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Research Paper



Measuring image sharpness using modulation transfer function in magnetic resonance imaging

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Abstract

Background/Objectives: The purpose of this study was to propose a method to maintain the objectivity and validity of measuring image sharpness by changes of ETL using MTF in MRI quantitatively and provide fundamental data for future evaluation and management of magnetic resource imaging quality.
Methods/Statistical analysis: We conducted phantom test using ACR MRI phantom. ImageJ and OriginPro programs were used for MTF measurement. For MTF measurement using edge method, after achieving ESF by using ImageJ, LSF was calculated by differentiation in OriginPro. Finally, MTF value was obtained through conversion. Image sharpness was defined based on 50% of MTF value.
Findings: Results of sharpness measurement by ETL increase revealed that MTF 50% was decreased when ETL was increased. Sharpness comparison between 1ch head coil and 8ch brain coil at 1.5T showed that it was higher for 1ch head coil, although the difference between the two was not statistically significant. However, sharpness of 1ch head coil at 3.0T MRI was found to be significantly higher than that of 8ch brain coil at 3.0T MRI.
Improvements/Applications: This study confirms the theoretical concept that MTF measured by ACR standard phantom can be used as a quantitative evaluation method for spatial resolution in the magnetic resonance medical image quality management. It can be considered a meaningful objective evaluation method.

Keywords: *Magnetic Resonance Imaging; Modulation Transfer Function; Quantitative Measurement; Quality Control; Spatial Resolution; ACR Phantom.*

1. Introduction

Magnetic resonance imaging (MRI) is a method that resonates proton in the human body using magnetic field and radio frequency (RF) to obtain imaging of indigenous physical and chemical characteristics of each cell with atomic nucleus by restructuring them using a computer [1]. Its resolution is excellent. In addition, radiation is not used in MRI for comparison between cells. Therefore, there is no radiation exposure to the human body during MRI. It is an accurate measurement method that allows imaging in desired directions without posture change.
Conventional spin echo (CSE) pulse sequence used in the beginning of MRI development fills one line inside K-space with a combination of one 90° pulse and one 180° pulse in one repetition time (TR). In other words, the image can be achieved by repeating status encoding steps. However, new fast imaging methods have been introduced due to scientific development and improvement in hardware and software. One such method is fast spin echo (FSE) pulse sequence that uses many 180° RF pulses. It can reduce image acquisition time significantly. The number of 180° RF pulses used in FSE is called echo train length (ETL). The higher the ETL, the shorter the scan time. However, echo time (TE) value also increases with increasing ETL. As T2 decay increases, reduced signal will fill K-space which can ultimately lead to more blurring of the image [2].
Sharpness is used to describe the clarity of image border. It affects the describing ability for details. It can be physically expressed as acutance. When comparison in the center of an image is big, the image is considered clear. If an image has large intensity difference between black and white with high acutance, it is considered unclear. An image with unclear outline due to blurring has low acutance. Such image is also considered as unclear [3].
Spatial resolution is used to describe the ability of an imaging device to distinguish two objects near each other. It also affects image quality. An equipment with low spatial resolution may not be able to display two objects when they are close to each other or if their differences are small. It is also closely related to the sharpness of an image. An image with low spatial resolution or low sharpness will show blurring in the edge. It may not be clear due to pixel stairs effect.
MRI's spatial resolution is evaluated by three pairs of rectangular images with four holes each in horizontal and vertical directions in ACR phantom image. Sizes of these holes are set to be 1.1 ㎜, 1.0 ㎜, and 0.9 ㎜ from the left. Pass criterion is that each of four bright dots can be visually distinguished in horizontal and vertical directions in 1 ㎜ arrangements. Because this kind of qualitative evaluation method depends on observation environment and the observer, quantitative methods that can evaluate by objective quantity set by definite theory or scientific laws are needed.

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Price et al. have proposed modulation transfer function (MTF) method as an ideal method to measure spatial resolution [4]. MTF is defined as an image system's response transmitted in the modulation process of incoming and output signals related to the image's spatial frequency. It can analyze image resolution and sharpness characteristics quantitatively [5].
MTF value is expressed as MTF curve, with X-axis representing spatial frequency and Y-axis representing size to spatial frequency which has a normalized value such as 0 and 1 or 0% and 100%. The situation when the output signal has no decrement or loss of signals is called 100% MTF or 1.0 MTF. The value of MTF curve's Y-axis 50% is used to measure image sharpness while its 10% value is defined as spatial resolution [6].
The purpose of this study was to propose a method to maintain the objectivity and validity of measuring image sharpness by changes of ETL using MTF in MRI quantitatively and provide fundamental data for future evaluation and management of magnetic resource imaging quality.

2. Materials and methods

2.1. Magnetic resonance imaging

This research used MRI administrated by K hospital in Seoul. Phantom scan was performed from March, 2015 until August 2016. Acquisition of image utilized 1.5 tesla (T) and 3.0T MRI (GE Healthcare, Milwaukee, WI, USA), 1 channel (ch) and 8 ch RF coil (GE Healthcare, Milwaukee, WI, USA). ACR standard phantom (JM specialty parts, San Diego, CA) was applied to quantitatively analyze MTF. This phantom is used for current medical image quality management.
For scan sequence, FSE T2 WI was used. For scan parameter, ETL was increased by 10, 20, and 40 with the following fixed conditions: TR, 4000 ㎳; TE, 100 ㎳; receive bandwidth, ± 31.25 ㎑; and average (NEX), 2.

2.2. Measurement of MTF

ImageJ version 1.50i (Wayne Rasband, National Institutes of Health, USA) and OriginPro version b93 (OriginLab Corporation, Northampton, MA, USA) were used to measure MTF. This research used edge method for MTF measurement and ACR standard phantom. A ramp bar was selected to replace edge block. The ramp bar in the image was revolved by 2° anticlockwise in the vertical condition by "CHIN" direction revolved clockwise by 2° from the vertical condition (Figure 1).
To remove staircase effect in digital radiation image system in advance research studies, decreasing valid sampling by rotation of slit's angle by 2° has been used [7]. All images were saved as DICOM 3.0 after they were transmitted to PACS from MRI work station. For MTF measurement using the edge method, after achieving ESF by using ImageJ, LSF was calculated by differentiation in OriginPro. Finally, MTF value was obtained through conversion.
After setting ROI size to find ESF in ImageJ, each of 6 ROI was positioned from six images in the left and right of the ramp bar (3 on each side). ROI's positions and sizes were all different. ROI was saved. A total of 18 ROI set-up values were obtained in ROI Manager of ImageJ. They were classified into three groups by image numbers. ROI with size and position data saved was used for all series, focusing on measurement's objectivity and reproducibility.
After copying X-axis and Y-axis values of ESF in ImageJ into OriginPro, Y-axis value was selected and LSF was derived through differentiation. After transforming LSF to fast Fourier, the definite value was picked from results consisting of real and imaginary parts. Noise was removed by applying a smoothing filter after selecting "Magnitude" graph among other graphs printed through fast Fourier transform (FFT). Savitzky-Golay method with various smoothing options was used in this research. Savitzky-Golay is a filter that can remove noise while retaining its shape in the maximum value. It is most suitable for removing noise without affecting the entire signal shape [8].
Smoothed data were converted into a range of 0 to 1 through normalization. We defined 50% value of MTF as sharpness. With this method, the average and standard deviation were calculated by repeating [1-6] ROI using respective image's MTF value.

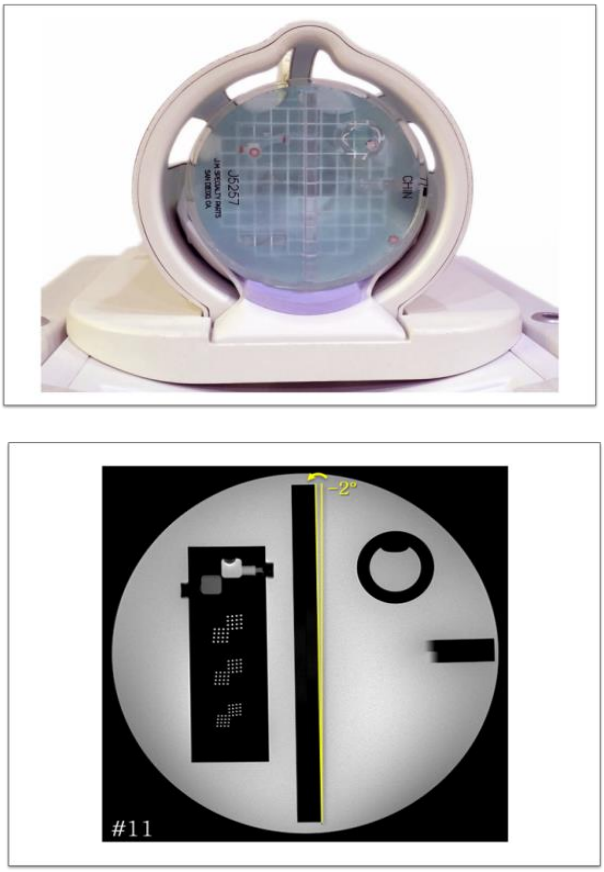


Fig 1: Phantom Image Acquisitioned by ACR Phantom (A) and 8 Channel Brain Coil (B).

2.3. Statistical analysis

Measured data were compared and analyzed using SPSS statistics package program to confirm each group's statistical significance. For each data comparison and analysis, average difference was used to compare sharpness based on changes of ETL. Statistical significance was considered at $p < 0.05$.

3. Results

ETL was set to be 10, 20, and 40 for sharpness evaluation. Results of comparison of image sharpness by changes of ETL and type of coil in 1.5T MRI are shown in Table 1. Results of image sharpness by change of ETL and type of coil in 3.0T MRI are shown in Table 2.
MTF50% values acquisitioned at 1.5T MRI and 1 ch head coil were: ETL10, 0.33236 ± 0.00901 lp/㎜; ETL20, 0.30799 ± 0.00819 lp/㎜; and ETL40, 0.26402 ± 0.00646 lp/㎜. Differences among them were found to be statistically significant ($f = 113.227$, $p < 0.001$).
MTF50% values acquisitioned at 1.5T MRI and 8 ch head coil were: ETL10, 0.33045 ± 0.01199 lp/㎜; ETL20, 0.30125 ± 0.00704 lp/㎜; and ETL40, 0.25603 ± 0.00478 lp/㎜. Differences among them were also statistically significant ($f = 117.030$, $p < 0.001$).
MTF50% values acquisitioned at 1.5T MRI with 1 ch head coil and 8 ch brain coil were 0.30142±0.03001 lp/㎜ and 0.29591±0.03250 lp/㎜, respectively. Although the value for 1 ch head coil was

higher, the difference between the two was not statistically significant (t = 0.529, $p > 0.05$).

MTF50% values acquisitioned at 3.0T MRI with 1 ch head coil were: ETL10, 0.38103 ± 0.00289 lp/㎜; ETL20, 0.36720 ± 0.00832 lp/㎜; and ETL40, 0.31016 ± 0.00806 lp/㎜. Differences among them were statistically significant (f = 178.244, $p < 0.001$).

MTF50% values acquisitioned at 3.0T MRI with 8 ch head coil were: ETL10, 0.30457 ± 0.01405 lp/㎜; ETL20, 0.32048 ± 0.01490 lp/㎜; and ETL40, 0.25739 ± 0.01297 lp/㎜. Differences among them were also statistically significant (f = 32.975, $p < 0.001$).

MTF50% values acquisitioned at 3.0T MRI with 1 ch head coil and 8 ch brain coil were 0.35280±0.03222 lp/㎜ and 0.29415±0.03054 lp/㎜, respectively. The value for 1 ch head coil was found to be significantly higher than that for 8 ch brain coil (t = 5.605, $p < 0.001$)

Table 1: Comparison of Image Sharpness by Change of ETL and Type of Coil in 1.5T MRI

	ETL 10[a]	ETL 20[b]	ETL 40[c]	Mean	f, $p^{\dagger}$	Duncan
1 ch head coil	0.33226 ± 0.00901	0.30799 ± 0.00819	0.26402 ± 0.00646	0.30142 ± 0.03001	f = 113.327, p<0.001	a >b > c
8 ch head coil	0.33045 ± 0.01199	0.30125 ± 0.00704	0.25603 ± 0.00478	0.29591 ± 0.03250	f = 117.030, $p < 0.001$	a > b > c
t, $p^{\dagger\ddagger}$	t = 0.529, p = 0.600					

Data presented mean ± standard deviation
†; One-way ANOVA, ‡; Independent t-test
ETL: echo train length; ch: channel

Table 2: Comparison of Image Sharpness by Change of ETL and Type of Coil in 3.0T MRI

	ETL 10[a]	ETL 20[b]	ETL 40[c]	Mean	f, p	Duncan
1 ch head coil	0.38103 ± 0.00289	0.36720 ± 0.00832	0.31016 ± 0.00806	0.35280 ± 0.03222	f = 178.244, p < 0.001	a > b > c
8 ch head coil	0.30457 ± 0.01405	0.32048 ± 0.01490	0.25739 ± 0.01297	0.29415 ± 0.03054	f = 32.975, P < 0.001	ba > c
t, p	t = 0.529, p = 0.600					

Data presented mean ± standard deviation
†; One-way ANOVA, ‡; Independent t-test
ETL: echo train length; ch: channel

4. Discussion

For medical image quality management, equipment is regulated, including MRI, CT, and mammography equipment. There are seven phantom image examination items in MRI: geometric accuracy, high contrast spatial resolution, slice thickness accuracy, slice position accuracy, image intensity uniformity, percent signal ghosting, and low contrast object detectability [9]. For spatial resolution, the radiology expert has to visually examine the degree of distinction for closely arranged dots to obtain horizontal and vertical resolutions. The passing criterion is that diameters of dots from the left are each 1.1 ㎜, 1.0 ㎜, and 0.9 ㎜ while horizontal and vertical resolutions should be distinguished in the group of dots with diameters under 1.0 ㎜. Qualitative method can be affected by subjective judgment. It may depend on the experience and skills of evaluators. Therefore, objective and quantitative evaluation methods need to be developed for such evaluation.

Spatial resolution affects the ability to separate two close objects in medical image. In general, length in [㎜] or [lp/㎜] unit made of black and white is used [10]. It is closely related to the scan time in MRI. Because an increase in scan time is directly related to an increase of equipment management, medical institutes have to consider disease diagnosis purpose and economic expense when deciding image quality.

As a method to reduce examination time in MRI, FSE can obtain signals by authorizing many 180° pulses in conventional spin echo sequence. The number of 180° pulses in FSE is called ETL. The examination time is reduced by 1/ETL. However, indiscriminate ETL will increase image blurring which can drop spatial resolution and sharpness.

Therefore, this research used an objective MTF method to evaluate image sharpness based on increase of ETL. MTF is defined as an image system response transmitted in modulation process of incoming and output signals [5]. Pin hole measurement, slit measurement, and edge measurement are commonly used measurement methods for MTF.

This research used ACR standard phantom and edge measurement method for MTF measurement. Fujita et al. [7] have stated that phantom should be rotated by about 2° to remove staircase effect that may occur in a digital environment. Regarding the algorithm used for the measurement, ImageJ and OriginPro programs have been used in the report "Quantitative analysis of the spatial resolution by the digital image post-process and the focus size in CR (computed radiography)" by Seong [6]. Woo et al. have measured MTF by using ImageJ and Excel programs and compared MTF values with those obtained with ImageJ and OriginPro [11]. They found that MTF values of two groups were within ignorable error ranges. Therefore, the measurement method using ImageJ and OriginPro in this research was proved to be trustworthy through the preceding research by Woo et al. [11].

For scan of MRI, change of MTF by increase in the number of ETL (10, 20, 40) was compared and analyzed while common items were fixed. Measured MTF was used to set 50% spatial frequency as sharpness. A unit of [lp/㎜] was used.

Results of sharpness measurement by ETL increase revealed that MTF50% was decreased when ETL grew. However, for sharpness of 3.0T MRI and 8ch head coil, it was the highest at ETL 20 but the lowest at ETL 40.

Result of sharpness measurement by coil types at 1.5T revealed that MTF50% value for 1ch head coil was higher than that for 8ch brain coil, although the difference between the two was not statistically significant. However, the value for 1ch head coil at 3.0T MRI was found to be significantly higher than that for 8ch brain coil.

Sze et al. have examined image blurring as ETL is increased to 4, 8, 12, and 14 in cervical MRI [12]. They also found that image blurring was increased as ETL increased. This trend was more noticeable in short images. The increase of blurring appeared at ETL 8, but not at ETL 4. It was more clearly shown at ETL 12 and ETL 14. The reason for this is that, as ETL lengthens, reduced signal by T2 decay will fill K-space. This can cause signal imbalance, thus increasing MTF [2], [13], [14]. In this research, the decreased MTF by increased ETL was due to increased blurring by increasing ETL. Therefore, MTF value measured for spatial resolution in MRI directly reflected results of preceding research studies.

This study has some limitations. First, measurement of low magnetic device was not considered because this research was focused on high magnetic MRI. Second, variables such as SNR or CNR were not strictly regulated. Based on results of this research, we have the following suggestions. First, we need to avoid qualitative method for spatial resolution, a magnetic resonance image quality management item. We need to adopt a quantitative evaluation method. Second, the ACR standard phantom purchased by many hospitals should be utilized for quantitative evaluation method. Standard values for each equipment should be decided through more researches. Third, a standardized quantitative method is needed. In addition, measurement tools need to be established. This should be decided and carried forward as a national political business.

5. Conclusion

In conclusion, our theoretical concept that MTF measured by ACR standard phantom could be used as a quantitative evaluation method for spatial resolution in magnetic resonance medical image quality management was proved in this study. It can be considered as a meaningful objective evaluation method. Results of this study not only provide a quantitative evaluation system for future magnetic

resonance medical image quality management, but also allow accurate quality management for medical images. This will contribute to the improvement of national health.

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