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Quality Assurance of Clinical MRI Scanners Using ACR MRI Phantom: Preliminary Results

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Clinical magnetic resonance imaging (MRI) scanners play an important role in the diagnosis of diseases and management of patient treatment. Quality assurance (QA) of the clinical MRI scanners is mandatory to obtain optimal images in a modern hospital. In this report, the phantom test for the American College of Radiology (ACR) MRI accreditation is used as the essential part of the MRI QA protocols. Seven important assessments of MR image quality are included as follows: geometric accuracy, high-contrast resolution, slice thickness accuracy, slice position accuracy, image intensity uniformity, percent signal ghosting, and low-contrast object detectability. In addition, signal-to-noise ratio and central frequency are monitored as well. The MRI QA procedures were applied to four clinical MRI scanners in our institute twice within 3 months. According to the QA results, the service engineers were more efficient in solving scanners problems when the ACR phantom test was run.

KEY WORDS: MRI, quality assurance, ACR, phantom, image quality

QUALITY ASSURANCE (QA) of medical imaging systems is important and necessary in a modern hospital. Computer-aided imaging systems, such as the computed tomography (CT) and magnetic resonance imaging (MRI) scanners, require specially designed QA tests on digital images. The QA of MRI scanners has been developed and applied clinically since the 1980s.[1] Early QA of MRI scanners focused on the signal quality[1-4] and measurement of the signal-to-noise ratio (SNR) to evaluate the stability of MRI scanners. In the late 1980s, a specially designed MRI phantom was introduced for QA of nuclear magnetic resonance (NMR) or MR spectroscopy (MRS) Scanners. Magnetization relaxation times were measured to evaluate scanner performance, which provided quantitative analysis of some physical aspects of the signal quality.[3] However, such studies could hardly provide sufficient information on the images quality.

During early 1990s, because of the non-zero mean background signal, a new method for measuring SNR was developed.[5] Consequently, the European Economic Communities (EEC) proposed their QA protocols and methodologies based on a series of specially designed MR phantoms (the Eurospin).[6,7] Assessments of image qualities such as geometric distortion, spatial resolution, signal uniformity, SNR, contrast-to-noise ratio (CNR), and slice thickness were included in the QA protocols. In addition, the suggested criteria for evaluation were established. Improvement in image quality has been attributed to several studies on the QA of clinical MRI scanners using new protocols and phantom design.[8-11] The Eurospin contains a series of MRI test phantoms for different purposes and applications. These phantoms can be used to evaluate most of the significant per-

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formance characteristics of an MRI scanner. However, the low cost-effectiveness and complexity of such systems make it difficult to apply them in the clinical setting.

Recently, a set of MR phantom test protocols was developed by the American College of Radiology (ACR) MRI Accreditation Program in United States.[12,13] A specially designed MR phantom was introduced for this purpose, which can be applied in almost all kinds of clinical MRI scanners. Seven important assessments of MR image quality were included: geometric accuracy, high-contrast resolution, slice thickness accuracy, slice position accuracy, image intensity uniformity, percent signal ghosting, and low-contrast object detectability. Thus the phantom test for ACR MRI Accreditation may represent an ideal QA program for clinical MRI scanners. In comparison with other MR QA tests, the ACR phantom tests use only one phantom, which means that each test can be accomplished in a reasonably short period of time (within one hour in our cases). Both quantitative and qualitative approaches are utilized to analyze the performance of clinical MRI scanners. According to the results of the tests, medical physicists and service engineers are able to correct the inadequate items and thus obtain images with improved quality.

In this report, the ACR phantom test is the essential part of the routine MRI QA program. The preliminary results of the test in our institute are presented here. In addition, SNR and the central frequency of the scanners are measured and monitored. According to the QA results, the service engineers are more efficient in providing regular services and trouble-shooting.

MATERIALS AND METHODS

All the proposed QA procedures were applied to the four clinical MRI scanners in our MRI center. Three of the scanners are 1.5 T (Signa 4× and 5×, GE, Milwaukee, WI, USA; and Magnetom Vision, Siemens, Erlangen, Germany), and one is 1.0 T (Magnetom Impact, Siemens, Erlangen, Germany). The QA test described in this study was performed twice with a time interval of 3 months, which synchronized the service engineers' maintenance period. In addition, daily and weekly quality control tests are routinely conducted at our site (data not shown) according to the ACR 2001 MRI QC Manual.[13]

Image Acquisition

The ACR MRI phantom is a short and hollow cylinder with acrylic plastic closed at both ends. It is filled with solution containing 10 mM $NiCl_2$ and 75 mM NACl.[12] The inner length of this phantom is 148 mm and the inner diameter is 190 mm. There are two words "NOSE" and "CHIN" labeled outside the phantom, which indicate the correct orientation for positioning the phantom in a head coil. Inside this phantom, are several complex structures that are used for generating desired images for either qualitative or quantitative analysis. The phantom test requires at least two sets of conventional MRI scans, eg, the spin echo T1- and T2-weighted imaging. The suggested protocols by ACR comply with the minimal requirement for all conventional MRI scanners. However, for the MRI accreditation program, the site protocols are to be tested as well.

To incorporate the phantom test into our routine QA program, we chose to use the ACR suggested protocols alone. After delicate positioning of the phantom at the center of the head coil, 11 axial images with a slice thickness of 5 mm and an inter-slice gap of 5 mm were acquired in each of the scans. A conventional spin echo sequence was used for the T1-weighted imaging (TR/TE = 500/20 ms). Dual echo images were obtained from the spin echo scan (TR/TE = 2000/20 ms, for the first echo, and 2000/80 ms for the second echo). In-plane resolution was set to be 1×1 mm.

Image Analysis

Following the ACR guidance, geometric accuracy, slice thickness accuracy, slice position accuracy, signal intensity uniformity, and percentage signal ghosting were quantitatively measured, whereas high-contrast spatial resolution and low-contrast object detectability were qualitatively determined.[12] The SNR of both T1- and T2-weighted imaging series was measured on the 8th slice. Using the region-of-interest (ROI) measurement tools on console, mean signal intensity of the central 80% area of the phantom was calculated. Consequently, noise was determined as the standard deviation of another ROI that was placed outside the phantom with an adequate area. To avoid ghosting effects, the location of the noise measurement was kept away from the phase-encoding direction. The SNR was then obtained by dividing the standard deviation of the outside ROI from the mean of the inside ROI. Static magnetic field was determined by the central frequency analysis provided on console. Both SNR and central frequency should be recorded daily to monitor scanner performance. Therefore these parameters were included in our QA program, in addition to the ACR phantom test. In general, the observed SNR and central frequency of each MRI scanner differ from one another. Therefore, these measurements are recorded only to evaluate the long-term stability of the corresponding scanners.

RESULTS

The results of the proposed QA program, as applied to four MRI scanners in our instituto, are illustrated in Table 1. Each MRI scanner was evaluated twice. The results of the ACR items are marked as either pass or fail according to the suggested criteria. Scanner 1 failed the geometric accuracy and the image intensity uniformity tests in the first QA, and it passed the same items in the second QA, after adjustments were made by ser-

Table 1. Results of MRI Quality Assurance

	Scanner No. / Test No.	1		2		3		4	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd
Geometric accuracy (mm)	Localizer	−2	0	−1	−2	−2	+1	−2	+1
	Slice 1[1]	−2	−1	−2	0	0	0	0	0
	Slice 1[2]	−1	−1	−1	−1	0	−1	0	0
	Slice 5[1]	−2	−1	−2	−2	0	0	0	−1
	Slice 5[2]	−1	0	−2	0	−1	−1	−1	−1
	Slice 5[3]	−3*	−1	−1	0	−1	0	−1	0
	Slice 5[4]	−3*	0	−1	−1	0	0	0	0
High-contrast spatial resolution (mm)	T1[5]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	T1[6]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	T2[5]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	T2[6]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Slice thickness accuracy (mm)	T1	+0.3	+0.6	+0.5	+0.4	+1.4[a]	+1.2[a]	+0.4	+0.6
	T2	+0.2	+0.1	+0.2	0	+0.3	+0.4	−0.1	+0.1
Slice position accuracy (mm)	T1[7]	+1	+1.5	+1	−2	+1.5	+1.5	0	−1
	T1[8]	+2	+1	+1	−1	+0.5	0	+0.5	−0.5
	T2[7]	+1.5	+1	+1.5	−1.5	+2	+1.5	0	−1
	T2[8]	+2.3	+2	+1	−1	+0.5	0	+0.5	−0.5
Image intensity Uniformity (%)	T1	88[a]	91	93	92	91	93	92	92
	T2	89[a]	93	92	94	91	92	92	94
Percent signal ghosting (%)	T1	0.04	0.8	0.05	0.03	1.2	0.4	0.2	0.4
Low-contrast object detectability (contrast level)	T1 (1.4%)	0	3	9	8	9	8	9	5
	T1 (2.5%)	9	9	10	9	10	9	10	6
	T1 (3.6%)	9	10	10	9	10	10	10	9
	T1 (5.1%)	9	10	10	10	10	10	10	10
	T2 (1.4%)	0	2	7	2	8	4	8	5
	T2 (2.5%)	0	8	10	8	9	9	9	7
	T2 (3.6%)	2	9	10	9	9	9	10	9
	T2 (5.1%)	9	10	10	9	9	10	10	10
Signal-to-noise ratio	T1	283	427	343	294	164	139	382	206
	T2	181	284	227	158	144	83	283	121
Central frequency (Hz)		63870647	63870545	63867509	63869411	63590094	63589389	40481340	40481282

[a]Measurement does not satisfy ACR criteria.
[1]:vertical dimension; [2]:horizontal dimension; [3]:diagonal dimension, from upper left to lower right; [4]:diagonal dimension, from upper right to lower left; [5]:horizontal resolution; [6]:vertical resolution; [7]:bias in superior slice; [8]:bias in inferior slice

vice engineers. Similarly, Scanner 3 failed the slice thickness accuracy test in both QA assessmento, but it passed in a recent QA (data not shown) after the correction.

DISCUSSION

The proposed QA protocol provides a simple and comprehensive assessment of the performance of an MRI scanner. Almost all the relevant features of clinical MR images are evaluated by either quantitative or qualitative approaches. The results show that our scanners passed most of the ACR QA tests. However, some items failed the test and are discussed in the following paragraphs.

Geometric Accuracy

The magnetic gradient, which was not optimally calibrated, resulted in image distortion and caused a failure of this test in one scanner

(Table 1). It caused the associated dimension (x, y, or z) in the images to change in length as compared to real values. Extremely low bandwidth during image acquisition is sometimes used to improve the SNR. However, using this technique leads to image distortion with normal heterogeneity of the main magnet. Except for previous causes, abnormally high heterogeneities of the magnet could possibly lead to failure of this test.

Comparing the geometric test (Table 1) with other tests of the same QA procedure, the primary reason of the failure in geometry is attributable to the combination effects of non-linearity of the gradient systems. The results of the low-contrast resolution test and the uniformity test in Table 1 imply the clues to this inference. The gradient systems were then calibrated and solved by the service engineers after the first QA.

Slice Thickness Accuracy

The thickness of each slice is determined by both the applied RF bandwidth and the slice-selective magnetic gradient. However, in most cases, the slice-selective gradient plays a more important role than the other. In case of our failure (Table 1), the raise time of the slice-selective gradient was somewhat delayed and exceeded the acceptable limits, which was discovered during the following routine maintenance. In such conditions, the gradient strength that the phantom experienced was below the desired value, and thus a broader slice thickness was excited. In our experience, the image quality does not change significantly, even from the MRI scanner that failed this test. However, to minimize the partial volume averaging, it is necessary for the service engineers to correct this failure. After the correction process, this item passed the third, most recent test. The poor RF profile and broader RF bandwidth would sometimes lead to failure of this test, in which case, the calibration of the RF pulse is necessary and must be able to solve this problem.

Image Intensity Uniformity

Poor phantom positioning, ghosting, and head coil failure are the potential causes of the failure in the uniformity test. Furthermore, instability, including motion and vibration, of the phantom would generate a ghosting signal that influences the uniformity of the image intensity. The failure observed in Table 1 was likely due to the non-linearity of the gradient systems as well as the geometric test. The non-linearity of gradient systems leads to greater inhomogeneity of the magnetic field. Therefore, the differences of the maximal and minimal signal intensity during the first QA is larger than those in the second measurement. This problem was solved after recalibration of the gradient systems by service engineering.

In this study, some of the test procedures, eg, central frequency, geometric accuracy, high- and low-contrast resolution, are also performed daily at our site, as suggested in the ACR QC Manual.[13] However, those tests were conducted for both T1- and T2-weighted images, whereas only T1-weighted images are tested daily. Other test procedures, including the slice thickness and position accuracy, image intensity uniformity, percentage signal ghosting, and SNR are performed every 3 months to synchronize the service engineer's maintenance protocol, instead of yearly as suggested by ACR. It was noted that two of the failed tests, slice thickness accuracy and image intensity uniformity, were discovered in this more frequent test interval.

In summary, a phantom test for the ACR MRI Accreditation Program was used as the QA protocol for clinical MRI scanners in this study. Clinically, manufacturers usually use their own test protocols and standards to evaluate MRI scanners. Most of these tests concentrate on the stability of mechanical components and electronic circuits (eg, gradient stability and performance, RF verification and homogeneity, saturation measurement, shim check, SNR, eddy-current testing, spike test, etc, all of which are performed at our scanners). However, image quality is the final product of all these components. The image quality may not be optimized even when a scanner complies with the component tests proposed by manufacturers.

In this report, an effective evaluation of the MRI performance is demonstrated. The proposed MRI QA protocol is based on the analysis of digital images by both qualitative and quantitative approaches. Furthermore, the success of our MRI QA tests provides sufficient evidence that it can lead to better maintenance and improved services.

REFERENCES

1. Covell MM, Gerashen DO, Caroson PL, et al: Automated analysis of multiple performance characteristics in magnetic resonance imaging systems. Med Phys 13:815-823, 1986

2. Kjaer L, Thomsen C, Henriksen O, et al: Evaluation of relaxation time measurements by magnetic resonance imaging. A phantom study. Acta Radiol 28:345-351, 1987

3. Steudel A, Traber F, Krahe T, et al: Qualitative control over quantitative MR tomography: *in vitro* and *in vivo* checks on relaxation time measurements. Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahr 152:673-676, 1990

4. Duina A, Mascaro L, Moretti R, et al: Results of the quality control of magnetic resonance images. Radiol Med 83:276-281, 1992

5. Miller AJ, Joseph PM: The use of power images to perform quantitative analysis on SNR MR images. Magn Reson Imaging 11:1051-1056, 1993

6. Podo F: Quality control in magnetic resonance for clinical use. Ann Ist Super Sanita 30:123-137, 1994

7. Hyde RJ, Ellis JH, Gardner EA, et al: MRI scanner variability studies using a semi-automated analysis system. Magn Reson Imaging 12:1089-1097, 1994

8. Mascaro L, Strocchi S, Colombo P, et al: Definition criteria for a magnetic resonance quality assurance program: multicenter study. Radiol Med (Torino) 97:389-397, 1999

9. Bourel P, Gibon D, Coste E, et al: Automatic quality assessment protocol for MRI equipment. Med Phys 26:2693-2700, 1999

10. Redpath TW, Wiggins CJ: Estimating achievable signal-to-noise ratios of MRI transmit-receive coils from radiofrequency power measurements: applications in quality control. Phys Med Biol 45:217-227, 2000

11. Firbank MJ, Harrison RM, Williams ED: Quality assurance for MRI: practical experience. Br J Radiol 73:376-383, 2000

12. Phantom test guidance for the ACR MRI accreditation program. American College of Radiology, Reston, 1998

13. MRI quality control manual. American College of Radiology, Reston, 2000