CURRENT TOPIC

Physiology of congenital heart disease

Sheila G Haworth, Catherine Bull

Congenital heart disease affects eight in 1000 liveborn babies. Though most of the abnormalities are simple and managed without urgency, some are structurally very complex, the affected babies presenting early and sick. The minutiae of the anatomical abnormalities in congenital heart disease can make detailed diagnosis seem complicated but presentation, natural history, and management are governed largely by physiology. Moreover, understanding the physiological consequences of congenital heart disease enables the physician to make intelligent use of the anatomical detail offered by cross sectional echocardiography and of the flow related information from Doppler techniques.

The traditional discrimination between 'pink' and 'blue' is rather broad to be a very helpful categorisation, so we suggest the physiology may be dominated by: left to right shunting, pulmonary venous hypertension, prejudiced systemic perfusion, low pulmonary blood flow, transposition streaming, or intracardiac mixing of oxygenated and desaturated blood.

(1) Left to right shunts

These patients are typically pink with pulmonary plethora on chest radiography. A communication between the systemic and pulmonary circulations can exist at atrial, ventricular, or great artery level, or a combination of these. Oxygenated blood flows from the left to the right heart, thence to the lungs and is returned to the left atrium. The magnitude of the shunt is governed by the size of the defect and by the relative resistances of the systemic and pulmonary circuits. The shunt volume is reflected in the physical signs: cardiac chambers receiving an excessive amount of blood enlarge and hypertrophy to cope with increased volume; when flow across a valve is greatly increased, a 'flow murmur' may be heard. The physiology also determines the natural history: volume overload can lead to failure of the corresponding ventricle and sustained high pulmonary blood flow damages small peripheral pulmonary arteries. A high pulmonary artery pressure compounds this complication and pulmonary arterial medial hypertrophy is succeeded by intimal damage and the pulmonary vascular resistance increases. The rapidity of the evolution of pulmonary vascular disease varies with the physiology of the causative lesion. As it evolves, flow through the defect then tends to diminish and eventually reverses, the patient becoming cyanosed (Eisenmenger reaction). Subacute

bacterial endocarditis can develop where a high velocity jet damages the endothelium, as in a small ventricular septal defect.

(A) ATRIAL SEPTAL DEFECT

In an atrial septal defect, the direction of blood flow is governed by the relative compliances of the two atria and ventricles which at birth are equally thick walled. After birth, interatrial shunting does not occur until the pulmonary vascular resistance has fallen and the right ventricle has become more compliant and the left dominant. Of the excessive blood returning to the left atrium, enough enters the left ventricle to sustain a normal systemic output but a greater volume recirculates through the atrial defect, right heart and lungs. Flow through the pulmonary circulation can be three times that through the systemic circulation, the increased flow producing a mid-diastolic tricuspid flow murmur, a pulmonary ejection murmur, and prolonging right ventricular ejection.

Cross sectional echocardiography determines the site and size of the defect and shows the enlarged right heart chambers (fig 1). Cardiac catheterisation is not required unless there is concern about the pulmonary vascular resistance, which rises only very slowly. However because the operative risk is very low, concern about pulmonary vascular disease, right ventricular failure, or arrhythmias in adult life – which can occur when a shunt of more than about 2:1 is sustained through childhood – justifies surgical closure of a large defect, even though the patients are usually asymptomatic.

(B) VENTRICULAR SEPTAL DEFECT

In systole, blood flows through the defect from left to right ventricle and recirculates through the lungs. Both ventricles and the left atrium dilate and right ventricular volume overload may make the liver enlarge. When the defect is large, the lungs are sufficiently stiff and incompressible to make the baby breathless and fail to thrive. The high left ventricular pressure is transmitted to the pulmonary circulation and the hypertensive pulmonary arteries may compress the lobar bronchi and predispose to respiratory tract infections. Both ventricles enlarge making the chest wall bulge and the apical impulse forceful. The shunt throughout systole produces a pansystolic murmur and when the pulmonary flow is more than about twice systemic, a mitral diastolic flow murmur is audible, though the pulmonary flow

Department of Paediatric Cardiology, Institute of Child Health, 30 Guilford Street, London WC1N 1EH
Sheila G Haworth
Catherine Bull

Correspondence to:
Professor Haworth.

Figure 1 Secundum atrial septal defect (ASD). (A) and (B) cross sectional echocardiograms showing a large ASD with dilated right heart chambers. Colour flow mapping in (B) shows a left to right shunt, indicated by arrows. Blood flowing towards the transducer is red and flowing away from the transducer is blue. LA=left atrium, LV=left ventricle, RA=right atrium, RV=right ventricle, mv and tv=mitral and tricuspid valves respectively, lpv=left pulmonary vein.

murmur is usually drowned by the loud pansystolic murmur when auscultating a small chest.

However large the defect and high the systolic pressure, when the pulmonary vascular resistance is low, the pulmonary artery diastolic pressure is nearly normal and the pulmonary component of the second heart sound is not accentuated. As the pulmonary vascular resistance increases, the pulmonary artery diastolic pressure (under which the pulmonary valve closes) rises and the second pulmonic heart sound (P_2) increases; pulmonary flow decreases, and the mitral diastolic murmur disappears. Eventually, when the pulmonary vascular resistance approaches systemic levels, the pansystolic murmur shortens and disappears. On chest radiography the enlarged heart becomes small and the plethoric lung fields become oligemic with pruning of the peripheral vessels.

The natural history of the lesion depends on the size of the defect. Most defects are small and 75% of small and about 10% of large defects close spontaneously. Right ventricular outflow tract obstruction develops in 10% of large ventricular septal defects; cyanosis develops, the physiology

coming to resemble that of tetralogy of Fallot. In defects that remain large, pulmonary vascular disease develops inexorably, so surgery is often recommended in the first year of life; if delayed, the pulmonary resistance postoperatively may not return to normal. Operative mortality is about 5%.

(C) PATENT DUCTUS ARTERIOSUS

In this abnormality the aortic pressure exceeds the pulmonary arterial pressure throughout the cardiac cycle and a continuous flow of blood from the aorta to the pulmonary artery produces a continuous murmur (fig 2). If the ductus is large, pulmonary venous return is high, the left heart is overloaded and so the apical impulse is prominent and a mitral mid-diastolic flow murmur is audible (fig 3). During diastole the blood 'steals' from the aorta to the pulmonary artery, and therefore the aortic diastolic pressure is low and the upstroke of the pulse is abrupt as blood is ejected into an empty aorta. This produces the characteristic bouncing pulse. If the ductus is small the diastolic pressure in the pulmonary artery is low and P_2 is normal but if the ductus is

Figure 2 Patent ductus arteriosus (PDA) shown in left parasternal views in (A) and (B). Also (B) shows flow towards the transducer from descending thoracic aorta (DAo) to the pulmonary artery, in red. (C) Continuous wave Doppler signal demonstrating flow throughout the cardiac cycle. AAo=ascending thoracic aorta, RPA and LPA=right and left pulmonary arteries respectively.

Figure 3 Dilated left atrium (atrial septum bowing to the right) due to high pulmonary venous return related to patent ductus arteriosus. LA=left atrium, LV=left ventricle, RA=right atrium, lpv=left pulmonary vein, rpv=right pulmonary vein.

large, left ventricular systole is prolonged and the aortic second sound (A_2) is delayed and so can produce a single second heart sound. Most children with a patent ductus arteriosus are asymptomatic but a premature baby readily develops heart failure. In a baby with the respiratory distress syndrome a large patent ductus arteriosus significantly increases the work of breathing and early ligation may be required. All large ducts can lead to progressive pulmonary vascular disease but ducts of all sizes are closed (nowadays, often at cardiac catheterisation) to prevent infective endocarditis.

Combinations of defects can lead to shunts at more than one level; symptoms may be more severe and pulmonary vascular disease more aggressive than with isolated lesions, so surgery is often needed at an early age. An example is atrioventricular septal defect: a spectrum of abnormalities which includes atrial and ventricular defects.

(2) Pulmonary venous congestion and oedema

These patients may be pink or blue but have signs of pulmonary oedema clinically and on radiography.

Obstruction to pulmonary venous return can occur in the pulmonary venous pathway

(obstructed total anomalous pulmonary venous drainage), within the atrium (cor triatriatum) or by obstruction to left ventricular inflow at supra-valvar, valvar, or submitral level (parachute mitral valve). Children with pulmonary venous obstruction usually present in early infancy with cyanosis and dyspnoea due to pulmonary oedema; those who present less acutely fail to thrive with respiratory symptoms.

In total anomalous pulmonary venous drainage, all the pulmonary veins drain into a confluence behind the heart and thence to the right atrium, usually indirectly via the innominate vein, coronary sinus or portal system. Saturated and desaturated blood mix in the right atrium; sufficient oxygenated blood crosses an atrial septal defect to support the systemic circulation while the remainder re-enters the right ventricle. The long pulmonary venous pathway is usually obstructive, causing pulmonary venous hypertension and pulmonary oedema and contributing to a high pulmonary vascular resistance. In this situation immediate corrective surgery is mandatory.

(3) Prejudiced systemic perfusion

These children, who may be pink or blue, have dominant features of poor peripheral pulses and acidosis. This can be a result of low left ventricular stroke volume (for example hypoplastic left heart syndrome; figs 4A, B), left ventricular outflow tract obstruction (most commonly aortic valve stenosis) or aortic obstruction (interrupted aortic arch and coarctation). Even when the anatomical obstruction is severe, the fetus survives because the right ventricle can provide systemic perfusion through the ductus (fig 4B). Systemic hypoperfusion or lower body hypoperfusion in coarctation occurs as the duct closes after birth, the pulses becoming impalpable. Progressive acidosis impairs the function of all organs including the heart, and a vicious circle of dysfunction accelerates the infant's collapse. Maintaining duct patency by prostaglandin infusion interrupts the vicious circle. These patients often have additional feature of pulmonary venous congestion due to the associated left ventricular failure in the face of a high afterload.

Figure 4 Hypoplastic left heart syndrome (different cases). (A) also shows the small mitral valve (mv) and interatrial communication. (B) postnatal study showing obligatory right to left ductal flow moving away from the transducer as a blue/white signal; this picture is the converse of fig 2(B). AAo=ascending thoracic aorta, DAo=descending thoracic aorta, LA=left atrium, LPA=left pulmonary artery, LV=left ventricle, PDA=patent ductus arteriosus, RA=right atrium, RPA=right pulmonary artery, RV=right ventricle, lpv and rpv=left and right pulmonary veins respectively, tv=tricuspid vein.

Figure 5 Tricuspid atresia apical four chamber view showing a thick bar of tissue separating right atrium (RA) and right ventricle (RV). The atrial septum bows to the left; compare with fig 3. LA=left atrium, LV=left ventricle, mv=mitral valve.

CYANOSIS

Cyanosis may be best 'explained' by three mechanisms, which can prevail in combinations: low pulmonary blood flow, transposition streaming, and complete intracardiac mixing.

For cyanosis to be observable a concentration 5 g/100 ml of desaturated haemoglobin is said to be required, making the diagnosis of cyanotic congenital heart disease difficult in the mildly desaturated or anaemic patient. Conversely polycythaemia may make cyanosis more conspicuous. In diagnostic doubt, the hyperoxic test is helpful, particularly as it can now be minimally invasive with the use of transcutaneous monitoring.

(4) Low pulmonary blood flow

These patients are blue but not breathless and have oligoemic lung fields on radiography.

Alveolar function is normal so the pulmonary venous blood is fully saturated but the pulmonary flow is low so there is little oxygenated blood to circulate. Because the lungs are oligoemic, they are compliant so the child is not breathless unless extremely blue. Low pulmonary flow is usually related to severe pulmonary valvar or subvalvar (infundibular) obstruction. When isolated, this can cause the right ventricle to hypertrophy to the extent that it is thicker and less compliant than the left ventricle in diastole. Systemic venous return to the right atrium then tends to stream preferentially across any defect in the atrial septum into the left atrium and ventricle, the reverse of the isolated atrial septal defect physiology (figs 5, 6).

More commonly, in the presence of a large

Figure 6 Pulmonary atresia with intact ventricular septum: subcostal four chamber view showing the interatrial septum (ias) bowing to the left and an obligatory right to left interatrial shunt; this picture is the converse of fig 1(B). LA=left atrium, LV=left ventricle, RA=right atrium.

ventricular septal defect, pulmonary valvar or infundibular stenosis causes a right to left shunt through the ventricular septal defect – the physiology of tetralogy of Fallot. In this context, the degree of right to left shunting and hence of cyanosis is determined by the relative resistances to right and left ventricular outflow. Most of the resistance to right ventricular ejection is the anatomic obstruction itself. This can be variable, particularly when it has a prominent infundibular 'muscular' element. The systemic vascular resistance is also variable, falling with exercise and other causes of widespread vasodilatation so that cyanosis typically increases on exertion. As less and less blood passes from right ventricle to pulmonary artery, the corresponding stenotic 'ejection' murmur gets shorter and the child bluer. This can happen gradually (tetralogy of Fallot is typically a progressive disease) or acutely as in a cyanotic spell. Management of a cyanotic spell depends on altering the relative resistances to right and left ventricular outflow, relaxing right ventricular infundibular spasm with propranolol and/or morphine and, if necessary, introducing an infusion of a powerful systemic vasoconstrictor such as noradrenalin. Troublesome cyanotic spells or progressive cyanosis are indications for surgery, which will usually be 'corrective' unless contraindications such as unfavourable right ventricular outflow tract or pulmonary artery anatomy pertain when a systemic to pulmonary shunt may be performed.

(5) Transposition streaming

These patients are obviously blue. Breathlessness suggests an additional lesion, such as a ventricular septal defect. The aorta arises from the right and the pulmonary artery from the left ventricle; systemic and pulmonary circuits thus operate in parallel rather than in series. Cyanosis is mainly related to the unfavourable streaming of desaturated caval return into the aorta. Survival depends on there being some potential

for mixing between streams: mixing is better at atrial level than ventricular level, better at ventricular than great artery level.

The right ventricle serves the systemic circulation and thus operates at high pressure. The left ventricle supplies the pulmonary circulation so in 'simple' transposition ('simple' implies no additional cardiac defects) its pressure falls as the pulmonary vascular resistance falls postnatally. Critical cyanosis in transposition is best managed by urgent balloon atrial septostomy, to improve atrial mixing. In simple transposition surgical management decisions must be made in the first two weeks or so of life, when the 'arterial switch' operation (which connects the great arteries to the appropriate ventricles) is still an option. Once the pulmonary vascular resistance has fallen postnatally the left ventricle 'hypo' trophies, as does the right ventricle of a normal heart, and when that has occurred the left ventricle is unable to sustain systemic pressures immediately after the operation.

A significant ventricular septal defect compounding transposition of the great arteries serves to maintain the subpulmonary left ventricle at high pressure and so a switch operation can be delayed. However, as the pulmonary vascular resistance falls the pulmonary blood flow can increase massively in the presence of parallel circulations. If the atrial septum is intact or the atrial foraminal flap is competent enough to prevent left to right atrial communication, plethora and pulmonary venous congestion can render the baby very breathless. Pulmonary venous hypertension, and cyanosis also makes relatively small left atrium. The combination of high pressure, high pulmonary flow, pulmonary venous hypertension and cyanosis also makes babies with this anatomy vulnerable to very premature and aggressive pulmonary vascular disease, only preventable by surgical correction within the first few months of life.

(6) Intracardiac mixing

These patients are mildly cyanosed and usually breathless. Complete intracardiac mixing of

saturated and desaturated blood can occur at atrial level (for example unobstructed total anomalous pulmonary venous drainage) at ventricular level (for example all 'univentricular' hearts) or at great artery level (for example truncus arteriosus). The level of cyanosis depends mainly on the relative amounts of saturated and desaturated blood in the mixture, itself dictated mainly by the total pulmonary blood flow. This may be restricted (by anatomic pulmonary valvar or subvalvar obstruction or by pulmonary vascular disease) or be very high. For example, there is rarely any organic obstruction between the aorta and pulmonary artery in truncus arteriosus and in such a situation the child suffers increasingly from the effects of a torrential pulmonary blood flow as pulmonary resistance falls postnatally.

Conclusion

Exact anatomical diagnosis in the field of complex congenital heart disease rests largely with cross sectional echocardiography. In a recent study, specialists reached a correct anatomical diagnosis on the basis of clinical features without echocardiography in only 64% of referred neonates; the 'score' for neonatologists was 34%. To aim at allocating patients to the appropriate physiological category is much more appropriate and all that is required for the initial management of a sick infant.

Further reading

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