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INTRODUCTION

Two-dimensional (2D) ultrasound imaging of the fetal heart has been steadily evolving since its original descriptions in the early 1980s (1,2). Using current ultrasound platforms, it is now possible to image the fetal heart with a high degree of spatial and temporal resolution, which allows clinicians to make precise anatomic and functional diagnoses in the fetus with acquired or congenital heart disease (CHD). Use of color flow and pulsed-wave Doppler techniques in fetal cardiac imaging has further augmented the diagnostic capabilities of fetal echocardiography, to the point where diagnostic accuracy in many regards rivals that of trans-thoracic echocardiography. Understanding the capabilities and limitations of fetal cardiac assessment is particularly important in the current era, where the possibility of fetal therapy is now possible. It is also important in the current era to understand the broadening indications for fetal echocardiography, particularly as it pertains to fetal therapy.

It is the purpose of this chapter to review the current status of fetal echocardiography with regard to (i) indications for and timing of fetal cardiac evaluation, (ii) standard imaging views and anatomic assessment, (iii) methods of assessing fetal cardiac function and rhythm, (iv) counseling the patient with fetal heart disease, and (v) highlight some of the newer advances and innovation in fetal echocardiography and fetal cardiology.

INDICATIONS FOR FETAL ECHOCARDIOGRAPHY

Cardiac defects in fetuses are one of the most frequently missed findings on prenatal ultrasound evaluation with significant complex consequences. This is partly related to the experience of the scanning examiner, capability of the scanning equipment used, natural history of evolution of CHD, and the number and timing of the scan. Therefore, specific indications for a detailed fetal echocardiographic evaluation at centers with appropriate expertise and facilities to screen for cardiac anomalies in fetuses at high risk have evolved. Although most of the infants are born to mothers who have no known risk factors, the yields of detection of CHD in fetuses in high-risk groups have been significantly higher than those in low-risk groups (3). A detailed fetal echocardiographic evaluation has been indicated in high-risk conditions (Table 1). The yield for the detection of CHD is variable with different indications. The family history as indication has 2% to 10% yield for detecting fetal heart defects, depending upon the number of previous siblings affected, type of CHD in the index sibling, associated syndrome, extracardiac malformations with CHD in the siblings, or parental heart defects (4,5). In contrast to this low-yielding indication, an abnormal obstetric sonogram suspecting anomalies of cardiac position or structures on screening examination has the

highest yield of 50% to 60% as an indicator (6). Fetal arrhythmias and extracardiac anomalies of gastrointestinal system and genitourinary system have intermediate yield of 25% to 30% as indicators (7,8). Nuchal translucency thickness of more than 5.5 mm (above 95th percentile) has a prevalence of major CHD ~20% (9). Table 1 does not include the indications for fetal echocardiography in low-risk groups. Fetal echocardiographic screening in low-risk groups has been undertaken in some centers and countries with conflicting results. With advancement in screening program in all groups, early detection of CHDs in fetuses may prove beneficial in terms of outcomes of fetal cardiac intervention in the future.

Early fetal echocardiography with the use of high-resolution transvaginal ultrasound between 13 and 16 weeks of gestation has provided the capability to demonstrate all cardiac structures and the majority of major CHDs. However, the reported sensitivity for detection of CHDs by early fetal echocardiography is up to ~65% (10). Limitation to the detection of some CHDs such as ventricular septal defect (VSD), double-outlet right ventricle (RV), as well as late-onset appearance of cardiac anomalies such as hypoplasia of one cardiac chamber/great artery in the presence of outflow tract obstruction and cardiac tumors suggest that early screening by transvaginal echocardiography should be followed by mid-gestational transabdominal echocardiography, which may yield an additional ~20% detection of CHDs (10).

STANDARD IMAGING VIEWS AND ANATOMIC ASSESSMENT OF THE FETAL HEART

Fetal echocardiography is commonly performed between 18 and 22 weeks of gestational age (11). In later gestation, imaging may be more difficult due to increasing calcification of fetal ribs and a relative decrease in amniotic fluid volume. High-resolution ultrasound equipment with transducer frequencies from 5 to 7 MHz should be used, with capabilities to perform M-mode, color Doppler, and spectral Doppler interrogation.

A comprehensive fetal echocardiogram includes 2D imaging of the cardiac anatomy, spectral and color Doppler assessment of blood flows, and evaluation of cardiac function and rhythm. Multiple tomographic planes used to image the fetal cardiovascular system have been described (11,12) (Figs. 1,2).

Fetal Position and Abdominal Situs

The first step in the evaluation of the fetal heart is to establish fetal position within the maternal abdomen (vertex, breech, transverse, supine, prone) and to establish fetal left and right sides. From a transverse section of the fetal abdomen, visceral situs is assessed by demonstrating the relative position of the stomach, hepatic vessels, abdominal aorta, and inferior vena cava (IVC). Normal abdominal situs (situs solitus) is characterized by the stomach bubble on the fetal left side,

Table 1 Indications for Fetal Echocardiography in Subpopulation at High Risk for Congenital Heart Disease (CHD)

Increased risk based on family history
Positive family history of CHD in previous child/children and parents
Positive family history of syndromes or malformations associated with CHD
CHARGE, DiGeorge, Holt–Oram, Marfan, Noonan, Williams–Beuren
Increased risk due to maternal conditions
Maternal diseases
Diabetes mellitus
Phenylketonuria
Collagen vascular disease
Exposure to teratogens in pregnancy
Teratogenic drugs: alcohol, amphetamine, anticonvulsants, lithium, retinoic acid, warfarin
Intrauterine infections
Rubella, myocarditis from cytomegalovirus, coxsackievirus, and parvovirus
High doses of ionizing radiation
Increased risk due to fetal conditions
Documented fetal anomaly
Abnormal obstetric sonogram
Suspected cardiac anomaly, abnormal cardiac position
Extracardiac malformations frequently associated with cardiac anomaly
Ectopia cordis, microcephaly, VACTERL, omphalocele, horseshoe kidney, single umbilical artery
Arrhythmia
Bradyarrhythmia
Tachyarrhythmia
Complete heart block
Nonimmune hydrops fetalis
Nuchal edema or hygromata, increased thickness of nuchal translucency
Amniotic fluid abnormality
In utero diagnosed chromosome anomaly
Twin gestation
Monozygous twin
Conjoint twin

Abbreviation: VACTERL, vertebral abnormalities, anal atresia, cardiac abnormalities, tracheoesophageal fistula and/or esophageal atresia, renal agenesis and dysplasia, and limb defects.

liver with hepatic vessels on the right side, abdominal aorta to the left of the fetal spine, and IVC to the right of the fetal spine and slightly anterior to the aorta (Fig. 3). In situs inversus, there is a mirror-image arrangement of these organs and vessels. Situs ambiguous denotes when neither situs solitus nor inversus is present; this is also referred to as heterotaxy and is commonly associated with complex congenital heart defects and splenic abnormalities (asplenia or polysplenia).

Four-Chamber View

Moving the transducer cephalad from the abdominal transverse view to a transverse view of the fetal chest should demonstrate the heart in the left hemithorax with the apex pointing to the left (levocardia). Also with this sweep, entrance of the IVC into the right atrium (RA) is demonstrated. Dextroposition of the heart is present when the fetal heart is found in the right hemithorax, such as when the heart is

externally shifted to the right by a left-sided diaphragmatic hernia or cystic adenomatous malformation, or when hypoplasia of the right lung is present; however, the cardiac apex still points to the left. The term “dextrocardia” denotes the apex of the heart is pointed to the right. Dextrocardia in the presence of normal situs solitus is associated with CHD in 95% of cases (13). By contrast, in situs inversus totalis, where both stomach and heart are on the right side, heart defects are rare.

A transverse section of the fetal chest provides a four-chamber view of the heart, and this is usually easily obtained (Fig. 4). The heart should fill about one-third of the thoracic area or about half the thoracic circumference (14,15). Cardiac axis refers to the angle between a line along the interventricular septum and the thoracic anteroposterior midline and is normally around 45° ± 20° (16–18). Significant levorotation of the cardiac axis is often the first clue to the presence of a congenital heart defect (17,18).

In the normal four-chamber view, the RA and left atrium (LA) are approximately equal in size, and the RV and left ventricle (LV) are also approximately equal in size and thickness, with the RV becoming slightly larger than the LV as gestation progresses (14). The LA is the most posterior cardiac chamber and lies anterior to the descending aorta. The flap of the foramen ovale (septum primum) moves from the RA into LA, billowing about half-way into the LA, consistent with the right-to-left direction of foramen ovale flow in fetal circulation. The RV is the most anterior cardiac chamber and sits just posterior to the sternum. The LV cavity comprises the cardiac apex. The RV can be identified by the moderator band that courses across the lower part of the RV, from the interventricular septum to the RV free wall. The RV is also identified by the tricuspid valve that inserts into it. The atrioventricular valves are slightly offset from each other, with the tricuspid valve attaching slightly more apically than the mitral valve. From the four-chamber view, a posterior sweep will show the coronary sinus, which should be a thin structure that courses within the LA (Fig. 5). A dilated coronary sinus is seen when a persistent left superior vena cava (SVC) or anomalous pulmonary veins are present.

Addition of color Doppler in the four-chamber view will demonstrate inflow from atria to ventricles. A small amount of tricuspid regurgitation may be seen in the normal fetus (19). Pulmonary venous flow is seen entering the LA; at least one pulmonary vein from both the left and the right should be demonstrated. Evaluation of atrial and ventricular septa by color Doppler to assess for septal defects is best undertaken in planes perpendicular to the septa. Foramen ovale flow is seen from RA to LA, and VSDs in the muscular and inlet parts of the ventricular septum may be seen in this view. Small muscular VSDs may be seen throughout gestation, and many spontaneously close prior to delivery.

In addition to VSDs, other heart defects may be identified in the four-chamber view (20). Ebstein’s anomaly of the tricuspid valve is characterized by apical displacement of the septal leaflet of the tricuspid valve with associated tricuspid regurgitation and atrialization of the RV. Atrioventricular canal (endocardial cushion) defects result in a spectrum of defects ranging from a primum atrial septal defect (ASD) with cleft mitral valve, to a complete atrioventricular canal defect

Figure 1 Illustration of the tomographic planes used to image the fetal cardiovascular system. 1, apical (four-chamber) view; 2, apical (four-chamber) view angled toward the aorta; 3, long-axis view of the left ventricular outflow tract; 4, long-axis view of the right ventricular outflow tract; 5, short-axis view at the level of the great vessels; 6, short-axis view with caudad angling at level of ventricles; 7, caval long-axis view; 8, ductal arch view; 9, aortic arch view. Source: From American Society of Echocardiography.

with a single common atrioventricular (AV) valve, primum ASD, and inlet VSD. A primum ASD is seen when the inferior aspect of the atrial septum is deficient. An inlet VSD is seen when the ventricular septum adjacent to the AV valves is deficient. An atrioventricular canal defect should be suspected when the AV valves appear at the same level in the four-chamber view, without the usual offset of tricuspid and mitral valves.

Ventricular hypoplasia or dilation is easily appreciated in the four-chamber view. A hypoplastic RV is seen in tricuspid atresia and in pulmonary atresia with intact ventricular septum. A small LV is seen in hypoplastic left heart syndrome; this is characterized by severe stenosis or atresia of the mitral and aortic valves and severe hypoplasia of the aortic arch. Other complex, functionally single ventricle lesions include double-inlet LV and unbalanced atrioventricular canal defects with hypoplasia of either ventricle. The latter are commonly associated with heterotaxy syndromes (situs ambiguous with asplenia or polysplenia) (13).

Ventricular dilation may signify the presence of regurgitation of the respective AV valve or obstruction of the respective

proximal outflow tract, and the addition of color and spectral Doppler should be used to assess these areas. RV dilation with RA dilation and tricuspid regurgitation is seen when there is obstruction to the ductal arch (e.g., premature ductal closure) or aortic arch (e.g., coarctation of the aorta).

Importantly, the four-chamber view is inadequate for excluding transposition of the great arteries and conotruncal defects such as tetralogy of Fallot and truncus arteriosus.

Long-Axis View

While the four-chamber view is the only view of the heart required for standard second- and third-trimester fetal examinations, the addition of outflow tracts has been shown to yield higher detection of congenital heart anomalies than the four-chamber view alone (21–23). From the four-chamber view, sweeping cephalad will demonstrate the ventricular outflow tracts and the relationship of the great arteries. The aorta arises from the posterior LV and aims toward the fetal right shoulder (Fig. 6). The pulmonary artery (PA) arises from the anterior RV and courses leftward and posteriorly, crossing the aorta, extending to the ductus arteriosus, which then meets the

Figure 2 Illustrations of the anatomical correlates for each of the designated tomographic imaging planes used for imaging the fetal cardiovascular system. Each numbered view relates to the clockwise illustration of the fetal heart in Figure 1. *Abbreviations:* Ao, Aorta; IVC, inferior vena cava; LA, left atrium; LV, left ventricle; MV, mitral valve; PA, pulmonary artery; PD, patent ductus; RA, right atrium; RV, right ventricle; SVC, superior vena cava. *Source:* From American Society of Echocardiography.

descending aorta. Continuity between the mitral and aortic valves is demonstrated in this view, and the anterosuperior aspect of the ventricular septum can be interrogated to rule out a VSD. Discontinuity of the mitral and aortic valves is characteristic of double-outlet RV lesions.

An aorta that overrides a large malalignment VSD is seen in tetralogy of Fallot, where there is associated pulmonary

outflow tract obstruction, and in truncus arteriosus, where there is a single semilunar (truncal) valve and the branch pulmonary arteries usually arise from the ascending aorta.

The subaortic area is also visualized in the long-axis view. Posterior malalignment of the ventricular septum produces a VSD and crowding of the left ventricular outflow tract producing varying degrees of subaortic obstruction. In these

Figure 3 Abdominal situs. Transverse view of abdomen. Abbreviations: St, stomach; Ao, Aorta; IVC, inferior vena cava; Sp, spine.

Figure 5 Coronary sinus. Abbreviations: RA, right atrium; RV, right ventricle; LV, left ventricle; CS, coronary sinus.

Figure 4 Four-chamber view. Abbreviations: RA, right atrium; RV, right ventricle; LA, left atrium; LV, left ventricle; Ao, aorta; Sp, spine. Note the moderator band traversing the inferior aspect of the RV.

Figure 6 Slight cephalad angulation from the four-chamber view shows the left ventricular outflow tract. Abbreviations: RA, right atrium; RV, right ventricle; LA, left atrium; LV, left ventricle; Ao, aorta; Sp, spine.

instances, obstruction or interruption of the aortic arch may also be present.

If the anterior vessel is the aorta, then transposition or malposition of the great arteries is present. D-Transposition of the great arteries is recognized by the anterior RV giving rise to the aorta and the PA arising from the LV. The outflow tracts do not cross normally and instead travel in a parallel fashion. VSDs may also be seen with transposition of the great arteries.

In the normal fetal heart, the pulmonary valve and PA are slightly larger than the aortic valve and proximal aorta, and normal reference values based on gestational age have been reported (24). If the PA is hypoplastic, pulmonary stenosis or tetralogy of Fallot should be suspected, and the valve morphology and Doppler gradient be carefully evaluated. The aorta is often dilated in tetralogy of Fallot and truncus arteriosus. If the aorta is small, aortic stenosis and/or other left heart obstructive lesions such as coarctation of the aorta or interrupted aortic arch may be present.

Three-Vessel View

Sweeping further cephalad in a transverse plane will produce the three-vessel view. This is a cross-sectional view at the level of the superior mediastinum, displaying the normal relationship and size differences of the PA, aorta, and SVC (Fig. 7). The PA is seen in long axis in this view and is the larger, most anterior, and leftward vessel; the aorta is slightly smaller, to the right, and posterior to the PA; and the SVC is the smallest, most posterior, and rightward vessel. Discrepancies in the size of the PA and aorta may signify subtle pathology of the outflow tracts or arches, and a dilated SVC may be seen when an interrupted IVC with azygous continuation or vein of Galen aneurysm is present (25).

Short-Axis View

The short-axis view is obtained by rotating perpendicular to the long-axis view. This view is important in confirming the normal relationship of the great arteries. The aorta is seen in

Figure 7 Three-vessel view. Abbreviations: PA, pulmonary artery; Ao, aorta; SVC, superior vena cava; Sp, spine.

Figure 8 Short-axis view. Abbreviations: LA, left atrium; AS, atrial septum; IVC, inferior vena cava; RA, right atrium; TV, tricuspid valve; RV, right ventricle; PV, pulmonary valve. The aortic valve is seen in cross section in the middle of the short-axis view.

cross section as a circular structure, with the PA wrapping around the aorta as it arises from the anterior ventricle (Fig. 8). The main PA can be seen bifurcating into the ductus arteriosus and right PA and slight angulation to fetal left will show the left PA.

Slight inferior angulation from the short-axis view of the great arteries shows the ventricles in short axis. Quantitative assessment of RV and LV function can be made from this view, and M-mode interrogation through the ventricles allows measurement of RV and LV systolic and diastolic dimensions (26). These dimensions can be used to quantitatively assess ventricular function by calculating a shortening fraction (end-diastolic dimension – end-systolic dimension/end-diastolic dimension). Normal shortening fraction for the RV and LV is $34 \pm 3\%$ (27).

Figure 9 Ductal arch view. The ductus arteriosus arises from the anterior right ventricle and connects to the descending aorta, making a "hockey-stick" configuration.

Figure 10 Aortic arch view. The aorta arises from the central thorax and normally gives rise to three brachiocephalic vessels. The aortic arch makes a "candy cane" configuration.

Ductal View

The ductal view is obtained in the fetal sagittal plane. The ductal arch has a flatter contour ("hockey-stick" shape) than the aortic arch as it arises anteriorly from the PA and connects to the descending aorta (Fig. 9). It lies more caudally than the aortic arch. Color Doppler interrogation demonstrates the normal right-to-left ductal flow (PA to descending aorta). Direction of ductal flow is reversed (aorta to PA) when there is obstruction to pulmonary blood flow, as in pulmonary atresia or severe pulmonary stenosis.

Aortic Arch View

The aortic arch is also best viewed in a sagittal plane and is obtained from the ductal view by slight angulation of the transducer. The aortic arch arises centrally from the heart in the mid-thorax and aims toward the fetal head. It has a "candy cane" contour and is identified by the three brachiocephalic vessels that arise from it (Fig. 10). Color Doppler interrogation confirms antegrade flow through the ascending aorta and

Figure 11 Bicaaval view. Abbreviations: IVC, inferior vena cava; SVC, superior vena cava; RA, right atrium; RV, right ventricle.

aortic arch. Both spectral and color Doppler are used to assess for obstruction; however, even in the setting of a normal-appearing arch, coarctation of the aorta cannot be ruled out owing to the presence of a large ductus arteriosus. Retrograde aortic arch flow from the ductus arteriosus is seen in critical left heart obstructive lesions such as hypoplastic left heart syndrome and critical aortic stenosis.

Caval Long-Axis View

This view is obtained from the aortic arch view by sliding from the left parasagittal chest to the right. Bicaaval return to the RA can be seen (Fig. 11). The septum primum is seen extending into the LA and use of color Doppler demonstrates the normal right-to-left flow across the foramen ovale. Reversal of foramen ovale flow, from LA to RA, is seen in critical left heart hypoplasia/obstructive lesions. The ductus venosus, a fetal shunt connecting the umbilical vein (UV) with the IVC, can be seen entering the left hepatic vein–IVC junction just below the diaphragm and RA.

It is important to note than even with a comprehensive fetal echocardiogram, there are congenital heart defects that cannot be ruled out. As flow normally occurs across the atrial septum via the foramen ovale, the presence of an ASD cannot be excluded, particularly of the secundum type. Coarctation of the aorta may be difficult to exclude in the presence of a large ductus arteriosus; secondary findings of RV dilation and tricuspid regurgitation may be seen with a significant coarctation and are clues to its presence.

FETAL CARDIAC FUNCTIONAL ASSESSMENT

The 2D and Doppler echocardiography have become not only an integral component in the assessment of anatomic anomalies of the fetal heart, but also an important tool in the assessment of fetal hemodynamic status. Various techniques for assessing fetal cardiovascular function exist and can be utilized to assess fetuses with cardiovascular compromise due to a variety of cardiac and noncardiac causes (Table 2). As many of the conditions associated with fetal cardiac

Table 2 Examples of Conditions Associated with Fetal Cardiac Compromise

Condition	
Cardiac disease	Severe valve regurgitations
	Tetralogy of Fallot with absent pulmonary valve
	AV septal defect with AV valve regurgitation
	Ebstein anomaly of the tricuspid valve
	Elevated ventricular afterload
	Bilateral semilunar valve stenosis
	Constriction of the ductus arteriosus
	Fetal arrhythmia
	Fetal tachyarrhythmia
	Complete AV block
	Restrictive foramen ovale
	Volume overload/high cardiac output lesions
	Fetal anemia
	Arteriovenous fistulae
Noncardiac disease	Sacroccygeal or cervical teratoma
	TRAP sequence
	Placental chorioangioma
	High cardiac afterload
	Recipient twin in TTTS
	Placental insufficiency
	Congenital cystic adenomatoid malformation
Abbreviations: AV, atrioventricular; TRAP, twin reversed arterial perfusion; TTTS, twin–twin transfusion syndrome.	

compromise now have fetal therapeutic options, understanding and identifying fetal cardiac dysfunction in the current era assume even greater importance, because accurate description of cardiac natural history should become an important component in determining patient selection and timing of intervention.

This section reviews common 2D and Doppler methods of assessing fetal cardiovascular status, describes the changes in these indices that are characteristic of fetal cardiac compromise, and offers a clinical approach to the comprehensive assessment of fetal cardiovascular function. The components of the complete fetal cardiac assessment are outlined in Table 3.

Assessment of Systolic Ventricular Function in the Fetus
The fetal myocardium differs maturationally from the “adult” state, and these features must be considered when evaluating cardiac function in the setting of altered loading conditions (28,29). The fetal myocardium responds to preload with higher resting and reduced active tension generation, due in part to higher concentrations of noncontractile proteins in the fetal versus the mature heart. The fetal response to afterload is also different, with a significant reduction in fiber shortening in the setting of increased afterload (29). These differences must be kept in mind when evaluating ventricular systolic function in settings where pathologic loading conditions likely exist.

2D Assessment of Fetal Systolic Function

In the past, assessment of fetal ventricular systolic function has often consisted of qualitative assessments. Current practice is generally more quantitative. On initial 2D imaging of the fetus, it is important to note the presence of hydrops fetalis and/or

its component findings. Overall, cardiac size is often a sign of altered hemodynamics in the fetus; in addition to qualitative assessment, the cardiothoracic ratio can be used to quantitatively express the degree of cardiac enlargement. In our lab, we utilize the ratio of the cardiac area (in the four-chamber view) to the thoracic area in the same view (Fig. 12), with normal values generally being <0.35 (30). It is also useful to examine why the heart is large, which may be due to ventricular enlargement, atrial dilation, ventricular hypertrophy, or a combination of these findings, as this may provide further clues as to the etiology of the cardiac abnormality. On 2D and/or M-mode imaging of the RV and LV, quantitative assessment of both RV and LV shortening fraction is also possible (27,31–33) (Fig. 12). In addition to subjective assessment of ventricular wall thickness, quantitation of RV and LV wall thickness is possible, and there are published normal values against which measurements can be compared (34).

Doppler Assessment of Fetal Cardiac Function: General Comments

The 2D and M-mode imaging can be limited on fetal echocardiography due to marginal acoustic windows or fetal

position, sometimes limiting the utility of these methods. There are now a number of Doppler indices—sometimes more readily obtained in the setting of marginal 2D imaging windows—on fetal echocardiography that describe systolic and diastolic cardiac functions. Classically, Doppler characterization of systemic venous flow—in the IVC, ductus venosus, UV, and artery—has been utilized to identify changes associated with elevations of central venous pressure and changes in vascular flow distribution. More recently, the Doppler myocardial performance index has emerged as a promising new index for assessment of global—systolic and diastolic—ventricular function.

Doppler Assessment of Fetal Systolic Function

Myocardial Performance Index

The myocardial performance index (MPI) was originally described by Tei and colleagues in 1995 (35). The MPI is in actuality an index of *global* ventricular function, as calculation of the index incorporates both diastolic and systolic time intervals into assessment of ventricular function. The MPI is calculated as

$$(IRT + ICT)/ET,$$

Table 3 Elements of Comprehensive Cardiovascular Functional Exam in the Fetus	
	Echocardiographic Assessment
General	Presence of hydrops fetalis Cardiothoracic area ratio
Systolic function	Color flow Doppler evaluation of AV valve regurgitation The 2D or M-mode assessment of RV and LV shortening fraction Myocardial performance index (global function)
Diastolic function	Ventricular dP/dt (when AV valve regurgitation present) Tricuspid and mitral AV valve inflow profile (E and A velocity, E/A wave ratio, presence of monophasic inflow profile) Myocardial performance index (global function) IVC or hepatic venous flow (ratio of reverse flow VTI and forward flow VTI) Ductus venosus flow (presence or absence of absent or reverse end-diastolic flow, increased pulsatility index) Umbilical venous flow (presence or absence of pulsations)
Abbreviations: AV, atrioventricular; IVC, inferior vena cava; LV, left ventricular; RV, right ventricular; VTI, Doppler velocity–time integral.

Figure 12 Left panel: Assessment of cardiothoracic ratio (CTR). The cardiac area in the four-chamber view is divided by the thoracic area. In this example, the CTR is mildly elevated at 0.37 (normal, ≤0.35). Right panel: Quantitation of ventricular shortening fraction (SF). In this example, M-mode through the right ventricular (RV) short axis allows measurement of the RV end-diastolic dimension (solid arrow) and end-systolic dimension (dashed arrow). The RVSF is calculated as (RV end-diastolic dimension – RV end-systolic dimension)/(RV end-diastolic dimension).

where IRT is the isovolumic relaxation time, ICT is the isovolumic contraction time, and ET is the ventricular ejection time. The sum of IRT and ICT can be derived from subtracting the ET from the time period “A” between cessation of atrioventricular valve inflow and onset of atrioventricular valve inflow in the next cardiac cycle (Fig. 13). With systolic dysfunction, ICT lengthens and ET shortens; diastolic dysfunction will manifest as prolonged IRT. Therefore, an elevation in the MPI indicates ventricular dysfunction, although the index does not allow specific identification of diastolic or systolic dysfunction. Normal values for both RV and LV MPI have been reported. In our laboratory, normal RV and LV MPI are 0.32 ± 0.08 and 0.33 ± 0.05 , respectively. Both Eidem and Mori et al. reported comparable normal values for RV MPI to be approximately 0.35 ± 0.06 (36,37), although higher LV MPI in normal fetuses (0.55 ± 0.13) has been reported (38). The MPI in the fetus has shown to be significantly elevated in a number of disease states, including twin–twin transfusion syndrome (39,40), fetuses of diabetic mothers (41), constriction of the ductus arteriosus (37), and cardiomyopathy (42).

Color Flow Doppler Assessment

In addition to the quantitative techniques described above, it is important to evaluate atrioventricular valve function—specifically, for evidence of valve regurgitation—by color flow Doppler imaging. Tricuspid and mitral regurgitation—with normal valve anatomy—often develops in the setting of fetal cardiac compromise (27,39,43–46) and should be evaluated during echocardiography in any fetus with suspected cardiac dysfunction.

Assessment of Diastolic Ventricular Function in the Fetus

Diastolic ventricular function is also “immature” in the fetal heart (28,47,48). Fetal ventricular relaxation is reduced in the fetus, although there are progressive changes in ventricular inflow Doppler patterns that demonstrate improving ventricular relaxation throughout gestation (47,49).

Ventricular compliance characteristics demonstrate increased “stiffness” of the fetal heart (50). In fact, it is likely that diastolic dysfunction precedes overt ventricular systolic dysfunction or hydrops in a number of settings, making an understanding of the Doppler manifestations of fetal diastolic dysfunction important. For example, it has been reported that Doppler evidence of diastolic dysfunction will often be present prior to onset of ventricular systolic dysfunction in recipient twins in the setting of twin–twin transfusion syndrome (39,40), as well as in fetuses with growth restriction (31).

Doppler assessment of diastolic function in the fetus consists of two primary components: (i) assessment of Doppler flow patterns in the fetal venous system and (ii) assessment of Doppler flow patterns across the atrioventricular valves.

Assessment of Doppler Flow Patterns in the Fetal Venous System

There is a large body of literature describing changes in fetal venous Doppler flow patterns in a variety of disease states. In all of these conditions, changes in Doppler venous flow patterns are felt to be a reflection of elevated central venous pressure related to increased ventricular filling pressures. The magnitude of these changes has been correlated to severity of compromise in several studies (51–55).

The central finding in the compromised fetus is an increase in the magnitude of the blood flow away from the heart during atrial systole. This is manifested as changes in the Doppler flow profile in several important vessels:

1. IVC/hepatic veins
2. Ductus venosus
3. UV

It should be noted that as fetal cardiac compromise leads to elevation of central venous and ventricular filling pressure, venous flow reversals during atrial systole will manifest first proximally, in the IVC and hepatic veins. As compromise worsens, findings will then move distally—or “upstream”—into the ductus venosus and UV (43).

Figure 13 Simultaneous pulsed-wave Doppler of left ventricular inflow (below baseline) and outflow (above baseline). The mitral valve inflow is characterized by an early diastolic E-wave and a late diastolic A-wave (see text). The myocardial performance index is calculated as: $(A - ET)/ET$ (see text).

IVC and Hepatic Veins

In the IVC and hepatic veins, normal venous flow consists of a phasic low-velocity pattern consisting of an S wave during ventricular systole, a D wave during passive diastolic filling, and a small reversal in flow—the A wave—during atrial systole (Fig. 14). Normal values for IVC and hepatic venous S, D, and A waves throughout gestation have been reported (56); interestingly, the magnitude of the atrial systolic flow reversal diminishes in the course of normal development, suggesting improvements in ventricular compliance (57,58). Another method of evaluating the magnitude of the atrial systolic flow reversal is as a ratio of reverse flow to forward flow. The time-velocity integral of both reverse and forward flow are measured and expressed as a percentage; it has been reported that ratios in excess of 7% are abnormal (43) (Fig. 14).

Ductus Venosus

Doppler assessment of the ductus venosus (DV) is important to incorporate into the comprehensive fetal echocardiogram, particularly if cardiac dysfunction is suspected, as changes in the DV and UV are reflective of the central venous and/or right atrial pressures. In some cases, this is not always a poor prognostic sign, as in the case of right heart obstructive lesions (59), such as tricuspid atresia or pulmonary atresia with intact ventricular septum, where the entire systemic and umbilical venous return is forced to cross the foramen ovale. In this setting, abnormalities of venous Doppler flow may be noted in a setting where fetal cardiovascular compromise is quite rare.

UV

The presence of umbilical venous pulsations is a finding associated with severe cardiovascular compromise and has

been correlated to poor prognosis in the setting of non-immune hydrops due to cardiomyopathy (44), twin-twin transfusion syndrome, arrhythmia, and structural heart disease (55,60). It has been suggested, however, that, although specific, UV pulsations are not sensitive enough to be clinically useful in identifying fetal cardiovascular compromise at a time when poor outcome could be avoided (61). Further work should probably be focused on which venous Doppler changes—in IVC, DV, or UV—have the greatest clinical utility in early identification of the fetus in distress, so that management may be initiated before the fetus presents in a pre-morbid state.

Doppler Assessment of AV Valve Inflow Doppler Flow Profile

Pulsed-wave Doppler assessment of both trans-mitral and trans-tricuspid flow patterns should be performed during fetal cardiac functional evaluation. The Doppler E-wave velocity reflects early diastolic ventricular filling, where the A wave reflects ventricular filling that occurs during atrial contraction (Fig. 13). In the fetus, the AV valve Doppler E-wave velocity is lower than the A-wave velocity. The ratio of E wave to A-wave velocity increases progressively during gestation (49,62), reflecting more rapid myocardial relaxation in diastole. In pathologic circumstances, a number of changes in AV valve inflow Doppler profiles have been described. In twin-twin transfusion syndrome and fetal cardiomyopathy, the AV inflow E- and A-wave velocity ratio increases (39). However, in other settings, the E- and A-wave ratio has been noted to decrease, such as in the setting of intrauterine growth restriction (31,63) or fetuses of diabetic mothers (64). In the most severe cases of

Figure 14 Hepatic venous Doppler evaluation. Normal hepatic venous flow (panel A) is characterized by a systolic S-wave, early diastolic D-wave, and an A-wave of reversed flow during atrial contraction (open arrows). The calculation of the forward and reverse (A-wave) velocity-time integral (VTI) is shown in red. With increasing central venous pressure, the magnitude of the hepatic venous A-wave will increase (solid white arrows, panel B).

ventricular dysfunction, the AV inflow profile becomes monophasic (Fig. 15), which is a finding consistent with severe diastolic dysfunction.

Doppler Assessment of “Critical” Outflow Tract Obstructive Lesions

Another “functional” aspect of fetal echocardiographic assessment is identification of critical outflow tract obstruction, for example, in the setting of severe pulmonary stenosis (RV outflow tract obstruction) or severe aortic valve stenosis (LV outflow tract obstruction). In these settings, identification of “reversed” physiologic shunting in the fetus can allow clinicians to make the diagnosis of critical outflow tract obstruction and make the appropriate perinatal management decisions for each case.

In the setting of RV outflow tract—or more specifically, pulmonary outflow tract—obstruction, identification of reversed flow in the ductus arteriosus (from aorta to PA) heralds a fetus who will require maintenance of ductal patency to avoid critical hypoxemia related to pulmonary outflow tract obstruction after birth (65). In the setting of a left heart obstructive lesion such as aortic stenosis, left to right flow across the foramen ovale and reversal of flow in the aortic arch can be identified and used to confirm the diagnosis of critical left heart obstruction (65). In this setting, maintenance of ductal patency postnatally will prevent compromise of systemic perfusion and impending shock.

In all of these settings, the physiologic data obtained on fetal echocardiography can be used to determine severity of the anatomic lesion and make appropriate management decisions, for example, delivery at a level III perinatal center, institution of prostaglandin infusion to maintain ductal patency, and transfer to a pediatric cardiac center, in advance of birth.

FETAL ARRHYTHMIAS

The fetal arrhythmias encountered in fetal cardiology practice can be broadly categorized into tachyarrhythmias, bradyarrhythmias, and irregular cardiac rhythms with a normal heart rate.

Fetal Tachyarrhythmias

Fetal arrhythmia causing tachycardia is an important cause of fetal morbidity and mortality (66–69). Fetal tachycardia is defined as a fetal heart rate ≥ 200 beats per minute (bpm) (69). Both sustained tachycardia (present ≥ 12 consecutive hours) (70) as well as intermittent tachycardias are risk factors for fetal congestive heart failure (67,71).

The majority of fetal tachycardias are due to supraventricular tachycardia (SVT). Characteristically, it shows 1:1 atrioventricular contraction sequence, abrupt onset and termination, and minimal (within 10bpm range) or no heart rate variability. The fetal heart rate can range from 220 to 300 bpm. Atrial flutter due to intra-atrial reentrant mechanism

Figure 15 Pulsed-wave Doppler evaluation of mitral valve inflow. The Doppler sample volume is below (downstream) the mitral valve. In this fetus with severe biventricular dysfunction, the mitral valve inflow pattern is consistent with a narrow, monophasic Doppler flow profile (white arrows). Note the absence of a normal E-wave/A-wave complex (see also Fig. 12).

is common next to atrioventricular reentrant SVT (68). In atrial flutter, the atrial rate is in excess of ventricular rate. It ranges from 300 to 500 bpm with variable atrioventricular block leading to a ventricular rate ranging from normal to ≥ 300 bpm. The ventricular rate is often irregular in contrast to the minimal variability seen in SVT.

Mechanistically, almost 90% of SVT in fetuses are due to atrioventricular reentrant tachycardia via common type of accessory pathway (67). SVT can also be due to atrioventricular nodal, permanent junctional, or multiple reentrant pathways as well as due to automatic ectopic focus confined to the atrium. These types of SVTs are much less common during fetal age (67,72,73).

Junctional ectopic tachycardia and ventricular tachycardia (VT) are rare in fetal life. In contrast to atrial flutter, they are characterized by ventricular rate in excess of the atrial rate and are often difficult to distinguish from each other. VT is often seen in association with fetal long QT syndrome, which arises due to gene mutations coding for different proteins in ion channels. Measurement of the QT interval by echocardiography is not possible, but this diagnosis can be suggested often by the presence of sinus bradycardia between the episodes of VT.

Fetal Bradyarrhythmias

Fetal arrhythmia causing bradycardia may be associated with significant fetal morbidity and mortality. Fetal bradycardia is defined as a persistent heart rate < 100 beats/min. Most commonly, fetal bradycardia is due to sinus bradycardia. It shows 1:1 atrioventricular contraction sequence, slow onset, and beat-to-beat heart rate variability. It is often seen in fetuses suffering from significant hypoxic insult and raised intracardiac volume due to inhibitory vagal reflexes initiated by umbilical cord and other vessel compression. A sustained fetal sinus bradycardia with blunted or no heart rate variability is often a predictor of impending morbidity and mortality. Sinus bradycardia is often seen in fetuses with heterotaxia syndrome with atrial laterality abnormalities and AV canal defect. Fetuses with long QT syndrome may present with sinus bradycardia (74).

Fetuses with frequent or multiple premature atrial beats, which are not conducted to the ventricle, will have overall decreased ventricular rate and may have bradycardia due to it. This is a benign self-resolving condition and most of them resolve by the third trimester and certainly by the first weeks of postnatal life. Nonconducted premature atrial beats can occur after every two, three, or four normal beats setting up atrial bigeminy, atrial trigeminy, or atrial quadrigeminy patterns, respectively. Only occasionally, premature atrial beats can be a harbinger of SVT by initiating reentry mechanism in the presence of an accessory pathway.

Atrioventricular block due to AV node or ventricular conducting pathway abnormalities are the most common cause of persistent fetal bradycardia. The atrioventricular block can be of first degree, which demonstrates prolonged AV interval > 150 msec (75); second degree, which has a fixed atrioventricular conduction block (2:1 or 3:1 block) or progressive prolongation of the AV interval until an atrial beat is nonconducted (Wenckebach); or third degree, which has permanent atrioventricular block (complete heart block)

with complete dissociation between atrial and ventricular contractions.

Complete heart block can occur in fetuses either with malformed hearts or in otherwise structurally normal hearts. Fetuses with malformed hearts (corrected transposition of the great arteries, atrial isomerism, or atrioventricular canal defect) and complete heart block or with a ventricular rate < 55 bpm carry a very poor prognosis (76,77). Complete heart block, when found beyond the stage of embryogenesis in a structurally normal heart, has been associated with mass lesions of the conducting system, or more frequently as a consequence of initial insult by maternal antibodies to SS-A/Ro and SS-B/La antigens in fetal heart and subsequently leading to degeneration of the conduction system. Persistent bradycardia can occur in fetuses with long QT syndrome due to atrioventricular block secondary to prolonged refractory period of the ventricle (78).

Diagnosis of Arrhythmia by Fetal Echocardiography

In practice, fetal arrhythmias are diagnosed by M-mode, pulsed Doppler, or color flow encoded M-mode fetal echocardiography. The M-mode, with cursor oriented across atrial and ventricular cavities, reveals the relationship of atrial and ventricular contractions and their individual rate of contraction. Alternatively, pulse Doppler interrogation with a wide sample placed at mitral-aortic continuity can be employed, which demonstrates the rate of and relationship between inflow and outflow. In normal synchronized atrioventricular conduction, each atrial contraction is followed by a ventricular contraction, and both have the same and normal rate. In atrial flutter, ventricular contraction rate is a fraction of the atrial rate due to variable atrioventricular block (Fig. 16). In SVT, both atrial and ventricular contractions are synchronized and have the same rate, but their rates are between 220 and 300 beats/min (Fig. 17). Types of SVT can be differentiated according to the ventriculoatrial (VA) time interval (72) illustrated in Figure 18. The majority of SVT have short VA times, which are characteristic of atrioventricular reentry via common type of accessory pathway. The long VA time is typical of permanent junctional reentrant tachycardia or atrial ectopic tachycardia. Simultaneous pulse Doppler interrogation of the inflow and outflow can also reveal irregular heart rate due to blocked premature atrial beats (Fig. 19). Furthermore, a simultaneous Doppler interrogation of venous flow (superior vena) and an adjacent artery (aorta) can reveal AV and VA intervals (equivalent of PR interval and RP interval, respectively, on electrocardiogram) (Fig. 20).

In sinus bradycardia there is a 1:1 atrioventricular conduction with both atrial and ventricular rates the same but < 100 bpm on M-mode and Doppler interrogation. Atrioventricular block of all degrees is assessed by using both M-mode and Doppler echocardiography to examine the relationship between contraction of the atrial and ventricular walls and their individual contraction rates. The latter provides the information about the (second or third) degree of heart block.

Assessment of Fetal Cardiac Structure and Function

In addition to discerning the diagnosis of the fetal arrhythmia, a thorough fetal echocardiographic evaluation should be undertaken to evaluate the cardiac structure, function,

Figure 16 M-mode fetal echocardiogram shows both fast atrial and ventricular contractions in a 27-week-old fetus with atrial flutter. The atrial rate (inverted arrow) is 400bpm, and ventricular rate (upright arrow) is 200bpm, with 2:1 AV block.

Figure 17 Pulsed-Doppler fetal echocardiogram shows both inflow waveforms due to atrial contractions (above the base line, labeled as A) and outflow waveforms due to ventricular contractions (below the base line, labeled as V) at a rate of 236bpm with 1:1 atrioventricular conduction in a 30-week-old fetus with supraventricular tachycardia.

associated cardiac defects, hemodynamics, and presence of fetal hydrops as outlined in the previous sections.

Structural malformations of the heart are seen in up to 5% of the fetuses with tachyarrhythmia, which include Ebstein

anomaly of the tricuspid valve, AV canal defect, hypoplastic left heart syndrome, and rhabdomyoma (66,68,69). Ventricular dysfunction can occur. The severity of tachycardia-induced ventricular dysfunction can be assessed by fractional

Figure 18 Pulsed-Doppler fetal echocardiogram shows the measurements of atrioventricular intervals in a 27-week-old fetus with supraventricular tachycardia and a heart rate of 260bpm. The inflow Doppler waveforms due to atrial contraction (above the base line, labeled as A) and outflow Doppler waveforms due to ventricular contractions (below the base line, labeled as V) with 1:1 atrioventricular conduction show that the A-V interval is shorter than the V-A interval, which is characteristic of atrioventricular reentry via common type of accessory pathway.

Figure 19 Pulsed-Doppler fetal echocardiogram shows inflow (below the baseline) and outflow (above the baseline) Doppler waveforms in a 30-week-old fetus with a nonconducted (blocked) premature atrial beat (buried in outflow waveform, marked by an arrow). Preceding and following inflow waveforms have normal early (E) and atrial (A) diastolic inflow waveforms. The premature atrial beat is blocked because of A-V node and ventricular refractory phase and is manifested by a late inflow valve opening (E-wave after the arrow), followed by a pause and normal atrial (first A-wave after the arrow) inflow waveform.

shortening, the degree and persistence of AV valve incompetence, and alternations of venous blood flow in IVC and ductus venosus (79,80). Fetal hydrops is characterized by the presence of any two or all of the following signs: skin edema, ascites, pericardial effusion, and pleural effusion (Fig. 21) carry a much higher mortality than a nonhydropic fetus.

Approach to the Treatment of Fetal Tachyarrhythmias

In order to avoid significant morbidities associated with preterm birth, the approach to the management of fetal arrhythmias is to strive to deliver fetuses at or near term in

normal sinus rhythm by intrauterine therapy, which mostly employs maternal administration of antiarrhythmic pharmaceutical agents. The mothers carrying fetuses with incessant tachycardia, tachycardia and major heart defects, or hydrops should be hospitalized to initiate the treatment with loading dose of antiarrhythmic agent, to monitor closely for adverse effects, and to modify the treatment. Continuous cardiac telemetry, serial ECG to assess the cardiac effects of the drug, serum chemistries, and repeated serum drug concentrations in the mother should be obtained. Both the mother and the fetus should be closely observed for any adverse effect of the

Figure 20 A simultaneous Doppler interrogation of superior vena cava and aortic flow shows reverse waveform due to atrial contraction (A) and outflow waveform in aorta with measured atrioventricular interval (A-V interval 125 ms), which is equivalent to PR interval of electrocardiogram.

Figure 21 Two-dimensional fetal echocardiogram of a hydropic fetus shows pleural effusion in the chest cavity (A) and a rim of pericardial effusion around the heart (B).

treatment. Once the fetal cardiac rhythm or rate is controlled and maintenance therapy is instituted, the mother can be discharged for regular outpatient follow-up. A detailed discussion on antiarrhythmic drug treatment is out of the purview of this chapter. In general, digoxin has been the first choice followed by flecainide for the maternal administration of antiarrhythmic agent in nonhydropic fetuses and amiodarone in hydropic fetuses (81–83). Depending on the fetal gestation, cardiac function, success rate of triple antiarrhythmic drugs, and parental wishes, urgent delivery may have to be undertaken. A multidisciplinary team including perinatologist, pediatric and adult cardiologists, and neonatologist should be involved in the management of such fetuses and neonates.

PATIENT COUNSELING IN FETAL CARDIAC DISEASE

Counseling of the mother who is carrying a fetus with significant CHD can be a complex and lengthy process. As accurate diagnosis is critical to reliable counseling, and as the medical and surgical management of cardiac anomalies is often complicated, collaboration with a fetal cardiac specialist is usually warranted, particularly in complex cases. Nonetheless, it is important for all fetal echocardiography providers to be prepared to provide basic counseling to patients in whom fetal cardiovascular anomalies are suspected.

In addition to accurate anatomic diagnosis of fetal cardiac anomalies, it is useful to categorize the various fetal cardiac lesions with regard to severity. One approach is to classify lesions based on need and complexity of

Table 4 System for Classifying Severity of Fetal Congenital Heart Disease

<i>Low-risk congenital heart disease</i>	
Minimal impact on quality of life or longevity	Atrial septal defect Small VSD Mild pulmonary stenosis
<i>Moderate-risk congenital heart disease</i>	
Low mortality for surgical/catheter intervention, likely to impact long-term survival	Atrioventricular canal defect Coarctation of the aorta DORV Ebstein’s anomaly of the tricuspid valve Large VSD Tetralogy of Fallot Totally anomalous pulmonary venous connection TGA, simple
<i>High-risk congenital heart disease</i>	
High mortality for surgical/catheter intervention, requiring multiple interventions, likely residual cardiac compromise, significant impact on longevity	Aortic stenosis, severe DORV, complex Ebstein’s anomaly, severe cardiomegaly Heterotaxy with atrioventricular canal defect, complete heart block Hypoplastic left heart syndrome Pulmonary atresia with intact ventricular septum Pulmonary atresia, VSD, major aortopulmonary collateral vessels Single ventricle, complex Totally anomalous pulmonary venous return, obstructed TGA, complex Tricuspid atresia Truncus arteriosus

Abbreviations: VSD, ventricular septal defect; DORV, double-outlet right ventricle; TGA, transposition of the great arteries. Source: From Ref. 68.

Table 5 Risk of Chromosomal Anomalies in Common Congenital Heart Lesions

<i>High-risk congenital cardiac anomalies</i>	
Risk of chromosomal anomalies >10%	Absent pulmonary valve syndrome (20%) Atrioventricular canal defect (35%) Coarctation of the aorta (29%) Double-outlet right ventricle (12%) Mitral valve atresia (18%) Tetralogy of Fallot (27%) Totally anomalous pulmonary venous return (30%) Truncus arteriosus (14%) Ventricular septal defect (48%)
<i>Low-risk congenital cardiac anomalies</i>	
Risk of chromosomal anomalies <10%	Hypoplastic left heart syndrome (4%) Pulmonary stenosis/atresia with intact ventricular septum (5%) Transposition of the great arteries (0%) Tricuspid valve anomaly/Ebstein’s (5%)

Source: From Ref. 6.

surgical repair/palliation and the likelihood of residual cardiac disability. An approach for categorizing congenital heart defects in this fashion has been proposed by Allan and colleagues (84) and is presented in Table 4. This approach involves characterizing fetal cardiac anomalies as either low, moderate, or high risk based on expected impact on quality of life and longevity, as well as the complexity, mortality risk, and “completeness” of available surgical palliative procedures.

Making predictions regarding the need for perinatal medical and/or surgical management is also helpful. Identification of “reversed” physiologic shunting in the fetus with either right or left ventricular outflow tract obstruction can allow clinicians to make predictions about the need for prostaglandin infusion to maintain ductal patency and the need for transfer to a cardiac center for management of critical outflow tract obstruction. In our center, fetuses fitting this clinical description are routinely started on prostaglandin infusion following recommended delivery at a level III perinatal center and transferred to our cardiac intensive care unit for management. Examples of common lesions presenting in this

manner include pulmonary stenosis/atresia, tetralogy of Fallot, tricuspid atresia, aortic stenosis, or variants of hypoplastic left heart syndrome. Other lesions that are routinely started on prostaglandin and transferred to the cardiac unit are severe coarctation and transposition of the great arteries. Generally, septal defects such as ASD, VSD, and AV canal defect do not require immediate intervention and can be evaluated more electively (after a confirmatory postnatal echocardiogram) at the birth hospital. In our center, all variants of single ventricle are delivered at a level III center and transferred to the cardiac unit for evaluation, given the complexity of cardiac issues involved in these cases. Given the complexity and diversity of congenital heart lesions, collaboration with a fetal cardiologist is important in arriving at a disposition for these complex fetuses.

Another major issue is genetic counseling for patients with the diagnosis of fetal CHD. Although we generally recommend genetic counseling for all mothers diagnosed with fetal CHD, it is known that certain cardiac lesions carry a particularly high risk of chromosomal abnormalities (6); these groups are outlined in Table 5. In addition to screening for aneuploidy, clinicians should also screen for microdeletions in chromosome 22, which is associated in high frequency with conotruncal defects and aortic arch anomalies. The presence of a significant chromosomal anomaly, as well as other extracardiac anomalies, has surgical implications, as most studies have identified these as risk factors for increased morbidity and mortality during surgical palliation, particularly in complex congenital heart defects.

ADVANCES IN FETAL CARDIAC DIAGNOSIS AND THERAPY

Evaluation of Fetal Arrhythmias by Magnetocardiography

Magnetocardiography elucidates electrical signals in the fetal heart by detecting and analyzing the related magnetic fields. It processes the sequence of electrical events rather than mechanical events of the heart and can provide the capability of measuring different electrical time intervals such as QRS and QT intervals (85). Therefore, potentially it can reveal the

Figure 22 A vector velocity imaging (VVI) of 24-week gestation fetus of a diabetic mother shows the magnitude and direction of the longitudinal strain of the left ventricle (LV) indicated by the length and direction of arrows along the endocardial border of the LV (A) in transverse view. The VVI of the same infant at 1 week of age after birth shows the magnitude and direction of the longitudinal strain of the LV in four-chamber view (B).

mechanisms of fetal arrhythmias and aid in the differential diagnosis of fetal tachycardia such as in distinguishing VT with 1:1 conduction versus SVT as well as VT with AV dissociation versus junctional ectopic tachycardia (73). Discerning the mechanisms of fetal arrhythmias will help select the appropriate anti-tachyarrhythmic agents and unify the approach to the treatment of fetal arrhythmias. This modality is not in clinical use yet because of its need to be performed in a magnetically shielded room. Advancement has been made in the use of the technique at the bedside in an unshielded environment, which may bring it for wider use in the clinical practice (85).

Evaluation of Fetal Cardiac Function by Strain Imaging

Cardiac function in fetuses has traditionally been measured by subjective assessment of contractility and observation for hydrops fetalis. Currently, myocardial functional assessment in the fetus has been limited by the reduced reproducibility due to the requirement for correct alignment to the structures being interrogated, lack of a concurrent electrocardiogram to time mechanical events accurately and unique properties of the fetal myocardium, which is made up of primarily noncontractile elements with fewer myocytes. Furthermore, most noninvasive methods of evaluation of cardiac function are load dependent (86). A novel method based on speckle-tracking techniques, including vector velocity imaging, has emerged that uses frame-by-frame tracking of myocardial speckles in 2D echocardiographic images to provide velocity and displacement data and permit quantification of the degree of myocardial deformation or strain (87) and strain rate, which is relatively load independent (88). The new method allows assessment of function independent of fetal lie, thus simplifying more sophisticated measures of function, such as strain and shear stress (89) (Fig. 22). This will help to improve the objectivity, reproducibility, and monitoring of fetal cardiac function.

Fetal Cardiac Intervention

Fetal cardiac intervention is a burgeoning field. Endeavors are being made in some centers to prevent fetal hydrops due to congenital heart defects, to recruit hypoplastic ventricles, to create a two-ventricle circulation after birth, and to remodel

the fetal pulmonary vascular bed whose outlet is obstructed (90). A successful open heart surgery in the fetus has yet to be done, but catheter-based interventions for improved cardiac outcomes are now being taken up.

Fetal echocardiography can identify midgestation fetuses with aortic and pulmonary outflow obstruction, which are at high risk for developing hypoplastic left and right heart syndromes, respectively. With the development of novel techniques, risk reduction to the fetus and the mother, timely and successful valve dilation may prevent left or right heart growth arrest and may result in normal ventricular anatomy and function at birth (91,92). There is an important learning curve for these procedures, and much remains to be learned about the selection of appropriate fetuses for prenatal intervention and further refinement in techniques of echocardiography, approach, and risk reduction in fetal intervention.

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