Published in final edited form as:

Magn Reson Imaging. 2010 November ; 28(9): 1270–1282. doi:10.1016/j.mri.2010.06.012.

Spin Echo SS-PARSE: A PARSE MRI Method to estimate frequency, R2 and R2' in a Single-shot

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Abstract

Spin echo signals allow separate measurements of irreversible and reversible relaxation rates in MRI. A spin echo version of Single-shot Parameter Assessment by Retrieval from Signal Encoding (SE-SS-PARSE) method has been developed to quantitatively and accurately map transverse magnetization magnitude, frequency, irreversible and reversible relaxation rates in a single shot. These image parameters can be applied to fMRI research as well as a number of neuroimaging applications. Following a description of the signal model, this paper demonstrates the performance of SE-SS-PARSE in simulations with different noise levels and in phantom experiments. By solving an inverse problem, the estimated irreversible and reversible relaxation rates in SE-SS-PARSE are highly correlated with the reference relaxation rates from a standard technique (correlation coefficients $r_1=0.9636$ for reversible relaxation rate, $r_2=0.9788$ for irreversible relaxation rate). The rapid SE-SS-PARSE technique has the potential to monitor transient changes in R2 and R2' while minimizing motion artifacts, and also is free of geometric and ghosting errors. It is expected that this fast scan technique will find applications in both scientific research and clinical diagnosis.

Keywords

Single-shot MRI; Spin echo; Transverse relaxation rate; Rapid MRI

1. Introduction

Fast scan MRI techniques have been highly developed and widely applied in both scientific research and clinical diagnosis for their ability to obtain images within a short time. Rapid data acquisition is in demand to minimize motion and undesirable flow artifacts as well as reduce the time and expense for both patients and hospitals. SS-PARSE (Single Shot-Parameter Assessment by Recovery from Signal Encoding) [1] is a novel quantitative parameter-based fast MRI technique. Using a continuous signal model, SS-PARSE promises improved accuracy and robustness in the estimation of local signal parameters (local transverse magnetization

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magnitudes M_{xy0} , transverse relaxation rates $R2^*$ ($1/T2^*$) and frequencies (f). The total observable transverse relaxation rate $R2^*$ depends on both macroscopic magnetic field inhomogeneities and pure spin-spin relaxation. The field inhomogeneities lead to the reversible signal dephasing characterized by the reversible relaxation rate, $R2'(1/T2')$, while the pure molecular effects cause the irreversible signal dephasing characterized by the irreversible relaxation rate, $R2$ ($1/T2$).

A spin echo signal permits separate measurements of $R2$ and $R2'$. This combined measurement is significant for both neuroscience research and clinical studies. In functional MRI (fMRI), separate measurement of $R2$ and $R2'$ has been recognized as an approach to distinguish BOLD responses in parenchyma from responses in large draining veins [2]. Also, the blood $R2$ values can be useful to measure tissue oxygen extraction fractions while the changes in $R2'$ are approximately linearly related to the changes in blood oxygenation level [3]. Clinically, the measure of $R2$, $R2'$ values are valuable to quantify iron deposition in neurological disorders, such as Parkinson's disease, Huntington's disease and Alzheimer's disease [4–8]. The excess iron in certain areas of the human brain causes the MR signal decay, which leads to the signal loss in the $T2$ -weighted images for such diseases. It has been demonstrated that brain iron measurement can also be used to assess the stage of stroke [9–11] and HIV-infected patients [12].

The conventional approach to separate $R2$ and $R2'$ values is to first measure $R2^*$ from multi-echo gradient echo images, and $R2$ from spin-echo data, then derive $R2'$ by subtracting $R2$ from $R2^*$. Numbers of methods have been proposed for mapping $R2$ ($T2$) values. The commonly used multi-echo Carr-Purcell-Meiboom Gill (CPMG) method [13,14] is most accurate, but not suited for rapid monitoring of dynamic changes in relaxation rates. Recently, some fast scan MRI methods have been proposed to reduce the data acquisition time in mapping $R2$, $R2'$ and $R2^*$ values. A single scan method, Gradient Echo Sampling of the Free Induction Decay and Echo (GESFIDE) was proposed by Ma and Wehrli [15]. In this method, $R2$ and $R2'$ maps are obtained by finding the differential evolution of the transverse magnetization between the ascending side and the descending side of a Hahn echo. Another $R2$ mapping technique, fast acquisition relaxation mapping (FARM), has been introduced by McKenzie et al. [16]. In this technique, quantitative $R2$ mapping can be reconstructed directly from k-space data obtained within 3 sec. However, both imperfect refocusing pulses and eddy currents can disturb the $R2$ decay, and maximum gradient amplitude and slew rates need to be controlled to minimize the eddy current effects. The single shot Echo Planar Imaging (EPI) technique [17] has been widely used in modern functional studies. It is capable of producing a set of whole brain images at video rates, which is useful in functional neuroimaging. However, EPI based imaging is vulnerable to geometric distortion artifacts [18–22]. Chen et al. [23] have recently proposed a less field inhomogeneity sensitive method, Line-Scan Echo Planar Spectroscopic Imaging (LSEPSI). However, the 30 sec data acquisition time for a 2-dimensional slice image is too long to monitor rapidly changing signals, such as the BOLD fMRI responses.

Here we propose a fast scan MRI method that can measure $R2$ and $R2'$ separately with a data acquisition time much less than a second. The spin echo SS-PARSE technique (SE-SS-PARSE) extends the FID-only SS-PARSE technique to provide estimation of four image parameters, M_{xy0} , f , $R2$ and $R2'$. Through use of an iterative optimization algorithm [24], these image parameters can be estimated simultaneously and quantitatively. The SE-SS-PARSE method is based on the PARSE technique, and is free of geometric errors and $N/2$ ghosting artifacts that commonly occur in single-shot techniques, such as EPI [24]. Moreover, the rapid data acquisition of SE-SS-PARSE eliminates the motion artifacts effectively. In general, SE-SS-PARSE may be well suited for several types of MRI studies, especially for tracking dynamic changes such as BOLD responses in fMRI.

2. Theory

The theory of using the SS-PARSE technique to estimate magnetization parameters from a FID signal has been previously described [1]. Each sample point in the PARSE acquisition is recognized as a point in the (k, t, b) space, where t refers to the time and b is an encoding parameter. The signal model of SS-PARSE considers both transverse magnetization decay and phase evolutions, and thus, in principle it can provide more robust and reliable image parameter estimates quantitatively. The parameter estimation in SS-PARSE employs a Progressive Length Conjugate Gradient (PLCG) algorithm, which works by iteratively searching the parameter space to minimize the sum square error between experimental signal and model signal [24].

In the SE-SS-PARSE method, a spin echo rf sequence is applied to produce both FID and echo signals. From these two signals, four image parameters, complex magnetization M_{xy0} , frequency f, and relaxation rates R2 and R2' can be modeled and estimated. The observed local signal S_c at time t_n during the data acquisition time can be modeled as:

$$S_c(t_n) = \begin{cases} \iint M_{xy0}(x) \cdot e^{-((R_2'(x) + 2\pi if(x) + R_2(x)) \cdot (t_n + \tau_0))} \cdot e^{-2\pi ik(t_n)x} dx, & 0 < t_n < \frac{TE}{2} - \tau_1 \\ \iint M_{xy0}(x) \cdot e^{(R_2'(x) - 2\pi if(x) - R_2(x)) \cdot (t_n + \tau_1 + \tau_2)} \cdot e^{-2\pi ik(t_n)x} dx, & \frac{TE}{2} - \tau_1 < t_n < TE - (\tau_0 + \tau_1 + \tau_2) \\ \iint M_{xy0}(x) \cdot e^{-(R_2'(x) + 2\pi if(x) + R_2(x)) \cdot (t_n + \tau_1 + \tau_2)} \cdot e^{-2\pi ik(t_n)x} dx, & TE - (\tau_0 + \tau_1 + \tau_2) < t_n \end{cases} \quad (1)$$

which is the integral of the individual pixel signal at location x over the space. The last part of the integral $e^{-2\pi ik(t_n)x}$ represents the spatial phase modulation imposed by the gradients [1] at time t_n . Here τ_0 refers to the time between the effective center of the 90 degree pulse and the beginning of data acquisition. τ_1 and τ_2 are delays before and after the middle of the 180 degree pulse, respectively, during which the signal is not sampled. The timing diagram of the SE-SS-PARSE sequence is shown in Fig. 1. The magnetization parameter M_{xy0} is estimated at $t=0$. In Eq. (1), the first part corresponds to the FID signal while the second and third parts correspond to the ascending and descending section of the echo signal. The PLCG algorithm was employed to estimate image parameters as in the SS-PARSE technique.

3. Methods

Simulations

SE-SS-PARSE was tested initially with a simulated numerical phantom. Both signal simulations and data reconstructions were implemented in Matlab (Version 7.5; The MathWorks, Inc., Natick, MA) running on a dedicated 8 AMD Opteron 880 dual-core processor computer with 64 GB of Random Access Memory (@Xi Computer Corp.). The simulated phantom (Fig. 2) was a clock shaped set of disks in a 12.8-cm field of view (FOV). The radius for the central disk and outside disks was 2.5 cm and 1 cm, respectively. The image resolution was 64 by 64. Magnitude of transverse magnetization, relaxation rates and frequency value were varied among disks, as indicated by Fig. 2. Random zero-mean Gaussian distributed noise was added to the simulated signal with four different magnitudes to simulate the experimental situation. The corresponding signal to noise ratios (SNR) were ∞ , 40 dB, 30 dB and 20 dB.

Phantom Study

The experimental acquisitions were performed with a four-tube phantom, consisting of four 1.6cm-diameter tubes in an 8cm-diameter beaker filled with water. Different concentrations

of agarose were added to different tubes to provide *in vivo* like R2 values [25]. Small quantities of FeSO₄ were added to two tubes to increase the R2' values. The chemical concentration for individual tubes is indicated in Table 1.

The R2 modifier agarose was used as a gelling agent as well. The R2 values and the agarose concentration are: 1.3% to 4% of agarose solution corresponding to R2 value of 15 to 7 sec⁻¹. We were unable to achieve larger R2 values with agarose alone, because the agarose concentration less than 1.3% was so low that it is insufficient to solidify. FeSO₄ was used in our study as the R2' modifier, which can effectively increase the R2' values with low concentration. Another R2' modifier used in our study was sephadex beads, however, the R2' values were not increased to the extent we expected with sephadex beads alone.

The experimental phantom study was implemented on a 4.7T 60cm-vertical-bore Varian primate MRI system (Varian Inc., Palo Alto, CA), using a stripline resonator quadrature head coil (Insight Neuroimaging, Worcester, MA). Data were sampled along the rosette k,t-trajectory [26,27]. To establish reference values of R2 and R2', standard multi-echo gradient echo (ME-GE) and multi-echo spin echo (ME-SE) techniques were used. In all cases, the FOV was 12.8cm, resolution was 64 by 64, and slice thickness was 2mm. For SE-SS-PARSE, six separate single shots were taken with the repetition time (TR) of 6 sec, and echo time (TE) of 98 msec. TR for ME-GE and ME-SE techniques were 300ms and 500ms, respectively. TE values for ME-GE and ME-SE method were (6, 7, 10, 15, 30) msec and (12, 14, 20, 30, 60) msec, respectively. The multiple-echo data were used to compute relaxation rates from the magnitude images. Parameter maps of M_{xy0}, f, R2 and R2' were estimated by the PLCG algorithm from the SE-SS-PARSE data. By fitting the magnitude decay along the echo time of each pixel in ME-GE/SE images, reference R2* and R2 maps were computed. Decay rates were computed by exponential fit to the decay of the magnitude image values through the series of echo times. Fitting was performed by nonlinear least-squares using Matlab, and R2' was then simply derived by subtracting R2 from R2*. Statistical methods were used to assess the accuracy of the SE-SS-PARSE results by comparing the R2 and R2' maps to the values computed from standard techniques.

4. Results

Simulations

The simulation results of the clock phantom are shown in Fig. 3. Four local parameter images of M_{xy0}, f, R2 and R2' were estimated with different noise levels. As the signal noise level increases, the final estimation parameter maps become noisier. To assess the accuracy of the estimates, four representative square areas were chosen from disk 1, disk 5, disk 9 and the central disk in the estimated R2 and R2' maps, as indicated by the black squares in the upper-left corner magnitude image in Figure 3. Fig. 4 illustrates the comparison between the reference and estimated R2 and R2' values from these selected areas. In each figure, the solid black line represents the reference R2 and R2' values while the estimation results are represented by the mean and standard deviations, as indicated by the error bars. Even with the high noise level (SNR=20dB), the estimated mean values in both R2 and R2' maps match the reference values well. As expected, larger estimate deviations were seen for higher signal noise levels.

Phantom Study

Fig. 5 demonstrates the estimation results for both SE-SS-PARSE technique and the standard ME-GE/SE technique. Note that the SE-SS-PARSE results were acquired with a single 148ms shot, in contrast to those requiring almost an hour with the ME-GE/SE technique. Also very different methods were employed to reconstruct final parameter maps for both techniques. The iterative PLCG algorithm was used in the SE-SS-PARSE technique to produce four parameter

maps of M_{xy0} , f , R_2 and R_2' at the same time. For the standard technique, a Fourier transform (FT) was used to convert raw k-space data into magnitude maps, and exponential decay curves were fitted to the magnitudes at each echo time to compute relaxation rate maps. A side-by-side comparison of the reconstructed R_2 and R_2' maps obtained using SE-SS-PARSE and the standard technique in Fig. 5 demonstrates that the SE-SS-PARSE results are highly consistent with the reference values.

To demonstrate convergence of the parameter search, four representative pixels were picked randomly from the inside area of four tubes, and their estimation histories during convergence were recorded, as shown in Fig. 6. For all four pixels, the estimation histories before 200 iterations were the same for R_2 and R_2' . In the PLCG searching process, the data length was progressively increased to avoid secondary minimum artifacts [24]. Before 200 iterations for this particular study, the data length was no more than the length of the FID signal, so the algorithm could not distinguish the difference between R_2 and R_2' . Estimates of R_2 and R_2' from FID data only were approximately equal. The estimation history of R_2 and R_2' began to differ as the echo signal was added to the PLCG search data length after 200 iterations. At the final PLCG stage, estimates from the whole data length converged to steady values, as seen in the flat portion at the end of the estimation history of Fig. 6.

To assess the accuracy of the estimation in SE-SS-PARSE, 100 3×3 pixel areas were picked in the R_2 and R_2' maps for both techniques used in this study, avoiding areas with pixels on the tube boundaries. Mean of the estimates from both techniques were calculated as $\overline{R_2}$ and $\overline{R_2'}$. Shown in Fig. 7 are the correlation results between $\overline{R_2}$ and $\overline{R_2'}$ values from the selected areas in the results from both SE-SS-PARSE and standard technique. Linear fits to the $\overline{R_2}$ and $\overline{R_2'}$ correlation data yield correlation coefficients of 0.9636 and 0.9788, respectively. The highly correlated results between the SE-SS-PARSE and the standard technique demonstrate the SE-SS-PARSE method is capable of accurate rapid R_2 and R_2' mapping.

In addition to the results shown in Fig. 5, five more shots of SE-SS-PARSE data were obtained and analyzed. Fig. 8 depicts profiles across R_2 and R_2' maps at row 46 from all six shots of SE-SS-PARSE and standard technique, which pass through both water and tube sections. The differences from shot to shot with the SE-SS-PARSE technique are expected due to signal noise. The mean and standard deviation of the profile at row 46 of R_2 and R_2' values from all shots were calculated. Fig. 9 compares the mean (dashed line) and standard deviation (dotted line) of the same profile from all six shots with the reference value from standard technique (solid line). Because of the Gibbs ringing artifacts and possible phantom shaking during the data acquisition, reference R_2 and R_2' values exhibited spatial variations, especially noticeable in R_2' . The variations could be decreased by averaging R_2 and R_2' values from neighborhood profiles. Here we did not average reference R_2 or R_2' values, in order to make a pixel by pixel based comparison with SE-SS-PARSE. The mean difference may come from bias errors arising from model discrepancies [24]. As noted above, the standard deviation in Fig. 9 reflects the random noise difference among different shots.

5. Discussion

A fast single-shot MRI technique, SE-SS-PARSE, has been described in this paper. Although obtaining data within only 200msec, SE-SS-PARSE is able to produce quantitative multiple parameter estimate images at the same time. The signal model in SE-SS-PARSE models the decay and precession of the local transverse magnetization during the data acquisition time, which enables more precise and robust estimation for local image parameters. More importantly, by using the dynamic signal model, SE-SS-PARSE is free of geometric and blurring artifacts, and in principle is less sensitive to large susceptibility gradients in vivo [1].

Because a spin echo signal is used in SE-SS-PARSE, the two image parameters R_2 and R_2' can be computed in addition to the M_{xy0} , f and R_2^* estimated using the SS-PARSE technique. Measurements of R_2 and R_2' values in both simulations and experiments from the SE-SS-PARSE technique are in good agreement with those from standard techniques, suggesting the reliability of this method.

Accurate timing plays an important role in the SE-SS-PARSE technique. The previously developed SS-PARSE technique measures all the data points within an uninterrupted time period. The estimation algorithm for SS-PARSE simply models this single signal. In contrast, the SE-SS-PARSE measures data in two separate time periods after the 90 and 180 degree rf-pulses. Spoiler gradients have been applied on both sides of 180 degree pulses to eliminate any FID signal from an imperfect refocusing pulse. The interval between the FID signal and the echo signal includes the time for the 180 degree pulse along with these spoiler gradients. The time durations of rf-pulses and spoiler gradients need to be noted precisely and represented in the signal model. These time durations can be measured once in the calibration process [28] and will only change if the rf-pulses or gradients change. Because the reconstruction in SE-SS-PARSE uses a signal that is a spliced combination of FID and echo signals, the difference between the two signals should be noted, such as the small net phase change in the echo induced by imperfect 180 degree pulse. In principle, and as verified in our results, this system-dependent difference in phase angle needs to be measured only once for a given refocusing pulse.

Although the SE-SS-PARSE results were highly correlated to the “gold standard” results, there are several aspects of the comparison that merit discussion. The difference between the estimated parameters and the actual parameters, here represented by the reference values, can be characterized as estimation errors. For the SE-SS-PARSE technique, estimation errors include both bias errors arising from signal model discrepancies and random errors caused by the measurement noise. Random errors in our phantom studies are characterized by the standard deviations in Fig. 9. Due to the space limit, only random errors in selected locations were presented. By implementing multiple shots, averaged estimates of R_2 and R_2' were obtained. The difference between the average and reference values can be characterized by bias errors coming from various sources [24], especially (1) The local signal model in SE-SS-PARSE did not measure the non-exponential effects of dephasing across the voxel that exist in the actual object (These effects may become worse with larger susceptibility variations increases in human tissue); and (2) The mismatch between evaluation k-band (square) and the acquisition k-band (disc) in the SE-SS-PARSE may lead to under- or over-estimates of high spatial frequencies from the gap between two k-bands. These sources of bias errors may be reduced and minimized by multiple solutions proposed in another report [24].

The reconstruction accuracy and efficiency in SE-SS-PARSE depends on the convergence behaviors of the PLCG algorithm. The typical convergence time for the spin echo four-tube phantom data on our computational platform is around 30min to an hour, which is very slow compared to the fast Fourier Transform (FFT). The algorithm may be optimized by (1) Reducing the progressive data lengths over which successive estimation are performed, which may speed the estimation (However, the number of lengths must be sufficient to prevent convergence to a secondary minimum), (2) Increasing the stopping tolerance for each PLCG data length (This can accelerate the searching process but can reduce estimation accuracy), (3) Adjusting weighting factors that scale the magnitude of the decay rate parameters relative to the other parameters. The weighting factors play an important role in the speed of convergence, especially when R_2 and R_2' are significantly different. Proper weighting factors can effectively balance the size of the search gradients for R_2 and R_2' , and thus accelerate the algorithm. Faster computing hardware (e.g., Graphical Processing Units) may offer substantial acceleration.

In comparison with many R_2 (or T_2) and R_2' measurement methods [13–23], SE-SS-PARSE has several potential basic advantages. In conventional methods, R_2' values are measured by subtracting R_2 from R_2^* values. The precision of the R_2' measurements is then limited by the errors introduced by both R_2 and R_2^* measurements. In contrast, the SE-SS-PARSE technique estimates R_2' values directly from the sampled data. In the past few decades, many fast scan R_2 mapping methods based on a single shot method such as EPI have been introduced to reduce the acquisition time. However, such single-shot methods suffer from geometric errors due to the field inhomogeneities as well as ghosting artifacts. Although sacrificing computational convenience, SE-SS-PARSE is totally free of such geometric or ghosting errors. Moreover, SE-SS-PARSE is capable of producing quantitative image parameter measurements. It should be emphasized that the amount of the data sampled in SE-SS-PARSE is associated with the time TE. Longer TE (consistent with expected T_2 values) allows for more data points and thus, theoretically more accurate estimations. Optimal choices of TE for estimation accuracy remain to be determined.

SE-SS-PARSE may be of significant value in fMRI research. The BOLD fMRI signal induced by the neural activities consists of a change in the local T_2^* values. A single-shot GE technique is normally used to obtain the dynamically changing T_2^* -weighted images in fMRI. The GE method is easy to implement and has high sensitivity in detecting local signal changes. However, the GE technique is also sensitive to field inhomogeneities induced by large draining veins. At high magnetic field, favored for increased sensitivity for fMRI, the field inhomogeneity problems such as through-slice dephasing, becomes worse, limiting the applications of GE methods. On the other hand, in the SE sequence, the 180 degree rf pulse refocuses the static intra-voxel dephasing around large vessels and hence reduces their contribution to the BOLD response [2]. By producing R_2 values instead of R_2^* values with rapid data acquisition, SE-SS-PARSE is well-suited to detect BOLD effects in fMRI studies.

In summary, a spin echo version of SS-PARSE (SE-SS-PARSE) technique has been developed and validated with tissue-equivalent phantom. It was shown that the simulation results were close to the actual values, even at high noise level with SNR of 20dB. The experimental results on a four-tube phantom were also highly correlated with the results from standard reference techniques. Future work will include application and development of the technique for *in vivo* studies, and acceleration of the offline reconstruction algorithm.

Acknowledgments

The authors gratefully acknowledge support from NIH EB003292 and the Alabama Eyesight Foundation.

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Fig. 1. Timing diagrams for the SE-SS-PARSE sequence (time axis not to scale). τ_0 , τ_1 and τ_2 were short delays. Note that the actual “phase” and “frequency” encoding readout gradients were sums of two sinusoids. For clarity, only a zoomed section of the waveform is shown in the figure.

Fig. 2. The clock phantom used in the simulations. The table indicates the actual input parameter values for each disk of the clock phantom.

Fig. 3.

Simulation results with 4 noise levels. Each column of this figure shows the estimation results, including magnitude map, frequency map and relaxation rates maps, of the clock phantom with a specific noise level, as indicated by the SNR. Noise was introduced into the simulation signal model. Four representative rectangular areas of interest were chosen from the estimated parameter maps, as shown as the black areas in the upper-left corner magnitude map. Mean and standard deviations of R_2 and R_2' were computed from these areas to compare with the actual values.

Fig. 4.

Actual values vs. estimated values for relaxation rate R_2 (A) and R_2' (B) in the 4 selected areas of the clock phantom [see Fig. 3]. The actual input R_2 and R_2' values are indicated by the solid black line. The blue error bars are the mean and standard deviations calculated from the four representative areas from both small and big disks of the clock phantom.

Fig. 5.

Estimated parameter maps with the SE-SS-PARSE technique and reconstructed parameter maps with ME-GE/SE technique. A, B, C and D are the estimated M_{xy0} map, f map, $R2$ and $R2'$ maps from SE-SS-PARSE technique. E and G are the $R2$ and $R2^*$ maps from non-linear fitting of the multi-echo GE and SE magnitude images. F is the $R2'$ map calculated by subtracting the $R2$ map from the $R2^*$ map. Note that there are some ringing artifacts in E, F and G. These may be caused by systematic Gibbs ringing, or by phantom shaking during the data acquisition.

Fig. 6.

Convergence history of R_2 (left column) and R_2' (right column) estimates in the iterative search for one pixel in each tube of the four-tube phantom. Numbers in the bracket at left side of the figures denotes the (x, y) coordinates of each pixel.

Fig. 7. The phantom results from SE-SS-PARSE and ME-GE/SE technique are highly correlated. A represents the mean of $R2$ values calculated from the 100 selected areas with both techniques. B illustrates the comparison between $R2'$ values. The correlation coefficients are 0.9636 for $R2$ and 0.9788 for $R2'$.

Fig. 8.

Estimated and reference R2 (A) and R2' (B) values at row 45 of the 4-tube phantom. Estimated values from all shots in SE-SS-PARSE are illustrated as dotted line while the reference values are represented by the solid line. The area outside of the phantom was shown as zero in the standard technique, while the corresponding sections for SE-SS-PARSE demonstrate noisy background. The variations in the reference profiles come from Gibbs ringing artifacts, and possible phantom shaking during the data acquisition.

Fig. 9. Estimated mean and standard deviations over multiple shots in SE-SS-PARSE compared with reference values. The variations in the reference profiles come from Gibbs ringing artifacts, and possible phantom shaking during the data acquisition.

Table 1

R2 and R2' value modifier concentration in 4 tubes.

Tube #	Agarose	FeSO ₄
1	3%	0.325%
2	2%	0
3	4%	0
4	3%	0.975%