# Cardiovascular Magnetic Resonance Imaging for Intensive Care Infants: Safe and Effective?

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**Abstract** *Background* Cardiac magnetic resonance imaging (MRI) is an important diagnostic tool for congenital heart disease (CHD), as reflected by class 1 recommendations for the use of cardiac MRI by various consensus panels. However, little is known about the safety and clinical utility of cardiac MRI for these critically ill infants with CHD, whose further management cannot be directed by echocardiography. This study aimed to assess the safety, the potential hemodynamic side effects, and the clinical benefits of cardiac MRI for infants with complex CHD during their intensive care unit stay. *Methods* Infants referred from the pediatric cardiac intensive care unit (PCICU) to the authors' cardiac MRI program in the past 2 years were retrospectively analyzed using the electronic chart system available at their institution. Data collected included age, diagnosis, inotropic support, urine output, diuretic medication, body temperature and lactate levels, length of MRI examination, adverse effects during and after the procedure, clinical implications of MRI, length of stay in the PCICU, and mean blood pressure and heart rate before, during, and after MRI. *Results* Among 592 patients in the past 2 years, 20 (3.4%) were referred for MRI testing during their stay in the PCICU. The mean age of the infants was $4.8 \pm 3.2$ months. Four of the patients were neonates, and eight were postoperative patients. Intracardiac malformations were present in 16 of the infants, vascular rings causing tracheal stenosis in 3 patients, and cardiomyopathy in 1 patient. The mean stay in the PCICU was $28 \pm 43$ days. Eight of the infants were ventilated, with a mean fraction of inspired oxygen ($FiO_2$) of $0.30 \pm 0.15$. Four were receiving inotropic support. All the nonventilated children were intubated for the MRI and extubated in the MRI laboratory. The mean duration of the MRI (door-to-door time) was $110 \pm 27$ min. All except one patient were hemodynamically stable, and no increase in catecholamine support was necessary during or after the scans. A 10-month-old girl receiving inotropic support needed a single dose of epinephrine due to a short episode of bradycardia after a breathhold for a contrast agent MRI angiography. Mean body core temperature at arrival to the PCICU was $36.8 \pm 0.7°C$. The mean serum lactate level after the MRI was $1.2 \pm 0.4$ mmol/l. The mean blood pressure and heart rate before, during, and after MRI were unchanged. The mean diuresis on examination day was insignificantly lower (2.4%) than the day before with unchanged medication ($5.09 \pm 1.58$ vs $5.53 \pm 1.77$ ml/kg/h). For 14 (70%) of the 20 patients, surgical or catheter interventional procedures were initiated based on novel MRI information. *Conclusion* Cardiac MRI can be performed safely with low risk and limited hemodynamic changes for infants during their stay in the PCICU. Cardiac MRI provides key information for invasive management decisions in this subset of patients.

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Magnetic resonance imaging (MRI) is an important diagnostic tool for congenital heart disease (CHD), as reflected by class 1 recommendations for the use of cardiac MRI by various consensus panels [3, 6, 12]. The use of cardiac MRI for infants before surgery or after cardiac surgery has been limited in the past due to the important role of echocardiography for this age group, the potential hazards during the transport of these sometimes critically ill children, and the challenging MRI environment, which carries several inherent risks [9, 14, 15].

Computed tomographic (CT) angiography, cardiac catheterization, and angiography are important and well-established alternatives to MRI. However, these diagnostic methods are invasive, causing significant exposure to ionizing radiation.

On the other hand, MRI provides a unique diagnostic capability for assessing all thoracic organs in neonates and infants with respiratory problems (e.g., patients with vascular rings and slings) [17]. Furthermore, functional cardiac MRI including flow measurements, volumetric analysis of ventricular size and function, and quantification of valvular incompetence is increasingly used, especially in complex cases [13].

Therefore, this study aimed to assess retrospectively the safety and any potential unwanted hemodynamic alteration during cardiac MRI in this setting. In addition, it sought to estimate the clinical impact of any novel MRI information on management decisions for this vulnerable patient group.

## Materials and Methods

We retrospectively enrolled all infants from our pediatric cardiac intensive care unit (PCICU) referred to the CHD-MRI unit from January 2005 to December 2006. A total of 20 patients with pre- and postoperative congenital heart defects were identified (Table 1). All the patients were referred for further diagnostic evaluation by MRI because either transthoracic echocardiography (18 patients) or cardiac catheterization (2 patients) was unable to visualize the relevant cardiovascular morphology sufficiently. All the patients were in sinus rhythm.

Transport from the PCICU to the MRI laboratory, located on the same floor, was performed by the PCICU staff. Nonventilated infants were electively intubated in the MRI unit and anesthetized for MRI, then subsequently extubated in the MRI laboratory. Anesthesia was performed by experienced cardiac anesthetists with intravenous introduction and inhalation anesthesia using volatile anesthetics.

Complete hemodynamic monitoring was performed during the scans including anesthetic vapor concentrations, end-tidal carbon dioxide analysis, invasive arterial and central venous pressures, noninvasive blood pressures, electrocardiography (ECG), and pulse oximetry. All examinations were performed on a standard 1.5-T whole-body MR scanner (Philips Intera; Best, The Netherlands) using a two-element phased-array head-neck or a five-element cardiac coil. Analysis was performed using our electronic patient documentation system in the PCICU that allows review of all hemodynamic data, respirator settings, and medications.

Data collected included age, diagnosis, length of stay in the PCICU, presence of indwelling catheters or drains, inotropic support, urine output, diuretic medication, body temperature, and lactate levels. Mean arterial blood pressures and heart rates were compared before, during, and after MRI. We documented the length of the MRI (door-to-door time) including the time needed for intubation in the MRI laboratory and positioning of the children for the scan as well as intra- or postprocedural complications.

Temperature and lactate levels were measured immediately after arrival back at the PCICU. Catecholamine dosage, diuresis, and the amount of diuretics were analyzed the day after the MRI examination. We also reviewed the subsequent clinical course of the patients for nosocomial infections and therapeutic implications derived from the MRI results.

## Results

The study investigated 20 infants (13 boys and 7 girls) representing 3.4% of all patients ($n = 592$) studied in our CHD-MRI program over the last 2 years. The mean age was $4.8 \pm 3.2$ months (range, 6 days to 12 months; median, 4.9 months), and the mean weight was $5.8 \pm 1.7$ kg (range, 3.2–9.3 kg; median, 6 kg).

Of the 20 infants, 8 had undergone surgery for congenital heart defects. Intracardiac malformations were present in 16 of the infants and vascular rings causing tracheal stenosis in 3 patients. One 4-month-old boy was referred because of cardiomyopathy (Table 1). Of the 20 patients, 4 needed inotropic support at the time MRI was requested, and 8 were ventilated with a mean fraction of inspired oxygen ($FiO_2$) of $0.3 \pm 15$ (range, 0.21–0.7).

Monitoring during transport from the PCICU to the MRI lab, a 5-min walking distance on the same floor, showed no significant differences in the vital parameters. The mean examination time in the MRI lab was $110 \pm 27$ min (range, 77–170 min; median, 104 min), including the time required to intubate the 12 nonventilated infants and position the patients on the MRI table, which was time consuming, especially for the 5 patients with arterial and central venous lines and the 2 patients with postoperative drains.

**Table 1** Patient characteristics

| Patient no. | Diagnosis | Age (mo) | Weight (kg) | Height (cm) | FiO$_2$ | MRI duration (min) | Total ICU stay (days) | Consequence |
|---|---|---|---|---|---|---|---|---|
| 1 | Stridor, suspected vascular anomaly | 0.26 | 3.24 | 51 | 0.21 | 100 | 6 | Discharged without intervention |
| 2 | TOF, absent pumonary valve | 0.20 | 4.21 | 51 | 0.21 | 125 | 49 | TOF repair |
| 3 | HLHS, Norwood 1 | 1.08 | 3.68 | 51 | 0.30 | 155 | 45 | Conservative treatment of Pericardial effusion |
| 4 | Double aortic arch, tracheal stenosis | 4.73 | 6.04 | 65 | 0.40 | 80 | 6 | Transsection of the right aortic arch |
| 5 | Cor triatriatum sinistrum, ASD | 12.33 | 8.40 | 76 | 0.21 | 148 | 7 | Resection of LA membrane, ASD closure |
| 6 | Right atrial isomerism, AVSD, TAPVR | 1.15 | 3.32 | 49 | 0.70 | 130 | 21 | Discharge without intervention |
| 7 | DILV, hypoplastic arch, Norwood 2 | 9.50 | 7.87 | 71 | 0.21 | 135 | 14 | Catheter intervention |
| 8 | ASD, VSD, ISTA | 5.49 | 5.00 | 62 | 0.21 | 102 | 7 | Operative repair |
| 9 | DORV, TGA, chromosomal anomaly | 9.90 | 9.31 | 75 | 0.30 | 125 | 164 | Discharged with home ventilation |
| 10 | VSD, ASD, diaphragmatic hernia | 6.58 | 6.00 | 66 | 0.21 | 118 | 7 | Operative repair |
| 11 | AVSD, IAA | 2.86 | 3.74 | 49 | 0.65 | 170 | 98 | Biventricular repair |
| 12 | ASD, VSD, hypoplastic aortic arch | 1.97 | 4.95 | 59 | 0.32 | 80 | 16 | Operative repair |
| 13 | AVSD | 7.27 | 8.00 | 65 | 0.50 | 83 | 96 | Comfort care |
| 14 | VSD, double aortic arch, tracheal stenosis | 5.79 | 6.23 | 66 | 0.30 | 88 | 8 | Operative repair |
| 15 | HLHC, Norwood 1 | 4.37 | 5.76 | 64 | 0.21 | 77 | 5 | Aortopulmonary shunt replacement |
| 16 | TAC | 4.14 | 6.14 | 64 | 0.21 | 100 | 1 | Operative repair |
| 17 | Pulmonary atresia, MAPCAs | 5.06 | 6.30 | 65 | 0.21 | 105 | 1 | Catheter intervention |
| 18 | ASD, VSD, PDA, PAPVR | 5.03 | 5.20 | 60 | 0.21 | 98 | 9 | Operative repair |
| 19 | HLHC, Norwood 1 | 5.13 | 6.50 | 66 | 0.21 | 83 | 1 | Catheter intervention |
| 20 | Cardiomyopathy | 3.78 | 6.40 | 60 | 0.30 | 105 | 2 | Listed for heart transplantation |

FiO$_2$, fraction of inspired oxygen; MRI, magnetic resonance imaging; ICU, intensive care unit; TOF, tetralogy of Fallot; HLHS, hypoplastic left heart syndrome; ASD, atrial septal defect; LA, left atrial; AVSD, atrioventricular septal defect; TAPVR, total anomalous pulmonary venous return; DILV, double-inlet left ventricle; VSD, ventricular septal defect; ISTA, coarctation of the aorta; DORV, double-outlet right ventricle; TGA, transposition of great arteries; IAA, interruption of the aortic arch; TAC, truncus arteriosus communis; MAPCAs, major aorto-pulmonary collateral arteries; PDA, persistent ductus arteriosus; PAPVR, partial anomalous pulmonary venous return; SVC, superior vena cava; HLHC, hypoplastic left heart complex

During the MRI scan procedures, all the patients except one were hemodynamically stabile, and no increase in intravenous catecholamine support was necessary. The mean blood pressure before MRI was 53 ± 7 mmHg (range, 38–65 mmHg; median, 55 mmHg). During the scans, the mean blood pressure was 52 ± 7 mmHg (range, 38–63 mmHg; median, 51 mmHg), and after arrival at the PCICU, it was 54 ± 6 mmHg (range, 37–65 mmHg; median, 55 mmHg). The heart rate changes before, during, and after the procedure were of no significance. The heart rate per minute was 139 ± 13 bpm (range, 120–180 bpm; median, 140 bpm) before the MRI, 125 ± 16 bpm (range, 100–170 bpm; median, 124 bpm) during the MRI, and 140 ± 13 bpm (range, 120–180 bpm; median, 140 bpm) after the MRI.

A 10-month-old girl (patient 9) with a double-outlet right ventricle, transposition of the great arteries, and chromosomal anomaly requiring a milrinone intravenous infusion needed a single dose (0.05 mg) of epinephrine due to a short episode of relative bradycardia (80 bpm) after one 15-s breathholding episode for a contrast agent–based angiography, which was the last scan in her examination. Here blood pressure, however, remained stable, and her bradycardia resolved with ventilation and epinephrine within 30 s.

All other examinations were completed successfully with the ability to produce diagnostic images in all cases. An example of the image quality is given in Fig. 1 (patient 14).

No indwelling catheters or drains were accidentally dislocated during transport or in the MRI laboratory. The mean body core temperature after return to the PCICU was 36.8 ± 0.7°C (range, 35.8–38.5°C; median, 36.9°C). The mean serum lactate level was 1.2 ± 0.4 mmol/l (range, 0.8–1.8 mmol/l; median, 1.2 mmol/l).

The mean diuresis on the examination day was insignificantly lower than the day before with unchanged
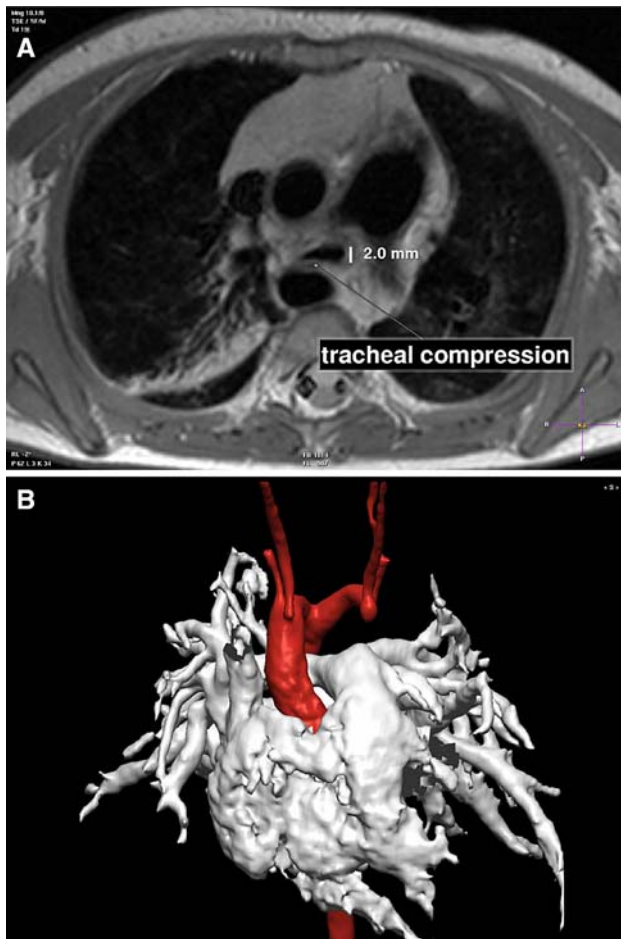
**Fig. 1** Patient 14 with tracheal stenosis due to a double aortic arch with an atretic left anterior part. (**a**) Transverse turbo spin-echo images displaying the tracheal stenosis by the right aortic arch. (**b**) Three-dimensional volume–rendered reconstruction of the double aortic arch with the atretic left anterior arch. Note that each arch gives rise to the ipsilateral common carotid and subclavian artery

medication (5.09 ± 1.58 vs 5.53 ± 1.77 ml/kg/h). The mean stay in the PCICU was 28 ± 43 days (range, 1–164 days; median, 8 days). No associated nosocomial infections were recorded up to 14 days after the MRI.

For 14 (70%) of the 20 patients, operative or catheter-interventional procedures were initiated after the MRI result. One 3-month-old baby was listed for heart transplantation (Table 2), and only one additional diagnostic direct heart catheterization (patient 20) was performed after the MRI. Four patients (patients 3, 9, 11, and 13) died due to their congenital heart disease during the study period.

## Discussion

Cardiac MRI has become a cornerstone for diagnostic imaging in congenital heart disease. Anatomic delineation of all thoracic organs and functional assessment of blood flow and myocardial cardiac function are possible for all age groups [2, 5, 16]. One major advantage of cardiac MRI is the lack of radiation, which is especially important for children. One major disadvantage of cardiac MRI is that it is slow, which is especially important in the imaging of critically ill patients.

Infants requiring intensive care are particularly vulnerable because of their impaired cardiac or respiratory function during transport to imaging sites with its potential additional hazards [19]. One recent study delineated a low overall rate of adverse events during cardiovascular magnetic resonance for congenital heart disease, with the highest rate of adverse events for patients from the intensive care unit [4].

The current study demonstrated that cardiac MRI for the infant in the intensive care unit, in an adequate setting, has no delayed hemodynamic effects, as indicated by the evaluated parameters including serum lactate, diuresis, and the amount of diuretics up to 24 h after the MRI. Although this approach may reflect our institutional approach, to some extent, the significant clinical value of cardiovascular MRI for sick infants with CHD is increasingly recognized by other investigators [1, 10].

Cardiac MRI appeared to have no significant unwanted hemodynamic effects, except for one infant, a 10-month-old girl receiving inotropic support who required a single dose of epinephrine after a breathhold scan of 15 s resulting in relative bradycardia, which resolved within 30 s. This patient's blood pressure remained stable throughout the procedure and the bradycardia event. This episode emphasizes the importance of complete hemodynamic monitoring during cardiac MRI for sick children and the close cooperation required between the anesthetist and radiologist, especially during breathhold scans.

Transport of a critically ill infant may involve significant risks. Therefore, hemodynamic stability should be optimized, and monitoring during transport is crucial [20]. In our study, transport from the PCICU to the MRI and back was within a 5-min walking distance on the same floor. The transport was carried out by one experienced pediatric cardiologist, an intensivist, and one or two nurses from the PCICU. Because many congenital heart defects cause an imbalance between systemic and pulmonary perfusion, special care was taken not to hyperventilate patients during transport.

No complications occurred during transport in our study, underscoring the importance of exact preparation for such transports. In all cases, the patient was assessed on the PCICU ward the day before MRI by the pediatric cardiologist responsible for our congenital cardiac MRI program.

Complete hemodynamic monitoring during the examinations including end-tidal carbon dioxide analysis,

**Table 2** Magnetic resonance imaging (MRI) indication, new findings by MRI, and clinical consequences

| Diagnosis | MRI indication | New findings | Consequences |
|---|---|---|---|
| Stridor, suspected vascular anomaly | Severe stridor postnatal | No aortic arch anomaly, no relevant tracheal stenosis | Discharged without intervention |
| TOF, absent pumonary valve | Failure of extubation, preoperative imaging | Bilateral severe bronchus compression | Early TOF repair |
| HLHS, Norwood 1 | Pleural and pericardial effusions, shunt compression? coarctation? | Shunt seroma, no shunt stenosis, no coarctation | Conservative treatment of pericardial effusion |
| Double aortic arch, tracheal stenosis | Suspected double aortic arch, preoperative imaging | Detailed aortic arch anatomy | Transsection of the right aortic arch |
| Cor triatriatum sinistrum, ASD | Suspected unroofed coronary sinus, shunt quantification | Qp/Qs 4:1, coronary sinus ASD | Resection of LA membrane, ASD closure |
| Right atrial isomerism, AVSD, TAPVR | Pulmonary vein anatomy | Detailed pulmonary vein and situs anatomy | Surgery postponed |
| DILV, hypoplastic arch, Norwood 2 | Suspected stenosis of the bicaval Glenn anastomosis | Stenosis of the right SVC anastomosis | Catheter intervention |
| ASD, VSD, ISTA | Suspected hypoplasia of the transverse arch, shunt quantification | No relevant hypoplasia of the arch | Operative repair without augmentation of the arch |
| DORV, TGA, chromosomal anomaly | Tracheal compression after DORV repair, ventilator dependant | Detailed tracheal anatomy, small residual vsd, Qp/Qs 1.3:1 | Surgery postponed, discharged with home ventilation |
| VSD, ASD, diaphragmatic hernia, trisomy 21 | Shunt quantification, preoperative imaging of the hernia | Detailed hernial anatomy, Qp/Qs 1.4:1 | Operative repair of the hernia first |
| AVSD, IAA repair, trisomy 21 | Postoperative low cardiac output, coarctation?, ventricular imbalance | Ventricle volumetry, no coarctation | Biventricular repair |
| ASD, VSD, hypoplastic aortic arch | Suspected additional anomalous pulmonary veins, shunt quantification | Detailed pulmonary vein and aortic arch anatomy, Qp/Qs 2:1 | Operative repair |
| AVSD | Postoperative low cardiac output, caval thrombus formation | Left ventricle hypoplasia by volumetry, severe tricuspid regurgitation | Comfort care |
| VSD, double aortic arch, tracheal stenosis | Suspected aortic arch anomaly, shunt quantification | Detailed aortic arch anatomy, Qp/Qs 3.23:1 | Transsection of the atretic left anterior arch, VSD closure |
| HLHC, Norwood 1 | Suspected shunt stenosis, ventricle volumetry | Shunt and bifurcational stenosis, balanced ventricles | Shunt replacement, biventriular repair later possible |
| TAC | Postoperative right pulmonary artery hypoplasia due to compression | Quantification of right lung perfusion | Surgical repair |
| Pulmonary atresia, MAPCAs | Ventricle volumetry, MAPCA anatomy | Balanced ventricles, detailed MAPCA anatomy, only membranous pulmonary atresia | Biventricular repair possible, catheter intervention |
| ASD, VSD, PDA, PAPVR | Suspected pulmonary vein anomaly, preoperative imaging | Detailed pulmonary vein anatomy, Qp/Qs 3.5:1 | Operative repair |
| HLHC, Norwood 1 | Suspected shunt stenosis, ventricle volumetry | Shunt stenosis, balanced ventricles | Stent dilation, biventricular repair later possible |
| Cardiomyopathy | Right ventricular failure, suspected PAPVR | No anomalous venous return, severe right heart dilation, low cardiac index | Listed for heart transplantation |

TOF, tetralogy of Fallot; HLHS, hypoplastic left heart syndrome; LA, left atrial; ASD, atrial septal defect; AVSD, atrioventricular septal defect; TAPVR, total anomalous pulmonary venous return; DILV, double-inlet left ventricle; SVC, superior vena cava; VSD, ventricular septal defect; ISTA, coarctation of the aorta; DORV, double-outlet right ventricle; TGA, transposition of great arteries; IAA, interruption of the aortic arch; HLHC, hypoplastic left heart complex; TAC, truncus arteriosus communis; MAPCAs, major aorto-pulmonary collateral arteries; PDA, persistent ductus arteriosus; PAPVR, partial anomalous pulmonary venous return

invasive arterial and central venous pressures, noninvasive blood pressures, ECG, and pulse oximetry allowed the treating physicians to adapt anesthesia continuously to the hemodynamic changes. Heart rate, blood pressure, and ventilation during anesthesia did not differ from those of the previous hemodynamic situation.

Joint meticulous planning and tailoring of the examination to the patient's hemodynamic and respiratory status is known to be very important, especially with small children [11]. At our institution, this is facilitated by performance of the scans by pediatric cardiologists in close collaboration with our radiologists.

All examinations could be completed successfully with good image quality during a mean examination time of $110 \pm 27$ min from the patient's arrival, including intubation, positioning, imaging, and return to the PCICU. This corresponds to the reported time needed for infant cardiac imaging by other institutions [16]. Duration of these tests is significant due to anesthetic management during the examination on the one hand and due to technical aspects of infant cardiac imaging on the other hand, in which higher heart rates and smaller vascular structures must be adapted to time-consuming navigator techniques or multiple signal averages [8].

No nosocomial infections, especially ventilator-associated pneumonia, were recognized up to 14 days after the examinations. Although the number of patients in this study was small, our strategy of elective ventilation for MRI appeared to be a wise approach.

For 14 of the 20 infants, operative or catheter interventional procedures were initiated after the MRI result during the same hospital stay. One 3-month-old baby was listed for heart transplantation. Details for MRI indications, new findings by MRI, and clinical consequences are presented in Table 2.

The noninvasive nature of MRI and its great clinical impact on management decisions render cardiac MRI particularly attractive for patients with impaired hemodynamics for whom direct cardiac catheterization poses additional risks such as arrhythmias, infections, and contrast agent load [17]. Alternatively, cardiac CT certainly is an important method, particularly for delineating extracardiac vessel malformations and airway problems. Its great advantage is its unique speed, with acquisition times of a few seconds. Obviously, this is most important with imaging procedures for unstable patients. However, CT is limited largely to morphologic assessment because no hemodynamic data can realistically be expected from CT with small children. Moreover, the increase in radiation sensitivity up to 10-fold for smaller children is particularly relevant for infants with complex CHD, for whom repeated X-ray-based procedures may be used [18].

Therefore, all efforts should be made to minimize the cumulative risk for the development of radiation-induced cancer [7, 18]. For this reason, cardiovascular MRI is considered the method of choice by many institutions when transthoracic echocardiography is inconclusive and the patient is stable enough to undergo a longer investigation under general anesthesia.

## Conclusion

We reviewed the infant patients from our PCICU undergoing cardiac MRI for hemodynamic consequences and intraprocedural complications, as well as the subsequent clinical value of the investigations. No acute or delayed hemodynamic adverse effects and no significant intraprocedural complications occurred. For 70% of our patients, surgical or catheter-based interventional procedures were initiated on the basis of the novel MRI information. This indicates that in an adequate setting, cardiovascular MRI is safe and has important management implications even for this highly vulnerable patient group.

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