Rapid Left-to-Right Shunt Quantification in Children by Phase-Contrast Magnetic Resonance Imaging Combined With Sensitivity Encoding

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Background—Parallel imaging by sensitivity encoding (SENSE) may considerably reduce scan time in MRI. For rapid flow quantification in children with congenital heart disease, we evaluated phase-contrast MRI (PC-MRI) techniques combined with SENSE.

Methods and Results—In 22 pediatric patients (mean age, 7.2 ± 6.2 years) with cardiac left-to-right shunt, blood flow rate in the pulmonary artery (Qₚ) and ascending aorta (Qₛ) and flow ratio Qₚ/Qₛ were determined by PC-MRI with SENSE reduction-factor 2 and 3 (SF-2 and SF-3). Additionally, we used PC-MRI with higher spatial in-plane resolution (1.6 × 2.1 versus 2.3 × 3.1 mm) with and without SF-3. Results were compared with a recently validated standard PC-MRI protocol and tested in vitro using a pulsatile flow phantom. Reduction of signal averages from 2 to 1 and application of SENSE accelerated flow measurements by a factor of 3.5 (5.2) using PC-MRI with SF-2 (SF-3) compared with standard PC-MRI. For blood flow rate through the pulmonary artery and aorta, as well as for the Qₚ/Qₛ ratio we found negligible differences of ±3%, lower limits of agreement (mean ± 2 SD) of −7% to −18%, and upper limits of agreement (mean ± 2 SD) of +3 to +24%, demonstrating good agreement with standard PC-MRI. Mean Qₚ/Qₛ ratio by standard PC-MRI was 1.69 ± 0.45 (range, 1.27 to 2.79). Interobserver variability was low, and high accuracy was confirmed in vitro for all protocols.

Conclusions—PC-MRI for flow quantitation may be combined with SENSE to achieve a substantive reduction of scanning time. In children with left-to-right shunt, Qₚ/Qₛ quantification is possible by PC-MRI+SF-3 in <60 seconds. Use of higher in-plane resolution did not improve measurement results. (Circulation. 2003;108:1355-1361.)

Key Words: heart defects, congenital • pediatrics • magnetic resonance imaging • shunts • imaging

In pediatric patients, noninvasive assessment or exclusion of cardiac left-to-right shunts by use of phase-contrast cine MRI (PC-MRI) has been demonstrated to be reliable and clinically useful.¹⁻³ Thus, hemodynamic information may be added to a morphological cardiac MR investigation. In the clinical setting, however, repeated flow measurements at multiple sites may be required. Because each measurement usually takes 2.5 to 5 minutes with standard PC-MRI protocols depending on heart rate and imaging parameter settings, a thorough hemodynamic MR investigation may be time consuming. Additionally, variations of heart rate and respiration may introduce artifacts. Therefore, a shorter acquisition time would be desirable. The sensitivity-encoding (SENSE) technique uses different single-coil sensitivities of a multi-element phased-array surface coil to spatially encode the MR signal independently from conventional gradient encoding. Thus, Fourier imaging may be accelerated by undersampling of lines in k-space. The resulting foldover is unfolded mathematically using the encoding information available from the surface-coil sensitivities.⁷ The purpose of this study was to evaluate the reliability of rapid PC-MRI techniques at different in-plane resolutions using the SENSE approach. In pediatric patients with cardiac left-to-right shunt, measurements in the ascending aorta and pulmonary artery were compared with a conventional retrospectively gated PC-MRI sequence that was recently validated in children.³

Methods

Study Population
From July 2001 to February 2002, we enrolled into the study 25 consecutive children with atrial or ventricular level left-to-right shunt clinically referred for additional diagnostic evaluation by MRI. Of these, 3 patients had no shunt as revealed by MRI and were excluded from analysis. The remaining 22 children (mean age, 7.2 ± 6.2 years; median age, 4.6 years; range, 1 to 17 years; 12 girls) formed the study population. Twelve had secundum atrial septal defect (ASD

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II), 2 had partial anomalous pulmonary venous return (PAPVR), 1 had ASD-II with PAPVR, 3 had superior sinus-venosus defect with PAPVR, 1 had primum ASD, and 3 had ventricular septal defect. All patients were in sinus rhythm. The study was approved by the institutional review committee and informed, written consent was obtained from parents or caretakers.

**Study Design**

Each patient underwent MRI to measure through-plane flow in the ascending aorta and pulmonary artery (Figure 1). A standard PC-MRI measurement (reference PC-MRI, Table 1) was repeated twice in each location to serve as a clinical reference method and to determine repeatability (i.e., precision, Figure 2). The mean value of both measurements was compared with 4 research PC-MRI pulse sequences (see below, Table 1) that were not repeated for the sake of total imaging time. In 6 randomly selected children, reference and research PC-MRI flow measurements were independently reanalyzed by 2 experienced observers to determine interobserver variability. Sedation was performed with midazolam and thiopental intravenously when necessary. Blood pressure, oxygen saturation, heart rate, and respiratory rate were monitored continuously.

![Figure 1](image1.png)

**Figure 1.** PC-MRI for determination of flow rate in the pulmonary artery. Top, Plan scans (A, sagittal view; B, transverse view) for flow quantification in the pulmonary artery (PA, arrows, C and D) used segmented k-space turbo field-echo (2 shots, repetition time 9.5 ms, echo time 2.4 ms, flip angle 20 degrees, field-of-view 250 mm², matrix 128×256, 6-mm slice thickness). Middle, Standard phase-contrast MRI (without SENSE), used as reference. In phase images (D), flow information is encoded through-plane for each pixel in the cross-sectional area (arrow, D). C, Corresponding magnitude image displaying anatomical information. Bottom, Magnitude (E) and phase images (F) by PC-MRI with SENSE reduction-factor 3 in the same patient (Table 1).

![Figure 2](image2.png)

**Figure 2.** Flow-vs-time curves. Mean flow volumes at multiple instants (20 phases) during an average cardiac cycle yield a flow-vs-time curve. The area under the curve represents the stroke volumes of the pulmonary artery (74.4 and 74.9 mL, respectively; mean 74.6 mL) and the ascending aorta (38.7 and 41.4 mL, respectively; mean 40.1 mL). Two flow measurements were obtained with the reference PC-MRI technique in each vessel to assess repeatability (precision); both flow curves are given in this figure. For each SENSE or high-resolution scan, one measurement was obtained (not shown). The shunt is the difference between pulmonary and aortic flow (i.e., 34.5 mL per cardiac cycle).

**TABLE 1.** Scan Protocols for Reference PC-MRI and Research PC-MRI With SENSE*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PC-MRI (Reference)</th>
<th>PC-MRI + SF-2</th>
<th>PC-MRI + SF-3</th>
<th>PC-MRIREF (Without SENSE)</th>
<th>PC-MRIREF + SF-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOV, mm</td>
<td>300</td>
<td>380</td>
<td>380</td>
<td>300</td>
<td>380</td>
</tr>
<tr>
<td>In-plane resolution, mm²</td>
<td>2.3×3.1</td>
<td>2.3×3.1</td>
<td>2.3×3.1</td>
<td>1.6×2.1</td>
<td>1.6×2.1</td>
</tr>
<tr>
<td>Rectangular FOV, %</td>
<td>70</td>
<td>100</td>
<td>100</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>Echo time TE, ms</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Signal averages</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>SF</td>
<td>...</td>
<td>SF-2</td>
<td>SF-3</td>
<td>...</td>
<td>SF-3</td>
</tr>
<tr>
<td>Scan time, min:s</td>
<td>1:37</td>
<td>0:27</td>
<td>0:19</td>
<td>2:28</td>
<td>0:27</td>
</tr>
<tr>
<td>Reduction of scan time†</td>
<td>28%</td>
<td>19%</td>
<td></td>
<td>18%‡</td>
<td></td>
</tr>
<tr>
<td>Acceleration factor</td>
<td>3.5</td>
<td>5.2</td>
<td></td>
<td>5.5§</td>
<td></td>
</tr>
</tbody>
</table>

*All sequences: free-breathing, retrospective vector-ECG-(VCG) gating, repetition time (TR) 15 ms, 20 to 25 reconstructed heart phases, slice thickness 6 mm, flip angle 30 degrees, and velocity-encoded value 200 cm/s.

Please refer to text (MRI Technique) for abbreviations of pulse sequence names.

†Percent of reference PC-MRI= index−PC-MRI×100/reference PC-MRI.

‡In percent of scan time of PC-MRIREF without SENSE.

§Related to PC-MRIREF without SENSE.
**MRI Technique**

All examinations were performed on a 1.5 Tesla whole-body MR scanner (Philips, ACS-NT, maximum gradient performance, 30-mT/m amplitude; slew rate, 150 mT/m per s). After the survey scans, a SENSE reference scan was performed, as follows: fast field-echo, coronal orientation, repetition time 8.0 ms, echo time 0.6 ms, flip angle 7 degrees, voxel size 16.5×16.5×18 mm, 8 signal averages, water-fat-shift 0.06 pixels, free-breathing, and scan duration <1 minute. The conventional standard PC-MRI pulse sequence for both in vivo and in vitro flow measurements (reference PC-MRI) was based on a protocol recently validated in children with left-to-right shunt\(^1\) (Table 1) and served as reference method in our study. The 4 research PC-MRI protocols included a combination of standard PC-MRI with SENSE reduction-factor (SF) of 2 (PC-MRI+SF-2), SF of 3 (PC-MRI+SF-3), and a PC-MRI protocol with higher spatial resolution with SF of 3 (PC-MRI\(_{HR}\)+SF-3) and without SENSE (PC-MRI\(_{HR}\)). In-plane resolution was \(\approx 2.3\times 3.1\) mm\(^2\) for PC-MRI with or without SENSE and 1.6\times 2.1 mm\(^2\) for PC-MRI\(_{HR}\) with or without SENSE, respectively. In PC-MRI techniques using SENSE, no rectangular field of view (FOV) was used to avoid backfolding because of the SENSE reconstruction algorithm.\(^7\) All PC-MRI measurements were obtained under free-breathing conditions and used retrospective vector-ECG\(^8\) gating to include end-diastole measurements were obtained under free-breathing conditions and with or without SENSE and 1.6\\(^2\) 2.1 mm\(^2\) for PC-MRI HR with or without SENSE, respectively. In PC-MRI techniques using SENSE, no rectangular field of view (FOV) was used to avoid backfolding because of the SENSE reconstruction algorithm.\(^7\) All PC-MRI measurements were obtained under free-breathing conditions and used retrospective vector-ECG\(^8\) gating to include end-diastole flow, repetition time 15 ms, \(\approx 20\) to 25 reconstructed heart phases, slice thickness 6 mm, flip-angle 30 degrees, and velocity-encoded value 200 cm/s. The body coil was used for signal transmission, and a 5-element phased-array surface (cardiac) coil was used for signal detection, with 3 elements placed in the back and 2 on the chest (patients positioned supine and head-first in the scanner). All flow measurements used a phase-correction algorithm provided by the manufacturer.

**In-Vitro Validation**

A polyvinylchloride tube with an inner diameter of 12.7 mm and a wall thickness of 2.4 mm was embedded in a glass tube (diameter 100 mm, length 340 mm) filled with copper sulfate solution (3 mmol). To approximate blood viscosity,\(^9\) the flow-phantom was filled with a mixture of distilled water and glycerol (60/40 vol/vol). The flow-phantom was placed parallel to the bore in the isocenter of the magnet. The cardiac surface coil was used for signal acquisition. The tubing was connected to a 60-ml artificial left ventricular system (Medos HIA VAD-System II) to deliver pulsatile flow. Flow pump and MR scanner were simultaneously triggered by an external system (Medos HIA VAD-System II) to deliver pulsatile flow. Flow rates (ie, 497, 854, 1127, 1401, 1827, and 2219 mL/min) were applied to the log-transformed data,\(^13\) because differences increased linearly with mean stroke volumes and Q\(_p\)/Q\(_s\) values. Estimation of precision of the limits of agreement (defined as mean±2 SD) was based on calculation of 95% CI. A mean value of 1.0 after anti-log transformation (dimensionless ratio) is expected in the case of no difference between 2 tested methods. All calculated values are detailed in Table 2 for pulmonary artery (Q\(_p\)), ascending aorta (Q\(_s\)), and the flow ratio Q\(_p\)/Q\(_s\). For through-plane flow measurements in the pulmonary artery (Figure 1) and ascending aorta and for the Q\(_p\)/Q\(_s\) ratio, we found a negligible difference of \(\approx 3\%\) (mean, 0.97 to 1.03) between reference PC-MRI and all research PC-MRI techniques. Upper limits of agreement were in the range of 1.03 to 1.16, and lower limits of agreement were between 0.86 and 0.93, respectively. Thus, reference and research PC-MRI sequences assessing cardiac stroke volumes and Q\(_p\)/Q\(_s\) may differ by 3% to 16% above and 8% to 14% below in 95% of the cases, demonstrating good agreement between reference and research PC-MRI. With PC-MRI+SF-3 for assessing Q\(_p\)/Q\(_s\), we observed slightly more scatter (Table 2), with upper and lower limits of agreement of 1.24 and 0.82 (95% CI, 1.14 to 1.35 and 0.75 to 0.89, respectively), but agreement was excellent (mean 1.01). Only little scatter was present with high-resolution PC-MRI+SF-3, where upper and lower limits of agreement were 1.12 and 0.89 (95% CI, 1.06 to 1.17 and 0.84 to 0.93, respectively).

**MR Image Analysis**

Data analysis was performed offline on a computer workstation using a computer algorithm for semiautomatic vessel border detection developed by one of the authors (P.B.)\(^3\) to accelerate image analysis and optimize measurement reproducibility.\(^10\) In all standard and research PC-MRI flow measurements of 1 subject (5 years, ASD), we determined the signal-to-noise ratio (SNR) in magnitude images\(^11\) and the velocity-to-noise ratio (VNR) in phase images\(^11\) in the pulmonary artery and aorta (maximum flow, systole). The formula used to calculate SNR was as follows:

\[
\text{SNR} = \frac{SI_{\text{mean}}}{SD_{\text{noise}}},
\]

and the formula for VNR was as follows:

\[
\text{VNR} = \sqrt{\frac{2V_{\text{enc}}}{\pi SD_{\text{v}}}},
\]

where \(SI_{\text{mean}}\) is signal intensity, \(SD_{\text{noise}}\) is standard deviation of noise, \(V_{\text{enc}}\) is the velocity encoding value, and \(SD_{\text{v}}\) is the standard deviation of velocity noise.

**Statistical Analysis**

All data are expressed as mean±SD. In vitro results were analyzed by 2-variable linear regression analysis. The analysis of Bland and Altman\(^13\) was used to determine PC-MRI interobserver variability and to evaluate the agreement between the different PC-MRI techniques and the mean of both reference PC-MRI measurements for flow rate in the pulmonary artery (Q\(_p\)) and aorta (Q\(_s\)) and flow ratio Q\(_p\)/Q\(_s\) (Figure 3).

**Results**

**In Vivo Results**

PC-MRI studies were completed within 15 to 20 minutes. Sedation for MRI was well tolerated. The mean heart rate was 101±20/min. Scan time was reduced to 28% with PC-MRI+SF-2 and to \(\approx 19\%\) with PC-MRI+SF-3 compared with the standard PC-MRI protocol and to 18% with PC-MRI\(_{HR}\)+SF-3 compared with PC-MRI\(_{HR}\) without SENSE, respectively (Table 1). Thus, scanning was accelerated by a factor of 3.5, 5.2, and 5.5 for PC-MRI+SF2, PC-MRI+SF-3, and PC-MRI\(_{HR}\)+SF-3, respectively. This was achieved by reduction of signal averages and by application of SENSE (Table 1).

**Comparison of Reference With Research PC-MRI in Children**

In our pediatric study population with cardiac left-to-right shunt, the mean Q\(_p\)/Q\(_s\) was 1.69 (SD±0.45), as assessed by reference PC-MRI. The Bland-Altman analysis was applied to the log-transformed data,\(^13\) because differences increased linearly with mean stroke volumes and Q\(_p\)/Q\(_s\) values. Estimation of precision of the limits of agreement (defined as mean±2 SD) was based on calculation of 95% CI. A mean value of 1.0 after anti-log transformation (dimensionless ratio) is expected in the case of no difference between 2 tested methods. All calculated values are detailed in Table 2 for pulmonary artery (Q\(_p\)), ascending aorta (Q\(_s\)), and the flow ratio Q\(_p\)/Q\(_s\). For through-plane flow measurements in the pulmonary artery (Figure 1) and ascending aorta and for the Q\(_p\)/Q\(_s\) ratio, we found a negligible difference of \(\approx 3\%\) (mean, 0.97 to 1.03) between reference PC-MRI and all research PC-MRI techniques. Upper limits of agreement were in the range of 1.03 to 1.16, and lower limits of agreement were between 0.86 and 0.93, respectively. Thus, reference and research PC-MRI sequences assessing cardiac stroke volumes and Q\(_p\)/Q\(_s\) may differ by 3% to 16% above and 8% to 14% below in 95% of the cases, demonstrating good agreement between reference and research PC-MRI. With PC-MRI+SF-3 for assessing Q\(_p\)/Q\(_s\), we observed slightly more scatter (Table 2), with upper and lower limits of agreement of 1.24 and 0.82 (95% CI, 1.14 to 1.35 and 0.75 to 0.89, respectively), but agreement was excellent (mean 1.01). Only little scatter was present with high-resolution PC-MRI+SF-3, where upper and lower limits of agreement were 1.12 and 0.89 (95% CI, 1.06 to 1.17 and 0.84 to 0.93, respectively).
Repeatability and Interobserver Variability in Children

Repeatability (precision or absence of random error) of the 2 reference PC-MRI flow measurements was excellent for the pulmonary artery (aorta), with a mean deviation of 2.3±1.7% (1.9±2.1%). Reevaluation of standard and research PC-MRI flow measurements by 2 observers (Bland-Altman analysis, data log-transformed) revealed a negligible mean difference of 0.99 to 1.01, with limits of agreement ranging from 0.93 to 1.10 (mean±2 SD), demonstrating low interobserver variability.

Table 2. Children With Left-to-Right Shunt: Comparison of Standard PC-MRI (Reference) with Research PC-MRI Using Bland-Altman Analysis of Agreement (Data Log-Transformed*)

<table>
<thead>
<tr>
<th>Bland-Altman Category</th>
<th>PC-MRI+SF-2</th>
<th>PC-MRI+SF-3 (Without SENSE)</th>
<th>PC-MRIsr+SF-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary artery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.99</td>
<td>1.01</td>
<td>0.99</td>
</tr>
<tr>
<td>Upper limit of agreement (mean ±2 SD)</td>
<td>1.11</td>
<td>1.16</td>
<td>1.10</td>
</tr>
<tr>
<td>Lower limit of agreement (mean ±2 SD)</td>
<td>0.89</td>
<td>0.87</td>
<td>0.89</td>
</tr>
<tr>
<td>Upper CI</td>
<td>1.06–1.16</td>
<td>1.09–1.23</td>
<td>1.05–1.16</td>
</tr>
<tr>
<td>Lower CI</td>
<td>0.85–0.92</td>
<td>0.82–0.92</td>
<td>0.85–0.94</td>
</tr>
<tr>
<td>Aorta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.01</td>
<td>1.00</td>
<td>0.97</td>
</tr>
<tr>
<td>Upper limit of agreement (mean ±2 SD)</td>
<td>1.11</td>
<td>1.11</td>
<td>1.03</td>
</tr>
<tr>
<td>Lower limit of agreement (mean ±2 SD)</td>
<td>0.91</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>Upper CI</td>
<td>1.07–1.15</td>
<td>1.06–1.16</td>
<td>1.00–1.06</td>
</tr>
<tr>
<td>Lower CI</td>
<td>0.88–0.95</td>
<td>0.86–0.94</td>
<td>0.88–0.93</td>
</tr>
<tr>
<td>Flow ratio Qp/Qs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.98</td>
<td>1.01</td>
<td>1.03</td>
</tr>
<tr>
<td>Upper limit of agreement (mean ±2 SD)</td>
<td>1.12</td>
<td>1.24</td>
<td>1.14</td>
</tr>
<tr>
<td>Lower limit of agreement (mean ±2 SD)</td>
<td>0.86</td>
<td>0.82</td>
<td>0.93</td>
</tr>
<tr>
<td>Upper CI</td>
<td>1.07–1.18</td>
<td>1.14–1.35</td>
<td>1.09–1.20</td>
</tr>
<tr>
<td>Lower CI</td>
<td>0.82–0.90</td>
<td>0.75–0.89</td>
<td>0.88–0.97</td>
</tr>
</tbody>
</table>

*After anti-log transformation, a mean value of 1.0 would reflect a close agreement between reference PC-MRI and any research PC-MRI pulse sequence, whereas a mean of 1.05 would reflect an overestimation of 5%. Please refer to text (MRI Technique) for abbreviations of pulse sequence names.
TABLE 3. Accuracy In Vitro: Reference vs Research PC-MRI Protocols

<table>
<thead>
<tr>
<th>Flow rate by stopwatch/graded cylinder, L/min*</th>
<th>Reference PC-MRI</th>
<th>PC-MRI+SF-2</th>
<th>PC-MRI+SF-3 (Without SENSE)</th>
<th>PC-MRIHR</th>
<th>PC-MRIHR+SF-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.497</td>
<td>0.511</td>
<td>0.495</td>
<td>0.492</td>
<td>0.458</td>
<td>0.469</td>
</tr>
<tr>
<td>0.854</td>
<td>0.860</td>
<td>0.823</td>
<td>0.834</td>
<td>0.805</td>
<td>0.816</td>
</tr>
<tr>
<td>1.127</td>
<td>1.180</td>
<td>1.135</td>
<td>1.132</td>
<td>1.086</td>
<td>1.098</td>
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<td>1.401</td>
<td>1.453</td>
<td>1.425</td>
<td>1.430</td>
<td>1.365</td>
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<td>1.827</td>
<td>1.820</td>
<td>1.779</td>
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<td>2.219</td>
<td>2.268</td>
<td>2.224</td>
<td>2.213</td>
<td>2.101</td>
<td>2.106</td>
</tr>
</tbody>
</table>

Linear regression \( y = mx + b \)

- Slope: 1.01, 1.00, 0.99, 0.96, 0.95
- \( y \)-intercept: 0.01, 0.00, 0.01, 0.01, 0.01
- Correlation coefficient: 0.999, 0.999, 0.999, 1.000, 1.000
- \( P \) value: N.S., N.S., N.S., 0.006, 0.013

*Mean values, determined 3 times each. Please refer to text (MRI Technique) for abbreviations of pulse sequence names.
†Mean values; flow rate was determined 3 times before and after MR measurements.

**Accuracy and Precision In Vitro**

Table 3 summarizes the in vitro flow measurements by timed collection (stopwatch/graded cylinder=true values) and by reference PC-MRI, PC-MRI+SF-2, PC-MRI+SF-3, and PC-MRIHR without SENSE and PC-MRIHR+SF-3. The flow values in Table 3 represent mean values of repeated measurements, which had a maximum deviation of ±2%, indicating high repeatability in vitro (ie, measurement precision) for all PC-MRI techniques. Results of linear regression analysis also presented in Table 3 demonstrate good correlation between true values and reference PC-MRI, PC-MRI with SF-2, and PC-MRI with SF-3, indicating high accuracy. However, we observed a small but statistically significant underestimation of flow rate using PC-MRIHR+SF-3 both with and without SENSE.

**Signal-to-Noise Ratio and Velocity-to-Noise Ratio**

SNR and VNR values are expressed as percentages of the standard (reference) PC-MRI protocol with cardiac surface coil for signal acquisition (100%). In the aorta (pulmonary artery), SNR was reduced to 47% (43%) with PC-MRI+SF-2, to 26% (26%) with PC-MRI+SF-3, and to 20% (15%) with PC-MRIHR+SF-3. When the standard PC-MRI was used with body coil instead of cardiac coil, SNR was reduced to 29% (37%).

In contrast, in the aorta (pulmonary artery), VNR was only reduced to 95% (88%) with PC-MRI+SF-2, to 95% (82%) with PC-MRI+SF-3, and to 88% (74%) with PC-MRIHR+SF-3. When the standard PC-MRI was used with body coil instead of cardiac coil, VNR was reduced to 95% (96%).

**Discussion**

In the SENSE approach, an array of multiple, simultaneously operated receiver coils for signal acquisition (eg, cardiac 5-element phased-array surface coil) is used to spatially encode the MR signal as a function of the sensitivity of each coil element. This allows to reduce the number of phase-encoding steps by increasing the distance of readout lines in k-space (ie, parallel imaging) and thus accelerate acquisition, but at the expense of a lower SNR. Therefore, combination with SENSE is only recommended when SNR is not of critical importance for diagnostic image quality.

This study demonstrates that standard PC-MRI under free-breathing conditions may be favorably combined with SENSE. Quantitative flow measurements can be accelerated by a factor of 3.5 to 5 by reduction of signal averages (from 2 to 1) and application of SENSE. The corresponding SNR reduction was no limiting factor. Therefore, in children with congenital heart disease, left-to-right shunt may be quantified reliably in less than 1 minute. The considerable time benefit is likely to be generally available in hemodynamic evaluation of congenital heart disease. Other possible applications include quantification of residual pulmonary valve regurgitation after surgery for Tetralogy of Fallot and the quantification of flows in the venae cavae and branch pulmonary arteries after Fontan palliation in patients with single-ventricle physiology. Thus, either an examination can be shortened (reduced duration of sedation/anesthesia in children or increased patient throughput) or more comprehensive flow information may be collected in a given amount of time (ie, multiple or repeated measurements to improve reliability). Additionally, in pediatric patients with higher heart rates, breath-hold scans during anesthesia have now become possible using a SENSE reduction factor of 3 (Table 1). This may additionally improve measurement accuracy, because artifacts from respiratory motion can thus be avoided. Although reliable, high in-plane resolution was not advantageous in our children but may be adequate for infants with smaller blood vessels to avoid possible flow overestimation resulting from partial volume effects.
measurement accuracy and precision were observed in vivo. This finding is surprising, because both reduction of numbers of signal averages and combination with SENSE result in lower SNR. This relates not only to SNR penalty bounded by a square-root function to the number of samples acquired but also contains noise from sensitivity maps as propagated in the SENSE reconstruction process, known to increase with higher SENSE-reduction factors. Our SNR estimations in PC-MRI magnitude images demonstrate considerable SNR improvement in vivo when a cardiac multi-element surface coil is used for signal acquisition instead of the body coil. This gain in signal can be invested to reduce scanning time. As apparent in Figure 1, SNR was sufficiently high even in PC-MRI+SF-3. Furthermore, our estimation of VNR in the phase images revealed no relevant decrease of VNR in research PC-MRI with reduced signal averages and SENSE compared with reference PC-MRI, although a decrease in SNR in the magnitude images was present. Useful phase-angle information, however, can still be extracted when SNR in magnitude images is reduced, because phase-angle images have an inherently better dynamic range compared with magnitude images reconstructed from the same raw data.

Methodological Issues: Reference PC-MRI
Although there is no gold standard available for quantitative flow measurements in pediatric patients, PC-MRI protocols comparable to our reference method have been validated in vivo and in vitro. Some changes in the reference PC-MRI protocol compared with the recently validated method need consideration. Use of the cardiac surface coil (increased SNR, see the Results section) allowed to reduce signal averages in the reference PC-MRI protocol from 4 to 2, thus limiting overall scan time. Moreover, vector-ECG instead of conventional 3-lead-ECG allowed more reliable ECG-monitoring and hence assignment of heart phases. Therefore, it seems reasonable to assume that measurement conditions of the reference PC-MRI sequence were improved, as reflected by the high precision of flow measurements.

In Vitro Results
The flow phantom experiments were designed to test the same PC-MRI protocols as were used in vivo and demonstrated high accuracy at lower in-plane resolution. Apparently, no major artifact was introduced when using PC-MRI with SENSE in this model. The FOV, however, was too large to allow that 2- and 3-fold undersampling would lead to actual foldover in the single coil data. Thus, no additional conclusions regarding the impact of SENSE acquisition and reconstruction on phase encoding of flow volume should be drawn. An adopted FOV with reduced matrix for a similar voxel size, however, would have been different from the PC-MRI protocols used in vivo.

High-resolution PC-MRI both with and without SENSE slightly underestimated flow volumes compared with values from timed collection (Table 3). Because stronger gradients are needed to achieve the higher in-plane resolution, we speculate that artificial effects from residual eddy currents and concomitant fields may be involved. Any possible explanation, however, suffers from the fact that this underestimation was not obvious in vivo (Table 2).

Limitations
No conclusions from our data are applicable to children with arrhythmia, irregular breathing pattern, or valvular stenosis with turbulent blood flow. Only relative changes should be emphasized in the SNR and VNR measurements, because absolute values may be influenced by background filtering in the reconstructed images, reducing the noise component.

Conclusions
PC-MRI for flow quantitation may be combined with SENSE to achieve a substantive reduction of scanning time. SNR reduction was not a limiting factor. In children with left-to-right shunt, Qp/Qs quantification is possible by PC-MRI+SF-3 in $\leq$60 seconds. Use of higher in-plane resolution did not improve measurement results but may be adequate for infants with smaller blood vessels. The method has potential for rapid quantification of hemodynamics in congenital heart disease.

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Rapid Left-to-Right Shunt Quantification in Children by Phase-Contrast Magnetic Resonance Imaging Combined With Sensitivity Encoding (SENSE)

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