Michael Hofbeck
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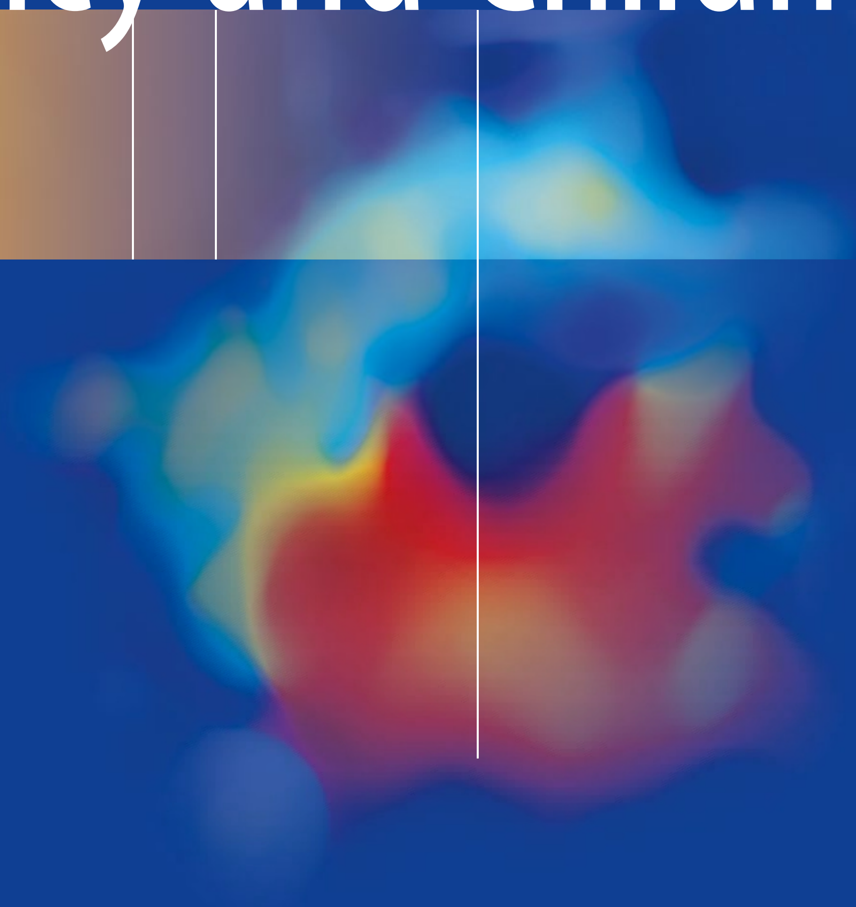
Doppler Echocardiography in Infancy and Childhood



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Preface

Echocardiography is the imaging modality of choice for the diagnosis of congenital heart disease in the neonatal period providing the possibility for exact noninvasive assessment of the majority of cardiac malformations. In addition, functional echocardiography plays an important role in the evaluation of critically ill children in neonatology and intensive care medicine.

This book addresses trainees in paediatric cardiology, paediatricians and neonatologists who are interested in the essentials of paediatric echocardiography. Since also rare cardiac malformations are included, this book should also serve as a valuable tool for professionals who are already skilled in echocardiography.

This book is written by Prof. Dr. Michael Hofbeck, a specialist in paediatric cardiology, and Prof. Dr. K. H. Deeg, a paediatric cardiologist, neonatologist and paediatrician.

The focus of this book is the precise diagnosis of structural congenital heart disease including its haemodynamic assessment. Since colour Doppler, pulsed wave and continuous wave Doppler are integral parts of the haemodynamic assessment of congenital heart disease, these modalities are described extensively for each cardiac malformation. The included videos are intended to allow a better understanding of the temporal and spatial relationships in congenital cardiac and vascular malformations.

The first chapter of this book addresses echocardiography and Doppler examination in the normal heart including examination of the great vessels. Chapters 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22 and 23 contain a detailed description of the different cardiac malformations, while Chaps. 24 and 25 are dedicated to neonatologists and paediatricians, who perform targeted neonatal echocardiography in the setting of a neonatal ICU.

We are aware that paediatric echocardiography is a technique that requires training and practise over a long time period. We hope that our book will serve as a good companion for those who are willing to become familiar with this important and beautiful imaging modality.

Bamberg, Bayern, Germany — Karl-Heinz Deeg
Tübingen, Germany — Michael Hofbeck

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The Normal Examination

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Electronic supplementary material The online version of this chapter (doi:10.1007/978-3-319-42919-9_1) contains supplementary material, which is available to authorized users.

1.1 Introduction

Echocardiography together with the different modalities of Doppler examination has become the most important noninvasive method for assessment of the heart in children (Daubeney et al. 1999; DeGroff et al. 2002; Higgins et al. 1990; Lai et al. 2006; Lai and Mertens et al. 2009; Mertens et al. 2010; Skinner et al. 2000; Snider et al. 1997). It is dependent on the presence of acoustic windows, allowing access of the ultrasound beam to the heart without the interference of air or skeletal structures. In the paediatric age group, echocardiography is greatly enhanced by the fact that the physical conditions and the acoustic windows for examination of the heart are much more favourable than in adults: shorter distances between the body surface and the heart and great vessels allow the application of high frequency transducers with excellent resolution in neonates and infants. In addition the subcostal window provides excellent conditions to visualize the heart in infants and children (Fig. 1.1). The precordial window is significantly larger in children due to less hyperinflation of the lungs and incomplete calcification of the sternum in young infants. Furthermore the large thymus gland in neonates and infants enlarges the acoustic window to the great vessels from the suprasternal and high parasternal views.

The following chapter provides an introduction into the different planes for two-dimensional and Doppler echocardiography and into the basics of colour Doppler and pulsed wave and continuous wave Doppler examination of the heart.

1.2 2D Echo and Colour Doppler Echocardiography

1.2.1 Parasternal Views

These views are obtained by placement of the transducer in the third left intercostal space close to the sternum (Fig. 1.2). For the *parasternal long-axis views*, the plane is oriented

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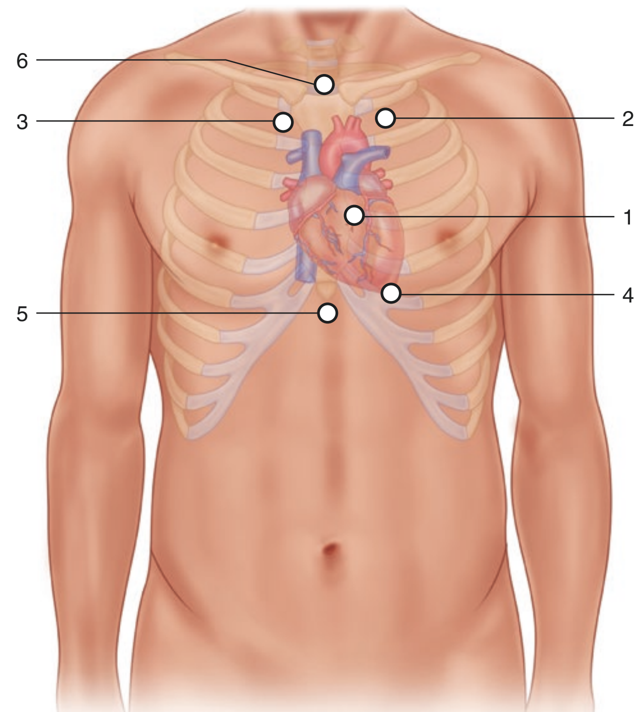


Fig. 1.1 Diagram depicting echocardiographic windows in children including the parasternal *1*, high left parasternal *2* and high right parasternal *3*, the apical *4*, subcostal *5* and suprasternal *6* windows

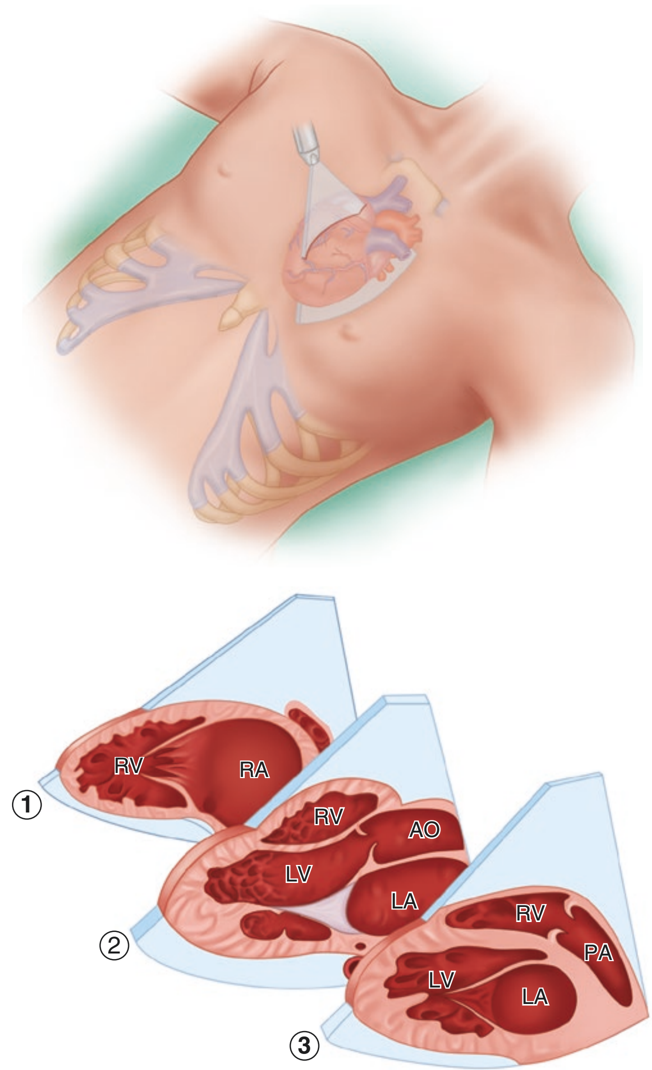


Fig. 1.2 Parasternal long-axis views with planes of the right ventricular inflow *1*, left ventricle *2* and right ventricular outflow tract *3*. *RV* right ventricle, *RA* right atrium, *LV* left ventricle

along the major axis of the heart with an external orientation from the patient's left hip to the right shoulder (Lai et al. 2006; Lai and Ko 2009; Snider et al. 1997).

The standard parasternal long axis displays a longitudinal section of the left ventricle and its outflow tract. The aortic valve and the mitral valve are depicted in the centre of the image displaying fibrous continuity between the anterior leaflet of the mitral valve and the posterior wall of the aortic root (Fig 1.3, Video 1.1). This plane is useful for the colour Doppler interrogation both of the aortic and of the mitral valves (Fig. 1.3b, c). While the angle of insonation is not really favourable for pulsed wave or continuous wave Doppler interrogation, the high velocities encountered in stenosis or leakage of aortic or mitral valve allow detection of regurgitant or turbulent flow in this plane. In the presence of aortic stenosis, accelerated flow and turbulence will be noted in the ascending aorta, and in the presence of aortic insufficiency, the regurgitant jet will be depicted in the left ventricle.

Tilting of the transducer towards the patient's right hip brings into view the parasternal long axis of the right ventricular inflow (Lai et al. 2006; Lai and Ko 2009; Snider et al. 1997) (Video 1.2). This plane shows the tricuspid valve with its inferior and anterior leaflet as well as the coronary sinus draining into the right atrium (Fig. 1.4, Video 1.3). Colour Doppler examination in this plane allows interrogation of the right ventricular inflow and verification of tricuspid regurgitation. In the presence of tricuspid regurgitation, PW and CW Doppler can be employed for quantification of the velocity of the regurgitant jet.

Back to the standard parasternal long axis of the left ventricle, tilting of the transducer in the opposite direction towards the patient's left shoulder opens the right ventricular outflow tract and the main pulmonary artery (Fig. 1.5, Video

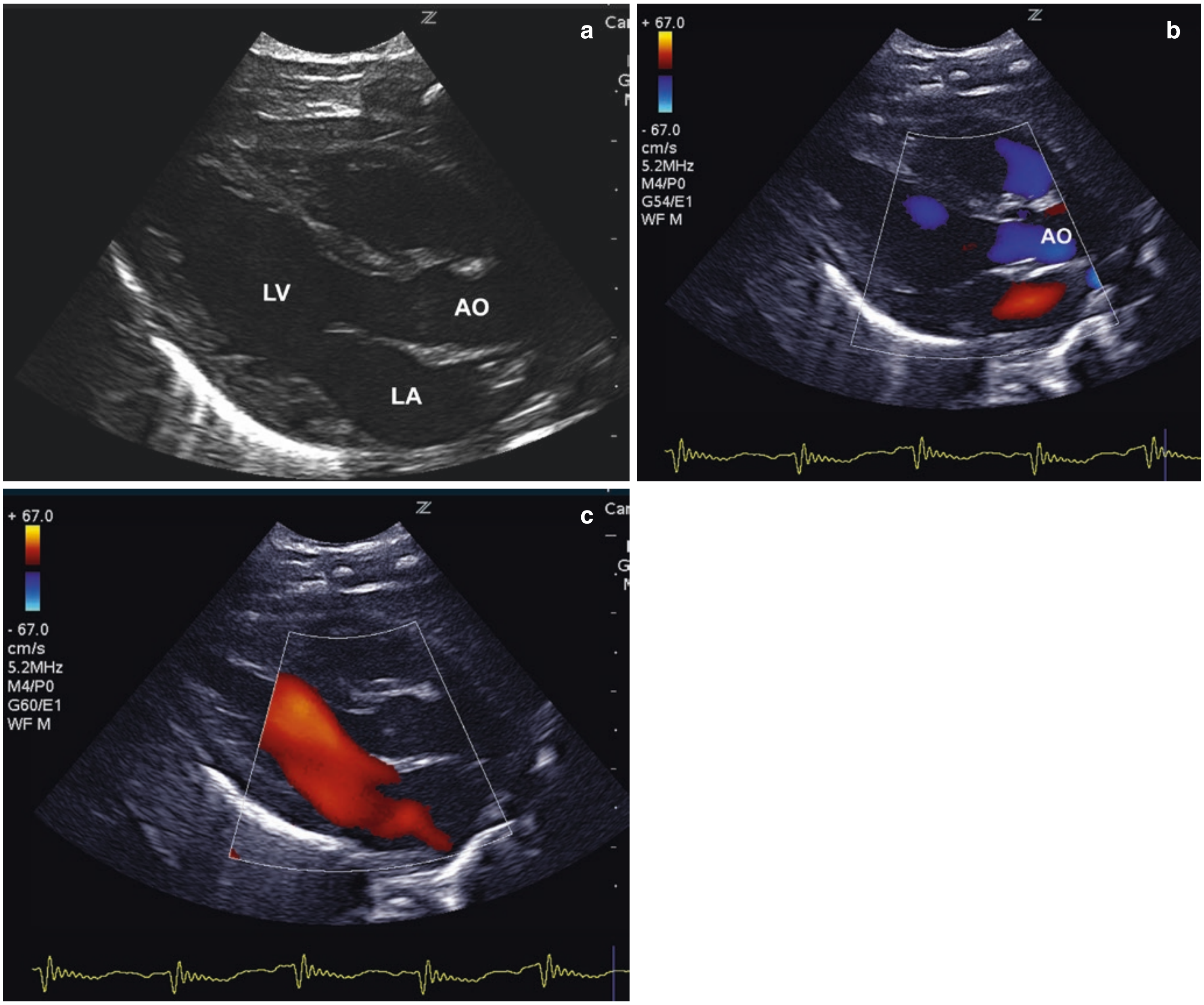


Fig. 1.3 Parasternal long-axis view of the left ventricle (*LV*) showing the inflow and the outflow tract (**a**). The left atrium (*LA*) is displayed behind the aorta (*AO*). Colour Doppler examination shows forward flow in the aorta during systole (**b**) and forward flow across the mitral valve during diastole (**c**)

1.4). Due to the favourable angle of insonation, this plane is well suited for colour Doppler and continuous and pulsed wave Doppler interrogation of the right ventricular outflow tract, the pulmonary valve and the main pulmonary artery (Videos 1.5 and 1.6).

The *parasternal short-axis views* are obtained by 90° clockwise rotation of the transducer from the parasternal long-axis view of the left ventricle (Fig. 1.6). This results in a scanning plane oriented from the patient's right hip to the left shoulder (Snider et al. 1997). Tilting of the transducer offers a family of different short-axis planes from the base of the heart to the apex (Lai et al. 2006; Lai and Ko 2009; Snider et al. 1997). The parasternal short-axis view of the base of the heart depicts the aortic valve in the centre of the image (Video 1.7). This plane allows visualization of the aortic valve cusps and their respective sinuses as well as the origin of the coronary arteries (Fig 1.7). The left atrium is displayed behind the aorta. Furthermore it shows the connection of the right atrium to the right ventricle, the right ventricular outflow tract, the pulmonary valve and the main

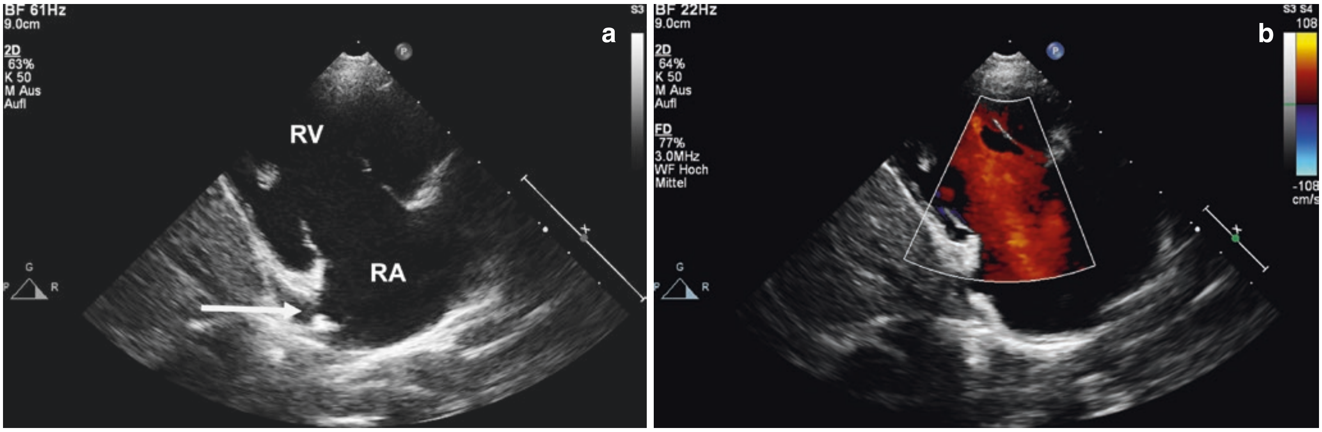


Fig. 1.4 The parasternal long-axis view of the right ventricular inflow displaying right atrium (RA), right ventricle (*RV*), the coronary sinus (*arrow*) and tricuspid valve (**a**); colour Doppler shows diastolic inflow into the right ventricle (**b**)

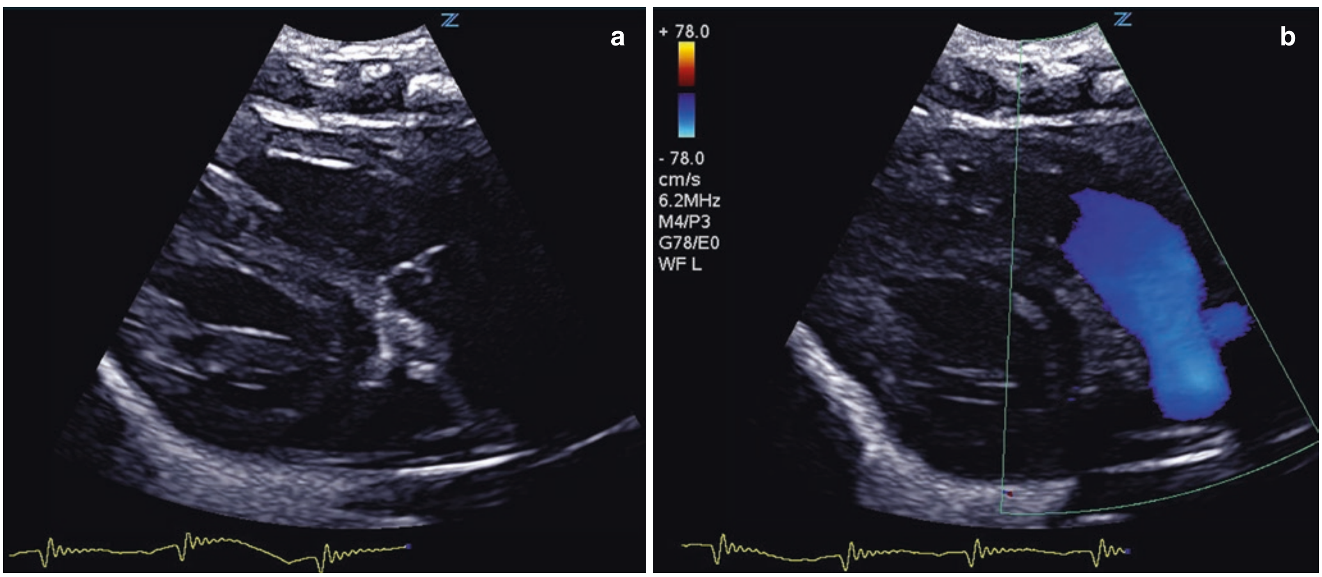


Fig. 1.5 The parasternal long-axis view of the right ventricular outflow tract shows the transition of the right ventricular outflow tract to the main pulmonary artery and the pulmonary valve (**a**); colour Doppler displays systolic flow in the main pulmonary artery in blue (**b**)

pulmonary artery (Video 1.8). This plane allows colour Doppler interrogation of the tricuspid valve, the right ventricular outflow tract and the pulmonary valve (Fig. 1.7 b, c). A sweep starting from this plane down to the apex of the heart displays the left ventricle in cross section and the different parts of the ventricular septum. Standardized planes are obtained at the level of the mitral valve leaflets and the papillary muscles (Figs. 1.8 and 1.9, Videos 1.9 and 1.10). Colour Doppler examination performed in this sweep from the base to the apex is extremely important in the search for ventricular septal defects.

Cranial tilt of the transducer starting from the plane across the base of the heart displays the left atrium and the pulmonary veins (Fig. 1.10, Video 1.11). Colour Doppler examination in this plane confirms a normal connection of the pulmonary veins to the left atrium. Pulmonary venous flow can be confirmed by pulsed wave Doppler interrogation of the different veins. Slightly cranial tilt of the transducer shows the main pulmonary artery, the pulmonary bifurcation and the right pulmonary artery in longitudinal section (Fig. 1.11. Video 1.12).

Counterclockwise rotation of the transducer in a high left parasternal position with the transducer notch at 12 o'clock displays the transition of the main pulmonary artery to the left pulmonary artery (Lai and Ko 2009). The distal aortic arch, the aortic isthmus and the proximal descending aorta

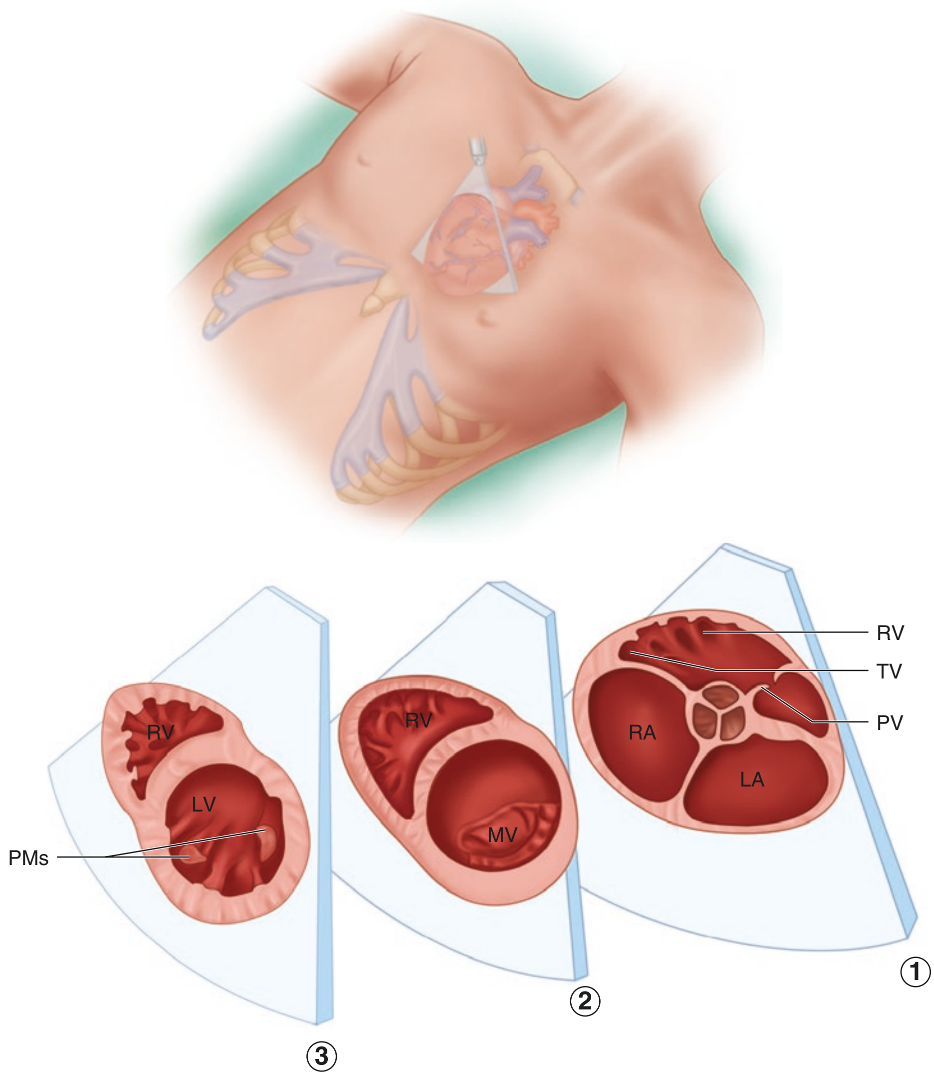


Fig. 1.6 Diagram displaying the parasternal short-axis views of the base of the heart *1*, the mitral valve *2* and the left ventricle in cross section *3*. *MV* mitral valve, *PM* papillary muscle

are displayed behind the left pulmonary artery (Fig. 1.12). On colour Doppler examination, both flow in the left pulmonary artery and in the descending aorta is directed away from the transducer and therefore displayed in blue. This plane, called "ductal view", is ideal for colour Doppler confirmation of patent ductus arteriosus, since flow entering the pulmonary artery via a patent duct is directed towards the transducer and therefore coded red (Lai and Ko 2009). Due to the favourable insonation angle, flow velocities across the ductus can be quantified by application of pulsed or continuous wave Doppler. Beyond infancy this plane frequently requires placement of the patient in a rather steep left lateral decubitus position.

Placement of the transducer close to the sternum in the second right intercostal space displays the *right parasternal views* (Lai et al. 2006; Lai and Ko 2009). A sagittal orientation of the ultrasound beam with the notch of the transducer at 12 o'clock allows visualization of the superior caval vein and its connection to the right atrium (Fig. 1.13). The right pulmonary artery is displayed behind the caval vein in cross section. Medial tilt of the transducer shows the ascending aorta (Fig. 1.14). This plane offers a good insonation angle for evaluation of flow across the aortic valve and can be employed for PW or CW Doppler assessment of systolic flow velocities in patients with aortic valve stenosis. In older children, this is facilitated by positioning the patient in a right lateral decubitus position (Lai and Ko 2009). A 90° clockwise rotation from the right parasternal sagittal view, bringing the notch of the transducer in the position of 3 o'clock, displays the innominate vein and its connection to the caval vein

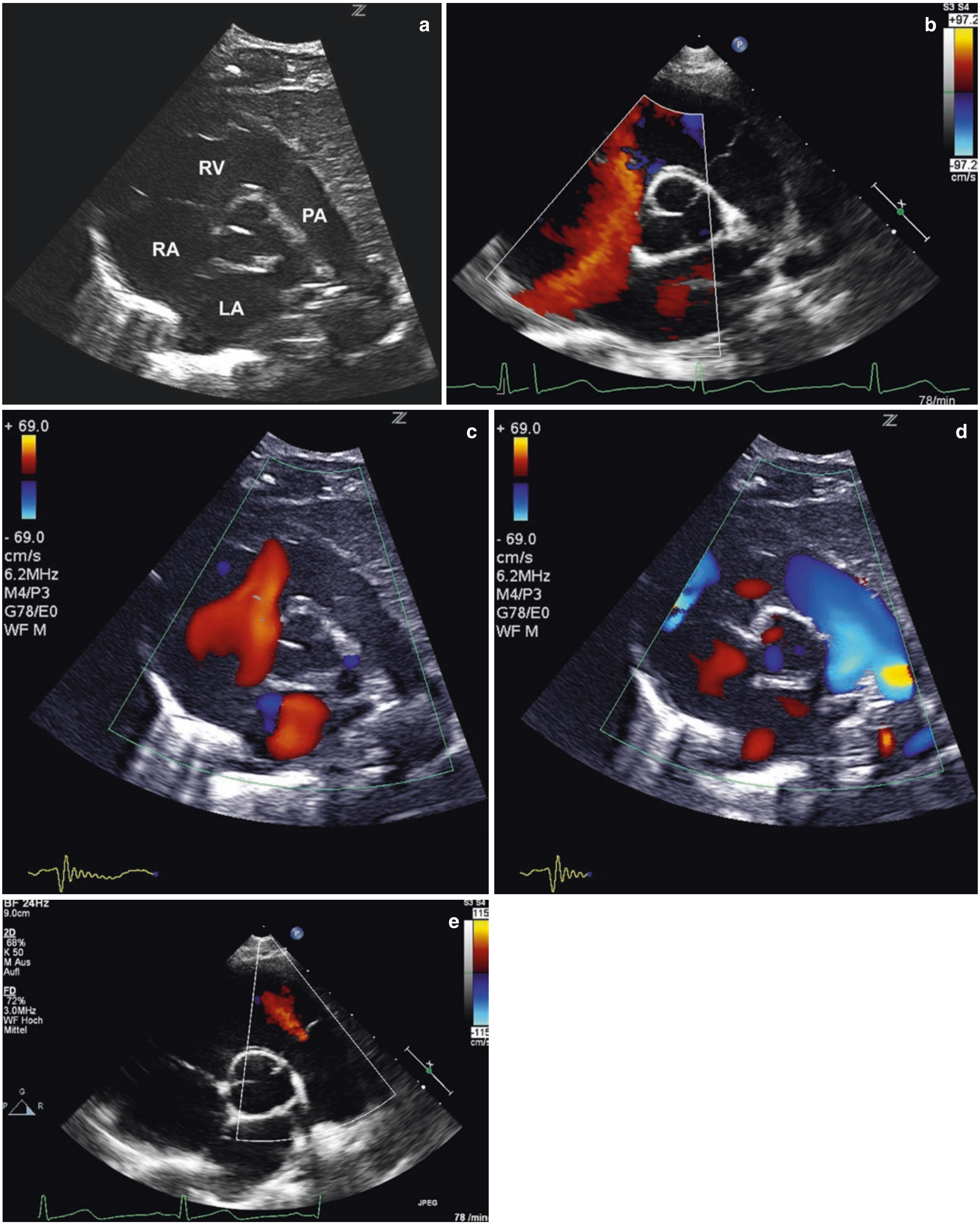


Fig. 1.7 The parasternal short axis at the base of the heart (**a**) shows the aortic valve with its three cusps in cross section, surrounded by the left atrium (*LA*), right atrium (*RA*), right ventricle (*RV*) and pulmonary artery (*PA*); colour Doppler displays venous inflow into the RA from the inferior vena cava (**b**), diastolic inflow into the right ventricle across the tricuspid valve (**c**) and systolic outflow into the main pulmonary artery (**d**). Minor pulmonary regurgitation is present in many normal children (**e**)

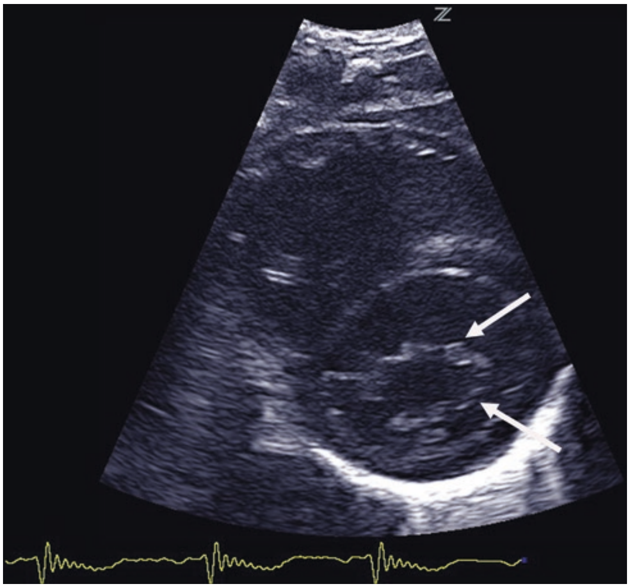


Fig. 1.8 Parasternal short axis of the left ventricle at the level of the mitral valve showing the anterior and posterior mitral valve leaflets (*arrows*)

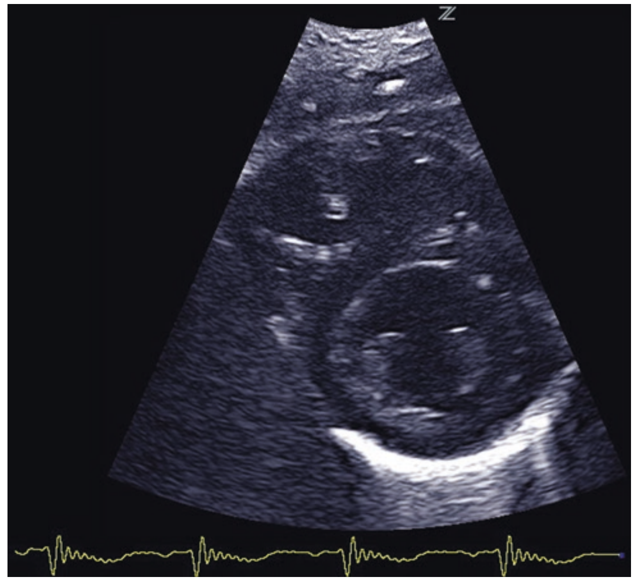


Fig. 1.9 Parasternal short axis of the left ventricle at the level of the papillary muscles

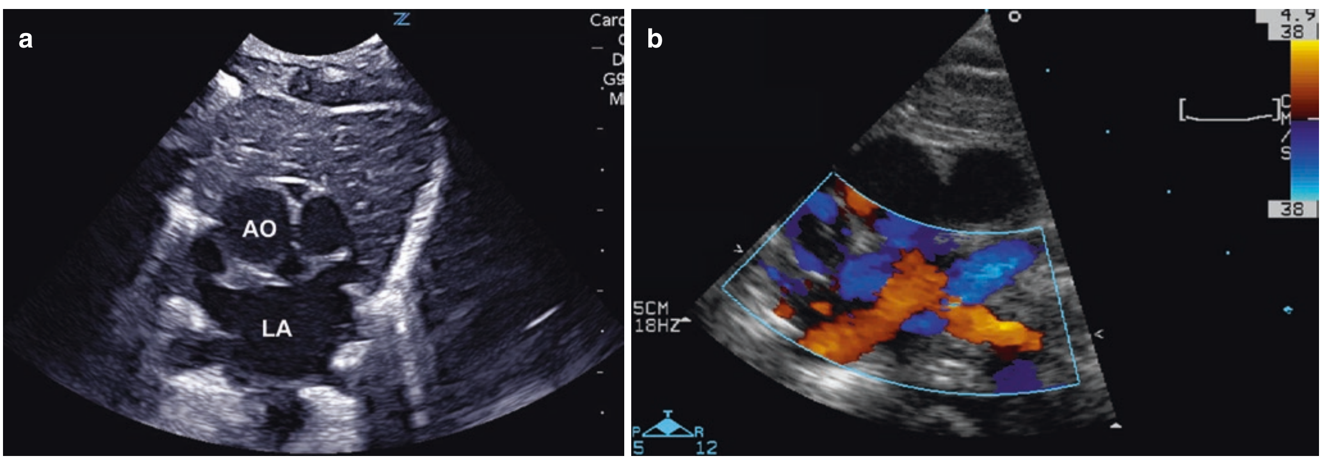


Fig. 1.10 Parasternal short axis cranial to the base of the heart (**a**) showing the left atrium (*LA*) and the pulmonary veins behind the aorta (*AO*). Colour Doppler in this view shows both upper and lower pulmonary veins entering the left atrium (**b**)

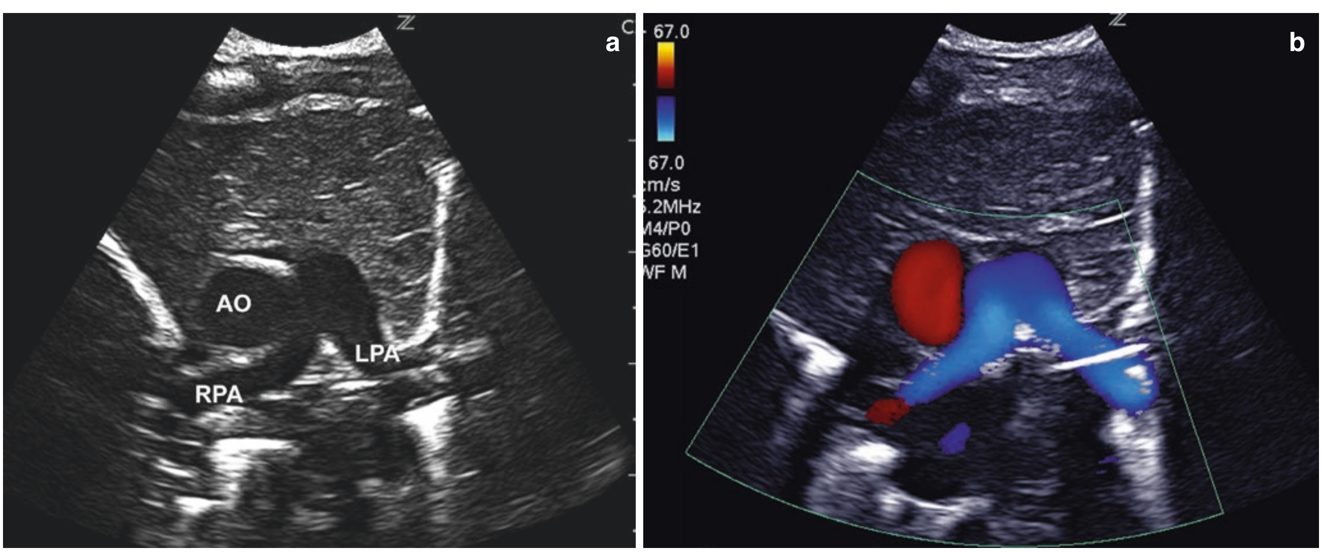


Fig. 1.11 Parasternal short axis of the pulmonary bifurcation depicting the aorta (*AO*) in cross section and right (*RPA*) and left (*LPA*) pulmonary artery (**a**); colour Doppler reveals systolic flow to both pulmonary arteries (**b**)

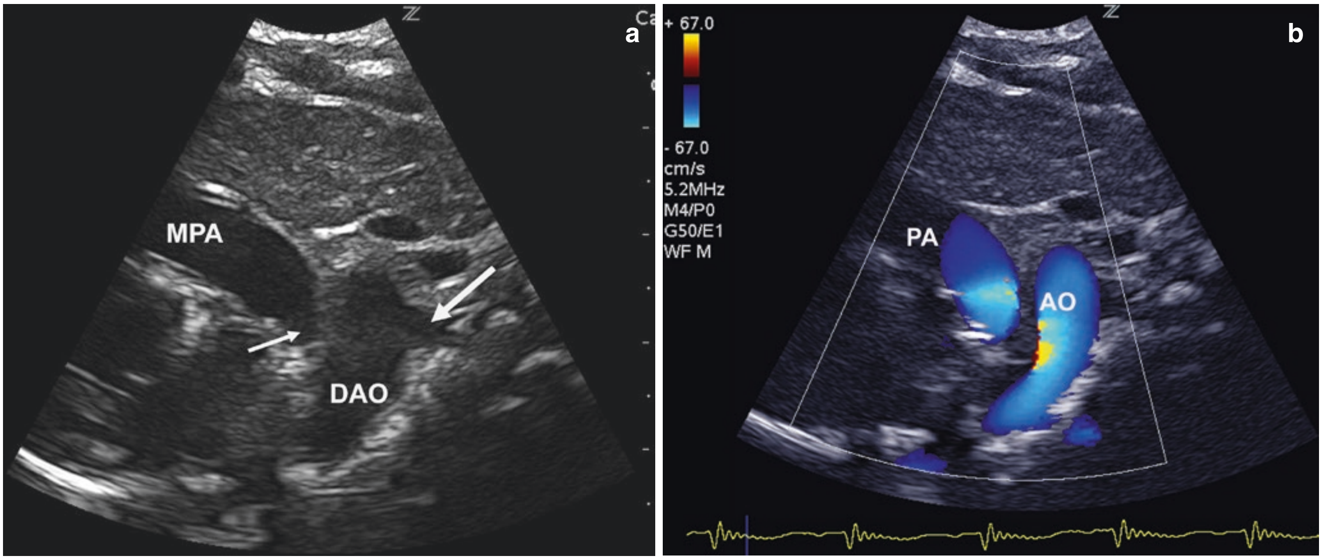


Fig. 1.12 "Ductal view" obtained from a high left parasternal window (**a**) displaying the main pulmonary artery (*PA*) with its transition into the left pulmonary artery (*small arrow*) and the distal aortic arch (*DAO*) with the left subclavian artery (*large arrow*). Colour Doppler in the ductal view reveals antegrade flow to the left pulmonary artery and in the distal aortic arch (**b**)

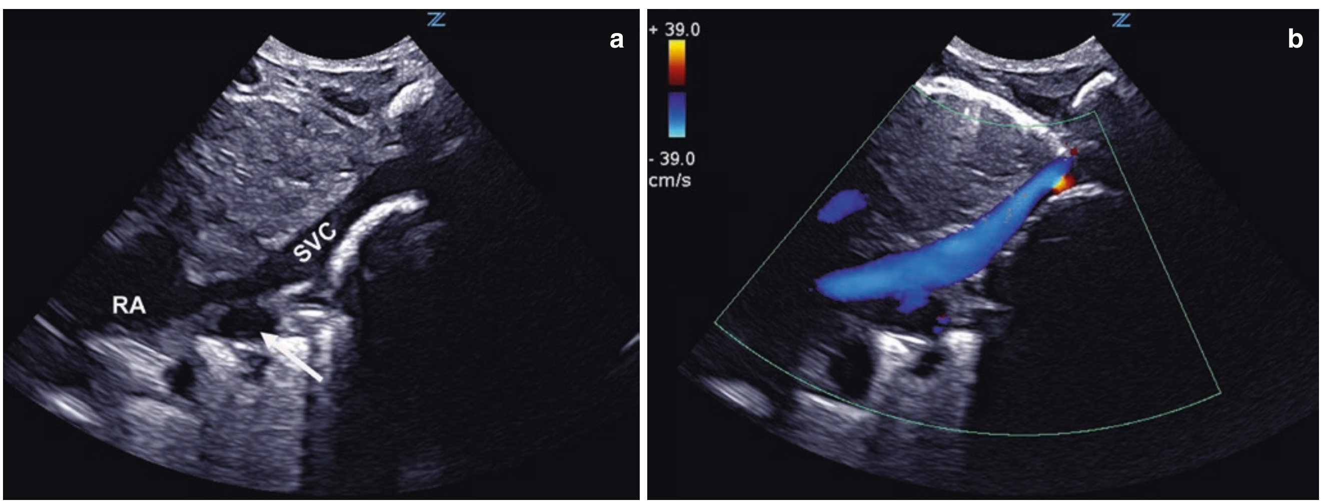


Fig. 1.13 The high right parasternal longitudinal view (**a**) shows the superior vena cava (*SVC*) draining into the right atrium (*RA*) with its course anterior to the right pulmonary artery, which is displayed in cross section (*arrow*); colour Doppler displays flow in the vena cava (**b**)

(Fig. 1.15). A caudal sweep displays the right pulmonary artery in longitudinal section, the right pulmonary vein and its connection to the left atrium (Lai and Ko 2009).

1.2.2 Apical Views

The *apical four-chamber views* are obtained by placement of the transducer directly over the cardiac apex (Lai et al. 2006; Lai and Ko 2009; Snider et al. 1997), which is usually located below the left mamilla. The transducer is nearly oriented in a coronal plane with the notch pointing towards the left axilla (Fig. 1.16). While the apical planes can be obtained in infants in the supine position, in children older than 2–3 years of age, it is favourable to place the child in a left decubitus position with elevation of the left arm to approximate the heart to the left chest wall (Lai and Ko 2009; Snider et al. 1997). The standard plane of the apical four-chamber view displays both atria and ventricles, the atrioventricular valves and the insertion of their leaflets, as well as the moderator band and apical trabeculation of the right ventricle (Fig. 1.17, Video 1.13). Ventricular and atrial septum should be displayed in the centre of the screen and should be

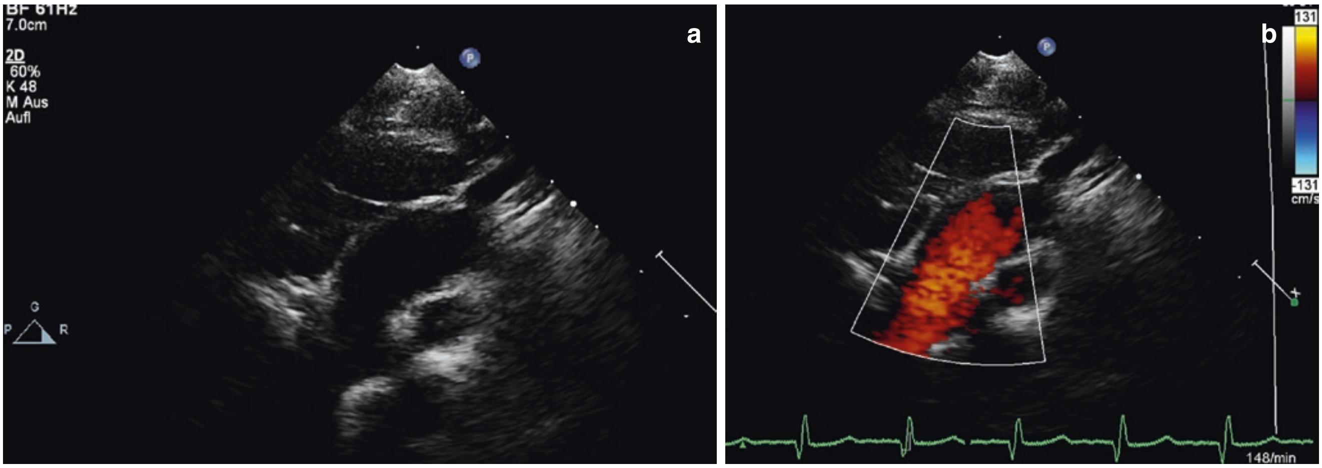


Fig. 1.14 Right parasternal short axis view of the ascending aorta (**a**); systolic flow in the ascending aorta (*AO*) is directed towards the transducer and coded in red (**b**)

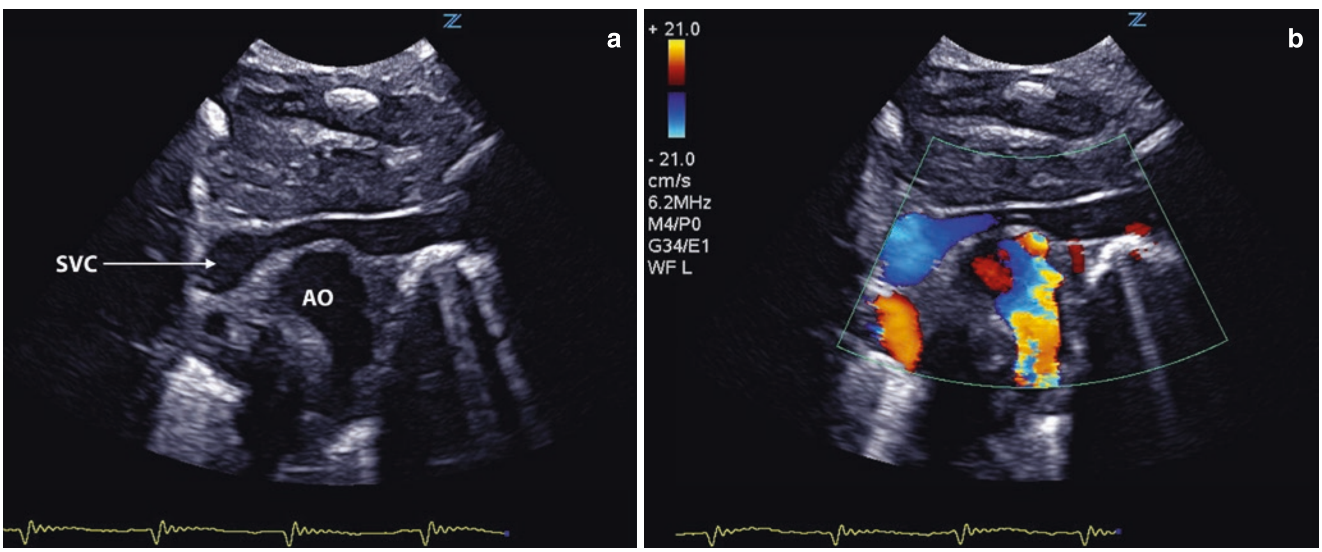
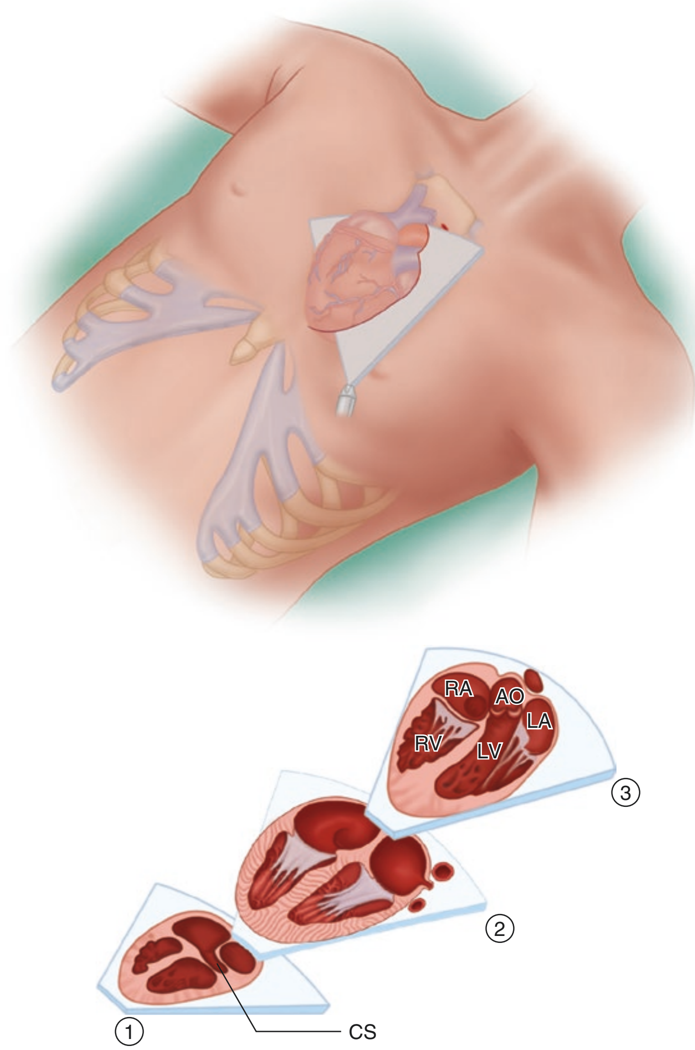


Fig. 1.15 High right parasternal short axis view (**a**) depicting the innominate vein superior to the aorta (*AO*) on its way to the superior vena cava (*SVC*); on colour Doppler, flow in the superior vena cava, directed from the transducer, is coded blue (**b**)

aligned parallel to the ultrasound beam. Posterior tilt of the transducer displays the muscular inlet septum and the coronary sinus coursing in the atrioventricular groove to the right atrium (Fig. 1.18, Video 1.14). Anterior tilt of the transducer shows a plane that is also termed "apical five-chamber view", visualizing the perimembranous ventricular septum, the left ventricular outflow tract and the aortic valve (Fig. 1.19, Video 1.15). The apical four-chamber view is the ideal plane for colour Doppler interrogation of both atrioventricular valves, since flow across the valves is directed towards the transducer (Fig. 1.17). In addition it offers optimal conditions for PW and CW Doppler quantification of diastolic inflow and systolic regurgitant flow in the presence of tricuspid and mitral regurgitation. Colour Doppler interrogation of the ventricular septum in the standard and in the posterior plane helps to detect defects in the apical and in the inlet parts of the muscular ventricular septum. The anterior plane ("apical five-chamber view") allows colour Doppler assessment of the left ventricular outflow tract and the aortic valve (Fig. 1.19, Video 1.15). Aortic regurgitation can be detected and quantified according to its extension back into the left ventricle. This plane is also important for interrogation of flow in the left ventricular outflow tract by pulsed or continuous wave Doppler especially in the presence of subaortic obstruction.

Fig. 1.16 Diagram depicting the planes of the apical four-chamber view including the posterior *1*, medial *2* and anterior plane *3*. *CS* coronary sinus



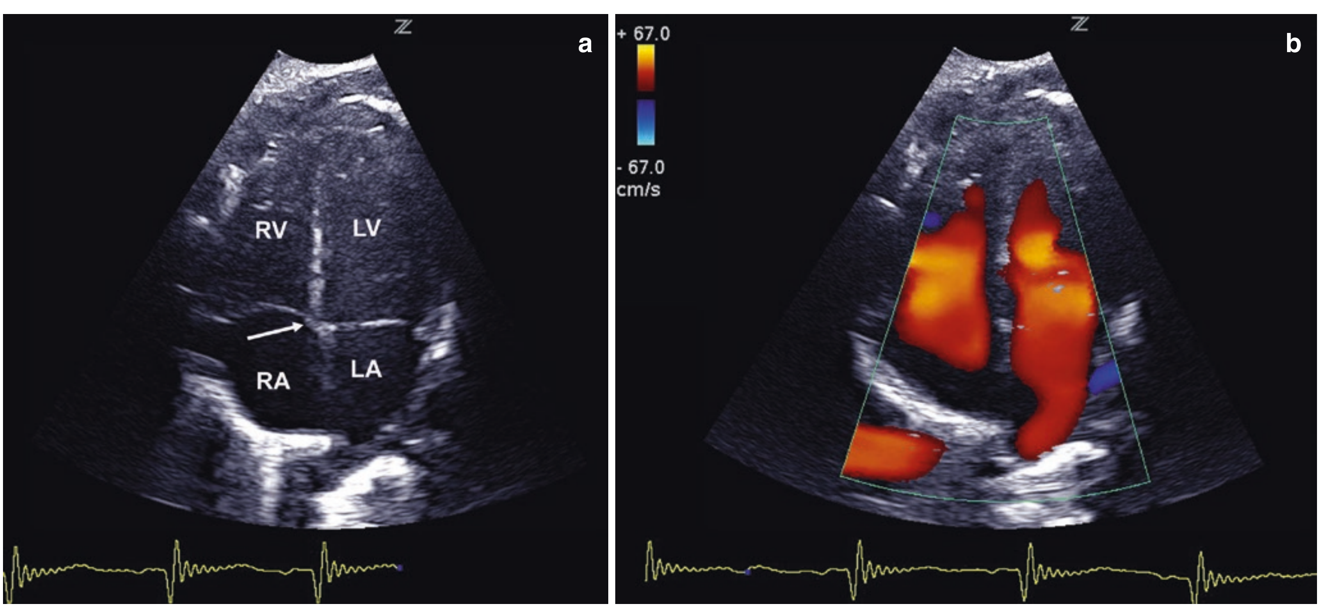


Fig. 1.17 The apical four-chamber view (**a**) visualizes both ventricles (*LV*, *RV*) and atria (*LA*, *RA*); the right ventricle is characterized by septal insertion of the tricuspid valve that is closer to the apex than the mitral insertion (*arrow*). The right ventricular apex is characterized by a septo-parietal moderator band and is more trabeculated than the left. Colour Doppler shows diastolic inflow directed towards the transducer (**b**)

1.2.3 Subcostal Views

Subcostal imaging starts with a transverse section of the upper abdomen to determine the position of the inferior caval vein and of the abdominal aorta (Lai et al. 2006, Lai and Ko 2009; Mertens et al. 2010; Tacy and Silverman 2001). In patients with situs solitus, the inferior caval vein is located to the right and the aorta to the left of the spine (Fig. 1.20, Video 1.16). Clockwise rotation of the probe for 90°, bringing the transducer notch to the 6 o'clock position, allows longitudinal visualization of these vessels (Fig. 1.21). Colour Doppler examination of the abdominal aorta in this plane displays the origin of the coeliac and upper mesenteric artery and provides the basis for pulsed wave interrogation of flow in these systemic arteries (Fig. 1.22). Since flow in the coeliac artery is directed towards the transducer, PW Doppler can be used for semiquantitative assessment of blood flow in the systemic circulation and will detect diminished systolic flow in the presence of critical coarctation and decreased or even negative diastolic flow in the presence of significant diastolic run-off from the aorta. The latter can be expected in the presence of severe aortic regurgitation, in neonates with truncus arteriosus communis or in the presence of a large ductus arteriosus or an aortopulmonary window.

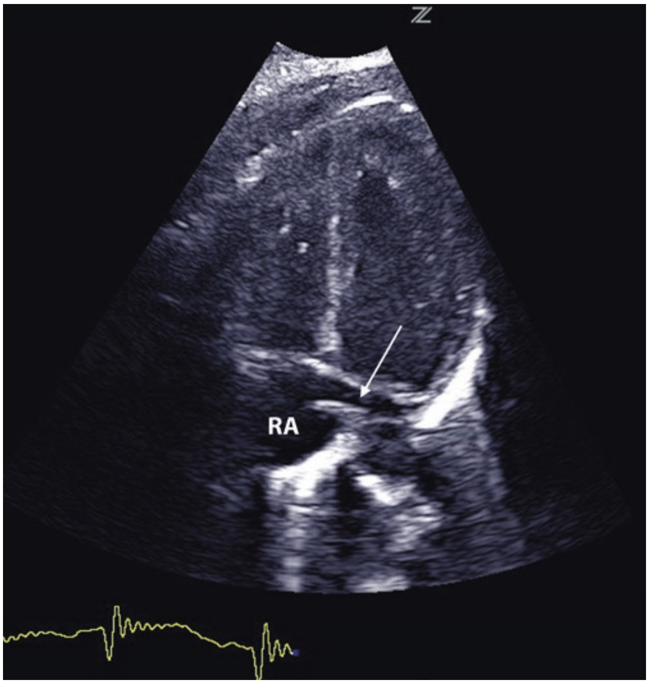


Fig. 1.18 The posterior plane of the apical four-chamber shows inferior parts of the muscular ventricular septum and the coronary sinus (*arrow*) coursing in the atrioventricular groove to the right atrium (*RA*)

Cranial tilt of the transducer from the transverse section of the abdomen shows the connection of the inferior caval vein with the right atrium. The hepatic veins join the right atrium just proximal to the right atrium. Subcostal examination of the heart includes coronal, sagittal and oblique views. For subcostal imaging, it is generally recommended to invert the imaging plane to display superior structures at the top of the image (Lai et al. 2006). The *subcostal long-axis* (*coronal*) *views* are obtained by placement of the transducer in the abdomen underneath and parallel to the sternum with an orientation of the ultrasound beam from right to left and the transducer notch in the 3 o'clock position (Snider et al. 1997). A series of planes can be obtained by tilting the transducer from a posterior to an anterior position (Fig. 1.23, Video 1.17). The posterior coronal view displays both atria

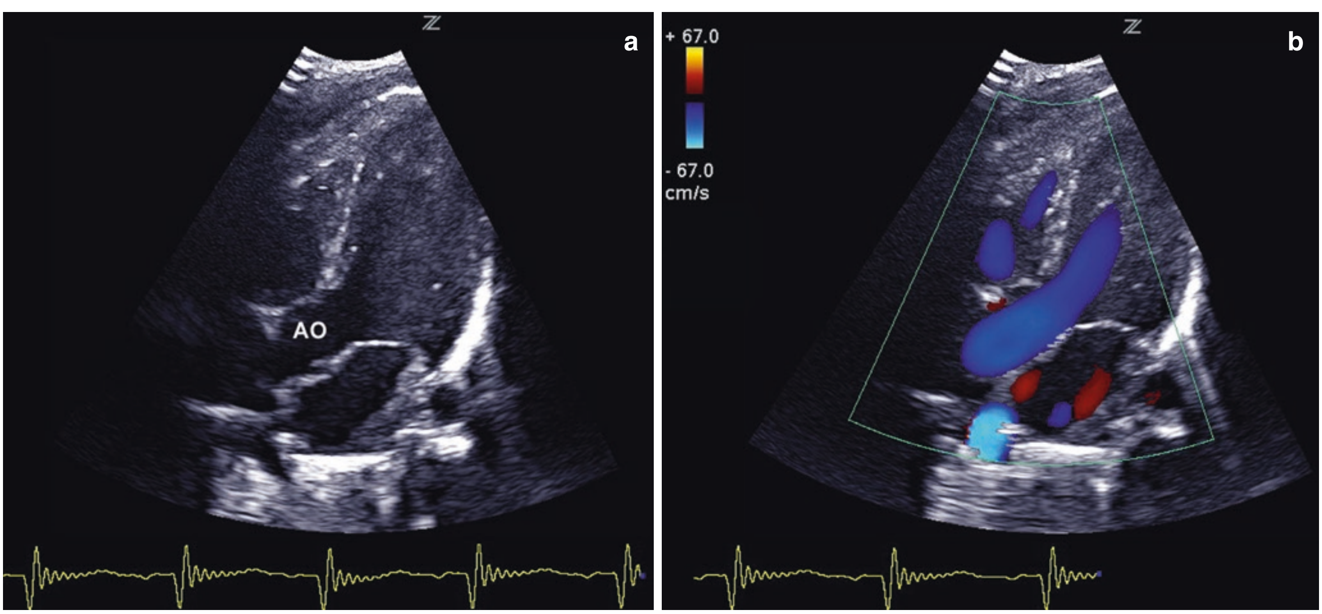


Fig. 1.19 The anterior plane of the apical four-chamber view (**a**) displays the left ventricular outflow tract and the aorta (*AO*); colour Doppler shows systolic flow from the left ventricle to the aorta (**b**)

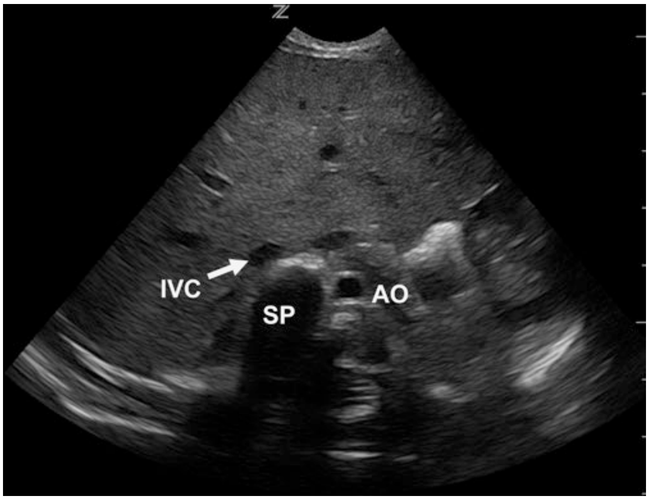


Fig. 1.20 The cross section of the great vessels in the upper abdomen shows the inferior vena cava (*IVC*) to the right and the abdominal aorta (*AO*) to the left of the spine (*SP*)

and the drainage of the superior pulmonary veins into the left atrium, which can be confirmed by colour Doppler examination (Fig. 1.24, Video 1.18). Anterior tilt of the transducer shows the left ventricle, parts of the ventricular septum, the left ventricular outflow tract and the aortic valve (Fig. 1.25). This coronal plane is very useful for colour Doppler examination of the left ventricular outflow tract and the aortic valve. Due to the favourable insonation angle, it offers the possibility for quantification of systolic flow across the aortic valve by pulsed and continuous wave Doppler. Further anterior tilt opens the right ventricle and the right ventricular outflow tract (Fig. 1.26, Video 1.19). This plane is especially helpful for colour Doppler interrogation of the right ventricular outflow tract and for detection of subvalvular obstruction (Video 1.20), which can be quantified by PW and CW Doppler assessment.

A 90° clockwise rotation of the transducer from the coronal planes, bringing the notch of the transducer into the

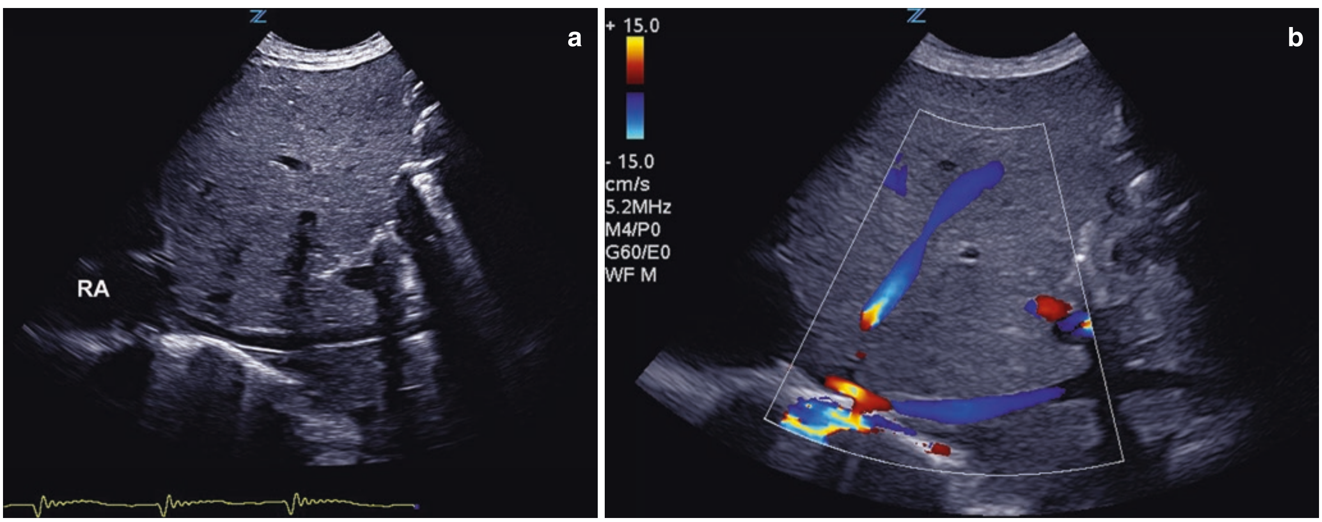


Fig. 1.21 Longitudinal view (**a**) and colour Doppler of the inferior vena cava (**b**) on its way to the right atrium (RA)

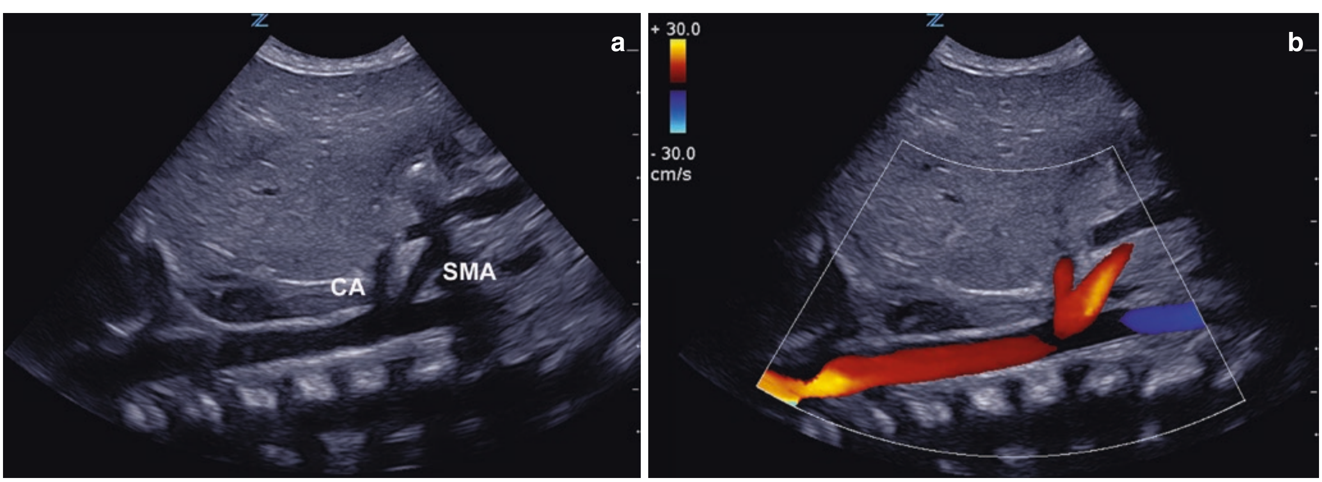


Fig. 1.22 Longitudinal view of the abdominal aorta (**a**) showing the origin of the coeliac (*CA*) and superior mesenteric artery (*SMA*), which are well displayed by colour Doppler (*b*)

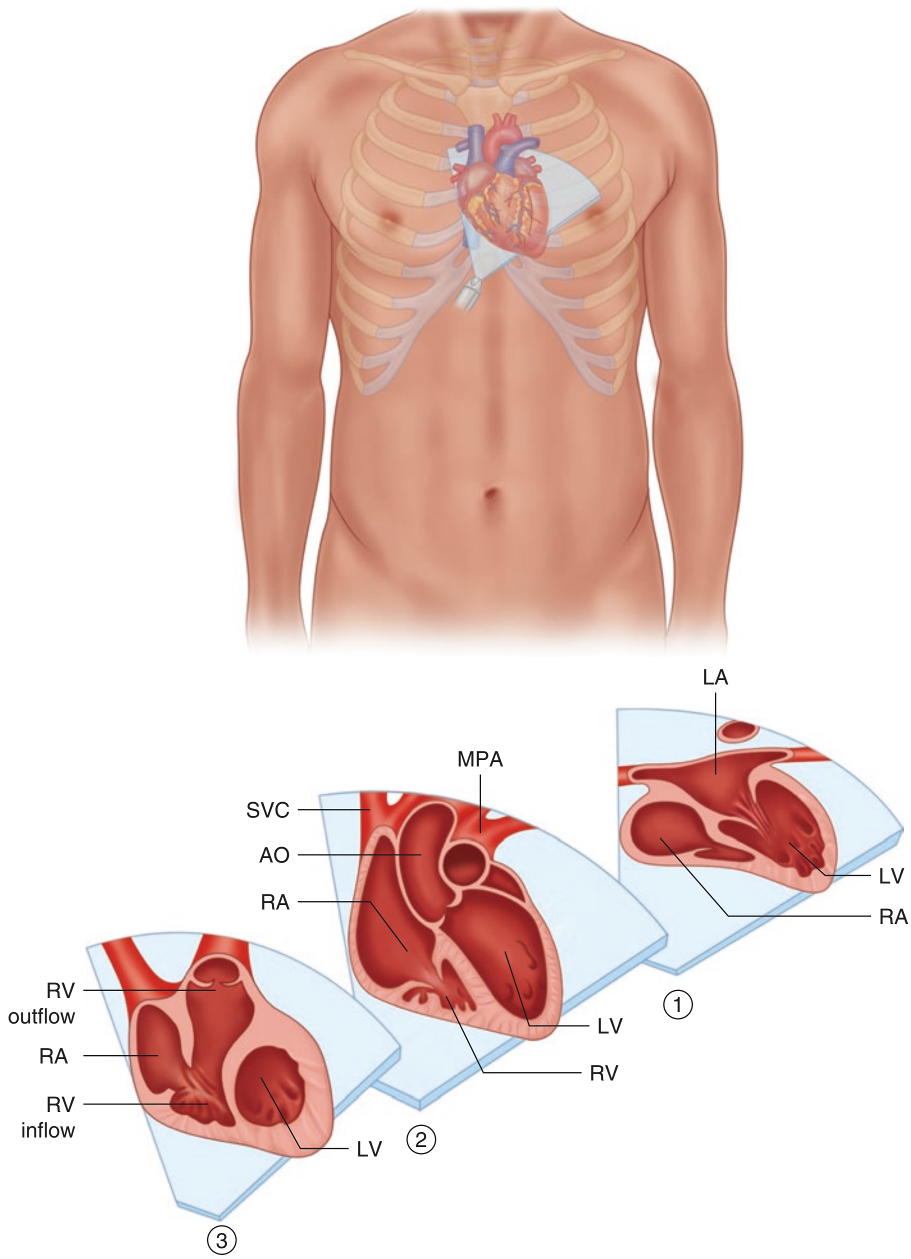


Fig. 1.23 Diagram of the subcostal coronal (long-axis) views starting with the posterior plane of the atria *1*, the medial plane of the left ventricular outflow tract *2* and the anterior plane of the right ventricular outflow tract *3*. *SVC* superior vena cava, *RV* right ventricle

6 o'clock position, displays the *subcostal short-axis* (*sagittal*) *views* (Lai et al. 2006; Snider et al. 1997) (Video 1.21). The most rightward of these planes shows the drainage of the superior and inferior caval veins into the right atrium (Fig. 1.27, Video 1.22). Furthermore this plane depicts the cranial part of the atrial septum (Fig. 1.28). Slight counterclockwise rotation in this plane results in a left oblique view with very nice elongation of the interatrial septum. Back in the sagittal plane, leftward sweep of the transducer reveals the sagittal plane of the right ventricular outflow tract (Fig 1.29, Video 1.23). It displays the infundibulum of the right ventricle, the pulmonary valve and the main pulmonary artery. This plane allows Doppler interrogation of the right ventricular outflow tract and the pulmonary valve. Further leftward tilt of the transducer towards the left shoulder shows the left ventricle in cross section (Fig. 1.30, Video 1.24).

The *subcostal RAO view* is an additional plane which is obtained by counterclockwise rotation of the transducer starting from a subcostal long-axis view (Lai and Ko 2009). It displays the tricuspid valve, the right ventricle and its infundibulum as well as the pulmonary valve and the main pulmonary artery (Fig. 1.31). This plane resembles the para-

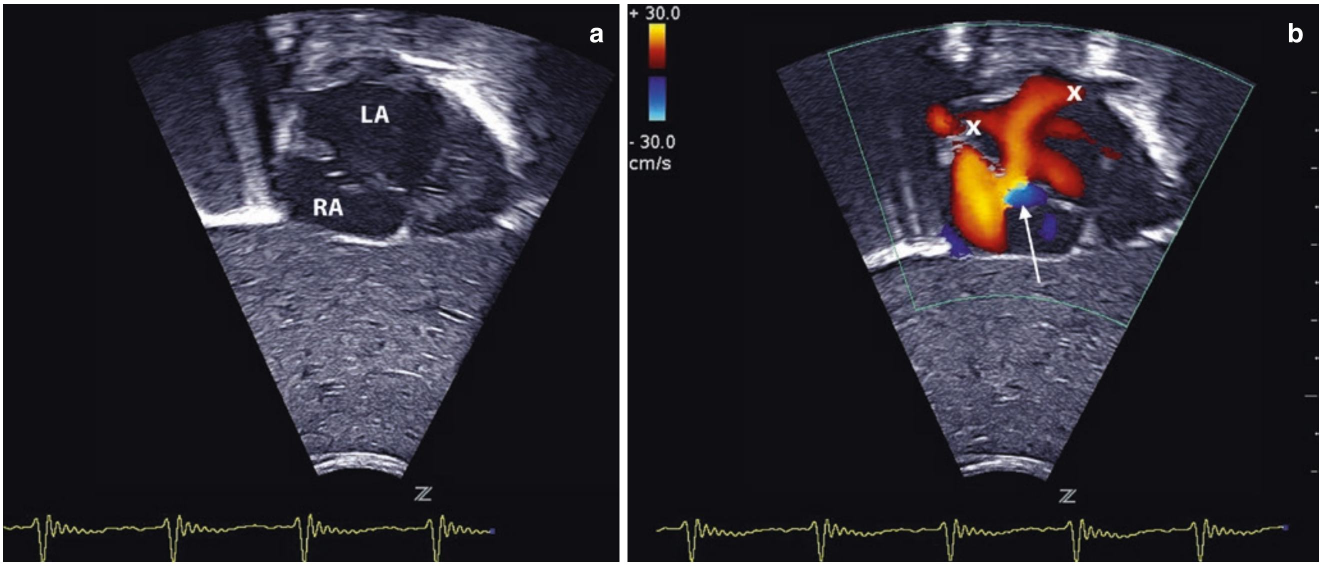


Fig. 1.24 Posterior subcostal coronal view of the atria (**a**) showing the left (*LA*) and right atrium (*RA*) as well as the atrial septum. Flow from both upper pulmonary veins (*x*) is apparent on colour Doppler (**b**); in this neonate there is still flow across a small patent foramen ovale (*arrow*)

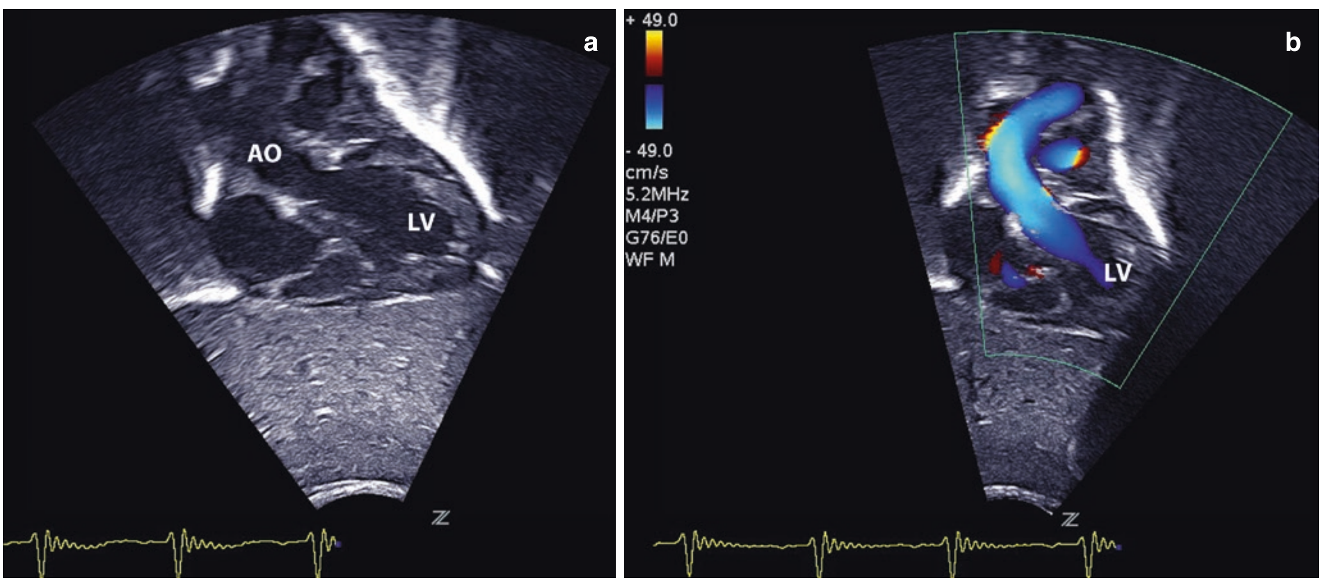


Fig. 1.25 Subcostal coronal view of the left ventricular outflow tract (**a**); colour Doppler (**b**) shows systolic flow from the left ventricle (*LV*) to the aorta (*AO*)

sternal short axis view with the aortic valve in cross section in the centre of the image. It allows CD interrogation of the perimembranous ventricular septum, of the right ventricular outflow tract and of the pulmonary valve (Fig. 1.31).

1.2.4 Suprasternal Views

The suprasternal views are obtained by placement of the transducer in the suprasternal notch. In neonates and young infants, the thymus gland enlarges the acoustic window, and similar views may be obtained from a high right parasternal window. Echocardiographic examination of these planes is greatly enhanced by elevation of the patient's shoulders by a towel or pillow (Lai and Ko 2009).

The *suprasternal short-axis* view displays the ascending aorta in cross section (Fig. 1.32, Video 1.25). The innominate vein is depicted superior to the aorta while the right pulmonary artery and the left atrium are displayed

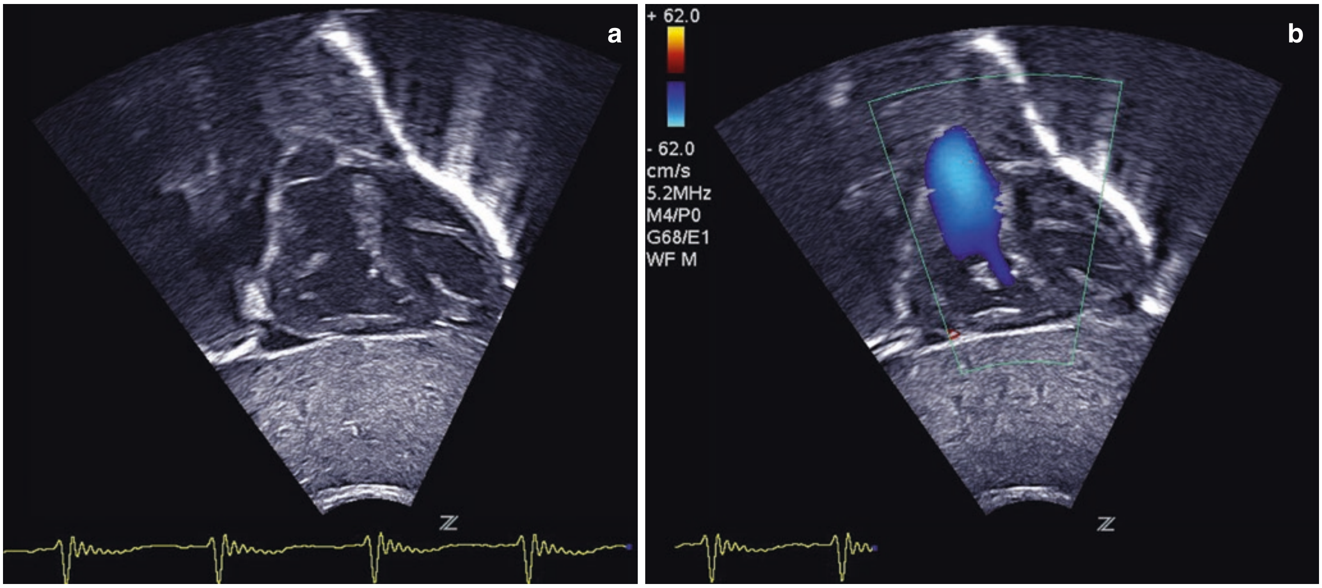


Fig. 1.26 Subcostal coronal view of the right ventricular outflow tract (**a**) and colour Doppler confirmation of systolic flow to the pulmonary artery (**b**)

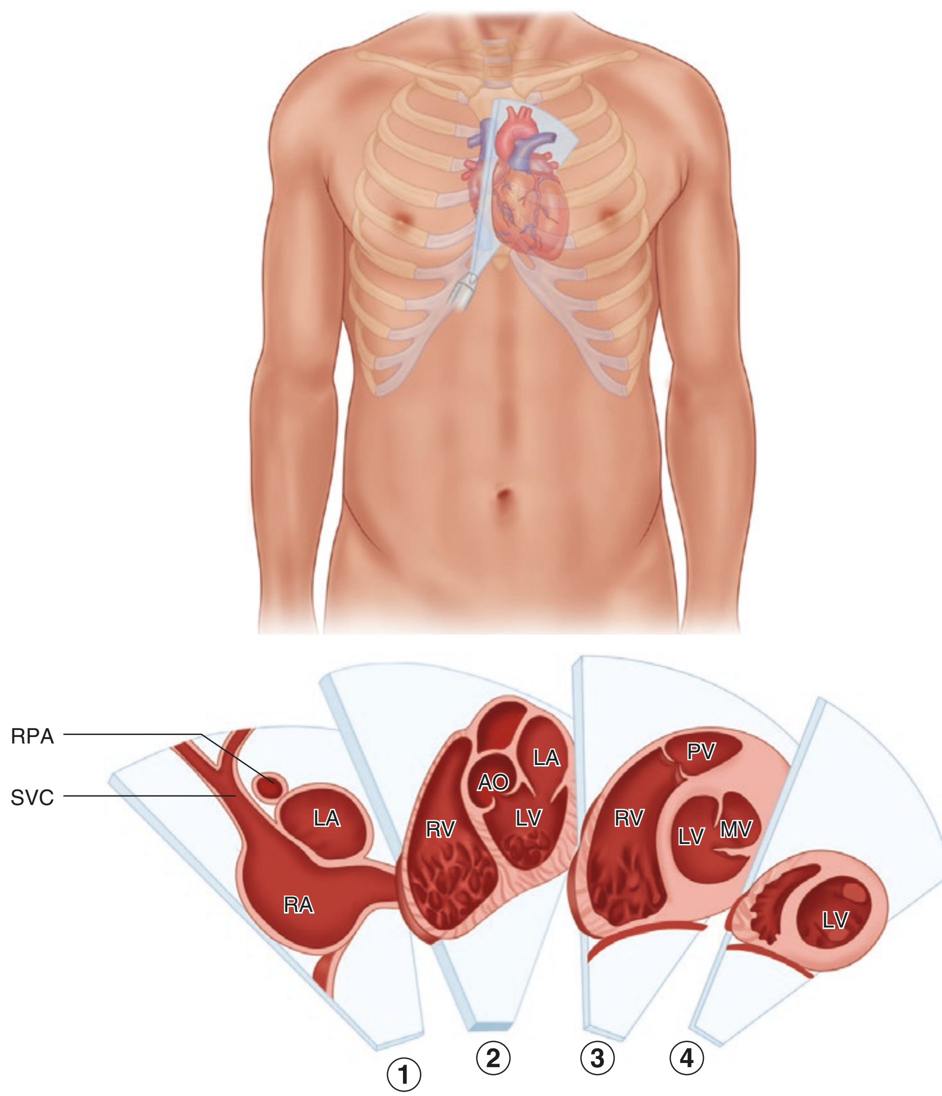


Fig. 1.27 Diagram of the subcostal short-axis (sagittal) views including from right to left the plane of the caval veins *1*, followed by the planes of the right ventricular outflow tract *2, 3* and finally the cross section of the left ventricle *4*. *SVC* superior vena cava, *RPA* right pulmonary artery, *RV* right ventricle, *LV* left ventricle, *MV* mitral valve, *PV* pulmonary valve

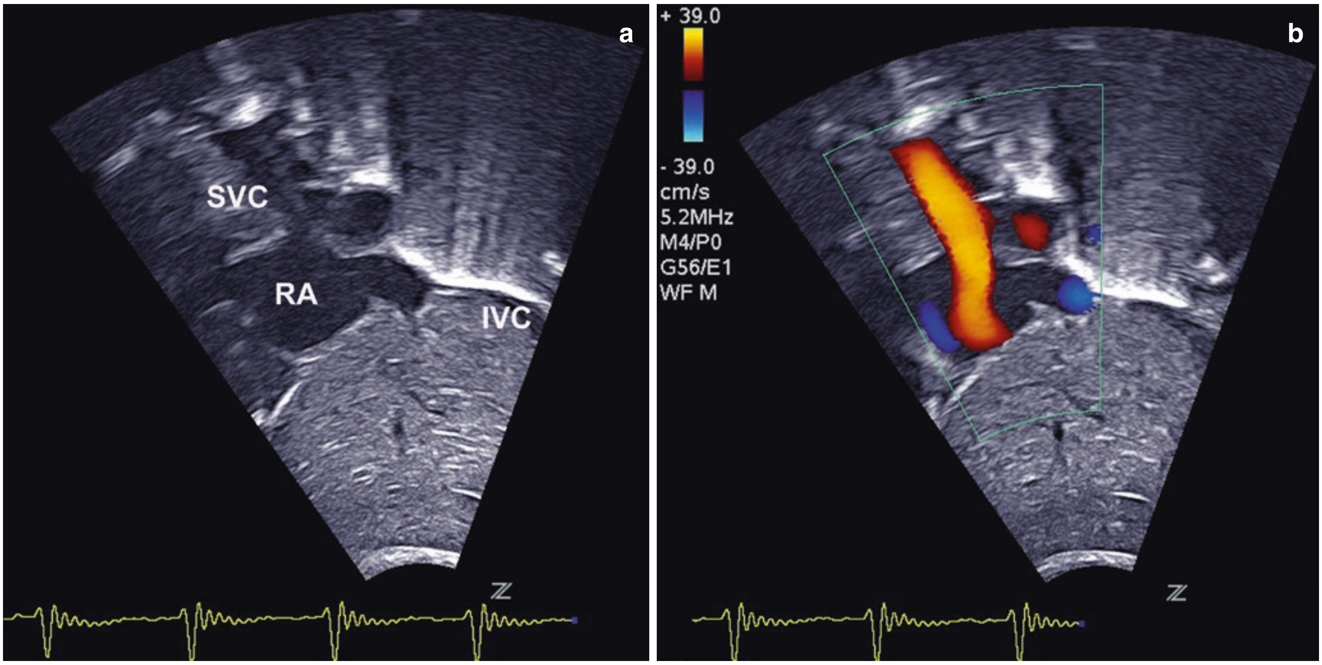


Fig. 1.28 Subcostal short-axis view of the caval veins (**a**) showing the superior (*SVC*) and inferior vena cava (*IVC*) entering the right atrium (*RA*) with confirmation of flow by colour Doppler (**b**)

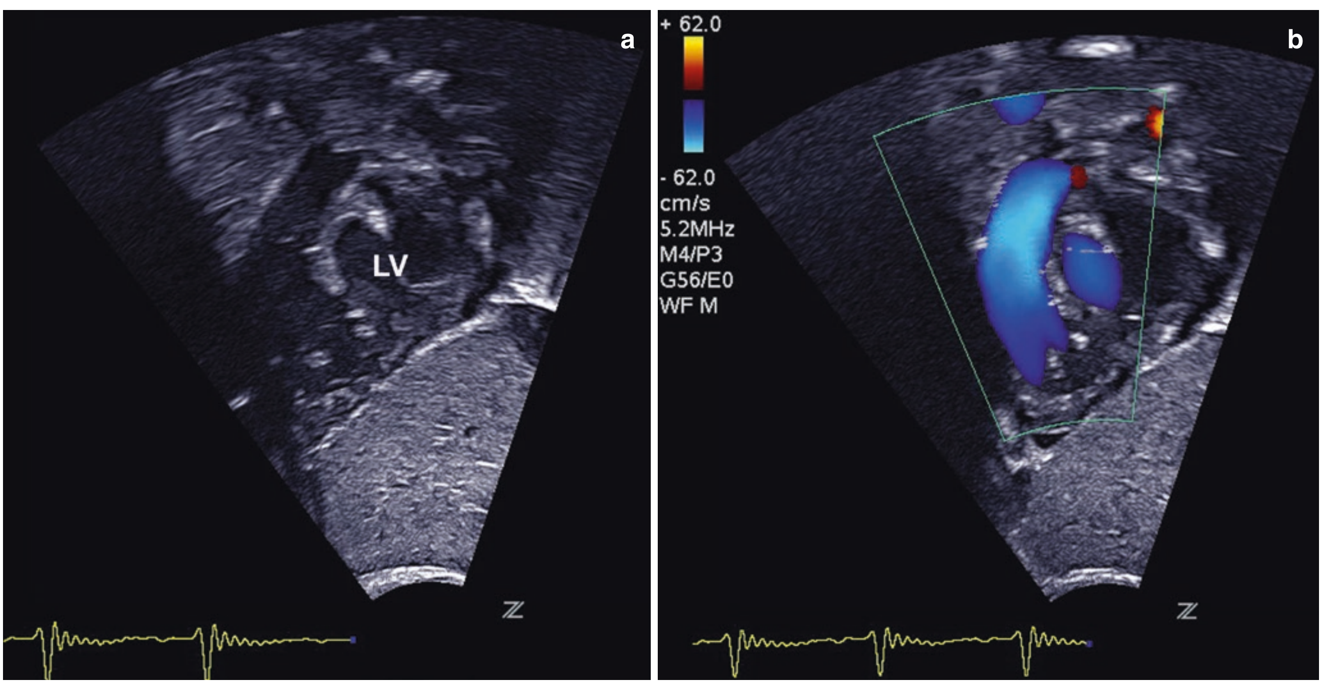


Fig. 1.29 Subcostal short-axis view of the right ventricular outflow tract and pulmonary valve (**a**). The left ventricle is displayed in cross section (*LV*). Colour Doppler depicts systolic flow from the right ventricle to pulmonary artery (**b**)

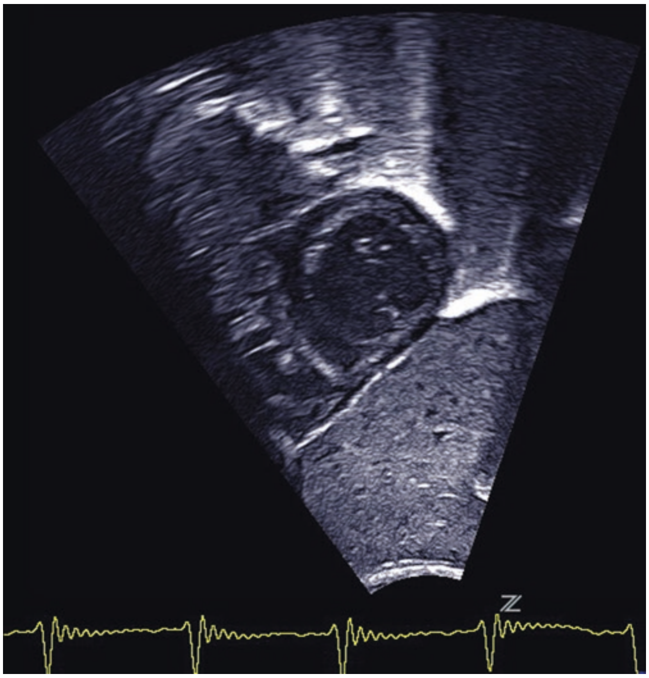


Fig. 1.30 Further leftward tilt results in the subcostal short-axis view of the left ventricle

below (Fig. 1.33). Cranial angulation of the transducer allows visualization of the brachiocephalic arteries (Videos 1.26 and 1.27). In the presence of a normal left aortic arch, the first vessel originating from the aorta will be the right innominate artery. This vessel can be opened and displayed in longitudinal section by clockwise rotation of the transducer (Fig. 1.33, Video 1.26 and 1.27). Visualization of the normal bifurcation into the right subclavian and right common carotid artery confirms the presence of a left aortic arch and excludes possible anomalies of the right subclavian artery, e.g. aberrant origin from the descending aorta (Lai and Ko 2009; Murdison et al. 1996; Snider et al. 1996). In the presence of a left aortic arch, counterclockwise rotation of the transducer starting from the suprasternal short axis opens the aorta and displays a longitudinal section of the entire aortic arch (Fig. 1.34, Video 1.28). This *suprasternal long-axis* view provides excellent conditions for colour Doppler examination of the aortic arch (Video 1.29). CDE helps to define whether there is antegrade or retrograde flow in different parts of the aortic arch, which is of special importance in the evaluation of neonates with left-sided obstructive lesions. However exact assessment of direction and timing of flow requires the application of pulsed wave Doppler interrogation. Quantification of significantly accelerated flow in the presence of severe aortic coarctation requires the application of continuous wave Doppler. It should be kept in mind, however, that circumscribed distal obstructions of the aortic isthmus may be missed in this plane. Furthermore visualization of a patent ductus arteriosus will not always be possible in this plane. *Therefore evaluation of the distal aortic arch and isthmic region should always include application of the ductal view* (Fig 1.12).

1.3 Pulsed Wave and Continuous Wave Doppler

1.3.1 Systemic Veins

Normal flow in the superior and inferior vena cave is characterized by a triphasic flow pattern (Mertens et al. 2010; Meyer et al. 1993; Reynolds and Appleton 1991; Snider et al. 1997). Systolic forward flow due to atrial relaxation and descent of the tricuspid annulus is termed S wave, while forward flow during diastole corresponding to opening of the tricuspid valve and rapid ventricular filling is termed D wave (Fig. 1.35). The A wave represents short duration retrograde flow that may occur in the caval veins towards the end of the diastole associated with atrial contraction. Flow velocities in the caval veins are influenced by respirations with a significant increase of flow velocities during inspiration. Tricuspid regurgitation results in a decrease of S wave and increase of D wave; during tachycardia S wave and D wave may merge to one peak (Snider et al. 1997). Hepatic venous flow is similar to caval venous flow except for lower flow velocities. In addition flow reversal during atrial systole is more common (81 %) in the hepatic veins (Meyer et al. 1993).

1.3.2 Tricuspid Valve

Doppler interrogation of the tricuspid valve can be performed in the apical four-chamber view, in the parasternal long axis of the right ventricular inflow and in the parasternal short axis (Fig. 1.36). Forward flow across the valve occurs during diastole with a first peak called E

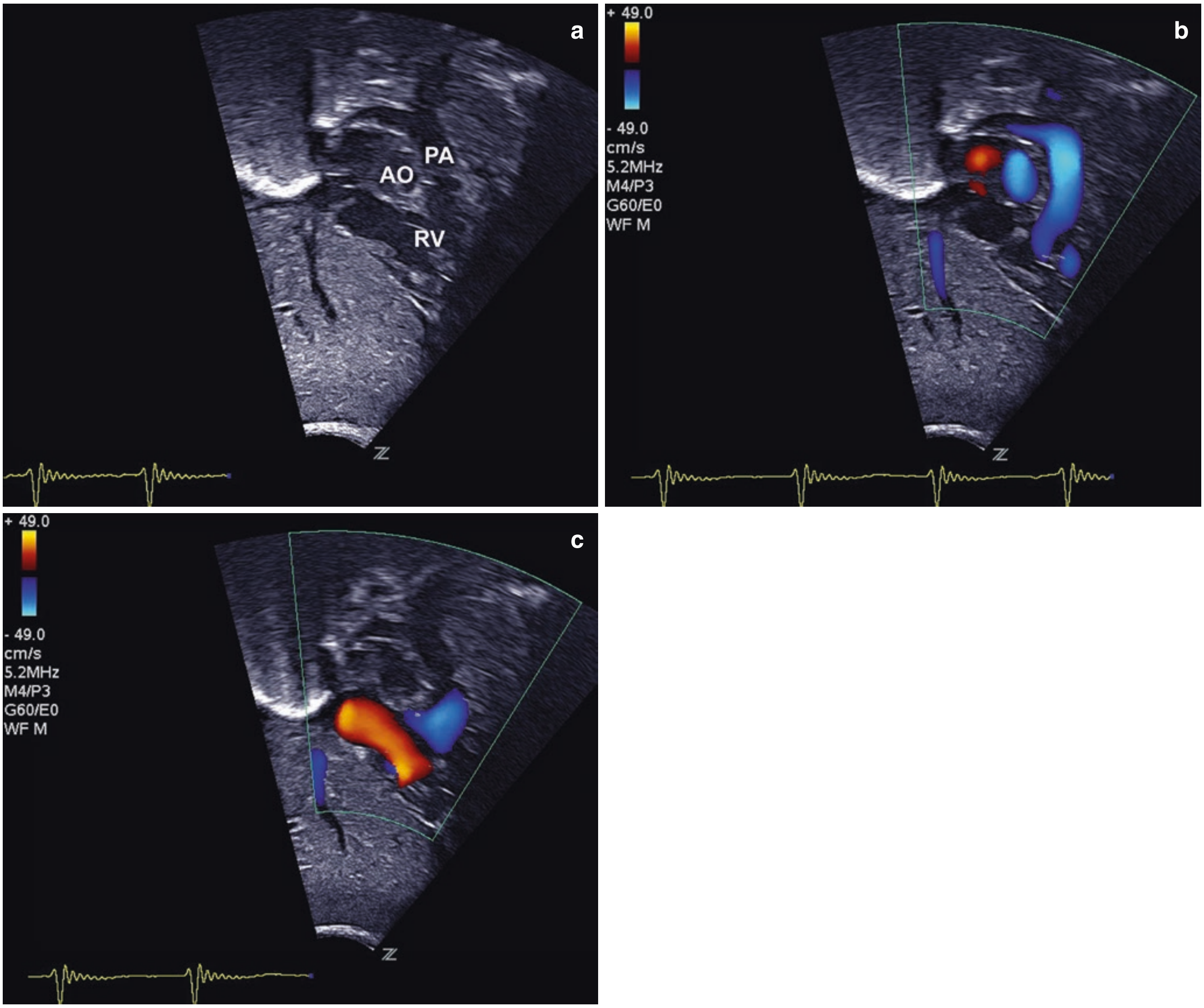


Fig. 1.31 The subcostal right anterior oblique view displays both right ventricular inflow and outflow with the aorta (*AO*) in the centre displayed in cross section (**a**); colour Doppler in systole (**b**) displays flow from the right ventricle (*RV*) to the pulmonary artery (*PA*), while the diastolic frame shows inflow from the right atrium (**c**)

wave, associated with rapid ventricular filling, and a second peak called A wave associated with atrial contraction (Mertens et al. 2010; Snider et al. 1997). While in the fetus and in the normal neonate the A wave exceeds the E wave, in infants and children, the ratio is inverted with dominance of the E wave (Snider et al. 1997). The different inflow pattern in the fetus and neonate is attributed to immaturity of ventricular myocardium with decreased compliance and dependency of ventricular filling on atrial contraction (Mertens et al. 2010; Snider et al. 1997). Normal tricuspid valve inflow velocities are lower than mitral valve velocities and show more respiratory alterations with an increase in flow velocities during inspirations.

1.3.3 Right Ventricular Outflow Tract and Pulmonary Artery

Planes for Doppler interrogation of the right ventricular outflow tract include the parasternal long axis view of the right ventricular outflow tract and the parasternal short axis and the subcostal long axis of the right ventricular outflow tract. For Doppler interrogation in the parasternal short axis, it may be favourable to position the transducer one or two intercostal spaces below the usual position to obtain optimal alignment of the Doppler beam with the outflow tract and main pulmonary artery (Snider et al. 1997). The normal peak velocity in the main pulmonary artery in children has been reported with 0.9 m/s with a

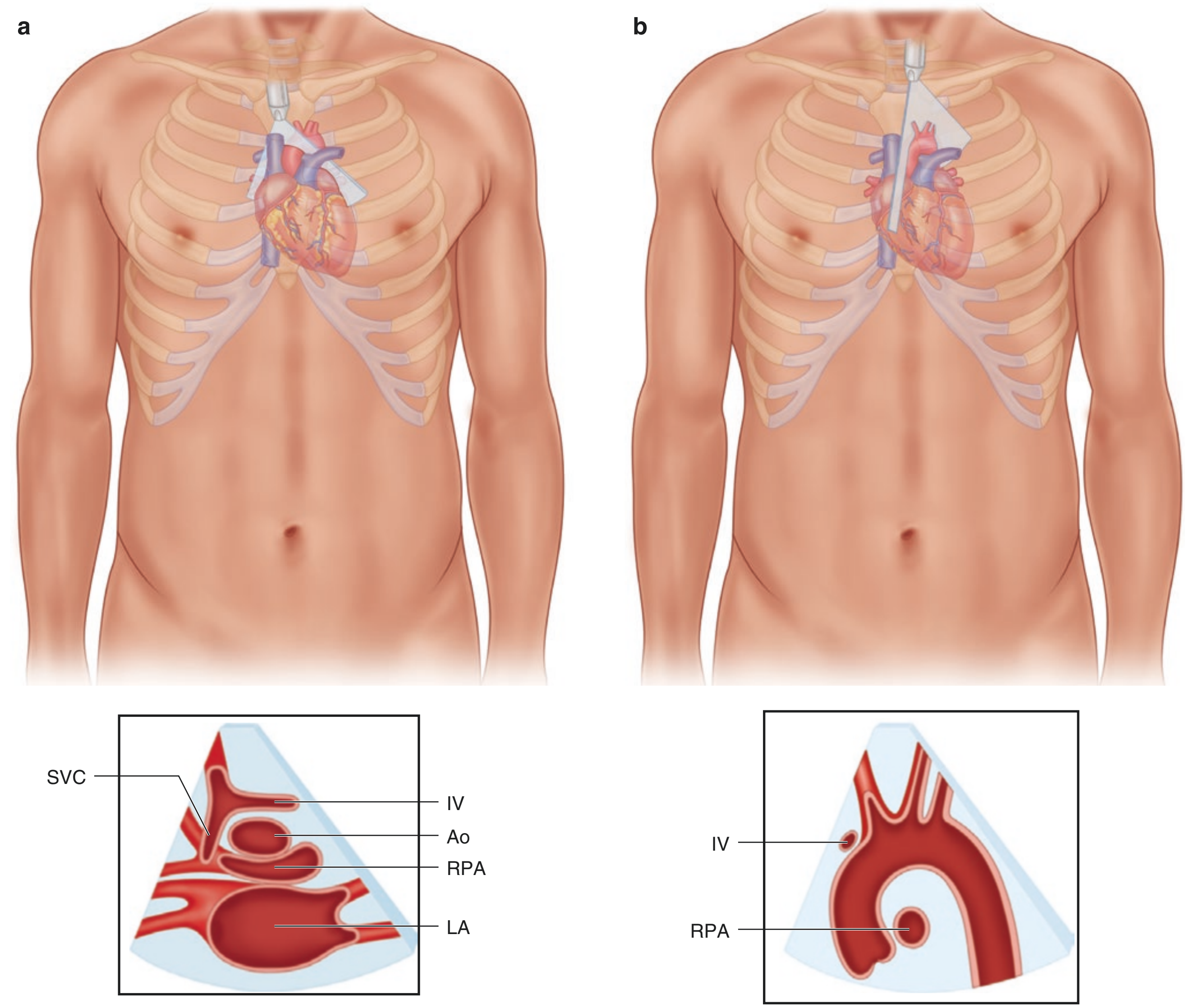


Fig. 1.32 Diagram of the suprasternal short-axis (**a**) and suprasternal long-axis views (**b**). *SVC* superior vena cava, *IV* innominate vein, *AO* aorta, *RPA* right pulmonary artery, *LA* left atrium

range of 0.7–1.1 m/s (Hatle and Angelsen 1985). Antegrade flow in the pulmonary artery during systole is directed away from the transducer (Fig. 1.37). In early diastole there may be a short retrograde flow, which is attributed to backward movement of the blood towards the closed pulmonary valve (Snider et al. 1997). There is only little flow during diastole, although sometimes antegrade flow in late diastole can be noted following right atrial contraction (Grenadier et al. 1984). An increase in systolic antegrade flow velocities in the main pulmonary artery may be due to stenosis of the outflow tract or pulmonary valve or due to an increased flow in the presence of congenital heart disease with left to right shunting. The most likely cause of left to right shunting is atrial septal defect (Chap. 2). Insufficiency of the pulmonary valve results in regurgitant flow directed towards the transducer in diastole (Chap. 7).

1.3.4 Pulmonary Veins

Doppler interrogation of flow in the pulmonary veins can be performed in the apical four-chamber view and in the subcostal coronal view. Visualization of all four pulmonary veins is possible in the suprasternal and high left parasternal short-axis views. In the latter plane, however, the angle of Doppler interrogation may be less favourable than in the previous views, resulting in some underestimation of the flow velocities. In order to measure flow within the veins, the sample volume should be

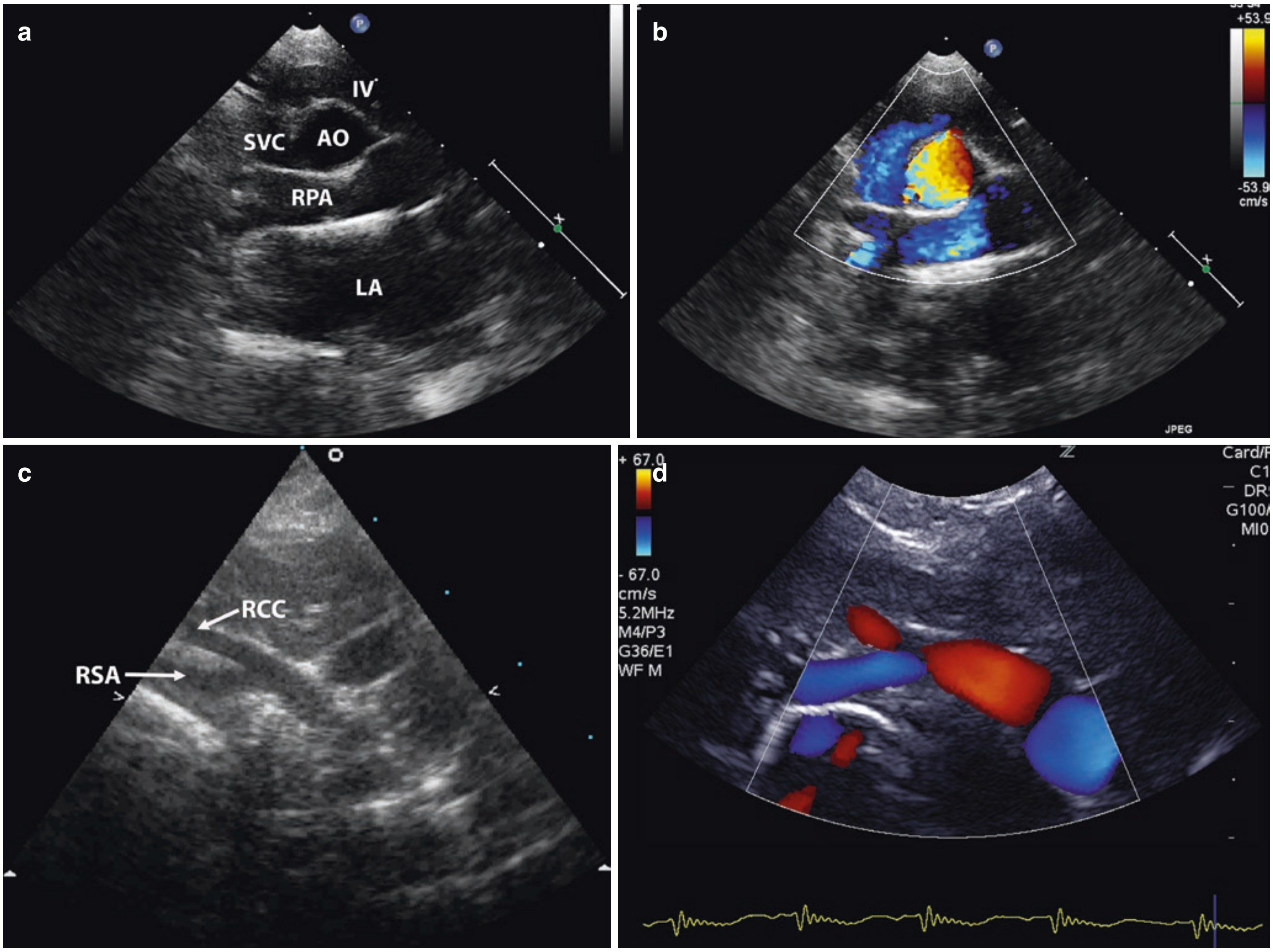


Fig. 1.33 Suprasternal short axis displaying the innominate vein (*IV*) connecting to the superior vena cava (*SVC*) and the aorta (*AO*) in cross section (**a**). The right pulmonary artery (*RPA*) and left atrium (*LA*) are displayed below the aorta. Colour Doppler shows flow in the RPA up to the hilum (**b**). Cranial tilt and clockwise rotation of the transducer result in this longitudinal view of the innominate artery (**c**) and its bifurcation into the right common carotid (*RCC*) and subclavian artery (*RSA*) which is confirmed by colour Doppler (**d**)

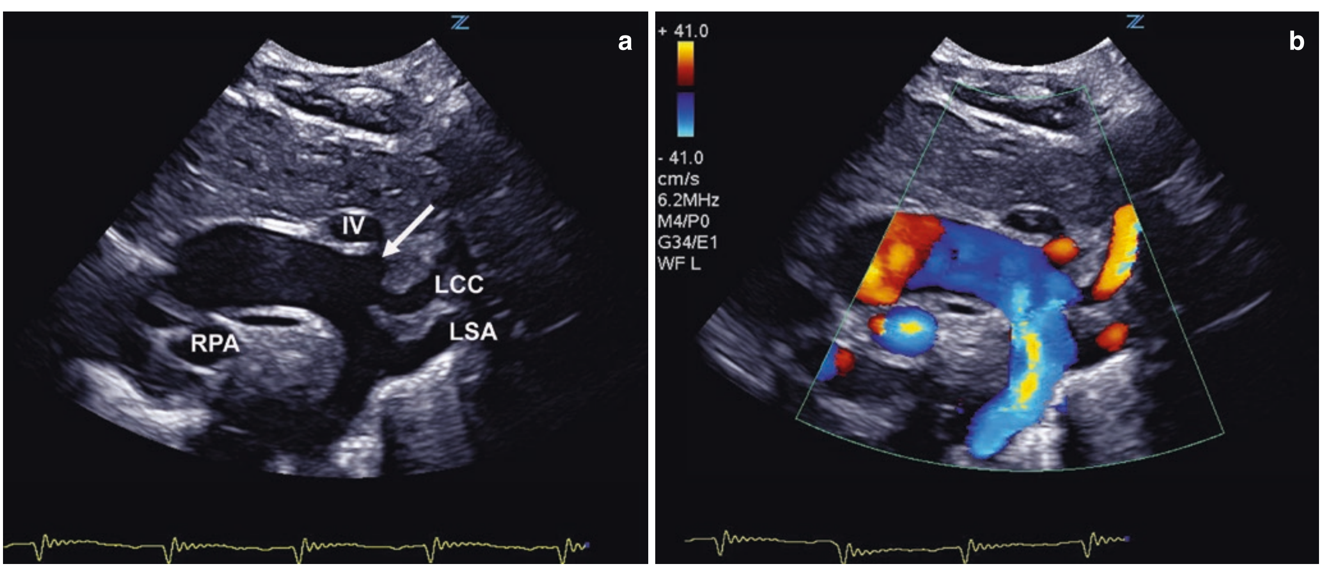


Fig. 1.34 Suprasternal long-axis view of the aortic arch (**a**), depicting innominate artery (*arrow*), left common carotid (*LCA*) and left subclavian artery (*LSA*); the right pulmonary artery is displayed underneath (*RPA*) the innominate vein (*IV*) above the aorta. Colour Doppler showing systolic flow in the aorta and brachiocephalic arteries (**b**)