CONGENITAL HEART DISEASE

Myocardial scars determined by delayed-enhancement magnetic resonance imaging and positron emission tomography are not common in right ventricles with systemic function in long-term follow up

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Objective: To test the hypothesis that myocardial scars are common in patients with systemic right ventricles.

Methods: 27 consecutive patients with systemic right ventricle were studied with delayed-enhancement magnetic resonance imaging and positron emission tomography. Of the 27 patients, 18 had had an atrial switch operation a mean of 21.8 (SD 4.5) years previously and were 23.4 (SD 5.3) years old. Nine patients without previous heart surgery had congenitally corrected transposition of the great arteries and were 35.3 (SD 15.6) years old.

Results: Only one patient had a subendocardial scar identified by delayed-enhancement magnetic resonance imaging. Positron emission tomography identified no myocardial scars.

Conclusions: This study shows that the hypothesis that myocardial scars are common in patients with systemic right ventricles is not correct.

The right ventricle (RV) functions as a systemic and pulmonary ventricle in mainly two patient groups. The first group consists of patients after an atrial switch operation for transposition of the great arteries (Senning¹ or Mustard² operation). The second group consists of patients with congenitally corrected transposition of the great arteries (ccTGA). In both patient groups the systemic RV often fails on long-term follow up.^{3–11} In patients after the atrial switch operation, the systemic RV fails in up to 10% of patients every 10 years.^{3–7} In many patients with ccTGA the systemic RV also fails, although the exact incidence of RV failure in ccTGA is unknown because the prevalence of ccTGA is unknown.^{8–11}

The RV has been proposed to fail because continuous exposure of the RV to a high-resistance systemic circulation results in a compensatory RV hypertrophy. This may lead, in a first step, to a mismatch between RV blood supply and systemic RV work and then, in a second step, to myocardial scars and therefore to systemic RV failure.^{12–16} The first step of the explanation is supported by an experimental model of pressure overload of the RV, in which RV hypertrophy is associated with a decrease in myocardial capillary density.¹⁷ Further support comes from studies with single photon emission computed tomography (SPECT) and positron emission tomography (PET) of patients after atrial switch^{12–15} and with ccTGA.^{14–16} These studies found stress-induced perfusion defects and impaired coronary flow reserve in these patients. The first step of the explanation, that patients with systemic RV have stress-induced ischaemia, perfusion defects and impaired coronary flow reserve, therefore is well established. However, these studies do not clearly support the second step of the explanation, that RV blood

supply and systemic RV work mismatch eventually leads to myocardial scars. In fact, the results of these studies are confusing. Studies with SPECT concluded that myocardial scars are common in patients after atrial switch operations^{12–13} and in patients with ccTGA.¹⁴ However, studies using the reference standard method PET did not find myocardial scars in patients after atrial switch operations¹⁵ and in patients with ccTGA.¹⁶ Whether myocardial scars are common in patients with systemic RV therefore remains unclear.

Direct imaging of myocardial scars is now possible by a modern magnetic resonance imaging (MRI) technique after the intravenous administration of a gadolinium chelate. This technique has been named delayed-enhancement MRI (DE-MRI) and shows myocardial scars as “hyperenhanced” or bright. A preponderance of both clinical and experimental data show that hyperenhancement is specifically localised to myocardial scars.¹⁸ Furthermore, DE-MRI seems to be superior to SPECT¹⁹ and PET²⁰ for the detection of left ventricular myocardial scars. Additionally, DE-MRI has specifically been shown to be superior to SPECT for the detection of RV myocardial scars.²¹

The objective of this study was therefore to test the hypothesis that myocardial scars are common in patients with systemic RV by using a modern non-invasive imaging

Abbreviations: ccTGA, congenitally corrected transposition of the great arteries; DE-MRI, delayed-enhancement magnetic resonance imaging; FFE, fast field echo; Gd-DTPA, gadolinium-diethylenetriamine pentaacetic acid; MRI, magnetic resonance imaging; PET, positron emission tomography; RV, right ventricle; SPECT, single photon emission computed tomography

technique. To test this hypothesis we studied 27 consecutive patients with systemic RV by DE-MRI. To strengthen the conclusion of the study the patients were additionally assessed by PET studies at rest, which is considered the reference standard for detection of myocardial scars in patients with ischaemic coronary heart disease.^{19 20 22–24}

METHODS

Patients

Consecutive patients of our outpatient clinic after atrial switch operation or with ccTGA without previous heart surgery were invited to participate. Patients with a permanent pacemaker in situ were excluded. All patients received routine clinical evaluation in our outpatient clinic. The clinical evaluation included determination of the grade of tricuspid regurgitation by echocardiography. The degree of tricuspid regurgitation was qualitatively assessed by colour Doppler imaging and graded as 0 (no regurgitation), I (mild regurgitation), II (moderate regurgitation) or III (severe regurgitation).¹³ The local research ethics committee approved the study, and all patients gave written informed consent.

Patients after atrial switch operation

Eighteen consecutive patients 21.8 (SD 4.5) years after atrial switch operation participated in the study (table 1). Four of these patients could not participate in the PET study for logistical reasons.

Patients with ccTGA

Nine consecutive patients with ccTGA without previous heart surgery were studied (table 2). These nine patients have contributed to an earlier study on coronary flow reserve determined by PET.¹⁶

Magnetic resonance imaging

Patients were examined in the supine position with a 1.5 T scanner (ACS NT, INCA software; Philips Medical Systems, Best, The Netherlands) equipped with fast gradients (amplitude 23 mT/m; slew rate 105 mT/m/ms) and a dedicated cardiac phased-array surface coil.

Multiphased balanced fast field echo sequence

For the calculation of RV ejection fraction and analysis of RV wall motion, multiphased balanced fast field echo (FFE) was carried out as previously reported.²⁶ In brief, short-axis scans covering the entire heart and long-axis scans covering the RV apex were acquired (slice thickness 6 mm without slice gap; field of view 350–400 mm; matrix 256 × 256; in-plane resolution 1.4–1.6 mm). Each slice was imaged in 12 phases of the cardiac cycle. Scans were retrospectively ECG triggered and recorded under breath hold. One investigator (SF) blinded to other MRI findings, PET findings, patient history and clinical data calculated RV ejection fraction on a separate work station by using dedicated software as previously described^{20 26} (MASS; Medis Inc, Leiden, The Netherlands). RV wall motion was determined by two investigators (SF, HCS) blinded to other MRI findings, PET findings, patient history and clinical data. Wall motion in the systemic RV was assessed in short- and long-axis scans. In short-axis scans, four segments (anterior, lateral, inferior and septal) at basal, mid-ventricular and near apical levels were assessed. In long-axis scans, the RV apex was assessed, resulting in a total of 13 segments for each patient. Wall motion in each segment was graded as normal or abnormal. Each investigator analysed all segments of all patients independently of the other investigator. Then all segments of all patients were reviewed by both investigators together until they agreed on all segments.

Delayed-enhancement magnetic resonance imaging

For the detection of myocardial scars DE-MRI was carried out as previously reported.²⁰ In brief, the presence of myocardial scars (presence of hyperenhancement) was assessed in short-axis and sagittal long-axis images that were acquired in end diastole 20–30 min after bolus injection of 0.2 mmol/kg body weight gadolinium-diethylenetriamine pentaacetic acid (Gd-DTPA) (Magnevist; Schering, Berlin, Germany). We chose to time our image acquisition 20–30 min after bolus injection of 0.2 mmol/kg body weight Gd-DTPA on the basis of previous studies by us²⁷ and others.²⁸ According to these studies delayed enhancement is best visualised 20–30 min after injection of 0.2 mmol/kg body weight Gd-DTPA. An inversion-recovery, three-dimensional, turbo-gradient echo

Table 1 Patients with transposition of the great arteries after atrial switch operation: characteristics and results

Patient	Sex	Type of OP	Age at OP (years)	Age at study (years)	RVEF (%)	Segments with abnormal wall motion*	Rhythm	TR	Mode of identification of scars	
									PET	DE-MRI
1	M	Mus	5.2	35.2	49	5	SSS	I	ND	Negative
2	F	S	0.8	25.8	59	6	SR	0	Negative	Negative
3	M	Mus	1.9	26.9	63	5	SR	I	Negative	Negative
4	M	S	0.1	20.5	20	13	SR	II	Negative	Negative
5	M	S	0.1	18.5	60	5	SR	I	Negative	Negative
6	M	S	0.1	20.3	44	6	SSS	I	Negative	Negative
7	M	Mus	1.6	28.2	49	6	SR	I	Negative	Negative
8	F	S	1.7	23.7	45	13	SR	III	ND	Negative
9	M	S	0.5	16.5	55	9	SSS	II	Negative	Negative
10	M	S	1.0	16.1	66	6	SSS	I	ND	Negative
11	F	Mus	0.0	27.2	63	7	SR	I	Negative	Negative
12	M	S	1.1	26.2	39	4	SR	II	Negative	Negative
13	M	S	1.2	17.6	47	5	SR	I	Negative	Negative
14	F	S	0.9	24.4	71	3	SR	I	ND	Negative
15	M	S	0.2	18.1	38	5	SSS	I	Negative	Negative
16	F	Mus	3.1	30.2	33	6	SR	I	Negative	Negative
17	F	S	0.1	19.2	52	5	SSS	I	Negative	Negative
18	M	Mus	1.8	19.8	37	4	SR	I	Negative	Negative
Mean (SD)			1.2 (1.3)	23.4 (5.3)	50 (13)	6 (2.8)				
Median (range)			0.9 (0.0–5.2)	22.3 (16.1–35.2)	49 (20–71)	6 (3–13)				

*Number of segments with abnormal wall motion of 13 analysed segments.

DE-MRI, delayed-enhancement magnetic resonance imaging; F, female; M, male; Mus, Mustard operation; ND, not done; OP, heart surgery; PET, positron emission tomography; RVEF, right ventricular ejection fraction determined by magnetic resonance imaging; S, Senning operation; SR, sinus rhythm; SSS, sick sinus syndrome; TR, grade of tricuspid regurgitation determined by echocardiography.²⁵

None of the patients with relatively small RVEF or with many segments with wall motion abnormalities had myocardial scars.

Table 2 Patients with congenitally corrected transposition of the great arteries: characteristics and results

Patient	Sex	Age at study (years)	RVEF (%)	Segments with abnormal wall motion*	Rhythm	TR	Mode of identification of scars	
							PET	DE-MRI
19	M	14.5	45	6	SR	I	Negative	Negative
20	F	30.3	34	4	SR	II	Negative	Negative
21	F	37.8	74	7	AVB III	II	Negative	Negative
22	F	32.3	43	10	SR	I	Negative	Negative
23	F	47.7	49	2	SR	I	Negative	Negative
24	M	40.7	35	12	SR	II	Negative	Negative
25	M	59.9	60	7	SR	II	Negative	Apical subendocardial
26	M	43.3	40	8	SR	I	Negative	Negative
27	M	10.4	54	3	SR	III	Negative	Negative
Mean (SD)		35.3 (15.6)	48 (13)	7 (3.2)				
Median (range)		37.8 (10.5–59.9)	45 (34–74)	7 (2–12)				

*Number of segments with abnormal wall motion of 13 analysed segments.

AVB III, atrioventricular block grade three; DE-MRI, delayed-enhancement magnetic resonance imaging; F, female; M, male; OP, heart surgery; PET, positron emission tomography; RVEF, right ventricular ejection fraction determined by magnetic resonance imaging; SR, sinus rhythm; TR, grade of tricuspid regurgitation determined by echocardiography.²⁵

None of the patients with relatively small RVEF or with many segments with wall motion abnormalities had myocardial scars.

technique with echo planar readout was used (echo time 3.3 ms; recovery time 5.4 ms; echo planar imaging factor 11; slice thickness 5 mm; spatial resolution $1.2 \times 1.2 \text{ mm}^2$; flip angle 15° ; acquisition time 284 ms; prepulse delay 225–300 ms). The DE-MRI study was analysed off line by two investigators (SF, HCS) blinded to PET findings, patient history and clinical data. Each investigator analysed all DE-MRI studies of all patients independently of the other investigator. Then both investigators together reviewed all DE-MRI studies of all patients. The two investigators initially did not agree on the extent of the myocardial scar only for patient 25.

Positron emission tomography

For the detection of myocardial scars PET at rest was carried out as previously reported.²⁹ In brief, the presence of myocardial scars was assessed at rest by static PET with nitrogen-13 ammonia. Images were acquired with an ECAT EXACT or an ECAT 951 scanner (Siemens/CTI, Knoxville, Tennessee, USA). After the patient was positioned, a transmission scan was acquired for correction of photon attenuation. Then ^{13}N -ammonia (approximately 0.3 mCi/kg) was injected intravenously at rest. A static emission image obtained at 10–20 min after injection was used for analysis.

The PET study was qualitatively analysed by an investigator (FMB) blinded to DE-MRI findings, patient history and clinical data. Tracer uptake in the systemic RV was assessed in transaxial, horizontal long-axis and vertical long-axis views. Four segments (anterior, lateral, inferior and septal) at basal and mid-ventricular levels, giving a total of eight segments, were assessed. The apex of the RV was excluded from analysis to avoid the influence of partial volume effects due to out-of-plane motion.³⁰ Tracer uptake in each segment was graded as normal (grade 0), mildly decreased (grade 1), moderately decreased (grade 2), severely decreased (grade 3) or no uptake at all (grade 4). Segments graded 2, 3 or 4 were defined as segments with scar. Tracer uptake was graded in two steps because the magnitude of segmental tracer uptake at PET may be influenced by varying segmental wall thicknesses.³¹ Additionally, segmental wall thickness varies usually substantially within a systemic RV. This is because a large variety of hypertrophied trabeculae, resulting in various segmental wall thicknesses, is found in systemic RV. In the first step the PET studies were therefore graded alone. Then, in the second step, tracer uptake in each segment was finally graded by simultaneous visualisation of the PET studies and multiphased balanced FFE sequences acquired by MRI. With

this step relatively low tracer uptake could be attributed to segmental wall thickening abnormalities or decreased tracer uptake. PET studies during stress were not performed because the objective of this study was to test the hypothesis that myocardial scars are common in patients with systemic RV. The study was not aimed at testing the well-established pathophysiology of stress-induced systemic RV ischaemia, perfusion defects and impaired coronary flow reserve.^{12–17}

RESULTS

Patients after atrial switch operation

DE-MRI or PET did not detect any myocardial scars in patients after atrial switch operation (table 1). None of the patients with relatively small RV ejection fractions or with many segments with wall motion abnormalities had myocardial scars.

Patients with ccTGA

DE-MRI detected only one subendocardial scar in patients with ccTGA (table 2). This scar could not be detected by PET. In all other patients with ccTGA no myocardial scars were detected by DE-MRI or PET. None of the patients with relatively small RV ejection fractions or with many segments with wall motion abnormalities had myocardial scars.

DISCUSSION

Our study showed that the hypothesis that myocardial scars are common in patients with systemic RV is not correct. In our series of 27 patients with systemic RV, we tested the occurrence of myocardial scars with two independent study methods (DE-MRI and PET). DE-MRI has been shown to be a highly specific imaging method that is quickly becoming the method of choice for direct imaging of myocardial scars.^{18–21} PET studies at rest are considered the reference standard for detection of myocardial scars in patients with ischaemic coronary heart disease.^{19 20 22–24} We found only one patient with a scar that was detected by only one method. This patient was the oldest patient in our study and the scar possibly was secondary to coronary heart disease. However, this patient has never undergone coronary artery angiography, so this possibility is speculative. It is also important to note that even the patients with relatively small RV ejection fractions and patients with many segments with wall motion abnormalities did not have myocardial scars. We showed that myocardial scars are not common in patients with systemic RV by using the modern MRI technique DE-MRI and the established reference standard PET.

Pathophysiology of systemic RV failure

Our results raise new questions about the pathophysiology leading to systemic RV failure. Considering the results of our study and previous studies, continuous exposure of the RV to a high-resistance systemic circulation clearly seems to result in compensatory RV hypertrophy. This seems to lead to a mismatch between RV blood supply and systemic RV work. These pathophysiological steps are supported by an experimental model of RV pressure overload by chronic pulmonary artery constriction, in which the developing RV hypertrophy was associated with a decrease in RV myocardial capillary density.¹⁷ Accordingly, patients after atrial switch operations^{12–13} and patients with ccTGA¹⁴ have been shown to have stress-induced myocardial ischaemia. And, more important, impaired coronary flow reserve has been shown in patients after atrial switch operations¹⁵ and in patients with ccTGA.¹⁶ But does this mismatch between RV myocardial blood supply and systemic RV work lead to RV failure? The mismatch between RV blood supply and systemic RV work has been proposed eventually to lead to myocardial scars and therefore to systemic RV failure.^{12–16} We do not think that this is correct. In our series of 27 patients with systemic RV, only one patient had a subendocardial scar. Accordingly, two previous studies that used PET^{15–16} also found no evidence of myocardial scars. Additionally, our patients were substantially older than all other previously studied patients,^{12–16} thus excluding the possibility that myocardial scars develop only later in life. We therefore cannot now answer the question of whether and how the mismatch between RV myocardial blood supply and systemic RV work leads to RV failure.

Discrepancy with previous studies

Why have previous investigators concluded that the mismatch between RV blood supply and systemic RV work eventually may lead to myocardial scars and therefore to systemic RV failure?^{12–16, 32} Principally, this question has three possible explanations.

Several observations seem to favour a *first possible explanation*, that myocardial scars may be common in *some* patients with systemic RV and the studied patient subgroups were different in the several studies. A careful look at the previous studies of patients after atrial switch operation shows that the timing of the atrial switch operation seems to correlate with the occurrence of myocardial scars. Throughout the studies, myocardial scars seem to be found in patients after atrial switch operation who were relatively older at the time of the operation. For example, the mean or median age at operation of patients who have been found to have myocardial scars was 38¹³ and 16 months.³² In contrast, the mean or median age at operation of patients who have not been found to have myocardial scars was 8,¹⁵ 10³² and 11 (our study) months. These observations seem to favour a theory suggesting that preoperative hypoxaemia and impaired coronary flow lead to myocardial injury and not to systemic RV intrinsically. Similarly, in patients with ccTGA a history of open heart surgery seems to correlate with the occurrence of myocardial scars. Throughout the studies, myocardial scars seem to be found in patients with ccTGA and a history of open heart surgery. For example, 14 of 20 patients with ccTGA who had undergone open heart surgery in a previous study¹⁴ had a high occurrence of myocardial scars. In contrast, in patients with ccTGA without a history of open heart surgery, as in our study, no myocardial scars were found.¹⁶ These observations also seem to favour a theory suggesting that open heart surgery leads to myocardial injury^{33–34} and not a systemic RV intrinsically.

Some observations point to a *second possible explanation*, that myocardial scars are not common in patients with systemic

RV and the studies finding myocardial scars had a methodological problem. Previous SPECT studies^{12–14} may have found more myocardial scars than in our study because those studies did not consider regional wall thickness for the assessment of segmental tracer uptake of systemic RV.³¹ For nuclear imaging techniques such as SPECT or PET, regional wall thickness is a determinant of measured regional tracer uptake due to lower recovery of radioactivity from structures below or in the range of the spatial resolution of the system. A myocardial segment with a thinner wall than other segments may therefore artificially appear as a segment with impaired tracer uptake. Additionally, segmental wall thickness varies usually substantially within a systemic RV. This is because a large variety of hypertrophied trabeculae resulting in various segmental wall thicknesses are found in systemic RV. We therefore assessed segmental wall thickness in multiphased balanced FFE sequences acquired by MRI and used this information for the interpretation of segmental tracer uptake in PET images. These observations seem to show that myocardial scars have been overestimated in these previous studies. Similarly, these SPECT studies^{12–14} might have overestimated the occurrence of myocardial scars due to a too-aggressive interpretation of the SPECT results. For example, one study¹² found, among patients after atrial switch operation, perfusion defects at rest in only 68 (26%) of the 264 studied segments. More important, only one of these defects was severe, only 20 (8%) were moderate and the vast majority, 47 defects (18%), were mild. Only very aggressive interpretation of SPECT results would regard mild perfusion defects at rest as myocardial scars.³³ Therefore, that study should not have concluded that myocardial scars are common in these patients.

We do not think that a *third possible explanation*, that myocardial scars are common in patients with systemic RV and that the studies not finding myocardial scars had a methodological problem, is correct. We did not find myocardial scars to be common and are very confident in our methods. Firstly, our results and conclusion are based on two independent study methods: PET and DE-MRI. Both methods have been studied extensively in patients with ischaemic coronary heart disease and have been shown to have a high diagnostic accuracy for detecting myocardial scars.^{19–23} Additionally, different experienced investigators blinded to the results of the other method analysed the PET and DE-MRI studies off line. Lastly, our results are supported by previous PET studies of patients after atrial switch operation¹⁵ and patients with ccTGA.¹⁶

Limitations

An important limitation of our study is that only very little is known about imaging of myocardial damage of the systemic RV. In fact, to our knowledge, the potential differences in imaging myocardial damage of systemic right compared with systemic left ventricles have not been systematically studied. Furthermore, very few studies have used DE-MRI in patients with systemic RV. The optimal timing of image acquisition and the optimal dose of Gd-DTPA are therefore not known. We chose to time our image acquisition 20–30 min after bolus injection of 0.2 mmol/kg body weight Gd-DTPA on the basis of previous studies by us²⁷ and others.²⁸

Another limitation of our study is the small number of included patients, excluding the possibility of a sound statistical analysis. However, patients with ccTGA without previous heart surgery are very rare, excluding the possibility of a larger subgroup. We therefore used two independent methods—PET and DE-MRI—carried out by different experienced investigators blinded to the results of the other method.

Conclusions

This study shows that the hypothesis that myocardial scars are common in patients with a systemic RV is not correct. Of 27 patients with a systemic RV, only one patient had an endocardial scar. Furthermore, none of the patients with relatively small RV ejection fractions or with many segments with wall motion abnormalities had myocardial scars. Myocardial scars are therefore not a reason for failure of the systemic RV.

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REFERENCES

- 1 **Senning A.** Surgical correction of transposition of the great vessels. *Surgery* 1959;**45**:966–80.
- 2 **Mustard WT, Keith JD, Trusler GA, et al.** The surgical management of transposition of the great vessels. *J Thorac Cardiovasc Surg* 1964;**48**:953–8.
- 3 **Turina M, Siebenmann R, Nussbaumer P, et al.** Long-term outlook after atrial correction of transposition of great arteries. *J Thorac Cardiovasc Surg* 1988;**95**:828–35.
- 4 **Merlo M, de Tommasi SM, Brunelli F, et al.** Long-term results after atrial correction of complete transposition of the great arteries. *Ann Thorac Surg* 1991;**51**:227–31.
- 5 **Gelatt M, Hamilton RM, McCrindle BW, et al.** Arrhythmia and mortality after the Mustard procedure: A 30-year single-center experience. *J Am Coll Cardiol* 1997;**29**:194–201.
- 6 **Meijboom F, Szatmari A, Deckers JW, et al.** Long-term follow-up (10 to 17 years) after Mustard repair for transposition of the great arteries. *J Thorac Cardiovasc Surg* 1996;**111**:1158–68.
- 7 **Roos-Hesselink JW, Meijboom FJ, Spitaels SE, et al.** Decline in ventricular function and clinical condition after Mustard repair for transposition of the great arteries (a prospective study of 22–29 years). *Eur Heart J* 2004;**25**:1264–70.
- 8 **Graham TP Jr, Parrish MD, Boucek RJ Jr, et al.** Assessment of ventricular size and function in congenitally corrected transposition of the great arteries. *Am J Cardiol* 1983;**51**:244–51.
- 9 **Dimas AP, Moodie DS, Sterba R, et al.** Long-term function of the morphologic right ventricle in adult patients with corrected transposition of the great arteries. *Am Heart J* 1989;**118**:526–30.
- 10 **Ikeda U, Furuse M, Suzuki O, et al.** Long-term survival in aged patients with corrected transposition of the great arteries. *Chest* 1992;**101**:1382–5.
- 11 **Presbitero P, Somerville J, Rabajoli F, et al.** Corrected transposition of the great arteries without associated defects in adult patients: clinical profile and follow up. *Br Heart J* 1995;**74**:57–9.
- 12 **Millane T, Bernard EJ, Jaeggi E, et al.** Role of ischemia and infarction in late right ventricular dysfunction after atrial repair of transposition of the great arteries. *J Am Coll Cardiol* 2000;**35**:1661–8.
- 13 **Lubiszewska B, Gosiewska E, Hoffman P, et al.** Myocardial perfusion and function of the systemic right ventricle in patients after atrial switch procedure for complete transposition: long-term follow-up. *J Am Coll Cardiol* 2000;**36**:1365–70.
- 14 **Hornung TS, Bernard EJ, Celermajer DS, et al.** Right ventricular dysfunction in congenitally corrected transposition of the great arteries. *Am J Cardiol* 1999;**84**:1116–9, A10.
- 15 **Singh TP, Humes RA, Muzik O, et al.** Myocardial flow reserve in patients with a systemic right ventricle after atrial switch repair. *J Am Coll Cardiol* 2001;**37**:2120–5.
- 16 **Hauser M, Bengel FM, Hager A, et al.** Impaired myocardial blood flow and coronary flow reserve of the anatomical right systemic ventricle in patients with congenitally corrected transposition of the great arteries. *Heart* 2003;**89**:1231–5.
- 17 **Murray PA, Baig H, Fishbein MC, et al.** Effects of experimental right ventricular hypertrophy on myocardial blood flow in conscious dogs. *J Clin Invest* 1979;**64**:421–7.
- 18 **Shan K, Constantine G, Sivananthan M, et al.** Role of cardiac magnetic resonance imaging in the assessment of myocardial viability. *Circulation* 2004;**109**:1328–34.
- 19 **Wagner A, Mahrholdt H, Holly TA, et al.** Contrast-enhanced MRI and routine single photon emission computed tomography (SPECT) perfusion imaging for detection of subendocardial myocardial infarcts: an imaging study. *Lancet* 2003;**361**:374–9.
- 20 **Klein C, Nekolla SG, Bengel FM, et al.** Assessment of myocardial viability with contrast-enhanced magnetic resonance imaging: comparison with positron emission tomography. *Circulation* 2002;**105**:162–7.
- 21 **Sato H, Murakami Y, Shimada T, et al.** Detection of right ventricular infarction by gadolinium DTPA-enhanced magnetic resonance imaging. *Eur Heart J* 1995;**16**:1195–9.
- 22 **Hutchins GD, Schwaiger M, Rosenspire KC, et al.** Noninvasive quantification of regional blood flow in the human heart using N-13 ammonia and dynamic positron emission tomographic imaging. *J Am Coll Cardiol* 1990;**15**:1032–42.
- 23 **Schwaiger M, Muzik O.** Assessment of myocardial perfusion by positron emission tomography. *Am J Cardiol* 1991;**67**:35D–43D.
- 24 **Kim RJ, Fieno DS, Parrish TB, et al.** Relationship of MRI delayed contrast enhancement to irreversible injury, infarct age, and contractile function. *Circulation* 1999;**100**:1992–2002.
- 25 **Rivera JM, Vandervoort PM, Vazquez de Prada JA, et al.** Which physical factors determine tricuspid regurgitation jet area in the clinical setting? *Am J Cardiol* 1993;**72**:1305–9.
- 26 **Eicken A, Fratz S, Gutfried C, et al.** Hearts late after Fontan operation have normal mass, normal volume, and reduced systolic function: a magnetic resonance imaging study. *J Am Coll Cardiol* 2003;**42**:1061–5.
- 27 **Klein C, Nekolla SG, Balbach T, et al.** The influence of myocardial blood flow and volume of distribution on late Gd-DTPA kinetics in ischemic heart failure. *J Magn Reson Imaging* 2004;**20**:588–93.
- 28 **Kim RJ, Chen E-L, Lima JAC, et al.** Myocardial Gd-DTPA kinetics determine MRI contrast enhancement and reflect the extent and severity of myocardial injury after acute reperfused infarction. *Circulation* 1996;**94**:3318–26.
- 29 **Bengel FM, Hauser M, Duvernoy CS, et al.** Myocardial blood flow and coronary flow reserve late after anatomical correction of transposition of the great arteries. *J Am Coll Cardiol* 1998;**32**:1955–61.
- 30 **Muzik O, Paridon SM, Singh TP, et al.** Quantification of myocardial blood flow and flow reserve in children with a history of Kawasaki disease and normal coronary arteries using positron emission tomography. *J Am Coll Cardiol* 1996;**28**:757–62.
- 31 **Gunning MG, Anagnostopoulos C, Davies G, et al.** Gated technetium-99m-tetrofosmin SPECT and cine MRI to assess left ventricular contraction. *J Nucl Med* 1997;**38**:438–42.
- 32 **Babu-Narayan SV, Goktekin O, Moon JC, et al.** Late gadolinium enhancement cardiovascular magnetic resonance of the systemic right ventricle in adults with previous atrial redirection surgery for transposition of the great arteries. *Circulation* 2005;**111**:2091–8.
- 33 **Nayler WG, Elz JS.** Reperfusion injury: laboratory artifact or clinical dilemma? *Circulation* 1986;**74**:215–21.
- 34 **Breisblatt WM, Stein KL, Wolfe CJ, et al.** Acute myocardial dysfunction and recovery: a common occurrence after coronary bypass surgery. *J Am Coll Cardiol* 1990;**15**:1261–9.
- 35 **Klocke FJ, Baird MG, Lorell BH, et al.** ACC/AHA/ASNC guidelines for the clinical use of cardiac radionuclide imaging—executive summary: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (ACC/AHA/ASNC Committee to Revise the 1995 Guidelines for the Clinical Use of Cardiac Radionuclide Imaging). *J Am Coll Cardiol* 2003;**42**:1318–33.