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Error Analysis of Cine Phase Contrast MRI Velocity Measurements used for Strain Calculation

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Abstract

Cine Phase Contrast (CPC) MRI offers unique insight into localized skeletal muscle behavior by providing the ability to quantify muscle strain distribution during cyclic motion. Muscle strain is obtained by temporally integrating and spatially differentiating CPC-encoded velocity. The aim of this study was to quantify measurement accuracy and precision and to describe error propagation into displacement and strain. Using an MRI-compatible jig to move a B-gel phantom within a 1.5T MRI bore, CPC-encoded velocities were collected. The three orthogonal encoding gradients (through plane, frequency, and phase) were evaluated independently in post-processing. Two systematic error types were corrected: eddy current-induced bias and calibration-type error. Measurement accuracy and precision were quantified before and after removal of systematic error. Through plane- and frequency-encoded data accuracy were within 0.4mm/s after removal of systematic error – a 70% improvement over the raw data. Corrected phase-encoded data accuracy was within 1.3mm/s. Measured random error was between 1 to 1.4mm/s, which followed the theoretical prediction. Propagation of random measurement error into displacement and strain was found to depend on the number of tracked time segments, time segment duration, mesh size, and dimensional order. To verify this, theoretical predictions were compared to experimentally calculated displacement and strain error. For the parameters tested, experimental and theoretical results aligned well. Random strain error approximately halved with a two-fold mesh size increase, as predicted. Displacement and strain accuracy were within 2.6mm and 3.3%,

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Conflict of Interest Statement

The authors have no conflict of interest to report.

respectively. These results can be used to predict the accuracy and precision of displacement and strain in user-specific applications.

Keywords

Cine phase contrast; accuracy; precision; strain; calibration error

Introduction

Two-dimensional cine Phase Contrast (CPC) is an MRI measurement technique that has been used by several research groups to calculate the distribution of strain in a single plane in skeletal muscles (Finni et al., 2003; Kinugasa et al., 2008; Pappas et al., 2002; Sinha et al., 2012; Zhou and Novotny, 2007). The imaging sequence is used to acquire a temporal sampling of spatial velocity distributions in the muscle over a motion cycle. The nodes of an applied muscle mesh are then tracked by temporally integrating the velocity data. Finally, the strain is calculated by spatially differentiating the mesh node displacement, often using continuum analysis methods (Silder et al., 2010; Zhou and Novotny, 2007). Applications of CPC measurement in the biceps brachii and supraspinatus under both active and passive tension have revealed non-uniform strain distributions (Pappas et al., 2002; Zhou and Novotny, 2007), which reflect the underlying muscle geometry and architecture (Pappas et al., 2002). Measuring and modeling strain distribution enhances our understanding of functional in vivo muscle deformation and may aid our understanding of mechanical muscle failure from strain-induced mechanisms.

CPC has been tested extensively using controlled phantom experiments. The reported outcomes include displacement tracking errors ranging from 0.09 to 1.5mm or 0.8 to 3.4% of total displacement (Behnam et al., 2011; Drace and Pelc, 1994; Lingamneni et al., 1995; Pelc et al., 1995; Zhu and Pelc, 1999). Unfortunately, these outcomes have limited applicability outside of the specific experiments as they are highly dependent on the imaging parameters and the post-processing integration method used (Pelc et al., 1995; Zhu et al., 1996). For example, a Fourier tracking method (Zhu et al., 1996) has been shown to reduce displacement error by more than thirty percent over a forward-backward method (Pelc et al., 1995). A useful supplement to the existing literature to assess the displacement and strain measurement capabilities of CPC is the accuracy and precision of the raw velocity measurements. This output is essential for understanding the predictive abilities of the CPC technique. Although experimental setup, scan parameters, and post-processing methods may be selected to maximize the accuracy and precision of displacement and strain, these outcomes are ultimately limited by the ability of the MRI equipment to accurately and precisely measure velocity.

There are two types of error that should be reported in any measurement system: systematic and random. Systematic error is repeatable error that can often be modeled and corrected. This error confounds the quantification of accuracy and must be corrected before the accuracy can be assessed. Eddy currents have previously been identified as one such source of systematic error in CPC data (Pelc et al., 1991).

Random error, also known as random uncertainty (Taylor, 1982), describes the distribution of a measurement about its mean and is considered a gauge of precision. It has been previously shown that the precision of CPC measurements is given by the equation

$$\sigma = \frac{\sqrt{2}v_{enc}}{\pi \cdot SNR \sqrt{N_p}} \quad (1)$$

where v_{enc} is the encoding velocity that produces a 180° phase shift, SNR is the signal-to-noise ratio, and N_p is the number of independent pixels averaged (Pelc et al., 1995). Random error cannot be corrected; rather, for every application it must be ensured that the magnitude of the signal of interest is sufficiently greater than the random error of the system. In this application it is also important to understand the extent to which this error propagates into displacement and strain, the output measures of interest.

The aim of this study was to quantify the precision and the accuracy improvement of CPC velocity measurements with removal of systematic error and to both experimentally and theoretically demonstrate the effects of these errors on downstream displacement and strain estimates. We expected that systematic error could be eliminated with correction of eddy currents and that the random velocity measurement error would match Equation 1. This report includes the authors' derived error propagation equations (see Theory) and our experimental results using controlled phantom motion.

Theory

Beginning with finite element principles, the propagation of random velocity error into displacement and strain can be mathematically derived:

$$\delta d = \sqrt{N} \cdot \Delta t \cdot \delta v \quad (2)$$

$$\delta E = \frac{\sqrt{2ND} \cdot \Delta t}{M} \delta v \quad (3)$$

where N is the number of tracked time segments, δd and δE are the random displacement and strain error, respectively, D is the spatial dimension order, t is the time segment duration, M is the mesh size (i.e. distance between mesh nodes), and δv is the random velocity error (Appendix A). It is important to note that the derivation of these equations assumes small strains and constant velocity between time segments. Equation 2 is consistent with a previous derivation of displacement error by Pelc et al. for the case where the number of time segments per cycle is not greater than the number of pulse sequence repetitions (Pelc et al., 1995). It has been demonstrated that random displacement error can be reduced using more sophisticated tracking schemes, such as the forward-backward method (Pelc et al., 1995) and the Fourier integration method (Zhu et al., 1996).

Methods

Setup

A custom MRI-compatible jig was designed to move a phantom within an MRI bore using a linear stepper motor (Oriental Motors, Tokyo, Japan) mounted at the end of the patient table (Figure 1a). The phantom (dimensions 7.6cm × 7.6cm × 3.3cm) was composed of 15% B-gel, selected for its ability to maintain form under mechanical motion and provide high signal-to-noise ratio (Wu et al., 2000). Two additional phantoms of the same material were placed in the field of view to serve as stationary references. The motor velocity (Figure 1b) was controlled by custom software (PMX-4EX-SA, Arcus Technology, Livermore, CA) and gated to a square wave (5V_{pp}, 2.5V offset, 0.5Hz) generated by a function generator (Model 33120A, Hewlett-Packard, Palo Alto, CA). A cardiac simulator (Model M311, FOGG, Aurora, CO) was triggered by the same output function and used to gate the CPC sequence. A stationary receive-only coil was attached to the jig such that it surrounded the phantom at all times without impeding motion.

Motor Speed Validation

The velocity control of the motor was independently validated using reflective markers and a motion analysis setup (120 Hz, EvaRT version 5.0.4, Motion Analysis Corporation, Santa Rosa, CA). Trajectory data measured by the motion system were filtered using a fourth order low-pass Butterworth filter with a 12 Hz cutoff frequency. Velocity was calculated by smoothing and differentiating the trajectories according to the Savitzky-Golay method using a third order polynomial function and a window size of five (Savitzky and Golay, 1964).

Scanning

Data were collected with a 1.5T MRI system (Signa HDX 16.0, GE Medical Systems, Waukesha, WI) using the commercially available Fast 2D Phase Contrast sequence, a 24cm field of view and 192×192 in-plane resolution (Table 1). Individual flow direction encoding was used (temporal resolution of ~150ms), and was aligned with the axis of motion. To ensure independent sampling, twelve time segments were collected over the 2s motion cycle; therefore 48 motion cycles were required per trial (Appendix B). Each scan generated one magnitude and one velocity image per time segment (24 images total). Due to differences in the scanning sequence between the three encoding directions (through plane, frequency, and phase), each was collected and assessed independently at five velocity settings (Table 2).

Data Processing

All data were processed using custom MATLAB scripts (The Mathworks, Natick, MA). The edges of both the motion phantom and the stationary reference phantoms were automatically detected using the magnitude images (Figure 2a). The algorithm identified transitions from regions of noise (mean signal ~ 0) to phantom (mean signal > 0) by identifying where the signal reached half of its maximum value. The analysis region of interest (ROI) was the Eulerian region within the motion phantom that contained signal at every time segment in the cycle. The velocity data within the stationary and motion phantom ROIs were then

smoothed by resampling each measurement as the average of the surrounding 3×3 pixel region (Figure 2b,c), consistent with the window size frequently used to measure strain distribution in skeletal muscle (Finni et al., 2003; Zhou and Novotny, 2007). Because the sample resolution was 192×192 and GE software auto interpolates the data to 256×256 pixels, the actual number of independent pixels averaged is 5.06. The mean and standard deviation of the velocity within the motion phantom ROI were recorded for each time segment of each trial.

Systematic Error Correction Part I: Eddy Currents—The temporally averaged velocity data from the stationary trials were used to model the eddy current effect. Using least squares regression, an equation of the form

$$z=a+bx+cy+dxy+ex^2+fy^2 \quad (4)$$

was fit to the data (Lingamneni et al., 1995). The statistical significance of each of the terms was ensured using stepwise regression (JMP, SAS, Cary, NC). A unique set of model coefficients was generated from the motion phantom ROI (middle phantom) and stationary reference phantom ROIs (outside phantoms; Figure 2a) for each velocity encoding direction and each trial. The coefficients were then averaged over the three trials. Comparisons were made between the motion phantom and the stationary phantom models as well as between the motion phantom models generated for each encoding direction. The modeled data from both the motion phantom and the stationary phantom were subtracted from their corresponding 0mm/s trials to compensate for eddy current effects (Figure 3) and the RMSE of results were compared (Table 3). Eddy current coefficients generated from the motion phantom region of the 0mm/s trials were used to correct the final data.

Systematic Error Correction Part II: Calibration Errors—Systematic bias and scaling were modeled using least squares fitting of the measured data to the linear equation

$$Data_{corr}=s*(Data_{meas}+b) \quad (5)$$

where s is the scaling factor and b is the bias. The measured input was a vector of data with equal constituents from each sampled velocity. Once again, data from each encoding direction were fit independently.

Velocity Accuracy and Precision—Accuracy of the velocity data was assessed after each stage of systematic error removal. Accuracy was defined as the difference between the mean corrected velocity measurement and the imposed velocity, averaged across the five velocity settings. Precision, defined as the magnitude of the random error, was quantified from the standard deviation of the corrected output. Specifically, precision was quantified as the standard deviation of each pixel measurement across all time segments, averaged over the phantom ROI.

Displacement and Strain—One-dimensional displacement was calculated along the velocity direction of each of the frequency-encoded 20 and 40mm/s trials. Nodes were initialized at the center of each pixel within the phantom ROI and their displacements were

tracked independently during constant forward motion (time segments 2 through 5) as well as during constant reverse motion (time segments 8 through 11) by multiplying sampled velocity by time segment duration. Velocity samples were obtained at fractional pixel locations by interpolating the two pixel velocities nearest to the current node location. Mean and standard deviation of the nodal displacements were assessed for each velocity direction (forward and reverse) and for each trial both before and after systematic error correction. Percent error of the mean was calculated using an expected displacement of 10mm (20mm/s for 0.5s) or 20mm (40mm/s for 0.5s).

One-dimensional strain was calculated along the velocity direction of each of the frequency-encoded 20 and 40mm/s trials at the end of constant forward motion (time segment 5) and at the end of constant reverse motion (time segment 11). Strain was calculated between neighboring pixel nodes as well as between nodes spaced five pixels apart. Mean and standard deviation of strain were calculated for each velocity direction and trial both before and after systematic error correction. Error of the mean was calculated as the absolute value of the mean strain, which was expected to be zero.

Results

Motor Velocity Validation

The results of the independent motor velocity validation showed a mean error less than 1% and a velocity standard deviation less than 3.5% of the mean (Figure 1c,d).

Uncorrected Data Summary

The measured velocity approximately followed the expected profile for all three encoding gradients at all three velocity settings, even during the acceleration periods (Figure 4). However, systematic calibration-type error was present (Figure 4). Measurement bias was apparent from the 0mm/s data and the measured velocity magnitude of both the through plane- and frequency-encoded data was repeatedly lower than expected (Figure 4).

Eddy Current Compensation

The eddy current model generated from the motion phantom region during the 0mm/s trials reduced the RMSE of the data slightly (Table 3). The model coefficients were similar between frequency- and phase-encoded data, but not between frequency- and through plane- or between phase- and through plane-encoded data (Table 3). When the eddy current model was instead generated from the stationary reference phantom signal, the model coefficients were different than those generated from the motion phantom (Table 3).

Calibration Error Correction

In addition to the eddy currents, previously unreported calibration errors were discovered in the data. Three distinct calibration correction equations were found for the through plane (D_{tp} ; Equation 6), frequency (D_f ; Equation 7), and phase (D_p ; Equation 8) encoding directions. With application of these correction equations, the systematic measurement error for the through plane- and frequency-encoded data was reduced, but not for the phase-encoded data (Figure 5).

$$Dtp_{corr} = 1.04 * (Dtp_{meas} - 0.35) \quad (6)$$

$$Df_{corr} = 1.05 * (Df_{meas} - 0.25) \quad (7)$$

$$Dp_{corr} = 0.96 * (Dp_{meas} - 0.46) \quad (8)$$

Velocity Accuracy and Precision

Eddy current compensation had little effect on the accuracy of the data (Figure 6a). Systematic error correction, on the other hand, improved the accuracy of the through plane- and frequency-encoded measurements greatly, but not the phase-encoded measurements (Figure 6a). After correction, the mean accuracy across the five tested velocities was found to be within 0.1mm/s for through plane-encoded data, 0.4 mm/s for frequency-encoded data, and 1.3mm/s for phase-encoded data (Figure 6a). This translates to greater than 70% reduction in velocity error in the through-plane and frequency-encoded data with systematic error correction.

The random error was between 1 to 1.4mm/s after correction of the 0mm/s trials (Figure 6b). The error was higher for the 20 and 40mm/s trials, except in the through plane-encoded direction. Given the parameters of this experiment ($v_{enc} = 50\text{mm/s}$, $N_p = 5.06$, $SNR \sim 6.2$) the expected random error due to thermal noise is $\sim 1.6\text{mm/s}$ (Equation 1; Pelc et al., 1995).

Displacement and Strain

Displacement error was reduced to less than 2.6mm with correction (Figure 7a). Displacement standard deviation was 0.62mm (20mm/s trial average) and 0.86mm (40mm/s trial average) after correction (Figure 7b). Based on Equation 2 and the data parameters ($N = 3$, $t = 0.17\text{s}$, $\delta v = 1.7$ or 2.4mm/s for 20 or 40mm/s data, respectively), the expected random displacement error was 0.49 and 0.69mm.

No meaningful difference was observed in the average strain error with increased node spacing for the 20mm/s data, but error increased with increased node spacing for the 40mm/s data (Figure 7c). Random strain error of the 20 and 40mm/s data was approximately halved with the two-fold increase in node spacing (Figure 7d). Based on Equation 3 and the data parameters listed in the previous paragraph, the expected random strain error for the 20mm/s data was 11% (5 pixel node spacing) and 5.6% (10 pixel node spacing) and for the 40mm/s data was 16% (5 pixel spacing) and 7.8% (10 pixel spacing).

Discussion

A series of studies have demonstrated experimental accuracy of displacement tracking using CPC (Behnam et al., 2011; Drace and Pelc, 1994; Lingamneni et al., 1995; Zhu and Pelc, 1999). The errors reported are highly variable between studies (0.09 to 1.5mm) likely due to the dependence not only on the measurement error, but on the particulars of the applied post-processing methods. It is also possible that a portion of the variability in reported errors

may be due to inherent random error. These factors make any generalized assessment of unique applications highly challenging. What has not yet been reported in the literature is the accuracy and precision of raw velocity measurements produced using CPC techniques. The propagation of velocity measurement errors into the quantities of interest (i.e. displacement or strain) can be mathematically derived for each custom application, making this measure a more generalizable and useful benchmark for researchers using CPC. The primary aims of this study, therefore, were to measure the accuracy of CPC velocity measurements before and after the correction of systematic error, to quantify the precision of the measurements as compared to theoretical predictions, and to demonstrate the impact of the velocity measurement errors on applications such as strain measures *in vivo*.

Systematic Error

The source and various means of correction of eddy current-induced bias have been previously described in the literature (Lingamneni et al., 1995; Pelc et al., 1991; Zhou and Novotny, 2007; Zhu et al., 1996). As expected, it was found that the eddy current model that was fitted to the motion phantom data during the 0mm/s trials was consistent from trial to trial and between frequency- and phase-encoded data. The model was unique for the through plane encoding direction, however, which can likely be explained by the fact that the axial cross-section of the phantom, from which the model was generated, was much smaller than the coronal cross-section. What was more surprising was that the eddy current model from data within the stationary phantoms surrounding the motion phantom was inconsistent with the model generated within the motion phantom itself. This raises questions about other studies that report using stationary reference phantoms to model the eddy currents (Drace and Pelc, 1994).

It was surprising that a larger source of systematic error than eddy currents was discovered: systematic calibration-type error. This calibration error has not been previously identified or described in the literature. It accounted for a scaling discrepancy in the data of 4 to 5%, depending on the encoding direction, and a bias of up to 0.5mm/s (Equations 7 through 9). Although the applied calibration substantially improved the accuracy of both the through plane-and frequency-encoded data, the accuracy of the phase-encoded data remained problematic. There was an apparent velocity-dependence of the calibration for the phase-encoded data, which merits future investigation.

The results of this study demonstrated an accuracy improvement in both the through plane-and frequency-encoded velocity data of over 70% with systematic error correction, with the largest improvement in the through plane-encoded data (Figure 6a). The primary contributor to this change was the calibration error correction (Figure 6a). Only minor improvement occurred in the phase-encoded data (Figure 6a).

The significance of the demonstrated improvement in velocity accuracy on the downstream measures of displacement and strain is not straightforward to quantify, particularly due to the nature of velocity-based tracking. The effects of each of the calibration error components – bias and scaling – must be considered independently.

Bias—Over the course of a single time segment, measurement bias leads to drift error in displacement but may have no effect on strain – which is a normalized quantity – as long as the bias is spatially uniform. However, drift in displacement leads to a velocity sampling error in subsequent time steps, which affects the accuracy of both the trajectory and the strain in a manner dependent on the local spatial velocity gradient. In this study's sample calculations displacement accuracy was found to improve with systematic error correction but not strain accuracy, indicating that the systematic velocity error generated displacement error but not strain error. This was because the velocity distribution was uniform in this application and sampling error did not apply as it would *in vivo* (Hodgson et al., 2006; Sinha et al., 2012). The magnitude of this sampling error *in vivo* is difficult to predict, but should be considered in an error analysis. Fortunately, sophisticated tracking algorithms such as the forward-backward method and the Fourier integration method have been developed, which compensate for bias errors based on the assumption that the trajectory of a cyclic motion must necessarily begin and end at the same point (Pelc et al., 1995; Zhu et al., 1996). Therefore, it is not necessary to quantify the bias error in advance in order to correct it.

Scaling—Like bias error, scaling has the potential to affect the accuracy of both displacement and strain. The effect of scaling on displacement error over an individual time segment is dependent on the magnitude of the scaling factor, the magnitude of velocity, and the time segment duration. This was illustrated in the data by the increased improvement in displacement accuracy with correction of the 40mm/s data over the 20mm/s data. The effect of scaling on strain error is dependent on the same factors listed for displacement error as well as on local spatial velocity gradients. As discussed previously, additional error may be introduced with inaccurate velocity sampling, which is also dependent on the spatial velocity gradients. Unlike bias error, measurement scaling error is not easily corrected without a priori knowledge of the scaling factor. Therefore, it is important to be aware of the presence of calibration error in the system, particularly scaling error, and to apply appropriate correction.

Random Error

As hypothesized, the magnitude of the measured random error of the velocity closely matched the theoretically predicted value of ~1.6mm/s (Figure 6b), which is based on thermal noise in the system and is specific to the experimental parameters used. This finding is significant because it is the first time that the random error in CPC velocity measurements has been demonstrated experimentally in the literature. The random error was higher in the 20 and 40mm/s trials for frequency and phase encoding, which was likely due to the motion artifacts and ghosting from in-plane motion. No in-plane motion was present in the 20 or 40mm/s through plane-encoded trials and random error was not increased for these trials. This demonstrates that in order to minimize error in CPC applications, in-plane motion should be minimized.

The propagation of the random velocity measurement error into displacement and strain can be approximated using Equations 2 and 3, respectively. The validity of these equations was demonstrated by comparing the measured random error of the displacement and strain to the

random error predicted by the equations. All measured values agreed with the predicted values.

Importantly, Equations 2 and 3 provide insight into parameters that affect random error propagation. For example, to minimize error propagation, both the number of tracked time segments and the time segment duration should be minimized. Naturally there are limitations to the minima of these parameters: the motion cycle is limited to a physiologically feasible range and the time segment is limited to the temporal resolution of the system (Appendix B). Another way to minimize random error in strain is to increase mesh size. The final option is to reduce the random error of the velocity measurement itself through acquisition means: by decreasing encoding velocity, increasing the signal-to-noise ratio, or increasing number of pixels averaged for each ROI (Equation 1). Finally, it should be noted from Equation 3 that if higher dimensions of strain are desired, these will incur correspondingly higher error.

Conclusions

In conclusion, this study has provided a baseline measurement of the accuracy and precision of velocity from a CPC MRI measurement protocol, has demonstrated over 70% improvement in measurement accuracy with eddy current compensation and calibration error correction, and has derived equations to approximate the propagation of random measurement error into both displacement and strain. The highest measurement accuracy was in the through plane-encoded data and the lowest was in the phase-encoded data, therefore specific accuracy requirements should be carefully considered when selecting the phase encoding direction in an experiment and when analyzing data acquired along that axis. The largest contribution to the accuracy improvement came from calibration error correction.

The significance of the demonstrated results is highly user-specific for multiple reasons. Firstly, although the scanner used in this study is calibrated and maintained to industry standards, inherent differences in individual gradient coils, amplifiers, receiver coils, and scan settings result in some of the reported errors being scanner-, hardware-, and parameter-specific. The reported data are not intended to represent the absolute limitations of the GE Signa MRI system. Rather, the methods are intended to serve as a roadmap for CPC users to identify the capabilities and limitations of their own setup. Secondly, whether the magnitude of the reported errors falls within an acceptable range is dependent on the user-specific application. The authors recommend that the requirements of each application be carefully considered on an individual basis to ensure that the resulting measurements are both accurate and meaningful. Our results can be used to provide a preliminary estimate of errors for such an evaluation and a useful benchmark for comparison with data acquired on a specific MRI system.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

(a) Motor and jig set-up used to move a phantom within the MRI bore. Slider motion was controlled by the rotation of the motor, which controlled the linear motion of the extension rod and phantom. (b) Velocity profile of the moving phantom. Three parameters could be adjusted to modify the shape: peak velocity, maximum displacement, and acceleration time. Peak velocity was set at 20 or 40mm/s. Maximum displacement was selected to ensure that the full cycle did not exceed 2 seconds (to allow for 0.5Hz triggering). Acceleration was limited to the motor torque-velocity capabilities. Displacement trajectory (blue line) and velocity (green line) of the moving phantom over one motion cycle, as measured using the motion analysis system, are shown for both the (c) 40mm/s and (d) 20mm/s settings.

Figure 2.

Data processing techniques employed. (a) Sample frequency-encoded velocity image acquired during 20mm/s motion of the middle (motion) phantom. Edge detection of all three phantoms is represented by the blue rectangles and the velocity key, shown in units of mm/s, is shown on the right. A close-up image of the motion phantom ROI is shown in raw (b) and resampled (c) form. The data were resampled using 3×3 pixel regions.

Figure 3.

Systematic error correction of eddy current-induced bias. (a) Temporally averaged data from a frequency-encoded no motion trial. The spatial measurement non-uniformity due to the eddy current effect is visible. The velocity key (on the right) is in units of mm/s. (b) Model of the eddy current effect. (c) Corrected data. Data from the first plot was corrected using the eddy current model, resulting in a more spatially uniform output.

Figure 4.

Measured velocity distribution within the phantom region for each encoding direction (columns), velocity setting (rows), and time segment (x-axis). The dashed lines indicate the prescribed velocities. (Acceleration regions were approximated.) In the 20mm/s and 40mm/s trials, the phantom was expected to be at constant positive velocity during time frames 1–5 and at constant negative velocity during time frames 7–11. Therefore, time segments 2 through 4 were selected for the analysis of +20 and +40mm/s velocities and time segments 8 through 10 were selected for analysis of –20, and –40mm/s velocities. All twelve time segments were included in the 0mm/s analysis.

Figure 5.

The velocity error (measured minus imposed) is shown at five discrete velocities before and after systematic error correction for (a) the through plane-encoded data, (b) the frequency-encoded data, and (c) the phase-encoded data.

Figure 6.

(a) Accuracy in each of the velocity encoding directions was quantified from the error between the imposed and the mean measured velocity. The velocity error, averaged across the five velocity settings (-40 , -20 , 0 , 20 , and 40 mm/s), is shown for each stage of error correction and each encoding direction. (b) Precision in each of the velocity encoding directions was quantified from the temporal standard deviation of each pixel measurement, averaged over the region of interest for each velocity. Corrected precision is shown at 0 , ± 20 , and ± 40 mm/s. Dashed line indicates predicted standard deviation based on Pelc's equation [11].

Figure 7.

Displacement and strain measurement accuracy (a,c) and precision (b,d) were quantified from the uncorrected and corrected frequency-encoded data by tracking nodes along the velocity encoding direction during the constant velocity time segments. Node displacement was calculated by temporally integrating velocity. Strain was calculated by spatially differentiating displacement for a mesh size of 5 pixels (4.7mm) and 10 pixels (9.4mm).

Table 1

Baseline imaging parameters selected.

Pulse sequence	Vasc PC
Imaging Options	Gat, Seq, Fast
Mode	2D
Coil	GPFLEX
Orientation	Feet-First Supine
Gradient	Whole
X/Y Resolution	192×192
Phase FOV	24 cm
Slice Thickness	5.0 mm
Shim	off
Flow quantification	off
Flow recon type	Phase Diff
Flow analysis	on
Encoding velocity (V_{enc})	5 cm/s
Acq. Flow direction images	S/I
Views Per Segment	4
# Time Segments	12

Table 2

Parameter variations for each data collection. All three velocity encoding gradients were tested by adjusting imaging plane between axial and coronal and adjusting frequency direction between superior/inferior (S/I) and right/left (R/L).

Velocity Encoding Gradient	Peak Velocity (mm/s)	Imaging Plane	Frequency Direction	# Trials
Through plane	0	Axial	S/I	3
Through plane	20	Axial	S/I	3
Through plane	40	Axial	S/I	3
Frequency	0	Coronal	S/I	3
Frequency	20	Coronal	S/I	3
Frequency	40	Coronal	S/I	3
Phase	0	Coronal	R/L	3
Phase	20	Coronal	R/L	3
Phase	40	Coronal	R/L	3

Coefficients of the eddy current model for each encoding direction, calculated from both the motion phantom and the stationary phantom data and averaged over the three 0 mm/s trials. All coefficients were found to be statistically significant. Also shown are the root-mean-square errors of the motion phantom data from the 0 mm/s trials both before and after the correction model was applied.

Table 3

Modeled Phantom	Encoding Direction	Const.	X Coef.	Y Coef.	XY Coef.	X ² Coef.	Y ² Coef.	RMSE Before	RMSE After
Motion	Through Plane	-12.2	0.011	0.14	1.4e-4	-5.9e-5	-5.9e-4	2.8	2.74
	Freq.	20.4	-0.17	-0.080	7.0e-4	2.4e-4	-2.0e-4	3.01	2.31
	Phase	16.5	-0.17	-0.065	7.3e-4	2.7e-4	-2.3e-4	2.27	2.14
Stationary	Through Plane	-1.4	3.1e-3	8.2e-3	2.1e-6	-1.1e-5	-4.0e-5	--	--
	Freq.	4.6	-0.023	8.8e-3	4.3e-5	7.0e-5	-8.2e-5	--	--
	Phase	1.1	-0.017	0.015	4.8e-5	4.3e-5	-1.2e-4	--	--