Fetal echocardiography: 20 years of progress

H M Gardiner

Considerable advances in ultrasound technology and close collaboration between the specialties of paediatric cardiology and fetal medicine have resulted in the increasing ability to diagnose congenital heart disease before birth over the last two decades. Fetal cardiology differs from paediatric cardiology not only in the spectrum of diseases seen, but also in the assessment of function because of the extended feto-placental circulation. Importantly, outcomes for specific lesions may differ as extracardiac abnormalities and chromosomal defects may alter the prognosis of otherwise straightforward cardiac lesions such as tetralogy of Fallot. Historically the examination of the fetal heart and circulation developed separately, obstetricians using Doppler to examine the uteroplacental circulation to study the pathophysiology of pregnancy, while cardiologists focused their attention on the morphological aspects of cardiac development using M mode and Doppler. In today’s practice a comprehensive evaluation of the fetal cardiovascular system includes both structural and functional assessment using new technologies to monitor the progression of cardiac defects and to aid management decisions such as the need for early delivery, treatment of arrhythmia or for interventions such as balloon valvuloplasty of semilunar valve obstruction.

The underlying problem
Congenital heart disease affects 6–8 per 1000 live births, at least half of which should be detectable before birth because of their serious nature. However, if examination of the fetal heart is confined to traditional high risk groups only about 20% of babies born with congenital heart disease will be identified (table 1). Therefore the focus must be to examine all pregnancies for cardiac malformations. The opportunity to do so is present in some centres at 11–14 weeks when nuchal fold thickness is measured to assess the risk of chromosomal defects in the fetus. However, in the UK most pregnant women are assessed for the first time in detail by sonographers at the level 2 or anomaly scan at about 20 weeks in their local obstetric ultrasound department.

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<td>Extracardiac anomalies</td>
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Scanning the fetal heart: specialised equipment and developments

**PROBES**
Transvaginal scanning of the heart is favoured in some centres as part of the first trimester scan at 11–14 weeks, and impressive views can be obtained because of the close proximity of the probe to the fetal heart when the fetal lie is favourable. Transabdominal fetal cardiac scanning is more commonly performed. Diagnostic views can be obtained at 14 weeks using modern probes with limits of resolution of about 50 µm in the axial plane at 6 MHz and less than 100 µm in the lateral plane, at normal obstetric scanning depths. A curvilinear probe with a cardiac package incorporating fast frame rates is ideal, although standard cardiac probes may also be used which have the advantage of continuous wave Doppler available to interrogate high velocity aortic/ventricular valve regurgitation or severe semilunar valve stenosis. Colour flow mapping and Doppler may be helpful adjuncts to early diagnosis but their use should be limited in the first trimester to avoid any possible damage to the developing fetus. Special presets for examination of the fetal heart should be used to ensure that the spatial–temporal average power output for colour and pulsed Doppler mode is < 100 mW/cm².

**NEW IMPROVEMENTS IN IMAGING**
Two dimensional imaging is still the most commonly used imaging modality in fetal echocardiography. Most probes in use have very fast frame rates, achieved by parallel processing where the transducer transmits one line and receives two, resulting in a doubling of previous rates. This is now standard practice and most useful in fetal echocardiography at the 5 or 4 MHz settings when high maternal body mass index makes visualisation difficult, or in polyhydramnios where the fetus may be at more than 20 cm depth. Transmitting at 2 MHz and receiving at 4 MHz greatly improves the resolution at depth and decreases interference caused by side lobes. This occurs at the expense of reduced frame rates, which can make fetal valvar structures appear “thicker” than they really are. A 4:1 ratio will soon be available but spatial resolution will
necessarily be compromised because the transmitting beam will cover four lines. More advanced techniques such as three dimensional rendering and spatial compounding may be of use in the future, but currently are used in more general imaging settings and as research tools. Spatial compounding creates a frame consisting of multiple lines of data from various locations on the transducer. The resulting image improves spatial resolution (again at the expense of frame rates) and reduces clutter with elimination of ultrasound artefacts. The major problem thus far in the application of this in fetal echo is the loss of frame rates multiple sampling entails. For example, a typical spatial compounding setting requires seven views temporally averaged over seven times the normal frame rate. For a fundamental rate of 49 Hz (49 frames/second), a seven view compounded image will contain frames taken over the last 7/49th of a second while the image is being updated every 1/49th second. This results in frame rates too slow for practical use so far in imaging the fetal heart.

COLOUR DOPPLER IMAGING

Colour flow mapping and particularly power Doppler are helpful in imaging flow in the very small heart. The advantages of colour flow mapping are that it allows assessment of valve opening and of symmetry in ventricular filling (fig 1A) in cases where visualisation using the grey scale alone, even with harmonic imaging, is difficult. It may highlight areas of turbulence or of important atrioventricular valve regurgitation that provide important clues to major structural defects during first trimester scanning. Power Doppler has certain advantages in early pregnancy as it fills the vessels well, particularly when there is a change in direction of flow that might lead to “black spots” in conventional colour velocity flow maps (figs 1B,C).

Pitfalls in the use of colour Doppler are its tendency to “bleed” through the cross sectional images creating misleading appearances, such as perimembranous ventricular septal defects, and falsely increasing the size of the great arteries.

Fetal cardiac function

An assessment of fetal cardiac function can be made using traditional M mode to provide information on wall thickness and ventricular shortening fraction, but it is somewhat crude. Fetal long axis function may provide additional insight into endocardial function, most usefully in the detection of early ischaemic changes before the development of sonographically detectable endocardial fibroelastosis (EFE). Long axis recordings show the importance of atrial function in the fetal heart (fig 2A) and Doppler tissue imaging (DTI) provides a transmoyocardial tissue velocity profile and permits assessment of radial and longitudinal strain rate (figs 2B,C), but the timing of cardiac events cannot be verified with a concurrent ECG recording and currently depends on surrogates such as mitral valve closure signals. Left ventricular DTI has shown increased duration of early diastole and reduced endocardial velocities in children with obstructive lesions (such as aortic stenosis) before obvious abnormalities of function are apparent. In the future these methods may be helpful in determining the timing of interventions such as either early

Figure 1 Colour Doppler energy scan of a 13 week fetal heart showing: (A) normal four chamber view with symmetrical flow into right (RV) and left (LV) ventricles; (B) normal aortic and (C) ductal arches that can easily be distinguished by the hooked and broad orientation they take as they arise from their respective ventricular origins.

Figure 2 (A) Long axis function of the fetal heart shows the excursion of the atrioventricular junction during the cardiac cycle and the importance of atrial contraction “(a)” in fetal function. (B) Doppler tissue imaging in M mode may reveal more about endocardial function than conventional M mode traces (C) as it allows calculation of transmoyocardial tissue velocity profile and longitudinal strain rates. Surrogate gating of the cardiac cycle utilises the mitral valve closing artefact (MV).
delivery of the fetus, or of in utero interventions such as fetal aortic balloon valvuloplasty, before irreversible damage to the endocardium occurs.

Congestive cardiac failure is seen in the fetus during tachyarrhythmias caused by the rise in systemic venous pressure and reduced ventricular filling time, but may also be seen secondary to viral myocarditis and restrictions to flow—for example, at the oval foramen level. Associated findings may include an increased cardiothoracic ratio, severe atrioventricular valvar regurgitation, reversal of flow in the systemic veins at end diastole, and the development of effusions or of fetal hydrops. A “heart failure score” has been developed using this profile and methods such as the Tei index, which is afterload independent, may prove useful in serial assessment of the fetus with hydrops.89

It is clear from these methods that fetal cardiac function is not assessed from measures of intracardiac function alone but by Doppler assessment of the fetal circulation, which provides a more complete evaluation of the effects of cardiac preload and afterload on fetal wellbeing. The salient features of the fetal circulation that differentiate it from the postnatal cardiovascular system and make Doppler such a useful tool are the arterial and venous ducts, the oval foramen, and the aortic isthmus, all of which close or differ functionally after birth. While the fetal ventricular arrangement is in parallel, the arterial and venous ducts and the oval foramen permit mixing of flows between the right and left sides of the circulation, thus allowing flow returning from the placental circuit (with the highest oxygen content) to reach the left heart (through the venous duct and oval foramen) and therefore perfuse the fetal brain. With increased pulmonary venous return after birth, left atrial pressure rises and the oval foramen becomes functionally closed, or if it remains patent flow reverses to become a left to right shunt. In addition, flow through the aortic isthmus increases with a concomitant increase in size.

An understanding of the role of these structures in the fetus helps with functional assessment and in serial assessment of the fetus with structural heart defects.

DEVELOPMENTAL CHANGES IN DOPPLER WAVEFORMS

Doppler patterns that may be indicators of fetal compromise in later pregnancy are a normal early finding. An appreciation of this is important if first trimester assessment of fetal cardiac function is performed.10 Flow in the early fetal descending aorta and in the umbilical arteries shows absent flow in diastole (fig 3A). This is abnormal in later gestation as mature arterial flow patterns show low velocity continuous prograde flow throughout diastole (fig 3B). The development of this pattern depends on a successful twofold fall in systemic impedance after 12 weeks gestation, secondary to placental angiogenesis.11 Failure of adaptation leads to increased left ventricular end diastolic pressure and reversal of flow in the descending aorta may be observed (fig 3C), with a reduction in...
ventricular compliance and myocardial contractility often associated with poor intrauterine fetal growth.

VENTRICOLO-VASCULAR COUPLING

Intracardiac Doppler is closely associated with flow in the systemic veins throughout gestation as evidenced during tachyarrhythmia. However, the early venous circulation is characterised by pronounced reversal of flow in the caval veins coincident with atrial contraction. Inferior caval vein (IVC) reverse flow at 12 weeks accounts for 25–30% of the total flow of the IVC and is sixfold more than that seen at later gestation (fig 3E). Atrial function is pivotal in the early fetal circulation with monophasic patterns of ventricular filling at eight week's gestation being replaced by differentiation into dominant A and smaller E waves by nine weeks and clear differentiation into mitral and tricuspid waveforms by 10–11 weeks (fig 3F). At all stages during gestation the atrial wave is dominant, but the E:A ratio approaches unity at term. Flow through the tricuspid valve is greater than through the mitral throughout gestation demonstrating right ventricular predominance. Umbilical venous pulsations are also normal before 14 weeks of gestation and are thought to be caused by transmission of pressure waves (cardiac pulsations) along the venous duct (fig 3D). However, flow in the venous duct always remains prograde towards the heart and is not characterised by reversal during atrial contraction except in fetal hypoxaemia. Maturity leads to a major increase in diastolic inflow in both the arterial and venous components of the circulation and an increase in cardiac compliance and relaxation rate.

Congenital heart disease: making a diagnosis

Despite the proven efficacy of training sonographers to recognise cardiac abnormality in the fetus only about a quarter of babies in the UK born with a cardiac malformation are diagnosed before birth. The detection of a fetus who will have a duct dependent circulation after birth or who has simple transposition of the great arteries with a restrictive atrial ventricle perfuses the ascending aorta, coronary, and cerebral circulation and the right ventricle only the pulmonary flow and descending aorta. With increasing downstream impedance there is reversal of flow about the aortic arch, easily detected on colour flow mapping. Because of the large arterial duct, detection of a discrete coarctation of the aorta may be difficult antenatally (and indeed may not be evident until the duct closes after birth). Therefore diagnosis often depends on surrogate measures such as an enlarged right ventricle or if tubular hypoplasia of the aortic arch is present by an abnormal “three vessel view”.

PITFALLS OF EARLY SCANNING

The heart is formed and septation completed by 50 embryonic days, and early imaging of the heart is possible from transvaginal views at about 11–12 weeks (63–70 days). Transvaginal scanning in a large series of almost 40 000 early pregnancies in Israel has detected cardiac abnormalities in almost 0.5%. Just over a quarter represented isolated abnormalities with 40% associated with chromosomal abnormalities. The majority (82%) was found in those formerly assessed as low risk pregnancies (table 1) but one third of the total had increased nuchal translucency indicating the potential importance of this in screening in the future. In one UK study, diagnostic images
were obtained using transabdominal echocardiography in 226/229 fetuses (98.7%) between 12–15 weeks, with abnormalities of the cardiac connections detected in 13 fetuses (5.7%) on the initial scan and another four cases detected later in gestation or postnatally (mostly ventricular septal defects).24 Conditions that are easier to detect in early gestation are those with an absent connection or large septal defect, those without a great arterial crossover, or an apparently single great artery. An important false negative finding at this early stage is when progressive stenosis of an apparently normal semilunar valve occurs and may result in severe conditions such as pulmonary atresia/intact ventricular septum or hypoplastic left heart syndrome later in pregnancy. Thus, it is important to perform sequential scans to confirm that growth is normal, or to clarify the findings and progression of any malformation identified in early gestation.

While echocardiographic screening hinges on incorporating five transverse views of the fetal abdomen and chest into the routine obstetric scan (fig 5), images of the fetal heart are more varied than those possible after birth and resemble cuts obtained using magnetic resonance imaging (fig 6). Limited scans, such as the four chamber view alone, are insufficient and although this view may detect absent connections such as tricuspid atresia (fig 7A), large septal defects (fig 7B), ventricular hypoplasia associated with pulmonary atresia and intact ventricular septum (fig 7C), and hypoplastic left heart syndrome (fig 7D), major cardiac abnormalities such as tetralogy of Fallot or transposition of the great arteries that may have normal four chamber views (figure 8A, C) are likely to be missed unless the scan is extended to include the outflow tracts, equivalent to the “five chamber view” (fig 8B, D) and views to assess the pulmonary trunk.25 Disproportion or abnormal flow on colour Doppler at the “three vessel view” is of tremendous importance in the fetal cardiac examination (fig 5F). There is no postnatal equivalent to this view that shows the transverse aortic and ductal arches and superior caval vein (or persistent left SVC) (fig 5G). 

![Figure 4](A) The pulmonary trunk extends into the arterial duct to form a ductal arch (D) that is of similar size to the transverse aortic arch (Ao), with flow in the same direction as shown on colour flow mapping. (B) Doppler velocity in the arterial duct is of high velocity and continuous. (C) Pulmonary atresia manifests in reversal of flow from the transverse aortic arch retrogradely to the atretic valve and may result in a curly “pig’s tail” duct (D). Tricuspid regurgitation of high velocity and long duration impairs ventricular filling (E).
Figure 5  (A) A full examination of the fetal heart may be obtained by five transverse sections through the abdomen and chest of the fetus. The first section shows abdominal situs (B) with the aorta (Ao) to the left of the spine and the inferior caval vein (IVC) anterior and to the right. The normal fetal stomach (St) and heart lie on the left side. The second section (C) illustrates the four chambers of the heart with the left atrium (LA) in front of the spine and the right ventricle (RV) just below the sternum. The third cut (D) shows the aorta arising centrally in the heart from the left ventricle (LV) and the fourth the pulmonary trunk (PV) arising from the anteriorly placed right ventricle and crossing to the fetal left over the ascending aorta (E). The fifth section shows the anteriorly positioned ductal arch (D) and the transverse aortic arch (Ao) to be of equal size traversing back to the fetal spine (F). A normal variant “three vessel” view is shown with a right sided aortic arch and persistent left superior caval vein (LSVC). The trachea (T) can be seen lying between the aortic (Ao) and ductal (D) arches (G).
Figure 6  Additional views are often required to make a full diagnosis in cases of abnormality. (A) Coronal view of the inferior bridging leaflet of the common valve in an unbalanced atrioventricular septal defect. (B) Sagittal views of the superior (SVC) and inferior caval (IVC) veins draining to the right atrium (RA), and (C) of the aortic arch. (D) Coarctation of the aorta may manifest as early ventricular disproportion with persistent enlargement of the right ventricle (RV).

Figure 7  Major abnormalities such as absent right connection (tricuspid atresia (A)), large septal defects (tetralogy of Fallot (B)), ventricular hypertrophy or hypoplasia (pulmonary atresia with intact ventricular septum, (C)) and hypoplastic left heart syndrome (D) may be diagnosed from these five screening views.
Abnormality of this may be the first clue of important semilunar valve or aortic arch malformation, as the diagnosis of coarctation of the aorta may be difficult because of the large patent arterial duct. The combination of disproportion at the four chamber view and three vessel view is sufficient to be forewarned and to arrange delivery of a fetus near to a cardiac centre for early postnatal assessment and possible surgery.

Coronal views of the fetal heart are particularly useful for looking at the atrioventricular valves and in delineating the features of a common valve in atrioventricular septal defect (AVSD), particularly in the setting of ventricular imbalance (fig 6A). These views are similar to postnatal subcostal views. Sagittal views of the fetus directed parallel to the fetal spine profile the systemic venous connections, the right ventricular outflow tract and ductal arch, and the aortic arch and its branches (fig 6B, C).

Progression of cardiac lesions: lessons and pitfalls

Major structural defects are relatively easy to detect early in pregnancy and counselling is straightforward—for example, an absent connection usually determines that the only surgical option will be univentricular palliation for the child (a Fontan type circulation). However, defects that worsen during the second and third trimester, such as pulmonary atresia with intact septum, may only show subtle morphological abnormalities at first—for example, tricuspid regurgitation and mild right ventricular hypertrophy—and the severity may be underestimated as the right ventricle fails to grow during pregnancy. Pulmonary stenosis has been shown to progress during pregnancy and postnatal evaluation of even mild fetal pulmonary stenosis is important. The assessment of adequacy of ventricular size for suitability for a functionally biventricular repair is difficult before delivery. The presence of a left superior caval vein draining to an enlarged coronary sinus in a normal heart may cause significant disproportion in early pregnancy, which is insignificant by term. In contrast, the heart with multiple ventricular septal defects and a slightly small aortic root may not be suitable for a biventricular repair after birth. Hypertrophic cardiomyopathy is usually only evident near term, or in infancy, and has not been described earlier in gestation. Therefore, where there is a family history, follow up arrangements should be set in place, despite the presence of a normal early fetal assessment, which should not be regarded as “reassuring”. Abnormalities of Doppler flow, such as reversal of flow in the pulmonary veins with increasing left atrial pressure, may provide early clues to developing or worsening cardiac disease in the setting of hypoplastic left heart syndrome or of a restrictive oval foramen in transposition of the great arteries—an early warning that the neonate may require early balloon atrial septostomy to prevent pulmonary haemorrhage and neonatal demise (fig 9A–D).

Figure 8 Important conditions such as transposition of the great arteries and tetralogy of Fallot may be missed on a four chamber view (A, C) and require visualisation of the great arteries to make the diagnosis (B, D).
Fetal treatment

ARRHYTHMIAS

Complete heart block is thought to occur in about 1:20 000 newborns. Tachycardias are more commonly seen during infancy with a prevalence of about 1:3000, although both bradycardia and tachycardia may be recognised more commonly in a fetal population.

The successful treatment of fetal tachycardia may be lifesaving as untreated these fetuses may become hydropic and die (fig 10A). Most tachycardias are atrial in origin and occur in fetuses without associated structural abnormalities. Indications for treatment are sustained tachycardia or fetal hydrops because there is a risk of intrauterine death, estimated between 20–50%.27 The diagnosis is made using M mode or Doppler tracing, and simultaneous Doppler interrogation of the aorta and SVC provides useful information as the reversed “a” wave of the venous trace represents atrial activity and its relation with the aortic flow allows assessment of the timing of atrial and ventricular activity and calculation of V-A intervals; thus, fetal tachycardias can be divided into long (automatic atrial tachycardia and persistent junctional reciprocating tachycardia) and short V-A (atrioventricular re-entrant tachycardias) intervals which guides therapeutic management (fig 10B, C).28 Doppler tissue imaging at the atrioventricular junction has also been used to calculate the A-V and V-A time intervals and looks promising. Newer developments such as fetal ECG and magnetocardiography also show promise but M mode and Doppler remain the most practical methods to date.

If there is no hydrops high dose digoxin may be given orally to the mother (transplacental route) with the addition of flecainide or verapamil if there is no cardioversion. Direct fetal treatment by umbilical vein puncture under ultrasound guidance (fig 10D) may be more successful in the presence of hydrops.

Similar methods are used to assess the fetus with heart block. Echocardiographic assessment is essential in these fetuses to exclude abnormalities of situs as about 40% will have complex structural heart disease, most often left atrial isomerism with a complete atrioventricular septal defect, or congenitally corrected transposition (double discordancy). These fetuses need sequential evaluation to anticipate
heart failure and hydrops and those with the lowest heart rates (atrial rate < 100 and ventricular rate < 45) are more likely to die in utero. Maternal steroids, ionotropes, and fetal pacing have all been tried but there is no clearly superior treatment. Maternal antibody status (anti-Rho and -SSA) should be checked and if positive the family counselled that there is a risk of recurrence in future pregnancies of up to 30%.

INTERVENTIONAL VALVULOPLASTY

Percutaneous ultrasound guided techniques aimed at opening the stenosed fetal aortic valve before birth have resulted in technical success in less than half of the cases (6/14) attempted worldwide with only one long term survivor. The indications currently for fetal intervention are limited and the risks and benefits of the procedure weighed carefully. Work is in progress in lamb models to improve this method using fetoscopic approaches guided by transoesophageal echocardiography, which improves the imaging when the balloon catheter is inside the fetal heart, but this approach has not yet been used in the human fetus.

Conclusions

Fetal echocardiography includes more than the detection of cardiac defects before birth. Using Doppler ultrasound we have gained insights into the pathophysiology of the fetal circulation during development and have the, albeit currently limited, ability to effect change in the fetal circulation before birth in the hope that the postnatal course will be ameliorated. Improvements in ultrasound imaging and close collaboration across specialties have enabled the majority of these improvements to take place.

References
