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Contrast-enhanced MR angiography of pulmonary venous abnormalities in children

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Abstract *Background*: Echocardiography and X-ray angiography have been considered as gold standards for evaluation of pulmonary venous abnormalities. However, each technique has its own limitations, such as limitation in visualization of the pulmonary veins within the lungs by echocardiography, and the invasive nature of and use of ionizing radiation in X-ray angiography. Contrast-enhanced MR angiography (MRA) is a fast noninvasive method of visualization of the vessels including the pulmonary arteries and veins. *Objectives*: To evaluate the utility of contrast-enhanced MRA in the evaluation of pulmonary venous abnormalities in pediatric patients and to compare its diagnostic accuracy with that of transthoracic echocardiography. *Materials and methods*: In 30 pediatric patients 31 contrast-enhanced MRA studies were performed for evaluation of pulmonary venous abnormalities. Each of 124 pulmonary veins was evaluated for site of connection, course within the lung, presence of obstruction, and topographic relationship with the adjacent structures. The findings of MRA were compared with echocardiographic findings for 116 veins in 29 studies in 28 patients. *Results*: Contrast-enhanced MRA visualized 99% (123 of 124) of the pulmonary veins investigated, while echocardiography visualized 89% (103 of 116). Exact agreement was found between the two methods in 72% of the veins with a weighted kappa of 0.60 (0.47–0.73, 95% CI). Echocardiography failed to diagnose an abnormal connection in 2 of 15 pulmonary veins, a discrete stenosis in 2 of 19 veins, and diffuse hypoplasia in 10 of 14 veins. In 29% of patients, MRA made the uncertain echocardiographic findings clear. In another 29%, MRA provided a new diagnosis. *Conclusions*: Contrast-enhanced MRA is a powerful, safe, and accurate fast-imaging technique for the anatomical evaluation of pulmonary venous abnormalities. MRA may obviate the need for conventional X-ray angiography. Cardiac catheterization may be reserved for those patients in whom pulmonary vascular resistance needs to be determined.

Keywords Contrast-enhanced MR angiography · Echocardiography · Pulmonary vein · Pulmonary venous abnormalities

Introduction

Pulmonary venous abnormalities include congenital partial or total anomalous connections and congenital stenosis or atresia of the individual veins. These defects may occur in isolation or in combination with others, particularly the heterotaxy syndromes [1]. Pulmonary venous obstruction may also occur secondary to surgical procedures [2, 3]. Since the patients with such abnormalities can be asymptomatic or present with nonspecific clinical manifestations, their recognition with cardiac imaging is important.

Echocardiography and conventional X-ray angiography have been considered as the most accurate methods for evaluation of pulmonary venous abnormalities [1, 4]. However, each technique has its own limitations. Although transthoracic echocardiography provides excellent images of the pulmonary veins in the mediastinum, it cannot visualize the pulmonary veins within the lungs [5, 6, 7]. In addition, the acoustic window is often limited in large or obese children and after surgery. Transesophageal echocardiography enables clearer visualization of the pulmonary veins [8, 9] but is an invasive method especially in pediatric patients. Conventional X-ray angiography is an invasive procedure that uses ionizing radiation and a potentially harmful contrast medium. For clear visualization of the pulmonary veins, it is often necessary to perform time-consuming and risky procedures, such as selective injection into the branch pulmonary arteries in wedged positions or into the individual veins [10].

Contrast-enhanced magnetic resonance angiography (MRA) is a fast imaging technique with a large field of view and high spatial resolution [11, 12, 13, 14, 15, 16, 17]. The source images can be reformatted in any desired plane and reconstructed in three dimensions for optimal viewing and better understanding of the vascular anatomy. Although contrast-enhanced MRA has been proven as useful in visualization of various vessels, its application to the evaluation of the pulmonary veins has been limited, especially in children [18, 19, 20, 21, 22, 23].

The purposes of our study were to evaluate the utility of contrast-enhanced MRA in the evaluation of the pulmonary venous abnormalities in pediatric patients and to compare its diagnostic accuracy with that of transthoracic echocardiography.

Materials and methods

Patient population

The patient population included 30 patients who underwent contrast-enhanced MRA primarily for the evaluation of the pulmonary veins ($n=27$) or in whom a pulmonary venous abnormality was incidentally diagnosed at MRA performed for other reasons ($n=3$) between April 1999 and December 2000. In the former group, contrast-enhanced MRA was requested for visualization of the entire pulmonary venous anatomy in the mediastinum and lungs that was not possible by echocardiography. As one patient underwent two studies before and after surgical treatment of the pulmonary venous abnormality, 31 contrast-enhanced MRA studies were performed. The age of the patients ranged from 2 weeks to 15 years with a median of 6.2 years, and their weight from 2 to 66 kg with a median of 22.8 kg. Nine patients were infants and six weighed less than 5 kg. The study was approved by the Research Ethics Board of our institution.

MR imaging

All examinations were performed with a 1.5-T MR unit (Signa CVMR; GE Medical Systems, Milwaukee, Wis.). A phased-array cardiac coil or a head coil was used, depending on the size of the patient. Contrast-enhanced MRA was performed using a 3-D fast spoiled gradient refocused echo sequence in the coronal plane with the following parameters: field of view 20–40 cm, minimal repetition time and echo time, flip angle 30°, 256×128 matrix, slice thickness 1.2–3 mm, 20–32 partitions, bandwidth 31.25 kHz, and linear k-space filling. The imaging time for each sequence ranged from 15 to 25 s. Dimeglumine gadopentetate (Magnevist; Berlex Laboratoires, Quebec, Canada) was used as contrast medium with a dose of 0.15 mmol/kg body weight. Contrast medium was injected manually for a period of approximately 10 s followed by a saline flush. The imaging sequence was initiated 3–7 s after the start of the injection of contrast medium according to the patient's size.

Three consecutive sets of images were acquired to visualize all the arteries and veins of both the systemic and the pulmonary circulation. In cooperative patients, the first set of images was acquired during breath hold, and the second and third sets during quiet breathing. When the patient was anesthetized, apnea was achieved by temporarily stopping the mechanical ventilation. The examination was performed under general anesthesia in 15 patients and under sedation in 4. MR source data were processed on a commercially available off-line workstation (Advantage Windows 3.0; GE Medical Systems, Milwaukee, Wis.) with maximum intensity projection algorithm. The entire course of each pulmonary vein was traced in multiple anatomical planes by using multiplanar reformation and 3-D volume-rendering techniques. For volume rendering, the images were manipulated as seen from behind with gradual thresholding and filtering of the data to prevent inadvertent image distortion. A pulmonary vein was considered normal only when no abnormality was found in at least two imaging planes.

Echocardiography

Available for review were 29 echocardiograms in 28 patients. The interval between the MRA and the echocardiography ranged from 1 to 363 days with a median of 30 days. Echocardiography was performed with either a Hewlett-Packard Sonos 5500 (Agilent, Andover, Mass.) or an ATL 5000 (Advanced Technology Laboratories, Seattle, Wash.) imaging system. A 2–12 MHz transducer was used for the HP 5500 system and 2–8 MHz for the ATL 5000 system. The pulmonary veins were visualized with both gray-scale and color Doppler mapping in the standard planes, including subcostal, apical, parasternal, and suprasternal views. Infants older than 3 weeks and children younger than 3 years were studied under sedation.

Data analysis and statistics

The contrast-enhanced MRA images and echocardiograms were reviewed by an experienced cardiac radiologist (S.J.Y.) and pediatric cardiologist (J.F.S.), respectively. Both reviewers were blinded to each other. Each pulmonary vein was evaluated for the site of connection, the course within the lung, the presence of obstruction or hypoplasia, and the topographic relationship to adjacent structures. The findings for each pulmonary vein were classified into six categories according to the presence or absence of abnormal connection, obstruction, and hypoplasia. The pulmonary veins were considered to be four in each patient; if an additional vein was present between the upper and lower veins, it was considered as a part of the upper vein. Numerical data are reported as mean values with standard deviations or as median values with ranges. The McNemar test was used to compare frequencies. Correlation between contrast-enhanced MRA and echocardiography is expressed as exact agreement and as weighted kappa.

Contrast-enhanced MRA findings were also compared with the findings at conventional angiography and with the operation findings whenever this information was available.

Results

Contrast-enhanced MRA visualized 123 of 124 pulmonary veins investigated (99%), while echocardiography visualized 103 of 116 veins (89%). In one patient the right upper pulmonary vein could not be visualized properly by MRA because of artifacts from a metallic device for closure of an atrial septal defect. At least the central two-thirds of the pulmonary veins were visualized in all other cases. The quality of the images was sufficiently diagnostic in all studies. Table 1 shows the diagnosis as revealed by contrast-enhanced MRA. Representative cases are shown in Figs. 1, 2, 3, 4 and 5.

Contrast-enhanced MRA confirmed the echocardiographic diagnosis in 13 patients (42%). It established a new diagnosis in 9 (29%) in whom echocardiography was not diagnostic. The diagnosis made by MRA in this group of patients included normal pulmonary veins in six patients, partial anomalous pulmonary venous connection in two, and a complex postoperative anatomy in one. In another nine patients (29%), MRA confirmed the suspected or unclear echocardiographic diagnosis.

The correlation between the findings of contrast-enhanced MRA and echocardiography for 116 pulmonary veins is shown in Table 2. Exact agreement was found for 84 veins (72%), with a weighted kappa of 0.60 and a 95% confidence interval of 0.47–0.73. Rate of visualization was significantly higher with contrast-enhanced MRA than with echocardiography (McNemar test, $P=0.001$): echocardiography failed to visualize 13 veins (11%), while MRA failed to visualize only one. Echocardiography failed to diagnose an abnormal connection in 2 of 15 pulmonary veins, a discrete stenosis in 2 of 19 veins, and diffuse hypoplasia in 10 of 14 veins. At Doppler echocardiography, pulmonary venous obstruction was suspected for 32 pulmonary veins based on turbulent flow. Among these veins, only 19 showed discrete stenosis at contrast-enhanced MRA. Contrast-enhanced MRA showed entirely normal anatomy in 7 of these veins and diffuse hypoplasia without discrete stenosis in 6.

In all six patients in whom X-ray angiograms were available and in both of the two who underwent surgery, the findings at MRA and echocardiography were confirmed.

Table 1 Diagnoses at contrast-enhanced MRA

Diagnosis	Number of studies
Normal pulmonary venous anatomy	11
Partial anomalous pulmonary venous connection	7
Total anomalous pulmonary venous connection	2
Unobstructed pulmonary veins after surgery	3
Obstructed pulmonary vein(s) after surgery	5
Primary stenosis of the pulmonary vein	3
Total	31

Discussion

This study demonstrates that contrast-enhanced MRA is very robust in the visualization of the pulmonary veins

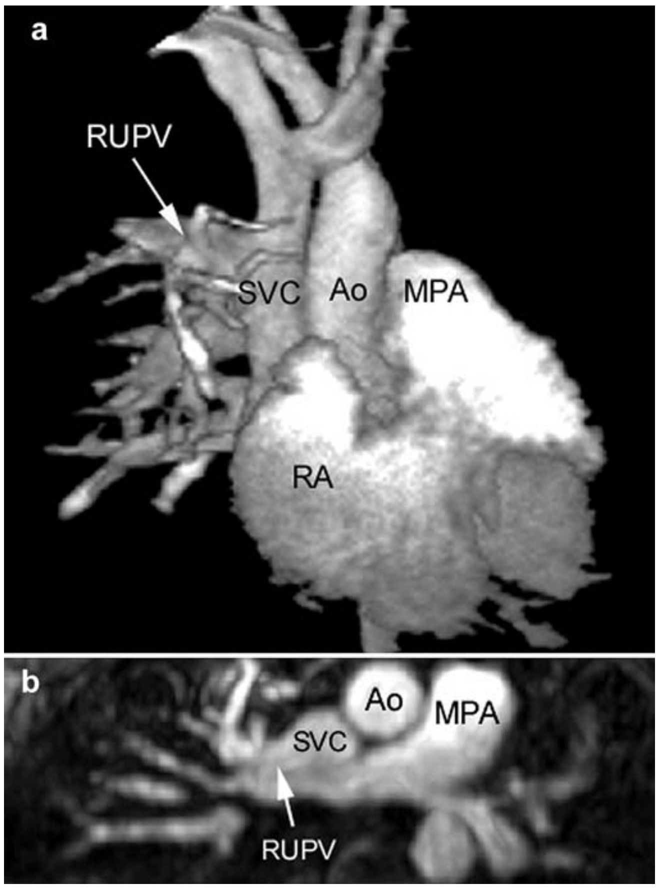

Fig. 1a, b Partial anomalous connection of the right upper pulmonary vein (*RUPV*) to the superior vena cava (*SVC*) shown in 3-D volume-rendered image (**a**) and maximum-intensity projection image reformatted in an axial plane (**b**) (*Ao* aorta, *MPA* main pulmonary artery, *RA* right atrium)

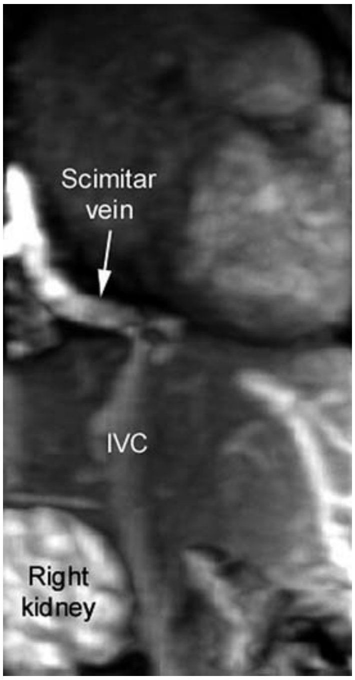

Fig. 2 Scimitar syndrome. Reformatted image in an oblique sagittal plane shows that the pulmonary veins from the right lung form a scimitar-shaped confluence. It is connected to the inferior vena cava (*IVC*) at its junction with the right atrium

even in young infants weighing as little as 2 kg. In our study in pediatric patients, the pulmonary veins were properly visualized in 99% (123 of 124) of the pulmonary veins investigated, the single failure being due to artifacts from a metallic device for closure of an atrial septal defect. Although the image quality varied according to the patient's size and to whether the images were acquired during apnea, complete diagnostic information could be obtained in all studies. Our data demonstrated the superiority of contrast-enhanced MRA over echocardiography in diagnosing pulmonary venous abnormalities in children. Contrast-enhanced MRA provided a new diagnosis for 29% of the pulmonary veins studied and confirmed the suspected but unclear diagnosis for another 29%. Similar results have very recently been reported by Greil et al. [24]. Our study, however, proved the usefulness of MRA in a younger age group. The most important advantage of MRA over echocardiography in our study was its ability to visualize every pulmonary vein in its entire course within the lungs as well as in the mediastinum.

Using Doppler echocardiography, pulmonary venous stenosis can be suspected in the presence of turbulent flow. In our study, however, 13 of 32 pulmonary veins showing turbulent flow at Doppler interrogation did not demonstrate any discrete stenosis at MRA. This observation suggests that the diagnosis of discrete stenosis cannot be made solely based on the presence of turbulent

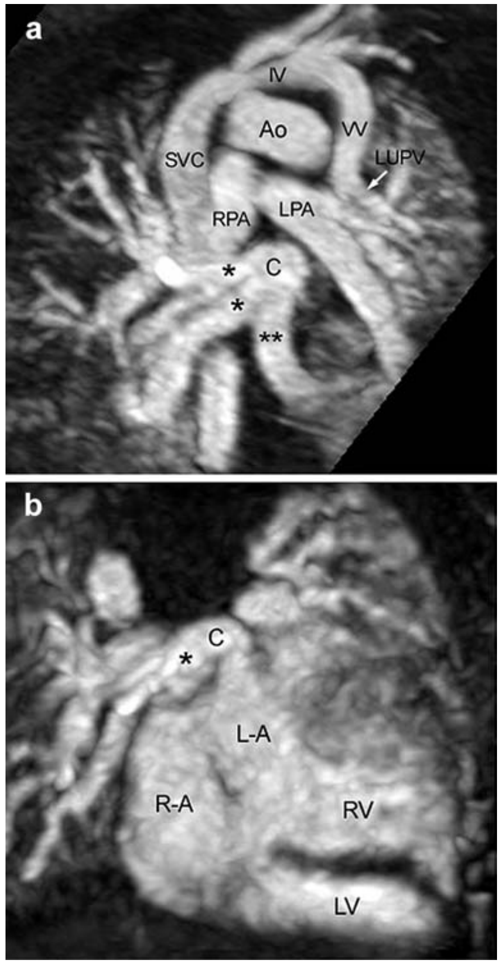

Fig. 3a, b Right atrial isomerism with mixed type of total anomalous pulmonary venous connection. Two reformatted images, coronal image (**a**) and slanted coronal image (**b**), show that the veins draining the entire right lung (*single asterisks*) and the left lower lobe (*double asterisks*) are connected to the left-sided atrium (*L-A*) through a confluent channel (*C*). The left upper pulmonary vein (*LUPV*) has a separate connection to the innominate vein (*IV*) through a vertical vein (*VV*). Right (*RPA*) and left (*LPA*) pulmonary arteries show a symmetrical branching pattern. There is a twisted atrioventricular connection with a superoinferior relationship of the right (*RV*) and left (*LV*) ventricles (*Ao* aortic arch, *R-A* right-sided atrium, *SVC* superior vena cava)

flow at Doppler examination. The blood flow velocity may be increased in the presence of tubular vascular hypoplasia as seen in six veins of our study, or with blood flow redistribution between the lungs, which results in a unilaterally increased pulmonary venous return. In both cases turbulent flow is not related to a discrete stenosis but to a relative disproportion between flow amount and size of the vessel. A prospective study is necessary, however, to correlate the pulmonary venous anatomy with the pulmonary arterial and venous flow dynamics by using both echocardiography and MR.

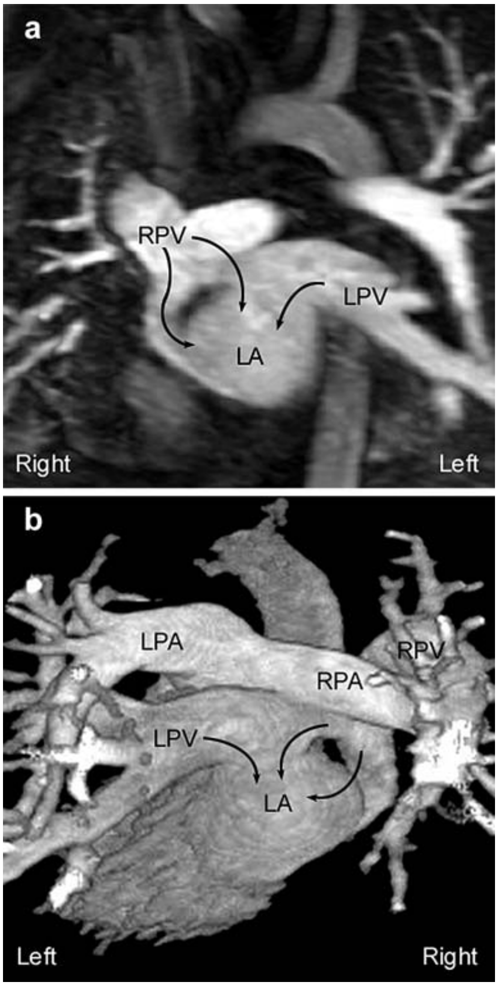

Fig. 4a, b Result of complex surgery for total anomalous pulmonary venous connection to the superior vena cava. Maximum intensity projection image in coronal plane (**a**) and 3-D volume-rendered image seen from behind (**b**) show two pathways (*arrows*) between the right pulmonary venous confluence (RPV) and the left atrium (*LA*). There is no evidence of pulmonary venous obstruction. Echocardiography was unable to visualize the right-sided pulmonary veins (*LPA* left pulmonary artery, *LPV* left pulmonary venous confluence, *RPA* right pulmonary artery

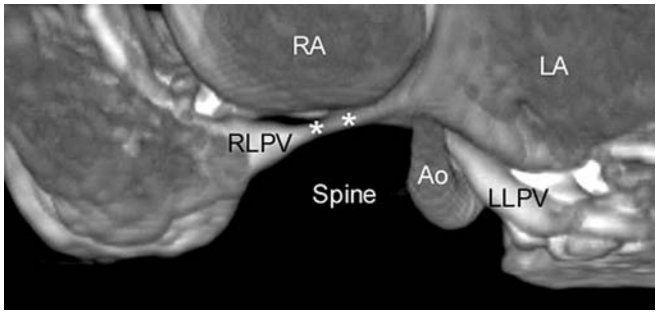

Fig. 5 Acquired pulmonary vein stenosis. In this girl with cardiomegaly and pulmonary hypertension, the 3-D volume-rendered image seen from below shows that the right lower pulmonary vein (*RLPV*) is compressed between the dilated right atrium (*RA*) and the spine as indicated by *asterisks*. The left lower pulmonary vein (*LLPV*) is also compressed by the descending aorta (*Ao*) from behind (*LA* left atrium)

Table 2 Correlation between findings at contrast-enhanced MRA and echocardiography for each pulmonary vein (*I* not demonstrated, *II* normal connection without obstruction, *III* normal connection with obstruction, *IV* abnormal connection without obstruction, *V* abnormal connection with obstruction, *VI* diffuse hypoplasia)

MRA findings	Echocardiographic findings					
	I	II	III	IV	V	VI
I	0	0	0	0	0	0
II	11	60	6	0	0	0
III	1	1	8	0	0	0
IV	1	1	0	3	1	0
V	0	0	0	0	9	0
VI	0	4	6	0	0	4

Conventional MR techniques for evaluation of the thoracic vessels include electrocardiographically gated spin-echo, cine gradient-echo and time-of-flight (TOF) sequences [13, 25, 26, 27, 28, 29, 30, 31]. Although these methods have been proven useful for evaluation of the aorta, central pulmonary arteries, and major systemic veins [14], they are not able to visualize all the peripheral pulmonary arteries and pulmonary veins properly. This limitation is related to relatively low spatial resolution, susceptibility to respiratory and cardiac motion artifacts and the tree-like branching of the pulmonary arteries and veins. The limitations of conventional MR techniques can be overcome by using contrast-enhanced 3-D MRA. Gadolinium chelate induces a shortening of the T1 relaxation time of blood and thereby improves signal-to-noise ratio [11, 12]. With an increased signal-to-noise ratio, either higher image resolution or reduced imaging time can be achieved. As the signal loss from in-plane saturation effects is eliminated, fewer slices can cover larger vascular territories and therefore a larger volume of tissue can be imaged in a single scan. A short acquisition time enables collection of 3-D data during a single breath-hold without cardiac and respiratory gating and therefore reduces motion artifacts. A short repetition time provides natural background suppression resulting in better contrast between the enhanced vessels and the surrounding tissue. If the region of interest is properly tailored, the data acquisition time seldom exceeds 30 s [14]. We usually select the imaging volume in a coronal plane from the reference axial images and keep it as small as possible to reduce scanning time. When higher spatial resolution is required, the reduction in acquisition time can be traded for a greater number of sections and a larger in-plane matrix size [11]. With all these advantages, contrast-enhanced 3-D MRA is considered as an ideal tool for evaluation of the pulmonary vessels [22, 24, 32].

The best image contrast is obtained when the data acquisition of the central k-space occurs at the time of peak concentration of the contrast medium within the vessels of interest [14]. Therefore, finding the right interval between contrast injection and the start of image acquisition determines the image quality [33, 34]. Some investigators set the timing after a preliminary test injection [35]; others use real-time monitoring to detect the arrival of contrast medium in the vessels to be investigated [36]. We do not use either method because virtually all the sizeable vessels in the thorax should be evaluated in our pediatric patients with congenital heart disease. By acquiring three consecutive series of data, all the pulmonary and systemic vascular structures, either arterial or venous, can be visualized with a single injection of contrast medium [20]. We determine the delay time of acquisition by using the ''best estimate'' method, based on the patient's size, heart rate, and underlying cardiovascular lesion. An interval of 3 to 7 s generally provided optimal opacification of the pulmonary arteries and veins in the first of the three series of data acquired. We did not find any difficulty in differentiating the pulmonary veins from the pulmonary arteries.

Unlike conventional radiographic intravenous contrast agents, gadolinium chelates are known to be exceedingly safe [37]. We did not observe any adverse effects of gadolinium-DTPA in our patients. The usual recommended dose of gadolinium-DTPA for angiographic purposes is 0.2 mmol/kg [38]. In our study, we were able to obtain images of sufficient diagnostic quality in all cases by injecting 0.15 mmol/kg of contrast medium. The image quality, however, was largely dependent on whether the data were acquired during breath-hold. Therefore, we obtained the best images in the anesthetized patients in whom ventilation was temporarily stopped during the data acquisition.

The combination of echocardiography and X-ray angiography has been considered the standard in evaluation of pulmonary venous abnormalities [1, 4]. In our study, contrast-enhanced MRA was more accurate than echocardiography in visualization of the pulmonary venous anatomy. On the other hand, we could not compare the diagnostic value of contrast-enhanced MRA with that of X-ray angiography because the latter procedure was performed in only six patients. The reason for this is that the number of invasive studies performed in our institution has been reduced after active utilization and recognition of the diagnostic value of contrast-enhanced MRA.

In conclusion, contrast-enhanced MRA is a powerful, safe, and accurate fast-imaging technique for the anatomical evaluation of pulmonary venous abnormalities. This method, in combination with echocardiography, can be considered as the most useful method for evaluation of the pulmonary veins and may obviate the need for conventional X-ray angiography. Cardiac catheterization can be reserved for those conditions in which pulmonary vascular resistance should be determined.

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References

1. Musewe NN, Smallhorn JF, Freedom RM (1992) Anomalies of pulmonary venous connections including cor triatriatum and stenosis of individual pulmonary veins. In: Freedom RM, Benson LN, Smallhorn JF (eds) Neonatal heart disease. Springer-Verlag, London, pp 309–331
2. Bando K, Turrentine MW, Ensing GJ, et al (1996) Surgical management of total anomalous pulmonary venous connection. Thirty-year trends. Circulation 94 [Suppl II]:II-12– II-16
3. Caldarone CA, Najm HK, Kadletz M, et al (1998) Relentless pulmonary vein stenosis after repair of total anomalous pulmonary venous drainage. Ann Thorac Surg 66:1514–1520
4. Smallhorn JF, Sutherland GR, Tommasini G, et al (1981) Assessment of total anomalous pulmonary venous connection by two-dimensional echocardiography. Br Heart J 46:613–623
5. Sahn DJ, Allen HD, Lange LW, et al (1979) Cross-sectional echocardiographic diagnosis of the sites of total anomalous pulmonary venous drainage. Circulation 60:1317–1325
6. Masui T, Seelos KC, Kersting-Sommerhoff BA, et al (1991) Abnormalities of the pulmonary veins: evaluation with MR imaging and comparison with cardiac angiography and echocardiography. Radiology 181:645–649
7. Reddy SCB, Chopra PS, Rao PS (1995) Mixed-type total anomalous pulmonary venous connection: echocardiographic limitations and angiographic advantages. Am Heart J 129:1034–1038
8. Stumper O, Vargas-Barron J, Rijlaarsdam M, et al (1991) Assessment of anomalous systemic and pulmonary venous connections by transoesophageal echocardiography in infants and children. Br Heart J 66:411–418
9. Romero-Cárdenas A, Vargas-Barrón J, Rijlaarsdam M, et al (1991) Total anomalous pulmonary venous return: diagnosis by transesophageal echocardiography. Am Heart J 121:1831–1834
10. Freedom RM, Mawson JB, Yoo S-J, et al (1997) Congenital heart disease. Textbook of angiocardiography. Futura Publishing Company, Armonk. pp 665–705
11. Prince MR (1998) Contrast-enhanced MR angiography: theory and optimization. Magn Reson Imaging Clin N Am 6:257–267
12. Korosec FR, Mistretta CA (1998) MR angiography: basic principles and theory. Magn Reson Imaging Clin N Am 6:223–256
13. Hartnell GG, Meier RA (1995) MR angiography of congenital heart disease in adults. Radiographics 15:81–794

14. Alley MT, Shifrin RY, Pelc NJ, et al (1998) Ultrafast contrast-enhanced three-dimensional MR angiography: state of the Art. Radiographics 18:273–285
15. Masui T, Katayama M, Kobayashi S, et al (2000) Gadolinium-enhanced MR angiography in the evaluation of congenital cardiovascular disease pre- and postoperative states in infants and children. J Magn Reson Imaging 12:1034–1042
16. Lam WW, Chan JHM, Hui Y, et al (1998) Non-breath-hold gadolinium-enhanced MR angiography of the thoracoabdominal aorta: experience in 18 children. AJR Am J Roentgenol 170:78–480
17. Roche KJ, Krinsky G, Lee VS, et al (1999) Interrupted aortic arch: diagnosis with gadolinium-enhanced 3D MRA. J Comput Assist Tomogr 23:197–202
18. Meaney JFM, Johansson LOM, Ahlstrom H, et al (1999) Pulmonary magnetic resonance angiography. J Magn Reson Imaging 10:326–338
19. Hoffman U, Schima W, Herold C (1999) Pulmonary magnetic resonance angiography. Eur Radiol 9:745–1754
20. Holmqvist C, Larsson E-M, Stahlberg F, et al (2000) Contrast-enhanced thoracic 3D-MR angiography in infants and children. Acta Radiol 42:50–58
21. Pilleul F, Merchant N (2000) MRI of the pulmonary veins: comparison between 3D MR angiography and T1-weighted spin echo. J Comput Assist Tomogr 24:683–687
22. Maki DD, Siegelman DA, Roberts DA, et al (2001) Pulmonary arteriovenous malformation: three-dimensional gadolinium-enhanced MR angiography – initial experience. Radiology 219:243–246
23. Ferrari VA, Scott CH, Holland GA, et al (2001) Ultrafast three-dimensional contrast-enhanced magnetic resonance angiography and imaging in the diagnosis of partial anomalous pulmonary venous drainage. J Am Coll Cardiol 37:1120–1128
24. Greil GF, Powell AJ, Gildein HP, et al (2002) Gadolinium-enhanced three-dimensional magnetic resonance angiography of pulmonary and systemic venous anomalies. J Am Coll Cardiol 39:335–341
25. Cohen MC, Hartnell GG, Finn JP (1994) Magnetic resonance angiography of congenital pulmonary vein anomalies. Am Heart J 127:954–955
26. White CS, Baffa JM, Haney PJ, et al (1997) MR Imaging of congenital anomalies of the thoracic veins. Radiographics 17:595–608
27. White CS, Baffa JM, Haney PJ, et al (1998) Anomalies of pulmonary veins: usefulness of spin-echo and gradient-echo MR images. AJR Am J Roentgenol 170:1365–1368
28. Choe YH, Lee HJ, Kim HS, et al (1994) MRI of total anomalous pulmonary venous connections. J Comput Assist Tomogr 18:243–249
29. Yoo SJ, Kim YM, Choe YH (1999) Magnetic resonance imaging of complex congenital heart disease. Int J Card Imaging 15:151–160
30. Vesely TM, Julsrud PR, Brown JJ, et al (1991) MR imaging of partial anomalous pulmonary venous connections. J Comput Assist Tomogr 15:752–756
31. Kastler B, Livolsi A, Germain P, et al (1992) Contribution of MRI in supracardiac total anomalous pulmonary venous drainage. Pediatr Radiol 22:262–263
32. White CS (2000) MR imaging of thoracic veins. Magn Reson Imaging Clin N Am 8:17–32
33. Saloner D (1998) Determinants of image appearance in contrast-enhanced magnetic resonance angiography. A review. Invest Radiol 33:488–495
34. Maki JH, Prince MR, Londy FJ, et al (1996) The effects of time varying intravascular signal intensity and k-space acquisition order on three-dimensional MR angiography image quality. J Magn Reson Imaging 6:642–651
35. Earls JP, Rofsky NM, DeCorato DR, et al (1996) Breath-hold single-dose gadolinium-enhanced three-dimensional MR aortography: usefulness of a timing examination and MR power injector. Radiology 201:705–710
36. Foo TKF, Saranathan M, Prince MR, et al (1997) Automated detection of bolus arrival and initiation of data acquisition in fast, three-dimensional, gadolinium-enhanced MR angiography. Radiology 203:275–280
37. Niendorf HP, Haustein J, Louton T, et al (1991) Safety and tolerance after intravenous administration of 0.3 mmol/kg Gd-DTPA. Results of a randomized, controlled clinical trial. Invest Radiol 26 [Suppl II]:S221–223
38. Niendorf HP, Haustein J, Cornelius I, et al (1991) Safety of gadolinium-DTPA: extended clinical experience. Magn Reson Med 22:229–232