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Phased-Array Combination for MR Spectroscopic Imaging Using a Water-Reference

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Abstract

Purpose—To evaluate methods for multichannel combination of 3D MR Spectroscopic Imaging (MRSI) data with a focus on using information from a water-reference spectroscopic image.

Material and Methods—Volumetric MRSI data was acquired for a phantom and for human brain using 8- and 32-channel detection. Acquisition included a water-reference dataset that was used to determine the weights for several multichannel combination methods. Results were compared using the signal to noise ratio (SNR) of the N-Acetylaspartate (NAA) resonance.

Results—Performance of all methods was very similar for the phantom study, with the whitened singular value decomposition (WSVD) and signal magnitude (S) weighting combination having a small advantage. For in-vivo studies, the S weighting, SNR weighting and signal to noise squared (S/N^2) weighting were the three best methods and performed similarly. Example spectra and SNR maps indicated that the SVD and WSVD methods tend to fail for voxels at the outer edges of the brain that include strong lipid signal contributions.

Conclusions—For data combination of MRSI data using water-reference information, the S/N^2 weighting, SNR and S weighting were the best methods in terms of spectral quality SNR. These methods are also computationally efficient and easy to implement.

Keywords

Phased-array combination; MRSI; multichannel detection; water-reference; SNR

INTRODUCTION

Phased-array detection is widely used for MRI to decrease the scan time and increase the signal-to-noise ratio (1,2). A common requirement for phased-array detection is that data from all channels should be combined, which in the case of a MR Spectroscopic Imaging (MRSI) acquisition results in a single free induction decay (FID) per voxel. The FID signal, $s(t)$, obtained from each channel can be represented as:

$$s(t) = A * e^{(i\omega - 1/T_2)t} * e^{i\phi} \quad (1)$$

where A is the signal magnitude, ω is the frequency, T_2 is the spin-spin relaxation time, and ϕ is the phase angle relative to the reference, which corrects the phase shift in each channel. After correcting the phase, signals of all channels are linearly combined to find a single FID signal for each voxel:

$$S(t) = \sum_{n=1}^k w_n * s_n(t) * e^{-i\phi_n} \quad (2)$$

in which s_n is the signal from n^{th} coil (channel), w_n is its corresponding weight (sensitivity) and k is the total number of coils. The simplest assumption is for w_n to be equal for all channels, but several methods have been proposed to calculate w_n and the phase correction coefficient, ϕ_n to maximize the signal to noise ratio (SNR) and minimize intensity variations across the field of view (FOV) that are associated with the sensitivity profiles of the individual coil elements. One consideration for the determination of the relative weighting is the coupling between coil elements that results in correlation of the noise between channels. A second consideration is the criteria used to determine w_n and ϕ_n and whether these are derived from the data directly or using a second calibration or reference measurement. Previously proposed array combination methods have considered both different methods for calculating the weighting factors and different methods for obtaining the relative signal magnitude and phase terms, and a summary of methods used for MRS studies is shown in Table 1. Despite the multiple reports of different combination methods the optimal method to find combined spectra with maximum SNR and minimum artifacts remains unclear, and may still depend on additional factors such as the geometry of the RF coil, number of coil elements, and relative SNR of the acquired data.

Roemer et al. (1) demonstrated that equal weighting cannot optimally combine the signals because of RF field inhomogeneity and unequal correlated noise. Their proposed formulation includes detailed RF field maps and correlated noise measurements. In a simpler approach, RF field inhomogeneity and noise correlation were assumed to be negligible, therefore it was proposed to weight each channel by the signal amplitude, which accounts for the voxel-to-coil distances (2,4). This was then modified by Wright and Wald (7) to use a measure of the SNR to determine the weighting factors to additionally account for the noise variations between different receive elements. They also suggested the use of the B_1 field map in the weight calculation to correct the signal intensity variation across the FOV (7). In a recent study, Hall et al. (3) proposed the signal to noise squared (S/N^2) weighting as the optimal combination method for MRSI data for the situation where the noise is not correlated between channels (20). They reported that the S/N^2 weighting performed better compared to the equal weighting and signal weighting, and slightly better than SNR weighting for a SVS data acquired with 32-channel detection at 7 T. It should be mentioned that the signal that is used for the signal, SNR and S/N^2 weighting is either the peak area of unsuppressed (or weakly suppressed) water spectrum or a metabolite peak from a water-suppressed spectrum, for which N-Acetylaspartate (NAA) is commonly used.

In a different approach, Erdogmus et al. (12) proposed a singular value decomposition (SVD) of the metabolite spectrum to separate the noise from the signal. It was shown that

the signal calculated from the first singular value will be optimal under the assumptions that the noise is uncorrelated with identical mean values (14). In recent years, several numerical techniques have been suggested for the noise decorrelation of MRSI data. Principal component analysis (PCA) has been demonstrated as one of these methods which was applied on both MRI (21) and MRS data (15). Martini et al. (15) proposed a noise decorrelation combination (nd-comb) technique in which the PCA noise decorrelation method in conjunction with the signal weighting were used for the combination of a SVS phantom data. They reported SNR improvements up to 6.7% (15). Rodgers and Robson (16) suggested the following steps for the MRSI signal combination: 1) whitening the noise, and 2) applying the SVD algorithm to find the optimal FIDs. In the whitening procedure, the noise is decorrelated using the noise covariance which is the same as the PCA algorithm, and results in a diagonal matrix for the noise covariance. Then, it further transforms the noise data to obtain an identity noise covariance. This way all channels are treated with equal importance. Rodgers and Robson (16) reported that their whitened singular value decomposition (WSVD) method performed better than the algorithm of Brown (8). Recently, Rodgers and Robson (17) revisited the WSVD method and applied temporal and spatial apodizations (WSVD+Apod and WSVD+Apod+Blur) before combination to improve this method.

An et al. (18) applied generalized least squares (GLS) to find the best linear unbiased estimator for the FID, which accounts for the noise correlation between the channels. They used the peak height of NAA to determine the coil sensitivities, and the coefficient of variation (CV) of creatine (Cr) area to evaluate the performance of the GLS method versus the WSVD and nd-comb methods. They reported an improved performance over the nd-comb and WSVD combination methods for a SVS data acquired with 32 channels at 7 T.

Strasser et al. (19) proposed a method called multichannel spectroscopic image calibration (MUSICAL) in which the weights were equal to the value of MRI data obtained from the corresponding channel. They applied Roemer's combination formula (1) in which the noise correlation factor is incorporated.

In this report, the performance of several multichannel combination methods was compared for reconstruction of volumetric ^1H MRSI data of the brain. For methods that calculate relative combination weights the aim was to make use of a water-reference MRSI dataset, which offers a high SNR dataset from which weighting and phase correction terms can be derived and used for multichannel combination of the metabolite SI dataset. For this study, the water MRSI dataset was acquired in an interleaved manner with the metabolite MRSI acquisition, thereby having minimal impact on the acquisition time of the metabolite MRSI; however, the results also apply to the case where a separate water reference MRSI acquisition is carried out.

MATERIALS AND METHODS

Data Acquisition

Volumetric MRSI data was acquired using a spin-echo acquisition with two-dimensional phase encoding, echo-planar readout in the k_y -time dimensions with continuous sampling,

and frequency-selective water suppression. Sequence details have been provided elsewhere (22,23). Following interpolation during image reconstruction a MRSI dataset of 64×64 voxels in-plane and 32-voxels through-plane was obtained over a FOV of $280 \times 280 \times 180$ mm³. The acquisition included a water-reference dataset obtained in an interleaved manner with identical spatial parameters as the metabolite MRSI. For in-vivo studies the MRSI acquisition was preceded by an inversion-recovery preparation, with TI = 198 ms, to suppress signal from subcutaneous lipids (22). A T1-weighted image (MPRAGE, Magnetization Prepared Rapid Gradient Echo) at 1 mm resolution (TR/TE/TI = 2150/4.4/1100) was also acquired for each study.

MRSI data were obtained using a spectroscopy phantom and for two normal subjects using a Siemens Trio, 3 T scanner. The phantom was 20 cm diameter and contained eight metabolites detected in the brain at typical physiological concentrations (23) and data was obtained using an 8-channel receiver coil. For the two normal subject measurements (male, 18 and 56 years old) data was obtained using 8-channel and 32-channel detection. Subjects were scanned after collecting their written informed consents in accordance with the procedure approved by our Institutional Review Boards.

Data Processing

All data were processed using the MIDAS (Metabolite Image Data Analysis System) software package (version 2) (24). The processing carried out prior to the point of the multichannel signal combination, for both the metabolite and water-reference MRSI datasets, included resampling of the EPI readout with combination of odd and even echo readouts (25), zero-filling in the spatial domain from $50 \times 50 \times 18$ points to $64 \times 64 \times 32$ points, and Fourier transformation in all three spatial dimensions.

Seven multichannel combination methods were programmed based on algorithms presented in the literature, namely: equal weighting (3,20), signal (S) weighting (2-6), SNR (S/N) weighting (7-11), S/N^2 weighting (3,20), SVD (12-14), WSVD (16,17), and GLS (18). Relative weights, signal phase, and time-domain SNR were calculated for each voxel within the brain using the water-reference data for all combination methods except the equal weighting, SVD and WSVD. For the GLS method, the coil sensitivity was obtained using the water-reference data whereas in the original report the NAA peak integral was used. The relative weights and phases were obtained after spatial reconstruction of each channel of the water-reference data, with the phase and magnitude determined from the first point of the time-domain signal at each voxel. The noise in each channel was assumed to be spatially uniform, thus it was derived from the last 100 points of the FID of 9 voxels in a region outside of the head where there is no signal. For the SNR weighting and S/N^2 weighting, the real part of the noise was used in calculations, whereas in the WSVD and GLS calculations the complex value of noise was used as per their formulations. In all cases the noise measurement was obtained from the water-reference signal. Following calculation of the weights and phase factors for multichannel combination from the water-reference data these were then used for the multichannel combination of the metabolite SI data, again after spatial reconstruction. Mild spatial smoothing (Gaussian, damping factor - 0.5) was applied to the water-reference MRSI prior to spatial reconstruction, whereas spatial smoothing of the

metabolite SI dataset (Gaussian damping factor -2.0) was applied after spectral Fourier transformation, B_0 correction, and lipid k-space extrapolation (26). Spectral filtering using a Gaussian 2 Hz line-broadening was also applied. The resolution of the reconstructed metabolite images corresponded to a voxel volume of 1.55 mL calculated at full width at half maximum. Following reconstruction of the MRSI data, the additional processing included parametric spectral fitting (27) to obtain maps of NAA, total Cr and total choline (Cho).

Data Analysis

Individual spectra obtained from different combination methods were compared for three voxels, one close to the center and two close to the edges. SNR was used as the measure for quantitative comparisons of different combination methods using the NAA peak height over the standard deviation (SD) of the noise (SNR_{PKH}) in the spectral domain, with the noise measurement taken from the last 100 points (0.64 to -0.35 ppm) of the spectrum. For formation of images showing the SNR distribution, the ratio of the fitted NAA area over SD of the noise in the spectrum (SNR_{Area}) was used since this accounts for changes in linewidth. In both cases the measurement was done after application of the spatial and spectral filter. Mean, SD, and coefficient of variation (CV) of SNR_{PKH} and SNR_{Area} were calculated for two regions of interest (ROIs), one near the center located in mid-axial plane at the center of lentiform nucleus, and one near the edge located in mid-axial plane at the center of left superior temporal gyrus. To determine the statistical significance of the differences in the SNR between the different combination methods a t-test was performed for both ROIs, and results presented using the S weighting method as the reference. Each ROI included $5 \times 5 \times 1$ voxels corresponding to $5.6 \times 5.6 \times 10 \text{ mm}^3$. To examine the spatial distributions of the relative performance in more detail, images of SNR_{Area} were produced for all cases.

RESULTS

Since some of the combination methods presented in this study account for the noise correlation between the channels, it is beneficial to investigate noise correlation levels for each dataset. As Fig. 1a demonstrates, the phantom data with 8-channel detection had low noise correlation between the coil elements with the mean value of the magnitude of 0.241. The in-vivo data with 8-channel detection (Fig. 1b) shows larger noise correlation compared to the phantom data and had a mean correlation of 0.351. The 32-channel in-vivo data (Fig. 1c) had the lowest noise correlation between the coil elements, with mean value of 0.133.

Phantom Experiment

Example spectra obtained from six different combination methods are shown in Fig. 2. It can be observed that all methods performed well and showed no visual difference. Two ROIs, shown in yellow on Fig. 2b, were selected for measurement of the mean, SD and CV of SNR_{PKH} for a central (ROI 1) and an edge (ROI 2) location and results are presented in Table 2. The mean values of SNR_{PKH} in ROI 1 were relatively close with the maximum of 188.9 obtained from the S weighting method. The S/N^2 weighting, WSVD and SVD also performed very well in this ROI. The SNR_{PKH} mean value for the S weighting method was

1.9% more than the equal weighting, 1.7% more than the SNR weighting, 0.4% more than the S/N^2 weighting, 1.0% more than SVD, 0.7% more than WSVD, and 2.2% more than GLS in ROI 1. In terms of the SD and CV of SNR_{pkH} , the SVD and S weighting were the best methods in ROI 1. It should be noted that SD and CV of SNR_{pkH} also includes the effects of linewidth variations within the ROI. Mean and SD of linewidth in ROI1 was 4.8 ± 0.0 and in ROI2 was 8.4 ± 1.5 . The p-values did not indicate significant differences between different combination methods as can be anticipated for a voxel that has approximately equal weights to all coil elements.

For the ROI near the edge (ROI 2), the maximum value of the mean SNR_{pkH} obtained from the WSVD combination was 21.5% more than the equal weighting, 1.9% more than the S weighting, 5.1% more than the SNR weighting, 3.6% more than the S/N^2 weighting, 2.9% more than SVD, and 10.7% more than GLS. It should be noted that lower mean SNR_{pkH} values in ROI 2 compared to ROI 1 is due to larger B_0 inhomogeneity near the edges that resulted in broader linewidths and smaller peak heights, as shown in Fig. 2. In this ROI, the S weighting and GLS methods had lower SD and CV values for SNR_{pkH} , which means more uniformity in SNR_{pkH} distribution within this ROI. The only statistically significant difference (for $p < 0.05$) was between the equal weighting method and the S weighting method.

In Vivo Experiment – 8 channels

Spectra from three different voxels for subject 1 are shown in Fig. 3. A visual evaluation of the frontal and central voxels (Fig. 3a and 3b) indicates that all methods produce comparable results, although some differences in the detailed noise patterns can be seen. For the voxel located in the parietal lobe (Fig. 3c), the SVD and WSVD methods failed (Fig. 3c. v and Fig. 3c. vi), while of the other methods no significant visual difference can be detected. The failure of the SVD was due to the presence of a large subcutaneous lipid component in the data.

The mean values of SNR_{pkH} and SNR_{Area} were calculated in two ROIs, shown in yellow on Fig. 3a, one selected in a central white-matter region and the second near the skull in the temporal lobe, and results are shown in Table 3. For the first ROI, the SNR weighting had the maximum value for the SNR_{pkH} which was 9.7% more than the equal weighting, 0.7% more than the S weighting, 0.7% more than the S/N^2 weighting, 5.0% more than SVD, 2.8% more than WSVD and 5.0% more than GLS methods. The S/N^2 weighting showed more uniformity in this ROI compared to other methods. Only the equal weighting method showed a statistically significant difference compared to the S weighting.

For the ROI 2, the S/N^2 weighting, the SNR weighting and S weighting had the maximum values for the SNR_{pkH} mean, respectively. The mean value of SNR_{pkH} obtained from the S/N^2 weighting was 14.7% more than the equal weighting, 1.0% more than the S weighting, 0.5% more than the SNR weighting, 16.8% more than SVD, 8.9% more than WSVD and 6.6% more than GLS methods. In terms of SNR_{pkH} uniformity within ROI 2, WSVD and GLS performed better compared to other methods. In this ROI, SVD and the equal weighting were the only methods with significantly lower performance.

In Vivo Experiment – 32 channels

Example spectra for the acquisition obtained using 32-channel detection, for three different voxel locations can be seen in Fig. 4. Similar performance is again noted with the different methods, with the exception of SVD and WSVD, which failed to properly combine signals for the voxel near the skull in the parietal lobe (Fig. 4c.v and Fig. 4c.vi).

As the data in Table 4 shows, for ROI 1, shown in yellow on Fig. 4a, the SNR and S/N^2 weighting methods had the maximum mean value of 21.2 which was 24.0% more than the equal weighting, 12.8% more than the S weighting, 15.2% more than SVD, 35.0% more than WSVD and 8.2% more than GLS. It can be observed that among the S, SNR and S/N^2 weighting, the S weighting performed better in term of SNR_{PKH} uniformity in ROI 1.

For the second ROI, shown in yellow on Fig. 4b, the mean value of SNR_{PKH} for the S/N^2 weighting was 20.2% more than the equal weighting, 3.7% more than the S weighting, 0.5% more than SNR weighting, 4.8% more than SVD, 23.3% more than WSVD and 3.7% more than GLS. In terms of SNR_{PKH} uniformity in this ROI, the S weighting method performed better compared with SNR and S/N^2 and GLS methods. For both ROIs, the performance of the WSVD method was significantly worse than the S weighing method.

Maps of SNR_{Area} images are shown for three slices from each of the studies in Fig. 5, using a color scale that was kept the same for all images within each study. The results for the phantom study (Fig. 4a) indicate that all methods performed well with the exception of the equal weighting (Fig. 5b.i). The WSVD (Fig. 5a.vi) method performed better in all three slices. It should be noted that the pattern of SNR_{Area} distribution also varied using different combination techniques.

For the 8-channel acquisition in human brain (Fig. 5b), the S weighting (ii), S/N weighting (iii), S/N^2 (vi), and GLS (vii) were all comparable as the best combination methods in all slices. The result of the SVD and WSVD methods showed very high SNR_{Area} values for voxels near the skull in the parietal lobe, which were not indicated in other methods. However, these hotspots indicate voxels where the SVD method performed poorly due to the presence of a large subcutaneous lipid component in the data from some of the channels, as shown in Figs. 3c and 4c, resulting in an incorrect peak identification for the automated SNR measurement. It appeared that whitening of the noise (using WSVD method) helped to reduce number of erroneous hotspots Fig. 4c (spectrum vi). A few of these hotspots can also be detected in SNR and S/N^2 results, shown in Fig. 4c iii and iv.

The 32-channel study (Fig. 5c) demonstrates larger difference in the SNR_{Area} between the edge and center voxels, as expected with the larger number of coil elements. From Fig. 5c.v and Fig. 5c.vi, it can also be observed that the SVD and WSVD combination failed in the last slice. The S weighting, SNR weighting, S/N^2 weighting and GLS were the top four combination methods in all slices. Also, by comparing results of SVD and WSVD (Figs. 5c.v and 5c.vi), it can be observed that the noise whitening resulted in worse results for all slices.

DISCUSSION

In this study, seven different techniques for combination of multi-channel MRSI data have been implemented, and evaluated using data obtained using 8- and 32-channels at 3 Tesla. A feature of the MRSI implementation used in this study is the use of a co-registered water-reference MRSI dataset that can be used to compute the phase and magnitude terms for the multichannel combination of the metabolite MRSI dataset. In this implementation the water signal is acquired in an interleaved manner, using a low flip-angle excitation, and has the same spatial coordinates as the metabolite MRSI acquisition. Given the minimal impact of this measurement on the total acquisition time and the high SNR of the measurement, this provides a convenient and high quality signal from which to calculate the weighting factors. An additional advantage of using a water signal as the reference, in comparison to methods that make use of a metabolite resonance, is that it remains visible even in lesions that may not exhibit any metabolite resonances.

A primary finding of this study is that for centrally-located voxels the relative performance of the different methods was similar, with a maximum difference of 9.7% for 8-channel detection and 34.9% for 32-channel detection. Measurement of SNR values indicated that the relative performance varied spatially and in a manner that depended on the number of coil elements; however, overall the S weighting, SNR weighting and S/N^2 weighting performed best, but without clear distinction between their relative performances. In addition, the SD and CV of the SNR measurement within a ROI have been used as measures of SNR non-uniformity, and in the phantom study the S weighting also performed better in terms of uniformity. It was also observed that the equal weighting, SVD and WSVD methods showed statistically significant differences in comparison to the S weighting method.

For the in-vivo studies, both S/N^2 and SNR weighting performed better than the S weighting with the maximum improvement of 12.4% for the mean value of SNR_{pKH} in the 32-channel detection study. However, the S weighting showed better SNR_{pKH} uniformity compared with SNR and S/N^2 weighting methods in the 32-channel detection study.

An additional finding of this study was that the SVD and WSVD method failed for voxels near the skull in the parietal lobe, indicating instability of the method that may be associated with large signal variations from subcutaneous lipid signals arising from locations close to the coil elements. In the SVD based methods, the combined signal is determined through the rank reduction of the data, which truncates a large portion of the data. Therefore, these combination methods tend to fail for voxels with low metabolite signals and high level of noise and artifacts, as it can be seen in Fig. 4c.v and Fig. 4c.vi. This is also the possible reason for the hotspots in Fig. 5b.v and Fig. 5b.vi, and the poor results in the third slice of in-vivo study with 32-channel detection (Figs. 5c.v and 5c.vi). While complications arising from strong subcutaneous lipid signals may impact any MRS measurement, this concern may be greatest for the MRSI acquisition method used in this study that aims to map metabolite distributions throughout the brain volume and therefore does not include any volume-selective excitation or saturation methods.

From the SVD and WSVD results, it was also observed that the whitening of the noise, which is the first step in the WSVD method, improved the results compared to the SVD method for both phantom and in-vivo studies with 8-channel detection. However, in the in-vivo study with 32-channel detection the WSVD method worsened the results compared to the SVD method. A possible explanation is the very small mean value of the noise correlation between channels in the 32-channel detection study (0.133), compared to the 8-channel detection phantom (0.241) and in-vivo (0.351) studies. This indicates that the whitening of the noise was an unnecessary manipulation of the data which resulted in worse combined signals compared to the SVD method. However, the GLS method, which also includes the noise correlation between the channels, performed relatively well and consistently in all studies. However, this study used a relatively small number of points to measure the noise covariance and a larger noise sample, perhaps obtained using a separate acquisition (17), can increase the accuracy of the noise covariance estimation, thereby improving the performance of the WSVD method.

In summary, this study finds that for multichannel combination of ^1H MRS data, in the case where a corresponding water reference dataset is available, is efficiently performed using weighting of the individual channel data by the relative value of the reference signal, SNR or S/N^2 magnitudes. In addition to providing good performance, all of these methods are simple to implement and computationally efficient.

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Figure 1. Noise correlation matrix for a) phantom data with 8-channel detection; b) in-vivo data with 8-channel detection; and c) in-vivo data with 32-channel detection.

Figure 2.

Example spectra obtained in the phantom study for 8-channel detection with multichannel combination using (i) equal weighting, (ii) S weighting, (iii) S/N weighting, (iv) S/N^2 weighting, (v) SVD weighting, (vi) WSVD and (vii) GLS methods. Spectra are shown for the voxel selections indicated in the images and the yellow boxes indicate the ROIs used for the SNR measurements.

Figure 3.

Example spectra obtained in the human brain for 8-channel detection with multichannel combination using (i) equal weighting, (ii) S weighting, (iii) S/N weighting, (iv) S/N^2 weighting, (v) SVD, (vi) WSVD and (vii) GLS methods. Spectra are shown for the voxel selections indicated in the images and the yellow boxes indicate the ROIs used for the SNR measurements.

Figure 4. Example spectra obtained in the human brain for 32-channel detection with multichannel combination using (i) equal weighting, (ii) S weighting, (iii) S/N weighting, (iv) S/N^2 weighting, (v) SVD, (vi) WSVD and (vii) GLS methods. Spectra are shown for the voxel selections indicated in the images.

Figure 5. SNR_{Area} maps obtained from (i) equal weighting, (ii) S weighting, (iii) S/N weighting, (iv) S/N² weighting, (v) SVD, (vi) WSVD and (vii) GLS methods for a) 8-channel phantom, b) 8-channel in-vivo, and c) 32-channel in-vivo.

Table 1

Summary of phased-array combination methods for MRS studies categorized according to whether they have been demonstrated for single voxel spectroscopy (SVS) or spectroscopic imaging (SI) and whether noise correlation was considered. Studies were for ^1H MRS except where noted. The full names for each method are described in the text.

Combination Method	SVS / SI	Reference Data Type	Field strength	no. of channels	Noise correlation?
1. Equal weighting (3)	SVS	-	7 T	32	No
2. S weighting (2-6)	SVS & SI	Metabolite or Water-reference	7 T	32	No
			3 T	4	
			2.9 T	8	
			3 T	8	
			1.5 T	4	
			1.5 T, ^{31}P	4	
3. S/N weighting (7-11)	SVS & SI	Metabolite or Water-reference	7 T	8	No
			9.4 T	8	
			3 T	32	
			1.5 T, ^{31}P	4	
			7 T	32	
4. S/N ² weighting (3)	SVS	Metabolite	7 T	32	No
5. SVD (12-14)	SVS-phantom	Metabolite	3 T	8	No
			3 T	4	
			4.7 T	4	
6. nd-comb (15)	SVS-phantom	Metabolite	1.5 T	8	Yes
7. WSVD (16,17)	SI	Metabolite	3 T, ^{31}P	8	Yes
			3 T	12	
			1.5 T	32	
8. GLS (18)	SVS	Metabolite	7 T	32	Yes
9. MUSICAL (19)	SI	Metabolite & MRI	7 T	32	Yes

Table 2

Mean, SD, and CV of SNR_{PKH} and p-value of t-test between the S weighting and other combinations methods for two ROIs from the phantom study, obtained using 8-channel detection.

Method	ROI 1 (center)				ROI 2 (edge)			
	Mean	SD	CV	p-value	Mean	SD	CV	p-value
Equal	185.3	16.59	0.090	0.428	49.3	15.45	0.313	0.041
S	188.9	15.24	0.081	-	58.8	16.48	0.280	-
SNR	185.7	16.59	0.089	0.481	57.0	16.76	0.294	0.704
S/N²	188.1	16.93	0.090	0.861	57.8	17.11	0.296	0.834
SVD	187.1	14.83	0.079	0.674	58.2	17.27	0.297	0.901
WSVD	187.6	15.53	0.083	0.766	59.9	17.74	0.296	0.821
GLS	184.9	15.92	0.086	0.369	54.1	15.35	0.284	0.302

Table 3

Mean, SD, and CV of SNR_{PKH} and the p-value of t-test between the S weighting and other combinations methods for two ROIs in the human brain, obtained using 8-channel detection.

Method	ROI 1 (center)				ROI 2 (edge)			
	Mean	SD	CV	p-value	Mean	SD	CV	p-value
Equal	13.4	2.27	0.169	0.071	17.0	3.02	0.178	0.024
S	14.6	2.32	0.159	-	19.3	3.91	0.203	-
SNR	14.7	2.31	0.157	0.879	19.4	3.80	0.196	0.927
S/N²	14.6	2.19	0.150	1.000	19.5	3.67	0.188	0.853
SVD	14.0	2.21	0.158	0.354	16.7	3.01	0.180	0.011
WSVD	14.3	2.60	0.182	0.669	17.9	2.36	0.132	0.132
GLS	14.0	2.47	0.176	0.380	18.3	3.07	0.168	0.320

Table 4

Mean, SD, and CV of SNR_{PKH} and p-value of t-test between the S weighting and other combinations methods for two ROIs in the human brain, obtained using 32-channel detection.

Method	ROI 1 (center)				ROI 2 (edge)			
	Mean	SD	CV	p-value	Mean	SD	CV	p-value
Equal	17.1	3.42	0.200	0.096	16.3	2.24	0.137	0.001
S	18.8	3.65	0.194	-	18.9	2.92	0.154	-
SNR	21.1	4.82	0.228	0.063	19.5	3.22	0.165	0.493
S/N²	21.2	5.02	0.237	0.059	19.6	3.22	0.164	0.425
SVD	18.4	3.60	0.196	0.698	18.7	2.85	0.152	0.807
WSVD	15.7	2.12	0.135	0.001	15.9	1.99	0.125	0.0001
GLS	19.6	4.12	0.210	0.471	18.9	3.06	0.162	1.000