Peak Velocity and Flow Quantification Validation for Sensitivity-Encoded Phase-Contrast MR Imaging[1]

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Rationale and Objectives. Phase-contrast (PC) magnetic resonance imaging (MRI) technique has important clinical applications in blood flow quantification and pressure gradient estimation by velocity measurement. Parallel imaging using sensitivity encoding (SENSE) may substantially reduce scan time. We demonstrate the utility of PC-MRI measurements accelerated by SENSE under clinical conditions.

Materials and Methods. Accuracy and repeatability of a SENSE-PC implementation was evaluated by comparison with a commercial PC sequence with five normal volunteers. Twenty-six patients were then scanned with SENSE-PC at reduction factors (R = 1, 2, and 3). Blood flow and peak velocity were measured in the aorta and pulmonary trunk in 16 patients and peak velocity was measured at the coarctation of 10 patients. Quantitative flow, shunt ratio, and peak velocity measurements obtained with different reduction factors were compared using correlation, linear regression, and Bland-Altman statistics. All studies were approved by an Institutional Review Board, and informed consent was acquired from all subjects.

Results. The correlation coefficients for all comparisons were >0.962 and with high statistical significance ($P < .01$). Linear regression slopes ranged between 0.96 and 1.11 for flow and 0.88 to 1.05 for peak velocity. For flow, the Bland-Altman statistics yielded a total mean difference ranging from −0.02 to 0.05) L/minute with 2 standard of deviation limits ranging from −0.52 to 0.75 L/minute. For peak velocity, the total mean difference ranged from −0.10 to −0.004) milliseconds with 2-SD limits ranging from −0.062 to 0.46 milliseconds. R = 3 to R = 1 comparisons had greater 2-SD limits than R = 2 to R = 1 comparisons.

Conclusion. SENSE PC-MRI measurements for flow and pressure gradient estimation were comparable to conventional PC-MRI.

Key Words: Flow; parallel imaging; cardiac imaging

Phase-contrast magnetic resonance imaging (PC-MRI) is a proven noninvasive technique for quantifying velocity and blood flow in the great arteries (1–3). Measurements of blood flow in the aorta and pulmonary trunk produce a wealth of information, including cardiac outputs of the left and right ventricles, regurgitant volumes and fraction of the aortic and pulmonary valves, and shunt ratio. Regurgitant fraction is a particularly important parameter that determines the need for valvular repair or replacement, whereas shunt ratio is an important parameter for

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evaluating the need for closing shunt lesions because of atrial septal and ventricular septal defects (4–8). Velocity of moving blood is related to the pressure gradient as described by the modified Bernoulli equation (9). This relationship is used extensively by echocardiography to estimate pressure gradient across stenotic cardiovascular lesions. Using a similar approach, PC-MRI has been applied to estimate the pressure gradient of coarctation of the ascending aorta (9). A PC-MRI scan usually requires a breath-hold to minimize the movement of the vessels through the imaging slice. However, conventional PC-MRI scans last on the order of 20–30 seconds. This duration may be difficult for children and noncompliant patients.

Sensitivity encoding (SENSE) (10) is an important technique that significantly reduces acquisition time. Implementations of SENSE for magnitude imaging are now widely available for clinical applications. A successful implementation of SENSE for PC-MRI promises shortened scan time or increased temporal resolution in segmented k-space techniques, thereby improving patient compliance in breath-hold imaging. An experimental version of SENSE PC-MRI has been tested on the measurement of shunt ratio (11,12). However, the potential applications of SENSE PC-MRI have yet to be fully explored in the measurement of flow velocity and the estimation of pressure gradients.

Feasibility of SENSE-accelerated PC-MRI has been demonstrated by experimental sequences (11–13) for flow quantification although a clinically practical and efficient implementation has not been reported. In particular, the SENSE paradigm requires an accurate, robust estimation of the coil sensitivities to unwrap the undersampled, aliased images. Hence, we have recently implemented a SENSE version of PC-MRI that uses a single, low-resolution three-dimensional (3D) volume acquisition for calibration. Data from this calibration scan are used to reconstruct subsequent, unlimited number of SENSE accelerated PC-MRI scans, provided that the regions of interest lie within the calibration volume. This implementation is capable of variable reduction factor R. For convenience, we refer to a nonaccelerated (R = 1) scan as SENSE-PCx1, a reduction factor 2 (R = 2) scan as SENSE-PCx2, and a reduction factor 3 (R = 3) scan as SENSE-PCx3.

In this article, we first establish the accuracy of flow and velocity measurements of SENSE-PCx1 against a standard, commercial PC-MRI sequence (Fastcard-PC, GE Healthcare, Waukesha, WI, 1.5 T) in normal volunteers. We then examine the repeatability of SENSE-PC measurements at reduction factors R = 1, 2, and 3. Finally, we compare the results from SENSE-PC at various reduction factors in a group of clinical patients. Specifically, we test the hypothesis that SENSE-PC at reduction factors 2 and 3 produces flow and peak velocity measurements statistically similar to R = 1 values under clinical conditions while simultaneously providing considerably shorter scan times.

MATERIALS AND METHODS

MR Imaging

Volunteer population.—We examined five normal volunteers (weight 61–89 kg, mean age 34.8 years ± 2.9 years, 4 male/1 female) for PC-MRI study. The mean heart rate was 70 beats/minute (range 59–80). PC-MRI scans were performed with flow quantification from the slices transverse to the ascending aorta and pulmonary trunk. Institutional Review Board approval was obtained for the study protocol, and informed consent was obtained from all volunteers.

All imaging was done on a 1.5-T TwinSpeed MRI Scanner (GE Healthcare) with 150 T/milliseconds maximum slew rate and 40 mT/minute gradients. An eight-channel cardiac phased-array coil (GE Healthcare) was used for all acquisitions. The regions of interest were centered as much as possible within the field of view. Volunteers were asked to hold their breath at deep inhalation at both the calibration and SENSE acquisition scans.

A calibration scan was first acquired using a 3D spoiled gradient-recalled echo (SPGR) sequence covering the full chest volume for all vessels of interest, namely the aorta and the pulmonary trunk. The sequence was not cardiac gated. A low flip-angle of 5°, a low-resolution matrix of 64 × 64, and averaging of two excitations produced high signal-to-noise ratio (SNR), low-contrast images for the coil sensitivity maps. The total calibration scan time was approximately 15 seconds for the 32 calibration slices.

After calibration, for each vessel of interest, Fastcard-PC scans were acquired twice, followed by two scans acquired by SENSE-PC at reduction factors R = 1, 2, and 3. The SENSE-PC sequence was implemented as a two-dimensional fast GRE segmented k-space, cardiac-triggered, phase-contrast sequence with retrospective gating (3,14). Imaging was performed with the slice perpendicular to the vessel lumen and flow encoding in the through-plane direction. For each vessel of interest, the same slice prescription was used for all the SENSE-PC