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Original Article

Quantification of morphologic and hemodynamic severity of coarctation of the aorta by magnetic resonance imaging

Matthias Gutberlet,[1] Norbert Hosten,[2] Michael Vogel,[3] Hasim Abdul-Khaliq,[4] Tilman Ehrenstein,[1] Holger Amthauer,[1] Titus Hoffmann,[1] Ulf Teichgräber,[1] Felix Berger,[4] Peter Lange,[4] Roland Felix[1]

[1]*Department of Diagnostic Radiology and Nuclear Medicine, Charité Campus Virchow Klinikum, Berlin, Germany;* [2]*Department of Diagnostic and Neuroradiology, University Greifswald, Germany;* [3]*GUCH-Unit, Cardiac Services, Middlesex Hospital, London, UK;* [4]*Department of Congenital Heart Disease, German Heart Institute Berlin, Germany*

Abstract *Objective:* As the morpholgic severity of coarctation of the aorta is difficult to assess, especially after previous repair, the value of the technique of multiplanar reconstruction of magnetic resonance imaging data to achieve a 3-dimensional reconstruction of the aortic arch was evaluated and compared to hemodynamic measurements. *Methods and Results:* We performed 30 examinations in 27 patients aged from 6 to 54 years, with a mean of 21 years, by magnetic resonance imaging using a 1.5 Tesla scanner with a standard body coil. Measurements of flow across the coarctation were performed using phase shift velocity mapping, and peak velocity was calculated at the site of stenosis. Aortic cross-sectional area before, at, and beyond the stenosis was reconstructed 3-dimensionally to calculate a percentage degree of stenosis. Morphologic severity of stenosis was correlated to invasively assessed hemodynamic gradients and morphologic data from biplane angiography in 23 patients. Among the 30 examinations, 24 patients had been previously treated by either surgery, in 17 patients, or balloon dilation, while 6 had native coarctation. 3-dimensional reconstruction was possible in all and better delineated the anatomy concerning the hemodynamic relevance of stenoses even as compared with biplane angiography. The correlation between severity of narrowing assessed by diameter measurements in the biplane angiography and 2-dimensional magnetic resonance imaging was $r = 0.94$, and multiplanar reformation with 2-dimensional magnetic resonance imaging was $r = 0.87$ with a tendency of higher grading with the 3-dimensional technique ($p = 0.0001$). The correlation of 2-dimensional magnetic resonance imaging with invasively measured hemodynamic gradients was $r = 0.67$ versus $r = 0.74$ for the areas assessed by multiplanar reformation, indicating that the hemodynamic relevance of a morphological approach to evaluate the degree of a stenosis should better be assessed 3-dimensionally. *Conclusions:* The 3-dimensional reconstruction of the morphologic severity of coarctation offers additonal information over conventional imaging especially in patients with kinking, complex geometry, or collaterals, in whom hemodynamic measurements can become unreliable.

Keywords: Coarctation; multiplanar reconstruction; magnetic resonance imaging; phase shift velocity mapping

COARCTATION OF THE AORTA IS A COMPLEX congenital lesion which, in older patients, is difficult to diagnose with non-invasive imaging. Echocardiographic visualization is not always possible and, in the presence of collaterals, simple hemodynamic measurements like assessment of peripheral blood pressure in all four limbs, or Doppler flow assessment in the descending aorta, frequently do not reflect the anatomic severity of coarctation.[1–3] Because of these known limitations of non-invasive imaging, invasive measurements with catheters and angiography are considered to represent the golden

Correspondence to: Dr Matthias Gutberlet, Diagnostic Radiology, Charité, Campus Virchow Klinikum, Berlin, Augustenburger Platz 1, D–13353 Berlin, Germany. Tel: 49 30 450 57001; Fax 49 30 450 57901; E-mail: matthias.gutberlet@charite.de

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standard of diagnosis of native or recurrent coarctation of the aorta. The technique of 3-dimensional reconstruction of magnetic resonance imaging data, with the use of multiplanar reconstruction, has the potential for grading of the anatomic severity of stenosis. The aim of this study was, firstly, to quantitate cross-sectional areas of the pre- and poststenotic as well as the coarcted segment of the aorta and, secondly, to correlate these data with invasively obtained morphologic and hemodynamic measurements.

Material and methods

Selection of patients

We examined 27 patients aged a mean of 21 years, with a range from 6 to 54 years, who underwent 30 examinations. Of these patients, 24 had previously been treated, with 7 undergoing balloon dilation and 17 submitted to surgery. All had suspected recoarctation, while six had native coarctation (Table 1). Of the patients with native coarctation, three were examined before and two days to three months after treatment by balloon dilation in two, and surgery in the other. The other three patients with native coarctation had no magnetic resonance imaging follow-up. The patients had been corrected by conduit reconstruction in 8 cases, resection and end-to-end anastomosis in four, patch aortoplasty in three, and subclavian flap aortoplasty in two patients. The examinations had been performed at a mean time of 6.9 years after treatment, with a range from 0.01 to 28 years.

Table 1. Complete table of all examined patients with the values for the estimated and invasively measured peak gradients by magnetic resonance imaging and cardiac catheter (CC) at the site of stenosis or restenosis. Furthermore, the percentage diameter (2D-MRI and 2D-CC) as well as the percentage area stenosis (3D-MRI) are indicated. Patient 14, 25 and 27 were examined before and after treatment. Therefore, the pre-treatment examinations are labelled 14', 25' and 27', the post-treatment 14", 25" and 27".

					Gradient (mmHg)			Percent		
Patient no.	**Age**	**Sex**	**Procedure**	**Collaterals**	**MRI**	**CC**	**Geometry**	**2D MRI**	**2D CC**	**3D MRI**
1	40	M	II	No	12	–	Short/Kinking	48	–	54
2	17	M	II	No	25	15	Long/Kinking	47	50	68
3	21	F	I	Yes	25	30	Short/Kinking	50	45	68
4	8	M	V	Yes	21	20	Long/Tubular	59	56	72
5	12	F	VI	No	25	–	Short/Tubular	39	–	28
6	14	M	III	Yes	49	40	Long/Kinking	72	77	71
7	10	M	V	Yes	13	10	Short/Tubular	30	47	63
8	35	F	VI	Yes	81	100	Short/Fileform	70	77	93
9	10	M	V	No	8	5	Short/Fileform	43	40	35
10	14	M	I	No	36	20	Short/Fileform	50	42	58
11	18	M	IV	No	29	30	Long/Tubular	33	40	43
12	38	M	IV	No	0	3	Short/Tubular	6	0	14
13	22	M	I	No	18	20	Short/Kinking	39	35	49
14'	53	M	VI	Yes	–	70	Short/Fileform	76	71	95
14"	54	M	IV	No	4	5	Long/Tubular	−7	0	6
15	14	M	IV	No	23	30	Long/Kinking	53	40	63
16	18	M	I	No	16	–	Long/Tubular	38	–	42
17	12	M	III	Yes	36	35	Short/Kinking	66	56	64
18	50	F	IV	No	34	–	Short/Fileform	46	–	75
19	26	F	VI	No	36	–	Short/Kinking	52	–	75
20	19	M	II	No	39	–	Short/Fileform	39	–	39
21	8	F	III/V	Yes	49	65	Short/Kinking	64	50	85
22	16	M	VI	Yes	52	50	Short/Fileform	63	55	74
23	19	F	IV	No	16	–	Long/Aneurysm	48	–	44
24	18	M	IV/V	No	40	40	Short/Fileform	67	63	68
25'	6	M	IV	Yes	61	80	Short/Fileform	58	59	72
25"	6	M	V	Yes	16	25	Short/Fileform	36	40	58
26	23	M	IV	No	36	40	Short/Kinking	52	45	56
27'	21	F	VI	Yes	64	40	Short/Fileform	69	64	85
27"	21	F	V	Yes	36	20	Short/Fileform	56	55	70
Mean	21.4			Collaterals	31.0	34.5		48.7	48.1	59.6
SD	13.0			n = 13	18.8	24.9		18.2	19.2	21.3

Abbreviations: M: male; F: female; *Procedure* – I: resection and end-to-end anastomosis; II: patch aortoplasty; III: subclavian flap aortoplasty; IV: conduit reconstruction; V: balloon dilation; VI: native coarctation; MRI: magnetic resonance imaging; CC: cardiac catheter; 2D: 2-dimensional; 3D: 3-dimensional

Magnetic resonance imaging

The magnetic resonance examinations were performed with a 1.5 Tesla Gyroscan ACS-NT scanner (Philips, Best, Netherlands) using a standard body coil. The 2-dimensional measurements were made using an electrocardiographically-triggered turbo spin-echo sequence in an angulated parasagittal plane approximating to the left anterior oblique equivalent through the aortic arch with the following parameters: repetition time = 571 ms, echo time = mean 40 ms, turbo factor = 8, Matrix = 256 : 256, field of view = 250–350 mm, slice thickness: 2–4 mm. The 2-dimensional diameter measurements were performed at the site of stenosis using the smallest diameter to calculate the percentage stenosis in comparison to the diameter of the descending aorta at the diaphragm and compared with the results of the biplane-angiography diameter measurements, which were available in 23 patients.[4,5] For 3-dimensional reconstruction, an electrocardiographically-triggered 2-dimensional non-contrast enhanced "in-flow" magnetic resonance angiography with transverse orientation, and an inverse prepulse with the following parameters was used: repetition time = 11 ms, echo time = 5.7 ms, flip-angle = 70°, effective slice thickness was 2 mm (4 mm, 2 mm overlap), matrix 128 : 256, field of view 250–350 mm, mean trigger delay depending on heart rate 260 ms. The calculation of the pre- and poststenotic cross-sectional areas were done initially by simple threshold segmentation of data from the in-flow magnetic resonance angiography (Fig. 1a–c) to 3-dimensionally reconstruct the aortic lumen (Fig. 2a, b, d). Within this 3-dimensional space, after multiplanar reconstruction, a flight path

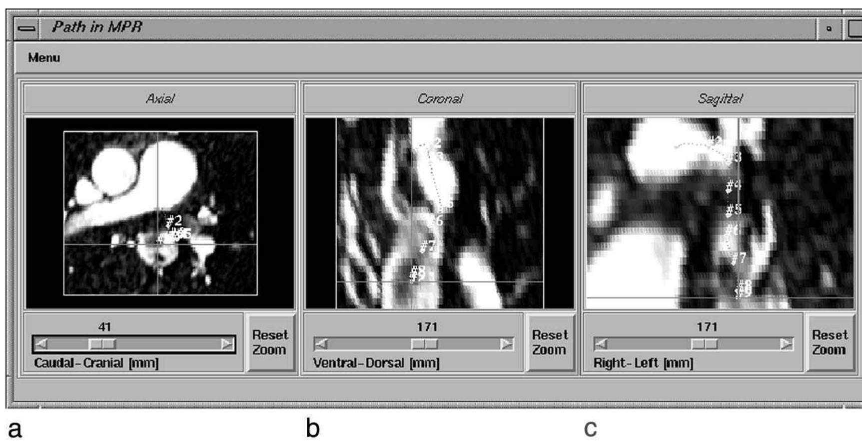

Figure 1.
"Screenshot" of the software used for multiplanar reconstruction (MPR). (a) Showed the original axial data set of the used "in-flow" magnetic resonance angiography (MRA) with a central # defining one point in this plane of the flight path. (b&c) In the corresponding reconstructed coronal and sagittal planes further points (#) of the flight path were defined.

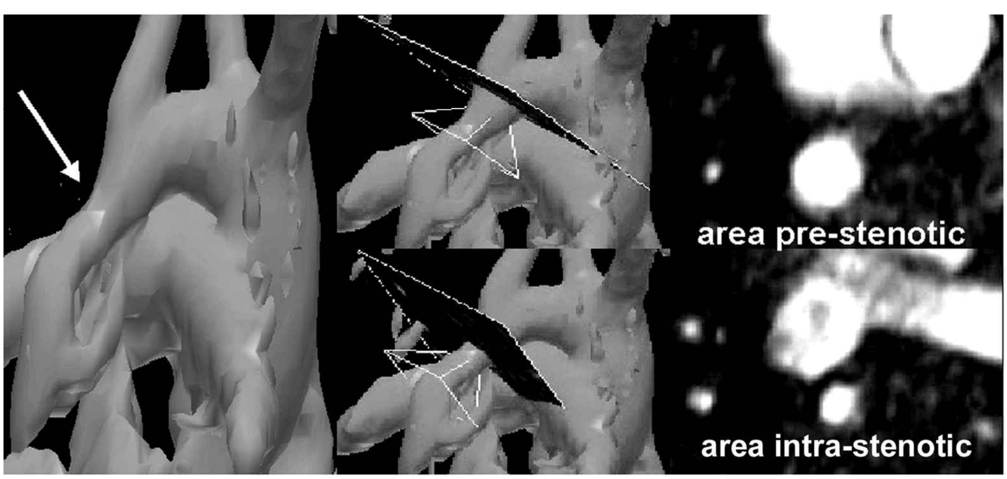

Figure 2.
(a) Three-dimensional (3D) reconstruction of the aortic lumen from a two-dimensional (2D) magnetic resonance angiography (MRA) data set from the right lateral view with a residual stenosis at the site of operation in the descending aorta and a collateral distal of the stenotic area. (b) Shows the flight path through the aortic lumen with the planes perpendicular to the vessel course of the reconstructed aorta pre- and intrastenotic in the same patient. (c) Resulting cross-sectional area after multiplanar reconstruction (MPR) shows a 64% area stenosis. (d) Patient with a high grade 94% fileform area stenosis (arrow) distal of the origin of the enlarged left subclavian artery from a left cranio-dorso-lateral view in a patient with native coarctation. The post-stenotic plane of the multiplanar reconstruction shows a centrally located signal void due to poststenotic turbulent flow. (e) Shows the resulting diagram for the changes in cross-sectional area of the stenotic site in the same patient. The total distance between the locations 1–15 on the x-axis was 30 mm.

was defined, following the course of the vessel. This was done by the user simply clicking onto the object surface and adjusting the spline point within the orthogonal reformations displayed. Along this path, two different representation modes were calculated: surfaces (virtual angioscopy – Fig. 2b) and reformatted image planes perpendicular to the vessel course (Fig. 2c). With the images representing the cross sectional area of the vessel, the lumen can be calculated at any point of the path. Thus, the percentage stenosis of the aorta is derived. The percentage stenosis of the aorta was derived using the smallest area at the site of stenosis compared with the cross-sectional area of the descending aorta at the diaphragm. Measurements of flow were performed with a flow-sensitive gradient echo sequence using phase shift velocity mapping to calculate peak velocity at the site of a stenosis. The gradient echo sequence used had the following parameters: repetition time = 20 ms, echo time = 2.4 ms, flip-angle = 30°, slice-thickness 3–6 mm, matrix = 96 : 128, retrospective gating, 12–32 phases per heart cycle.

Measurements were first performed "in-plane", parallel to the vessel course, and afterwards "through-plane" perpendicular to the course of the main flow-vector at the site of suspected stenosis or restenosis.[6,7] The maximum pressure gradient at the stenosis was estimated using the Bernoulli-equation from the measured peak velocity and compared with cardiac catheter (23 patients) data (Table 1). If the prestenotic peak velocity in the ascending or descending aorta was above 1 m/s as evaluated by the "in-plane" measurement, it was taken into account and the extended modified Bernoulli-equation was used.[6,7]

Biplane-Angiography and invasive assessment of pressure gradient

Biplane Angiography of the thoracic aorta was performed on a Philips system Integris or Polydiagnost using the posterior-anterior and left anterior oblique (60°) projections with 25 frames/sec with a 4–7 french pigtail catheter. The 2-dimensional diameters were measured at the site of stenosis using the smallest diameter of the two planes to calculate the percentage stenosis in comparison to the diameter of the descending aorta at the diaphragm.[4,5] Furthermore, the invasively measured peak gradients at the site of stenosis were compared with the instantaneous peak gradients estimated by magnetic resonance flow measurements. Standard fluid filled catheters were used coupled to a Steatham transducer for assessment of peak-to-peak gradient across the coarcted site. The gradient was measured by pull-back of the catheter from the ascending to descending aorta.

Statistical analysis

The correlation between the invasively measured peak-to-peak gradient and anatomic severity of stenosis by magnetic resonance imaging and biplane angiography measurements, the 2-dimensional calculations of percentage stenosis and the area derived from 3-dimensional reconstruction were assessed using a linear regression analysis. Furthermore, limits of agreement between invasive and non-invasive flow, 2-dimensional- and 3-dimensional-measurements were assessed as described by Bland and Altmann.[8] Statistical analyses were performed using the Wilcoxon-signed-rank-Test for paired data. A statistical significance was stated with a p-value <0.05. For the analysis the software StatView® version 4.02 (Abacus Concepts) was used.

Results

3-dimensional reconstruction versus 2-dimensional imaging

The 2-dimensional- and 3-dimensional-reconstruction could be performed in all examinations. Nevertheless, a fully automatic threshold segmentation from the magnetic resonance angiography data for the 3-dimensional reconstruction was not possible in 20 of the 30 cases at the area of stenosis due to signal loss by turbulences or accelerated flow (Fig. 2d). The comparison of the percentage diameter stenosis calculated by 2-dimensional magnetic resonance imaging with the results of the measurements by biplane angiography showed a good correlation (Fig. 3a), with an r-value of 0.94 for the data available from 23 patients, and a slight but non-significant tendency to higher graded stenosis by magnetic resonance imaging. The mean percentage stenosis was graded 2% higher, with a standard deviation of 7%, as compared to 2-dimensional evaluation by biplane angiography (Fig. 3b). The comparison of the percentage diameter stenosis calculated by 2-dimensional magnetic resonance imaging with the results of the percentage area stenosis calculated by 3-dimensional magnetic resonance imaging (Fig. 3c, d) also showed a good correlation, with an r-value of 0.87 for measurements in all 27 patients. A significantly higher grading of stenosis, with a p-value <0.0001, was obtained when compared to 2-dimensional magnetic resonance imaging or the calculations achieved from biplane angiography. Nevertheless, the linear regression analysis of 2-dimensional evaluation by biplane angiography with 3-dimensional magnetic resonance imaging showed a good correlation, with an r-value of 0.92, but the mean percentage area of stenosis calculated with multiplanar reconstruction was 14% higher, with a standard deviation of 8%, as compared to the proportional stenosis calculated from biplane angiography.

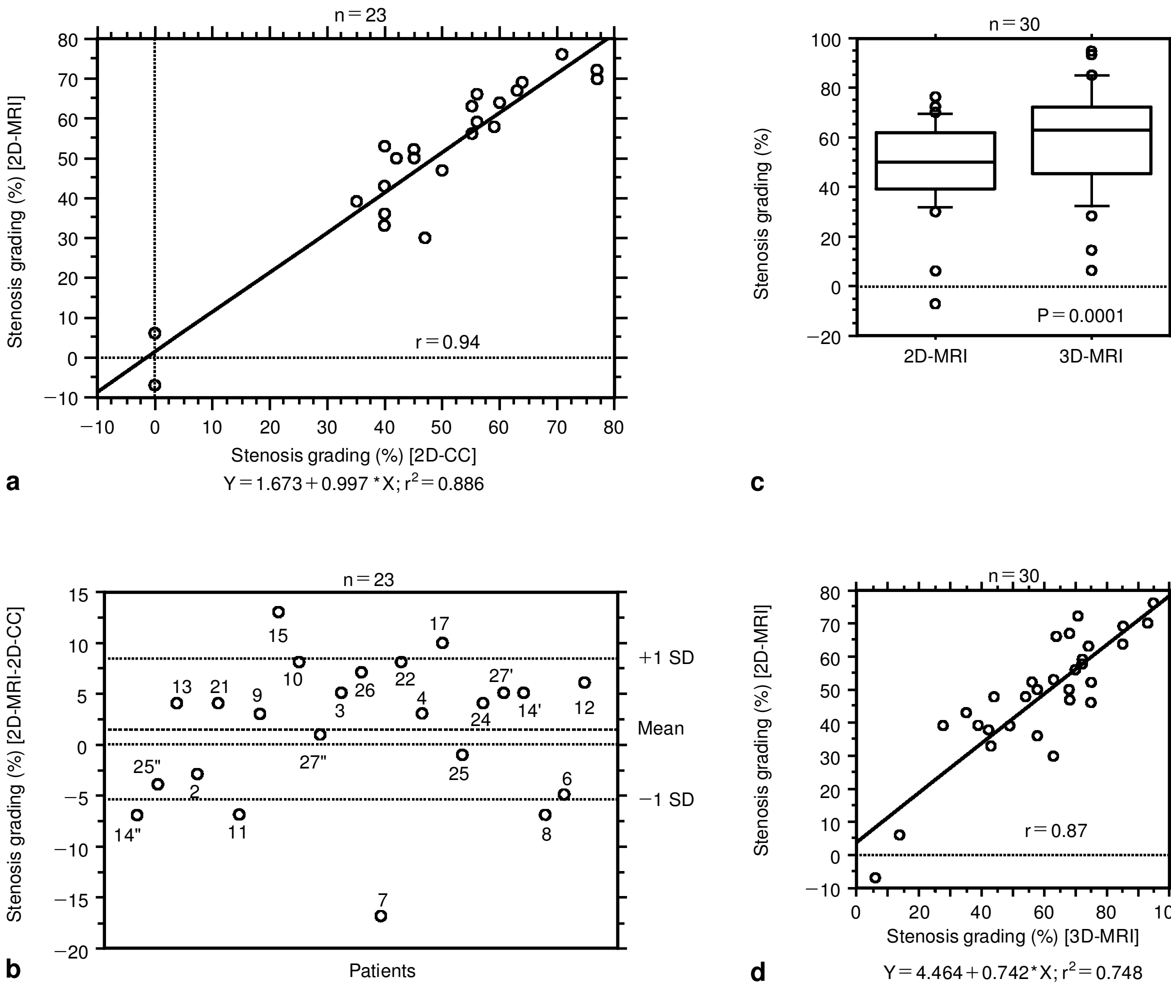

Figure 3.

(a) Linear regression analysis of the two-dimensionally (2D-CC) calculated percentage diameter stenosis from biplane angiography (cardiac catheter – CC) with the two-dimensionally (2D-MRI) calculated percentage diameter stenosis from the magnetic resonance spin-echo images in 23 patients shows a good correlation with an r-value of 0.94. The regression equation was $Y = 1.673 + 0.997X$; $r^2 = 0.886$. (b) To assess the "limits for agreement" (8) the deviation of the difference of the 2D-MRI and 2D-CC diameter measurement from the mean of all measurements was calculated. The mean percentage stenosis graded by 2D-MRI was (SD) 2 (7)% higher as compared to the 2D-CC measurements. That means the limits for agreement of the diameter stenosis measurements were −5% to 9%. The circles for each patient in this diagram are labelled by their patient number in Table 1. (c) The comparison (30 patients) of the box-plots of the 2D-MRI calculations for percentage diameter stenosis versus 3D-MRI calculations for percentage area stenosis show a significant ($p = 0.0001$) higher grading by 3D-MRI of stenosis with a mean value of (standard deviation) 59.6 (21.3)% as compared to a mean value of (standard deviation) 48.7 (18.2)% for 2D-MRI. (d) Nevertheless, the linear regression analysis of 2D-MRI calculation of the percentage diameter stenosis versus 3D-MRI calculation of the percentage area stenosis show a good correlation with an r-value of 0.87.

Measurements of flow

In 2 of the 27 patients with severe and untreated stenosis, with a gradient greater than 80 mmHg, magnetic resonance flow measurements highly underestimated the stenosis, or failed to quantify it due to turbulent flow. In general, the estimated instantaneous pressure gradients calculated by magnetic resonance imaging showed a good correlation as compared to invasively measured peak gradients by cardiac catheter achieved in 22 patients, with an r-value of 0.89 (Fig. 4a–c). The mean difference between both methods was calculated as zero, but with a standard deviation of 11 mmHg (Fig. 4c).

Comparison of flow-measurements and anatomical assessment of severity of stenosis by both methods

In 13 of 30 examinations, collaterals partially bypassing the coarcted aortic segment could be demonstrated by magnetic resonance imaging. In 11 of the

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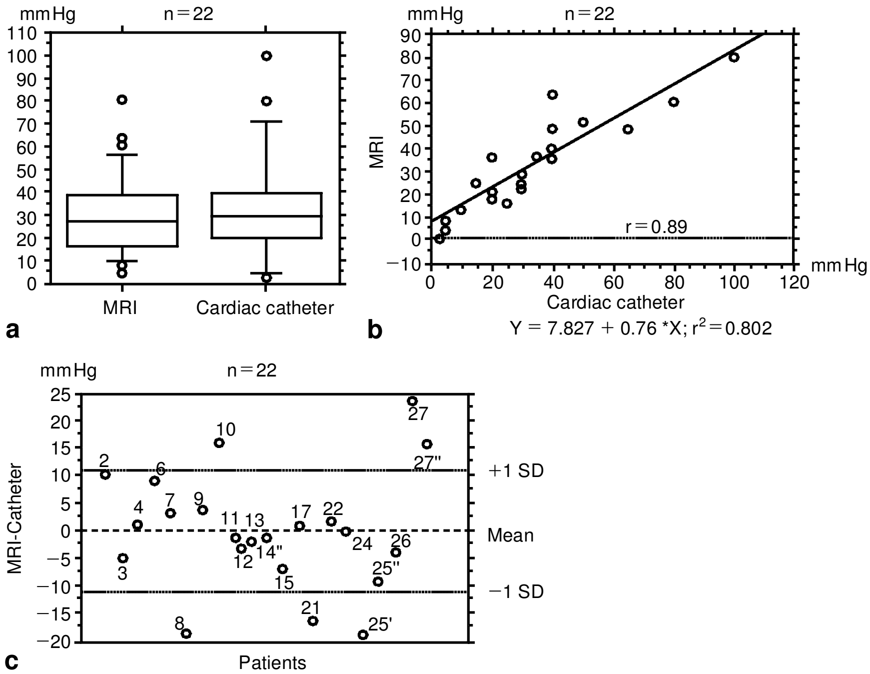

Figure 4.
(a) The box-plot of the estimated pressure gradients by MRI as compared to invasively measured peak-to-peak gradients show a slight underestimation of the peak gradient by magnetic resonance imaging. (b) Linear regression analysis of the estimated peak gradients by magnetic resonance imaging with invasively measured peak-to-peak gradients show a good correlation with an r-value of 0.89. (c) The limits for agreement (22 patients) of the peak gradient measurements were −11 mmHg to 11 mmHg with a mean value for the difference of 0 mmHg. The circles for each patient in this diagram are labelled by their patient number in Table 1.

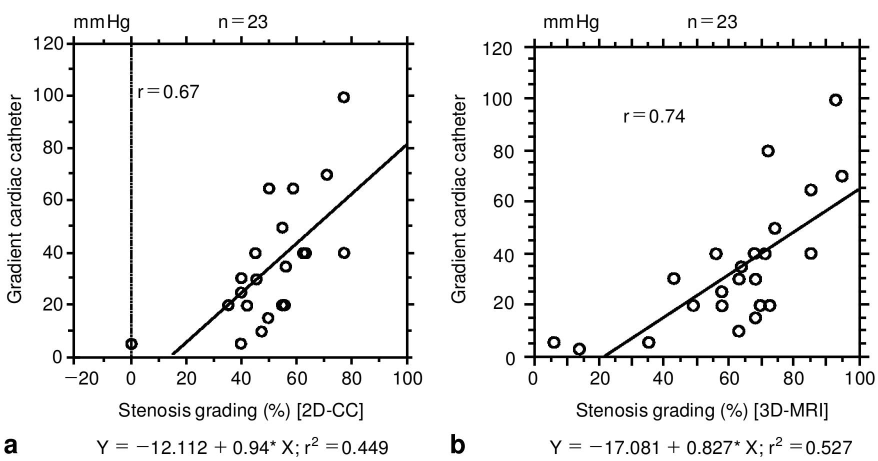

Figure 5.
(a) Linear regression analysis of the 2D-CC grading of percentage diameter stenosis with the invasively measured pressure gradient (23 patients) show only a poor correlation with an r-value of 0.67. The regression equation was $-12+0.94X$; $r^2 = 0.449$. (b) Linear regression analysis of the 3D-MRI grading of percentage area stenosis by multiplanar reformation shows also a poor correlation to invasively measured pressure gradients due to collateral flow with an r-value of 0.74, but better as compared to the 2-dimensional measurements.

examinations, a severe stenosis, with a reduction in cross-sectional area greater than 70% (Table 1), could be detected by multiplanar reformation. Of these 11 patients with severe coarctation, 9 had already developed collaterals. Of these 9, 5 were postoperative and/or postinterventional patients. The geometry of the stenoses showed short fileform stenoses in 2, and kinking in 3. Four of the patients with severe stenoses and collaterals showed an invasively measured gradient below 40 mmHg (Table 1).

The presence of collaterals influenced the correlation between the morphologic grading of stenosis with 3-dimensional-reconstruction and the invasive hemodynamic assessment. The correlation between 2-dimensional magnetic resonance imaging and hemodynamic severity evaluation ($r = 0.67$, Fig. 5a) was less good than the one with 3-dimensional reconstruction ($r = 0.74$, Fig. 5b).

Acquisition time and time for post-processing

The average time for the total examination, including turbo spin-echo sequence, flow-measurements in two-planes and "in-flow" magnetic resonance angiography, was about 45 minutes. The average post-processing time, including flow-measurement and multiplanar reconstruction of the aortic arch was about 30 minutes.

Discussion

Our data shows that the technique of 3-dimensional reconstruction of the aortic arch by resonance imaging using multiplanar reconstruction can offer additional clinically relevant information over conventional 2-dimensional techniques, as it allows better assessment of anatomic severity, even as compared to biplane angiography.

Diagnostic accuracy of detection of coarctation

The golden standard for diagnosis of coarctation or restenosis after treatment has been invasive hemodynamic measurement and biplane angiography during cardiac catheterization.[1] Whereas cross-sectional, in combination with Doppler, echocardiography yields acceptable results in newborns, infants, and young children, it may fail to detect coarctation in up to half of older patients, especially those with a recoarctation.[2,9] Transoesophageal echocardiography in combination with transthoracic Doppler improves the rate of detection, but is invasive and may not be tolerated by every patient.[10] The simple method of measuring a gradient in pressure between arms and legs is, unfortunately, not reliable for diagnosis of the presence of native coarctation or recoarcation in older patients.[2] The correlation between peripheral measurements of blood pressure and the anatomic severity of coarctation is poor, as many patients with recoarction have developed collateral vessels.[11–13] Doppler echocardiography in the descending and abdominal aorta has been found useful in diagnosing the presence of coarctation, but does not yield information about its location, and has limitations in the assessment of the severity. It may occasionally fail in older patients with extensive flow through collateral vessels.[14–16]

As an alternative non-invasive method of evaluation of the aortic arch, resonance imaging is widely used nowadays, and is already considered to represent the golden standard of non-invasive assessment of coarctation and recoarctation of the aorta.[17–19] Measurements of flow, in combination with imaging of anatomy, have further expanded the clinical use of the technique.[20] Cine-magnetic resonance has been proven to be superior to spin-echo techniques in the detection of coarctation.[21] As the coarctation can sometimes be complex, single imaging planes are frequently inadequate for detection of coarctation.[22] The logical development of magnetic resonance imaging has thus been the development of techniques which enable 3-dimensional reconstruction. Initial work had required the use of gadolinium as contrast agent.[23] The advantage of the method used in this study is that no contrast is required, with the disadvantage that, due to the lower signal-to-noise ratio, an automatic threshold segmentation was often not possible. Acquisition of data, therefore, takes more time. Furthermore, young children are often not able to perform breath-hold techniques, which is usually necessary for contrast enhanced magnetic resonance angiography. Our data show that the method of 3-dimensional reconstruction and multiplanar reformation of the aortic arch and the coarctation offers clinically useful information, especially in patients with severe coarctation and collaterals, which make the clinical assessment of coarctation difficult. The grading of the anatomic severity by measurement of effective areas of orifice of the aorta before, at, and beyond the coarcted segment has a much better correlation with hemodynamic measurements, and thus much better reflects the true severity of the lesion. This is independent of the fact whether or not collaterals are present.

Almost one-third of the patients examined in this study were considered to have severe stenosis in 3-dimensional reconstruction. They showed, in the majority, collaterals as an indicator for hemodynamically relevant severe stenoses. The majority of these patients with severe stenoses and collaterals were postoperative and/or postinterventional examined patients with restenosis who might have developed a stenosis with complex geometry due to the operative or interventional procedure, and changes during growth of the child or young adult. Almost half of these patients with severe stenosis and collaterals had an invasively measured peak gradient below 40 mmHg, indicating that, even with invasive procedures, the hemodynamic assessment by calculating or measuring would not be reliable in the setting of severe stenosis.

Although we have not formally studied the assessment of mild versus moderate or severe narrowing, we submit that, especially in milder forms of coarctation in whom clinical decision making is frequently difficult, the method will yield important new information, since it is the true hemodynamic severity of the coarctation which is being assessed. Nevertheless, in severe stenosis, signal void becomes a problem. But it can be identified in the images after multiplanar reconstruction, and corrected by manually outlining the contours of the vessel.[5] In older patients, who are able to hold their breath, contrast enhanced resonance angiography should be performed. Multiplanar reconstruction using automatic contour detection might be successful and less time consuming. But we could show in this study that, even with suboptimal images from an "inflow" angiography data set, the technique of multiplanar reconstruction was able to provide additional information about the hemodynamic severity of coarctation or re-coarctation.

Limitations of the studys

We have not formally compared the reconstructions with measurements obtained at surgery or autopsy. Furthermore, the comparison of "instantaneous" pressure gradients with invasively achieved "peak-to-peak" gradients is problematic, especially in patients with high-grade stenosis, because it is not a comparison of like with like. Nevertheless, this study like others,[24] could demonstrate magnetic resonance imaging measurements of flow are reliable in estimating pressure gradients for mild to moderate stenoses. As with all studies involving magnetic resonance imaging, metal material such as vascular clips near a site of repair limits its use in some patients.[17] The examination is still rather long, and some younger patients may require sedation. At present, the times needed for off-line reconstructions are also long, which currently limits this new method to well-staffed academic centres. Improvements in software and hardware, nonetheless, will rapidly overcome these limitations.

Conclusion

We conclude that the technique of 3-dimensional reconstruction yields important information on the anatomic severity of coarctation. This may aid in decision making regarding interventional procedures, suggesting further clinical applications for the technique.

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References

1 Stern HC, Locher D, Wallnofer K, Weber F, Scheid KF, Emmrich P, Buhlmeyer K. Noninvasive assessment of coarctation of the aorta: comparative measurements by two-dimensional echocardiography, magnetic resonance, and angiography. Pediatr Cardiol 1991; 12: 1–5.

2 Muhler EG, Neuerburg JM, Ruben A, Grabitz RG, Gunther RW, Messmer BJ, von Bernuth G. Evaluation of aortic coarctation after surgical repair: role of magnetic resonance imaging and Doppler ultrasound. Br Heart J 1993; 70: 285–290.

3 Seifert BL, DesRochers K, Ta M, Giraud G, Zarandi M, Gharib M, Sahn DJ. Accuracy of Doppler methods for estimating peak-to-peak instantaneous gradients across coarctation of the aorta: an in vitro study. J Am Soc Echocardiogr 1999; 12: 744–753.

4 Teien DE, Wendel H, Björnebrink J, Ekelund L. Evaluation of anatomical obstruction by Doppler echocardiography and magnetic resonance imaging in patients with coarctation of the aorta. Br Heart J 1993; 69: 352–355.

5 Gutberlet M, Hosten N, Beier J, Rohlfing T, Abdul-Khaliq H, Vogel M, Mäurer J, Venz S, Hetzer R, Lange P, Felix R. Quantification of the degree of a stenosis using multiplanar reformation (MPR) of a Magnetic Resonance Angiography (MRA) data set and 2-dimensional MR images compared with MR flow measurements in patients with coarctation. CARS '99 Proceedings of the 13th International Congress and Exhibition in Paris: 124–128.

6 Hosten N, Gutberlet M, Kühne T, Oellinger H, Vogel M, Bockel T, Bock J, Frank J, Felix R. Cardiac MR flowmetry: experimental validation and results in patients with operated cardiac deficiencies. Fortschr. Röntgenstr. 1998; 168(5): 480–487.

7 Gutberlet M, Venz S, Kahl A, Ehrenstein T, Puls R, Hosten N, Frei U, Felix R. Blood flow quantification in haemodialysis fistulae by phase contrast MR angiography (PC-MRA) in comparison to duplex sonography. Fortschr. Röntgenstr. 1998; 169(2): 163–169.

8 Bland JM, Altmann DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 2: 307–310.

9 Smallhorn JF, Huhta JC, Adams PA, Anderson RH, Wilkinson JL, Macartney FJ. Cross-sectional echocardiographic assessment of coarctation in the sick neonate and infant. Br Heart J 1983; 50: 349–361.

10 Engvall J, Sjoqvist L, Nylander E, Thuomas KA, Wranne B. Biplane transoesophageal echocardiography, transthoracic Doppler, and magnetic resonance imaging in the assessment of coarctation of the aorta. Eur Heart J 1995; 16: 1399–1409.

11 Julsrud PR, Breen JF, Felmlee JP, Warnes CA, Connolly HM, Schaff HV. Coarctation of the aorta: collateral flow assessment with phase-contrast MR angiography. AJR Am J Roentgenol 1997; 169: 1735–1742.

12 Chernoff DM, Derugin N, Rajasinghe HA, Hanley FL, Higgins CB, Gooding CA. Measurement of collateral blood flow in a porcine model of aortic coarctation by velocity-encoded cine MRI. J Magn Reson Imaging 1997; 7: 557–563.

13 Gunthard J, Buser PT, Miettunen R, Hagmann A, Wyler F. Effects of morphologic restenosis, defined by MRI after coarctation repair, on blood pressure and arm-leg and Doppler gradients. Angiology 1996; 47: 1073–1080.

14 Carvalho JS, Redington AN. Shinebourne EA, Rigby ML, Gibson D. Continuous wave Doppler echocardiography and coarctation of the aorta: gradients and flow patterns in the assessment of severity. Br Heart J 1990; 64: 133–137.

15 Guenthard J, Wyler F. Doppler echocardiography during exercise to predict residual narrowing of the aorta after coarctation resection. Pediatr Cardiol 1996; 17: 370–374.

16 Scott PJ, Wharton GA, Gibbs JJ. Failure of Doppler ultrasound to detect coarctation of the aorta. Int J Cardiol 1990; 28: 379–381.

17 Simpson IA, Chung KJ, Glass RF, Sahn DJ, Sherman FS, Hesselink J. Cine magnetic resonance imaging for evaluation of anatomy and flow in infants and children with coarctation of the aorta. Circulation 1988; 78: 142–148.

18 Kaemmerer H, Mugge A, Prokop M, Schirg E, Oelert F, Bahlmann J, Lichtlen PR, Kallfelz HC. Diagnostic imaging in follow-up of surgically treated stenosis of the aortic isthmus in adolescents and adults. Wiener Med Wochenschr 1995; 145: 206–210.

19 Rees S, Somerville J, Ward C, Martinez J, Mohiaddin RH, Underwood R, Longmore DB. Coarctation of the aorta: MR imaging in late postoperative assessement. Radiology 1989; 173: 499–502.

20 Mohiaddin RH, Kilner PJ, Rees S, Longmore DB. Magnetic resonance volume flow and jet velocity mapping in aortic coarctation. J Am Coll Cardiol 1993; 22: 1515- 1521.
21 Riquelme C, Laissy JP, Menegazzo D, Debray MP, Cinqualbre A, Langlois J, Schouman-Claeys E. MR imaging of coarctation of the aorta and its postoperative complications in adults: assessment with spin-echo and cine-MR imaging. Magn Reson Imaging 1999; 17: 37–46.
22 Greenberg SB, Marks LA, Eshaghpour EE. Evaluation of magnetic resonance imaging in coarctation of the aorta: the importance of multiple imaging planes. Pediatr Cardiol 1997; 18: 345–349.
23 Prince MR, Narasimham DL, Jacoby WT, Williams DM, Cho KJ, Marx MV, Deeb GM. Three-dimensional gadolinium-enhance MR angiography of the thoracic aorta. AJR Am J Roentgenol 1996; 166: 1387–1397.
24 Gutberlet M, Boeckel T, Hosten N, Vogel M, Kühne T, Oellinger H, Ehrenstein T, Venz S, Hetzer R, Bein G, Felix R. Arterial Switch Procedure for D-Transposition of the Great Arteries: quantitative midterm evaluation of hemodynamic changes with cine MR imaging and phase-shift velocity mapping – initial experience. Radiology 2000; 214: 467–475.