Novel method for evaluating spatial resolution of magnetic resonance images

Tomokazu Takeuchi1 · Norio Hayashi1 · Yuta Asai2 · Yuka Kayaoka3 · Kiichi Yoshida2

Received: 17 August 2021 / Accepted: 22 February 2022 / Published online: 1 March 2022
© Australasian College of Physical Scientists and Engineers in Medicine 2022

Abstract
Recently, several methods for evaluating the spatial resolution of magnetic resonance imaging have been reported. However, these methods are not simple and can only be used for specific devices. In this study, we develop a new method (the ladder method) and evaluate its measurement accuracy by adapting the International Electrotechnical Commission (IEC) method to evaluate the spatial resolution. First, the suitable condition for the ladder method was determined by numerical experiments. The ladder method uses a phantom with a periodic pattern which is based on IEC method. Subsequently, the ladder method is evaluated in terms of spatial resolution by dividing the standard deviation (SD) by the average signal in the region of interest (ROI) on the ladder phantom image. To evaluate the precision of the ladder method, it is compared with the modulation transfer function (MTF) calculated from an edge image. The numerical experiment result shows that the evaluation of the spatial resolution using the ladder method is viable, in which a single regression analysis’s coefficient of correlation between ladder and MTF of 0.90 or higher is obtained for all evaluations. The ladder method can be assessed using only the signal mean value and SD in the ROI on the target image and exhibit a strong correlation with the MTF. Therefore, the ladder method is a promising method as a substitute for the MTF.

Keywords MRI · Image quality assessment · Spatial resolution · MTF · Ladder method

Introduction

Recently, imaging methods for magnetic resonance imaging (MRI) that are optimized for clinical use have been developed [1–4]. In these processes, image quality assessments are often performed, where the signal-to-noise ratio, contrast properties, and spatial resolution are considered. The modulation transfer function (MTF) is used the most owing to its definition properties, which are quantifiable and highly precise [4–10]. However, the magnitude signal obtained from MRI using the MTF cannot satisfy systems whose output scales linearly with input (linearity). This problem makes it difficult to determine the MTF of MRI [11–14]. In some studies, signals obtained prior to the absolute value arithmetic operation, which means the complex signals before making the magnitude image, were used to calculate the correct MTF; however, obtaining these complex signals is not possible in all devices. Some studies used the magnitude image with partial volume effect to calculate the MTF; for these methods, a highly accurate phantom arrangement is required. In the analysis section, calculating MTF has some difficult operations, such as differentiation of the edge profile, Fourier transformation of the line spread function, and correction for finite-element differentiation. Therefore, it is generally difficult to calculate the correct MTF of MRI. The International Electrotechnical Commission (IEC) 62,464–1 reported a method that uses the magnitude image to assess the spatial resolution of MRI [15]. This method uses periodic pattern images which contained high and low magnetic resonance (MR) signal layers. And by calculating the ratio between the signal mean and standard deviation inside the periodic pattern image, the images spatial resolution was evaluated. This periodic pattern arrangement is related to the spatial frequency, so by changing this

1 Graduate School, Gunma Prefectural College of Health Sciences, Maebashi, Gunma, Japan
2 Department of Radiology, Nippon Medical School Hospital, Tokyo, Japan
3 MedCity21, Division of Premier Preventive Medicine, Osaka City University Hospital, Osaka, Japan
arrangement the point of spatial frequency also changes. This method stipulates that when this ratio exceeds 0.56, the required spatial resolution level is achieved. Therefore, this method is simple and could be performed on the console, by setting the region of interest (ROI) on the image and by calculating the ratio between mean and standard deviation. However, this IEC method specified some conditions about the phantom arrangement and the effect of changing these conditions are not examined. In addition, this method only assessed a single spatial frequency, and the imaging parameter is assigned in this method. For these reasons, the IEC method was used to assess the spatial resolution of a specific MRI device. Hence, it is unsuitable for assessing the resolution of different imaging sequences.

In this study, we developed a method to evaluate the spatial resolution of different MRI sequences using a new application of IEC 62,464–1. We named this method the “ladder method.” By comparing the ladder method results with the MTF method results, we aim to confirm the validity of the ladder method and establish it as a viable method for evaluating the spatial resolution of MRI.

**Material and methods**

**Numerical experiment of ladder method**

In the IEC method, certain conditions are specified for the phantom arrangement. However, the effect of changing these conditions on the evaluation was not examined. The effect of changing the phantom arrangement was evaluated by using the numerical experiment.

Our proposed method for evaluating spatial resolution is a modification of the IEC 62,464–1 method. The method recommended by the IEC includes determining the image quality to ascertain and maintain the performance evaluation of medical devices. The phantom used for this method contains both high and low magnetic resonance signal layers to obtain a periodic pattern image (Fig. 1). The spatial resolution was evaluated by the modulation of this periodic pattern. It is possible to assess one spatial frequency using one phantom. Therefore, the evaluation value is expressed as $m(v)$, which indicates the modulation (m) at a specific spatial frequency (v). For the analysis, an elliptical ROI is set on the periodic pattern inside the most lateral plate. The size of the ROI should be set as large as possible; however, it should not exceed the circumference of the plates of the phantom and encompassed less than 90% of the phantom length. The signal standard deviation (SD) and the mean of the intensity (S) of the pixel inside the ROI were calculated. The $m(v)$ at spatial frequency $v$ [cycles/mm] is defined as shown in the following Eq. (1).

$$m(v) = \frac{SD}{S}$$ (1)

The spatial frequency $v$ is calculated as shown in Eq. (2).

$$v = \frac{1}{L}$$ (2)

where $L$ corresponds to the sum of the plate thickness and the distance between adjacent plates (Fig. 1). IEC 62,464–1 stipulates that when the calculated $m(v)$ exceeds 0.56, the required spatial resolution level is achieved. It is noteworthy that IEC 62,464–1 recommends the phantom periodicity below and also does not restrict the plate thickness. Regarding plate thickness, this means that spatial frequency is not restricted, and it makes the differences larger in evaluation value $m(v)$. The plate thickness is indicated by $d$, the distance between adjacent plates is $d_a$, and the sum of $d$ and $d_a$ is $L$, as illustrated in Fig. 1. The IEC recommends a $d_a/L$ ratio between 0.61 and 0.70. Therefore, the $d_a/L$ occurs as a range, and the effect of changing this condition is not examined. To study the effects of these values on the results, we performed a numerical experiment and varied each term using Excel (Microsoft Corporation, Washington, USA). When the ratio of $d$ to $d_a$ is 1 to 2, the $d_a/L$ is 0.67 and is fitted to the IEC condition, by changing the ratio of $d$ to $d_a$ is 1 to 1 and 2 to 1, the $d_a/L$ will be 0.50 and 0.80. The numerical experiment was performed using $d_a/L$ values of 0.50, 0.67, and 0.80, and plate thicknesses $d$ of 1, 2 and 3 mm for each of the $d_a/L$ cases. Through this numerical experiment, a suitable $d_a/L$ was to be obtained. In the numerical experiment, the signal was assumed to be that of the pixel arrayed in one dimension and some measurements with the values listed were conducted; also, we accounted for the ideal and blurry images. Numerical experiments based on different $d_a/L$ values and plate thicknesses were performed with a high signal.
of 100 and a low signal of 0. Figure 2 shows the signal array for a plate thickness of 2 mm and different da/L values used in the numerical experiment. When the one-pixel signal was set as $x_i$, the adjoining pixel signals was represented as $x_{i+1}$, $x_{i+2}$, ..., $x_{i+(n-1)}$. Using these pixel signals, the signal mean value and SD was calculated.

A blurry image was obtained by convoluting the convolution filter to the ideal signal. The convolution filter was a three-term filter whose weight ratio was 1:2:1.

The changes of $m(v)$ at da/L = 0.50 were further investigated with plate thicknesses of 1.0, 1.5, 2.0, 2.5, 3.0, and 4.0 mm (0.50, 0.33, 0.25, 0.20, 0.16, and 0.13 cycles/mm). In this situation, sharp and blurry images were examined. A blurry image was assumed by convoluting the convolution filter. The weight ratios of the convolution filter were changed to four stages, i.e., 1:1.5:1, 1:2:1, 1:3:1, and 1:4:1, where the 1:4:1 ratio presented a sharp image, and the 1:1.5:1 presented the most blurred image (Fig. 3).

**MR imaging of ladder method**

Phantoms containing periodic patterns, as shown in Fig. 1, were used to verify the ladder method. The phantoms were made of 10 parallel acrylic plates (density 1.19 g/cm$^3$). The plate thickness (d) and the distance between plates (da) were set to the same value. To achieve parallel acrylic plates and to maintain a certain distance between the plates, a 15 mm wide acrylic plate was sandwiched on both sides of the plates and then adhered using an acrylic resin (Fig. 1). Similar to the IEC method, the plate width (a) was set to twice the slice thickness of MR imaging, and the plate length (b) was set to ten times the length L (Fig. 1). Six different phantoms with plate thicknesses of 1, 1.5, 2, 2.5, 3, and
4 mm were fixed in a nickel sulfate aqueous solution (1.25 g NiSO₄ · 6H₂O + 1000 g H₂O). The details of the custom-developed phantom are shown in Table 1, and a custom-developed phantom with a plate thickness of 2 mm is shown in Fig. 4a. Each phantom was constructed using sections that were cut from the same acrylic plates. Hence, the accuracy of the phantom construction was high, as the different phantoms did not yield significantly different results. The angle between the phantom’s major axis (x-axis) and the magnetic bore was 13° in the initial setup. The frequency-encoding direction was matched to the x-direction of the phantom, as shown in Fig. 4b. For the imaging, the slice was set on the x–z plane, as shown in Fig. 1, to obtain the image shown in Fig. 4c.

For the analysis, the ROI was set on the periodic images. The size of the ROI was set as large as possible; however, it did not exceed the circumference of the plates of the phantom and encompassed less than 90% of the

| Phantom no. | No.1 | No.2 | No.3 | No.4 | No.5 | No.6 |
|-------------|------|------|------|------|------|------|
| d [mm]      | 4    | 3    | 2.5  | 2    | 1.5  | 1    |
| L [mm]      | 8    | 6    | 5    | 4    | 3    | 2    |
| b [mm]      | 90   | 70   | 60   | 50   |      |      |
| Spatial frequency [cycles/mm] | 0.125 | 0.167 | 0.200 | 0.250 | 0.333 | 0.500 |

The da/L is 0.50 and length of a[mm] was 20 mm

Fig. 4 a Periodic pattern phantom with plate thickness of 2 mm. b Placement of ROI on phantom image for ladder method. c Magnetic resonance image of periodic pattern phantom with plate thickness of 2 mm
phantom length. Therefore, the size of the ROI changes at different phantom. The specific ROI size at each phantom with plate thickness of 1, 1.5, 2, 2.5, 3, and 4 mm were $16 \times 44$, $27 \times 44$, $31 \times 44$, $46 \times 50$, $49 \times 56$ and $67 \times 80$ (short axis [mm] × long axis [mm]).

The S and SD of all pixels in the ROI were measured. The ladder method evaluated the spatial resolution by dividing the SD by the S in the ROI on the ladder phantom image using Eq. (1). The S and SD in the ROI were measured using ImageJ (National Institutes of Health, Bethesda, MD).

The ladder method uses the same periodic pattern phantom and involves an analysis based on IEC 62,464–1. However, the da/L ratio of the phantom was 0.50, and by changing the plate thickness, this method indicates the spatial frequency characteristics.

**Calculation of MTF**

The MTF was calculated for a comparison with the ladder method. To obtain the correct MTF, we used the partial volume effect [14]. This method uses the phantom that constructed the edge part using high-and low-magnitude signals. From this edge, the edge spread function (ESF) was obtained. To obtain this MR image, the slice was set vertical to the edge and set as the slice, including the phantom edge. Using this ESF, the line spread function (LSF) was obtained, and the MTF was calculated by a Fourier transform with respect to the LSF. Additionally, if the slice was not vertical to the edge, an error occurred in the MTF. An acrylic plate with a thickness of 20 mm was fixed in a nickel sulfate aqueous solution to evaluate the MTF (Fig. 5a). Figure 5b shows the details of the edge phantom and the relation between the phantom arrangement and the x, y, and z axes. The location of the slice used for imaging is shown in Fig. 5a–c shows a photograph of the edge phantom. The slice was set in the middle of the acrylic plate and nickel sulfate aqueous solution on the y-axis to offset the ESF baseline and eliminate all the negative lobes. This setting, based on the partial volume effect, yielded the MTF linearity. For imaging, the phantom edge, which was located in the middle of the z-axis, was set parallel to the magnetic bore. The x- and frequency-encoding directions of the images were matched (Fig. 5b). Images of the edges were obtained, and Fig. 5d shows the obtained MR image obtained. For the analysis, the square of the ROI was set on the edge of the image, and the ESF was obtained from the profile inside the ROI. The ROI measured 40 mm along the x-axis, and its length was 150 mm (Fig. 5e). To obtain the MTF, we first differentiated the ESF using Eq. (3), that is, we performed finite-element differentiation (FED), and obtained an LSF [14].

$$LSF(X_j) = ESF(X_j) - ESF(X_{j-1})$$

where X is the spatial location, and j is the number of samples. Finally, a Fourier transform was performed in the LSF operation, and the MTF was calculated. The adjustment was performed for FED using Eqs. (4) and (5), and the true MTF was calculated [16].

$$MTF(f) = MTF_e(f) \times \alpha(f)$$

$$\alpha(f) = \frac{1}{\text{sinc} \left( \frac{2f}{fc} \right)} , \quad fc = \frac{fs}{2} ,$$

where MTF(f) is the true MTF, MTF_e(f) is the experimental MTF, fc is the Nyquist frequency, and fs is the sampling frequency. ImageJ was used to set the ROI on the image and calculate the edge profile. The MTF was calculated using Excel.

**Imaging parameter**

All scans were performed using the abovementioned phantom with a loading device in a 15–channel head array coil on a 1.5 T MR system (Ingenia Philips Medical Systems, Best, The Netherlands). Data were collected using single slices via a spin echo sequence. Ten images of different resolutions were obtained for each of the six phantoms used in this study. The scanning parameters for the ladder method were based on conventional magnitude imaging, with Repetition Time (TR) = 1000 ms, Echo Time (TE) = 50 ms, slice thickness = 5 mm, and field of view = 256 mm × 256 mm. IEC 62,464–1 recommends a Signal to Noise Ratio (SNR) greater than 50. All images used for the ladder method had SNRs of 50 or higher when the number of excitations (NEX) was 1. Hence, the NEX was set to 1. The matrix size was varied to obtain images with different resolutions. The 10 different matrix sizes used were 112, 128, 160, 192, 256, 288, 352, 384, 448 and 512. Using Eq. (2), the spatial resolution was evaluated at spatial frequencies of 0.125, 0.167, 0.200, 0.250, 0.333, and 0.500 cycles/mm using the six different phantoms. Table 2 shows the plate thickness of each phantom and the spatial frequency that each phantom can evaluate.

The imaging parameters for the edge phantom were the same used for the ladder method, with NEX set to 15 to reduce the noise.

**Correlation between ladder method and MTF**

The m(v) and MTF were calculated for each of the 10 different resolutions. To evaluate the accuracy of m(v), specific cutoff values were used as described in [17]. In this paper, the
cutoff frequencies are the ones matching the following m(v) and MTF values. This specific value of the m(v) and MTF was 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8. Therefore, the cutoff frequency of m(v) and MTF at specific values (0.3 to 0.8) were calculated. If m(v) expresses the exact image resolution, it should match the MTF. If it is established, the cutoff frequencies of m(v) and MTF have a linear correlation. For this reason, the correlation coefficient between m(v) and the MTF cutoff frequency was compared in this study. The correlation coefficient was calculated with Pearson’s correlation by using IBM SPSS Statistics (Version 26, IBM Deutschland GmbH, Ehningen, Germany).

Fig. 5  a Diagram of edge phantom in y–z plane for calculating MTF.  b Detailed diagram of edge phantom shown in three dimensions.  c Custom-developed edge phantom.  d Magnetic resonance image of edge phantom with matrix size of 512.  e Placement of ROI on edge phantom image to calculate MTF
Results

Numerical experiment of ladder method

The $m(v)$ values measured at three different ratios of $da/L$ (0.50, 0.67, and 0.80) and three plate thicknesses $d$ (1.0, 2.0, and 3.0 mm) are shown in Fig. 6a. The results indicate that the $m(v)$ of the phantom with $da/L = 0.50$ varied the most with different plate thicknesses. Therefore, the phantom with $da/L = 0.50$ was used in the ladder method.

Furthermore, the numerical experiment results obtained by assuming a completely sharp image based on $m(v)$ at different spatial resolutions when $da/L = 0.5$ are shown in Fig. 6b. The evaluated results of $m(v)$ did not vary from the maximum value of 1 at different spatial frequencies owing to the changes in the plate thickness. Figure 6c shows the results of the blurry pattern using four different convolution filters. These results show that $m(v)$ decreased at high spatial frequencies and increased at high resolutions.

MR imaging of ladder method

The $m(v)$ values obtained using the ladder method for each plate thickness in the images of the 10 different matrix sizes

Table 2 Plate thickness of phantom for ladder method, and spatial frequency that each phantom can present

| Phantom plate thickness [mm] | Spatial frequency [cycles/mm] |
|-----------------------------|-----------------------------|
| 4.0                         | 0.125                       |
| 3.0                         | 0.167                       |
| 2.5                         | 0.200                       |
| 2.0                         | 0.250                       |
| 1.5                         | 0.333                       |
| 1.0                         | 0.500                       |

Fig. 6  

(a) $m(v)$ vs plate thickness evaluated for different $da/L$.  
(b) $m(v)$ vs spatial resolution for $da/L = 0.50$.  
(c) $m(v)$ vs spatial frequency for four different convolution filters
are shown in Fig. 7. The m(v) value decreased as the spatial frequency increased. The m(v) was low in the low-resolution images, similarly for the small matrix sizes.

**Calculation of MTF**

Figure 8 shows the MTF of the ten different resolution images obtained by changing the matrix size. For the low-resolution image, the MTF indicated a low value. Each MTF was calculated until the Nyquist frequency was reached.

**Correlation between ladder method and MTF**

Figures 9 shows the relationship between m(v) and the MTF cutoff frequency at m(v) and MTF values of 0.3, 0.5, and 0.8, respectively, in the 10 different resolution images. The regression lines and correlation coefficients (r) were calculated and are reported in Fig. 9. The correlation coefficient was 0.974 for the m(v) and MTF value of 0.3, 0.989 for 0.5, and 0.797 for 0.8. These values indicate a strong correlation between m(v) and the MTF.

Table 3 shows the correlation coefficient between m(v) and the MTF cutoff frequency for every value investigated.

| m(v) and MTF value | Correlation coefficient |
|--------------------|-------------------------|
| 0.3                | 0.974                   |
| 0.4                | 0.993                   |
| 0.5                | 0.989                   |
| 0.6                | 0.978                   |
| 0.7                | 0.920                   |
| 0.8                | 0.979                   |

**Discussion**

Spatial resolution has been evaluated extensively using various methods [9, 10]. However, some of these methods require the use of complex signals before making the magnitude image, which is difficult to obtain, and calculate the MTF with difficult calculations. Therefore, we propose a simpler “ladder method” to evaluate the spatial resolution of MRI. The ladder method evaluates the spatial resolution by dividing the SD by the average signal in the ROI on the phantom image of the ladder. We compared the ladder method and MTF to validate the ladder method. The numerical experiment results show that the m(v) of the phantom with da/L = 0.50 varied the most with different plate thicknesses. The phantom with da/L = 0.50 can be assumed to be
rectangular waves with a duty ratio of 1:1. This rectangular wave contained the repetition frequency and the frequency of odd harmonics. Meanwhile, at $da/L = 0.67$ and 0.80, the duty ratio was not 1:1. At this time, the rectangular wave contained the repetition frequency and the frequency of odd and even harmonics. The ladder method evaluates the spatial resolution at a single spatial frequency based on a single phantom; hence, using a phantom that contains many frequencies is not suitable for evaluating the spatial frequency of a pin point. As such, the $m(v)$ value of the phantom with $da/L = 0.50$ varied the most with different plate thicknesses. Therefore, it was clear that the phantom with $da/L = 0.50$ was the most suitable for evaluating the spatial resolution in different imaging sequences. With regard to the ladder phantom characteristics, the IEC suggests a $da/L$ of 0.61–0.70, based on the relationship with the MTF. However, the numerical experiment results indicate that $da/L = 0.50$ is suitable for evaluating the spatial resolution of different imaging sequences. The phantom structure is simple and easy to understand, that is, the phantom ratio of plate thickness and distance between plates is 1:1. The $m(v)$ value was obtained by dividing the SD by S in the ROI. The edge profile of the phantom plate became blurred, and gradation occurred in the low-resolution images. This gradation decreased the SD and hence $m(v)$. For images of the same resolution with thin plate thicknesses, the phantom cycles became finer and increased the gradation. Hence, $m(v)$ decreased. For phantoms with thin plate thicknesses, the ladder method can evaluate high-frequency spatial resolutions based on Eq. (2). Theoretically, the maximum value of $m(v) = 1$ can be obtained using Eq. (6):

$$m(v) = \sqrt{\frac{(L - d)}{d}} \tag{6}$$

This result is exhibited in the numerical experiment results for the ideal case. Based on the comparison, the correlation coefficient between $m(v)$ and the MTF cutoff frequency exceeded 0.90 for all values of $m(v)$ and MTF, which indicated a strong correlation.

Visual evaluation has been performed in many studies to evaluate the spatial resolution of MRI. It is performed by using the bar pattern or comparing the clinical images obtained in a different situation [18–22]. Visual evaluation can easily occur; however, it is a subjective evaluation. Therefore, a quantitative evaluation is required for evaluating the image quality. Quantitative evaluations for the MRI’s spatial resolution, MTF, and IEC method are proposed. Previous studies have evaluated the MRI’s spatial resolution using MTF [5, 7–9, 11]. To calculate the correct MTF, complex signals obtained prior to the absolute value arithmetic operation are required. However, these complex signals cannot be obtained in all devices. A method that uses the partial volume effect was also proposed for calculating the MTF. This method does not require the use of a complex signal; however, it requires an accurate slice setting to obtain the correct MTF. MTF represents the ratio of the output spatial frequency component to the input spatial frequency component; therefore, the MTF Fourier transform must be calculated. This is also the reason for the difficulty and complexity of calculating the MTF. The IEC method evaluates the spatial resolution of MRI with the ratio of the signal standard deviation and the mean of the intensity of the pixel inside the ROI on the periodic pattern image. However, this method only evaluates one spatial frequency and assigns the imaging parameter to evaluate the spatial resolution of the MRI device; therefore, it is not suitable for use in different imaging sequences. In contrast to these methods, the ladder method evaluates the spatial resolution with quantitative values and uses the magnitude image for calculating the evaluation value. As for the analysis, it is simpler than calculating the MTF, as in the IEC method. In addition, the ladder method uses several phantoms to evaluate different spatial frequencies, and by not specifying the imaging parameter, it is suited to evaluate different imaging sequences. Therefore, the ladder method is a useful yet easy method for evaluating spatial resolution.

In this study, we used plate thicknesses of 1, 1.5, 2, 2.5, 3, and 4 mm. However, it is unclear whether these configurations are sufficient for the spacing requirements. Hence, different plate thicknesses should be used to evaluate the spatial resolution in future studies. Although several different resolution images were evaluated in this study, images with different contrasts or distortions were not analyzed. Some issues may emerge when using different imaging sequences; therefore, further investigations are required to expand the applicability of this method.

**Conclusion**

In this study, we demonstrated that the ladder method exhibited a strong correlation with the MTF, and that it can be used to evaluate the spatial resolution of MRI. An additional benefit of the ladder method is that it is measured only using the S and SD in the ROI on the target image. Therefore, the ladder method is a useful method that can be a substitute for the MTF.

Further studies will be conducted in order to expand the feasibility of this method.

**Acknowledgements** I am grateful to Dr. A. Ogura for giving me constructive comments and warm encouragement. I also thank Dr. T. Miyati for clear advice and comments.

**Authors contributions** NH made the substantial contributions to the conception. YA, YK and KY interpreted the phantom data.
Funding No finding was received.

Data availability Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The author declared that they have no conflict of interest.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Research involved in human and animal rights This article does not contain any studies with human participants performed. This article does not contain any studies with animals performed.

References

1. Aritrick C, Carla H, Aytekin O (2020) New prostate MRI techniques and sequences. Abdom Radiol 45:4052–4062
2. Jerome P, Marie L, Wafa S et al (2014) New dynamic three-dimensional MRI technique for shoulder kinematic analysis. J Magn Reson Imaging 39:729–734
3. Yi W, Tian L (2015) Quantitative susceptibility mapping (QSM): decoding MRI data for a tissue magnetic biomarker. Magn Reson Med 73:82–101
4. Paul S, Ankur D, Lisa L et al (2020) New arterial phase enhancing nodules on MRI of cirrhotic liver: risk of progression to hepatocellular carcinoma and implications for LI-RADS classification. AJR 215:382–389
5. Delakis L, Xantthis C, RI K (2009) Assessment of the limiting spatial resolution of an MRI scanner by direct analysis of the edge spread function. Med Phys 36:1637–1642
6. Borri M, Scurr ED, Richardson C, Usher M, Leach MO, Schmidt MA (2016) A novel approach to evaluate spatial resolution of MRI clinical images for optimization and standardization of breast screening protocols. Med Phys 43:6354–6363
7. Lim WT, Jung HR (2016) Evaluation on availability of MTF measurement using the ACR phantom in MRI. Indian J Sci Technol 9:1–5
8. Mohapatra SM, Turley JD, Prince JR, Blechinger JC, Wilson DA (1991) Transfer function measurement and analysis for a magnetic resonance imager. Med Phys 18:1141–1144
9. Steckner MC, Drost DJ, Plato FS (1993) A cosine modulation artifact in modulation transfer function computations caused by the misregistration of line spread profiles. Med Phys 20:469–473
10. Cunningham IA, Reid BK (1992) Signal and noise in modulation transfer function determinations using the slit, wire, and edge techniques. Med Phys 19:1037–1044
11. Miyati T, Fujita H, Kasuga T et al (2002) Measurements of MTF and SNR(f) using a subtraction method in MRI. Phys Med Biol 47:2961–2972
12. Steckner MC (1990) Magnitude reconstruction distorts Gibb’s phenomenon in magnetic resonance imaging. Proceedings of the Society of Magnetic Resonance Imaging (SMRM), 9th Annual Meeting, SNRM, New York
13. Steckner MC, Drost DJ, Plato FS (1992) Comments and reply:’ “Transfer function measurements and analysis for a magnetic resonance imager”’ (Mohapatra et al 1991). Med Phys 19:511–512
14. Steckner MC, Drost DJ, Plato FS (1994) Computing the modulation transfer function of a magnetic resonance imager. Med Phys 21:483–489
15. IEC 62464–1, Magnetic resonance equipment for medical imaging – Part1. Determination of essential image quality parameters. 2018
16. Cunningham IA, Fenster A (1987) A method for modulation transfer function determination from edge profile with correction for finite-element differentiation. Med Phys 14:533–537
17. Kwon M, Legge G (2011) Spatial-frequency cutoff requirements for pattern recognition in central and peripheral vision. Vision Res 51:1995–2007
18. Ullrich T, Quentin M, Oelers C et al (2017) Magnetic resonance imaging of the prostate at 15 versus 30T: a prospective comparison study of image quality. Eur J Radiol 90:192–197
19. Vos E, Lagemaat M, Barentsz J et al (2014) Image quality and cancer visibility of T2-weighted Magnetic Resonance Imaging of the prostate at 7 Tesla. Eur Radiol 24:1950–1958
20. Rosenkrantz A, Bennett G, Doshi A et al (2015) T2-weighted imaging of the prostate: Impact of the BLADE technique on image quality and tumor assessment. Abdom Imaging 40:552–559
21. Caglic I, Hansen N, Slough R et al (2017) Evaluating the effect of rectal distension on prostate multiparametric MRI image quality. Eur J Radiol 90:174–180
22. Gassenmaier S, Afat S, Nickel D et al (2021) Deep learning-accelerated T2-weighted imaging of the prostate: Reduction of acquisition time and improvement of image quality. Eur J Radiol 137:109600

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.