Real-Time Magnetic Resonance Assessment of Septal Curvature Accurately Tracks Acute Hemodynamic Changes in Pediatric Pulmonary Hypertension

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Background—This study assesses the relationship between septal curvature and mean pulmonary artery pressure and indexed pulmonary vascular resistance in children with pulmonary hypertension. We hypothesized that septal curvature could be used to estimate right ventricular afterload and track acute changes in pulmonary hemodynamics.

Methods and Results—Fifty patients with a median age of 6.7 years (range, 0.45–16.5 years) underwent combined cardiac catheterization and cardiovascular magnetic resonance. The majority had idiopathic pulmonary arterial hypertension (n=30); the remaining patients had pulmonary hypertension associated with repaired congenital heart disease (n=17) or lung disease (n=3). Mean pulmonary artery pressure and pulmonary vascular resistance were acquired at baseline and during vasodilatation. Septal curvature was measured using real-time cardiovascular magnetic resonance. There was a strong correlation between mean pulmonary artery pressure and \( S_{\text{min}} \) at baseline and during vasodilator testing (\( r = -0.81 \) and \(-0.85\), respectively; \( P<0.01 \)). A strong linear relationship also existed between pulmonary vascular resistance and minimum septal curvature indexed to cardiac output both at baseline and during vasodilator testing (\( r = -0.88 \) and \(-0.87\), respectively; \( P<0.01 \)). Change in septal curvature metrics moderately correlated with absolute change in mean pulmonary artery pressure and pulmonary vascular resistance, respectively (\( r = 0.58 \) and \(-0.74\); \( P<0.01 \)). Septal curvature metrics were able to identify responders with a sensitivity of 83% (95% confidence interval, 0.36–0.99) and a specificity of 91% (95% confidence interval, 0.77–0.97), using the Sitbon criteria. Idiopathic pulmonary arterial hypertension subgroup analysis revealed 3 responders with \( \Delta S_{\text{min}} \) values of 0.523, 0.551, and 0.568. If the middle value of 0.551 is taken as a cutoff, the approximate sensitivity would be 67% and the specificity would be 93%.

Conclusions—Septal curvature metrics are able to estimate right ventricular afterload and track acute changes in pulmonary hemodynamics during vasodilator testing. This suggests that septal curvature could be used for continuing assessment of load in pulmonary hypertension. (Circ Cardiovasc Imaging. 2014;7:706-713.)

Key Words: hypertension, pulmonary ▪ pediatrics ▪ vasodilator agents

Cardiovascular magnetic resonance (CMR) is increasingly used in pulmonary hypertension (PH) because of its ability to accurately measure right ventricular (RV) volumes and function. In adults, conventional breath-held, cardiac-gated CMR is easy to use and has proven prognostic utility. However, conventional CMR is problematic in pediatric PH because many of these children find breath-holding difficult. Thus, real-time CMR is a more attractive option, and this technique has recently been used to successfully assess the RV in children with PH.

Optimal management of PH also benefits from assessment of either mean pulmonary artery pressure (mPAP) or indexed pulmonary vascular resistance (PVRi). Although the reference standard method of measuring mPAP and PVRi is cardiac catheterization, noninvasive methods are used during routine follow-up. For instance, mPAP and PVRi can be noninvasively estimated using CMR by measuring interventricular septal curvature. In adults, septal curvature measured using conventional CMR strongly correlates with mPAP and PVRi. However, the use of septal curvature has not been validated in children, particularly those imaged with real-time CMR. Furthermore, the ability of septal curvature to track changes in mPAP or PVRi has not been definitively proven, which is vital if septal curvature is to be used to assess response to therapy or disease progression.
The main aims of this study were (1) to demonstrate that real-time CMR-derived septal curvature is abnormal in pediatric PH; (2) to assess the relationship between septal curvature and both mPAP and PVRi in pediatric PH; and (3) to evaluate the ability of septal curvature to track acute changes in mPAP and PVRi.

This study was performed in large cohort of pediatric patients with PH who were undergoing CMR-augmented cardiac catheterization with vasodilator testing as part of their clinical care. In this technique, real-time CMR is performed with invasive catheters in situ, allowing simultaneous assessment of mPAP, PVRi, and septal curvature. Thus, it represents the ideal setting for investigating the relationship between these metrics.

Methods

Study Population

Consecutive children with a history of PH (defined as a previous invasively measured mPAP ≥25 mm Hg or an estimated systolic pulmonary artery pressure >50 mm Hg measured from tricuspid regurgitant jet on echocardiography) referred for clinical CMR-augmented cardiac catheterization between December 2009 and August 2013 were considered for inclusion into this study. Referral criteria were as follows: (1) mPAP and PVRi assessment after initial diagnosis of PH; (2) clinical worsening; and (3) assessment on PH-specific therapy. The inclusion criterion was mPAP ≥25 mm Hg. Exclusion criteria were (1) complex congenital lesions or univentricular circulation and (2) large cardiac shunt (Qp:Qs >1.2:1 or <0.8:1). All patients were in sinus rhythm at the time of cardiac catheterization with vasodilator testing as part of their routine invasive measurement of RV and right atrial pressure, allowing simultaneous assessment of mPAP, PVRi, and septal curvature. Thus, it represents the optimal setting for investigating the relationship between these metrics.

CMR-Augmented Cardiac Catheterization

All examinations were performed in an interventional magnetic resonance (MR) suite that consisted of a 1.5T CMR scanner (Avanto; Siemens Medical Solutions, Erlangen, Germany) and a biplane angiography system (Axoim Artis; Siemens Medical Solutions, Erlangen, Germany) separated by a radio frequency–shielded door. A 12-element phased array coil was used for signal reception, and a vectorcardiogram system was used for cardiac gating. Inhaled sevoflurane was used for maintenance of general anesthesia during the whole procedure. After routine invasive measurement of RV and right atrial pressure, a 5F to 6F balloon tipped wedge monitoring catheter was fluoroscopically guided into either the left or right pulmonary artery for vasodilator testing. A control population of 15 healthy pediatric volunteers also underwent CMR and assessment of septal curvature without concomitant cardiac catheterization or general anesthetic. Ethics approval was obtained from the National Ethics Committee, and all parents/legal guardians gave consent.

CMR Protocol

The following CMR protocol was performed at baseline (21% FiO₂) and during an acute vasodilator phase (20 ppm NO and 100% FiO₂).

All image processing was performed using in-house plug-ins for the open-source OsiriX digital imaging and communications in medicine software.

Flow imaging was performed using a velocity-encoded phase-contrast MR sequence during free breathing (acquisition time, 1–3 minutes). To overcome problems associated with flow errors in the dilated main pulmonary artery, pulmonary blood flow (Qp) was measured by summing the flow in the branch pulmonary arteries. In addition, phase-contrast MR data were segmented using a semi-automated vessel edge detection algorithm with operator correction and Qp was calculated as previously described. mPAP was recorded during flow imaging, and pulmonary capillary wedge pressure was evaluated at the end of flow imaging (required wedge catheter balloon inflation). PVRi was calculated by dividing the transpulmonary gradient (mPAP – pulmonary capillary wedge) by the body surface indexed total pulmonary blood flow (Wood units·m⁻² [WU·m⁻²]).

Biventricular volumetric and functional assessment was performed using real-time radial k-t sensitivity encoding sequence. This sequence has been previously described and validated in children with congenital heart disease. It provides high spatiotemporal resolution real-time imaging and permits data acquisition during normal ventilation. This is vital when performing CMR-augmented catheterization because apneic scans may increase mPAP and PVRi. Although this was a real-time sequence, it was possible to R-wave trigger the start of acquisition for each slice. This allowed timing synchronization between septal curvature and both the R-wave and the ECG-gated flow data. The scans were planned in the ventricular short axis with 7 to 13 contiguous slices required to cover both the ventricles. The biventricular end-diastolic volume and end-systolic volume were measured by manual segmentation of the endocardial borders excluding trabeculations. Segmentation of the epicardial border of the RV at end systole allowed calculation of RV free-wall mass. Ventricular stroke volume, ejection fraction, and tricuspid regurgitation fraction (TRF) were calculated as previously described.

In the control population, biventricular volumetric assessment was performed using the same real-time radial k-t SENSE sequence. These scans were performed in unsedated children during free breathing and processed in the same way as the patient population.

Septal Curvature Calculations

Septal curvature was measured in the short-axis plane at the level of the left ventricular (LV) papillary muscles in patients and healthy children. This ensured that neither the outflow tracts nor valve tissue was in the images. The septum and lateral wall were segmented using a previously described registration-based algorithm built into the OsiriX software. Segmentation was initialized by drawing 3-point arcs on the endocardial surface of RV septal wall and the epicardial surface of the LV free wall in a single frame (Figure 1). These regions of interest were then propagated through time and manually corrected if necessary. The curvature of the septal and lateral walls was calculated using real-time radial k-t SENSE sequence. These scans were performed in unsedated children during free breathing and processed in the same way as the patient population.

Figure 1. A, Regions of interest applied to lateral free wall and septum during left ventricular bowing. B, Curvature across 1 cardiac cycle in the septum (red line), lateral wall (green line), and curvature ratio (blue line). Aortic ejection was from 0 to 321 ms.
lateral walls in each frame was then calculated as the inverse of the circle circumscribed by the 3 points in the regions of interest. The final septal curvature was calculated as the ratio of the septal and lateral wall curvatures. Negative septal curvature denoted a leftward convexity of the septum (septum bowing into the left ventricle). Minimum septal curvature (SC_{min}) was taken as the lowest or most negative value of the septal curvature time curve. Minimum septal curvature indexed to Qp (SC_{min}/Qp) was used as a surrogate for PVRi.

### Statistical Analysis

All statistical analyses were performed using SPSS v21 and Prism 5F (GraphPad). Data are presented as median (interquartile range, IQR) unless it was more appropriate to describe the range, in which case this is explicitly stated. Mann–Whitney test was used to assess the difference between the populations, and Wilcoxon signed-rank test was used to assess the difference between hemodynamic parameters at baseline and during vasodilatation. The relationship between the septal curvature and the invasive hemodynamic data was explored using Pearson correlation. ANCOVA was used to assess the difference between regression lines at baseline and during vasodilatation testing. A P value of <0.05 was considered statistically significant. Two investigators analyzed the septal curvature in a randomized group of 20 studies including both controls and patients with PH. Intraobserver variability was performed on a similar randomized group. Both interobserver variability and intraobserver variability were explored using the intraclass correlation coefficient. Receiver-operating characteristic curve analysis was performed to evaluate the diagnostic accuracy of septal curvature metrics in identifying patients with vasoresponder status using the Sitbon criterion defined as a decrease in mPAP of ≥10 mm Hg reaching a mPAP value of ≤40 mm Hg and an increased or unchanged cardiac output. The optimum cutoff value was chosen to maximize the Youden index (sensitivity + specificity –1).

### Results

#### Study Population

During the study period, 118 patients underwent CMR-augmented cardiac catheterization, of which 114 fulfilled the inclusion criteria (mPAP ≥36.0 mm Hg). Sixty-four patients were excluded because of either large cardiac shunts (with Qp:Qs>1.2:1 or <0.8:1) or univentricular hearts/complex congenital heart disease. Thus, the final study population consisted of 50 patients, with a median age of 6.7 years (range, 0.45–16.5 years) and a female preponderance (n=35, 70%). In the study population, 30 of 50 had idiopathic pulmonary arterial hypertension (IPAH), 17 of 50 had pulmonary arterial hypertension associated with congenital heart disease, and 3 of 50 had PH associated with lung disease. In the pulmonary arterial hypertension associated with congenital heart disease group (Table 1), all patients were post repair of their primary lesion. The median age at surgery was 0.07 years (range, 0.01–3.47 years), with all but 1 patient undergoing repair within the first year of life. Four patients had small residual defects with no discernable shunt (1 atrial septal defect, 1 patent foramen ovale, and 2 tiny apical ventricular septal defects).

The median baseline mPAP was 47.0 mm Hg (36.0–62.3 mm Hg), PVRi was 11.8 WUm^-2 (7.8–17.8 WUm^-2), and Qp was 3.2 L/min/m² (2.3–3.9 L/min/m²). Patient clinical data and CMR-derived LV and RV volumetric data are detailed in Tables 2 and 3, respectively. Median TRF was 10.3 (5.5%–22.6%), 1 patient had severe TRF (>40%) and 2 patients had moderate TRF (>25%).

The median QRS duration was 0.084 ms (IQR, 0.075–0.093 ms) with 1 patient having evidence of right bundle branch block as defined by morphology of the QRS complex and relevant duration for their age. Twenty-four patients had evidence of RV hypertrophy and 8 demonstrated RV strain.

#### Feasibility and Variability

Septal curvature analysis was feasible in all subjects (patients and controls). The automated segmentation took ≈1 minute and manual correction took another 2 to 3 minutes. The interobserver intraclass correlation coefficient for assessment of SC_{min} was 0.977 (95% confidence interval [CI], 0.944–0.999) and the intraobserver intraclass correlation coefficient was 0.966 (95% CI, 0.955–0.966). A representative septal curvature curve for the whole cardiac cycle is shown in Figure 1. The median time from the R-wave to SC_{min} was 440 ms (360–480 ms). For comparison, the median time from the R-wave to the end of aortic ejection (as measured using phase contrast MR) was 321 ms (164–425 ms) and the median RR interval was 770 ms (611–926 ms).

### Table 1. Primary Congenital Heart Defects in 17 Patients

<table>
<thead>
<tr>
<th>Type of Defect</th>
<th>Status</th>
<th>n</th>
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<tbody>
<tr>
<td>PDA*</td>
<td>Postligation</td>
<td>5</td>
</tr>
<tr>
<td>Transposition of the arteries†</td>
<td>Post ASO</td>
<td>5</td>
</tr>
<tr>
<td>AVSD</td>
<td>Post full operative repair</td>
<td>2</td>
</tr>
<tr>
<td>Coarctation of the aorta‡</td>
<td>Post full operative repair</td>
<td>2</td>
</tr>
<tr>
<td>Perimembranous VSD</td>
<td>Post full operative repair</td>
<td>2</td>
</tr>
<tr>
<td>Aortopulmonary window</td>
<td>Post full operative repair</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>17</td>
</tr>
</tbody>
</table>

*One patient in this group had a patent foramen ovale.
†Two patients in this group had small residual apical VSDs with a Qp:Qs ratio of 1:1:1.
‡One patient in this group had a small atrial septal defect.

### Table 2. Patient Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Median (IQR)</th>
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<tbody>
<tr>
<td>Age (y)</td>
<td>6.7 (4.5–11.2)</td>
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<tr>
<td>Heart rate (bpm)</td>
<td>79.5 (64.5–98.5)</td>
</tr>
<tr>
<td>O₂ saturations (%)</td>
<td>95.0 (92.0–97.0)</td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>0.85 (0.67–1.16)</td>
</tr>
<tr>
<td>RV mass (g)</td>
<td>47.9 (35.9–65.6)</td>
</tr>
<tr>
<td>RVEDVi (ml/m²)</td>
<td>73.0 (60.8–86.5)</td>
</tr>
<tr>
<td>RVESVi (ml/m²)</td>
<td>28.5 (24.0–41.3)</td>
</tr>
<tr>
<td>LVEDVi (ml/m²)</td>
<td>59.5 (49.3–67.3)</td>
</tr>
<tr>
<td>LVESVi (ml/m²)</td>
<td>21.0 (16.8–25.0)</td>
</tr>
<tr>
<td>RVO1 (L/min/m²)</td>
<td>3.2 (2.4–3.9)</td>
</tr>
<tr>
<td>LVO1 (L/min/m²)</td>
<td>2.8 (2.4–3.4)</td>
</tr>
</tbody>
</table>

Values are represented as median (interquartile range). BSA indicates body surface area; IQR, interquartile range; LVO1, left ventricular cardiac index calculated using volumetric data; LVEDVi, indexed left ventricular end-diastolic volume; LVESVi, indexed left ventricular end-systolic volume; RV, right ventricular; RVO1, right ventricular cardiac index calculated using volumetric data; RVEDVi, indexed right ventricular end-diastolic volume; and RVESVi, indexed right ventricular end-systolic volume.
There was a significant difference ($P<0.001$) between median $SC_{\text{min}}$ in the patient group ($–0.23; \text{IQR, } –0.36$ to 0.07) compared with the control group ($1.06; \text{IQR, } 0.98–1.12$). In addition, there was no overlap between $SC_{\text{min}}$ (range, 0.902–1.175) in normal controls and $SC_{\text{min}}$ in patients (range, 0.556–0.796) as shown in Figure 2. Median age of the control population was 11.8 years (IQR, 10.3–13.4 years), which was significantly older than the patient population ($P=0.002$). However, there was no correlation between $SC_{\text{min}}$ and age in either the controls ($r=0.29; \text{P}=0.29$) or patients ($r=–0.063; \text{P}=0.66$). In addition, in an age-matched sample of the patient population, (n=15; median age, 11.8 years), there was still a significant difference in $SC_{\text{min}}$ (patient=–0.18; IQR, –0.48 to 0.21 versus control=1.06; IQR, 0.98–1.1; $P<0.0001$).

There was a curvilinear relationship between PVRi and $SC_{\text{min}}$ (Figure 4A). However, there was a strong linear relationship between PVRi and $SC_{\text{min}}/Qp$ (Figure 4B) both at baseline and during vasodilator testing ($r=–0.88$ and –0.87, respectively). In addition, there was no significant difference in the regression equations in the 2 conditions (PVRi=–55.1×$SC_{\text{min}}/Qp+4.4$ at baseline and PVRi=–50.0×$SC_{\text{min}}/Qp+10.7$ during vasodilation, $P=0.66$).

In this small patient group, no correlation between $SC_{\text{min}}$ and TRF or QRS duration could be demonstrated ($P=0.60$ and 0.90, respectively).
Vasoresponder status was also separately analyzed in the IPAH subgroup (n=30). Only 3 patients (10%) fulfilled the Sitbon criteria, which makes formal receiver-operating characteristic curve analysis problematic. Nevertheless, inspection of the data allows an estimation of diagnostic accuracy. The responders had ΔSC_{min} values of 0.523, 0.551, and 0.568. If the middle value of 0.551 is taken as a cutoff, the approximate sensitivity would be 67%, the specificity would be 93%, the positive predictive value would be 50%, and the negative predictive value would be 96%.

**Discussion**

Assessment of pulmonary hemodynamics is vital in the management of pediatric PH. The most commonly used non-invasive method is measurement of tricuspid regurgitation velocity using Doppler echocardiography. Unfortunately, tricuspid regurgitation is absent in ≈9% of children with PH, and there are concerns about its reliability. Thus, an alternative approach is desirable, and several adult CMR studies have shown that septal curvature correlates well with pulmonary artery pressure. However, this is the first pediatric CMR study to investigate the relationship between septal curvature and pulmonary hemodynamics. Furthermore, it is the first study to compare septal curvature with simultaneously acquired pulmonary hemodynamic data. This was possible because of the use of MR-augmented cardiac catheterization, which allows CMR to be performed with pressure catheters in situ. The main findings were as follows: (1) there was a significant difference in septal curvature parameters between normal controls and children with PH; (2) septal curvature–derived metrics correlated with mPAP and PVRi in patients; and (3) septal curvature–derived metrics were able to track acute changes in pulmonary hemodynamics during vasodilator testing. We think that these results show that septal curvature metrics (SC_{min}) could be used as a noninvasive adjunct to catheter assessment in pediatric PH.

In healthy children, LV pressure exceeds RV pressure throughout the cardiac cycle. This gives the LV a circular shape in the short axis, and in this study, all healthy children had a SC_{min} ≈1. However, in PH, the LV–RV pressure gradient is reduced or even reversed, causing the septum to become either flattened or bow into the LV. Thus, SC_{min} was <1 in all of our patients, and there was no overlap with the healthy population. This raises the possibility that SC_{min} could be used as a screening tool for PH in children. Unfortunately, the current study was not designed to test this capability, and therefore, no strong conclusions can be made without further work.

In the patient population, we have shown that SC_{min} significantly correlates with mPAP and that it occurs ≈100 ms after aortic valve closure. This leads to an overlap between late RV systole and early LV diastole, and during this period, the trans-septal pressure gradient is at its highest. Thus, the septum is mechanically deformed most at this point in the cardiac cycle. Other factors, such as tricuspid regurgitation and prolonged QRS duration/right bundle branch block, also theoretically affect septal curvature, although in our study no correlations were demonstrated.

The correlations found in this study were not sufficient for septal curvature to be used as a replacement for catheterization or as an accurate method of estimating mPAP. Nevertheless, CMR assessment of septal curvature could still have an important role to play in patient management, particularly during follow-up. Currently, CMR is mainly used to evaluate ventricular volumes and function in PH. However, RV failure only represents part of the pathophysiology of the disease, the other part being increased ventricular afterload. We have shown that septal curvature metrics can provide an approximation of RV afterload, and if combined with CMR, volumetry may provide a more comprehensive assessment of PH.

We also demonstrated that changes in SC_{min} and SC_{min}/Qp correlated reasonably well with changes in mPAP and PVRi during vasodilator testing. Hemodynamic response to vasodilators provides information about prognosis and operability.
Chronic changes in afterload. Clearly, acute vasodilator testing is not an adequate model of response to therapy or disease progression. Nevertheless, animal studies have used MR to track chronic changes in RV afterload, and it would be useful to confirm this in pediatric patients.

One major difference between our study and previous adult studies was the use of real-time CMR. Children with PH are often dyspneic and find conventional breath-hold CMR difficult to perform. The benefit of real-time CMR is that it can be performed during free breathing, making it feasible in pediatric PH. The drawback of real-time CMR is that it is usually acquired at low temporal and spatial resolution, which can affect accuracy. Recently, novel high-resolution real-time sequences have been developed and validated in the pediatric population. In this study, we used one such technique (radial k-t SENSE) that has a similar spatial and temporal resolution to conventional breath-hold cine imaging. This is vital because the septum often displays a flicking motion that is difficult to appreciate at low temporal resolution. Because the correlation between SCmin and mPAP was similar to previously reported results, we think that the temporal resolution of this sequence is sufficient to accurately assess SCmin. Therefore, we think that real-time CMR is a practical and accurate method of assessing SC in children with PH.

Limitations

The main limitation of this study was that all patients were under general anesthesia. This was necessary because the study was performed during MR-augmented catheterization, which in our institution is always done under general anesthesia. However, we are unable to definitely say that the relationships seen in this study reflect the situation in awake children. Nevertheless, even though pulmonary artery pressure may be different, there is no reason to think that the mechanical underpinning of the relationship will change. A further related issue is that real-time imaging may not perform as well in awake children with irregular breathing patterns. Ventricular volumes assessed using the same real-time imaging in awake children do compare well with the reference standard breath-hold techniques. Consequently, we think that the real-time imaging would be sufficient even in this group of pediatric patients, although formal testing is required. It would also be important to confirm prognostic ability of septal curvature metrics measured with routine CMR.

Conclusion

In conclusion, we have shown that septal curvature–derived metrics correlate with pulmonary hemodynamics in pediatric PH. In addition, we have shown that septal curvature metrics can track change in hemodynamics during acute vasodilator testing. We think that these findings demonstrate that septal curvature assessed using real-time CMR may have an important role in estimating afterload during routine follow-up of children with PH.

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Disclosures
None.

References


In this study, 50 children (median age, 6.7 years) with pulmonary hypertension underwent a combined cardiovascular magnetic resonance catheter study, which allowed simultaneous assessment of pulmonary artery pressure and septal curvature. Significant correlations were demonstrated between mean pulmonary artery pressure and septal curvature at baseline and during vasodilator testing ($r=-0.81$ and $r=-0.85$, respectively). A strong linear relationship also existed between pulmonary vascular resistance and minimum septal curvature indexed to cardiac output both at baseline and during vasodilator testing ($r=-0.88$ and $r=-0.87$, respectively; $P<0.001$). This suggests that septal curvature may be of use in making an estimate of right ventricular load during follow-up. This is particularly true because change in septal curvature also correlated with change in hemodynamics during vasodilator testing. In addition, these metrics could be used to identify vasoresponders with a high specificity in all patients in the study population and in the idiopathic pulmonary arterial hypertension subgroup ($n=30$). This may allow better identification of patients who need formal invasive testing of vasoresponsiveness, reducing the total number of catheterizations these children must undergo.
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