

Chapter

1

The Fetal Circulation and Patent Ductus Arteriosus

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Introduction

In contrast to the adult, who is surrounded by air with a changing environmental temperature, the developing fetus is surrounded by amniotic fluid at 37°C. The fetus relies upon the maternal circulation for provision of nutrients, removal of metabolites and respiration, including oxygen supply and carbon dioxide removal. The fetus is a rapidly developing organism, but it exists in a state of relative hypoxia. The developing brain is the most sensitive organ to hypoxia, and the fetal cardiovascular system ensures delivery of the highest oxygenated blood to the brain, whilst blood is distributed to the remaining organs depending on local requirements.

Comparison of the Adult and Fetal Circulations

In health, the adult circulation contains approximately 5 litres (66 mL/kg) of blood, equivalent to 6 to 8 per cent of body weight. Eighty per cent of the circulating volume is in the systemic veins, right side of the heart and pulmonary circulation. The cardiac output is approximately 5 litres/min (~66 mL/kg/min) secondary to a left ventricle contracting 70 times per minute and ejecting a stroke volume of 70 mL with each contraction. Deoxygenated blood returns to the right ventricle, and the entire cardiac output passes via the pulmonary arteries to the lungs for the purposes of gas exchange. Oxygenated blood returns via the pulmonary veins to the left ventricle and systemic circulation. The right and left sides of the heart are separate, and the pulmonary and systemic circulations are in series. The pulmonary circulation is low pressure (25/10 mmHg) compared to the systemic circulation (120/80 mmHg).

In the fetus, gas exchange occurs at the placenta. For oxygenated blood to return to the systemic circulation and deoxygenated blood to the placenta there are several communications or shunts present, and

the two circulations are in parallel with both ventricles contributing to the total cardiac output. The fetal circulation is illustrated in Figure 1.1.

The fetal cardiac output is approximately 300 mL/min/kg, with the right ventricle contributing approximately two-thirds of the total cardiac output. The heart rate is 130 to 160 beats/min. Approximately 40 per cent of the cardiac output perfuses the placenta and returns to the heart via the umbilical venous

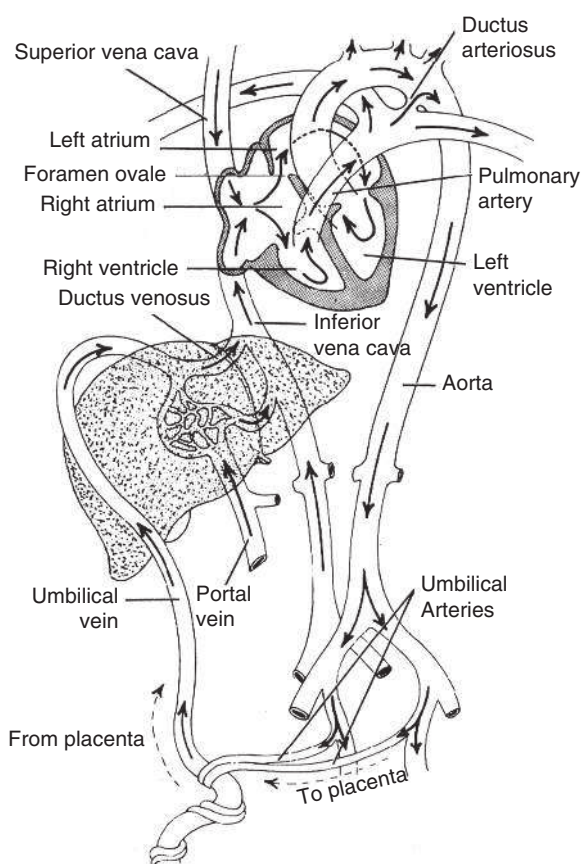


Figure 1.1 Fetal circulation.
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Table 1.1 Oxygen Saturations within the Fetal Circulation

Location	Oxygen saturation (%)
Umbilical veins	80
Ductus venosus	75
Left atrium	70
Ascending aorta	65
Right ventricle	55
Ductus arteriosus	52
Descending aorta	55
IVC (below the ductus venosus)	25
SVC	25

system with an oxygenation saturation of approximately 80 per cent. This is the most highly saturated fetal blood in the circulation. Half this blood supplies the liver, and the rest passes via the ductus venosus to the inferior vena cava (IVC), where it meets the desaturated systemic venous drainage from the lower body. Selective streaming of these two flows minimizes mixing with the well-oxygenated blood from the ductus venosus, which is directed posterior and leftward in the IVC. The blood from the IVC enters the right atrium, and further streaming occurs via the anatomical configuration of the Eustachian valve and the upper margin of the foramen ovale to split the stream of blood into an anterior rightward stream that enters the right atrium and a posterior leftward stream (well-oxygenated ductus venosus blood) to the left atrium. Despite this arrangement, some mixing does occur, but the oxygen saturation of the left atrial blood is approximately 70 per cent (Table 1.1). This blood is ejected by the left ventricle to supply the heart and brain. Desaturated blood returning from the upper body via the superior vena cava (SVC) is directed through the tricuspid valve along with the desaturated blood from the coronary sinus into the right ventricle. This accounts for approximately 60 per cent of the venous return to the heart and explains why the right ventricle contributes to two-thirds of the cardiac output. The right ventricular blood is approximately 55 per cent saturated. Only 8 per cent of the combined ventricular output passes to the pulmonary circulation; the remainder passes directly via the ductus arteriosus to the descending aorta. The pulmonary vascular resistance is very high due to the presence of relatively few arteries and because the lungs are not expanded. The right atrial pressure is higher than the left,

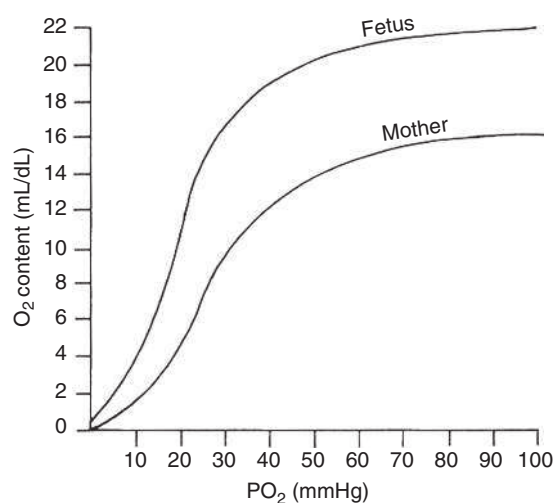


Figure 1.2 Oxygen dissociation curve of fetal and maternal haemoglobin.

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reflecting the greater blood flow through the right atrium. The ductus arteriosus creates little resistance, and the right ventricular and pulmonary artery pressure is 1 to 2 mmHg higher than that of the aorta (55/35 mmHg) and left ventricle (55/2 mmHg).

Fetal Haemoglobin

The maternal arterial blood in the placenta has an oxygen saturation of 80 to 90 per cent. The essential characteristic of fetal haemoglobin is that it has a higher affinity for oxygen than maternal haemoglobin. Fetal haemoglobin (Hb-F) has an oxygen dissociation curve that is displaced to the left compared to adult/maternal haemoglobin (Figure 1.2). This displacement increases the slope of the curve, and consequently, for a given partial pressure of oxygen (PO_2), more HbO_2 is formed. The difference is due to Hb-F binding 2,3-diphosphoglycerate less effectively than maternal Hb. At birth, 80 per cent of the fetal haemoglobin is Hb-F, and this falls to approximately 10 per cent by four months of age.

Changes in Fetal Circulation at Birth

At birth, the pulmonary circulation is established, followed by closure of fetal shunts (Figure 1.3). The placental circulation is interrupted, which increases systemic vascular resistance and decreases IVC return and right atrial filling. There is an increase in oxygen utilization secondary to increased work of breathing

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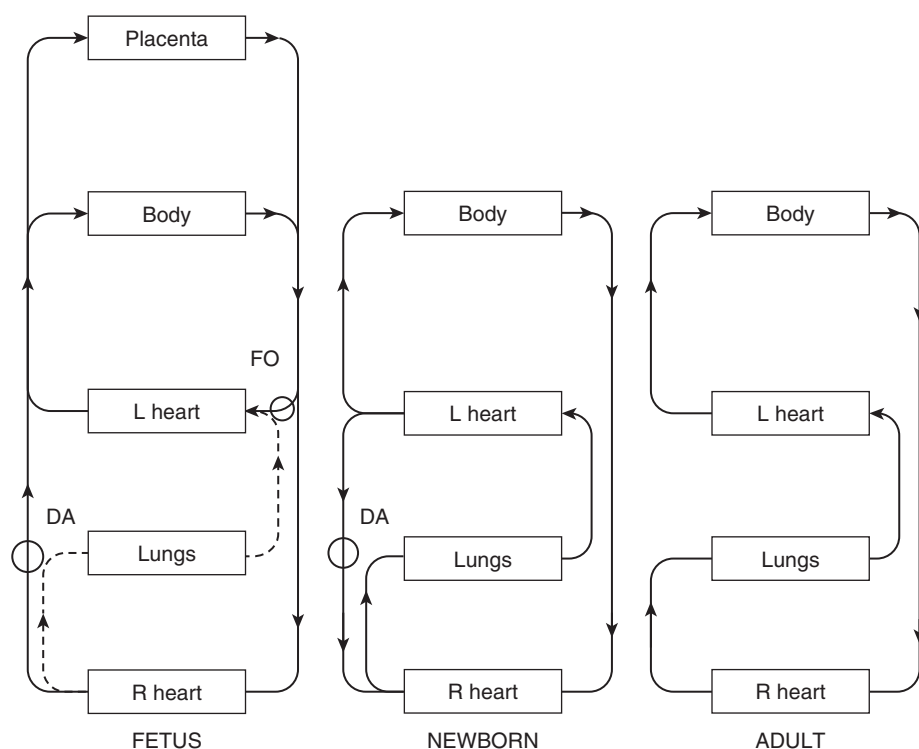


Figure 1.3 Changes in the fetal circulation at birth.
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which is accompanied by an increase in cardiac output. As the lungs are expanded, oxygen levels increase, and vasodilators including nitric oxide are released. The pulmonary vascular resistance falls to approximately half the systemic values by the first 24 hours of life. There is an eight- to tenfold increase in pulmonary blood flow resulting in increased blood flow to the left atrium. The pressure difference between the right and left atrium is reversed, and this closes the flap valve of the foramen ovale. The ductus arteriosus begins shunting left to right before it begins to constrict due to the production of bradykinin stimulated by increasing oxygenation and the fall in circulating prostaglandins.

Persistent fetal circulation or 'persistent pulmonary hypertension of the newborn (PPHN)' occurs in approximately 0.1 to 0.2 per cent of live births. The usual changes at birth of pulmonary vasodilatation, ductal closure and closure of the foramen ovale do not occur. The pulmonary vascular resistance remains high, even in excess of systemic vascular resistance. This results in decreased blood flow to the lungs, and instead, blood passes from the pulmonary artery via the patent ductus arteriosus to the systemic circulation. This results in a right-to-left shunt. In addition, the right ventricular and right atrial pressures remain elevated and in excess of left

atrial pressure. The flap valve of the foramen ovale does not close, and a further right-to-left shunt occurs at atrial level, with blood bypassing the pulmonary circulation. The presence of right-to-left shunts and decreased pulmonary blood flow results in hypoxia.

Patent Ductus Arteriosus

The patent ductus arteriosus (PDA) usually closes in the first month of life. In premature babies, ductal closure may not occur such that 80 per cent of premature babies weighing less than 1,200 g will have a patent duct (PDA). Many of these babies are asymptomatic, but those with a large duct and a significant left-to-right shunt will present in congestive cardiac failure with bounding pulses, continuous murmur and a volume-loaded left ventricle. Initially, the baby is managed with anti-failure medication. A course of indomethacin or ibuprofen can be used to precipitate ductal closure, but if this is unsuccessful, the duct has to be closed surgically, usually via a left lateral thoracotomy. Indomethacin is contra-indicated in patients with renal insufficiency or intra-cranial haemorrhage. The use of these drugs has reduced the need for surgical closure from 30 to 5 per cent of haemodynamically significant ducts.

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In larger children (>4 kg), the duct may be occluded using a trans-catheter device.

Morphology. The arterial duct connects the main pulmonary artery with the descending aorta, just distal to the origin of the left subclavian artery. If there is a left aortic arch, it is usually left sided; in right aortic arch, it may be left or right sided. In some conditions, it may be absent or, rarely, bilateral. It varies in length and diameter. The media consists of spirally arranged smooth muscle, and the intima is thicker than the aorta. After birth, the media contracts, thus shortening and occluding the duct. The endothelial layer folds, the subintimal layers proliferate and the duct thus closes permanently within two to three weeks of birth. This process can be delayed by prostaglandins E1 and E2 and prostacyclin.

Pathophysiology. After birth, the pulmonary vascular resistance falls, and there is left-to-right shunting from the aorta to the pulmonary arteries, leading to over-circulation and congestive heart failure.

Presentation

Premature infants with this defect may be ventilator dependent or require long periods of non-invasive ventilation. Many older children may be asymptomatic. Large shunts may present as congestive heart failure early in life.

Procedure. In the United Kingdom, the majority (90 per cent) of surgical PDA ligations are performed in premature neonates. The approach is via left lateral thoracotomy in the fourth intercostal space. Access in the small chest cavity, retracting the congested lung, is limited. The duct is frequently the same size as the descending aorta, and the anatomy of the arch must be clearly defined to prevent inadvertent ligation of the aortic arch. Once defined, the PDA is either ligated with a ligature or with LIGACLIPS according to surgical preference. Encircling with a ligature gives better definition of the anatomy but may carry greater risk of damaging the fragile ductal tissue. There should be immediate improvement in diastolic pressure.

Ligation in older children is now virtually unknown due to the success of interventional device closure. However, if referred an older child the duct will have become a much more rigid structure and surgery may require formal mobilization, transection and over-sewing of the PDA to ensure that there is no residual shunt.

The greatest risk in these fragile babies is haemorrhage, but the incidence is less than 0.5 per cent. Other complications include recurrent laryngeal nerve injury, chylothorax and pneumothorax. Despite being a safe procedure, the 30-day mortality remains relatively high (5 per cent) reflecting the comorbidities of (what is often) extreme prematurity.