
Body	13	5	38.5%

16 Channel Coils			
Description	Count	Problems	% prob
Body	8	3	37.5%
Extremity	2	1	50.0%
Hd/Nk/Sp	19	6	31.6%
NVA	11	3	27.3%
Torso	5	1	20.0%
Totals:	45	14	31.1%

32 Channel Coils			
Description	Count	Problems	% prob
Head 32	1	0	0.0%
Torso 32	2	0	0.0%
Cardiac 32	1	0	0.0%
Totals:	4	0	0.0%

Summary of # of Problems vs # of Channels			
# channels	# coils	# Problems	% Problems
1	1004	102	10.2%
2	298	33	11.1%
3	61	33	31.1%
4	608	157	31.1%
5	36	8	22.2%
6	99	40	40.4%
7	30	4	13.3%
8	320	82	25.6%
12	13	5	38.5%
16	45	14	31.1%
32	3	0	0.0%
All Coils:	2517	478	19.0%
Multi-Channel:	1513	376	24.9%



From the summary table above, we see that there is little difference in one and two channel coils, roughly 10% have some sort of problem. 25% of all multi-channel phased array coils have a problem. If you ignore the two channelcoils then the % of coils with a problem goes up to 28%. Unless the physicist looks at each channel, many of these problems will be missed.

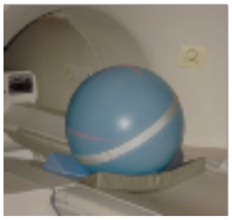
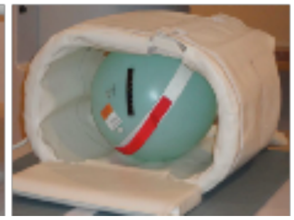
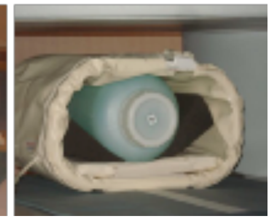
Magnetic Field Homogeneity Testing

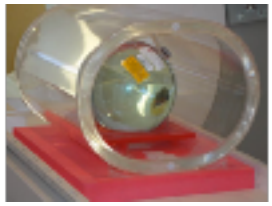
One of the most important parts of a new magnet installation and continuing maintenance is insuring that the magnetic field is as homogeneous as possible. Poor magnet homogeneity can result in obvious geometric distortion, can make it difficult to perform fat saturation and make it difficult to take advantage of advanced techniques such as Echo Planar Imaging (EPI) or 3D Balanced Gradient echo imaging. Unfortunately, measuring magnet homogeneity is not a simple task. The ACR QC manual suggests various methods of varying degrees of sophistication and utility. During the last 10 years of testing, the following methods have been used, starting with the oldest (and least useful) to the most recent (and most useful):

1. Looking at the most recent Service Engineers Report
2. Recording FWHM frequency spread of an FID
3. Counting phase wraps in 2D GRE sequences
4. Counting phase wraps in the Phase subtractions of 2D GRE sequences with two different echo times.
5. 2D Phase unwrapping from #4 then calculating peak to peak variation across different FOVs
6. 2D Phase unwrapping and Peak to Peak variations on 3D GRE phase difference images.
7. True 3D Phase Unwrapping and Peak to Peak determination over continuous spherical volumes.
8. Determining the spherical harmonic coefficients fitted to the 3D unwrapped data from #7

Phantoms for Homogeneity Testing

An important part of testing magnet homogeneity is the selection of a phantom. The best choice is a uniform sphere, the larger the better, in order to measure over the largest volume. Only two companies provide spherical phantoms with all of their scanners. GE provides either a 31 or 32 cm sphere (depending on system) filled with water and NiCl at 1.5T or lower and a 32 cm sphere filled with oil at 3T. Siemens provides 24 cm spheres, also water or oil filled. Philips provides a 38 cm wide disk that is 10 cm thick. This is good for looking at large FOVs, but only along the main axes and only after re-orienting the phantom and waiting for the fluid to settle. It is useless for looking at off axis components of the shim. Hitachi provides a 20 cm wide bottle, roughly 25 cm in length. Toshiba only provides a jug that looks like a large gas can. Frankly, it is totally useless. By far, the best choices are the GE 32 cm spheres. We have purchased both a water and oil filled phantom from the manufacturer (Dielectric Corp., Menomonee Falls, WI) and now use these phantoms to test homogeneity on all systems. (Hitachi systems can only use the 27 cm sphere.)

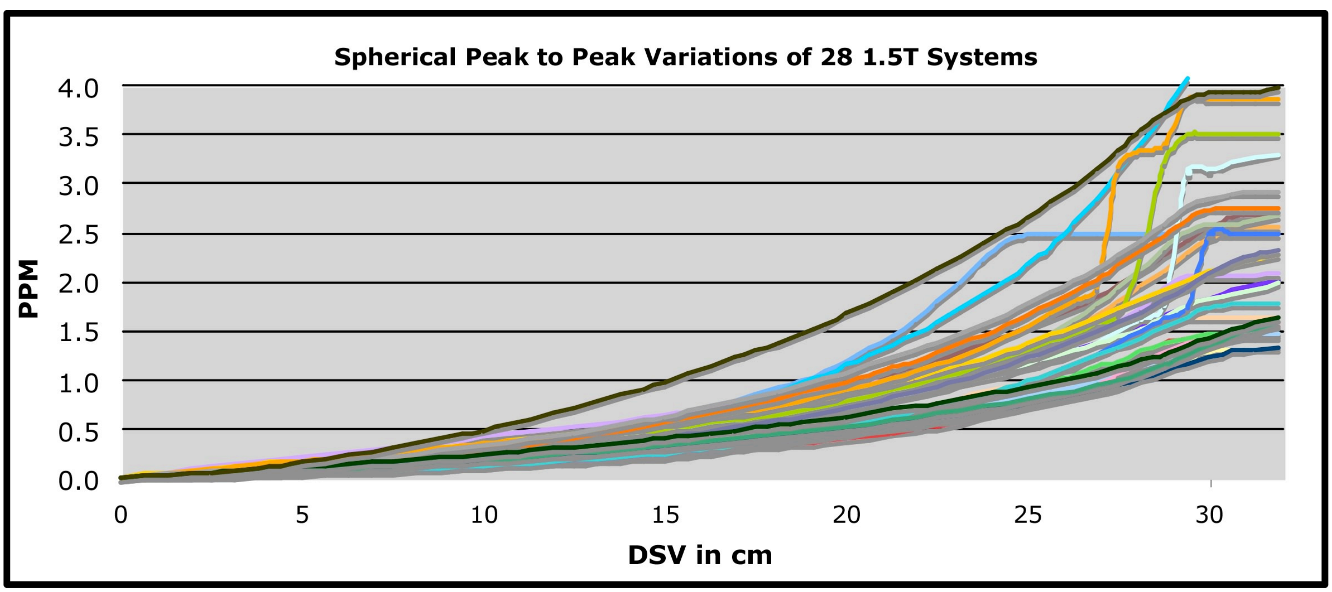
    

Homogeneity Test Results

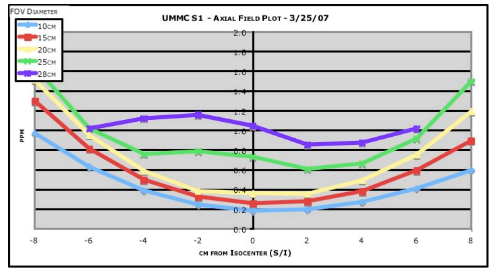
Over the 10 year period, the quality of shimming by all vendors has gotten steadily better. Out of the 534 yearly performance evaluations, 61 systems were found to have homogeneity issues. Sometimes the problem was simply metal in the magnet bore. Other times the supercon shim currents had drifted. The two worst cases were systems that had not been reshimmed after multiple quenches. One system has a steady drop in the Center Frequency of 100 Hz/week and must be reshimmed 3 to 4 times per year. (Typical magnet drifts are 1 to 5 Hz / month)

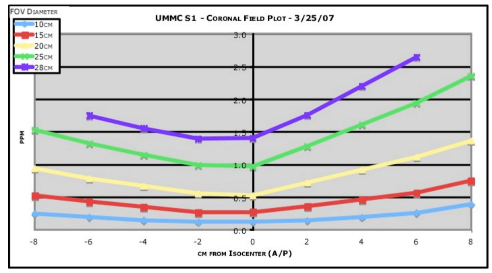
Most vendors specify magnet homogeneity in terms of Root Mean Square (RMS) values in PPM over various Diameter Spherical Volumes (DSV). This measurement is useful for getting an idea of the overall homogeneity. However, this method will often miss a localized problem (metal in the magnet, malfunctioning high order shim coil). A more useful value is the Peak to Peak variation across a DSV. Below is a graph of results obtained on 28 1.5T systems. In general, I feel that a value of less than 2 PPM over 28 cm DSV is acceptable.

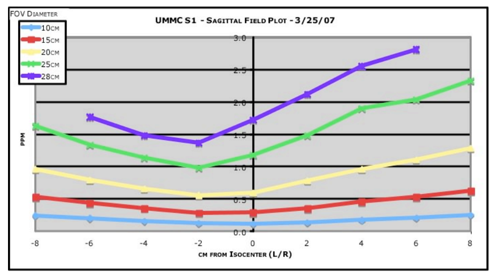


Homogeneity Case Result #1

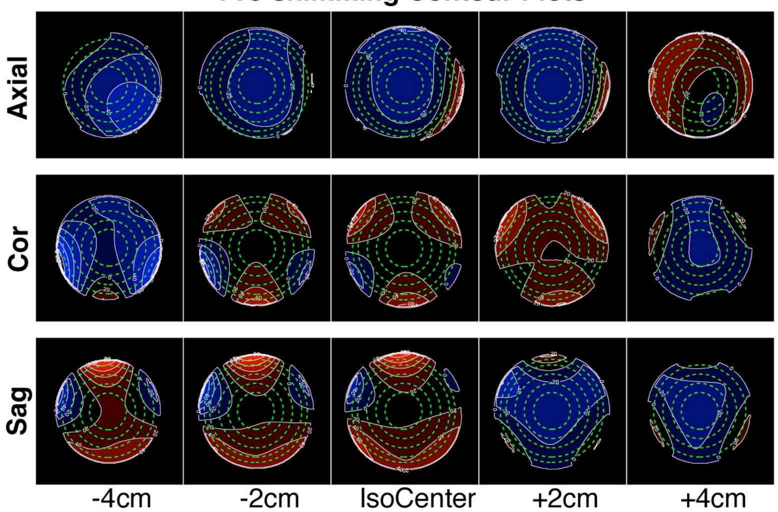
During the annual testing of a Siemens 1.5T Symphony system, it was noted that while the homogeneity looked good up to about 20-22 cm diameter, it deteriorated rapidly after that. The site service engineer reported that the system passed, if barely, Siemens' own homogeneity test which used the 24 cm sphere. He acknowledged that the data over the larger 32 cm sphere looked problematic and agreed to bring a full shim test rig in to evaluate the system. He found that it did, indeed, fail Siemens spec over a DSV of 40 cm so the magnet was reshimmed with excellent results, (see below.) This clearly demonstrate that a 24cm sphere is not adequate for homogeneity testing of a whole body scanner.

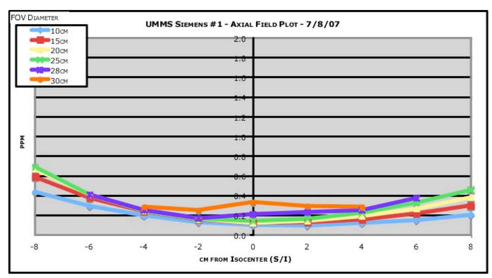


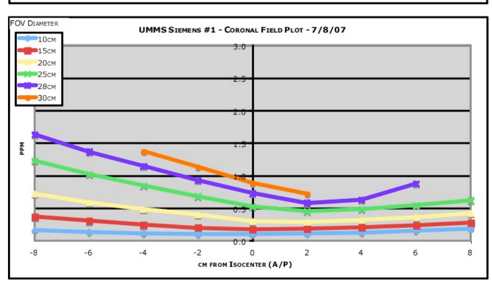


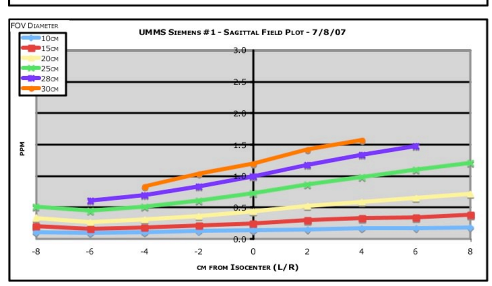


Pre-shimming Contour Plots

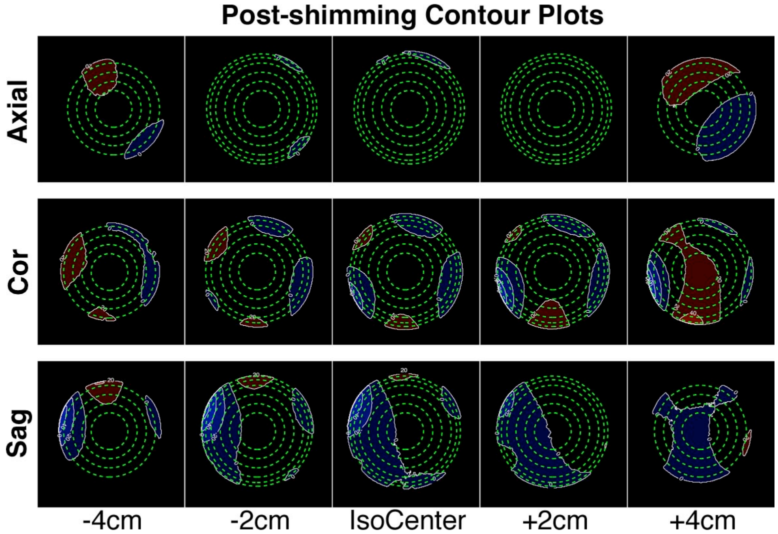






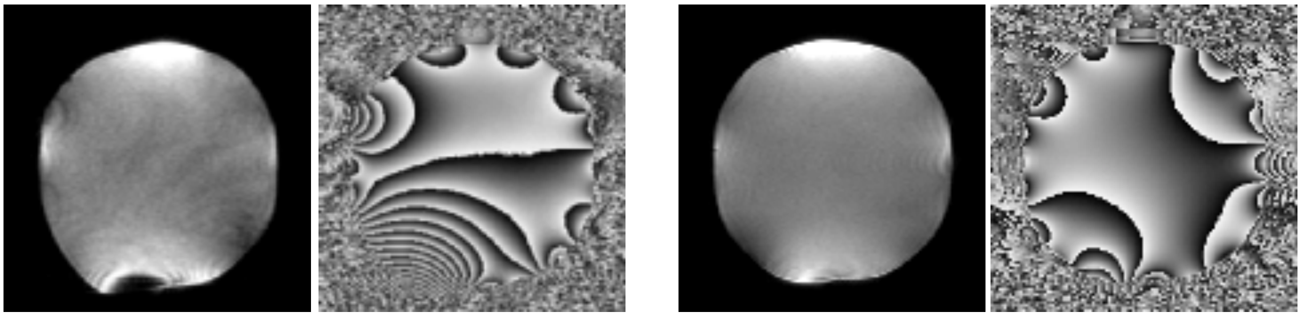


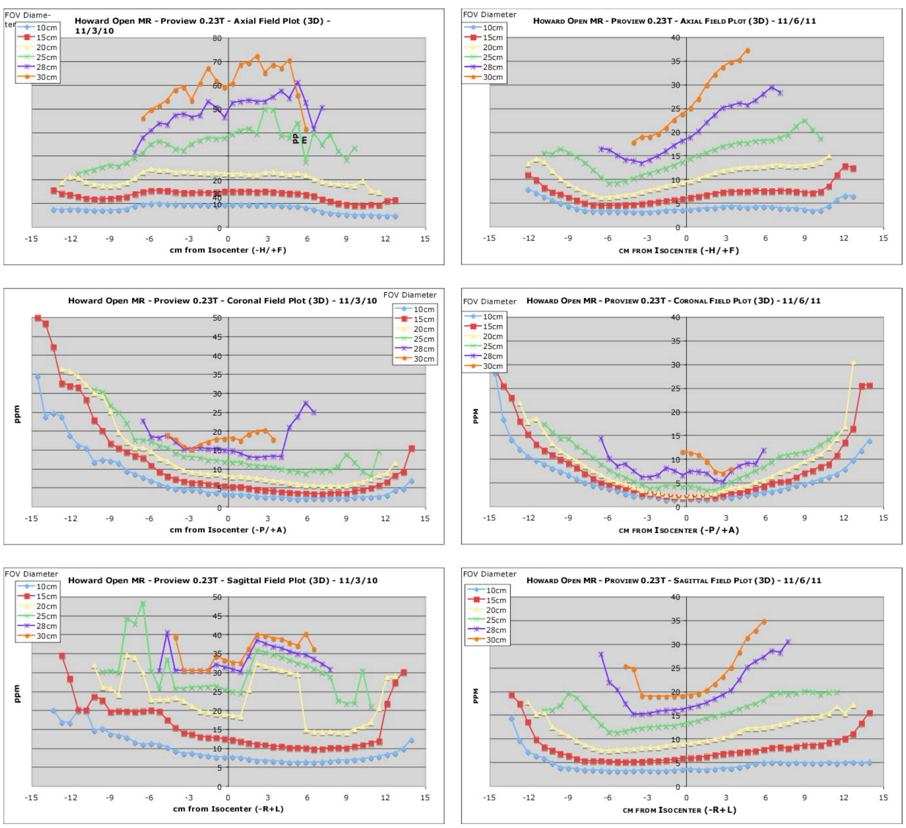
Post-shimming Contour Plots



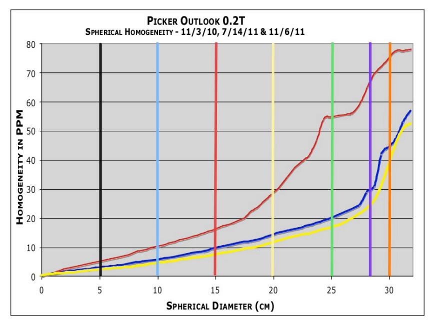
Homogeneity Case Result #2

At high fields, magnetic homogeneity is critical for fat saturation and echo planar imaging. The chemical shift at low fields is too small to allow for fat saturation. However, because low field scanners tend to use very low receiver BW to improve SNR, poor homogeneity can result in noticeable geometric distortion. A Picker 0.2T Outlook facility was unable to obtain images of the ACR phantom that would meet ACR spec due to geometric distortion. The pre-shimming GRE images showed obvious distortion, loss of signal and over 12 phase wraps. After reshimming, the distortion was greatly reduces and the phase wraps were reduced to four.





The plot immediately below shows the spherical homogeneity prior to the reshim and at two subsequent visits.

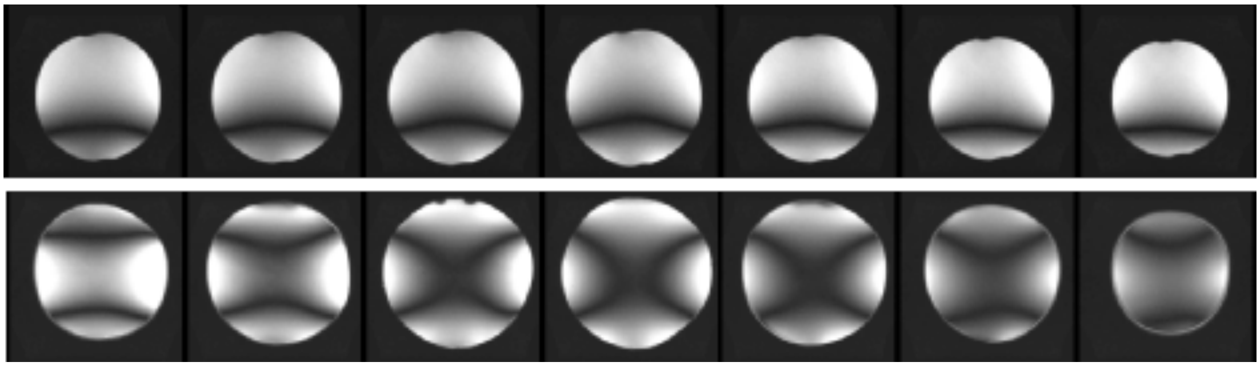


<u>What's being missed out there?</u>

In August, 2011, I was asked to do a complete evaluation of three GE magnets prior to the service contract changing service companies. This site had had a board certified medical physicist perform the annual testing just two months prior. Based upon his reports, he had made a conscientious effort to follow the ACR's guidelines. His reports found no problems with any of the systems. However, those guidelines do not give guidance on how to test phased array coils. During my testing I found 6 PA coils with at least one completely dead channel, one coil with a 'sick' channel, a positioning laser off by 10 mm (spec is ±2) and a minor problem with one system's gradient calibration.

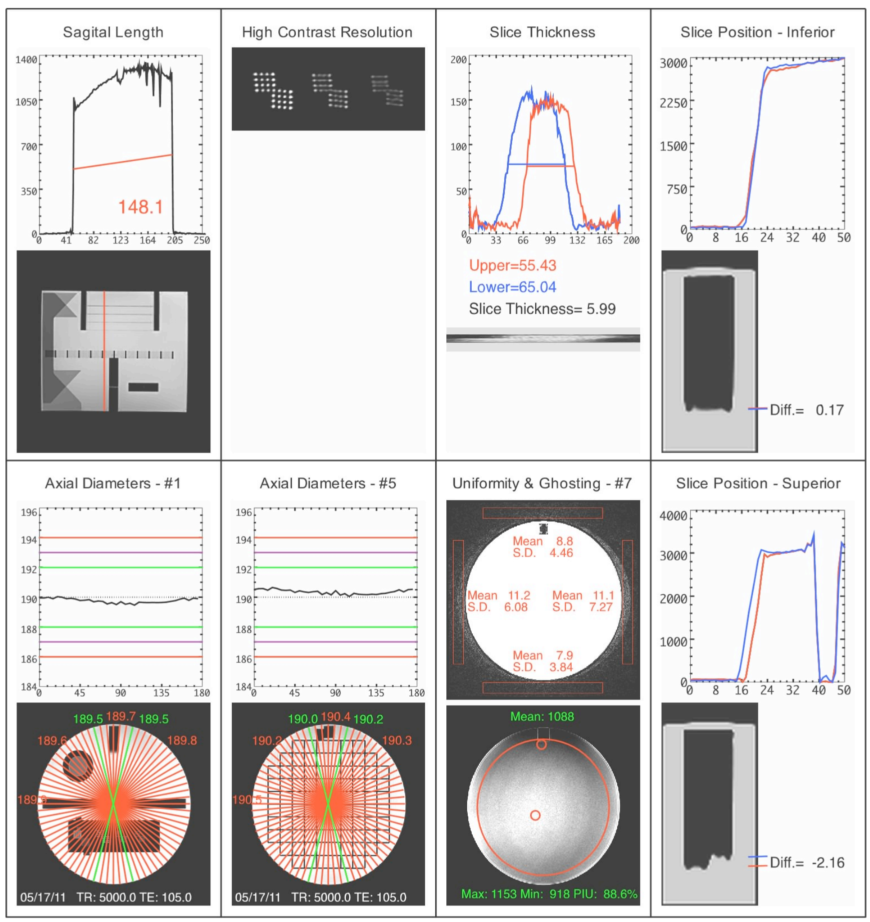
In addition, to the PA coil problems, I noted a never before seen shading in the body coil images on the 0.7T OpenSpeed system. The hypothesis was that the top half of the Body transmit coil was dead. We were able to verify this by running a GRE sequence with a 180° flip angle. Anywhere in the image that actually experienced a 180° pulse would have little or no signal. The images below show that the 180° band was only on the bottom half of the images, as compared to a normal scanner where there is an obvious upper and lower component.

7 slices about Isocenter using GRE with 180° flip angle



Daily/Weekly QA Program

The ACR requires that all facilities perform at least weekly testing of the ACR phantom, although daily testing is strongly recommended. While some sites are conscientious about this, others find the need to manually make all of the required measurements rather tedious. They would often run the QA scans and then only analyze them when they had a bunch to process. Additionally, most vendors do not provide very good tools for making the measurements. In April, 2009 an on-line, automated daily QA program was put in place. Technologists run a Sagittal Localizer, Axial T1 and Axial T2 study. Typical scan time is 5-6 minutes. The data is DICOM transferred to a remote server where the images are analyzed and the results stored in an online database which is reviewed daily for potential problems.



The graphs on the right depict 32 months of automated daily QA analysis. Of particular note are the jumps in the sagittal length values along with corresponding changes in the axial diameters. The deviations from the ideal ACR spec values occurred every time the GE service engineer performed a PM and were restored to the ideal values at the physicist's next visit.

In addition to what as been discussed all above, the table on the right lists the number of times other types of problems were detected during the annual performance analysis visits.

Miscellaneous Problems		
Description	**Count**	**% of tests**
Magnet Shim	61	11.4%
RF Noise	29	5.4%
Gradient Calibration	46	8.6%
Ghosting	36	6.7%
Image Uniformity	22	4.1%
Soft Copy	65	12.2%
Hard Copy	50	9.4%
5 Gauss Line	20	3.7%
Fire Extinguisher	27	5.1%
General Safety	20	3.7%

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