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FULL PAPER

Novel practical SNR determination method for MRI using double echo with longest second echo time (DELSET)

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Objective: We devised a practical method using double echo with the longest second echo time (DELSET) for simple and accurate signal-to-noise ratio (SNR) measurement of MRIs.

Methods: The DELSET method is based on the double-echo sequence in which the first and second echo times (TE) are set, respectively, as the clinically acceptable time for the signal image and as the longest time for the noise image. The second TE needs to be at least 8 times longer than T_2 (for spin-echo) or T_2^* (for gradient-echo) of the objective tissue. For example, second TE > 560 ms for the case of $T_2 = 70$ ms: the real part of signal intensity theoretically reaches the same order of magnitude as the quantization limit, due to the T_2 relaxation process. SNR was calculated by dividing mean signal intensity in the first echo image by signal standard deviation (SD) in the second echo image in identical regions of interest after necessary noise correction. We determined the SNRs of cylindrical phantom images with different coils [quadrature (QD) and array coils] and sequences

(spin-echo and spoiled gradient-echo sequences) and compared them between the DELSET and subtraction or background methods. The ratio of the mean signal intensity and SD in the second echo image with QD coil was determined to confirm whether the signal intensity had reached noise level.

Results: There were no significant differences in the phantom SNRs with both coils and sequences when DELSET was compared with the other two methods ($p > 0.05$ for all). The ratios of mean signal intensity and SD in the second echo images with both sequences were found to be in general agreement with a theoretical value. It was possible to obtain SNR images of the phantom, brain and abdomen with the DELSET method.

Conclusion: The DELSET method enables simple and accurate SNR quantification. This practical method is applicable to *in vivo* parallel imaging.

Advances in knowledge: Practical SNR quantification based on the DELSET method is feasible for application in MRI systems used clinically.

INTRODUCTION

The signal-to-noise ratio (SNR) of MRIs is the key indicator for quality assurance and control, as well as for acceptance testing or the performance evaluation of new hardware.^{1,2} Numerous methods for accurate SNR quantification have previously been reported.^{3–7}

One of the simplest measurement of SNR is the background method whereby mean signal intensity in a region of interest (ROI) placed on an image object is divided by the standard deviation (SD) of signal in an ROI placed on the background area outside the object.^{8,9} However, this method assumes that noise is spatially invariant over the entire image and, therefore, is not applicable when using

parallel imaging or image non-uniformity correction that causes a spatial variation in noise, resulting in that the estimated noise depends on the measurement position.^{10–15}

The most reliable SNR measurement is the image subtraction method, also known as the National Electrical Manufacturers Association method 1,⁵ which has been identified as a gold standard in measurements of SNR for MRI combined with parallel imaging or image non-uniformity correction.^{13,15} This method can provide a noise image by subtracting two identical images obtained under identical imaging conditions. Consequently, it can eliminate the effects of image non-uniformity and truncation artifact.^{13,15} However, because this method requires

repeated scans that doubles the scan time, it has a high sensitivity to system drift and image misregistration induced by subject motion, resulting in erroneous results.⁶ Thus, this method is not necessarily practical for *in vivo* SNR measurements in clinical practice.¹⁴ While there is an alternative method capable of obtaining the noise image with a single acquisition,⁶ thereby eliminating the effects of artifacts including non-uniformity and system drift, it requires the special settings for data reconstruction.

Therefore, the development of a more practical SNR quantification method for application in clinically used MRI systems is still required. In this study, we proposed a practical method using double echo with the longest second echo time (DELSET) for simple and accurate SNR measurement of MRIs. The proposed method was tested in phantom and *in vivo* experiments.

METHODS AND MATERIALS

DELSET method

The DELSET method is based on the double-echo sequence in which the first and second echo times (TE) are set as the clinically acceptable time for the signal image and as the longest time, *i.e.* the maximum available TE in the sequence, for the noise image, respectively. Note that the second TE needs to be at least 8 times longer than T_2 [for spin-echo (SE) sequence] or T_2^* (for gradient-echo sequence) of the objective tissue or material. Consequently, the real part of signal intensity theoretically reaches the same order of magnitude as the signed 16-bit quantization limit ($1/32,768$, *i.e.* $3.1 \times 10^{-3}\%$ of signal intensity at TE = 0 ms); that is, signal is attenuated as low as possible to noise level because of the T_2 relaxation process. For instance, when the T_2 of the tissue is 70 ms, the second TE of the DELSET method should be > 560 ms. We determined mean signal intensity in the ROIs on the first echo image (signal image) and considered it as a signal estimate for SNR calculation. The noise SD in identical ROIs on the second echo image (noise image) was also determined. Since conventional MRIs are computed by a magnitude operation, the noise signal in the second echo image can be described by a Rayleigh distribution, assuming it was sufficiently low and reached the background noise level. When a Rayleigh distribution is assumed, the noise SD is erroneously biased and thus could not be used directly as a true noise estimate.⁹ Therefore, an appropriate correction must be applied to the noise SD for determination of the noise estimate.⁸ Moreover, the noise estimate is also biased when the background noise in a phased-array multichannel coil image is used for noise determination.^{16,17} For the practical use of multichannel coils, images from each coil are reconstructed as a composite magnitude image by using the sum-of-squares algorithm, which is a frequently used image reconstruction method.^{18,19} Another previously reported correction factor, $1/\sqrt{2N - \beta(N)}$,² is required to estimate noise in multichannel coil images because the noise signal is distributed by the non-central chi distribution rather than by the Rayleigh distribution.²⁰ Thus, the correction factor was applied to the SD in the noise region, and corrected SD was considered as estimated noise:

$$\text{Noise} = SD_m / \sqrt{2N - \beta(N)^2} \quad (1)$$

where SD_m is the standard deviation in the ROI placed on the second echo (noise) magnitude image and N is the number of coil channels. $\beta(N)$ is defined by the following:

$$\beta(N) = \sqrt{\pi/2} [(2N - 1)!!] / [2^{N-1} (N - 1)!] \quad (2)$$

where the symbols (! and !!) denote factorial and double factorial, respectively. Although an additional correction should be used to reduce bias induced at low SNR,¹⁷ no such correction was performed because the SNRs measured in the present study were sufficiently high (see Results).

Finally, SNR was computed by dividing mean signal intensity of the first echo image by estimated noise.

Other SNR measurements

Two other SNR measurements, subtraction and background methods, were performed for comparison.

We determined SNR with the subtraction method, which is the most commonly used SNR measurement.^{5,6} In this method, a difference image was obtained by subtracting two identical images. The noise was then determined by dividing the SD in an ROI on the difference image (SD_{sub}) by an appropriate correction factor, defined as follows:

$$\text{Noise} = SD_{\text{sub}} / \sqrt{2} \quad (3)$$

where $\sqrt{2}$ is the correction factor for the bias induced by the image subtraction process. Then, SNR was calculated by dividing mean signal intensity in the ROIs on the two signal images by estimated noise.

For the background method, an ROI was positioned outside the image object in order to measure the background noise of the image. Care was taken to avoid placing the background ROI over ghost artifact along the phase-encoding direction (which is caused by flow within the phantom solution) and motion artifact (which is caused by vascular pulsation and respiration *in vivo*), both of which would yield erroneous noise estimates. The noise estimate was determined on the basis of the SD in the background ROI with the same correction factor as for the DELSET method. SNR was then calculated by dividing mean signal intensity in the signal ROI by estimated noise.^{5,8,9}

Phantom experiments

Phantom experiments were performed on a 3.0 T MRI unit (Signa HDxt, GE Healthcare, Milwaukee, WI) using a quadrature (QD) coil and a 12-channel phased-array head coil. A uniform cylinder phantom filled with low-dielectric synthetic oil (dimethylpolysiloxane), of which the diameter and length were 16.5 and 27.3 cm, respectively, and the T_1 , T_2 and T_2^* values were 216.3, 29.3 and 28.0 ms, respectively, was scanned using two different pulse sequences: a double-echo SE sequence and a double-echo spoiled gradient-echo (SPGR) sequence. The single-slice double-echo SE sequence was performed with the following parameters: TE, 12 ms (first echo) and 982 ms (second echo); repetition time (TR), 1000 ms; field of view (FOV),

Figure 1. An overview of the DELSET method. This method is based on the double-echo sequence in which the first and second TE are set, respectively, as the clinically acceptable time for the signal image and as the longest time, *i.e.* the maximum available TE in the sequence, for the noise image. Note that the second TE needs to be at least 8 times longer than T_2 (for spin-echo sequence) or T_2^* (for gradient-echo sequence) of the objective tissue or material to attenuate signal as low as possible so that the noise is the dominant effect. DELSET, double echo with the longest second echo time; TE, echo time.

256 mm; flip angle (FA), 90°; imaging matrix, 256 × 256; slice thickness, 5 mm; number of signals averaged (NSA), 1; and total acquisition time, 4 min 16 s. The single-slice double-echo SPGR sequence was performed with the following parameters: TE, 2.4 ms (first echo) and 296 ms (second echo); TR, 300 ms; FOV, 256 mm; FA, 50°; imaging matrix, 256 × 256; slice thickness, 5 mm; NSA, 1; and total acquisition time, 1 min 19 s. Some image filters (*e.g.* image intensity normalization filter or large-FOV correction filter) may affect the distribution of noise.¹³ Thus, no image filter was applied. In both sequences, two scans with identical imaging parameters were performed for the subtraction method. The five different circular ROIs (center, top, bottom, right and left) were placed on the phantom images, as shown in Figure 1. Each ROI contained 112 pixels. Although a large ROI is used in the National Electrical Manufacturers Association method,⁵ we assessed SNR with the five small ROIs at different positions for the following two reasons: first, SNR in the phantom is likely to be different depending on the ROI position because image intensity non-uniformity results from the use of multichannel coil, the dielectric effect in phantom solutions, or the radio frequency field inhomogeneity.²¹ Second, the use of multiple small ROIs can minimize the effect of a low spatial frequency artifact that may still remain in the difference image in the subtraction method and overestimate noise.²¹ Identical ROIs were used for both signal and noise estimates in the two methods except for the background method; an additional square ROI containing 256 pixels was placed outside the phantom for the background method. These experiments were repeated 20 times for statistical comparison. Statistical analyses were performed with SPSS for Windows, v. 24.0 (SPSS, Chicago, IL). We compared the SNRs between the DELSET and the other two methods using a *t*-test with a Bonferroni correction for multiple comparisons. A *p* value of < 0.05 was considered statistically significant.

To confirm whether signal intensity reached noise level, we also determined the ratio of mean signal intensity and SD in ROIs on a series of second echo images obtained with QD coil. A ratio differing significantly from 1.91 indicates that signal intensity did not reach noise level.^{19,22}

For the MRIs using QD and array coils and the DELSET method, SNR images were obtained by calculating local mean signal intensity of the first echo image and corrected SD of the second echo image in a sliding ROI with size of 7 × 7 pixels, respectively.^{14,23}

In vivo experiments

To demonstrate the validity of the DELSET method *in vivo*, SNR measurements were performed using images of two healthy volunteers. The protocols for all investigations were explained in detail to both subjects. Informed consent was obtained from each participant prior to examination. This study was approved by the local institutional review board. For each subject, the head and upper abdomen were scanned with axial slices. For the head scans, we used the same 12-channel phased-array head coil and identical imaging parameters as the phantom experiments. The upper abdomen scans of the subjects were performed on a 1.5 T MRI unit (Signa HDxt, GE Healthcare, Milwaukee, WI) with an 8-channel phased-array torso coil with four anterior and four posterior elements. The upper abdominal images were acquired with the double-echo SPGR sequence in combination with a parallel imaging technique (array spatial sensitivity encoding technique) with the following parameters: TE, 2.4 ms (first echo) and 296 ms (second echo); TR, 300 ms; FOV, 320 mm; FA, 50°; imaging matrix, 256 × 192; slice thickness, 5 mm; NSA, 1; parallel imaging factor, 2.5; and total acquisition time, 22 s. For both head and abdominal images with the DELSET method, SNR, signal and noise images were also created in the same manner as mentioned above. The SD of the second echo image was corrected for the effects of the magnitude operator and multichannel image reconstruction in the same way as mentioned in the DELSET method section. An SNR image was then obtained by dividing the signal image by the noise image, on a pixel-by-pixel basis.

RESULTS

Table 1 shows the comparisons of various SNR measurements of the phantom with different coils and sequences. There were no significant differences in phantom SNRs with both coils and both sequences, when DELSET was compared with the other two methods (*p* > 0.05 for all). The ratios of mean signal intensity and SD in the second echo images with QD coil were 1.84 ± 0.11 for SE sequence and 1.91 ± 0.13 for SPGR sequence, respectively. Figure 2 shows typical examples of phantom SNR images with QD and array coils with the DELSET method. There was a larger heterogeneity in SNR image of the phantom with the array coil compared with the QD coil.

The head and abdominal SNR, signal and noise images with the DELSET method are shown in Figure 3. The head noise image without parallel imaging appeared to have relatively uniform noise distribution, whereas the abdominal noise image with a parallel imaging factor of 2.5 clearly showed an increase in noise

Table 1. Comparison between the DELSET method and the subtraction or background methods for phantom SNR obtained with different coils and pulse sequences

Coil	Position	Spin-echo			Spoiled gradient-echo		
		DELSET	Subtraction	Background	DELSET	Subtraction	Background
QD	Center	243.2 ± 16.9	237.9 ± 12.8	240.4 ± 5.8	164.2 ± 14.3	164.1 ± 11.6	161.5 ± 4.5
	Top	245.1 ± 21.1	237.0 ± 15.3	238.6 ± 5.7	159.3 ± 10.2	168.4 ± 10.0	161.1 ± 4.4
	Bottom	245.5 ± 19.3	241.9 ± 19.0	242.9 ± 5.8	165.5 ± 13.1	166.0 ± 15.0	162.9 ± 4.5
	Right	238.7 ± 18.8	235.6 ± 13.9	241.3 ± 5.7	165.5 ± 7.0	165.9 ± 16.3	163.6 ± 4.6
	Left	246.0 ± 17.5	234.9 ± 15.4	238.6 ± 5.9	159.9 ± 17.5	156.8 ± 9.1	158.2 ± 4.4
Array	Center	240.9 ± 19.0	228.7 ± 17.6	237.6 ± 5.6	212.1 ± 22.5	206.1 ± 14.4	211.7 ± 4.3
	Top	267.3 ± 17.8	258.5 ± 17.7	271.1 ± 6.4	238.7 ± 16.2	226.3 ± 13.2	245.1 ± 5.0
	Bottom	255.9 ± 13.5	259.0 ± 18.3	251.1 ± 6.0	244.3 ± 19.7	244.1 ± 12.8	238.5 ± 4.7
	Right	249.0 ± 17.6	246.5 ± 18.3	250.2 ± 6.1	245.5 ± 16.3	245.9 ± 23.4	237.2 ± 4.8
	Left	254.4 ± 19.3	243.4 ± 18.0	246.7 ± 5.9	250.2 ± 23.8	236.5 ± 19.4	238.0 ± 4.9

DELSET, double echo with the longest second echo time; QD, quadrature; SNR, signal-to-noise ratio. Mean ± SD are shown for each method.

around the central area in the anteroposterior direction. The abdominal image also shows that air background signals and noise have been suppressed by a thresholding algorithm involved in parallel imaging reconstruction.

DISCUSSION

The feasibility of the DELSET method to accurately calculate SNR was evaluated by comparing the results with the other two methods. The phantom SNRs with both coils and both sequences with the DELSET method were quantitatively comparable with those calculated with the other methods including the subtraction method, which is a reliable SNR determination *in vivo* when using an array coil.^{13,15} The general consistency in the measured SNR between the proposed and other two methods supports the validity of the method proposed in this study. Moreover, the ratios of mean signal intensity and SD in the second echo images with both sequences were found to be in general agreement with a theoretical value of 1.91.^{19,22} This result indicates that signal intensities in the second image had a Rayleigh distribution, that is, reached noise level, supporting validity of the noise image obtained with the DELSET method.

Figure 2. SNR images of the phantom with (a) QD and (b) array coils with the DELSET method. DELSET, double echo with the longest second echo time; QD, quadrature; SNR, signal-to-noise ratio.

As demonstrated in Figure 2, SNR with a QD coil and the DELSET method was homogeneous throughout the image, whereas SNR with an array coil was inhomogeneous and appeared to be higher in the periphery close to the coil elements and lower in the center far away from the coil elements. These results suggest that when using the DELSET method, it is possible to visually assess SNR characteristics originating from the different receiver sensitivity between the QD and array coils.^{18,24,25}

As shown in Figure 3, it was also possible to obtain *in vivo* SNR, signal and noise images with the DELSET method, even with the combination of an array coil and parallel imaging. As expected, the noise was amplified in the center of the abdominal image. This indicates an important characteristic related to the coil geometry, that is, the g-factor is introduced when using

Figure 3. (a, d) SNR, (b, e) signal and (c, f) noise images of the (a–c) head and (d–f) abdomen using an array coil and the DELSET method. Noise was erroneously enhanced in cerebrospinal fluid (arrow) (reflected as a long T_2 value), because signal intensities remained at the longest second echo time. DELSET, double echo with the longest second echo time; SNR, signal-to-noise ratio.

parallel imaging. When evaluating SNR in MRIs reconstructed with the parallel imaging technique, the background method is not valid because the noise is not uniformly distributed within the images.^{10,11,16} The subtraction method, which requires the two identical scans, is sensitive to system drift and image misregistration induced by motion and, therefore, is not applicable to abdominal images. In contrast, the main advantage of the DELSET method is that both signal and noise images can be acquired at one time. Consequently, it is insensitive to the effects of system drift and image misregistration. In addition, it does not require a special sequence or setting as opposed to the other previously proposed SNR determinations for parallel imaging.^{3,4} Therefore, the proposed method has high versatility and is feasible in MRI systems used clinically.

There were some important limitations to this study. First, it is important to note that the noise was erroneously enhanced in the cerebrospinal fluid (reflected as a long T_2 value), because signal intensities remained at the longest second TE. Thus, for accurate SNR quantification, it is necessary to place ROIs to avoid long T_2 tissues. Second, the applicability of our proposed method is limited. The DELSET method is not applicable to short TR sequences including three-dimensional SPGR and steady-state free precession sequences because our proposed method requires fairly long TE and therefore long TR. In addition, when using a

fast SE sequence, SE signals with different TE filled in a k-space may potentially affect signal characteristics in the second echo image and the appropriateness of the noise image. Our results demonstrate the validity of the DELSET method only in standard two-dimensional SE and SPGR sequences by yielding SNR comparable with those of other reference measurements. Thus, this method may be more practical for routine quality assurance or performance evaluation of new hardware than for comparison of image quality obtained with difference pulse sequences and imaging parameters. Regardless of the above-mentioned limitations, we believe that the DELSET method has the further advantages over the other methods described herein, including its simplicity to implement and resistance to system drift and artifacts whose magnitude is substantially dependent on the presence of signal in the image, such as ghosting or truncation artifacts.

CONCLUSION

The DELSET enables simple and accurate SNR quantification. This practical method is applicable to *in vivo* parallel imaging with multichannel array coil.

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REFERENCES

- Jackson E, Bronskill M, Drost D, Och J, Pooley R, Sobol W, et al. *Acceptance testing and quality assurance procedures for magnetic resonance imaging facilities*. Maryland: American Association of Physicists in Medicine. One Physics Ellipse College Park; 2010.
- McRobbie D, Sempke S. *Quality control and artefacts in magnetic resonance imaging: institute of physics and engineering in medic*. York: Institute of Physics and Engineering in Medic; 2017.
- Sodickson DK, Griswold MA, Jakob PM, Edelman RR, Manning WJ. Signal-to-noise ratio and signal-to-noise efficiency in SMASH imaging. *Magn Reson Med* 1999; **41**: 1009–22. doi: [https://doi.org/10.1002/\(SICI\)1522-2594\(199905\)41:5<1009::AID-MRM21>3.0.CO;2-4](https://doi.org/10.1002/(SICI)1522-2594(199905)41:5<1009::AID-MRM21>3.0.CO;2-4)
- Kellman P, McVeigh ER. Image reconstruction in SNR units: a general method for SNR measurement. *Magn Reson Med* 2005; **54**: 1439–47. doi: <https://doi.org/10.1002/mrm.20713>
- National Electrical Manufacturers Association (NEMA). Determination of signal-to-noise ratio (SNR) in diagnostic magnetic resonance imaging. *NEMA Standards Publication MS 1-2008* 2008; 2018.
- Steckner MC, Liu B, Ying L. A new single acquisition, two-image difference method for determining MR image SNR. *Med Phys* 2009; **36**: 662–71. doi: <https://doi.org/10.1118/1.3036118>
- Steckner MC. A simple method for estimating the noise level in a signal region of an MR image. *Med Phys* 2010; **37**: 5072–9. doi: <https://doi.org/10.1118/1.3480511>
- Henkelman RM. Measurement of signal intensities in the presence of noise in MR images. *Med Phys* 1985; **12**: 232–3. doi: <https://doi.org/10.1118/1.595711>
- Kaufman L, Kramer DM, Crooks LE, Ortendahl DA. Measuring signal-to-noise ratios in MR imaging. *Radiology* 1989; **173**: 265–7. doi: <https://doi.org/10.1148/radiology.173.1.2781018>
- Sodickson DK, Manning WJ. Simultaneous acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency coil arrays. *Magn Reson Med* 1997; **38**: 591–603. doi: <https://doi.org/10.1002/mrm.1910380414>
- Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. *Magn Reson Med* 1999; **42**: 952–62. doi: [https://doi.org/10.1002/\(SICI\)1522-2594\(199911\)42:5<952::AID-MRM16>3.0.CO;2-S](https://doi.org/10.1002/(SICI)1522-2594(199911)42:5<952::AID-MRM16>3.0.CO;2-S)
- Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, et al. Generalized autocalibrating partially parallel acquisitions (GRAPPA). *Magn Reson Med* 2002; **47**: 1202–10. doi: <https://doi.org/10.1002/mrm.10171>
- Dietrich O, Raya JG, Reeder SB, Reiser MF, Schoenberg SO. Measurement of signal-to-noise ratios in MR images: influence of multichannel coils, parallel imaging, and reconstruction filters. *J Magn Reson Imaging* 2007; **26**: 375–85. doi: <https://doi.org/10.1002/jmri.20969>
- Yu J, Agarwal H, Stuber M, Schär M. Practical signal-to-noise ratio quantification for sensitivity encoding: application to coronary MR angiography. *J Magn Reson Imaging* 2011; **33**: 1330–40. doi: <https://doi.org/10.1002/jmri.22571>
- Goerner FL, Clarke GD. Measuring signal-to-noise ratio in partially parallel imaging MRI. *Med Phys* 2011; **38**: 5049–57. doi: <https://doi.org/10.1118/1.3618730>
- Constantinides CD, Atalar E, McVeigh ER. Signal-to-noise measurements in magnitude images from NMR phased arrays. *Magn*

- Reson Med* 1997; **38**: 852–7. doi: <https://doi.org/10.1002/mrm.1910380524>
17. Koay CG, Basser PJ. Analytically exact correction scheme for signal extraction from noisy magnitude MR signals. *J Magn Reson* 2006; **179**: 317–22. doi: <https://doi.org/10.1016/j.jmr.2006.01.016>
 18. Roemer PB, Edelstein WA, Hayes CE, Souza SP, Mueller OM. The NMR phased array. *Magn Reson Med* 1990; **16**: 192–225. doi: <https://doi.org/10.1002/mrm.1910160203>
 19. Dietrich O, Raya JG, Reeder SB, Ingrisch M, Reiser MF, Schoenberg SO. Influence of multichannel combination, parallel imaging and other reconstruction techniques on MRI noise characteristics. *Magn Reson Imaging* 2008; **26**: 754–62. doi: <https://doi.org/10.1016/j.mri.2008.02.001>
 20. Gilbert G. Measurement of signal-to-noise ratios in sum-of-squares MR images. *J Magn Reson Imaging* 2007; **26**: 1678. doi: <https://doi.org/10.1002/jmri.21171>
 21. McCann AJ, Workman A, McGrath C. A quick and robust method for measurement of signal-to-noise ratio in MRI. *Phys Med Biol* 2013; **58**: 3775–90. doi: <https://doi.org/10.1088/0031-9155/58/11/3775>
 22. Gudbjartsson H, Patz S. The Rician distribution of noisy MRI data. *Magn Reson Med* 1995; **34**: 910–4. doi: <https://doi.org/10.1002/mrm.1910340618>
 23. Miyati T, Imai H, Ogura A, Doi T, Tsuchihashi T, Machida Y. Novel SNR determination method in parallel MRI. *Proc SPIE* 2006; **6142**: 1244–50.
 24. Hoult DI, Chen CN, Sank VJ. Quadrature detection in the laboratory frame. *Magn Reson Med* 1984; **1**: 339–53. doi: <https://doi.org/10.1002/mrm.1910010305>
 25. Gizewski ER, Maderwald S, Wanke I, Goehde S, Forsting M, Ladd ME. Comparison of volume, four- and eight-channel head coils using standard and parallel imaging. *Eur Radiol* 2005; **15**: 1555–62. doi: <https://doi.org/10.1007/s00330-005-2730-0>