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Validation of Velocity-SS-PARSE for Single-shot Flow Measurement

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Abstract

As a variant of SS-PARSE (Single-Shot Parameter Assessment by Retrieval from Signal Encoding), Velocity-SS-PARSE (V-SS-PARSE), a single-shot imaging method has been developed to realize fast and straightforward flow quantification by solving an inverse problem. A robust signal model is described here that includes the local magnetization and its phase evolution during the signal, resulting in a more precise representation of the sampled signal. Magnitude, velocity, relaxation rate and frequency information can be retrieved without any extra reference image acquisitions, as demonstrated by phantom studies. Retrieved magnitude and velocity maps show results comparable to those obtained by phase contrast (PC) methods (correlation of $r > 0.99$ at $p = 0.005$) in the presence of stationary background, even with brief single-shot 70 ms acquisition.

Keywords

velocity measurement; single-shot MRI; parametric imaging; inverse problems; velocity images

1. Introduction

With their accurate measurement and convenient implementation, phase contrast (PC) methods have gained popularity in blood flow measurement throughout the body [1], especially cardiac imaging. One drawback, however, is that a reference phase image has to be acquired in addition to the velocity encoded image. This lengthens the image acquisition time and makes the image acquisition more complicated. Significant efforts have been made to speed up flow mapping such as applying fast data sampling trajectories (EPI, spiral etc.), image interleaving, parallel imaging and partial Fourier image acquisition. These methods, in combination with ECG triggering, have made real time blood flow measurement possible [2–6]. In the study of Thompson and McVeigh, flow velocity was not only measured, but also employed as an alternative cardiac gating method to retrospectively reconstruct images in real time [7].

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Despite this, acquisition of two images is still necessary for PC flow imaging. Sometimes, an extra two images need to be taken in the stationary state in order to determine the phase discrepancy introduced by eddy currents during the two different velocity-encoded images. This can make in vivo blood flow quantification very difficult, especially if flow is changing dynamically. A new method which can measure flow velocity with a single-shot would have significant advantages in many applications. Some techniques have been studied for non-subtractive flow mapping [8], but depend on the assumption that background phase varies slowly over space. This approach may be appropriate in situations such as the study of small vessels, but it is not suitable for general usage.

Single-Shot Parameter Assessment by Retrieval from Signal Encoding (SS-PARSE) has demonstrated the ability to estimate parameters describing the local signal, with potential for accurate and robust performance in fMRI studies [9]. In theory, it acquires a signal in (k, t) space in order to determine the magnitude and phase change of the signal during image acquisition. This is significant because most single-shot images have long acquisition times while conventional imaging methods assume all data points were acquired at the same time, thus ignoring the magnitude decay and off resonance frequency evolution. As a result, SS-PARSE is inherently free of distortion and artifacts that would be present in conventional methods.

An extension of SS-PARSE to velocity measurement, V-SS-PARSE, has been proposed [10]. In that preliminary report, a prototype version of V-SS-PARSE was tested, with a reduced set of basic parameters. A more robust model and accurate method would include estimation of T_2^* related signal decay and off resonance frequency effects. This is especially important for the cases in which there are areas with significant off resonance frequencies. Reported here is an experimental validation of the V-SS-PARSE method including estimation of decay and off-resonance frequency. Furthermore, in the previous preliminary study, no stationary spins were present as would be the case in normal situations.

This study provides validation of the extended V-SS-PARSE for mapping flow velocity in a phantom. A PC flow measurement method was used in the study to provide a reference.

2. Theory

In the original model of velocity estimation, the T_2^* decay factor and off resonance frequency factor were both omitted for simplification, leading to this expression of the measured signal:

$$S = \iint \rho_{xy} \exp(-i2\pi(\Psi_b + \Psi_v)) \exp(-i2\pi(k_x x + k_y y)) dx dy \quad (1)$$

ρ_{xy} is the proton density, Ψ_b is the non-flow-related background phase, Ψ_v is the flow induced phase shift and is related to the flow velocity by the gradient first moment k_v [11]:

$$\Psi_v = k_v v \quad (2)$$

Because local signal decay and off resonance frequency cause local magnetization to evolve continuously with time, a more robust model would be:

$$S = \iint \rho_{xy} \exp(-i2\pi(\Psi_b + \Psi_v)) \exp(-(R_2^* + i\omega)t) \exp(-i2\pi(k_x x + k_y y)) dx dy \quad (3)$$

Replacing Ψ_v with Eq. (2), and using magnetization M_{xy} to denote $\rho_{xy} \exp(-i2\pi\Psi_b)$, Eq. (3) becomes

$$S = \iint M_{xy} \exp(-i2\pi(k_v v)) \exp(-(R_2^* + i\omega)t) \exp(-i2\pi(k_x x + k_y y)) dx dy \quad (4)$$

The added two parameters R_2^* and ω are unknown and need to be determined. Therefore, as S , k_{vi} , k_x and k_y are already known in Eq. (4), by inverting the equation, independent unknown parameters M_{xy} , v , R_2^* and ω can be estimated.

In the previous study, the first part of the acquired data, which is free of velocity encoding and will contain stationary background phase information, was used to provide initial estimates for spin density and background phase. The current computation algorithm skips this step; all unknown parameters were identified by a search with initial parameter estimates zero (Fig.1.). Through the signal model described in Eq. (4), an estimated signal was generated. Since the goal is to find the unknown parameters that best match the estimated signal with the measured signal, the sum square error of their discrepancy was calculated as the cost to be minimized. The efficient conjugate gradient search algorithm was employed for calculating the composite search direction in multiple dimensions (stationary magnetization M_{xy} , velocity v , relaxation factor R_2^* and off resonance frequency ω) for each pixel in the reconstructed image. After the search direction was determined, the incremental change was obtained by one-dimensional golden search for the smallest cost in that direction. Then the parameter estimates (M_{xy} , Ψ_v , R_2^* and ω) were updated with the optimal values along the current search direction and a new estimated signal and cost were calculated. The search began with a short length of sampled points (the 5 initial part of the sampled signal is composed of around 1/3 of the sampling points prior to the velocity encoding gradients), for the purpose of calculating the local frequency without aliasing and determining the magnitude and the background phase. As iterations proceeded, more sampling points were added to refine the estimation. The search was repeated until the fractional decrease of the cost was less than a preset threshold and all the sampling points were used, the unknown parameters were then retrieved.

3. Methods

Data were acquired on a Varian/Magnex 4.7 T 60 cm vertical bore scanner (Varian, Inc., Palo Alto, CA) equipped with gradients capable of 32 mT/m magnitude and 160 T/m/s slew rate. Experiments were implemented with phantoms. Two reservoirs A and B were used. Reservoir B was placed higher than reservoir A. A pump in reservoir A moved water into reservoir B. Flow exiting reservoir B then passed through the phantom in the bore of the magnet, and returned upward through the phantom to reservoir A; thus creating two cross-sections with flow in opposite directions in the image plane. For constant flow measurement, an overflow exit was made at the wall of reservoir B. This kept the head pressure constant. Valves were installed at the in-flow and out-flow ports of reservoir B to control the flow rate.

Figure 2 shows the pulse sequences for velocity mapping with PC and V-SS-PARSE methods. Velocity encoded phase shifts along slice selective direction were introduced by inserting 4 bipolar gradients into the gradient waveform [10]. A rosette k-trajectory was employed for data sampling due to its excellent frequency selectivity and sample distribution in k space [12]. For multiple reasons, such as imperfect gradient amplifier performance, gradient pulse induced eddy currents and readout timing errors, actual sampling trajectories often deviate from their ideal locations in k space [13]. To account for this, the k-trajectory was experimentally calibrated for use in the PARSE reconstruction computations [14].

A birdcage volume coil with 26 cm inner diameter was used for RF signal transmission and signal reception. The following image parameters were used for both PC and V-SS-PARSE methods: FOV = 12.8 cm, slice thickness = 2 mm, image resolution 64×64. For the PC method, TR/TE = 20/6.6 ms was used. This corresponded to 2560 ms for the two image acquisitions to obtain the phase difference map. In this study, data acquisition time for V-SS-PARSE was 70 ms with a 180 kHz sampling frequency. The velocity encoding (VENC) produces a phase shift of π in the PC method and corresponds to the inverse of k_{vi} increment in V-SS-PARSE. The

peak velocity that can be measured without aliasing should be larger than the expected peak velocities according to the Nyquist criterion. With a laminar flow profile in the tube, the peak velocity would be twice the mean velocity. This implies that the maximum mean constant flow velocity that can be measured is 25 cm/s for $VENC = 50$ cm/s. If a larger VENC is desired, either the gradient strength or the duration of the bipolar gradient waveform needs to be adjusted in PC methods. In V-SS-PARSE the gradient waveform should be adjusted to generate a smaller k_{vi} increment.

The velocity calibration was performed by using a “bucket-and-stopwatch” technique (using the bucket for measuring volume, stopwatch for timing). Both velocity measurements with PC and V-SS-PARSE techniques were repeated 4 times to test measurement repeatability.

All images were reconstructed offline using reconstruction/post-processing routines programmed in Matlab (Version 7.0, The MathWorks Inc., Natick, MA).

4. Results

Figure 3 shows the computed local parameter images: magnitude, velocity, relaxation rate and frequency. The map intensities are proportional to the corresponding parameter estimates. The estimated velocity map indicates that the two tubes contain flow in opposite directions. The ringing effect seen in the velocity map, relaxation map and frequency map is a fixed artifact introduced by the rosette oversampling at the edge of k space.

The parameter estimates from the V-SS-PARSE technique evolve systematically over multiple iterations (Fig. 4). Three pixels were picked from the positive flow, negative flow and the stationary background and their parameter estimations through iterations were recorded separately. For all three pixels, the magnitudes increased promptly as the search begins, and converged to well-defined values throughout the process. In contrast to this, the velocity values of the three pixels did not change until the duration of the sampled signal points used reached the velocity encoding onset (the initial part of the sampled signal is free of velocity encoding information). After searching, they converged to steady values.

The magnitude maps and the velocity maps computed from the V-SS-PARSE method and the PC method are shown in Fig. 5. Note that the V-SS-PARSE results were acquired with a 70 ms snapshot in contrast to those acquired at a 2560 ms imaging time with PC method. In the magnitude map acquired with the PC method, the bottle signal is lower than the tube signal, even though they demonstrate similar signal strength in the V-SS-PARSE magnitude map. There are two reasons for this; both are related to the long image acquisition time used in this PC method: 1. flow refreshment that enhances the signal in the tube; 2. faster signal decay in the agar filled bottle compared with the water filled tube.

Comparison of the computed velocities from the PC method and the V-SS-PARSE method versus the calibrated velocities obtained from the “stopwatch-and-bucket” demonstrates that the velocities retrieved from the V-SS-PARSE are consistent with actual velocities and are comparable with results computed with the PC method (Fig. 6). Shown are the results computed from averaging the 4 repetitions for each specific velocity measurement, the error bars indicate the standard deviation. A linear correlation analysis yielded an $r = 0.9921$ between the PC and the V-SS-PARSE method. The measured velocities demonstrated high repeatability with minor variability. The Bland-Altman analysis indicates a bias of 0.65 cm/s, which is the mean of the difference between the two methods; agreement is defined as the mean ± 2 SD [15]. Precision was quantified by use of the 95% confidence intervals of the differences between the two velocity estimates. Proportional errors are observed in the plot.

5. Discussion

The results of the earlier study [10] indicate that the flow velocity could be estimated by using the V-SS-PARSE technique. In this study, validation of the single-shot flow imaging method was accomplished by using the PC method as a gold standard. A more direct “bucket-and-stopwatch” approach was employed as well for actual velocity calibration. The velocity measurements from V-SS-PARSE are in good agreement with both methods, suggesting potential application to in vivo flow quantification.

The current signal model extends the signal model of the previous prototype V-SS-PARSE method to include parameters describing decay and precession of local transverse magnetization during signal acquisition. Therefore, not only is the velocity estimation more accurate, but the local relaxation rate and the frequency maps are retrieved. More importantly, the more precise representation of the signal model is free of geometric errors caused by off resonance frequencies and should offer greater tolerance to the large susceptibility gradients found in vivo [9].

Though the PC method shows better magnitude and velocity estimations in the studies, it should be noted that the PC method served as a validation method. It used a conventional gradient echo sequence and the imaging time is relatively long (2560 ms) compared with the snapshot V-SS-PARSE approach (70 ms). Much higher temporal resolution for PC could be achieved by employing FLASH, EPI, or spiral sequences. These sequences can be designed with interleaving or parallel imaging to compensate the acquisition speed drawback. Nevertheless, a reference image is mandatory for flow mapping with PC methods. The V-SS-PARSE method is capable of single-shot imaging, capturing an entire flow measurement within a short time period. This technique is also compatible with parallel acquisitions or image interleaving for additional temporal and spatial resolution improvement. With further development, V-SS-PARSE could be designed for multiple-shot imaging and is expected to produce a cine flow movie by overlaying the flow map on the magnitude map with much shorter scan time compared to conventional PC techniques. For that purpose, cardiac triggering should be employed to ensure the multiple signals are taken at the same epoch during successive cardiac cycles. As mentioned earlier, the retrieved velocity waveform itself could also be used as a self-navigating signal for retrospective gating [7]. Moreover, collecting multiple slice V-SS-PARSE images with sufficient coverage of the region of interest (ROI) will generate 3D flow images, and thus could be retrospectively analyzed in multiple ways such as panning through a stack of 2D images, volume images or maximum intensity projection (MIP) images.

One thing that needs to be kept in mind is that velocity underestimation might result if the angle α between the flow direction and the imaging plane is not normal. All the velocity estimates will be smaller than the actual values by a factor of $\sin(\alpha)$. A simple localization sequence could be used to measure the angle between the two directions, permitting after-the-fact compensation for accurate velocity compensation (it should be noted that flow estimates based on velocity perpendicular to the plane and measured vessel lumen area in the plane will remain accurate even for oblique vessels). Another solution is 3D flow measurement. The composite velocity vector is not subject to underestimation due to its orientation.

In principle, it is possible to achieve 3D velocity measurement in a 2D slice with a single V-SS-PARSE image acquisition if sufficiently powerful gradients and slew rates are available. To accomplish this, it would be necessary to insert velocity encoding gradients along readout, phase encoding and slice selective directions separately at different times during the readout, and still have sufficient k -sampling for spatial encoding.

For the current study, only two different k_y values were designed with a symmetric waveform distribution. By designing an unsymmetrical first moment gradient waveform, 3 or more k_y

values could be obtained; this may offer velocity measurements over a larger range of velocities while conserving sufficient velocity resolution. The feasibility of this approach needs to be tested with computer simulation.

The rosette trajectory was chosen for data sampling in SS-PARSE because it frequently samples the center of k space. This corresponds to a wide temporal frequency band and less aliasing from the neighboring frequency sidebands. In addition to repeatedly intersecting itself, the rosette trajectory samples the edge of k space frequently. This high frequency emphasis leads to undesirable high-frequency noise characteristics as observed in the parametric maps. Two possible designs that might improve this situation are either constructing a non-symmetrically distributed rosette trajectory or discarding some of the data at the high spatial frequencies. Use of a density compensation filter in processing has been helpful in dealing with this same problem in SS-PARSE.

In summary, a single-shot flow imaging method—V-SS-PARSE was developed and validated with phantom experiments. The retrieved velocity estimates are consistent with the results achieved from the conventional PC method while saving the necessity of acquiring an extra phase reference image. At present, this method is still under development. However, it is expected in vivo studies will be carried out in the near future. Like the PC method, V-SS-PARSE basically is a velocity quantification method and is not confined to flow velocity measurement alone. Therefore, future possible applications might also include muscular-skeleton motion tracking. Given time, the method might ultimately be applied to pulsatile flow quantification in arteries, detection and quantification of valvular diseases (stenosis, regurgitation, etc.) as well as quantitative assessment of muscular-skeletal motion in vivo.

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Fig 1.
Flow chart of the algorithm.

Fig 2.

Diagrams for (A) PC and (B) V-SS-PARSE pulse sequences. Four bipolar gradients were inserted in V-SS-PARSE to provide k_y offsets for encoding velocity information.

Fig 3.
Estimated parameter maps with V-SS-PARSE from a 70 ms single-shot image acquisition.
(A): magnitude map; (B): velocity map; (C): relaxation rate map; (D): frequency map.

Fig 4.

Evolution of parameters during iterative search. Three representative pixels were picked from (1) stationary water in the surrounding bottle, and tube sections with (2) positive flow and (3) negative flow. Positions of these pixels are shown in (A) the magnitude map; and (B) the velocity map. History of estimates of (C) magnitude and (D) velocity are shown during the iterative search.

Fig 5.

Computed magnitude maps and velocity maps from the PC method (2560 ms for an acquisition of two images to calculate the velocity) and the V-SS-PARSE method (70 ms). The signal from the stationary background in the magnitude map from the PC approach (A) is lower than that from the V-SS-PARSE approach (B) due to the long image acquisition time used in this PC method. Velocity component in the stationary part is not completely suppressed in the velocity map from the V-SS-PARSE (D), as in the velocity map from the PC (C); this might correspond to the high frequency noise introduced by the intensive rosette sampling at the edge of k space.

Fig 6.

(A) Velocity measured using PC and V-SS-PARSE with varied constant velocities calibrated by the “bucket-and-stopwatch” technique, results shown are the computed velocities after 4 averaging with error bars indicating the standard deviation. Both results agreed with the actual velocities; (B) Bland & Altman analysis indicates a scatter diagram of the differences plotted against the averages of the two measurements. Comparison of the velocity estimates from V-SS-PARSE and PC yielded a correlation of $r = 0.9921$ at $p = 0.005$.