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Applications of phase-contrast velocimetry sequences in cardiovascular imaging

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KEYWORDS
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Abstract
Aims: To describe and illustrate the main applications of phase-contrast flow quantification in cardiovascular imaging.
Conclusion: Phase-contrast velocimetry sequences provide an accurate, reliable, reproducible and non-invasive study of blood flow, information which is sometimes not available from other investigation methods. The haemodynamic information obtained from these complement MRI angiography images. They appear to have a range of clinical applications, firstly improving pathophysiological understanding but also contributing to the treatment and follow-up strategy after surgical or endovascular treatment.

Technical bases

The role of MRI in the investigation of cardiovascular diseases is now to provide accurate functional haemodynamic information in addition to anatomical findings. Phase-contrast velocimetry MRI sequences (PCV-MRI) examine the loss of phase of mobile protons along a bipolar linear magnetic gradient. Application of the first gradient causes a shift in spin

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phase.This is cancelled out by the second gradient (inverse) for stationary protons. The inverse gradient causes a phase shift ($\Delta\phi$) for mobile spins which is directly proportional to their speed (Fig. 1), whereby:

$\Delta\phi=\gamma GVT^2$

where γ is the gyromagnetic ratio, G is the amplitude of the gradient, V is the proton speed and T is the application time for one of the gradients [1]. The phase shift generated (measured in degrees from -180 to $+180^\circ$) is therefore dependent on the properties of the magnetic gradient and the user must set the coding speed for each type of investigation, in order that the maximum speeds generate a phase shift of close to $\pm 180^\circ$ and therefore a maximal signal. An aliasing effect may develop if the phase shift exceeds 180° (or -180°), in which case the speeds calculated will be over-estimated and flow will appear to be locally reversed. Conversely, excessive coding speeds will increase noise with repercussions on the accuracy of measurements.

PCV-MRI acquisitions may be made in the plane of the flow or in a perpendicular plane, the latter being used for quantification. For accurate measurements the angle between the section plane and the axis of flow must be close to 90°. Two sequences are reconstructed from the raw data: magnitude images which do not provide information about flow speeds (anatomical imaging) and phase images which are coded for flow direction and speed. Synchronisation with the ECG allows velocimetry to be analysed during the different phases of the cardiac cycle.

PCV-MRI also allows pressure gradients (ΔP mmHg) to be measured each side of a stenosis, similarly to Doppler ultrasound but resolving problems of the acoustic window, at the same time reducing the operator-dependency of the investigation. The equation used is the modified Bernoulli equation:

$\Delta P = 4V^2$

in which V is the maximum speed (in m/sec) in the smallest vascular cross-section. The temporal resolution of the sequence must be sufficient in order to correctly identify the peak speed.

The momentary flow rate is obtained by multiplying the mean flow speed by the area of the vessel cross-section. The integral of all of these flows over a cycle multiplied by the heart rate represents the cardiac output. These measures appear to be accurate and provide additional information to conventional morphological sequences, during the same MRI investigation.

Clinical applications

Congenital abnormalities

Coarctation of the aorta

Coarctation, or isthmic stenosis of the aorta, is a congenital stenosis of the isthmus of the aorta at the junction between the transverse and descending aorta, distal to the opening of the left subclavian artery, at the level of the arterial ligament [2]. It is the commonest aortic malformation and in 20% of cases it is diagnosed after childhood. The physiological repercussions of the stenosis can be studied accurately by PCV-MRI. Severity is firstly assessed by measuring the pressure gradient across the stenosis, estimated from the maximum speed using the modified Bernoulli equation (Fig. 2).

Patients suffering from coarctation of the aorta develop a collateral arterial network in order to perfuse regions distal to the stenosis. A large collateral network can invalidate both pressure measurements across the stenosis and the differential limb arterial pressure, which also appears to correlate poorly with the severity of the anatomical obstruction. Collateral vessels can be

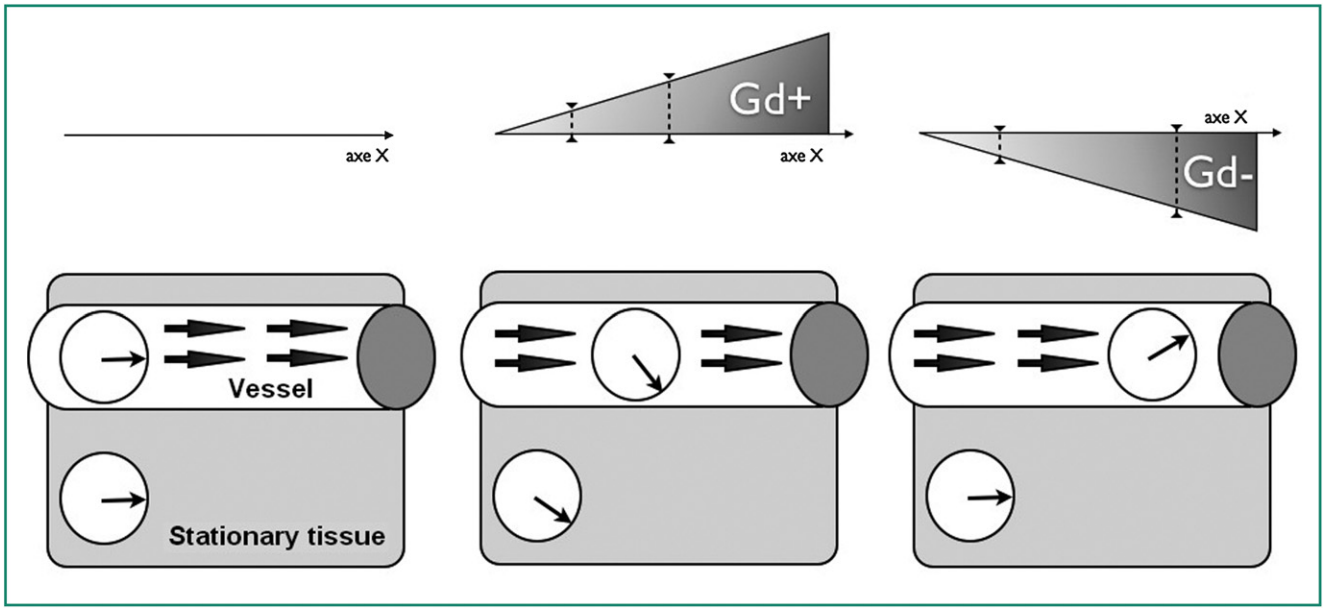

Figure 1. Diagrammatic representation of the principle of phase-contrast velocimetry MRI. When the first phase of the bipolar gradient (Gd+) is applied, spins shift phase depending on their position on the x-axis. When the second, same intensity and duration but reverse polarity, gradient (Gd−) is applied, the phase shift of stationary protons is cancelled out whereas the phase shift of moving protons becomes proportional to their speed.

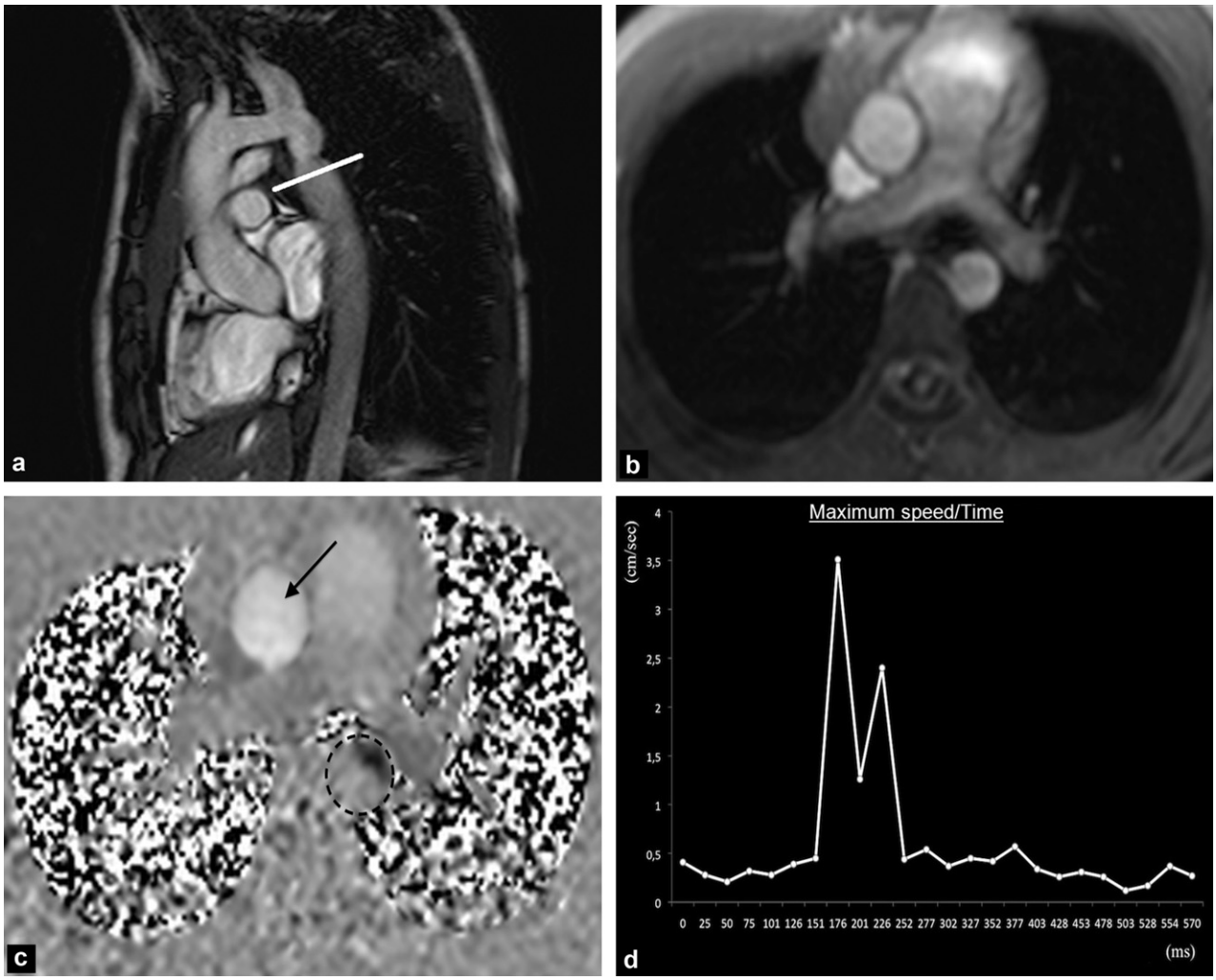

Figure 2. A 25-year-old patient with coarctation of the aortic isthmus: a: Steady State Free Precession (SSFP) cine sequence used to position the PCV-MRI immediately beneath the coarctation (line); b: magnitude imaging; c: phase imaging; the ascending aorta (arrow) contains inferosuperior flow shown in white and the descending aorta (circle) contains a flow in the opposite direction, therefore coded in black; d: graph showing maximum speeds in the post-stenotic aorta, obtained from the region of interest recorded on phase imaging (circle). Maximum speeds are 3.51 m/s, representing a pressure gradient across the stenosis of 49 mmHg using the modified Bernoulli equation.

examined by subtracting the proximal aortic flow (post-stenotic) from the distal flow (at the diaphragm). In a healthy person, proximal aortal flow is slightly greater than distal flow (approximately 7%): in coarctation, the collateral supply is significant if the distal flow is greater than the proximal flow.

A high pressure gradient and large collateral arterial network are factors strongly supporting surgery. Post-treatment follow-up is also performed using flow MRI sequences to investigate for post-angioplasty, stenting or post-surgical restenosis.

Congenital shunts

The severity of congenital heart disease with an abnormal communication between the cardiac chambers can be assessed by calculating the ratio between pulmonary and systemic flow (Q_p/Q_s). This value is obtained from MRI by measuring the flow rates in the pulmonary artery trunk and aorta using a phase-contrast sequence [3]. These are equivalent, with a ratio of close to 1 in a healthy person (Fig. 3). In patients with a right/left shunt (tetralogy of Fallot), the flow in the pulmonary arterial trunk is less than that in the aorta. In patients with an inter-atrial or interventricular communication, flow is greater in the pulmonary artery than in the aorta.

Tetralogy of Fallot

Tetralogy of Fallot is the commonest of the congenital cyanotic heart diseases and makes up almost 8% of all congenital heart disease. The main abnormalities are stenosis of the right ventricular outflow tract and an interventricular communication. MRI is used here after surgical repair. One of the frequent late complications is pulmonary valve insufficiency. In this case the role of PCV-MRI is to quantify the pulmonary regurgitation in order to determine whether valve replacement is indicated before right heart failure develops [4].

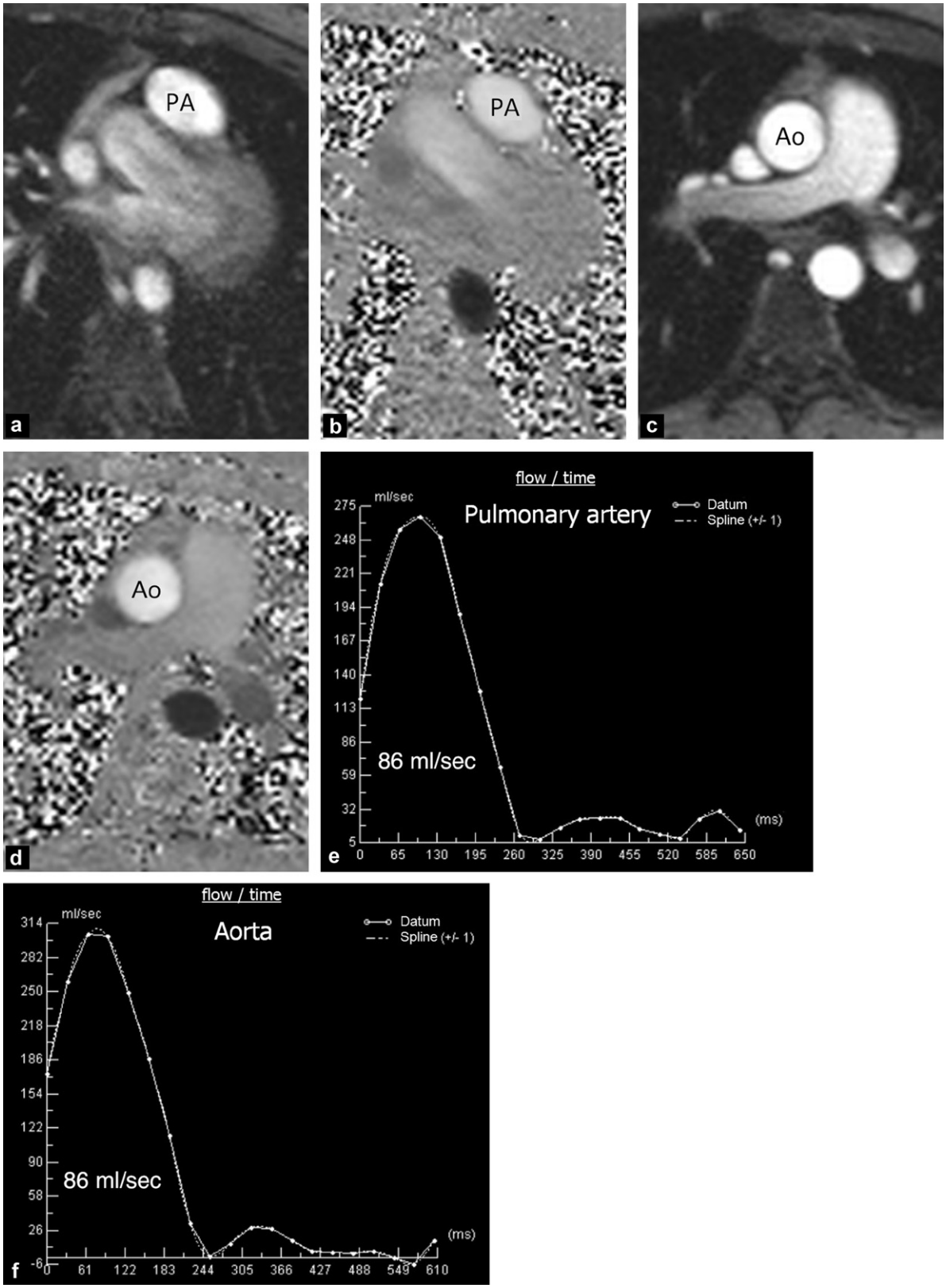

Figure 3. Quantification method for a cardiac shunt. Magnitude imaging (a) and phase imaging (b) in the plane of the pulmonary arterial trunk (PA). Magnitude imaging (c) and phase imaging (d) in the plane of the ascending aorta (Ao). Graph showing flow in the pulmonary artery (e) and in the aorta (f) during the cardiac cycle; the area under the curve is the flow rate during this cycle. The ratio between these flows (Q_p/Q_s) in this healthy subject is 1. In the case of a right-left shunt (tetralogy of Fallot) the ratio is less than 1 and in a left-right shunt (interatrial or interventricular communication) it is greater than 1.

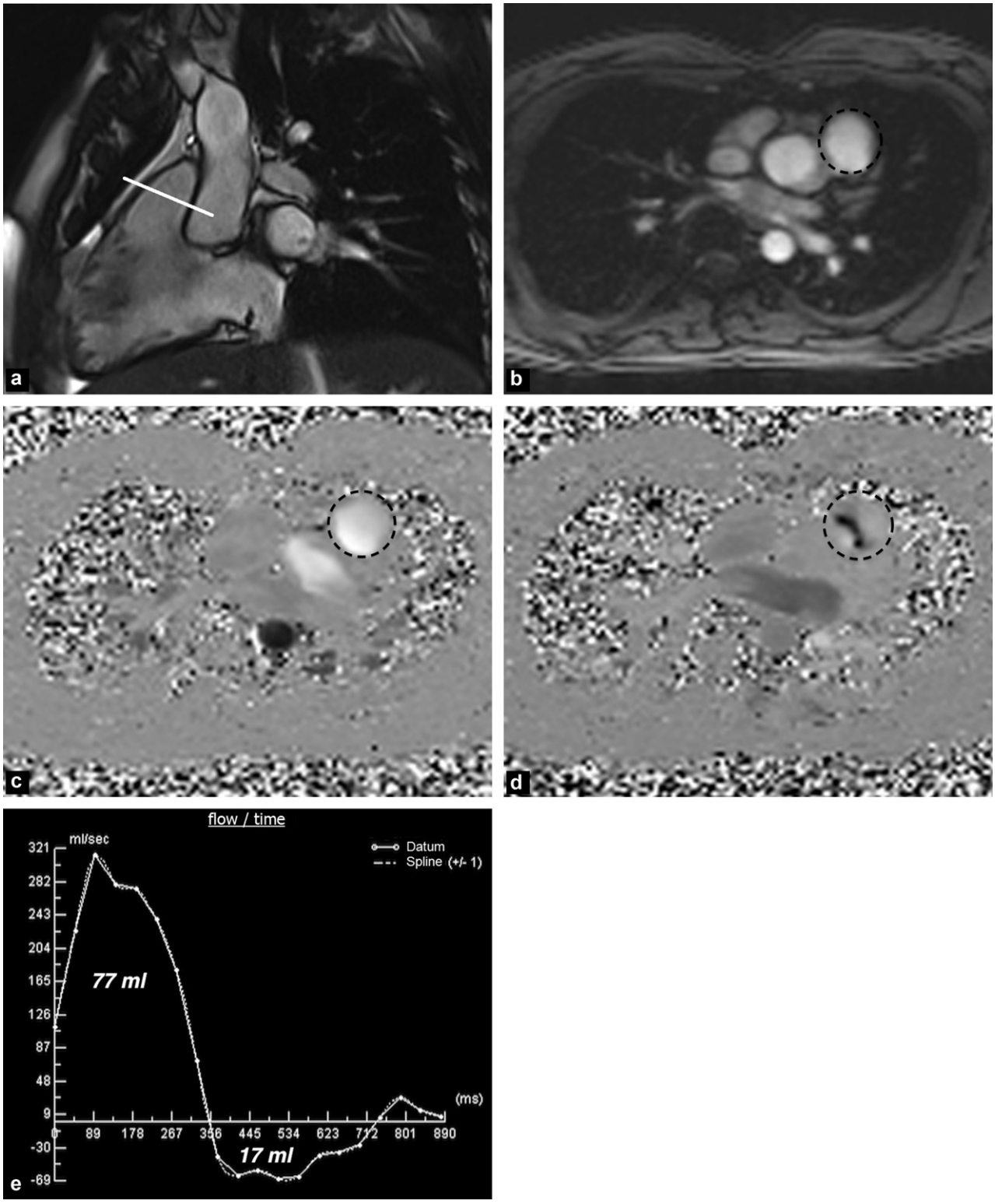

Figure 4. A 39-year-old female patient with a past history of surgery for tetralogy of Fallot 30 years previously; the follow-up ultrasound shows pulmonary valve insufficiency: a: Steady State Free Precession (SSFP) cine sequence used to position the PCV-MRI sections in the plane of the pulmonary valve (line); b: magnitude imaging of the plane of the pulmonary valve (circle); c, d: phase imaging in the plane of the pulmonary valve (circle). During systole (c), the signal is intense, reflecting anterograde flow. During diastole (d), the reduced signal reflects retrograde flow due to regurgitation; e: graph showing pulmonary valve flow during a cardiac cycle; showing anterograde flow of 77 mL and retrograde flow 17 mL representing a regurgitation fraction of 18%.

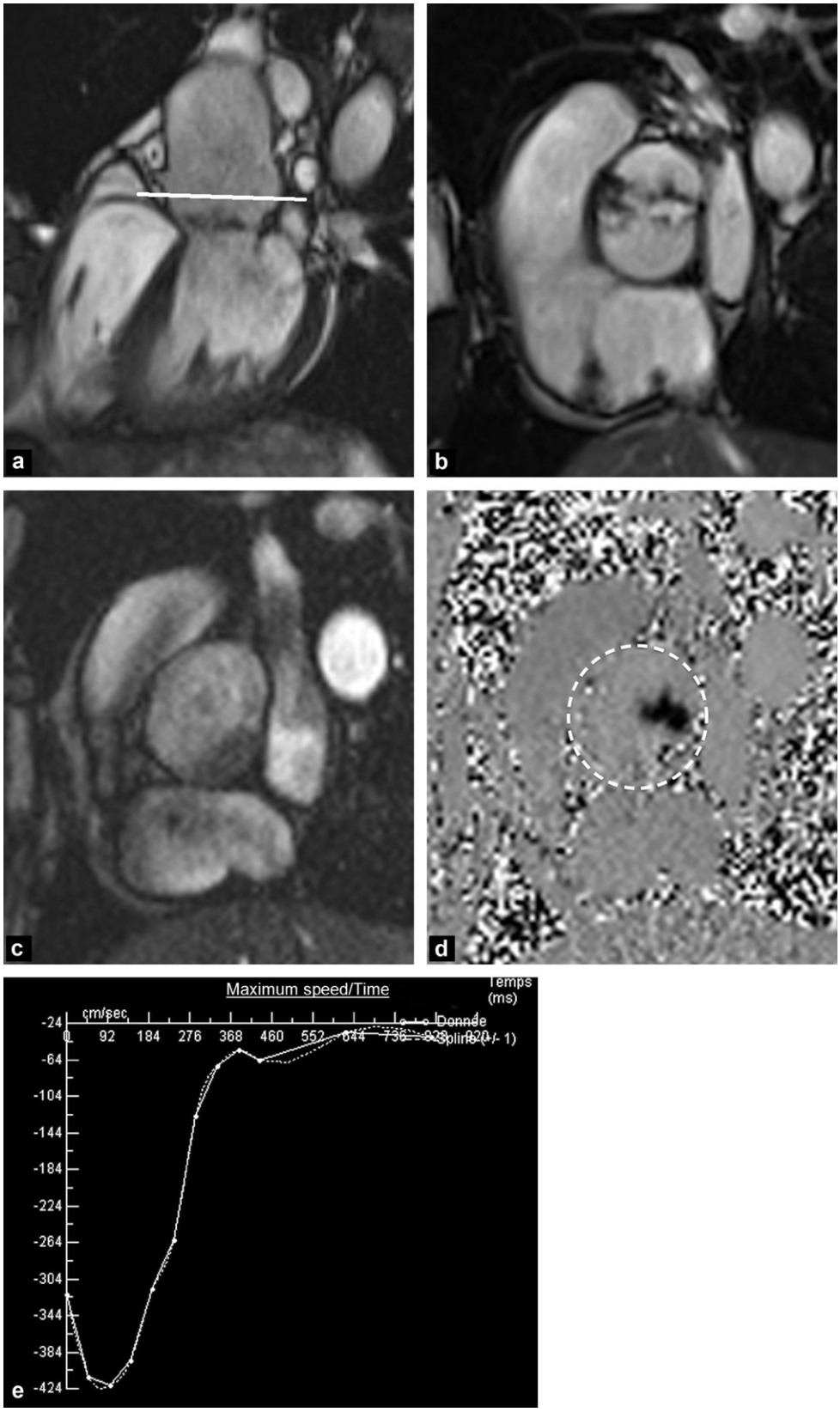

Figure 5. A 61-year-old patient with bicuspid aortic valve stenosis: a: Steady State Free Precession (SSFP) cine sequence used to position the PCV-MRI sections through the sinus of Valsalva (line); b: SSFP cine sequence showing bicuspid valve; c, d: magnitude imaging (c) and phase imaging (d) through the plane of the aortic valve (circle); e: graph showing maximum speeds with peak speed of 4.2 m/s representing a high pressure gradient of 70 mmHg according to the modified Bernoulli equation.

Valve disease

Doppler echocardiography is the fundamental investigation in valve disease although MRI, particularly with flow sequences, can resolve problems of the acoustic window and provide further haemodynamic information in order to assess the severity of the disease [5].

Valve insufficiency

This is assessed from the regurgitation fraction, i.e. the retrograde flow/anterograde flow ratio × 100%. Flow values

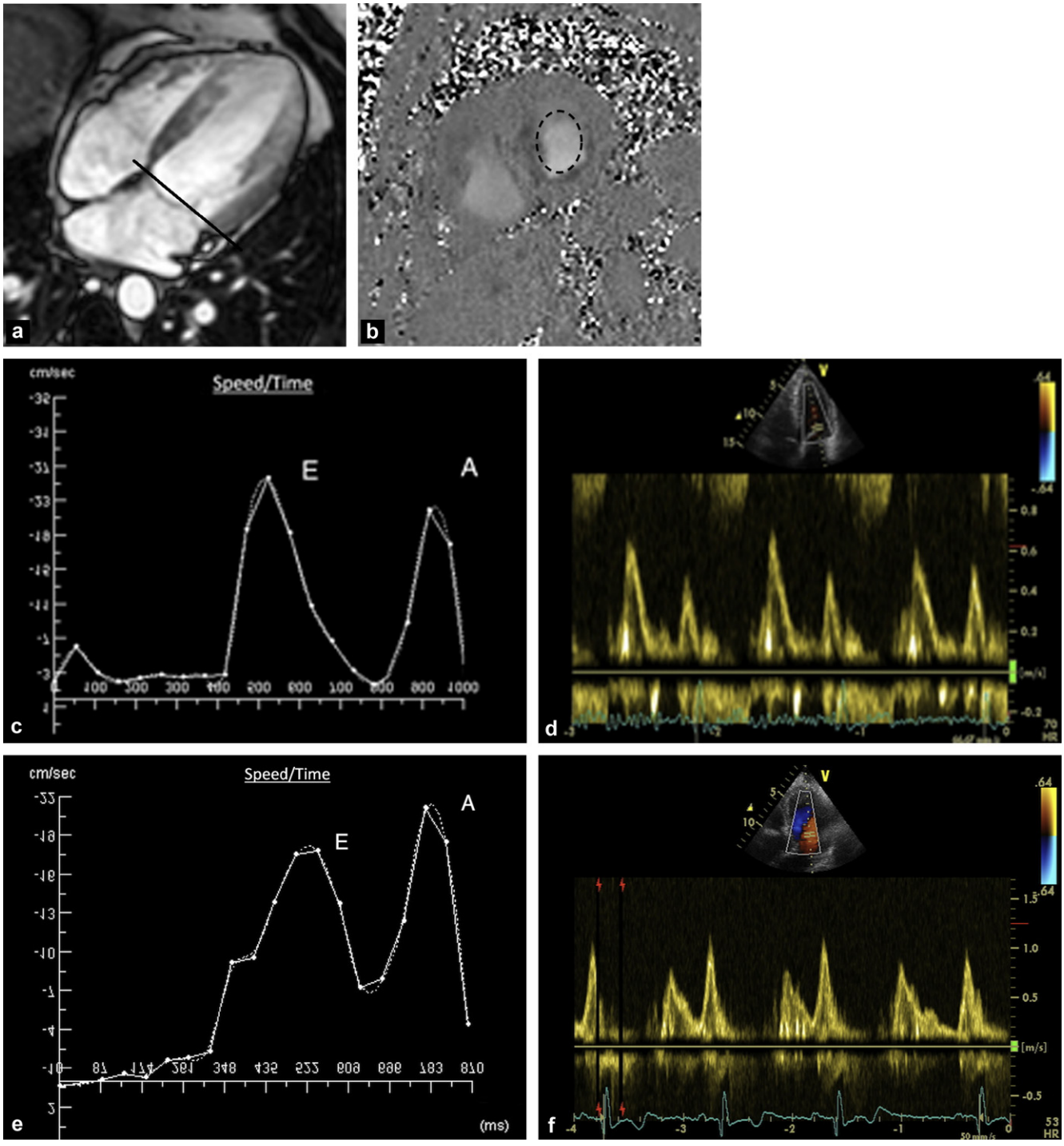

Figure 6. Transmitral flow: a: balanced turbo field echo (BTFE) four cavity sequence used to position the sections in the plane of the mitral valve (line); b: phase imaging through the plane of the mitral valve; c: normal diastolic function: early anterograde wave (E) greater than late wave (A) with an E/A ratio of between 1 and 1.5; d: corresponding transthoracic echocardiogram image; e: abnormal relaxation: reduced early ventricular filling shown by an E wave which is less than the A wave; f: corresponding transthoracic echocardiograph image; g: restrictive profile: E/A ratio greater than 2 generally reflecting high filling pressures; h: corresponding transthoracic echocardiograph image.

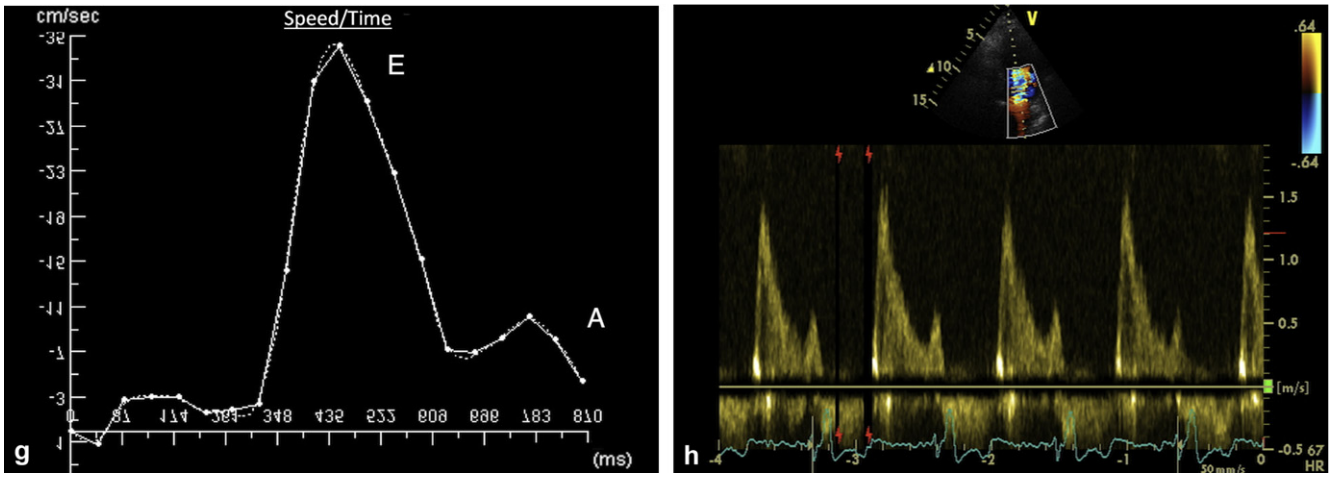

Figure 6. (*Continued*).

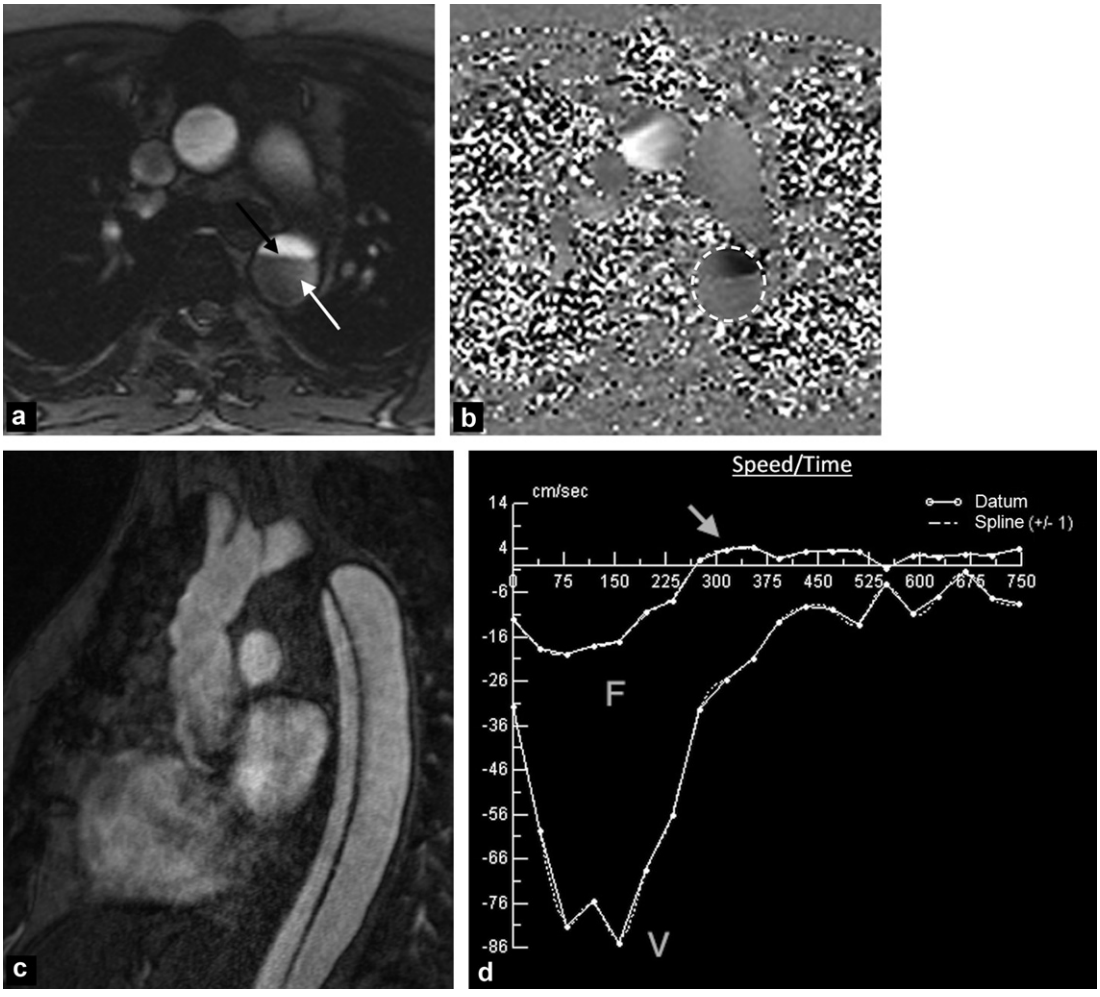

Figure 7. A 41-year-old patient with chronic dissection of the descending aorta: a: axial magnitude image passing through the thoracic aorta showing a true lumen (black arrow) and a false lumen (white arrow); b: axial phase imaging passing through the thoracic aorta (circle); c: 3D MR angiography of the thoracic aorta; d: graph showing mean speeds in the true (V) and false (F) lumens; speeds are higher in the true lumen, and a retrograde component is only found in the false lumen.

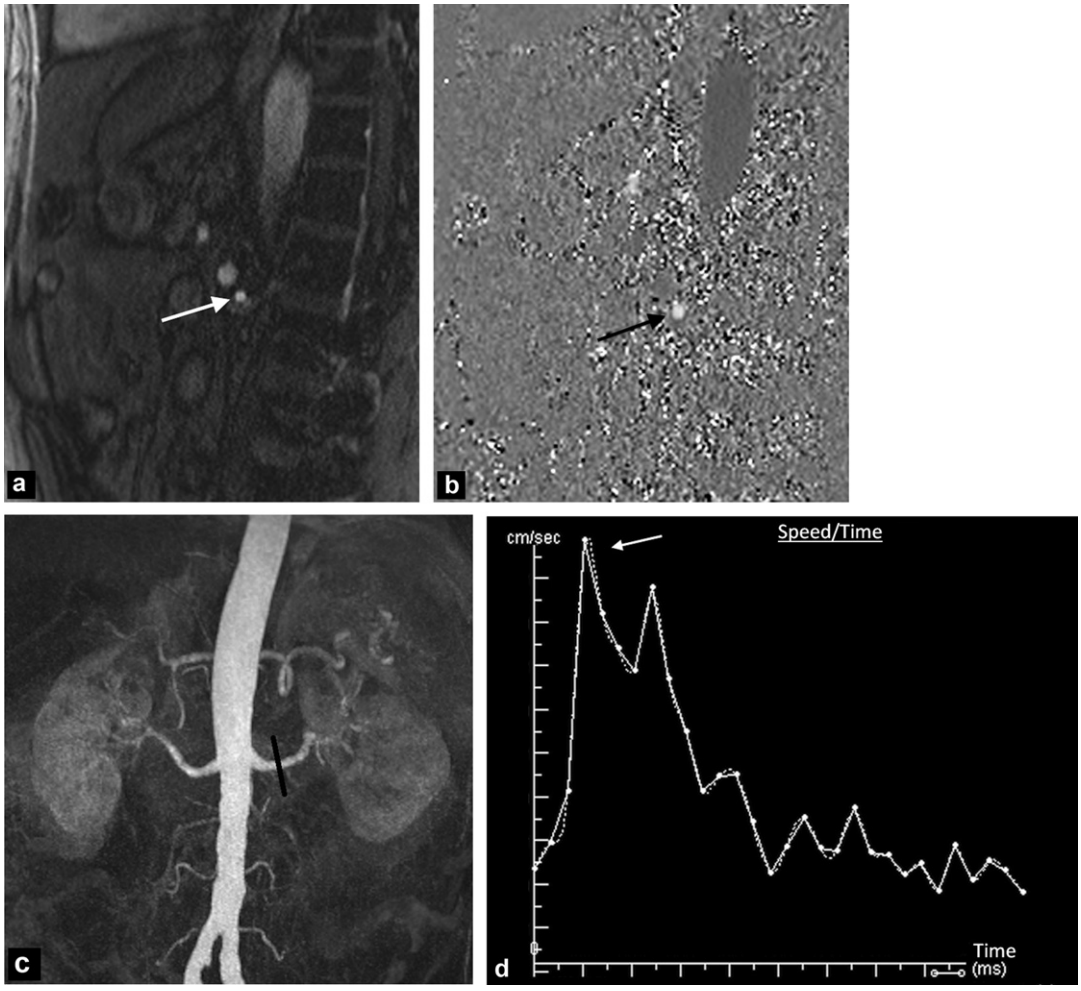

Figure 8. Renal artery investigation method in a hypertensive patient: a, b: magnitude (a) and phase (b) imaging in a plane perpendicular to the axis of the left renal artery (arrow); c: Maximum Intensity Projection (MIP) mode reconstruction of a 3D MR angiogram of the abdominal aorta after gadolinium injection showing no renal stenosis (black line corresponding to the plane of section of the flow sequences); d: graph showing mean speeds in the proximal part of the left renal artery: persistent early systolic peak (arrow) indicating normal renal speeds.

are measured in the sinus of Valsalva and in the pulmonary artery trunk for the aortic and pulmonary valves respectively (Fig. 4). Conversely, this method is difficult to use for the mitral and tricuspid valves as the cross-sectional plane through these valves varies considerably during the cardiac cycle because of the longitudinal contraction movement. Unless the recently developed valve tracking methods (echo navigators) are used, which take sections across the plane of the valve regardless of heart movements, the following equation is used: (Ejection fraction − Anterograde flow)/Ejection fraction × 100%. Anterograde flow is measured using a phase-contrast sequence in the aorta and pulmonary artery respectively and the ejection fractions are calculated by subtracting the tele-systolic volume from the tele-diastolic volume measured on the Steady State Free Precession (SSFP) cine.

Valvular stenosis

The severity of the stenosis is assessed by calculating the pressure gradient across the valve using the modified Bernoulli equation, from measurements of the maximum rate of blood flow (Fig. 5). The acquisitions are made in sections which are parallel and perpendicular to the flow rather than to the vessel and using high coding speeds. The sequences in the plane generally allow the whole abnormal flow jet to be assessed, although there is a risk of error if the flow jet is narrow because of partial volumes or because the flow jet leaves the plane of the section. Conversely, sequences across the flow only investigate a thin section of the jet. These may therefore not contain the maximum speeds if the sections are made too distally or suffer interference by artefacts from turbulent flow if the sections are too proximal. It is therefore useful to take two acquisitions to obtain reliable measurements.

Valve diameter

An indirect measurement of the surface area of the aortic and pulmonary valve openings can be made from the continuity equation. Two acquisitions are made, a first flow sequence at the level of the valve and a second in an adjacent vessel with an easily measurable diameter, such as the aorta. Then, assuming that flow is preserved and is equal to the product of mean speed and the surface area

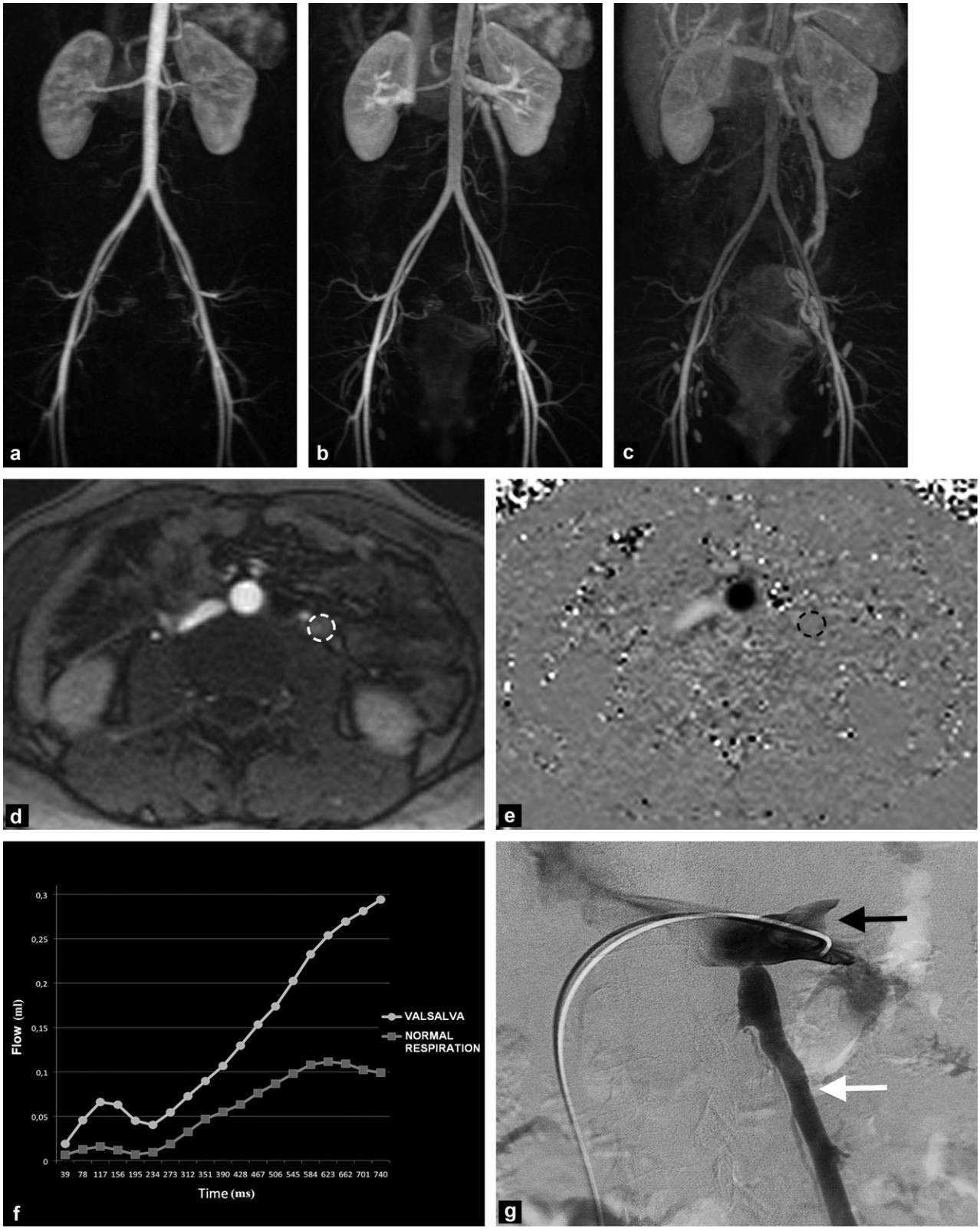

Figure 9. A 30-year-old female patient with a clinical syndrome of pelvic congestion. 4D MR angiography in the early arterial phase (a), late arterial phase showing retrograde opacification of a dilated left ovarian vein (b) and a venous phase showing opacification of peri-uterine varicosities (c). Magnitude (d) and phase (e) imaging in a plane perpendicular to the left ovarian vein (circle). Graph showing mean speeds in the left renal vein in normal respiration and during a Valsalva manoeuvre (f). Venous flow in a cardiac cycle is then doubled increasing from 0.099 mL to 0.195 mL. Left renal vein arteriogram (black arrow) confirming severe reflux in the left ovarian vein (white arrow) (g).

of the vessel section, the valve surface area can then be calculated during the cardiac cycle.

Assessment of cardiac function

Cardiac output

Momentary cardiac output is the product of the surface area of a vessel section and the mean speed of the flow passing through it. The sum of the momentary speeds during systole represents the systolic ejection volume. The systolic ejection volume multiplied by heart rate gives the cardiac output which can be measured very accurately by phase-contrast using a section passing through the root of the aorta for the left ventricle or through the pulmonary artery trunk for the right ventricle [6]. An alternative commonly used to obtain these measurements is SSFP cine sequences, although this investigation is limited in valve insufficiency.

Diastolic function

Left ventricular diastolic dysfunction causing abnormal ventricular filling is considered to be an important pathophysiological factor in many heart diseases. Patients with diastolic heart failure have symptoms of heart failure with a preserved ejection faction. This may precede or accompany systolic dysfunction and is believed to be responsible for at least 50% of cases of heart failure [7]. By measuring flow across the mitral valve, phase-contrast MRI can be used to study the different phases of left ventricular filling [8]. This is genuine flow and not a speed sampled at the centre of the mitral ring as is obtained by Doppler ultrasound. The flow curve obtained contains an E wave (initial rapid filling) and an A wave (atrial systole); the ratio between the E/A peak speeds is between 1 and 1.5. Three abnormalities of flow across the mitral valve have been identified: an E/A ratio of less than 1 reflects abnormal left ventricular relaxation, and an E/A ratio of greater than 2 represents a restrictive profile (Fig. 6) and the third, pseudo-normal profile, is a transition phase between these in which the E/A ratio is normal but the deceleration time is greatly shortened. The particular clinical application of this is for measurement of left ventricular filling pressures. The transmitral flow curve generally shows normal filling pressures if E/A less than 1 and generally high pressures if E/A greater than 2.

Peripheral vascular system

Aortic dissection

PCV-MRI has a role in monitoring chronic aortic dissections in order to assess flow in the false lumen and therefore attempt to predict aneurysmal change and its rate of development [9]. Phase-contrast sequences also have a role in this situation to identify and quantify any aortic insufficiency. Occasionally, in ambiguous cases or if gadolinium injection is contraindicated, analysis of flow profiles can help to distinguish the true from the false lumen (Fig. 7).

Renal artery stenosis

MRI is playing an increasingly important role in the assessment of renal artery stenosis. PCV-MRI is used in particular to identify the loss of the early systolic peak which represents a loss of self-regulation ability and therefore a significant fall in renal blood flow (Fig. 8). Unlike 3D sequences with gadolinium injection, velocimetry can be interpreted even after angioplasty and stenting. Combined use of morphological and functional MRI findings has been shown to increase diagnostic performance and reduce inter-observer variability (with a sensitivity and specificity of more than 95%) [10].

Pelvic congestion syndrome

Pelvic venous incompetence is a common cause of chronic pelvic pain in which the vascular origin must be diagnosed in order to allow endovascular treatment by embolisation, which is generally very effective [11]. Several non-invasive techniques can identify non-specific pelvic varicose dilatations although PCV-MRI both identifies and quantifies the retrograde flow due to valve incompetence (Fig. 9). The role of PCV-MRI in this disease still has to be assessed.

Conclusion

Phase-contrast velocimetry appears to have a wide-range of applications. These sequences provide accurate reproducible haemodynamic information when the acquisition settings and section planes are chosen carefully. They appear to be underused in common practice, partly because of a lack of large series comparing their use with that of conventional methods (invasive or non-invasive).

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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