Chronic thromboembolic pulmonary hypertension (CTEPH) is characterized by dyspnea, fatigue, exercise intolerance caused by proximal thromboembolic obstruction, and distal remodeling of the pulmonary circulation. These findings lead to elevated mean pulmonary arterial pressure (mPAP), increased pulmonary vascular resistance (PVR), and progressive right ventricular (RV) failure in the course of the disease.1–3 Its cumulative incidence after an episode of acute pulmonary embolism ranges between 1.5% and 3.8%.4,5 Pulmonary endarterectomy is the established surgical method for the removal of the thromboembolic material.6 For assessment of operability, many criteria have to be considered, one of which is evidence of surgically accessible thrombi that are best depicted by a state-of-the-art ECG-gated multidetector computed tomography angiography.7,8 However, pulmonary hemodynamics (mPAP and PVR) still have to be determined in the preoperative work-up, requiring invasive catheter-based measurements (simultaneously measured mPAP) and with right heart catheterization measurements.9

Noninvasive Assessment of Pulmonary Hemodynamics in Patients With Chronic Thromboembolic Pulmonary Hypertension by High Temporal Resolution Phase-Contrast MRI

Correlation With Simultaneous Invasive Pressure Recordings*

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Background—Right heart catheterization is the gold standard for assessment of pulmonary hemodynamics in patients with chronic thromboembolic pulmonary hypertension. To date, MRI has not been able to produce precise measurements of mean pulmonary arterial pressure (mPAP). The purpose of the study was to create a model for estimating mPAP and pulmonary vascular resistance in patients with chronic thromboembolic pulmonary hypertension by high temporal resolution phase-contrast MRI (PC-MRI) and to correlate the results with simultaneously acquired, invasive catheter-based measurements (simultaneously measured mPAP) and with right heart catheterization measurements.

Methods and Results—A total of 19 patients with chronic thromboembolic pulmonary hypertension underwent right heart catheterization and—after digital subtraction angiography of the pulmonary arteries—subsequent PC-MRI at 1.5 T with simultaneous recording of mPAP. Velocity– and flow–time curves of PC-MRI were used to calculate absolute acceleration time (Ata), maximum of mean velocities (MV), volume of acceleration (AV), and maximum flow acceleration (dQ/dt). On the basis of these parameters, multiple linear regression analysis revealed maximum achievable model fit (B=0.902) for the following linear combination equation to calculate mPAP (mPAP_cal): mPAP_cal=69.446−(0.521×Ata)−(0.570×MV)+(1.507×AV)+(0.002×dQ/dt). There was a statistically significant equivalence of mPAP_cal and simultaneously measured mPAP with a goodness of fit of 0.892. Pulmonary vascular resistance was overestimated by calculated pulmonary vascular resistance on the basis of PC-MRI in comparison with right heart catheterization–based measurements by a median of −112 dyn·s·cm−5, the pairwise regression formula revealed a goodness of fit of 0.792.


Key Words: chronic disease ■ hemodynamics ■ magnetic resonance imaging ■ pulmonary embolism
Several studies have shown significant correlations between CMR-derived parameters and RHC-derived values of systolic and mPAP values. However, controversies on their overall applicability and accuracy remain. Abolmaali et al. in an experimental setting of acute PH and simultaneous invasive pressure recordings, demonstrated that mPAP can be estimated using velocity-encoded phase-contrast MRI (PC-MRI). Our own clinical examinations of patients with CTEPH first revealed encouraging results. However, there were significant deviations between measured and calculated mPAP values in 20% of the patients.

We speculated that these differences were caused by physiological variations in mPAP or different situations on volume load. Thus, the purpose of this study was to analyze how closely the assessment of mPAP in patients with CTEPH using high temporal resolution PC-MRI correlates with invasive catheter-based measurements that were simultaneously acquired. Furthermore, we analyzed how accurately PVR can be estimated using parameters that are derived from velocity-encoded PC-MRI.

Methods

In a 24-month period, 19 patients with suspected CTEPH underwent a routine preoperative work-up consisting of ECG-triggered multidetector computed tomography angiography, pulmonary digital subtraction angiography (DSA), and RHC. There were 8 women and 11 men with a mean age of 51 years (range, 23–78 years).

On the basis of results of multidetector computed tomography angiography and DSA, all patients had CTEPH, and 17/19 patients were considered to be technically operable. Two of these 17 patients were considered to be nonoperable because of severe comorbidities, so that in a total of 15 patients, pathological-anatomic specimens confirmed the diagnosis of wall-adherent thromboembolic material consistent with CTEPH. According to echocardiographic and CT assessment, patients had different degrees of right heart impairment, with RV ejection fractions ranging between 18% and 55%.

MRI was performed immediately after RHC. The study was conducted in accordance with Good Clinical Practice (CPMP/ICH/135/95; 1996) and was performed in compliance with the Declaration of Helsinki (Helsinki, Finland, 1964) and its subsequent amendments and clarifications. All patients gave informed consent to the study protocol which was approved by the local ethics committee (837.375.01).

Right Heart Catheterization

We performed RHC using a 7.5F Swan-Ganz catheter (Edwards Lifesciences, Irvine, CA) via a femoral (n=16) or transcubital (n=2) approach. This yielded, among others, values such as mean right atrial pressure, systolic PAP, mPAP, and diastolic PAP; pulmonary capillary wedge pressure (PCWP); and RV cardiac output (RV-CO; thermodilution method). PVR was calculated as the difference between mPAP and CWP divided by the RV-CO and multiplied with 80:

$$\text{PVR} = \frac{(\text{mPAP} - \text{CWP}) \times 80}{\text{RV-CO}} \quad (1)$$

After RHC, we performed selective DSA of the pulmonary arteries as described elsewhere.

At the end of the examination, a 4F pigtail catheter (Cordis Cooperation, Miami, FL) was inserted and placed in the main pulmonary artery (PA). The patients were then transferred to the MR unit. In the MR unit, the pigtail catheter was connected to a MR-compatible monitoring device (Magnitude 3150; Saegeling Medizintechnik, Heidenau, Germany). Zero alignment was done before the measurements. The system allowed for a continuous monitoring of mPAP during the MR measurements. This simultaneously measured mPAP (mPAP_sim) was considered the reference standard for the mPAP as determined by MR-derived parameters (calculated mPAP [mPAP_cal]; see below).

Magnetic Resonance Imaging

MRI was performed using a 1.5T MR system (Magnetom Sonata; Siemens Medical Solutions, Erlangen, Germany) that is equipped with a high-performance gradient system characterized by an amplitude of 40 mT/m and a slew rate of 200 mT/m per millisecond. For signal detection, a 6-element phased-array coil was placed over the anterior chest wall covering the region of the heart of each patient. The main PA was centered in the B0 field as far as possible to minimize phase shift errors caused by eddy currents, and Maxwell term correction was applied. For velocity-encoded MRI, a prospectively ECG-triggered, 2-dimensional (2D) nonsegmented fast low angle shot sequence was used which covered >90% of the RR interval. It was planned perpendicular to the main PA and had an upper velocity limit of 100 cm/s. In addition, we took care to ensure that the imaging plane remained between the pulmonary valve and PA bifurcation throughout the cardiac cycle. With a bandwidth of 975 Hz/pixel and a slice thickness of 6 mm, a minimum echo time (TE) and repetition time (TR) of 1.7 and 10 ms were achieved, respectively. The field-of-view of 260×320 mm2 and the image matrix of 208×256 pixels resulted in an in-plane resolution of 1.25×1.25 mm². With the selected pulse sequence, TR equaled the temporal resolution.

Three measurements were averaged to increase the signal-to-noise ratio, leading to a total heart frequency-dependent acquisition time ranging between 7 and 11 minutes. The measurements were performed during free breathing of the patients to include the effects of respiration on CO and pulmonary flow. The application of long-term averaging compensated for the respiratory motion.

MR Analysis

We analyzed the acquired MR data sets using commercially available flow quantification software (Argus; Siemens Medical Solutions, Erlangen, Germany). The inner contours of the main PA were outlined in each cardiac phase on the magnitude images by 2 independent observers. The integration of PA areas and flow enabled determination of the following parameters: peak velocity (cm/s), average velocity during the complete cardiac cycle (mean velocity [MV cm/s]), PA net forward volume, PA areas, and PA flow (mL/s). On the basis of velocity- and flow–time curves (Figures 1 and 2), the following parameters were derived (Table 1): CO, absolute acceleration time (Ata), maximum of MVs, volume of acceleration (AV), and maximal flow acceleration (dQ/dt).

Intra- and interobserver reliability was evaluated by means of Bland–Altman diagrams from a descriptive perspective and by means of dependent contrast tests, respectively. These approaches confirmed the averaging of repeated measurements. The process of averaging lead to a high statistical power of the confirmatory analysis (see below) as it tended to reduce data variation.

![Figure 1. Velocity–time curve with velocity-derived parameters. Ata indicates absolute acceleration time; and MV, maximum of mean velocities.](image-url)
These average replicate measurements of both observers were, therefore, used for a further assessment of pulmonary hemodynamics. The parameters listed in Table 1 were analyzed for correlations with mPAP_sim using multiple regression analysis. An α level of <0.01 was selected as the measure of statistical significance. In addition, linear combination equations were computed to assess the mPAP using MR-velocity-encoded data (mPAP_cal). After calculation of mPAP_cal, PVR was estimated using Equation 2.

\[ \text{PVR}_\text{cal} (\text{ dyn} \cdot \text{s} \cdot \text{cm}^{-5}) = (\text{mPAP}_\text{cal} - \text{CWP}) \times \frac{80}{\text{RV} - \text{CO}_\text{MR}} \]  

(2)

where PVR_cal is the calculated PVR, mPAP_cal is the calculated mPAP derived from velocity-encoded parameters, and RV-CO_MR the RV-CO as determined by PC-MRI. As the PCWP could not be determined by MR-based parameters, this value was empirically set to 10 mm Hg in each patient.

**Statistical Analysis**

Exploratory and confirmatory statistical analysis was performed by means of the SPSS software (release 19.0 for Windows); all evaluations of the raw data were implemented by an independent biometrician.

**Confirmatory Analysis**

The intraindividual comparison of mPAP measurements by means of the mPAP_sim and mPAP_cal (based on the replicate measurement of MR-derived parameters) was based on the asymptotic Bootstrap 95% confidence interval estimation of the median intra-individual difference. During the planning phase of the investigation, equivalence of the measurement series was characterized by a 2-sided tolerance of ±5 mm Hg for intraindividual deviations. As a consequence, diagnostic equivalence of mPAP_sim and mPAP_cal at a 5% significance level was declared as established, as soon as the 95% confidence interval for the median difference can be found fully covered by the assumed tolerance interval of ±5 mm Hg.

The same nominal equivalence testing approach was then implemented for the exploratory comparison of mPAP_sim with mPAP values determined during RHC (mPAP_RHC) and for the comparison of mPAP_cal and mPAP_RHC, respectively. The resulting exploratory comparisons were interpreted as indicative of a locally significant equivalence on the basis of respective 95% confidence intervals for the median difference.

The confirmatory analysis approach was also applied for the exploratory comparison of PVR_cal as calculated from MR-derived parameters and PVR_RHC as determined during RHC. It was applied for the exploratory comparison of CO as determined by PC-MRI (CO_MRI) and CO as determined by RHC (CO_RHC) too. For PVR, equivalence of the measurement is given as soon as the 95% confidence interval for the median difference could be found fully covered by a tolerance interval of ±120 dyn s cm⁻⁵. For CO, an equivalence of the measurement was assumed as soon as the 95% confidence interval for the median difference was fully covered by a tolerance interval of ±0.5 L/min.

For the sake of a descriptive analysis of intraindividual difference distributions, we applied modified Bland–Altman plots, where again the 95% confidence intervals of the median difference were displayed as indicators of agreement/diagnostic equivalence. We further used local sign tests to examine whether there were locally significant over- or underestimations of hemodynamic parameters as determined on the basis of MR-derived parameters in comparison with invasively measured parameters during RHC or simultaneously during MRI, respectively. Results of these exploratory significance comparisons were summarized in terms of P values; a P value <0.05 was considered as an indicator for local significance. For further data description, we used medians and quartiles because of the small overall sample size for both the respective raw data and the above-mentioned intraindividual differences’ distributions.

**Exploratory Analysis**

Exploratory analysis contrasted the precision of mPAP_RHC modeling in dependency of mPAP_sim and mPAP_cal. For mPAP_sim, we used an univariate linear regression modeling. For mPAP_cal that was based on the MR-derived data Ata, MV, PVR, and dQ/dt, a multivariate linear regression modeling was applied. The maximum achievable model quality was summarized by a linear goodness of fit estimate after forward regression model building, for which we used local 5% likelihood ratio tests. Furthermore, a corresponding linear regression formula for the RHC-based assessment of PVR was derived on the basis of respective MR-based PVR assessment. Linear regression results were then displayed by scattergrams, the linear model function, and an asymptotic 95% mean regression estimate confidence interval.

**Results**

All measurements were performed successfully. The time interval between the measurements during RHC and in the MR unit ranged between 20 and 35 minutes. Flow quantification was not hampered neither by any significant motion artifacts related to respiration nor by susceptibility artifacts related to the pigtail catheter that was placed in the main PA.

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**Table 1. Parameters Derived From Phase-Contrast Measurements in the Main Pulmonary Artery**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Abbreviation</th>
<th>Unit</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac output</td>
<td>CO</td>
<td>L/min</td>
<td>Cardiac output in the MPA</td>
</tr>
<tr>
<td>Absolute acceleration time</td>
<td>Ata</td>
<td>ms</td>
<td>Time from the opening of the pulmonary valve to the maximum flow in the MPA</td>
</tr>
<tr>
<td>Maximum of mean velocities</td>
<td>MV</td>
<td>cm/s</td>
<td>Maximal systolic flow in the MPA</td>
</tr>
<tr>
<td>Volume of acceleration</td>
<td>AV</td>
<td>mL</td>
<td>Area under the flow curve from the opening of the pulmonary valve to the maximum flow in the MPA</td>
</tr>
<tr>
<td>Maximal flow acceleration</td>
<td>dQ/dt</td>
<td>mL/s²</td>
<td>Maximal upward slope of the flow curve</td>
</tr>
</tbody>
</table>

MPA indicates main pulmonary artery.
The results from invasive and noninvasive assessment of pulmonary hemodynamics are summarized in Tables 2 and 3. On the basis of the averaged replicate measurements of the 2 observers, multiple linear regression analysis revealed a maximum achievable model fit (B=0.902) for the following linear combination equation to calculate mPAP with noninvasively measured data:

\[
\text{mPAP}_{\text{cal}}(\text{mm Hg}) = 69.446(\text{mm Hg})
- (0.521[\text{mm Hg} / \text{ms}] \times A \text{a}[\text{ms}])
- (0.570[\text{mm Hg} / \text{cm} / \text{s}] \times \text{MV}[\text{cm} / \text{s}]) \\
+ (1.507[\text{mm Hg} / \text{mL} \times \text{AV}[\text{mL}])
+ (0.002[\text{mm Hg} / \text{mL} / \text{s}^2] \times \text{dQ} / \text{dt}[\text{mL} / \text{s}^2]).
\]

There was an encouraging concordance between mPAP_cal and mPAP_sim: with a median intraindividual deviation of −1 mm Hg and the 95% confidence interval (−2 mm Hg; +3 mm Hg) for this median difference, statistically significant equivalence of mPAP_cal based on the averaged replicate measurement of MR-derived parameters and mPAP_sim was shown at the 5% significance level (Table 2). There was a tendency of an overestimation of mPAP during the simultaneous measurement of mPAP in the bore of the magnet (mPAP_sim) and by calculation from MR-derived parameters (mPAP_cal) compared with mPAP_RHC (Table 3; Figure 5).

The comparison of mPAP_sim and mPAP_cal with mPAP_RHC showed locally significant intraindividual deviations with a median deviation of −6 mm Hg and the 95% confidence interval ranging from −12 to −4 mm Hg and from −7 to −3 mm Hg, respectively (Table 3). There was a tendency of an overestimation of mPAP during the simultaneous measurement of mPAP in the bore of the magnet (mPAP_sim) and by calculation from MR-derived parameters (mPAP_cal) compared with mPAP_RHC (Table 3; Figure 5).

Thus, PVR_cal overestimated PVR_RHC, the pairwise regression formula revealed a goodness of fit of 0.792 (Figure 7).

In addition, there was a valid concordance between CO_MRI and CO_RHC with a median intraindividual deviation of 0.3 L/min and a 95% confidence interval ranging from −0.5 to +0.3 L/min. As a consequence, a locally significant equivalence of CO_MRI based on the averaged replicate measurement of PC images and the CO determined during RHC (CO_RHC) was established (Table 3).

### Table 2. Distribution Characteristics for mPAP_RHC, mPAP_sim, and mPAP_cal

<table>
<thead>
<tr>
<th>mPAP</th>
<th>Median (Q1; Q3), mm Hg</th>
<th>95% Confidence Interval for Median Difference, mm Hg</th>
<th>95% Bland–Altman Agreement Limits, mm Hg</th>
<th>P (Sign Test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mPAP_RHC</td>
<td>38 (26; 45)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>mPAP_sim</td>
<td>47 (31; 53)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>mPAP_cal</td>
<td>46 (33; 52)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>mPAP_sim–PAP_cal</td>
<td>−1 (−2; +3)</td>
<td>(−2; +3)</td>
<td>(−7; +6)</td>
<td>1.000</td>
</tr>
<tr>
<td>mPAP_RHC–mPAP_sim</td>
<td>−6 (−12; −4)</td>
<td>(−12; −4)</td>
<td>(−18; +1)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>mPAP_RHC–PAP_cal</td>
<td>−6 (−15; −2)</td>
<td>(−13; −3)</td>
<td>(−19; +2)</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Medians and quartiles for 19 patients, as well as for their intraindividual assessment deviations; 95% confidence interval for median difference and corresponding nonparametric Bland–Altman 95% agreement limits; P values derived from local sign tests; mPAP_cal assessment based on the replicate measurements of 2 independent observers. mPAP_cal indicates calculated mean pulmonary arterial pressure based on averaged replicate measurement of MR-derived parameters; mPAP_RHC, mean pulmonary arterial pressure as measured during right heart catheterization; and mPAP_sim, mean pulmonary arterial pressure as measured during MRI.

### Table 3. Distribution Characteristics for Assessment of PVR_RHC, PVR_cal, CO_RHC, and CO_MRI

<table>
<thead>
<tr>
<th>PVR, dyn-s-cm⁻⁵</th>
<th>Median (Q1; Q3)</th>
<th>95% Confidence Interval for Median Difference</th>
<th>95% Bland–Altman Agreement Limits</th>
<th>P (Sign Test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVR_RHC</td>
<td>427 (398; 567)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>PVR_cal</td>
<td>562 (427; 679)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>PVR_RHC–PVR_cal</td>
<td>−112 (−133; −69)</td>
<td>(−129; −79)</td>
<td>(−237; 138)</td>
<td>0.019</td>
</tr>
<tr>
<td>Cardiac output, L/min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO_RHC</td>
<td>5.1 (4.0; 5.9)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>CO_MRI</td>
<td>5.3 (4.3; 6.0)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>CO_RHC–CO_MRI</td>
<td>0.3 (−0.7; +0.4)</td>
<td>(−0.5; +0.3)</td>
<td>(−3.0; +1.9)</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Medians and quartiles for 19 patients, as well as for their intraindividual assessment deviations; 95% confidence interval for median difference and corresponding nonparametric Bland–Altman 95% agreement limits; P values derived from local sign tests; PVR_cal and CO_MRI assessments based on the averaged replicate measurements of 2 independent observers. CO_MRI indicates cardiac output, averaged measurement by MRI; CO_PVR, cardiac output as measured during right heart catheterization; PVR_cal, calculated mean pulmonary arterial pressure based on averaged replicate measurement of MR-derived parameters; and PVR_RHC, pulmonary vascular resistance as measured during right heart catheterization.

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The comparison of mPAP_sim and mPAP_cal with mPAP_RHC showed locally significant intraindividual deviations with a median deviation of −6 mm Hg and the 95% confidence interval ranging from −12 to −4 mm Hg and from −7 to −3 mm Hg, respectively (Table 3). There was a tendency of an overestimation of mPAP during the simultaneous measurement of mPAP in the bore of the magnet (mPAP_sim) and by calculation from MR-derived parameters (mPAP_cal) compared with mPAP_RHC (Table 3; Figure 5).

Thus, PVR_cal overestimated PVR_RHC, the pairwise regression formula revealed a goodness of fit of 0.792 (Figure 7).

In addition, there was a valid concordance between CO_MRI and CO_RHC with a median intraindividual deviation of 0.3 L/min and a 95% confidence interval ranging from −0.5 to +0.3 L/min. As a consequence, a locally significant equivalence of CO_MRI based on the averaged replicate measurement of PC images and the CO determined during RHC (CO_RHC) was established (Table 3).
Discussion

In the diagnostic work-up of CTEPH, selective pulmonary angiography and RHC are still regarded as reference methods for diagnosis of CTEPH and assessment of its hemodynamic severity with documentation of an increased mPAP (≥25 mm Hg), increased PVR (>160 dyn-s-cm⁻⁵), and normal PCWP.²³ Albeit there may be evidence that ECG-gated multidetector computed tomography angiography makes a sufficient evaluation of the pulmonary arterial tree possible, large and multicenter studies are still missing.⁸

The results of the present study suggest that parameters derived from PC-MRI enable noninvasive estimation of mPAP. The applied model revealed an encouraging concordance with mPAP_sim during the MR measurement with a 95% confidence interval between –2 and +3 mm Hg. Thus, on the basis of multiple linear regression analysis, mPAP is computable exclusively on the basis of noninvasive data derived from MR flow measurement. To the best of our knowledge, this study is the first in which simultaneous recordings of mPAP together with acquisition of functional velocity-encoded data MR data have been performed in humans. As opposed to prior work on PC-MRI in patients with PH,¹²,¹⁴,¹⁶ the velocity-encoded sequence in our study was characterized by its high temporal resolution of 10 ms. This is in line with the work of Abolmaali et al,¹⁹ who used a velocity-encoded sequence with a temporal resolution of 9.5 ms in their experimental setting of acute PH and simultaneous invasive pressure recordings in animals. This high temporal resolution seems to be a basic supposition for successful noninvasive assessment of mPAP.¹²,¹⁴,¹⁹

However, when compared with the mPAP data from RHC, both mPAP_cal and mPAP_sim showed significant intraindividual deviations with a tendency of overestimating mPAP of ≈6 mm Hg (Table 3; Figure 5). This can be explained by 2 factors: first, after selective pulmonary angiography because of its volume load of ≈150 mL of contrast agent, there is a significant increase in mPAP: Pitton et al²¹ in an angiographic study with continuous hemodynamic surveillance of patients with CTEPH showed a significant increase of mPAP immediately after completion of the angiographic study. Depending of the height of systolic PAP before angiography, mPAP increased in a range between 4.3 and 6.3 mm Hg. This may explain systematic overestimation of mPAP_cal and mPAP_sim compared with mPAP_RHC in our study. Second, it is known from the literature that there might be spontaneous variations in pulmonary hemodynamics²⁴,²⁵: the range may be ≤22% of baseline mPAP values or variations of ≤6 mm Hg in patients with PH. Keeping in mind the different examination conditions for the patient in the angiography suite and in the bore of the magnet, we anticipate that these hemodynamic variations may also contribute to the observed intraindividual deviations in the registered mPAP (Table 3; Figure 5).

Table 4. Pairwise Linear Regression Formulae (and Respective Linear Goodness of Fit Estimates) Between mPAP_cal, mPAP_sim, and mPAP-RHC

<table>
<thead>
<tr>
<th>Regression Approach, mm Hg</th>
<th>Regression Model, mm Hg</th>
<th>Goodness of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>mPAP_sim</td>
<td>1.029×mPAP_cal (mm Hg) – 1.194</td>
<td>B=0.892</td>
</tr>
<tr>
<td>mPAP_RHC</td>
<td>0.783×mPAP_sim (mm Hg) + 1.859</td>
<td>B=0.759</td>
</tr>
<tr>
<td>mPAP_RHC</td>
<td>0.754×mPAP_cal (mm Hg) + 3.163</td>
<td>B=0.593</td>
</tr>
</tbody>
</table>

mPAP_cal assessment based on the replicate measurements of 2 independent observers. mPAP_cal indicates calculated mean pulmonary arterial pressure based on MR-derived parameters; mPAP_RHC, mean pulmonary arterial pressure as measured during right heart catheterization; and mPAP_sim, mean pulmonary arterial pressure as measured during MRI.
The PVR_cal showed a significant overestimation compared with those PVR values that were obtained during RHC. This again is a sequelae from the volume load because of pulmonary DSA: as patients with CTEPH reveal a loss of vasodilation capacity there is an increase of PVR after angiography. The median deviation of $-112 \text{ dyn} \cdot \text{s} \cdot \text{cm}^{-5}$ in our study is well comparable with those deviations that were measured during the study by Pitton et al\textsuperscript{21} with continuous hemodynamic surveillance at the end of angiography. Again, even spontaneous variations in pulmonary hemodynamics may contribute to intraindividual deviations: The variation coefficient of PVR may be $\leq 20\%$.\textsuperscript{25}

In the present study, the PCWP was empirically set to 10 mm Hg in every patient, a value that corresponds well to those patients with hemodynamic surveillance at the end of the angiographic study,\textsuperscript{24} where the PCWP values ranged between 9 and 10 mm Hg after selective DSA.

In a recent study, Garcia-Alvarez et al\textsuperscript{26} presented a different MR-based method for assessment of PVR. Their statistical model is based on standard cine and PC sequences, with a temporal resolution for the latter ranging between 55 and 105 ms. These sequences were acquired in 100 patients with RHC performed on the same day; the model combining natural log-transformed PA average velocity and RV ejection fraction showed the best statistical performance with invasively measured PVR. With that model, the area under the receiver operating characteristic curve for estimated PVR to detect increased PVR was 0.96 for the derivation cohort and 0.97 for the validation cohort, respectively. There were no statistical differences in diagnostic accuracy between different forms of PH, and the 95% confidence interval ranged from $-4.71$ to $+4.89$ wood units, corresponding to $-376.8$ to $+391.2 \text{ dyn} \cdot \text{s} \cdot \text{cm}^{-5}$ in the derivation cohort. Compared with and in contrast to our study, the model of Garcia-Alvarez et al\textsuperscript{26} has the great advantage that knowledge of PCWP is not necessary.

In the present study, there were only minor differences in CO as determined by MRI and during RHC, which we regard as clinically not significant.

We acknowledge several limitations of our investigation. First, the number of patients with simultaneous pressure recordings is small. Therefore, because of the small cohort size, our study could only create a model for estimating pulmonary hemodynamics on the basis of MR-derived parameters. However, the patients covered a wide range of

![Figure 5](http://circimaging.ahajournals.org/)

**Figure 5.** Nonparametric box plots for the pairwise intraindividual difference distributions between calculated mean pulmonary arterial pressure based on MR-derived parameters (mPAP_cal), mean pulmonary arterial pressure as calculated measured during MRI (mPAP_sim), and mean pulmonary arterial pressure as measured during right heart catheterization (mPAP_RHC). Horizontals indicate the median difference and the 25%/75% quartiles for the respective difference distributions; mPAP_cal assessment is based on the replicate measurements of 2 independent observers.

![Figure 6](http://circimaging.ahajournals.org/)

**Figure 6.** Bland–Altman diagram for comparison of pulmonary vascular resistance as measured during right heart catheterization (PVR_RHC) versus linear regression based estimated calculated mean pulmonary arterial pressure based on averaged replicate measurement of MR-derived parameters (PVR_cal) assessment. Horizontals indicate the 95% confidence interval for the median difference; PVR_cal assessment is based on the replicate measurements of 2 independent observers.

![Figure 7](http://circimaging.ahajournals.org/)

**Figure 7.** Linear regression diagram for the regression of pulmonary vascular resistance as measured during right heart catheterization (PVR_RHC) on calculated mean pulmonary arterial pressure based on averaged replicate measurement of MR-derived parameters assessment including the 95% confidence interval for the linear regression mean; PVR_cal assessments based on the replicate measurements of 2 independent observers.
mPAP values reaching from 23 to 60 mm Hg with a nearly equal distribution of different degrees of PH, and there were no substantial deviations in higher or lower mPAP values between mPAP_cal and mPAP_sim. For implementation to clinical routine, it is completely sufficient to determine PC-MRI parameters by 1 person, postprocessing requires ≈20 to 30 minutes. Second, we do not know how patients with an elevated mPAP can be differentiated from patients with normal mPAP values using high temporal resolution PC-MRI. Thus, the accuracy of detecting patients with PH remains unclear by the use of this method. Third, it remains unclear how closely the results of the present study can be transferred to other forms of PH: it may be assumed that for patients with resistance-based PH, that is, those with primary PH or who have a reduction of the total pulmonary capillary cross-sectional area related to pulmonary diseases, the used multiple linear regression analysis will provide similar results. However, this has to be proven in a study on the basis of a validation population. Fourth, we expect that in patients with PH related to cardiac diseases (left heart or congenital heart disease), an estimation of PVR might not be possible when using our model, as those patients present with CWPs ≈20 to 30 minutes. Second, we do not know how patients with normal mPAP values using high temporal resolution PC-MRI together with acquisition of velocity-encoded MR data have been performed in humans. The results of this study indicate that noninvasive estimation of mPAP using parameters derived from high temporal resolution PC-MRI is feasible. For patients with normal PCWP, the applied model also allows for an estimation of PVR.

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**Disclosures**
None.

**References**
Right heart catheterization remains the gold standard for assessment of pulmonary hemodynamics in patients with pulmonary hypertension, and is routinely performed in the preoperative work-up of these patients. The aim of the present study was to examine how well pulmonary hemodynamics could be estimated in patients with chronic thromboembolic pulmonary hypertension by the use of high temporal resolution phase-contrast MRI. Comparison was made to simultaneously acquired invasive catheter-based measurements of mean pulmonary arterial pressure. On the basis of MR-derived parameters, a multiple linear regression analysis revealed maximum achievable model fit of $B=0.902$. There was an encouraging concordance between calculated and directly measured mean pulmonary arterial pressure values with a median intraindividual deviation of $-1$ mmHg and a 95% confidence interval between $-2$ and $+3$ mmHg. MR-based calculation of pulmonary vascular resistance showed an overestimation with a median value of $-112$ dyn$\cdot$s$\cdot$cm$^{-5}$ compared with data from right heart catheterization. This was ascribed to the volume load caused by pulmonary angiography performed between right heart catheterization and MR measurement which increases pulmonary vascular resistance in these patients. These promising results using a relatively straightforward approach warrant validation in a larger patient population with different forms of pulmonary hypertension.
Noninvasive Assessment of Pulmonary Hemodynamics in Patients With Chronic Thromboembolic Pulmonary Hypertension by High Temporal Resolution Phase-Contrast MRI: Correlation With Simultaneous Invasive Pressure Recordings*  
Karl-Friedrich Kreitner, Gesine Maria Wirth, Frank Krummenauer, Stefan Weber, Michael Bernhard Pitton, Jens Schneider, Eckhard Mayer and Christoph Dueber

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