

# Management of Pregnancy in Patients With Complex Congenital Heart Disease

## A Scientific Statement for Healthcare Professionals From the American Heart Association

**ABSTRACT:** Today, most female children born with congenital heart disease will reach childbearing age. For many women with complex congenital heart disease, carrying a pregnancy carries a moderate to high risk for both the mother and her fetus. Many such women, however, do not have access to adult congenital heart disease tertiary centers with experienced reproductive programs. Therefore, it is important that all practitioners who will be managing these women have current information not only on preconception counseling and diagnostic evaluation to determine maternal and fetal risk but also on how to manage them once they are pregnant and when to refer them to a regional center with expertise in pregnancy management.

Expanded diagnostic, medical, and surgical management options have improved the long-term survival of patients with congenital heart disease (CHD). Thus, most women born with CHD will reach reproductive age. The ability to bear children is a major point of care for this growing population. As a result, pregnancy counseling and management are among the major noncardiac issues facing pediatric and congenital cardiac providers.

For the majority of patients, the ability to conceive and carry a pregnancy to term will present little problem. However, for those with complex CHD, pregnancy may be associated with an increased risk compared with women with milder forms of CHD, regardless of whether they are clinically stable at the time of conception. This document provides an overview of the management of the patient with complex CHD who becomes pregnant.

### DEFINING THE POPULATION

Simple CHD lesions include mild pulmonary valve stenosis, a small, uncomplicated atrial septal defect or ventricular septal defect, patent ductus arteriosus, and successfully repaired atrial septal defect, ventricular septal defect, patent ductus arteriosus, and anomalous pulmonary venous connection without important residua. Complex CHD, on the other hand, includes any complex anatomical or physiological lesion as defined by the Bethesda conference.<sup>1</sup> Some patients with simple CHD lesions would, however, be considered high pregnancy risk because of the presence of comorbid conditions. An example is the patient with an atrial septal defect and pulmonary hypertension or atrial fibrillation; this patient would require a higher level of care during pregnancy and in the peripartum period. Thus, a designation of simple versus complex CHD is not adequate when referring to patients with CHD considering pregnancy.

Mary M. Canobbio, RN,  
MN, FAHA, Chair  
Carole A. Warnes, MD,  
FRCP, Co-Chair  
Jamil Aboulhosn, MD  
Heidi M. Connolly, MD  
Amber Khanna, MD  
Brian J. Koos, MD, DPhil  
Seema Mital, MD, FAHA,  
FRCP  
Carl Rose, MD  
Candice Silversides, MD,  
FRCP  
Karen Stout, MD, FAHA  
On behalf of the American Heart Association Council on Cardiovascular and Stroke Nursing; Council on Clinical Cardiology; Council on Cardiovascular Disease in the Young; Council on Functional Genomics and Translational Biology; and Council on Quality of Care and Outcomes Research

**Key Words:** AHA Scientific Statements ■ heart defects, congenital ■ heart diseases ■ pregnancy

© 2017 American Heart Association, Inc.

The modified World Health Organization (WHO) classification categorized patients into 4 pregnancy risk classes (classes I–IV) as determined by their medical condition (Table 1).<sup>2</sup> Patients in class I have no detectable increased risk of maternal mortality and either no or a mild increase in morbidity; thus, they are not included in this document. Women in class II might have a small increase in maternal mortality or a moderate increase in morbidity with pregnancy, and those in class III might have a significant increase in maternal mortality or severe morbidity. Those in class IV, however, may carry an extremely high risk of maternal mortality or severe morbidity such that pregnancy is ill advised. These patients should be counseled to avoid pregnancy. If pregnancy is confirmed in a woman in WHO class IV, then termination is advised.

High-risk patients are further identified in observational data to include patients with prosthetic valves or those with more than moderate atrioventricular valve regurgitation or New York Heart Association (NYHA) class II or higher heart failure before pregnancy.<sup>4–7</sup>

## PHYSIOLOGICAL ADAPTATION OF PREGNANCY

Maternal organ systems undergo significant physiological alterations during pregnancy. The following sections highlight the physiological changes that have particular relevance to the management of gravidas with CHD.

### Antepartum

#### Blood Volume

Maternal blood volume begins to increase with the early hormonal changes of conception.<sup>8</sup> Overall, pregnancy increases maternal blood volume by  $\approx 40\%$  for a singleton and  $67\%$  for twins, with peak values at  $\approx 32$  weeks of gestation<sup>8,9</sup> (Figure 1). Both plasma volume and red cell mass contribute to the hypervolemia, with respective increases of  $\approx 45\%$  to  $55\%$  and  $20\%$  to  $30\%$ .<sup>10–12</sup> Estrogen has a key role in plasma volume expansion and promotes sodium and water retention by upregulating the production of angiotensinogen, renin, and aldosterone.<sup>13–15</sup> The disproportionate expansion of plasma volume relative to red cell mass contributes to the physiological anemia of pregnancy, with mean $\pm$ SD hemoglobin concentrations of  $10.9\pm 0.6$  and  $12.4\pm 1.0$  g/dL for the second and third trimesters, respectively.

#### B-Type Natriuretic Peptide

The median level of B-type natriuretic peptide (BNP) in normal pregnant woman is about twice that of nonpregnant control subjects, rising early in pregnancy and remaining high throughout gestation<sup>16–18</sup> until  $\approx 72$  hours after delivery.<sup>19,20</sup> Adverse maternal cardiac events have been associated with high BNP concentrations ( $>100$  pg/mL), but its use as a negative predictive indicator appears to be of most value. In 1 series, the negative pre-

dictive value of NT-pro-BNP  $<128$  pg/mL at 20 weeks' gestation exceeded  $95\%$ .<sup>21</sup>

#### Colloid Oncotic Pressure

Circulating albumin concentrations fall  $12\%$  to  $18\%$  in pregnancy, with the lowest levels at  $\approx 24$  weeks' gestation.<sup>22</sup> The decline in colloid oncotic pressure, along with increased femoral venous pressure caused by uterine compression of the inferior vena cava, elicits the edema of pregnancy.<sup>22,23</sup> The fall in oncotic pressure can be hemodynamically significant, particularly when combined with generous intravenous infusion of crystalloid, and thus the gravida is more susceptible to pulmonary edema under these conditions.

#### Cardiac Output

Maternal cardiac output begins to rise after conception and plateaus at  $\approx 24$  weeks of gestation, as shown in Figure 2.<sup>24–33</sup> Maternal cardiac output increases  $30\%$  to  $50\%$  in a singleton pregnancy, with an additional  $10\%$  to  $20\%$  increment in a twin pregnancy.<sup>34–37</sup> Maternal posture can significantly affect cardiac output, especially after 20 weeks' gestation when the gravid uterus compresses the vena cava and pelvic veins.<sup>38</sup> Compared with measurements in late pregnancy in the left lateral recumbent position, cardiac output is lowered by  $\approx 14\%$  in the supine position and by  $\approx 30\%$  in lithotomy.<sup>39</sup> In fact,  $\approx 8\%$  of gravidas become hypotensive in later pregnancy when in the supine position, with pallor, nausea, and dizziness. The hemodynamic effects vary widely, with the fall in arterial pressure ranging from mild to severe.<sup>31</sup> These women can also manifest a blunted rise in heart rate or even a bradycardia. Severe hypotension can even occur without maternal symptoms.<sup>40</sup>

#### Cardiac Rhythm

Maternal heart rate progressively rises 10 to 20 bpm over pregestational rates, peaking in the late second or early third trimester. Pregnancy also lowers the threshold for isolated rhythm disturbances, including atrial and ventricular premature beats and reentrant supraventricular tachycardia (SVT). Similarly, ventricular arrhythmias, although rare in labor, have been reported in  $5\%$  of normal gravidas.<sup>41</sup> Common changes observed on the ECG are listed in Table 2.

#### Arterial Vasculature

The vascular tree undergoes remodeling to accommodate increased blood volume. Along with the hyperkinetic circulation, structural alterations increase the risk of aortic root enlargement and dissection, particularly in gravidas with aortopathies such as Marfan or Turner syndrome.

Pulmonary vascular resistance (PVR) declines by  $\approx 24\%$  by the eighth week of gestation and remains stable over the remainder of pregnancy. The decrease in PVR accommodates the  $\approx 47\%$  increase in pulmonary flow; thus, the mean pulmonary artery pressure remains unaltered in a normal pregnancy.<sup>42–45</sup>

**Table 1. Modified WHO Classification of Maternal Cardiovascular Risk**

WHO Pregnancy Risk Category	Risk Description	Maternal Risk Factors
I	No detectable increase in maternal mortality and no/mild increase in morbidity risk	Uncomplicated small/mild pulmonary stenosis, PDA, mitral valve prolapse
		Successfully repaired simple lesions (ASD, VSD, PDA, anomalous pulmonary venous drainage)
		Atrial or ventricular ectopic beats, isolated
II	Small increase in maternal mortality and moderate increase in morbidity risk	If otherwise well and uncomplicated:
		Unoperated ASD, VSD
		Repaired TOF
		Most arrhythmias
II–III	Moderate increase in maternal mortality morbidity risk	Mild LV impairment
		Hypertrophic cardiomyopathy
		Native or tissue valvular disease (not considered risk category I or IV)
		Marfan syndrome without aortic dilation
		Aortic dilation <45 mm in bicuspid aortic valve aortopathy
		Repaired coarctation
III	Significantly increased maternal mortality or severe morbidity risk. Expert counseling required. In the event of pregnancy, intensive specialist cardiac and obstetric monitoring needed throughout pregnancy, childbirth, and the puerperium.	Mechanical valve
		Systemic RV
		Fontan circulation
		Cyanotic heart disease (unrepaired)
		Other complex CHD
		Aortic dilation 40–45 mm in Marfan syndrome
		Aortic dilation 45–50 mm in bicuspid aortic valve aortopathy
IV	Extremely high maternal mortality or severe morbidity risk. Pregnancy is contraindicated. In the event of pregnancy, termination should be discussed. If pregnancy continues, care should follow class III recommendations.	Pulmonary arterial hypertension (of any cause)
		Severe systemic ventricular dysfunction (LV ejection fraction <30%, NYHA class III–IV)
		Previous peripartum cardiomyopathy with any residual impairment of LV function
		Severe mitral stenosis, severe symptomatic aortic stenosis
		Aortic dilation >45 mm in Marfan syndrome
		Aortic dilation >50 mm in bicuspid aortic valve aortopathy
		Native severe coarctation

AS indicates aortic stenosis; ASD, atrial septal defect; CHD, congenital heart disease; LV, left ventricular; NYHA, New York Heart Association; PDA, patent ductus arteriosus; RV, right ventricle; TOF, tetralogy of Fallot; VSD, ventricular septal defect; and WHO, World Health Organization.

Modified from Thorne et al<sup>2</sup> with permission from the BMJ Publishing Group Ltd. Copyright © 2006, BMJ Publishing Group Ltd and the British Cardiovascular Society. Modified from Balci et al<sup>3</sup> with permission from the BMJ Publishing Group Ltd. Copyright © 2014, BMJ Publishing Group Ltd and the British Cardiovascular Society.

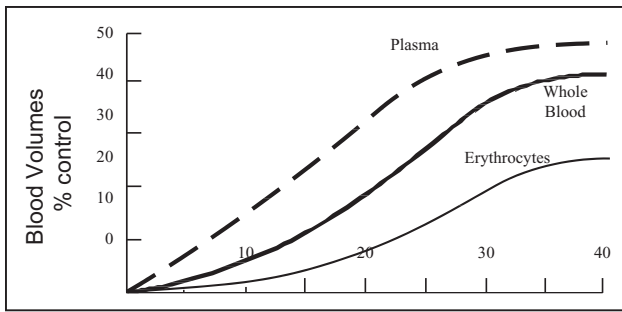
A primary fall in systemic vascular resistance (SVR), which reduces preload and afterload, may trigger many of the changes in the hemodynamics and volume homeostasis that accompany early pregnancy. Within 8 weeks after the last menstrual period, SVR has fallen by ≈30%, reaching a nadir at ≈24 weeks' gestation (Figure 2).<sup>23,25,27,43,46–50</sup> After 24 weeks' gestation, SVR begins to increase again, approaching preconception levels by term.

The fall in SVR is associated with 10 to 15 mmHg reduction in diastolic pressure at 20 to 24 weeks' gesta-

tion (measured in the lateral recumbent position), which is followed by a rise toward nonpregnant measurements (Figure 2).<sup>27,51</sup>

### **Respiratory Changes**

Tidal volume increases 40% with a proportional rise in minute ventilation.<sup>52–54</sup> This physiological hyperventilation is greater than the increase in oxygen consumption and accounts for the breathlessness that begins in early pregnancy.<sup>55–58</sup>



**Figure 1. Pregnancy changes in blood volume.**

Reprinted with permission from Longo et al.<sup>13</sup> Copyright © 1983, American Physiological Society.

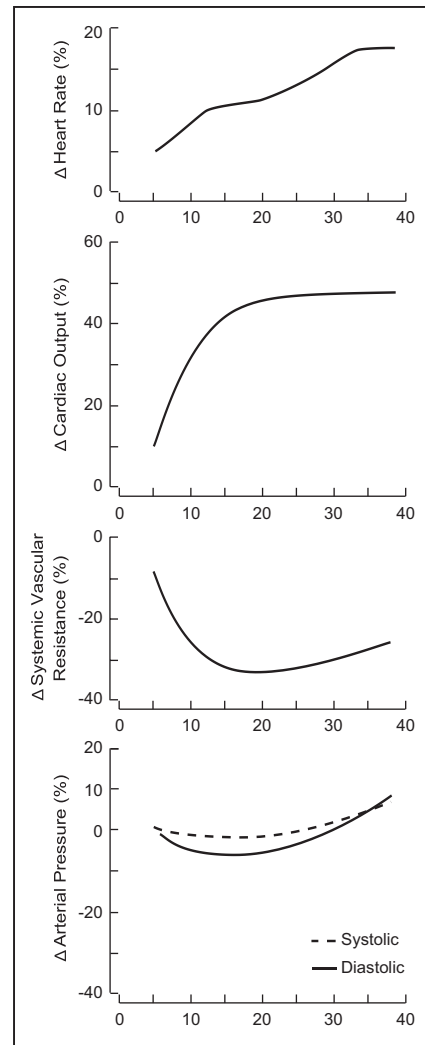
### Intrapartum

Labor results in important hemodynamic changes, including elevations in heart rate, central venous pressure, and cardiac output.<sup>59–61</sup> A change from the supine to a lateral recumbent position between contractions (basal conditions) increases maternal cardiac output by  $\approx 22\%$  and decreases heart rate by  $6\%$ .<sup>60</sup> Basal systemic arterial pressure rises with the progression of the first stage of labor, with further increases during uterine contractions.<sup>33,59,61</sup> Uterine contractions augment maternal cardiac output as a result of enhanced sympathetic activity (via anxiety, pain) and expulsion of uterine blood into the central venous circulation.<sup>58–60</sup> During a contraction, the uterus expels up to 400 mL blood into the central venous circulation, leading to a rise in central venous pressure, right atrial pressure,<sup>62</sup> cardiac output, and arterial pressure. The labor-induced augmentation of cardiac output is attenuated by effective epidural anesthesia.

Maternal position modulates these hemodynamic responses. In the supine position, contractions are associated with an  $\approx 15\%$  rise in cardiac output; in the lateral position, cardiac output rises only  $\approx 8\%$  to  $11\%$ .<sup>32,35,63</sup> In the supine position, compression of the inferior vena cava by the gravid uterus reduces venous return and cardiac output, whereas virtual occlusion of the distal aorta and its branches by the uterus results in a greater increase in arterial pressure.<sup>63,64</sup> Lateral recumbency is not associated with impeded venous return or elevations in systemic arterial pressure. Overall, maternal cardiac output increases 10% to 30% during the first stage of labor and up to 50% in the second stage.<sup>32,46,58–60,65,66</sup>

The labor-associated rise in arterial pressure can be attenuated by effective pain control (eg, epidural) and lateral tilting of the patient.<sup>67,68</sup> Because epidural anesthesia via venodilatation can reduce return of blood to the heart, cautious incremental dosing is advised, especially in gravidas whose maternal cardiac output is sensitive to falls in preload.

The pelvic descent of the fetus in the second stage of labor elicits pressure and an urge to bear down against a closed glottis in a gravida without effective epidural anesthesia. When performed in the absence of contrac-



**Figure 2. Pregnancy changes in maternal systemic hemodynamics.**

Reproduced with permission from Robson et al.<sup>24</sup> Copyright © 1989, American Physiological Society.

tions or between contractions, the Valsalva maneuver typically elicits a moderate transient fall in cardiac output resulting from decreased venous return.<sup>58</sup> Minimizing maternal expulsive effort by passive delivery and facilitating the second stage by assisted delivery (forceps or vacuum extraction) to avoid the Valsalva maneuver and thereby minimize hemodynamic perturbations should be considered in those with critical obstructive lesions (eg, aortic stenosis [AS]), fragile aortas (bicuspid aortic valve with aortopathy, coarctation), and pulmonary hypertension.<sup>68</sup>

### Postpartum

Further challenges to maternal cardiac reserve occur at delivery, that result from increased preload via caval decompression and extrusion of blood from the contracted uterus into the inferior vena cava. Augmented



**Table 2. Normal Electrocardiographic Changes Associated With Pregnancy**

Left axis shift is seen, with the greatest shift in the third trimester caused by elevation of the diaphragm.
Shortening of the PR, QRS, and QT intervals may accompany the increase in resting heart rate.
Nonspecific ST abnormalities, including segment depression or flattened and inverted T waves in lead III, occur frequently.

venous return increases maternal cardiac output by 60% to 80% after vaginal delivery.<sup>58–62,65</sup> This abrupt rise in cardiac output dissipates to prelabor values within ≈1 hour postpartum and falls further over the following 24 weeks. Mean arterial pressure can be elevated for 1 to 2 days postpartum<sup>60</sup> before declining over the ensuing 2 weeks. PVR rises to preconception values within 6 months postpartum.<sup>42</sup>

Maternal blood loss in the first postpartum hour averages 600 mL for vaginal and 1000 mL for cesarean delivery.<sup>69</sup> Excessive blood loss is associated with maternal tachycardia and decreased stroke volume.<sup>70,71</sup>

## ASSESSMENT AND EVALUATION

### Preconception Counseling and Diagnostic Evaluation

Optimal preconception diagnostic cardiovascular evaluation should accurately assess an individual patient's pregnancy risk and direct appropriate therapies to reduce risk. At present, risk algorithms are imperfect for assessing individual risk but provide a framework from which to evaluate patients. The most reliable appears to be the modified WHO classification of maternal cardiovascular risk (see Estimating Maternal and Fetal Risk and Table 1).<sup>3</sup>

#### Preconception Counseling

All women of reproductive age with CHD should be counseled about pregnancy early in their medical care by a provider who is knowledgeable in the care of the CHD patient. Ideally, age-appropriate counseling should be initially offered at or soon after sexual maturity in the patient's teen years. Counseling should include a discussion of the anticipated impact of pregnancy on maternal heart disease and the importance of pregnancy planning, including effective contraception options.

For the woman with complex CHD, preconception planning is imperative. The woman and her partner should have a clear understanding of the potential risk of pregnancy for her and her offspring. For the woman contemplating an immediate pregnancy, a more focused conversation is required about pregnancy risk and possible need to undergo additional diagnostic cardiovascular evaluation to determine maternal risk, to optimize ma-

ternal status, and to treat or repair any residual defects or other problems before conception as needed. The discussion should also include the possibility that pregnancy may contribute to a decline in maternal cardiac status that may not recover to baseline after pregnancy. It is also important to identify any potential impediments such as insurance, transportation, and geographic distance from the tertiary center. Finally, it is important to stress that women with complex CHD must be cared for by an obstetrician and cardiologist experienced in the management of adult CHD.<sup>68,72</sup>

A brief overview of the anticipated delivery plan (vaginal versus cesarean delivery, anesthesia) should also be discussed (Figure 3). A preconception visit with a maternal-fetal medicine obstetrician can be helpful, particularly for women at higher risk for complications.

Genetic counseling may be particularly valuable to women for whom there is a significant risk of recurrence in offspring. The risk for recurrence of CHD varies widely from 3% to 50%, depending on the type of maternal heart disease<sup>73,74</sup> (see Estimating Maternal and Fetal Risk).

#### Diagnostic Evaluation

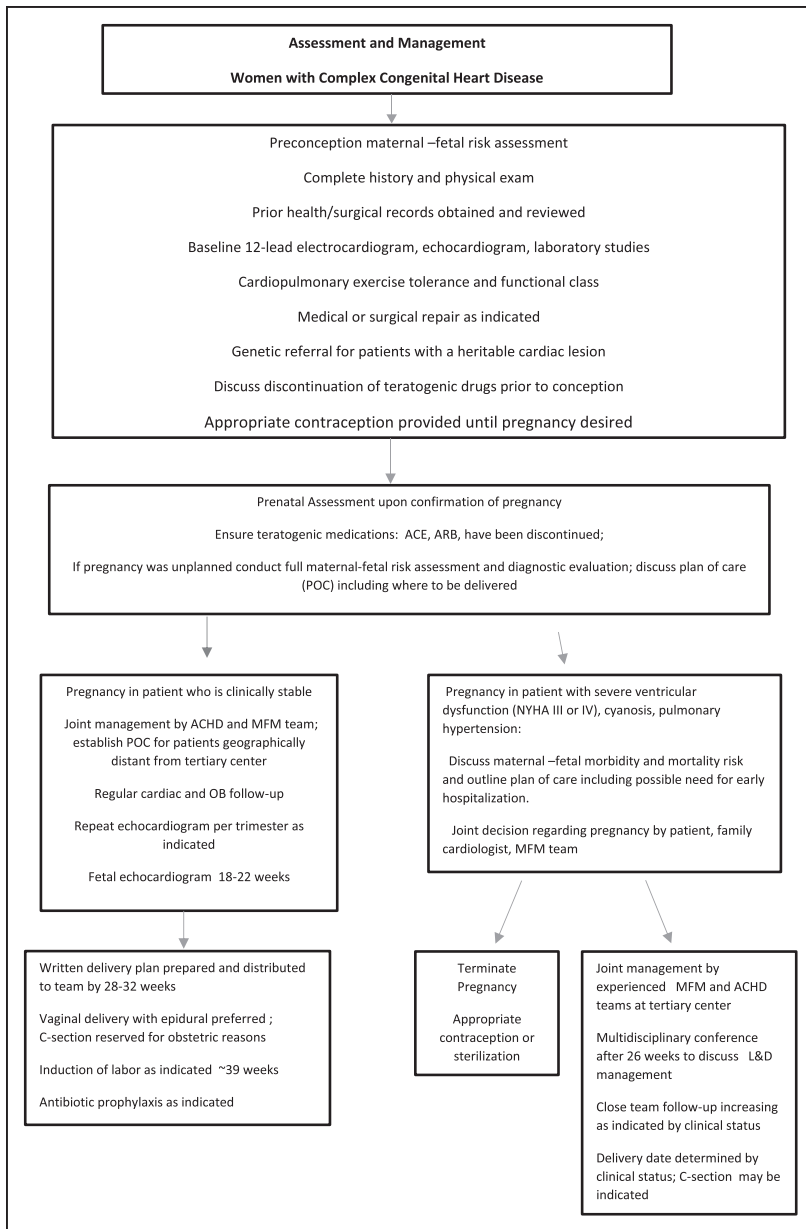
The preconception evaluation of a patient with complex CHD begins with a thorough review of medical records that include information on the primary defect, surgical history, including both palliative and reparative procedures, and the presence of comorbidities and any residual or sequelae associated with the specific cardiac lesions or surgery. Similarly, reports from prior testing such as echocardiograms, magnetic resonance imaging (MRI), and exercise tests should be available for comparison. The initial diagnostic evaluation includes measurement of arterial oxygen saturation, ECG, and echocardiogram.

Because maternal functional capacity is an important predictor of a woman's ability to tolerate pregnancy, assessment of exercise capacity may be helpful. For most patients with complex disease, objective exercise testing by a cardiopulmonary exercise test or an exercise stress test may be in order to obtain an objective assessment of functional capacity and to facilitate the identification of exercise-induced arrhythmias, particularly because many patients underreport or underrecognize the degree of their limitation.<sup>75,76</sup>

#### Suggestions for Clinical Practice

The initial diagnostic evaluation should include the following:

- Detailed history, including any current cardiovascular symptoms and family history
- Review of medications for benefits and risks, with appropriate adjustment or changes of drugs known to be teratogenic
- Arterial oxygen saturation
- Baseline laboratory studies, including complete blood count, electrolytes, and thyroid and liver function tests



**Figure 3. Assessment and management of women with complex congenital heart disease.**

ACE indicates angiotensin-converting enzyme; ACHD, adult congenital heart disease; ARB, angiotensin receptor blocker; L&D, labor and delivery; MFM, maternal-fetal medicine; NYHA, New York Heart Association; OB, obstetrics; and POC, plan of care.

- ECG
- Cardiopulmonary or exercise stress test
- Comprehensive echocardiogram
- Consideration of genetic counseling

Additional testing, including imaging or invasive studies, should be carried out only to further investigate anatomy, ventricular function or integrity of valve function, or calculation of shunts or to determine the presence of pulmonary hypertension. If there is doubt about the presence or absence of pulmonary hypertension, cardiac catheterization should be performed.

### Estimating Maternal and Fetal Risk

Maternal risk in pregnancy is dependent not only on the complexity of the primary cardiac lesion but also on the presence of residual lesions and clinical sequelae such

as heart failure, arrhythmias, or cerebrovascular events that contribute to overall risk.<sup>77-79</sup>

### Maternal Risk

Several risk stratification scores, including the Canadian Cardiac Disease in Pregnancy (CARPREG) score<sup>74</sup> and the Zwangerschap bij Aangeboren HARTafwijkingen (ZA-HARA; translated in English as “Pregnancy and Congenital Heart Disease”) score,<sup>4</sup> have been developed to predict maternal risk during pregnancy. Both models identify predictors of maternal cardiovascular and fetal events and attribute points to each predictor in an attempt to delineate more precisely maternal cardiovascular and offspring risk to the pregnancy. These risk scores have significant limitations, however, because they are highly population dependent. For example, Canadian Cardiac Disease in Pregnancy included 22% of patients with ac-

quired heart disease, and 4% of the population were included because of arrhythmias. Therefore, in an effort to prevent high-risk patients from becoming pregnant, including those with severe pulmonary hypertension and severely dilated aortas and those who are not represented in these studies, a prepregnancy counseling session should be organized in an adult CHD center.

More recently, a prospective validation study reported that the modified WHO classification of maternal cardiovascular risk was the most reliable predictor of maternal cardiovascular complications, the most common of which are arrhythmias and heart failure.<sup>3</sup> The recommendation to each patient, however, should be individualized. If a reparable lesion or clinical problem is identified at the time of prepregnancy counseling, a recommendation for directed therapies to address the problem is made.

For some patients, the evaluation may suggest a pregnancy risk that is unacceptable to the patient. Appropriate contraception is vital for those women who are counseled against pregnancy and for those women who choose not to pursue pregnancy.

### **Fetal Risk**

Maternal CHD is major determinant of risk to the fetus and the neonate, resulting in the following:

- Higher frequency of spontaneous abortions, ranging between 15% and 25%, and intrauterine fetal demise in selected defects.<sup>79,80</sup>
- Higher frequency of recurrence of CHD, underscoring the need to offer fetal echocardiography to all pregnant women with CHD at 18 to 22 weeks.
- Higher preterm birth rate (10%–12%), especially in those with complex CHD (22%–65%).
- Higher frequency of neonatal events, for example, small for gestational age, respiratory distress syndrome, interventricular hemorrhage, and neonatal death (27.8%). Specific maternal risk factors such as subaortic ventricular outflow obstruction, maternal cyanosis, and reduced cardiac output have been reported as predictors of adverse perinatal events.<sup>79,80</sup>
- Higher perinatal mortality that may be >4-fold higher than in the general population (<1%) and is common with premature delivery or recurrence of CHD. Perinatal mortality is highest in patients with Eisenmenger syndrome (27.7%).<sup>4,78,79</sup>

### **Genetic Counseling**

It is important to provide genetic counseling to women with CHD on the potential for recurrence risk in the offspring, ideally before conception.

Genetic counseling should include the assessment of genetic risk, a discussion of the genetic screening tests available and the implications of genetic test results, and pretest and posttest counseling. Positive consequences include a more accurate estimation of transmission risk

to offspring and greater awareness and better management of comorbid conditions that can influence fetal and maternal outcomes. A detailed 3-generation family history, including history of consanguinity and history of miscarriages, should be obtained in all pregnancies.<sup>81,82</sup>

Maternal and paternal evaluation should be performed for clinical features suggestive of a syndromic phenotype. The absence of typical phenotypic features does not preclude the presence of a genetic or chromosomal anomaly; therefore, genetic testing may still be offered if the index of suspicion for a genetic pathogenesis is high. Most genetic conditions associated with CHD are autosomal dominant conditions, which have a transmission risk of 50%, including the Marfan, Holt-Oram, Noonan, Alagille, CHARGE (coloboma, heart defect, atresia choanae, retarded growth and development, genital abnormality, and ear abnormality), 22q11.2 microdeletion, and Williams syndromes. For CHD that arises de novo, the risk of CHD recurrence in offspring is between 3% and 5%.<sup>83</sup> The risk of recurrence is higher with heterotaxy, atrioventricular septal defect, and obstructive lesions of the left ventricular outflow tract.<sup>84</sup> Besides genetic factors, it is important to assess for environmental risk factors such as obesity, diabetes mellitus, hypertension, infections, alcohol, smoking, and teratogenic medications that can negatively affect fetal growth and well-being and increase the risk of fetal birth defects.<sup>85</sup>

Because a number of conotruncal abnormalities may be associated with chromosomal abnormalities such as 22q11.2 deletion syndrome, genetic testing should be offered not only to women with strong family history of CHD but also to women with cardiac lesions known to be associated with genetic disorders. These include interrupted aortic arch, truncus arteriosus, tetralogy of Fallot, pulmonary atresia, ventricular septal defect with aortic arch anomaly, isolated aortic arch anomaly, and discontinuous branch pulmonary arteries.

Two consensus statements from the American Heart Association (AHA) and the Canadian Cardiovascular Society provide excellent guidance for genetic testing in CHD.<sup>85,86</sup>

### **Suggestions for Clinical Practice**

- A 3-generation family history, including any consanguinity, should be completed.
- Genetic evaluation should be made available to all women with CHD to determine recurrence, particularly in those patients with a family history of CHD and those with possible autosomal dominant lesions (eg, 22q 11 deletion).

## **PREGNANCY MANAGEMENT**

Ideally, the cardiovascular evaluation should occur before conception. For the patient who presents for the first time with an unplanned pregnancy, however, the

diagnostic workup must be individualized with consideration of the potential risk to both mother and fetus.

## Diagnostic Testing in Pregnancy

### Electrocardiogram

A standard 12-lead ECG is a simple method for evaluating abnormal heart rhythm, chamber enlargement, evidence of ischemia, and medication effects. Normal electrocardiographic changes associated with pregnancy are listed in Table 2. Holter monitors and extended event recorders may be helpful in the evaluation of a patient with palpitations, presyncope, or syncope.

### Echocardiography

Transthoracic echocardiography remains a mainstay of cardiac evaluation in the CHD population and can provide information on cardiac structure, anatomic abnormalities, chamber and great vessel dimensions, ventricular function, valvular function, and hemodynamics.

The use of agitated saline during pregnancy has not been systematically studied but is generally considered safe.<sup>87</sup> Intravenous contrast agents such as perflutren lipid microspheres (Definity) or perflutren protein type A (Optison) have not been studied in pregnant women. Either may be used if a clear maternal benefit is defined.

An echocardiogram taken before the pregnancy is useful in establishing the baseline status and may be repeated safely throughout pregnancy.<sup>88</sup> In those with limited echocardiographic windows, transesophageal echocardiography is relatively safe during pregnancy but with attention to airway protection to avoid the risk of vomiting and aspiration.<sup>68,89</sup>

### Exercise Stress Testing

Exercise stress testing and measurement of maximal oxygen consumption ( $\dot{V}O_2\text{max}$ ) during exercise can be useful in evaluating cardiopulmonary reserve, functional status, or potential exercise-induced arrhythmias during pregnancy, although they are rarely necessary.<sup>90–93</sup> A submaximal stress protocol (80% of the maximal predicted heart rate) is recommended.<sup>68,91</sup> A stress echocardiogram is indicated to determine the risk of myocardial ischemia in patients with suspected or confirmed underlying coronary artery disease or in patients with mildly reduced ventricular function.

## Imaging

### Chest Radiography

Chest radiography is generally not advocated during pregnancy unless specifically indicated. Even the normal heart may appear to be increased in size during pregnancy.<sup>94</sup>

### Magnetic Resonance Imaging

MRI is particularly useful for evaluating extracardiac vascular structures, including the aorta and left ventricular

myocardium. The majority of studies evaluating MRI safety during pregnancy report that maternal risk associated with the use of MRI is the same as for nonpregnant patients.<sup>95–97</sup> Safety concerns arise, however, with respect to the fetus. Although no ill effects to the fetus have been reported, concerns include the potential for fetal acoustic damage because MRI coils produce a loud tapping noise.<sup>98,99</sup> Limited data on organogenesis are available, but MRI is probably safe after the first trimester.<sup>68</sup> The American College of Radiology recommends that gadolinium be avoided and used only when other imaging (transthoracic and transesophageal echocardiography) is insufficient for diagnosis and that the risks and benefits be discussed with the pregnant patient and referring physician.<sup>96,97</sup> If required, it is preferable to wait until the second or third trimester when organogenesis is completed.<sup>97,100</sup>

### Computed Tomography

The risk of radiation exposure from computed tomography (CT) procedures varies, depending on gestational age and dose of radiation. CT is recommended only if other imaging is insufficient for the diagnosis.<sup>87,101</sup> If pulmonary embolism is suspected and CT is thought necessary for definitive diagnosis, CT of the chest may be performed at low dose of fetal exposure with a thorough discussion of risks and benefits.<sup>68,101</sup> V/Q scans carry similar risk. The threshold for fetal risk appears to be increased at doses >100 mGy.<sup>101,102</sup>

### Cardiac Catheterization

Concerns exist over the short- and long-term consequences of fetal radiation exposure during diagnostic and interventional cardiac catheterization. However, in clinical instances when hemodynamic compromise or an emergent intervention requires either right-sided heart or full cardiac catheterization, radiation exposure can be minimized by ensuring shortened fluoroscopy time and ensuring that the radiation dose remains at lower levels.<sup>102</sup>

The radiation exposure to the fetus arises predominantly from scattered radiation within the patient. External lead shielding of the maternal pelvis is of limited value although generally still used. The radiation dose absorbed by the fetus without shielding is only 3% higher than that with external shielding for all periods of gestation.<sup>87,97</sup>

## Medications in Pregnancy

The relative safety of any medication during pregnancy involves the comparative determination of maternal benefit versus potential fetal risk. Teratogenicity occurs primarily during postmenstrual weeks 4 to 12, with exposures during the first 2 weeks after conception considered to result in either loss of pregnancy or no significant effect. Table 3 presents an overview of common medica-



tions encountered in the adult CHD population, highlighting specific concerns during pregnancy. The individual Micromedex REPROTOX drug summaries (Micromedex 2.0) provide a more comprehensive discussion.<sup>103</sup>

Currently, the US Food and Drug Administration classifies drugs into risk categories based on safety during pregnancy and breastfeeding.<sup>1</sup> Table 4 shows the risk category for some commonly used drugs in patients with heart disease.

Angiotensin-converting enzyme (ACE) inhibitors and angiotensin receptor blockers are pregnancy category D drugs because of the risk of reduced fetal renal function and increased fetal and neonatal morbidity and death, especially with use during the second and third trimesters. Cooper et al<sup>104</sup> reported an additional risk of malformation among infants exposed to ACE inhibitors during the first trimester. Ideally, women taking an ACE inhibitor or angiotensin receptor blocker who desire to become pregnant should be advised to stop taking these drugs before conception to minimize the risk of fetal abnormality. During this time, repeated clinical evaluation with echocardiography should be carried out to reassess ventricular function and exercise capacity. Stability in ejection fraction suggests that patients are less likely to be intolerant of the volume load that pregnancy imposes.

$\beta$ -Blockers have a favorable safety profile, and no teratogenic risks have been reported with their use.<sup>105</sup> They have been associated with an increase in small-for-gestational-age infants and neonatal bradycardia and hypoglycemia but in practical terms are considered safe to use. Atenolol has been associated with low birth weight and therefore is not the  $\beta$ -blocker of choice during pregnancy.<sup>106</sup>

The routine use of diuretics is discouraged because of the potential reduction in maternal plasma volume early in gestation that is potentially harmful to the fetus.<sup>107</sup> If indicated, they should be used judiciously. Thiazides have been associated with maternal and fetal thrombocytopenia. Although listed as a category C agent, spironolactone is not recommended for use during pregnancy or lactation because of the reported antiandrogenic effects and feminization of male fetuses. Amiodarone has been associated with a 9% incidence of fetal hypothyroidism and a 21% incidence of intrauterine growth retardation and should be reserved for cases of refractory ventricular arrhythmias.<sup>108</sup>

Drugs listed as category X include the following:

- Anticoagulants. Vitamin K antagonists cross the placenta and are potentially fetotoxic. They are commonly used in women with mechanical valves, and the risks and benefits associated with their use should be discussed with the patient before pregnancy is contemplated (see Mechanical Valves and Anticoagulation).
- Endothelin receptor antagonists (bosentan, ambrisentan, and macitentan) (Micromedex and REPROTOX).

- Statins. Although inadvertent exposure to statins during early pregnancy appears unlikely to increase the risk of adverse pregnancy outcome, theoretical considerations concerning the role of cholesterol in embryo development and the lack of demonstrated benefit of treating hyperlipidemia during gestation are reasons for not recommending statins during pregnancy.<sup>109,110</sup> They remain pregnancy category X drugs in the United States.

## Fetal Screening During Pregnancy

Formal fetal echocardiography at 18 to 22 weeks' gestation is recommended for all patients with CHD and partners of male patients with CHD<sup>68</sup>; earlier echocardiographic screening may be recommended in patients with high rates of familial CHD recurrence and more severe cardiac defects. Referral to a maternal-fetal medicine specialist, pediatric cardiologist, neonatologist, and geneticist is indicated if fetal CHD is discovered to discuss prognosis and perinatal management.

## Antepartum Care

Existing adult CHD and pregnancy guidelines recommend that patients with complex CHD should be managed and delivered at a regional or tertiary center where a multidisciplinary team with knowledge and experience in adult CHD is available.<sup>68,73,86</sup> This team includes a cardiologist, a high-risk obstetrician, an anesthesiologist, and a neonatologist. Additional providers, including a geneticist, an advanced practice nurse, a social worker, and an ethicist, should be identified to assist in the coordination of care as required. Early coordination and ongoing communication between members of the multidisciplinary team are crucial to optimizing maternal outcomes. Prenatal care is individualized on the basis of the patient's maternal risk, accounting for the complexity of the CHD, the patient's functional capacity, and the presence of any existing or potential clinical issues (ie, rhythm disturbances). Practical factors such as current social situation, insurance coverage, and proximity to the adult CHD center and delivery hospital should be considerations in clinical scheduling.

## First Trimester (0–14 Weeks)

### Cardiology Care

The initial visit should include a review of the patient's cardiac history and preconception diagnostic evaluations to elucidate any new symptoms such as palpitation, shortness of breath, or edema. The physician should perform a comprehensive cardiovascular examination, keeping in mind the normal physiological changes apparent at 12 weeks of pregnancy (Table 5). Particular attention should be given to the development of arrhythmias, new murmurs, or clinical evidence of heart failure.

**Table 3. Medications During Pregnancy**

	Common Examples	FDA Pregnancy Category	Teratogenic Risks (First Trimester)	Other Pregnancy Concerns (Second and Third Trimesters)	Suggested Evaluation	Lactation	Notes
Antihypertensives							
$\beta$ -Blockers	Metoprolol Propranolol Carvedilol Atenolol	C C C D	None reported	Possible association with fetal growth restriction in second and third trimesters (atenolol, propranolol), neonatal bradycardia (esmolol, nadolol)	Consider serial fetal sonography to assess interval fetal growth in second and third trimesters	Except for atenolol, probably safe	
Combined $\alpha$ - $\beta$ -blockers	Labetalol	C	None reported	No		Yes	
Calcium channel blockers	Nifedipine Verapamil Diltiazem	C	None reported	Caution if used in combination with magnesium sulfate		Yes	
ACE inhibitors	Captopril Enalapril Lisinopril	C (first trimester) D (second and third trimesters)		Fetal renal dysplasia, oligohydramnios, growth restriction, and intrauterine demise reported in second and third trimesters	Consider fetal echocardiography with first trimester exposure, serial sonography to assess interval fetal growth and amniotic fluid volume in second and third trimesters	Yes (captopril and enalapril) Unknown (lisinopril)	Avoid if possible during pregnancy
$\alpha_2$ -Adrenergic agonists	Methyldopa Clonidine	B C	None reported	Induction of positive indirect Coombs testing (methyldopa), rare neonatal hypertension (clonidine)		Yes (methyldopa) Probably safe (clonidine)	
Vasodilators	Hydralazine Epoprostenol Nitroprusside Nitroglycerin Isosorbide dinitrate Sildenafil	C B   B	None reported	Possible transient fetal bradycardia (nitroprusside)		Yes (hydralazine) Probably safe (nitroglycerin) Unknown (epoprostenol, nitroprusside, isosorbide dinitrate, sildenafil)	
Diuretics							
Thiazide diuretics	Hydrochlorothiazide	B	None reported	Possible increased risk of neonatal hypoglycemia and thrombocytopenia	Consider neonatal blood count and electrolyte evaluation	Yes (AAP) No (WHO)	Maintenance therapy permissible, but therapy not usually started during pregnancy

(Continued)

**Table 3. Continued**

	Common Examples	FDA Pregnancy Category	Teratogenic Risks (First Trimester)	Other Pregnancy Concerns (Second and Third Trimesters)	Suggested Evaluation	Lactation	Notes
Diuretics Continued							
Loop of Henle diuretics	Furosemide	C	None reported	Possible association with neonatal PDA and sensorineural hearing loss	Maternal electrolyte monitoring	No	
Potassium-sparing diuretics	Spironolactone (not recommended)	C	None reported			Yes (probably safe; (not recommended)	
Anticoagulants							
Heparin (including LMWHs)	Heparin Enoxaparin Dalteparin	C	None reported	Possible maternal osteoporosis, heparin-induced thrombocytopenia, and bleeding	Maternal platelet and coagulation status monitoring (as appropriate)	Yes	
Vitamin K antagonists	Warfarin	X	Fetal warfarin syndrome (craniofacial and skeletal anomalies) with exposure in weeks 6–9; fetal intracranial hemorrhage in second and third trimesters		Comprehensive fetal sonography at 18–20 wk of gestation	Yes	Teratogenicity appears to be related to doses >5 mg daily
Antiplatelet agents	Aspirin (full dose)  Clopidogrel	D (third trimester) B	None reported	Premature closure of fetal ductus arteriosus at ≥32 wk of gestation	Empirical recommendation to discontinue clopidogrel 7 d in advance of anticipated delivery	Unknown (AAP) No (WHO)	Low-dose aspirin (≤100 mg/d) does not appear to have deleterious effects
Direct thrombin inhibitors	Argatroban	B	None reported			Unknown	
Indirect factor Xa inhibitors	Fondaparinux	B	None reported	Possible neonatal factor Xa inhibition		Unknown	
Direct factor Xa inhibitors	Rivaroxaban	C	None reported	Theoretical risk of maternal hemorrhage		Unknown	
Fibrinolytics	Streptokinase	C	None reported			Unknown	
Inotropic/vasopressors							
Cardiac glycosides	Digoxin Digitalis	C	None reported			Yes	

(Continued)

**Table 3. Continued**

	Common Examples	FDA Pregnancy Category	Teratogenic Risks (First Trimester)	Other Pregnancy Concerns (Second and Third Trimesters)	Suggested Evaluation	Lactation	Notes
Inotropic/vasopressors Continued							
Adrenergic agents	Epinephrine Norepinephrine Phenylephrine Dopamine Isoproterenol	C	Possible association with gastroschisis or hemifacial microsomia (phenylephrine)			Probably safe (dopamine) Unknown (epinephrine, norepinephrine, phenylephrine, isoproterenol)	
Antiarrhythmics							
β-Blockers	Metoprolol Propranolol Carvedilol Atenolol	C C C D	None reported	Association with fetal growth restriction in second and third trimesters (atenolol, propranolol), neonatal bradycardia (esmolol, nadolol)	Consider serial fetal sonography to assess interval fetal growth in second and third trimesters	Except for atenolol, probably safe	
Class 1A	Quinidine Procainamide	C C	None reported			Yes	
Class 1C	Flecainide	C	None reported			Yes	
Class III	Sotalol Amiodarone	B D	None reported	Thyroid dysfunction		No No WHO)/ (AAP Yes)	
Purine nucleosides	Adenosine	C	None reported			Unknown	

AAP indicates American Academy of Pediatrics; ACE, angiotensin-converting enzyme; FDA, US Food and Drug Administration; LMWH, low-molecular-weight heparin; PDA, patent ductus arteriosus; and WHO, World Health Organization.

The current medication regimen should also be reviewed for appropriate indications, potential risks, and any need for dose adjustments or discontinuation. For the patient who presents for the first time early in pregnancy for cardiac care, the initial visit should include a

thorough assessment as described previously for a patient contemplating pregnancy.

The frequency of cardiology visits is largely individualized by estimated risk and the development of symptoms or complications. Once antepartum care has been

**Table 4. FDA Drug Classifications**

Rating A	Controlled studies in women fail to demonstrate a risk to the fetus in the first trimester; no evidence of a risk.
Rating B	Either animal-reproduction studies have not demonstrated a fetal risk but there are no controlled studies in pregnant women or animal-reproduction studies have shown adverse effect (other than a decrease in fertility) that was not confirmed in controlled studies in women in the first trimester (and there is no evidence of a risk in later trimesters).
Rating C	Either studies in animals have revealed adverse effects on the fetus (teratogenic, embryocidal, or other) and there are no controlled studies in women or studies in women and animals are not available. Drugs should be given only if the potential benefit justifies the potential risk to the fetus.
Rating D	There is positive evidence of human fetal risk, but the benefits from use in pregnant women may be acceptable despite the risk (eg, if the drug is needed in a life-threatening situation or for a serious disease for which safer drugs cannot be used or are ineffective).
Rating X	Studies in animals or human beings have demonstrated fetal abnormalities, there is evidence of fetal risk based on human experience, or both, and the risk of the use of the drug in pregnant women clearly outweighs any possible benefit. The drug is contraindicated in women who are or may become pregnant.

FDA indicates US Food and Drug Administration.

Data are from REPROTOX.<sup>103</sup>



established, patients who remain clinically asymptomatic may be seen at the beginning of the second trimester and again at the beginning of the third trimester.<sup>68</sup> Those deemed at moderate to high risk or who are symptomatic would require more frequent visits ranging from bi-monthly to weekly.

### Obstetric Care

CHD guidelines recommend that these patients be managed by an obstetrician trained in maternal-fetal medicine or experienced in caring for patients with CHD.<sup>72</sup> However, attending scheduled prenatal visits can be a logistical challenge for patients who reside remote from a specialized care center. Therefore, maintaining clear and consistent communication between local and tertiary center providers about maternal and fetal clinical status is of paramount importance. A plan including both expedient transport in the event of an acute complication and consideration of the patient relocating proximate (<1 hour distant) to the tertiary facility in the early or mid third trimester (34–36 weeks) will also optimize the probability of delivery occurring in a properly supervised manner.

Prenatal care appointments are generally scheduled on a chronological basis. In uncomplicated pregnancies, visits are typically scheduled every 4 weeks through 28 weeks' gestation, every 2 weeks through 36 weeks, and then weekly thereafter until delivery. Because a subset of the CHD population may require more frequent evaluation to assess the response to the progressive intravascular volume load of advancing gestational age, the frequency of prenatal visits may be modified as individually appropriate.

### Lifestyle Issues

- Physical activity. The level of physical activity is dependent on the patient and prepregnancy functional ability. Many patients can (and should) continue a regular exercise program such as walking or swimming but should restrict maneuvers that might impair cardiac output. Significant fatigue is common in the first trimester; thus, patients may need to adjust their schedule to allow sufficient intervals of rest. Excessive heat exposure can cause peripheral vasodilation with consequent decreased cardiac output. Elevated core temperature may be teratogenic. Thus, patients should avoid exhaustive activity on hot days and prolonged hot bathing; the use of saunas or hot tubs should be discouraged.<sup>94,111</sup>
- Hydration. Maintenance of adequate maternal hydration (which may be influenced by environmental factors) is generally recommended for all pregnancies but may have more significance in the CHD population. Limitation of salt intake is prudent in those with impaired ventricular function who are vulnerable to heart failure.
- Prevention of thromboembolism. Pregnancy represents a hypercoagulable state. Lower-extremity

**Table 5. Clinical Signs and Symptoms Observed in Normal Pregnancy**

Hyperventilation causing shortness of breath and dyspnea
Brisk, full carotid upstroke with distended jugular veins with prominent A and V waves
Diffuse, displaced left ventricular impulse; palpable RV impulse
Increased first heart sound; persistent splitting of second heart sound
Systolic ejection-type murmurs at the left lower sternal border over the pulmonary area
Anemia
Weight gain

RV indicates right ventricular.

graduated compression stockings may reduce orthostatic effects and symptomatic lower-extremity edema but may not reduce the risk of thrombosis.<sup>112</sup>

- Employment. Many patients are able to safely continue working throughout their pregnancy. Providers should assess the individual patient's work situation and discuss anticipated potential accommodations that may be necessary, particularly with advancing gestation.
- Sexual activity. Cardiovascular effects (heart rate, blood pressure, oxygen uptake) vary greatly among different patients, but in general, sexual activity is equivalent to moderate physical activity. Similar to physical activity and work, sexual activity should be symptom limited and may be restricted for obstetric reasons (placenta previa, cervical incompetence, history of preterm labor). Although not specifically studied in the CHD population, there is no evidence that sexual activity during pregnancy increases the risk of adverse pregnancy outcomes.<sup>113</sup>

### Suggestions for Clinical Practice

- Patients considered low risk without specific clinical issues may receive prenatal care locally. However, evaluation should be performed early in pregnancy at a regional adult CHD center to establish a regimen for prenatal management and then repeated in the third trimester to evaluate current maternal status and candidacy for local delivery.
- Patients considered to be at moderate risk who live geographically remote from a regional adult CHD center may also receive routine prenatal care locally but should be evaluated at a regional center by both a cardiologist and a maternal-fetal medicine obstetrician each trimester with an explicit plan that delivery will be carried out at the regional adult CHD center.
- High-risk patients should be managed exclusively at a regional adult CHD center for prenatal care

and delivery. If geographical and financial concerns preclude this option, coordinated shared care between a regional center and a local obstetrician and cardiologist who are willing to communicate directly with the regional adult CHD should be explored once fetal viability has been established.

- For patients considered exceedingly high risk for maternal morbidity or mortality such as those with elevated pulmonary pressures or important aortic root enlargement, therapeutic termination of the pregnancy should be offered (see Termination of Pregnancy).

### **Second Trimester (14–28 Weeks)**

The second trimester is associated with the greatest magnitude of hemodynamic changes (Figures 1 and 2). The frequency of evaluation must be individualized. A repeat echocardiogram may be indicated to evaluate the hemodynamic effects of the pregnancy on cardiac and valvular function. Comprehensive fetal echocardiography is usually performed at 18 to 22 weeks' gestation and may be repeated if any fetal anomaly has been detected.

A clear and coordinated plan for labor, delivery, and postpartum care should be developed by the end of the second trimester and distributed to all members of the multidisciplinary team, including labor and delivery staff, in the event of spontaneous or indicated preterm delivery. For patients deemed at particularly high risk (eg, those who have pulmonary hypertension or severe AS), an initial multidisciplinary planning meeting including all providers potentially involved in their care should be organized once fetal viability has been established, usually after week 23 to 24. A specific delivery plan is outlined with contingencies for early hospital admission and requirement for urgent delivery. If cardiac support systems such as ventricular assist devices are required or if cardiac surgery is being considered during pregnancy or concomitant with delivery, members of the cardiothoracic team should also be included. The involvement of social services and possibly an institutional ethics team should be also considered in high-risk cases.

### **Third Trimester (28–42 Weeks)**

The frequency of cardiac evaluation in late pregnancy must be individualized. Once the peak hemodynamic load of pregnancy is reached, normal symptoms of pregnancy (edema, dyspnea on exertion) may worsen, so patients must be monitored closely to distinguish such symptoms and signs of normal pregnancy from those that may reflect hemodynamic compromise. Continued participation in physical activity, work, and sexual activity may prove difficult as the pregnancy progresses; all activities should be limited by symptomatology or obstetric concerns. Planning and contingencies for delivery should be finalized in the third trimester.

### **Obstetric Complications**

Because these patients remain at risk for the spectrum of obstetric complications independently of their cardiac condition, specific obstetric concerns in this population include the following:

- Spontaneous abortion. The rate of spontaneous abortion varies between 12% and 15%, depending on the primary cardiac anomaly.<sup>79,114</sup>
- Fetal growth restriction. Small-for-gestational-age neonates (birth weight <10%) have been reported in 4% to 8% of pregnancies, with intrauterine demise reported in 3%.<sup>79</sup>
- Preterm delivery. Approximately 17% to 21% of all patients with CHD ultimately deliver preterm as a result of either spontaneous preterm labor/preterm premature rupture of membranes (59%) or indicated delivery (41%).<sup>74,79</sup> The use of tocolytic agents is generally considered safe, but caution is warranted with the use of terbutaline, particularly in patients with a history of arrhythmias.
- Hypertension. Increases in SVR such as with gestational hypertension/preeclampsia may be poorly tolerated in patients with marginal cardiac output.

### **Termination of Pregnancy**

For the patient with complex CHD in whom continuation of pregnancy presents a substantial risk of maternal morbidity or mortality, a forthright discussion of the advisability of therapeutic termination is imperative. However, because termination incurs an increased maternal risk with advancing gestational age regardless of method, expediency in patient decisiveness is important. The therapeutic benefit of termination for patients presenting at  $\geq 20$  weeks of gestation is controversial because many of the physiological cardiopulmonary adaptations are established by this time and consequently would not necessarily be mitigated by interruption of the pregnancy.

- First trimester. Surgical dilation and suction curettage represents the most common method of pregnancy termination through 12 weeks' gestation. Complication rates are low for skilled practitioners, and selection of anesthetic technique may be dictated by maternal status. The procedure should be carried out in a hospital setting where careful monitoring is accessible. Medical abortion regimens using combined antiprogesterone (mifepristone) and prostaglandin E1 (misoprostol) agents are similar in efficacy to suction curettage if administered within the first 7 weeks of pregnancy; however, because the process and subsequent hemorrhage typically occur in a relatively unpredictable manner in an unmonitored outpatient setting, this may not be an appropriate option for hemodynamically fragile patients.

- Second trimester. Midtrimester medical termination can be accomplished with transvaginal misoprostol to induce labor on an inpatient basis. Disadvantages of this approach include prolonged duration (>24 hours), intrapartum discomfort, and potential requirement for uterine curettage if placental retention occurs. Surgical dilation and evacuation is more frequently performed, offering the principal advantage of effecting termination under controlled circumstances in a surgical suite. Although no studies have specifically evaluated adult patients with CHD, in the general population, dilation and evacuation by experienced providers appears to have a lower complication rate than labor induction at gestational ages between 13 and 24 weeks.<sup>115</sup>

### Intrapartum Care

Clinically stable patients with complex CHD should anticipate a normal labor and delivery. The risks for gravidas with functionally significant CHD can be minimized by proper planning and management of labor, delivery, and the puerperium. In these high-risk cases, elective induction of labor under controlled conditions is recommended.<sup>116</sup> Careful consideration should be given to maternal benefit versus neonatal risk when elective delivery before 39 weeks is contemplated because induction of labor may be less successful at earlier gestational ages.<sup>116</sup>

From a practical point of view, inductions should be initiated so that delivery will likely occur during regular hours when the adult CHD teams are readily available. Labor should be conducted in a right or left lateral tilt position to maximize maternal hemodynamic stability; this posture reduces compression of the inferior vena by the gravid uterus, which maintains cardiac preload. Vaginal delivery with adequate relief of pain with parental narcotic analgesia or epidural anesthesia is generally preferred. Cesarean delivery is typically reserved for obstetric indications.

The uterine contractions of the second stage of labor (which extends from the time of complete cervical dilatation until delivery) are normally augmented by maternal Valsalva maneuvers. Historically, Valsalva maneuvers have been discouraged for patients with significant cardiac disease because of the associated increase in maternal O<sub>2</sub> consumption and reduction in cardiac return and cardiac output. Management should be individualized; with some cardiac disorders, a passive second stage of labor may be more appropriate (the fetus descends through the birth canal exclusively via uterine contractions), particularly in women whose venous return or myocardial contractility is significantly compromised. Regional epidural anesthesia can suppress the Valsalva reflex arising from fetal pelvic descent, which can be reinstated by reducing the intensity of anesthesia. Forceps-

or vacuum-assisted operative delivery may be performed to facilitate delivery from a low or outlet station.

Neuraxial anesthetic techniques should be used cautiously if cardiac output is sensitive to a reduction in preload; a narcotic combined spinal-epidural may be optimal. General anesthesia may be used, but the inhalation agents must be carefully selected and administered by an anesthesiologist.

### Intrapartum Management

- Intravenous crystalloid should be administered when necessary for hydration with close monitoring of fluid balance. All patients with right-to-left shunts should have filtered vascular lines to prevent paradoxical air embolization.<sup>117</sup> Patients with complex CHD should have continuous pulse oximetry for monitoring changes in systemic arterial oxygen saturation (Sao<sub>2</sub>). In those with right-to-left shunts, Sao<sub>2</sub> provides a continuous estimate of the extent of the right-to-left shunt.<sup>118</sup> Maintenance of systemic pressures in these gravidas is critical to maintain the balance of systemic and pulmonary blood flow. A decrease in SVR or an increase in PVR leads to increased right-to-left shunting, resulting in an increase in hypoxemia and an increase in the risk of maternal and fetal death.<sup>117</sup>
- Continuous ECG monitoring (eg, via telemetry) is indicated for patients with history of arrhythmias before or during pregnancy or for gravidas with reduced ventricular function who have become symptomatic during gestation.
- Invasive hemodynamic monitoring is rarely required for the vast majority of patients with complex CHD; exceptions include patients with clinical evidence of congestive heart failure and volume overload, in whom a central venous catheter may be useful to guide intravenous fluid administration. An arterial line can be helpful in monitoring fluid shifts and blood loss. If implemented, hemodynamic monitoring should continue for 24 hours after delivery.
- Neither transvaginal nor cesarean delivery is considered to inherently impart a high risk of bacteremia. Consequently, the AHA<sup>119</sup> does not recommend antibiotic prophylaxis for delivery. Because patients with CHD can suffer life-threatening consequences (eg, patients with Eisenmenger syndrome, cyanotic patients<sup>7</sup>) should they develop endocarditis, it is not unreasonable to administer antibiotics to high-risk patients. When indicated, antibiotics for endocarditis prophylaxis should be given at least 30 minutes before anticipated delivery.

### Postpartum Care

Immediately after delivery, the intravascular volume is augmented by an "autotransfusion" of 500 mL blood

from the involuting uterus. In uncomplicated pregnancies, stroke volume and cardiac output increase immediately by 71% and 60% to 80%, respectively. These changes begin to reverse shortly after delivery and continue to decrease over the next 24 hours, resolving over the next 6 to 8 weeks.<sup>59–61,120,121</sup> The extravascular fluid accumulation that occurs during gestation will typically resolve over a similar time interval.

Because many of these hemodynamic changes occur concurrently, cardiopulmonary complications may ensue immediately after delivery, depending on the maternal hemodynamic compensatory ability. Consequently, recommendations for postpartum monitoring are largely dependent on the patient's underlying congenital cardiac abnormality, predisposition to arrhythmias, presence or absence of heart failure signs or symptoms, and clinical course during pregnancy and delivery.<sup>122</sup> Telemetry cardiac monitoring should continue for at least 24 hours for those patients with symptoms or signs of significant antepartum or intrapartum arrhythmias. For the patient considered at highest risk or who has demonstrated signs of decompensation during the pregnancy or delivery period, management in an intensive care unit/critical care unit setting for the first 24 to 48 hours after delivery for hemodynamic monitoring should be considered.

If a patient is delivered in a local or community-based institution with limited resources or staff unfamiliar with managing complex CHD, it may be prudent to care for these patients in an intensive care unit/critical care unit setting, along with appropriate obstetric nursing surveillance, for the first 24 to 48 hours postpartum. Standard postpartum units are less likely to have cardiac monitoring capability or clinical experience in recognizing and managing early cardiopulmonary decompensation. However, patients who have remained clinically stable throughout pregnancy and delivery may be transferred directly to postpartum units with instructions to monitor for cardiopulmonary symptoms. Early ambulation and continued use of support stockings may reduce the risk of thromboembolism.<sup>117</sup>

The hemodynamic effects of pregnancy typically resolve primarily during the initial 6 to 12 weeks postpartum but may persist for up to 6 months.<sup>123</sup> Thus, discharge planning should include appropriate return visits for routine postpartum and cardiac evaluation and detailed patient instructions for signs and symptoms meriting medical evaluation.

### Contraception

Contraception is an important topic to readdress periodically throughout the reproductive life of a woman with complex CHD. The optimal method is governed by medical candidacy, potential side effects, compliance, and risk of unplanned conception. The ideal time to discuss contraceptive methods is before conception, but it is equally important to have a discussion on con-

traceptive choices with the pregnant patient as part of her postpartum management. Typical methods include the following:

- Combination estrogen-progesterone oral contraceptive pills. Advantages include predictable menstrual cyclicality, high efficacy, and reduction in incidences of gynecologic malignancy. In general, estrogen-containing oral contraceptives have historically been avoided during lactation because of concern about a pharmacological reduction in milk supply, although existing data are conflicting.<sup>124</sup> Other contraindications in the CHD population include a history of previous thrombosis (not requiring maintenance anticoagulation), cyanosis, or elevated hepatic functions. Because of the relatively thrombophilic state immediately postpartum, combination oral contraceptive pills are usually initiated 21 to 30 days after delivery.
- Progesterone-only contraception. This category includes progesterone-only contraceptive pills, depot medroxyprogesterone acetate injections, and subdermal etonogestrel implants. Because progesterone is not considered to increase the risk of thrombosis, any of these methods may be initiated during the postpartum inpatient hospitalization. Long-acting (36-month) subdermal etonogestrel implants (Implanon, Nexplanon) are also widely available. For patients with a history of venous thromboembolism or those with cyanotic conditions, progesterone-only contraception may represent an optimal selection.
- Intrauterine device. Although historically the intrauterine device was avoided in patients with CHD because of concern about maternal bacteremia and anemia from menorrhagia, the newer levonorgestrel-releasing intrauterine devices (Mirena, Skyla) may strike an optimal compromise between risk of unplanned pregnancy and effective contraception. Insertion is usually delayed until  $\geq 4$  weeks postpartum to minimize the incidence of spontaneous expulsion, although insertion immediately postpartum after placental delivery or at the time of cesarean section has been described. Neither type of intrauterine device appears to affect lactation.<sup>125</sup>
- Sterilization. If subsequent fertility is not desired, sterilization via tubal ligation or occlusion procedures may offer the lowest risk of future unintended conception. If cesarean delivery is planned or required, concurrent bilateral tubal ligation may be performed expediently, with a low cumulative 10-year risk of failure (1:133).<sup>126</sup> Office-based hysteroscopic fallopian tubal occlusion with a metallic insert (Essure) offers an efficacious alternative to an abdominal surgical approach, although interval contraception is required until subsequent imaging



is performed to confirm complete occlusion 3 months after the procedure. Recent reports have raised concern that patients with metal allergies or a history of pelvic inflammatory disease or other autoimmune conditions maybe suboptimal candidates for this procedure.<sup>127</sup>

Although partner vasectomy may be an option for couples in a monogamous relationship, this procedure does not directly address the risk of pregnancy in an individual CHD patient. Furthermore, because in some cases the male partner may outlive the female partner with CHD, the decision for vasectomy should factor in the possibility that later he may wish to have a family.

## CARDIAC COMPLICATIONS

### Arrhythmias

#### *Arrhythmia Risk During Pregnancy*

Pregnancy is associated with physiological changes that can cause shortening of the PR, QRS, and QT intervals as a result of an increase in heart rate or a leftward shift of the axis (small q wave, inverted T wave in lead III) resulting from an elevation of the diaphragm causing rotation of the heart. Ectopic beats are common and usually benign.<sup>41</sup> However, pregnancy can also lower the threshold for ventricular arrhythmias and reentrant SVT; therefore, clinically significant arrhythmias are not uncommon in pregnant women with CHD, particularly in those with history of arrhythmias. These are often related to the extra volume load, enhanced adrenergic receptor excitability, and presence of surgical scar. In a single-center study of 73 women with 83 pregnancies, 44% of women showed recurrence of tachyarrhythmias during pregnancy or early postpartum.<sup>128</sup> Recurrence rates were 50% to 52% in those with a history of SVT or paroxysmal atrial fibrillation/atrial flutter and 27% in those with a history of ventricular tachycardia. Adverse fetal events occurred in 20% of pregnancies with a 3- to 4-fold higher risk in those who developed antepartum arrhythmias. Thus, the presence of a pre-existing arrhythmia in women with complex CHD must be considered at the time of prepregnancy counseling because the recurrence risk may be high. Appropriate antiarrhythmic medications should be continued during pregnancy, with consideration given to increasing the dose as the volume load of pregnancy increases and drug levels decline.

#### *Arrhythmia Management During Pregnancy*

In general, the principles of arrhythmia management in pregnant women are similar to those in nonpregnant women, but the underlying hemodynamic conditions specific to each congenital anomaly must be considered. In patients with repaired complex CHD who have residual ventricular dysfunction or other abnormalities, tachyarrhythmias may be associated with hemodynamic com-

promise and significant maternal and fetal morbidity (eg, single-ventricle physiology after the Fontan operation). The same is true for those with tenuous hemodynamics (eg, those with Eisenmenger syndrome). It should be kept in mind that untreated maternal arrhythmias lead to poor placental and fetal perfusion, which can result in fetal compromise and even preterm delivery. Additionally, during labor and the postpartum period, cardiac arrhythmias are more prevalent; therefore, women with a history of arrhythmias before conception or who have had documented arrhythmias during pregnancy should be placed on continuous cardiac monitoring (direct or telemonitoring) throughout labor, delivery, and the postpartum period.

Many antiarrhythmic drugs cross the placenta and may adversely affect fetal development; the risk-benefit ratio must be considered in every case. In general, drugs are avoided in the first trimester unless necessary, but if they are required for arrhythmia control, several options are available. Table 4 gives the US Food and Drug Administration classification of the safety of antiarrhythmic drugs during pregnancy. Additionally, direct current cardioversion is safe and may be used to treat hemodynamically unstable arrhythmias. Radiofrequency catheter ablation therapy, however, is discouraged and should be considered only in drug-refractory, poorly tolerated arrhythmias (see Cardioversion).

#### *Paroxysmal SVT*

Digoxin or  $\beta$ -blockers are often used to treat SVT or paroxysmal atrial fibrillation during pregnancy. Adenosine or  $\beta$ -blockers are used for acute exacerbation. Adenosine does not cross the placenta, does not have adverse fetal effects, and will terminate most SVTs involving the atrioventricular node as part of a reentry circuit. Although  $\beta$ -blockers can cross the placenta and may result in fetal bradycardia, hypoglycemia, premature birth, and low birth weight, they are generally well tolerated. The exception is atenolol, which should be avoided during pregnancy because of an increased association with fetal growth retardation.<sup>129</sup> Calcium channel blockers are negatively inotropic, leading to slowing of atrioventricular conduction and reduced heart rate. Used for arrhythmias and maternal hypertension and as tocolytic agents to prevent premature labor and preeclampsia, they pose no teratogenic risk to the fetus.<sup>105,130,131</sup>

Antiarrhythmic drugs such as quinidine, procainamide, and digoxin may be used in patients with concealed accessory pathway. Digoxin is the safest; most other drugs are in category C. Hemodynamically unstable SVT should be treated with direct current cardioversion.

#### *Atrial Flutter or Fibrillation*

Rhythm control is the first step for treatment of atrial tachycardia or flutter. Selective  $\beta$ -blocking agents (eg,

metoprolol) are recommended drugs of first choice and are considered safe in pregnancy.<sup>68</sup> Sotalol is the only oral antiarrhythmic drug that is considered category B during pregnancy and can be used for atrial flutter, atrial fibrillation, or ventricular tachycardia. Calcium channel blockers can be used for long-term management if other atrioventricular node–blocking agents fail. Drugs such as diltiazem, verapamil, and ibutilide are considered relatively safe (category C) during pregnancy. Because of their potential proarrhythmic effect, class 1C agents such as propafenone and flecainide (category C) should be used when necessary with monitoring for proarrhythmia at initiation. Amiodarone should not be used unless absolutely necessary because of the risk of fetal toxicity. Protection against thromboembolism is recommended in women considered high risk such as those with atrial flutter. The choice of antithrombotic therapy (heparin, antiplatelet therapy) depends on the relative risk and the stage of pregnancy.<sup>68</sup>

### Ventricular Tachyarrhythmias

Ventricular arrhythmias may arise or be exacerbated during pregnancy. Patients receiving  $\beta$ -blocker therapy for arrhythmias should continue treatment throughout pregnancy, delivery, and postpartum unless specifically contraindicated because  $\beta$ -blockers are considered safe for mother and fetus.<sup>132</sup> Short-term treatment of ventricular tachycardia includes intravenous lidocaine, which is considered safe during pregnancy (category B) but should not be used during delivery. Intravenous mexiletene and amiodarone can be used in emergency situations. Cardioversion may be necessary for those with hemodynamic compromise.

### Heart Block

Atrioventricular block during pregnancy is often progressive and should be closely monitored for need for pacing. If permanent pacing becomes necessary during pregnancy, the procedure should be performed after the eighth week of gestation, and echocardiography-guided insertion is preferred to avoid fetal radiation exposure (see Imaging).<sup>68</sup>

In patients paced before pregnancy, pacing is well tolerated.<sup>133</sup> In patients with sick sinus syndrome, the lower rate limit of the pacemaker should be increased to parallel the physiological increase that occurs in first trimester.

## Suggestions for Clinical Practice

- Cardiac monitoring (direct vs telemonitoring) is recommended during active labor and delivery for women with history of preconception arrhythmias or those who have developed arrhythmias during pregnancy.
- Pacemaker function, including battery life, should be checked before pregnancy.

## Mechanical Valves and Anticoagulation

Pregnancy in women with mechanical heart valves is associated with significant maternal, fetal, and neonatal risks. Maternal risks include valve thrombosis, thromboembolic complications, heart failure, arrhythmias, endocarditis, and hemorrhage. Fetal and neonatal risks include fetal loss, still births, preterm births, growth restriction, and prematurity.<sup>134–148</sup> The rates of complications vary in relation to the woman's underlying cardiac condition, the function and location of the mechanical valve, and the type of anticoagulation used during pregnancy. Because of the high-risk nature of these pregnancies, all women should be seen for preconception counseling by a cardiologist with expertise in pregnancy and valve disease.

The most common life-threatening complication in pregnant women with mechanical valves is valve thrombosis. The prothrombotic state of pregnancy and the challenge of maintaining therapeutic anticoagulation contribute to thromboembolic complications in this group of women. The risk of thromboembolic complications is higher in women with older mechanical valves (ie, ball and cage valves), in women with valves in the mitral position (compared with the aortic position), when there is >1 implanted mechanical valve, when the valve does not function normally, and when heparin is used for anticoagulation compared with warfarin. Patient compliance is a major factor affecting outcome regardless of the types of anticoagulants used.

To prevent serious thromboembolic complications, therapeutic anticoagulation is required in all pregnant women with mechanical valves. Anticoagulation options include vitamin K antagonists (eg, warfarin), low-molecular-weight heparin (LMWH), and unfractionated heparin (UFH). New direct oral anticoagulants are not used in patients with mechanical valves. The risks and benefits of various anticoagulation options should be discussed with women before pregnancy or, if not previously addressed, at the time of the first antenatal visit. All forms of anticoagulation increase the risk of spontaneous abortion, retroplacental bleeding, stillbirth, and fetal death. Warfarin is the safest anticoagulant for the mother, associated with the lowest rates of maternal thromboembolic complications (2.9%–3.9% of pregnancies) and maternal mortality (1.1%–1.3%).<sup>149,150</sup> However, warfarin crosses the placenta and can cause an embryopathy if exposure occurs during embryogenesis (6–12 weeks' gestation). Warfarin embryopathy is less common when lower doses of warfarin ( $\leq 5$  mg/d) are adequate to achieve therapeutic anticoagulation.<sup>151</sup> LMWH does not cross the placenta and is therefore not associated with an embryopathy. However, LMWH is associated with higher rates of thromboembolic complications in pregnant women with mechanical valves. Most thromboembolic complications often occur when LMWH levels are subtherapeutic,

and therefore, close monitoring of peak anti-Xa levels is necessary. In studies of pregnant women with mechanical heart valves on LMWH who also had anti-Xa monitoring during pregnancy, thromboembolic complications occurred in 4% to 16% of pregnancies.<sup>143–148</sup> Rates of thromboembolic complications with UFH range from 13% to 33%.<sup>149,150</sup> Long-standing use of UFH is associated with osteoporosis and thrombocytopenia.

### Management

The management of the pregnant patient on anticoagulation is challenging, with no method being totally devoid of maternal or fetal risk. Detailed preconception counseling should be provided to the patient and partner by a team with expertise in CHD and pregnancy with valvular disease. The importance of compliance with scheduled clinical visits and laboratory appointments to maintain dose adjustments should be emphasized. For women who live far from the adult CHD center, arrangements need to be explored to ensure compliance with the prescribed protocol.

Guidelines on the management of anticoagulation in pregnant women with mechanical valves are available from the European Society of Cardiology<sup>68</sup> and the AHA/American College of Cardiology (ACC).<sup>152</sup> The AHA/ACC guidelines for the management of patients with valvular heart disease suggest that women who are therapeutic on  $\leq 5$  mg/d warfarin should be maintained on warfarin throughout pregnancy until before delivery. Women requiring  $> 5$  mg/d warfarin can use LMWH with meticulous monitoring (administered at least twice per day) or continuous intravenous UFH during the first trimester with an activated partial thromboplastin time more than twice normal. Because of the difficulty in attaining stable therapeutic anticoagulation with subcutaneous UFH, it is not recommended in the “2014 AHA/ACC Guideline for the Management of Patients with Valvular Heart Disease.”<sup>152</sup> Current guidelines recommend that during the second trimester, all women should be transitioned to warfarin. Women with mechanical valves require close follow-up throughout pregnancy and postpartum. Follow-up, as frequently as weekly, may be required, depending on the clinical status and anticoagulation monitoring requirements. Joint care with an anticoagulation clinic can optimize outcomes.<sup>147</sup> Women taking warfarin should be maintained on the dose necessary to achieve an international normalized ratio between 2.5 and 3.5. For those who elect to use LMWH, weight-based dosing is inadequate, and meticulous anticoagulation monitoring must be used, aiming for a target anti-Xa level between 0.8 and 1.2 U/mL measured 4 to 6 hours after administration. The measurement of trough levels may also be helpful, although data are scant.<sup>153–155</sup> In addition to anticoagulants, all pregnant women with mechanical valves should receive low-dose aspirin (75–100 mg once a day).

A coordinated plan for delivery must be developed, documented, and circulated to the obstetric and adult CHD team as the patient approaches her scheduled admission date to allow the transition from warfarin to UFH. It is necessary to discontinue warfarin well before delivery ( $> 1$  week) because maternal warfarin use close to delivery results in persisting warfarin effect in the fetus and increases the risk for fetal intracranial hemorrhage during vaginal delivery. Intravenous UFH should be substituted when warfarin is withdrawn and discontinued just before labor. Because of the risk of preterm labor that is known to occur in some women with complex CHD, transfer to UFH or LMWH should be considered at  $\approx 32$  to 34 weeks. The timing of induction is individualized but should factor in the individual's risk of a premature delivery. If the patient is on LMWH, it should be withdrawn at least 36 hours before delivery and changed to intravenous UFH.<sup>68</sup> Once active labor begins, heparin is withheld so that epidural anesthesia may be administered. Regional anesthesia should be performed only after clotting studies (activated partial thromboplastin time) have been restored to normal to avoid spinal hemorrhage. A cesarean delivery is required if the mother has not stopped her oral anticoagulant at least 1 week before delivery. Postpartum bleeding is increased in women receiving anticoagulation. UFH should be restarted as soon after delivery as deemed safe by the obstetric team, typically 6 to 8 hours after delivery. The timing of the reintroduction of warfarin varies among centers, but warfarin commonly is restarted within 48 hours of delivery unless there is a hemorrhagic complication.

If valve thrombosis is suspected or if a woman presents with a thromboembolic event, transesophageal echocardiography is the most direct and usually quickest way to assess valve function and thrombus burden. If the transesophageal echocardiography does not provide a definitive answer, fluoroscopy can be used after a discussion with the patient and in accordance with protocols to minimize radiation exposure to the fetus. Pregnant women with thromboembolic complications such as valve thrombosis should be managed at a tertiary care center by a multidisciplinary team that includes cardiac surgeons. Treatment options for a woman with documented valve thrombosis should be individualized and should take into account her clinical status, the severity of valve dysfunction, the thrombus burden, the maternal cardiac status, and the gestational age of the fetus. Treatment options include continuous intravenous UFH, thrombolytic therapy, and valve replacement. Surgery during pregnancy continues to carry a significant fetal risk, with fetal mortality of up to 33% in earlier reports (see Cardiovascular Surgery).<sup>156–158</sup>

### Suggestions for Clinical Practice

- All women with mechanical valves should undergo prepregnancy counseling by a cardiologist with



expertise in valvular heart disease and pregnancy in accordance with the AHA/ACC guidelines. The risks to both mother and baby of embarking on a pregnancy should be reviewed in detail, as well as the risks and benefits of each anticoagulation strategy.

- Before pregnancy, a comprehensive clinical evaluation should be undertaken, including transthoracic echocardiography to assess valve function.
- A detailed plan of care stressing the importance of compliance with scheduled clinical visits and laboratory appointments to maintain therapeutic anticoagulation must be provided to the woman who desires pregnancy and her partner.
- To prevent serious thromboembolic complications, therapeutic anticoagulation with frequent monitoring is required in all pregnant women with mechanical valves.
- Patients should be managed throughout pregnancy and delivery at a tertiary care center by a multidisciplinary team with expertise in the management of such patients.
- Continuation of low-dose aspirin (75–100 mg/d) is recommended in the second and third trimesters in accordance with AHA/ACC guidelines.
- Discontinuation of warfarin with substitution of LMWH or UFH to achieve therapeutic anticoagulation is recommended at least 1 week before planned delivery. LMWH must be discontinued at least 36 hours before epidural anesthesia, at which time UFH may be substituted.

### Heart Failure

For women with complex CHD, a number of potential factors may increase the risk of developing heart failure during pregnancy. Tachyarrhythmias such as atrial fibrillation or intra-atrial reentrant tachycardia can occur during pregnancy and can precipitate heart failure. The discontinuation of cardiac medications such as ACE inhibitors before or during pregnancy may also increase the risk. Obstetric complications such as gestational hypertension, preeclampsia, and anemia can precipitate heart failure in the high-risk patient.

A history of heart failure before pregnancy<sup>4,74</sup> and reduced subaortic ventricular systolic function (ejection fraction <40%) identify women at risk for cardiac complications and mortality. In the ROPAC study (Registry on Pregnancy and Cardiac Disease), cardiomyopathy, NYHA functional class III or higher, WHO risk classification of 3 or greater, prepregnancy heart failure, and pulmonary hypertension were predictors of developing heart failure during pregnancy.<sup>159</sup> Women with left-sided obstructive lesions, D-transposition of the great arteries (D-TGA) with Mustard or Senning operation, congenitally corrected transposition of the great ar-

teries (CC-TGA), Eisenmenger syndrome, or significant subaortic ventricular dysfunction are at risk of developing pulmonary edema.<sup>5–7,78,114,157,160–165</sup> Women with repaired right ventricular (RV) outflow tract obstruction (eg, tetralogy of Fallot or pulmonary atresia) are at risk of developing right-sided heart failure.<sup>78,166,167</sup> Pregnancy is contraindicated in women with severe systemic ventricular dysfunction (left ventricular ejection fraction <30%, NYHA class III or IV).<sup>1</sup> Women should also be informed of the potential for deterioration (both reversible and irreversible) with systemic ventricular dysfunction during pregnancy.<sup>163,168</sup>

For pregnant women with chronic heart failure, medications should be optimized before delivery. In general, women who develop heart failure should be treated similarly to nonpregnant patients, avoiding fetotoxic medications (ie, ACE inhibitors, angiotensin receptor blockers, aldosterone antagonists), and  $\beta$ -blockers should be continued. Hydralazine and oral isosorbide dinitrate can be used as afterload-reducing agents as alternatives to ACE inhibitors and angiotensin receptor blockers.

Acute heart failure typically occurs in the late second or third trimester or early postpartum and may be precipitated by eclampsia or preeclampsia.<sup>159</sup> It is important to differentiate the normal signs and symptoms of pregnancy from those of heart failure. Although avoidance of radiation is optimal, if the diagnosis of pulmonary edema is in question, a chest radiograph should be performed to facilitate a diagnosis of pulmonary edema. Serum BNP can be helpful for diagnosis.<sup>18</sup> Potential precipitants such as hypertension or anemia should be treated. Women with pulmonary edema or right-sided heart failure should be treated with loop diuretics such as furosemide, but these should be used judiciously, beginning with a low dose, because they can decrease placental flow. Digoxin is safe in pregnancy. Vasodilators such as nitroprusside and nesiritide have potential fetal toxicity. Although safety data are not available, inotropic drugs such as dopamine or dobutamine have been used in women with heart failure who are not responding to conventional medical therapy.

### Management

Women with ventricular dysfunction require close follow-up throughout pregnancy and delivery at a regional center by an adult CHD multidisciplinary team with a preliminary delivery plan in place in the event of early decompensation necessitating early delivery. Women with refractory heart failure should be managed at a center with ventricular assist device and heart transplantation capabilities.

During the antenatal period, heart failure therapy is tailored to the individual patient and is based on information from the patient on changes in symptoms such as sudden weight gain and peripheral edema in excess of expected changes during pregnancy. The patient should



be instructed on exercise allowances and limitations and the need to rest/sleep in the lateral decubitus position.

Women who are clinically symptomatic may require weekly visits; women who remain clinically stable may be seen less frequently. Repeated transthoracic echocardiograms facilitate the assessment of ventricular function, valvular regurgitation, and RV systolic pressure when necessary.

Induction of labor is determined by the clinical course but should be delayed beyond week 37 unless there is a threat to maternal or fetal morbidity and mortality. Early delivery may be required in pregnant women with refractory heart failure, and this may necessitate a cesarean section delivery. Careful pain management with early epidural analgesia and a facilitated second stage of labor may help to prevent complications.<sup>168a</sup> Fetal lung maturity must be addressed, and corticosteroids should be given when necessary. Prostaglandin E analogs, used during induction, can decrease SVR and contribute to reflex tachycardia; these changes can be detrimental to women with heart failure, and careful monitoring is required. Oxygen saturation monitoring should be used at the time of labor and delivery in women with heart failure. Arterial blood pressure monitoring and Swan-Ganz catheterization may be used in women with acute heart failure or significant subaortic ventricular dysfunction to optimize hemodynamic monitoring and fluid status. To avoid fetal compression of the inferior vena cava, women should labor in the left lateral decubitus position. The amount of intravenous fluid administered at the time of labor and delivery should be minimized to prevent volume overload. Reassessment of volume status after delivery is important.

The risk of heart failure continues after delivery, and frequent clinical evaluations should continue in the postpartum period. ACE inhibitors may be restarted postpartum; both captopril and enalapril have been used in breastfeeding women.<sup>169</sup> Most  $\beta$ -blockers can be used during breastfeeding, although atenolol is not recommended.

### Suggestions for Clinical Practice

- Preconception counseling is important for women at risk of developing heart failure during pregnancy.
- Pregnancy is contraindicated in women with severe systemic ventricular dysfunction (left ventricular ejection fraction <30%, NYHA class III or IV).
- For pregnant women at high risk for heart failure, frequent surveillance during pregnancy is necessary.
- Women who develop heart failure during pregnancy should be treated similarly to nonpregnant patients, avoiding fetotoxic medications.
- Women should be followed up at a center with experience in pregnancy and heart disease.

- Before delivery, a detailed delivery plan should be circulated to all members of the healthcare team.

### Cyanosis (Excluding Patients With Eisenmenger Syndrome)

Cyanosis in a patient with unrepaired or palliated complex CHD indicates the presence of a right-to-left shunt at the atrial, ventricular, or ductal level. As pregnancy advances, hypoxemia may worsen because of the fall in SVR, which increases the right-to-left shunt.<sup>7,68,117</sup> Because of the inherent clotting abnormalities associated with cyanosis, patients are at increased risk of both thrombosis and hemorrhage. The prothrombotic state of pregnancy enhances the risk of thrombosis, in addition to the other risks of heart failure, arrhythmias, hemoptysis, and endocarditis.<sup>7,68,117</sup>

Maternal cyanosis also carries substantial risk to the fetus with a higher chance of fetal loss in the first trimester, prematurity, and small-for-gestational-age infants. The risk is higher with greater maternal hypoxia, and if maternal oxygen saturation is  $\leq 85\%$ , only 12% of infants are born alive.<sup>7,79,169a</sup>

### Management

Little is known about the optimal management of women with cyanosis during pregnancy, but because cyanosis poses serious risks for the mother and the fetus, pregnancy should be discouraged until the defect is repaired. If pregnancy is unplanned, termination should be considered. If a decision to proceed with pregnancy is made, patients with cyanosis require very close monitoring at a regional center with an experienced adult CHD team (see Pregnancy Management). Hemoglobin and hematocrit should also be monitored, with careful iron supplementation to avoid relative anemia.<sup>68</sup> Phlebotomy is not recommended because of the risk of iron deficiency and lack of benefit in nonpregnant patients.<sup>169b</sup> Oxygen saturations should be measured at each clinic visit. Supplemental oxygen is unlikely to improve saturations dramatically in women with CHD, but it may slightly increase oxygen delivery to the placenta, and its initiation should be individualized for the patient. Given the increased risk of prematurity and small-for-gestational-age neonates, fetal growth should be closely monitored.

Anticoagulation remains a complex issue. Heparin, either UFH or LMWH, may be useful, particularly for women who are on bed rest. Compression stockings or sequential compression devices should be considered in women who are hospitalized or on bed rest.

The timing and mode of delivery should be individualized. Delivery should be in a center with expertise in high-risk obstetrics and preferably with adult CHD. Oxygen would generally be used during labor and delivery. Because of the right-to-left shunting, air filters should be used on all intravenous lines. Diuretics should be used

cautiously to avoid hemoconcentration. Vaginal delivery is preferred, with cesarean section typically reserved for obstetric indications. If a cesarean section is indicated, anesthesia should be managed by a cardiac anesthesiologist.<sup>170</sup>

Repair of the hysterotomy should be done inside the abdomen without exteriorization of the uterus to prevent venous air embolus. For vaginal delivery, an assisted second stage may be required. Patients should be monitored by telemetry with continuous pulse oximetry. There should be close monitoring for postpartum hemorrhage with aggressive management. Volume status should be carefully monitored during labor and postpartum. Patients will be at risk of both volume depletion and volume overload.

Because the critical period for major cardiovascular events is the first 24 to 48 hours after delivery, close observation in the intensive care unit is usually indicated. Early ambulation with support stockings can reduce risk of thromboembolism. Because of the continued risk of future pregnancies, contraception should be discussed with appropriate arrangements before discharge stressing the importance of avoiding an unplanned pregnancy. Cardiac follow-up commonly should be within 1 to 2 weeks of discharge. The patient should be instructed on any worrisome signs and symptoms to report before scheduled follow-up appointments.

### Suggestions for Clinical Practice

- Prepregnancy counseling should be provided by a cardiologist with expertise in the management of such patients. Because of the increased risk associated with cyanosis to the mother and high risk of fetal loss, pregnancy termination should be considered.
- Thromboembolic prophylaxis should be used for patients on prolonged bed rest for cardiac or obstetrical reasons, including compression stockings, sequential compression devices, air filters on intravenous lines, and use of low-dose heparin, but each case should be individualized.
- Patients with right-to-left shunts should have filtered vascular lines to prevent paradoxical air embolization.
- Delivery of patients with cyanotic CHD should be managed by a multidisciplinary team in a tertiary care center.

### Interventional Therapies

#### *Transcatheter Diagnostic Procedures and Interventions*

Transcatheter diagnostic and interventional procedures may be performed during pregnancy when necessary and when no alternative is available (see Imaging).<sup>87</sup> Minimizing fetal radiation exposure can be accomplished

by shortening fluoroscopic time, reducing the x-ray tube voltage, reducing the tube current, reducing the imaging frames per second to the lowest setting (usually 7.5 frames per second), using single-plane fluoroscopy, and avoiding cineangiography. Internal jugular or subclavian/radial approaches are preferable, avoiding femoral access if possible. In addition, the use of complementary imaging modalities such as transthoracic echocardiography, intracardiac echocardiography, transesophageal echocardiography, and 3-dimensional MRI and CT overlay techniques may significantly reduce radiation exposure.

Invasive diagnostic catheterization is seldom necessary during pregnancy in women with CHD. The rare patients who may require it include those in whom pulmonary artery pressure and arterial resistance cannot be estimated with noninvasive methods. Transcatheter interventional procedures are rarely performed during pregnancy, and if a procedure is considered, the patient should be referred to an adult CHD center with interventional expertise in the treatment of such conditions.<sup>171</sup> RV obstructive lesions are generally well tolerated, and an intervention to relieve pulmonary stenosis is rarely necessary during pregnancy in the absence of RV failure or symptoms of RV pressure overload.<sup>167</sup> Pulmonary balloon valvuloplasty may be performed successfully during pregnancy with expected improvement in the degree of stenosis.<sup>172</sup> Transcatheter occlusion of various shunts can be performed with transcatheter techniques but is rarely indicated during pregnancy. Transcatheter closure of atrium-level shunts could be considered in pregnant women with cyanosis because of right-to-left shunting at the atrial level and poor fetal growth. However, this should not be done in the presence of elevated pulmonary arterial resistance or right heart failure. In the context of paradoxical embolism and stroke, closure of an atrial septal defect or patent foramen ovale is not usually performed in pregnancy. Severe aortic valve stenosis may be associated with maternal and fetal cardiac complications, including premature labor and heart failure (see AS and Left Ventricular Outflow Tract Obstruction).<sup>161,173</sup> Transcatheter balloon aortic valvuloplasty may be performed successfully during pregnancy, but only in those with a mobile, pliable valve and no more than mild aortic regurgitation.<sup>174</sup>

#### *Cardiovascular Surgery During Pregnancy*

Cardiothoracic surgery should be avoided during pregnancy unless absolutely necessary. When other treatment options fail, an experienced multidisciplinary team usually can safely perform and facilitate cardiovascular surgery on the pregnant patient. Emergent surgery confers a higher risk of maternal and fetal complications than elective surgery. Fetal prematurity and death are associated with urgent, high-risk surgery, maternal morbidity, and early gestational age.<sup>158,176</sup>

Patients with CHD often have had 1 or more prior operations when they become pregnant. These patients are more likely to require urgent or emergent operations during pregnancy than patients without CHD. Maternal mortality associated with cardiopulmonary bypass (CPB) during pregnancy was once reported to be 3% to 15%.<sup>171</sup> In the current era, the maternal mortality rate is similar to that of CPB in nonpregnant women.<sup>156,177</sup>

Fetal mortality rates of 16% to 33% have been reported in early series when CPB is required during pregnancy.<sup>156</sup> Maternal mean arterial blood pressure decreases during CPB, and there is a reduction in pulsatile uterine blood flow. These factors can cause uteroplacental hypoperfusion, which can precipitate uterine contractions.

Fetal loss is associated with urgent, high-risk cardiac surgery, maternal comorbidities, and operations performed at an early gestational age. Data suggest that fetal mortality can be decreased when cardiac surgery is delayed and the fetus is allowed to mature.<sup>176,178</sup>

Additional measures used to reduce fetal risks include avoiding hypothermia,<sup>179</sup> minimizing intraoperative blood loss, using normothermic CPB, minimizing CPB times, maintaining a high CPB flow rate ( $>2.5 \text{ L}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$ ), and maintaining a mean arterial pressure  $>70$  mmHg while the patient is on CPB.<sup>180</sup> In addition, maintaining uterine displacement to avoid aortocaval compression appears to provide fetal protection by avoiding impairment of uteroplacental blood flow. Uterine displacement is performed for any parturient at a gestation of  $>20$  weeks and can be accomplished by placing the patient in the left lateral recumbent position during CPB.

Cardioplegia may increase serum potassium levels, particularly in cases with prolonged periods of cardioplegic arrest. Maternal serum potassium concentration is closely monitored and modified as needed. In addition, optimizing maternal oxygen saturation and avoiding maternal hypoglycemia are important for preventing fetal bradycardia.<sup>181,182</sup>

Delaying maternal cardiac surgery when possible minimizes the risks associated with prematurity and fetal demise. Fetal heart rate monitoring during CPB is generally recommended at a gestational age  $>24$  weeks. CPB flow rates, mean arterial pressure, and maternal temperature are optimized to maintain fetal heart rates between 110 and 160 bpm. Prolonged fetal bradycardia ( $<80$  bpm) that is unresponsive to therapeutic strategies is an indication for cesarean delivery if the fetus is at a viable gestational age.

Limited data document the safety of anesthetic agents used for cardiac operations during pregnancy. Adverse maternal and fetal outcomes from cardiac surgery during pregnancy are generally related to the underlying cardiac status of the mother and the urgency and duration of CPB. Sympathomimetic agents such as ephedrine and phenylephrine can be used to maintain perfusion pres-

sure, although increasing CPB flow rates is preferable and will result in increased placental perfusion.<sup>183</sup>

One of the most critical and challenging decisions in the management of the parturient with cardiac disease is determining the optimal timing of cardiac surgical intervention. Maternal risk may decrease with early intervention, but early intervention increases the risk of fetal compromise.

Delaying cardiac surgery until after delivery may result in excess maternal morbidity and mortality. If the fetus is of advanced gestational age and the planned maternal surgery is anticipated to be complicated or prolonged in length or anticoagulation will be needed, delivery before CPB should be considered. Cesarean delivery has been successfully performed immediately before or even while the mother was on CPB.<sup>184</sup>

## Other Cardiac Therapies

### Cardiopulmonary Resuscitation

Cardiac arrest occurs in 1 in 30 000 pregnancies,<sup>185</sup> with CHD being the third most common cause of arrest in cardiac patients. Management is in accord with current resuscitation guidelines with the same protocols as for nonpregnant patients<sup>185,186</sup> with modifications that account for the impact of the gravid uterus on maternal cardiopulmonary function. At a gestation age of 20 weeks and beyond, the pregnant uterus can press against the inferior vena cava and the aorta, impeding venous return and cardiac output. Uterine obstruction of venous return can produce prearrest hypotension or shock and in the critically ill patient may precipitate arrest.<sup>186</sup> Positioning the patient in the left lateral tilt results in improved maternal hemodynamics.<sup>186</sup>

In accordance with the 2015 guidelines, a “bundled emergency code call” (eg, maternal code blue) to all necessary responders may save time and avoid confusion.<sup>185</sup> This team should include obstetrics, obstetrical anesthesiology, cardiology, and neonatology.

Defibrillation can be performed according to the recommended advanced cardiac life support guidelines because pregnancy does not change thoracic impedance or defibrillation thresholds. Although there is a small risk of fetal arrhythmias, defibrillation is considered safe at all stages of pregnancy.<sup>185</sup> Additionally, if fetal monitoring is being used, it should be removed during defibrillation. Intravenous access should be above the umbilicus (diaphragm) because medications and volume given via femoral access may be limited by aortocaval compression by the uterus.

Cardiopulmonary resuscitation may require a more cephalad hand positioning than usual if the uterus is above the umbilicus. Manually pushing the uterus leftward  $\approx 1.5$  cm from midline will alleviate the aortocaval compression more effectively than left lateral positioning while retaining the advantages of supine positioning

for cardiopulmonary resuscitation.<sup>187</sup> If resuscitation is ongoing for 4 minutes and the uterus is sufficiently large to cause aortocaval compression, a cesarean section should be performed. The cesarean delivery early in resuscitation may be lifesaving for the mother because it alleviates aortocaval compression.<sup>187</sup>

### Cardioversion

Cardioversion can be performed safely with standard protocols.<sup>188,189</sup> Because the energy transmission to the fetus is minimal, the risk of inducing fetal arrhythmia is very small and should not preclude effective treatment of maternal arrhythmias requiring cardioversion.

### Ablation

Although ablation is seldom required in pregnancy, it may be indicated in patients who develop tachyarrhythmias that are poorly tolerated and refractory to medical therapy. There are case reports of ablations performed in pregnancy, with a general strategy to minimize fluoroscopy during the procedure.<sup>189,189a,190</sup> Fetal exposure can be minimized, particularly with current mapping technology and the use of short bursts of fluoroscopy, as previously described (see Pregnancy Management). Only providers with expertise in minimizing fluoroscopy should perform ablations in pregnant women.<sup>68</sup>

### Implantable Defibrillators and Pacemakers

Implantable cardiac defibrillators (ICDs) are well tolerated in pregnant women.<sup>190,191</sup> Similarly, pacemakers present no problem in pregnancy. However, the pacemaker should be interrogated, ideally before pregnancy, to evaluate lead function, battery life, presence of arrhythmias, and determination of pacemaker dependency. For patients with pacemakers for sick sinus syndrome, the lower rate limit of the pacemaker should be increased to parallel the physiological heart rate increase that normally occurs during pregnancy.<sup>105,133</sup>

Pacemaker or ICD implantation can be performed with little to no radiation. For ICD implantation, one should consider the hemodynamic impact of testing the device on maternal and fetal stability. As with ablation, providers experienced in techniques that minimize radiation should perform these procedures. There is no evidence suggesting that an ICD should be turned off during delivery. Recent studies show that no arrhythmias or ICD discharges were precipitated during delivery.<sup>191</sup> However, if electrocautery is used for cesarean section, the ICD should be deactivated with a portable defibrillator on standby.

## SPECIFIC LESIONS

### Pulmonary Arterial Hypertension

Pulmonary hypertension, considered one of the least well-tolerated conditions in the pregnant patient, is de-

finied as an increase in mean pulmonary arterial pressure  $\geq 25$  mmHg at rest.<sup>192,193</sup> In patients with CHD, pulmonary arterial hypertension (PAH) most commonly occurs as a result of long-term left-to-right shunting, leading to increased pulmonary flow that eventually causes high PVR, resulting in reversed or bidirectional shunts, which is referred to as Eisenmenger syndrome. It should be noted, however, that PAH may also develop in patients who have undergone surgical or transcatheter repair of their defects.

Eisenmenger syndrome is associated with decreased oxygen saturation in the systemic circulation, cyanosis, and erythrocytosis.<sup>194–197</sup> Although maternal mortality has declined in recent years, it remains unacceptably high, reportedly between 30% and 50%, and thus, pregnancy is contraindicated.<sup>4</sup> The greatest risk of death is in the postpartum period but may extend beyond 6 weeks after delivery.<sup>4,164,193</sup> The hemodynamic factors occurring in pregnancy that contribute to poor clinical outcomes in PAH include the following:

- Pulmonary vascular disease prevents the fall in PVR normally associated with pregnancy, leading to a further rise in pulmonary artery pressure. The obligatory increase in cardiac output cannot be achieved, thereby resulting in right-sided heart failure.
- Plasma volume increases by 50% by the third trimester with resultant volume overload of a poorly compliant RV that is unable to adequately augment its output.
- In Eisenmenger syndrome, the decrease in SVR of pregnancy augments right-to-left shunting, worsens hypoxia and cyanosis, and thus may increase the pulmonary arterial resistance.
- During labor and delivery, the risk of cardiovascular collapse increases as a result of hemodynamic perturbations, including volume shifts caused by blood loss and uterine contractions, withdrawal of sympathetic tone, or RV failure.
- The prothrombotic changes of pregnancy may contribute to in situ pulmonary thrombosis in the context of abnormal pulmonary vasculature and preexisting pulmonary thrombus.

Death may be attributed to arrhythmias, RV failure, or hemorrhage, which decreases blood volume and increases left-to-right shunting as a result of a decrease in SVR, which increases cyanosis and tissue hypoxia. Fetal loss is equally high, with rates of spontaneous abortion of 40% to 50%.<sup>164,193–197</sup> The fetus is typically exposed to a hypoxic environment and is at risk for intrauterine growth restriction and preterm delivery.

The prognosis in patients with PAH, whether they are cyanotic or not, is driven largely by RV function. Those with preserved RV systolic function and normal central venous pressure are well compensated; those with failing RVs, as manifested by increased central venous



pressure and decreased cardiac output, are decompensated and have a far worse prognosis. The degree of pulmonary arterial resistance elevation plays a major role, but so does the chronicity of pulmonary hypertension. Those with large central congenital defects (eg, ventricular septal defect or patent ductus arteriosus) have a high pressure and high flow pulmonary arterial circuit until the pulmonary arterial resistance inevitably rises, eventually resulting in the Eisenmenger syndrome. Patients with congenital heart disease with pulmonary hypertension and cyanosis are invariably limited by cyanosis and a variety of other multisystem derangements, but their RV function may be preserved. On the other hand, RV function in women who develop PAH later in life (eg, those with atrium-level shunts or idiopathic pulmonary hypertension) is often reduced, as is the cardiac output.

Women with PAH should be strongly counseled against pregnancy at the time the diagnosis of PAH is made with appropriate contraceptive provided. If they do become pregnant, the safer option is termination of pregnancy, but termination in these patients, particularly beyond 12 weeks, is also considered high risk and managed accordingly (see Termination of Pregnancy).

In the current era of pulmonary vasodilators and pulmonary vascular remodeling agents, the outcomes of pregnancy in Eisenmenger syndrome have improved somewhat, and the use of such agents should be considered early in pregnancy.<sup>4,5,68</sup> Although endothelin receptor antagonists are teratogenic and prohibited in pregnancy, phosphodiesterase-5 inhibitors are used and may be effective. Both nebulized iloprost and intravenous iloprost have been used safely.<sup>198</sup> More intensive parenteral or subcutaneous infusion with prostacyclin can also be used during pregnancy to decrease the likelihood of RV failure. These targeted pulmonary vascular therapies are aimed at reducing pulmonary arterial resistance to stabilize the RV function and can be used in conjunction with the cautious use of diuretics. However, the outcome for many of these women is still often fatal, and publication bias means that the poor outcomes are often not reported. The choice of therapy and the stage of pregnancy at which it should be introduced remain uncertain.

### Management

For the woman who chooses to proceed with pregnancy, a detailed plan of care must be organized once fetal viability is established at about 24 to 28 weeks of gestation. The pregnancy and delivery should be carried out in a tertiary center with a multidisciplinary team that includes a pulmonary hypertension specialist. Management is focused on the optimization of RV preload and systolic function and reduction in PVR. Therefore, the patient should be followed up monthly or more frequently as needed because deterioration may occur as early as the second trimester. The arterial saturation should be moni-

tored, and if it drops below 85%, admission is warranted for fetal monitoring. Baseline laboratory studies should include a complete blood count, platelets, electrolytes, and coagulation panel. In the patient with Eisenmenger syndrome, iron deficiency may occur. Iron supplementation should be given in small doses, and the erythrocyte response should be checked periodically to ensure that excessive erythrocytosis does not occur.<sup>94,195</sup> Echocardiography should be obtained regularly to monitor decreases in RV function and tricuspid regurgitation. If the patient exhibits sign of failure with significantly elevated jugular venous pressure, the addition of diuretics such as furosemide is indicated. Although important in controlling RV volume overload, diuretics should be used judiciously to avoid hemoconcentration and intravascular volume depletion. Spironolactone is contraindicated because of antiandrogenic effects.

If followed up on an outpatient basis, the patient should be cautioned to minimize cardiac demands through reduced activity levels, enhanced bed rest with legs elevated, limited salt intake, and resting in a lateral position to avoid caval vein compression and to maintain venous return. The addition of anticoagulation is controversial but should be considered if the patient has a pre-pregnancy indication such as atrial fibrillation or history of thrombotic event or when admitted for bed rest.<sup>5,199</sup>

Hospital admission for bed rest and monitoring is usually recommended by the third trimester.<sup>5,68,193,195</sup> Cardiac monitoring, pulse oximetry, peripheral vein access for fluids with bubble filters to avoid the risk of air emboli, and compression stockings to avoid venous stasis should be standard care for all in-patients. Oxygen therapy is indicated in the event of arterial desaturation or maternal decompensation. Low-dose subcutaneous heparin may be used, but there is greater concern for hemorrhagic complications in the cyanotic patients who have an inherent bleeding diathesis with concomitant thrombocytopenia.<sup>164</sup>

More invasive monitoring such as with an arterial line and central venous catheter for monitoring right atrial pressure should be considered for the patient who begins to show signs of decompensation, in preparation for delivery, and for managing fluid volume, as well as for careful monitoring during the postdelivery period. Placement of a pulmonary artery catheter should be avoided because the benefits of the information obtained are outweighed by the risks.<sup>195,196</sup>

The timing and mode of delivery, although contentious, will depend on the clinical status of the mother and fetal maturity. If vaginal delivery is selected, then induction of labor is recommended. Careful regional anesthesia may be used with an assisted second stage of labor because bearing down must be avoided. For many patients, delivery by cesarean is elected in an attempt to abbreviate the duration of hemodynamic perturbations or because of maternal decompensation.<sup>4,5,162,195</sup>

Regional anesthesia has been used, but if epidural anesthesia is selected, then small incremental doses must be used, and single-dose spinal anesthesia must be avoided because of the risks of hypotension.

Large-volume boluses and excessive blood loss can destabilize the hemodynamics of the patient during the peripartum period and should be avoided. Volume overload should be treated with diuretics. Inhaled nitric oxide can decrease pulmonary arterial resistance further and improve pulmonary blood flow and oxygenation and is indicated for women with cardiac decompensation. Inhaled supplemental oxygen is often used in conjunction with nitric oxide to improve oxygenation. Continuous ECG, pulse oximetry, and invasive arterial pressure monitoring are important during delivery. Oxytocic drugs may have harmful effects and should be avoided.

Given the reported high risk of mortality in postpartum period, these patients should recover in an intensive care unit with the capability of monitoring cardiac pressure, arterial pressure, oxygen saturation, and central venous pressure. Intravenous anticoagulation such as UFH is used in the postpartum period to reduce the risk of thromboembolic complications. However, the benefit of these agents must be weighed against the risk of postpartum bleeding, which is higher in a cyanotic patient because of the inherent bleeding diathesis.

Hospital discharge should be delayed 7 to 10 days after delivery or longer to continue monitoring for complications such as RV failure and to adjust the dose of pulmonary vasodilators.

### AS and Left Ventricular Outflow Tract Obstruction

Congenital bicuspid aortic valve is the most common cause of AS in women of childbearing age. Patients with severe AS may first become symptomatic during pregnancy. Echocardiography is the diagnostic test of choice for patients with suspected AS; it confirms the diagnosis, determines the severity, and identifies associated conditions. Prepregnancy exercise testing is recommended in asymptomatic patients with AS to confirm symptom status and to identify high-risk features such as reduced exercise capacity, abnormal blood pressure response, ischemic electrocardiographic changes, and arrhythmias during exercise.<sup>152</sup>

Bicuspid aortic valve is often associated with aortic dilatation. All women with a bicuspid aortic valve should undergo imaging of the aorta before pregnancy to assess aortic dimensions and to rule out coarctation. Ascending aortic replacement should be considered before pregnancy when the aortic diameter is >50 mm.

Maternal cardiac morbidity during pregnancy is related to AS severity and symptoms. The increased cardiac output that occurs during pregnancy adds a volume load to a pressure-loaded left ventricle, which, in addition to the fall in afterload, can lead to an increase in gradi-

ent.<sup>200</sup> Pregnancy is well tolerated in asymptomatic patients with mild (mean gradient <25 mmHg) or moderate (mean gradient, 25–40 mmHg) AS. Patients with severe AS (mean gradient >40 mmHg, atrioventricular area <1.0 cm<sup>2</sup>) may tolerate pregnancy and remain asymptomatic, but careful individualized assessment is needed<sup>173,201,202</sup> because complications occur with increased frequency. The most common complications include heart failure and arrhythmias; angina is less common.<sup>161</sup>

Pregnancy is not advised for symptomatic patients with severe AS or asymptomatic patients with severe AS and impaired left ventricular function, abnormal exercise test with the development of arrhythmia, evidence of myocardial ischemia, failure to augment blood pressure, or ventricular dysfunction, as well as severe left ventricular hypertrophy. These patients should be referred for valvuloplasty or valve replacement before pregnancy. Recent progression of AS severity warrants additional surveillance before declaring whether it is safe to proceed with pregnancy.<sup>68,152</sup>

### Management

During pregnancy, the patient with moderate or severe AS should receive regular follow-up by an experienced multidisciplinary team. These patients may become more symptomatic as pregnancy progresses as the volume load increases and the fall in afterload exaggerates the aortic gradient. They should be evaluated frequently to assess for early signs and symptoms of heart failure, angina, or syncope/presyncope. The frequency of evaluations is individualized. High-risk patients may need to be hospitalized and seen daily; others, weekly or monthly. Echocardiography is recommended frequently to reassess AS severity and ventricular function. An ECG should be reviewed initially for signs of left ventricular strain or ischemia and thereafter if the patient develops chest pain or tachycardia. Congestive symptoms should be promptly assessed, and surgical or percutaneous intervention should be considered.

Percutaneous valvuloplasty can be undertaken during pregnancy in severely symptomatic patients not responding to medical therapy when AS is associated with a noncalcified valve and there is minimal regurgitation.<sup>203</sup> For patients with life-threatening symptoms and AS not amenable to percutaneous therapy, valve replacement may be required. This can be performed during pregnancy or timed with caesarean delivery.<sup>158</sup>

Before delivery, a detailed delivery plan should be developed and circulated to all members of the multidisciplinary team. A planned induction of labor is suggested; the timing depends on the patient's cardiovascular status. In the stable patient, labor is generally induced at or after 39 weeks' gestation in an effort to prevent spontaneous onset of labor during off-hours when an experienced multidisciplinary team is not available. The timing of induction may vary, depending on maternal hemodynamics and symptom status.

In nonsevere AS, vaginal delivery is generally favored. If the aorta is dilated or if the patient is clinically stable, the delivery is facilitated by the use of forceps or vacuum delivery. Regional anesthesia and analgesia are used, and the aim is to avoid a decrease in peripheral vascular resistance during delivery. In a symptomatic patient with severe AS, caesarean delivery with endotracheal intubation and general anesthesia may be considered.

Limited data are available on the preferred mode of delivery in patients with bicuspid aortic valve and dilated aorta. If the aorta has increased substantially in size during pregnancy or is >4.5 cm, it is reasonable to consider a caesarean delivery.<sup>68</sup>

Monitoring during labor and delivery is dictated by the severity of the AS and functional status of the patient. In the absence of symptoms, electrocardiographic monitoring may be used during active labor and delivery. Placement of an arterial line and a pulmonary artery catheter can be considered in the patient with left ventricular dysfunction in an effort to maintain ventricular pressures by maintaining cardiac filling without excessive preload, which could result in pulmonary edema.<sup>204</sup>

Antibiotic prophylaxis for endocarditis at the time of vaginal delivery is not routinely recommended. However, some experts continue to administer antibiotics because the risk of developing endocarditis has such serious consequences.

Patients with severe AS also have increased potential for obstetric complications. Intrauterine growth retardation, preterm birth, and low birth weight have been reported to occur in up to 25% of the offspring of mothers with moderate and severe AS.<sup>161</sup>

Although less common, AS in pregnant women may be attributable to subvalvular and supravalvular AS. These lesions are managed during pregnancy with principles similar to those for patients with valvular AS, although percutaneous intervention is not an option in either of these disorders.

After delivery, the patient who is clinically stable may recover similarly to the general obstetric patient but with telemonitoring for the first 24 hours. The hemodynamic changes of pregnancy may take up to 6 months to normalize; the patient is generally seen by the cardiologist within the first few months after delivery to reassess clinical status. Long-term follow-up is critical for women with moderate to severe AS to reassess the hemodynamics and to provide counseling about future pregnancy.<sup>173</sup>

### **D-Transposition of the Great Arteries (D-TGA): Congenitally Corrected Transposition of the Great Arteries (CC-TGA or L-TGA)**

Transposition of the great arteries most commonly occurs as 1 of 2 abnormalities, either D-TGA or L-transposition of the great arteries.

L-transposition of the great arteries is often referred to as CC-TGA because, in addition to transposed great vessels, ventricular inversion is present, which results in a physiologically normal circulation, although with the RV as the systemic pump. Patients with CC-TGA may have had prior surgery or may be unoperated. Surgery is most common in those with concomitant abnormalities such as ventricular septal defect or pulmonary stenosis. Adults with CC-TGA are at risk for complete heart block and systemic atrioventricular valve regurgitation (the anatomic tricuspid valve) and heart failure.

D-TGA must be repaired, however, because the parallel circulation that results from the aorta arising from the RV and pulmonary artery from the left ventricle is not compatible with long-term survival. However, the type of repair depends on the era in which the child was born and concomitant cardiac abnormalities.

### **Atrial Repair**

The atrial repair of D-TGA, also known as an atrial switch (Mustard or Senning repair), involves the redirection of the systemic and pulmonary venous return at the atrial level so that deoxygenated blood returns to the left ventricle and then to the pulmonary artery, and oxygenated blood returns to the RV and then the aorta. With an atrial switch repair, the circulation is physiologically normal, but again, the RV serves as the systemic ventricle. Adults with an atrial switch repair are at significant risk for sinus node dysfunction and atrial arrhythmias resulting from atrial surgical scarring related to the Mustard or Senning repair and sudden death resulting from ventricular arrhythmias.<sup>205</sup> Baffle obstruction or leak can occur; heart failure caused by systemic ventricular dysfunction is a significant concern; and pulmonary hypertension is seen in a minority of patients.<sup>206,207</sup>

Pregnancy in a patient with a systemic RV, whether D-TGA with an atrial switch or CC-TGA, may be poorly tolerated. The increased blood volume, heart rate, stroke volume, and cardiac output that occur with pregnancy may unmask heart failure, worsen tricuspid regurgitation, or exacerbate arrhythmias.<sup>32,162,205</sup> In a multicenter study of 70 pregnancies, cardiac complications occurred in 36% of pregnancies, including arrhythmias, heart failure, and hemoptysis, with these complications developing in the third trimester.<sup>162</sup>

Some data suggest that pregnancy accelerates the decline in systemic RV function and progression of systemic atrioventricular valve regurgitation. This may result in an irreversible decrement in either systolic function, functional capacity, or both.<sup>163,208,209</sup> Other studies suggest, however, that RV function is not changed by pregnancy.<sup>210</sup> Because data are derived from small case series, the data are controversial, and as with many concerns about pregnancy and CHD, it is difficult to determine whether the decline in systemic RV function is simply a function of time or truly is made worse by preg-

nancy.<sup>168</sup> Regardless of cause, heart failure can complicate both the pregnancy and the years after pregnancy. Thus, patients who want to become pregnant should be counseled accordingly.

Preconception evaluation of the patient with D-TGA or CC-TGA should be directed toward ventricular and valvular function and the presence of arrhythmias and should include echocardiogram or MRI, cardiopulmonary exercise testing, and Holter monitoring.

More invasive hemodynamic assessment is indicated only if history, examination, imaging, or exercise testing suggests a significant hemodynamic lesion that warrants invasive investigation or treatment such as heart failure, residual shunt, pulmonary hypertension, coronary ischemia, or obstruction of Mustard/Senning pathways.

Patients with moderate to severe ventricular dysfunction (NYHA class III or IV) should be advised against becoming pregnant.

### Management

Because of the potential for deterioration during pregnancy, once pregnancy is confirmed, a careful history and clinical examination are needed with a baseline ECG and echocardiogram. In patients with moderate or severe ventricular dysfunction, baseline BNP may be useful as an indicator of ventricular overload in patients who begin to develop symptoms during pregnancy. For those with a history of arrhythmias, an ECG or interval ambulatory ECG monitoring should be done if the patient complains of palpitations.

If clinically stable, the patient may be seen by a cardiologist every 4 to 6 weeks in the second trimester and every 2 to 4 weeks in the third. Women who become symptomatic may require visits as often as every 1 to 2 weeks. Patients who remain asymptomatic may continue routine activities but should be cautioned to restrict active exercise as they progress with pregnancy and to rest at regular intervals; they should also monitor the amount of dietary sodium and report persistent peripheral edema, especially if associated with increased dyspnea.

Before delivery, a detailed delivery plan should be developed and disseminated to team members. If a patient has become symptomatic, induction of labor should be considered after week 39 or earlier as indicated by clinical presentation. Depending on the clinical status at the time of admission, pulse oximetry and cardiac monitoring during active labor and delivery may be all that is required.

Women with good functional status and no significant ventricular or valvular dysfunction or arrhythmias may do well. If, however, a patient is admitted with heart failure or arrhythmias, labor may be poorly tolerated, and she will require more acute management (see Arrhythmias; Heart Failure).

Vaginal delivery with a facilitated second stage of labor and regional anesthesia is recommended unless cesarean delivery is warranted for obstetric reasons. Regional anesthesia is recommended to minimize hemodynamic perturbations of labor.

The increase in maternal blood volume that occurs in the first 24 to 48 hours after delivery may result in clinical heart failure, in some cases even if heart failure had not previously been present. However, if the patient is clinically stable at the time of delivery, she may be transferred to postpartum care with cardiac monitoring for 24 hours, with the nursing staff instructed to observe for symptoms of volume overload or arrhythmias. Patients must continue to be monitored because symptoms of decreased ventricular function may not occur until 3 to 5 days after delivery and have been reported to occur as late as 4 to 6 months after delivery.<sup>168</sup>

### Arterial Switch

The more modern repair of D-TGA is the arterial switch repair, which moves the great arteries and coronary arteries so that the aorta arises from the left ventricle and the pulmonary artery from the RV. This repair affords both physiologically and anatomically normal circulation. The arterial switch repair was not commonly performed until the late 1980s and 1990s, so neither the long-term sequelae of the repair nor the experience with pregnancy and the arterial switch repair is robust. However, patients with an arterial switch thus far have done well, with neo-aortic dilation, aortic valve regurgitation, supra-valvular and branch pulmonary stenosis, and coronary abnormalities developing in a minority of patients.<sup>211-213</sup> Women with an arterial switch repair are anticipated to do well in pregnancy, provided that there are no hemodynamically important residua such as valve dysfunction, supra-valvular or branch pulmonary stenosis, supra-valvular AS, coronary ischemia, or ventricular dysfunction. Thus far, there are scant data on pregnancy in women with an arterial switch repair, and complications in 1 series were related to associated abnormalities that would have been identified as high risk in any circumstance (mechanical valve replacement and left ventricular dysfunction).<sup>214</sup>

Evaluation and management during pregnancy will be dictated by symptoms or residual hemodynamic abnormalities. In the asymptomatic woman with an arterial switch and no hemodynamic abnormalities, evaluation and management may be similar to that in lower-risk cardiac patients. In women with pulmonary stenosis in the main or branch pulmonary arteries, supra-valvular AS at the anastomotic site, neo-aortic dilation, or aortic regurgitation or coronary ischemia, more frequent and more intensive evaluation may be necessary. Neo-aortic dilation may require an early epidural and good pain management and may necessitate a facilitated second stage of delivery or even a cesarean section, depending on the severity.



## Single-Ventricle Physiology/Fontan Palliation

Single-ventricle physiology refers to the presence of a dominant systemic ventricle and typically a second hypoplastic “ventricle”; less commonly, patients present with a true single ventricle. There are a host of morphological and anatomical variants of single-ventricle physiology (ie, tricuspid atresia, double-inlet left ventricle, hypoplastic left ventricle), but all have the presence of only 1 functional pump that must be used to perfuse the systemic arterial bed. Surgical palliations consist of a variety of systemic arterial to pulmonary arterial and systemic venous to pulmonary arterial connections.<sup>215,216</sup>

The Fontan operation is considered definitive repair in that the deoxygenated systemic venous flow is directed to the pulmonary arterial circulation without the presence of an intervening pump, resulting in alleviation of cyanosis but also in a host of long-term sequelae related to chronically elevated systemic venous pressure, diminished cardiac output, and cardiac reserve.<sup>217</sup>

Clinically, patients tend to do well for many years after the procedure, but a number of clinical problems and complications occur over time, including arrhythmias, reduced functional capacity resulting from impaired ventricular function, protein-losing enteropathy, thromboembolism, and portal hypertension.<sup>218–220</sup>

These data present a challenge in the setting of pregnancy given the obligatory increase in heart rate, cardiac output, and plasma volume, especially during the second and third trimesters.

Additionally, during delivery, there are invariably increases in central venous pressure and decreases in cardiac output with straining, the vasoplegic effects of anesthetic agents may be magnified,<sup>6</sup> and the fluid shifts noted in the postpartum period may result in volume overload and necessitate diuresis. Arrhythmias are another area of concern in patients with Fontan circulation, especially in those with the older right atrial to pulmonary artery connections. Data emerging on the risk of pregnancy in the setting of Fontan physiology indicate that in selected, clinically stable women, those with good ventricular function with no history of atrial arrhythmias or thromboembolic events, pregnancy and delivery may be well tolerated but are not without risk,<sup>114,221–224</sup> and early delivery is frequently necessary because of maternal decompensation. Atrial arrhythmias, particularly in those with history of prepregnancy arrhythmias, thromboembolic events, and heart failure, are the primary cardiac events to be reported.<sup>114,224</sup> Obstetric complications have also been reported, including a high rate of fetal loss (miscarriage or fetal demise), premature rupture of membranes, and preterm labor leading to small-for-gestational-age neonates and low birth weight.<sup>224</sup> Therefore, it is important that these patients undergo a full preconception diagnostic evaluation to determine ventricular function, the presence of intracardiac thrombosis, the

risk of developing arrhythmias, oxygen saturation, and pulmonary pressures.

### Management

These patients must be under the direct management of an experienced adult CHD multidisciplinary team. Because of the potential for deterioration during pregnancy, once pregnancy is confirmed, a full cardiac medication and obstetric history and a clinical examination are required. A repeat echocardiogram should be considered at the start of each trimester to determine ventricular function. For those with a history of arrhythmias or if the patient complains of persistent palpitations, ambulatory electrocardiographic monitoring may be indicated. Baseline arterial oxygen saturation and liver function studies should be obtained. Oxygen saturations should be obtained at each clinic visit.

For women who were on anticoagulation before pregnancy, the need to continue anticoagulation throughout pregnancy is controversial, but for those who have a history of a thromboembolic event or atrial arrhythmias, the use of LMWH would seem to be justified (see Mechanical Valves and Anticoagulation). For those on low-dose aspirin, there are no data showing increased obstetric bleeding or adverse fetal effects, but the degree of benefit is unclear.

Regular cardiology follow-up visits should be scheduled and increased if the patient becomes symptomatic. Patients who remain asymptomatic may continue routine activities but should be cautioned to restrict active exercise as they progress with pregnancy, to rest at regular intervals, and to monitor the amount of dietary sodium. They should be instructed to report persistent palpitations and the presence of early or persistent peripheral edema, especially if associated with increased dyspnea.

Before delivery, a detailed delivery plan should be developed and circulated to all members of the multidisciplinary team, including labor and delivery. Because of the risk of preterm labor, the delivery plan should be drafted and distributed at the beginning of the third trimester if not earlier. If the patient has become symptomatic, induction of labor should be considered after week 38 or earlier as indicated by clinical presentation.

Depending on the clinical status at time of admission, cardiac monitoring, pulse oximetry, peripheral vein access for fluids, and compression stockings to avoid venous stasis should be standard care for all in-patients. Intravenous air filters should be used if shunts have been detected to avoid the risk of air emboli. The patient should labor in the left lateral position.

Oxygen therapy is indicated only in the event of arterial desaturation or in the event of maternal decompensation. More invasive monitoring such as arterial line and central venous catheter should be considered only for the patient who begins to show signs of decompensation.

Labor may be poorly tolerated in the patient with poor ejection fraction who is admitted with symptomatic heart failure or arrhythmias, and she will require more acute management (see Arrhythmias; Heart Failure) and early delivery. This may necessitate cesarean section delivery. Vaginal delivery, usually with a shortened second stage of labor and regional anesthesia, is otherwise recommended unless cesarean delivery is warranted for obstetric reasons. Fluid management in the patient with Fontan circulation is a delicate balance. Excessive use of crystalloids may tip the balance, resulting in heart failure, but dehydration should be avoided because volume depletion can lower the central venous pressure and interfere with blood flowing through the cavopulmonary or atriopulmonary connection to the lungs.

After delivery, the significant fluid shifts that occur in the first 24 to 48 hours after delivery are of concern. However, if the patient remains clinically stable at the time of delivery and has had an uncomplicated delivery, she may be transferred to the postpartum unit with remote cardiac monitoring for 24 hours, with the obstetric nursing staff instructed to observe for symptoms of volume overload or palpitation. For patients with compromised cardiac function, admission to the intensive care unit for 24 to 48 hours is prudent.

## FOOTNOTES

The American Heart Association makes every effort to avoid any actual or potential conflicts of interest that may arise as a result of an outside relationship or a personal, professional, or business interest of a member of the writing panel. Specifically, all members of the writing group are required to complete

and submit a Disclosure Questionnaire showing all such relationships that might be perceived as real or potential conflicts of interest.

This statement was approved by the American Heart Association Science Advisory and Coordinating Committee on June 7, 2016, and the American Heart Association Executive Committee on July 20, 2016. A copy of the document is available at <http://professional.heart.org/statements> by using either "Search for Guidelines & Statements" or the "Browse by Topic" area. To purchase additional reprints, call 843-216-2533 or e-mail [kelle.ramsay@wolterskluwer.com](mailto:kelle.ramsay@wolterskluwer.com).

The American Heart Association requests that this document be cited as follows: Canobbio MM, Warnes CA, Aboulhosn J, Connolly HM, Khanna A, Koos BJ, Mital S, Rose C, Silversides C, Stout K; on behalf of the American Heart Association Council on Cardiovascular and Stroke Nursing; Council on Clinical Cardiology; Council on Cardiovascular Disease in the Young; Council on Functional Genomics and Translational Biology; and Council on Quality of Care and Outcomes Research. Management of pregnancy in patients with complex congenital heart disease: a scientific statement for healthcare professionals from the American Heart Association. *Circulation*. 2017;135:e50–e87. doi: 10.1161/CIR.0000000000000458.

Expert peer review of AHA Scientific Statements is conducted by the AHA Office of Science Operations. For more on AHA statements and guidelines development, visit <http://professional.heart.org/statements>. Select the "Guidelines & Statements" drop-down menu, then click "Publication Development."

Permissions: Multiple copies, modification, alteration, enhancement, and/or distribution of this document are not permitted without the express permission of the American Heart Association. Instructions for obtaining permission are located at [http://www.heart.org/HEARTORG/General/Copyright-Permission-Guidelines\\_UCM\\_300404\\_Article.jsp](http://www.heart.org/HEARTORG/General/Copyright-Permission-Guidelines_UCM_300404_Article.jsp). A link to the "Copyright Permissions Request Form" appears on the right side of the page.

*Circulation* is available at <http://circ.ahajournals.org>.

## DISCLOSURES

### Writing Group Disclosures

Writing Group Member	Employment	Research Grant	Other Research Support	Speakers' Bureau/Honoraria	Expert Witness	Ownership Interest	Consultant/Advisory Board	Other
Mary M. Canobbio	UCLA School of Nursing	None	None	None	None	None	None	None
Carole A. Warnes	Mayo Clinic	None	None	None	None	None	None	None
Jamil Aboulhosn	David Geffen School of Medicine at UCLA	None	None	None	None	None	None	None
Heidi M. Connolly	Mayo Clinic	None	None	None	None	None	None	None
Amber Khanna	University of Colorado, Denver	None	None	None	None	None	None	None
Brian J. Koos	David Geffen School of Medicine at UCLA	None	None	None	None	None	None	None

(Continued)

**Writing Group Disclosures Continued**

Writing Group Member	Employment	Research Grant	Other Research Support	Speakers' Bureau/Honoraria	Expert Witness	Ownership Interest	Consultant/Advisory Board	Other
Seema Mital	Hospital for Sick Children	None	None	None	None	None	None	None
Carl Rose	Mayo Clinic	None	None	None	None	None	None	None
Candice Silversides	Toronto General Hospital	None	None	None	None	None	None	None
Karen Stout	University of Washington	None	None	None	None	None	None	None

This table represents the relationships of writing group members that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all members of the writing group are required to complete and submit. A relationship is considered to be "significant" if (a) the person receives \$10 000 or more during any 12-month period, or 5% or more of the person's gross income; or (b) the person owns 5% or more of the voting stock or share of the entity, or owns \$10 000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

**Reviewer Disclosures**

Reviewer	Employment	Research Grant	Other Research Support	Speakers' Bureau/Honoraria	Expert Witness	Ownership Interest	Consultant/Advisory Board	Other
Jack M. Colman	University of Toronto (Canada)	CIHR (pregnancy and heart disease funded research studies)*; HSFC (pregnancy and heart disease funded research studies)*	None	None	Expert witness for a defendant hospital in a maternal mortality case*; expert witness for a defendant doctor in a maternal mortality case*	None	None	ACC/AHA 2015 ACHD guidelines (in process), member of the writing group*
Ian S. Harris	University of California, San Francisco	None	None	None	None	None	None	None
Marla A. Mendelson	Northwestern University	None	None	None	None	None	None	None

This table represents the relationships of reviewers that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all reviewers are required to complete and submit. A relationship is considered to be "significant" if (a) the person receives \$10 000 or more during any 12-month period, or 5% or more of the person's gross income; or (b) the person owns 5% or more of the voting stock or share of the entity, or owns \$10 000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

\*Modest.

## REFERENCES

1. Warnes CA, Liberthson R, Danielson GK, Dore A, Harris L, Hoffman JL, Somerville J, Williams RG, Webb GD. Task force 1: the changing profile of congenital heart disease in adult life. *J Am Coll Cardiol*. 2001;37:1170–1175.
2. Thorne S, MacGregor A, Nelson-Piercy C. Risks of contraception and pregnancy in heart disease. *Heart*. 2006;92:1520–1525. doi: 10.1136/hrt.2006.095240.
3. Balci A, Sollie-Szarynska KM, van der Bijl AG, Ruys TP, Mulder BJ, Roos-Hesselink JW, van Dijk AP, Wajon EM, Vliegen HW, Drenthen W, Hillege HL, Aarnoudse JG, van Veldhuisen DJ, Pieper PG; ZAHARA-II Investigators. Prospective validation and assessment of cardiovascular and offspring risk models for pregnant women with congenital heart disease. *Heart*. 2014;100:1373–1381. doi: 10.1136/heartjnl-2014-305597.
4. Drenthen W, Boersma E, Balci A, Moons P, Roos-Hesselink JW, Mulder BJ, Vliegen HW, van Dijk AP, Voors AA, Yap SC, van Veldhuisen DJ, Pieper PG; ZAHARA Investigators. Predictors of pregnancy complications in women with congenital heart disease. *Eur Heart J*. 2010;31:2124–2132. doi: 10.1093/eurheartj/ehq200.
5. Bédard E, Dimopoulos K, Gatzoulis MA. Has there been any progress made on pregnancy outcomes among women with pulmonary arterial hypertension? *Eur Heart J*. 2009;30:256–265. doi: 10.1093/eurheartj/ehn597.
6. Weiss BM, Zemp L, Seifert B, Hess OM. Outcome of pulmonary vascular disease in pregnancy: a systematic overview from 1978 through 1996. *J Am Coll Cardiol*. 1998;31:1650–1657.
7. Presbitero P, Somerville J, Stone S, Aruta E, Spiegelhalter D, Rajajoli F. Pregnancy in cyanotic congenital heart disease: outcome of mother and fetus. *Circulation*. 1994;89:2673–2676.
8. Hytten FE, Paintin DB. Increase in plasma volume during normal pregnancy. *J Obstet Gynaecol Br Emp*. 1963;70:402–407.
9. Rovinsky JJ, Jaffin H. Cardiovascular hemodynamics in pregnancy, I: blood and plasma volumes in multiple pregnancy. *Am J Obstet Gynecol*. 1965;93:1–15.
10. Caton WL, Roby CC, Reid DE, Caswell R, Maletskos CJ, Fluharty RG, Gibson JG 2nd. The circulating red cell volume and body hematocrit in normal pregnancy and the puerperium by direct measurement using radioactive red cells. *Am J Obstet Gynecol*. 1951;61:1207–1217.
11. Dahlstrom H, Ihrman K. A clinical and physiological study of pregnancy in a material from northern Sweden, IV: observations on the blood volume during and after pregnancy. *Acta Soc Med Ups*. 1960;65:295–304.
12. Pritchard JA. Changes in the blood volume during pregnancy and delivery. *Anesthesiology*. 1965;26:393–399.
13. Longo LD. Maternal blood volume and cardiac output during pregnancy: a hypothesis of endocrinologic control. *Am J Physiol*. 1983;245(pt 1):R720–R729.
14. Yusef YR, Thomas W, Harvey BJ. Estrogen increases ENaC activity via PKC $\delta$  signaling in renal cortical collecting duct cells. *Physiol Rep*. 2014;2:e12020. doi: 10.14814/phy2.12020.
15. Lumbers ER, Pringle KG. Roles of the circulating renin-angiotensin-aldosterone system in human pregnancy. *Am J Physiol Regul Integr Comp Physiol*. 2014;306:R91–R101.
16. Chisholm M. A controlled clinical trial of prophylactic folic acid and iron in pregnancy. *J Obstet Gynaecol Br Commonw*. 1966;73:191–196.
17. Hameed AB, Chan K, Ghamsary M, Elkayam U. Longitudinal changes in the B-type natriuretic peptide levels in normal pregnancy and postpartum. *Clin Cardiol*. 2009;32:E60–E62. doi: 10.1002/clc.20391.
18. Tanous D, Siu SC, Mason J, Greutmann M, Wald RM, Parker JD, Sermer M, Colman JM, Silversides CK. B-type natriuretic peptide in pregnant women with heart disease. *J Am Coll Cardiol*. 2010;56:1247–1253. doi: 10.1016/j.jacc.2010.02.076.
19. Resnik JL, Hong C, Resnik R, Kazanegra R, Beede J, Bhalla V, Maisel A. Evaluation of B-type natriuretic peptide (BNP) levels in normal and preeclamptic women. *Am J Obstet Gynecol*. 2005;193:450–454. doi: 10.1016/j.ajog.2004.12.006.
20. Yoshimura T, Yoshimura M, Yasue H, Ito M, Okamura H, Mukoyama M, Nakao K. Plasma concentration of atrial natriuretic peptide and brain natriuretic peptide during normal human pregnancy and the postpartum period. *J Endocrinol*. 1994;140:393–397.
21. Kampman MA, Balci A, van Veldhuisen DJ, van Dijk AP, Roos-Hesselink JW, Sollie-Szarynska KM, Ludwig-Ruitenbergh M, van Melle JP, Mulder BJ, Pieper PG; ZAHARA II Investigators. N-terminal pro-B-type natriuretic peptide predicts cardiovascular complications in pregnant women with congenital heart disease. *Eur Heart J*. 2014;35:708–715. doi: 10.1093/eurheartj/ehf526.
22. Robertson EG, Cheyne GA. Plasma biochemistry in relation to oedema of pregnancy. *J Obstet Gynaecol Br Commonw*. 1972;79:769–776.
23. Brown MA, Zammit VC, Mitar DM. Extracellular fluid volumes in pregnancy-induced hypertension. *J Hypertens*. 1992;10:61–68.
24. Robson SC, Hunter S, Boys RJ, Dunlop W. Serial study of factors influencing changes in cardiac output during human pregnancy. *Am J Physiol*. 1989;256(pt 2):H1060–H1065.
25. Duvekot JJ, Cheriex EC, Pieters FA, Menheere PP, Peeters LH. Early pregnancy changes in hemodynamics and volume homeostasis are consecutive adjustments triggered by a primary fall in systemic vascular tone. *Am J Obstet Gynecol*. 1993;169:1382–1392.
26. Chapman AB, Abraham WT, Zamudio S, Coffin C, Merouani A, Young D, Johnson A, Osorio F, Goldberg C, Moore LG, Dahms T, Schrier RW. Temporal relationships between hormonal and hemodynamic changes in early human pregnancy [published correction appears in *Kidney Int*. 1999;55:1185]. *Kidney Int*. 1998;54:2056–2063. doi: 10.1046/j.1523-1755.1998.00217.x.
27. Ueland K, Metcalfe J. Circulatory changes in pregnancy. *Clin Obstet Gynecol*. 1975;18:41–50.
28. Clark SL, Cotton DB, Pivarnik JM, Lee W, Hankins GD, Benedetti TJ, Phelan JP. Position change and central hemodynamic profile during normal third-trimester pregnancy and post partum [published correction appears in *Am J Obstet Gynecol*. 1991;165:241]. *Am J Obstet Gynecol*. 1991;164:883–887.
29. McLennan FM, Haites NE, Rawles JM. Stroke and minute distance in pregnancy: a longitudinal study using Doppler ultrasound. *Br J Obstet Gynaecol*. 1987;94:499–506.
30. Armstrong S, Fernando R, Columb M, Jones T. Cardiac index in term pregnant women in the sitting, lateral, and supine positions: an observational, crossover study. *Anesth Analg*. 2011;113:318–322. doi: 10.1213/ANE.0b013e31821f125c.
31. McRoberts WA Jr. Postural shock in pregnancy. *Am J Obstet Gynecol*. 1951;62:627–632.
32. Quilligan EJ, Tyler C. Postural effects on the cardiovascular status in pregnancy: a comparison of the lateral and supine postures. *Am J Obstet Gynecol*. 1959;78:465–471.
33. Ueland K, Hansen JM. Maternal cardiovascular dynamics, II: posture and uterine contractions. *Am J Obstet Gynecol*. 1969;103:1–7.
34. Kametas NA, McAuliffe F, Krampl E, Chambers J, Nicolaides KH. Maternal cardiac function in twin pregnancy. *Obstet Gynecol*. 2003;102:806–815.
35. Kuleva M, Youssef A, Maroni E, Contro E, Pilu G, Rizzo N, Pelusi G, Ghi T. Maternal cardiac function in normal twin pregnancy: a longitudinal study. *Ultrasound Obstet Gynecol*. 2011;38:575–580. doi: 10.1002/uog.8936.
36. Robson SC, Hunter S, Boys RJ, Dunlop W. Hemodynamic changes during twin pregnancy: a Doppler and M-mode echocardiographic study. *Am J Obstet Gynecol*. 1989;161:1273–1278.
37. Veille JC, Morton MJ, Burry KJ. Maternal cardiovascular adaptations to twin pregnancy. *Am J Obstet Gynecol*. 1985;153:261–263.



38. McLennan CE. Antecubital and femoral venous pressure in normal and toxemic pregnancy. *Am J Obstet Gynecol.* 1943;45:568–591.
39. Vorys N, Ullery JC, Hanusek GE. The cardiac output changes in various positions in pregnancy. *Am J Obstet Gynecol.* 1961;82:1312–1321.
40. Kinsella SM, Lohmann G. Supine hypotensive syndrome. *Obstet Gynecol.* 1994;83(pt 1):774–788.
41. Knotts RJ, Garan H. Cardiac arrhythmias in pregnancy. *Semin Perinatol.* 2014;38:285–288. doi: 10.1053/j.semperi.2014.04.017.
42. Robson SC, Hunter S, Boys RJ, Dunlop W. Serial changes in pulmonary haemodynamics during human pregnancy: a non-invasive study using Doppler echocardiography. *Clin Sci (Lond).* 1991;80:113–117.
43. Bader RA, Bader ME, Rose DF, Braunwald E. Hemodynamics at rest and during exercise in normal pregnancy as studies by cardiac catheterization. *J Clin Invest.* 1955;34:1524–1536. doi: 10.1172/JCI103205.
44. Clark SL, Cotton DB, Lee W, Bishop C, Hill T, Southwick J, Pivarnik J, Spillman T, DeVore GR, Phelan J, Hankins GDV, Benedetto TJ, Tolley D. Central hemodynamic assessment of normal term pregnancy. *Am J Obstet Gynecol.* 1989;161(pt 1):1439–1442.
45. Werko L. Pregnancy and heart disease. *Acta Obstet Gynecol Scand.* 1954;33:162–210.
46. Walters WA, MacGregor WG, Hills M. Cardiac output at rest during pregnancy and the puerperium. *Clin Sci.* 1966;30:1–11.
47. Clapp JF 3rd, Capeless E. Cardiovascular function before, during, and after the first and subsequent pregnancies. *Am J Cardiol.* 1997;80:1469–1473.
48. Capeless EL, Clapp JF. Cardiovascular changes in early phase of pregnancy. *Am J Obstet Gynecol.* 1989;161(pt 1):1449–1453.
49. Easterling TR, Benedetti TJ, Schmucker BC, Millard SP. Maternal hemodynamics in normal and preeclamptic pregnancies: a longitudinal study. *Obstet Gynecol.* 1990;76:1061–1069.
50. Veille JC, Morton MJ, Burry K, Nemeth M, Speroff L. Estradiol and hemodynamics during ovulation induction. *J Clin Endocrinol Metab.* 1986;63:721–724. doi: 10.1210/jcem-63-3-721.
51. Moutquin JM, Rainville C, Giroux L, Raynauld P, Amyot G, Bilodeau R, Pelland N. A prospective study of blood pressure in pregnancy: prediction of preeclampsia. *Am J Obstet Gynecol.* 1985;151:191–196.
52. Awe RJ, Nicotra MB, Newsom TD, Viles R. Arterial oxygenation and alveolar-arterial gradients in term pregnancy. *Obstet Gynecol.* 1979;53:182–186.
53. Rees GB, Broughton Pipkin F, Symonds EM, Patrick JM. A longitudinal study of respiratory changes in normal human pregnancy with cross-sectional data on subjects with pregnancy-induced hypertension. *Am J Obstet Gynecol.* 1990;162:826–830.
54. DeSwiet M. Pulmonary disorders. In: Creasy RK, Resnik R, ed. *Maternal-Fetal Medicine.* 4th ed. Philadelphia, PA: WB Saunders; 1999:921–934.
55. Lehmann V. Dyspnea in pregnancy. *J Perinat Med.* 1975;3:154–160.
56. Milne JA, Howie AD, Pack AI. Dyspnoea during normal pregnancy. *Br J Obstet Gynaecol.* 1978;85:260–263.
57. Hirnle L, Lysenko L, Gerber H, Lesnik P, Baranowska A, Rachwalik M, Leszczyszyn J, Strozeccki L. Respiratory function in pregnant women. *Adv Exp Med Biol.* 2013;788:153–160. doi: 10.1007/978-94-007-6627-3\_23.
58. Hendricks CH, Quilligan EJ. Cardiac output during labor. *Am J Obstet Gynecol.* 1956;71:953–972.
59. Robson SC, Dunlop W, Boys RJ, Hunter S. Cardiac output during labour. *Br Med J (Clin Res Ed).* 1987;295:1169–1172.
60. Ueland K, Hansen JM. Maternal cardiovascular dynamics, 3: labor and delivery under local and caudal analgesia. *Am J Obstet Gynecol.* 1969;103:8–18.
61. Adams JQ, Alexander AM Jr. Alterations in cardiovascular physiology during labor. *Obstet Gynecol.* 1958;12:542–549.
62. Palmer AJ, Walker AH. The maternal circulation in normal pregnancy. *J Obstet Gynaecol Br Emp.* 1949;56:537–547.
63. Lee W, Rokey R, Miller J, Cotton DB. Maternal hemodynamic effects of uterine contractions by M-mode and pulsed-Doppler echocardiography. *Am J Obstet Gynecol.* 1989;161:974–977.
64. Bieniarz J, Yoshida T, Romero-Salinas G, Curuchet E, Caldeyro-Barcia R, Crottogini JJ. Aortocaval compression by the uterus in late human pregnancy. IV. Circulatory homeostasis by preferential perfusion of the placenta. *Am J Obstet Gynecol.* 1969;103:19–31.
65. Hendricks CH. The hemodynamics of a uterine contraction. *Am J Obstet Gynecol.* 1958;76:969–982.
66. Atkins AF, Watt JM, Milan P, Davies P, Crawford JS. A longitudinal study of cardiovascular dynamic changes throughout pregnancy. *Eur J Obstet Gynecol Reprod Biol.* 1981;12:215–224.
67. Metcalfe J, Ueland K. Maternal cardiovascular adjustments to pregnancy. *Prog Cardiovasc Dis.* 1974;16:363–374.
68. Regitz-Zagrosek V, Blomstrom Lundqvist C, Borghi C, Cifkova R, Ferreira R, Foidart J-M, Gibbs JSR, Gohlke-Baerwolf C, Gorenek B, Iung B, Kirby M, Maas AH, Morais J, Nihoyannopoulos P, Pieper PG, Presbitero P, Roos-Hesselink JW, Schaufelberger M, Seeland U, Torracca L; ESC Committee for Practice Guidelines. ESC guidelines on the management of cardiovascular diseases during pregnancy: the Task Force on the Management of Cardiovascular Diseases During Pregnancy of the European Society of Cardiology (ESC). *Eur Heart J.* 2011;32:3147–3197.
69. Ueland K. Maternal cardiovascular dynamics. VII. Intrapartum blood volume changes. *Am J Obstet Gynecol.* 1976;126:671–677.
70. James CF, Banner T, Caton D. Cardiac output in women undergoing cesarean section with epidural or general anesthesia. *Am J Obstet Gynecol.* 1989;160(pt 1):1178–1184.
71. Robson SC, Boys RJ, Hunter S, Dunlop W. Maternal hemodynamics after normal delivery and delivery complicated by postpartum hemorrhage. *Obstet Gynecol.* 1989;74:234–239.
72. Warnes CA, Williams RG, Bashore TM, Child JS, Connolly HM, Dearani JA, del Nido P, Fasules JW, Graham TP Jr, Hijazi ZM, Hunt SA, King ME, Landzberg MJ, Miner PD, Radford MJ, Walsh EP, Webb GD. ACC/AHA 2008 guidelines for the management of adults with congenital heart disease: a report of the American College of Cardiology/American Heart Association, Task Force on Practice Guidelines (Writing Committee to Develop Guidelines on the Management of Adults With Congenital Heart Disease). *Circulation.* 2008;118:e714–e833. doi: 10.1161/CIRCULATIONAHA.108.190690.
73. Whittemore R, Hobbins JC, Engle MA. Pregnancy and its outcome in women with and without surgical treatment of congenital heart disease. *Am J Cardiol.* 1982;50:641–651.
74. Siu SC, Sermer M, Colman JM, Alvarez AN, Mercier LA, Morton BC, Kells CM, Bergin ML, Kiess MC, Marcotte F, Taylor DA, Gordon EP, Spears JC, Tam JW, Amankwah KS, Smallhorn JF, Farine D, Sorensen S; Cardiac Disease in Pregnancy (CARPREG) Investigators. Prospective multicenter study of pregnancy outcomes in women with heart disease. *Circulation.* 2001;104:515–521.
75. Diller GP, Dimopoulos K, Okonko D, Li W, Babu-Narayan SV, Broberg CS, Johansson B, Bouzas B, Mullen MJ, Poole-Wilson PA, Francis DP, Gatzoulis MA. Exercise intolerance in adult congenital heart disease: comparative severity, correlates, and prognostic implication. *Circulation.* 2005;112:828–835. doi: 10.1161/CIRCULATIONAHA.104.529800.
76. Lui GK, Silversides CK, Khairy P, Fernandes SM, Valente AM, Nickolaous MJ, Earing MG, Aboulhosn JA, Rosenbaum MS, Cook S, Kay JD, Jin Z, Gersony DR; Alliance for Adult Research in Congenital Cardiology (AARCC). Heart rate response during exercise and pregnancy outcome in women with congenital heart disease. *Circulation.* 2011;123:242–248. doi: 10.1161/CIRCULATIONAHA.110.953380.
77. Opatowsky AR, Siddiqi OK, D'Souza B, Webb GD, Fernandes SM, Landzberg MJ. Maternal cardiovascular events during

- childbirth among women with congenital heart disease. *Heart*. 2012;98:145–151. doi: 10.1136/heartjnl-2011-300828.
78. Drenth W, Pieper PG, Roos-Hesselink JW, van Lottum WA, Voors AA, Mulder BJ, van Dijk AP, Vliegen HW, Yap SC, Moons P, Ebels T, van Veldhuisen DJ; ZAHARA Investigators. Outcome of pregnancy in women with congenital heart disease: a literature review. *J Am Coll Cardiol*. 2007;49:2303–2311. doi: 10.1016/j.jacc.2007.03.027.
  79. Khairy P, Ouyang DW, Fernandes SM, Lee-Parritz A, Economy KE, Landzberg MJ. Pregnancy outcomes in women with congenital heart disease. *Circulation*. 2006;113:517–524. doi: 10.1161/CIRCULATIONAHA.105.589655.
  80. Gelson E, Curry R, Gatzoulis MA, Swan L, Lupton M, Steer P, Johnson M. Effect of maternal heart disease on fetal growth [published correction appears in *Obstet Gynecol*. 2011;113(pt1):364]. *Obstet Gynecol*. 2011;117:886–891. doi: 10.1097/AOG.0b013e31820cab69.
  81. Burchill L, Greenway S, Silversides CK, Mital S. Genetic counseling in the adult with congenital heart disease: what is the role? *Curr Cardiol Rep*. 2011;13:347–355. doi: 10.1007/s11886-011-0188-z.
  82. Pierpont ME, Basson CT, Benson DW Jr, Gelb BD, Giglia TM, Goldmuntz E, McGee G, Sable CA, Srivastava D, Webb CL. Genetic basis for congenital heart defects: current knowledge: a scientific statement from the American Heart Association Congenital Cardiac Defects Committee, Council on Cardiovascular Disease in the Young. *Circulation*. 2007;115:3015–3038. doi: 10.1161/CIRCULATIONAHA.106.183056.
  83. Øyen N, Poulsen G, Boyd HA, Wohlfahrt J, Jensen PK, Melbye M. Recurrence of congenital heart defects in families. *Circulation*. 2009;120:295–301. doi: 10.1161/CIRCULATIONAHA.109.857987.
  84. Gill HK, Splitt M, Sharland GK, Simpson JM. Patterns of recurrence of congenital heart disease: an analysis of 6,640 consecutive pregnancies evaluated by detailed fetal echocardiography. *J Am Coll Cardiol*. 2003;42:923–929.
  85. Jenkins KJ, Correa A, Feinstein JA, Botto L, Britt AE, Daniels SR, Elixson M, Warnes CA, Webb CL. Noninherited risk factors and congenital cardiovascular defects: current knowledge: a scientific statement from the American Heart Association Council on Cardiovascular Disease in the Young. *Circulation*. 2007;115:2995–3014. doi: 10.1161/CIRCULATIONAHA.106.183216.
  86. Silversides CK, Marelli A, Beauchesne L, Dore A, Kiess M, Salehian O, Bradley T, Colman J, Connelly M, Harris L, Khairy P, Mital S, Niwa K, Oechslin E, Poirier N, Schwerzmann M, Taylor D, Vonder Muhll I, Baumgartner H, Benson L, Celermajer D, Greutmann M, Horlick E, Landzberg M, Meijboom F, Mulder B, Warnes C, Webb G, Therrien J. Canadian cardiovascular society 2009 consensus conference on the management of adults with congenital heart disease: executive summary. *Can J Cardiol*. 2010;26:143–150.
  87. Colletti PM, Lee KH, Elkayam U. Cardiovascular imaging of the pregnant patient. *AJR Am J Roentgenol*. 2013;200:515–521. doi: 10.2214/AJR.12.9864.
  88. Naqvi TZ, Elkayam U. Serial echocardiographic assessment of the human heart in normal pregnancy. *Circ Cardiovasc Imaging*. 2012;5:283–285. doi: 10.1161/CIRCIMAGING.112.974808.
  89. Campos O. Doppler echocardiography during pregnancy: physiological and abnormal findings. *Echocardiography*. 1996;13:135–146.
  90. MacPhail A, Davies GA, Victory R, Wolfe LA. Maximal exercise testing in late gestation: fetal responses. *Obstet Gynecol*. 2000;96:565–570.
  91. Moore DH, Jarrett JC 2nd, Bendick PJ. Exercise-induced changes in uterine artery blood flow, as measured by Doppler ultrasound, in pregnant subjects. *Am J Perinatol*. 1988;5:94–97. doi: 10.1055/s-2007-999663.
  92. van Doorn MB, Lotgering FK, Struijk PC, Pool J, Wallenburg HC. Maternal and fetal cardiovascular responses to strenuous bicycle exercise. *Am J Obstet Gynecol*. 1992;166:854–859.
  93. Piran S, Veldtman G, Siu S, Webb GD, Liu PP. Heart failure and ventricular dysfunction in patients with single or systemic right ventricles. *Circulation*. 2002;105:1189–1194.
  94. Perloff JK, Koos B. Pregnancy and congenital heart disease: the mother and the fetus: medical considerations. In: Perloff JK, Child JS, eds. *Congenital Heart Disease in Adults*. Philadelphia, PA: WB Saunders; 1998:144–164.
  95. Patenaude Y, Pugash D, Lim K, Morin L; Diagnostic Imaging Committee; Lim K, Bly S, Butt K, Cargill Y, Davies G, Denis N, Hazlitt G, Morin L, Naud K, Ouellet A, Salem S; Society of Obstetricians and Gynaecologists of Canada. The use of magnetic resonance imaging in the obstetric patient. *J Obstet Gynaecol Can*. 2014;36:349–363.
  96. Kanal E, Barkovich AJ, Bell C, Borgstede JP, Bradley WG Jr, Froelich JW, Gilk T, Gimbel JR, Gosbee J, Kuhn-Kaminski E, Lester JW Jr, Nyenhuis J, Parag Y, Schaefer DJ, Sebek-Scoumis EA, Weinreb J, Zaremba LA, Wilcox P, Lucey L, Sass N; ACR Blue Ribbon Panel on MR Safety. ACR guidance document for safe MR practices: 2007. *AJR Am J Roentgenol*. 2007;188:1447–1474. doi: 10.2214/AJR.06.1616.
  97. American College of Radiology (ACR); Society for Pediatric Radiology (SPR). Practice guideline for the safe and optimal performance of fetal magnetic resonance imaging (MRI). 2010 (Resolution 13). <http://www.acr.org/-/media/CB384A65345F402083639E6756CE513F.pdf>. Accessed December 9, 2013.
  98. Glover P, Hykin J, Gowland P, Wright J, Johnson I, Mansfield P. An assessment of the intrauterine sound intensity level during obstetric echo-planar magnetic resonance imaging. *Br J Radiol*. 1995;68:1090–1094. doi: 10.1259/0007-1285-68-814-1090.
  99. Baker PN, Johnson IR, Harvey PR, Gowland PA, Mansfield P. A three-year follow-up of children imaged in utero with echo-planar magnetic resonance. *Am J Obstet Gynecol*. 1994;170(pt 1): 32–33.
  100. Shellock FG, Spinazzi A. MRI safety update 2008, part 2: screening patients for MRI. *AJR Am J Roentgenol*. 2008;191:1140–1149. doi: 10.2214/AJR.08.1038.2.
  101. Chen MM, Coakley FV, Kaimal A, Laros RK Jr. Guidelines for computed tomography and magnetic resonance imaging use during pregnancy and lactation. *Obstet Gynecol*. 2008;112(pt 1):333–340. doi: 10.1097/AOG.0b013e318180a505.
  102. Damilakis J, Perisinakis K, Voloudaki A, Gourtsoyannis N. Estimation of fetal radiation dose from computed tomography scanning in late pregnancy: depth-dose data from routine examinations [published correction appears in *Invest Radiol*. 2000;35:706]. *Invest Radiol*. 2000;35:527–533.
  103. REPROTOX database. [www.reprotox.org](http://www.reprotox.org). Accessed September 1, 2014.
  104. Cooper WO, Hernandez-Diaz S, Arbogast PG, Dudley JA, Dyer S, Gideon PS, Hall K, Ray WA. Major congenital malformations after first-trimester exposure to ACE inhibitors. *N Engl J Med*. 2006;354:2443–2451. doi: 10.1056/NEJMoa055202.
  105. Lee JCR, Wetzel G, Shannon K. Maternal arrhythmia management during pregnancy in patients with structural heart disease. *Prog Pediatr Cardiol*. 2004;19:71–82.
  106. Lip GY, Beevers M, Churchill D, Shaffer LM, Beevers DG. Effect of atenolol on birth weight. *Am J Cardiol*. 1997;79:1436–1438.
  107. Lindheimer MD, Katz AL. Pregnancy and the kidney. *J Reprod Med*. 1973;11:14–18.
  108. McKenna WJ, Rowland E, Krikler DM. Amiodarone: the experience of the past decade. *Br Med J (Clin Res Ed)*. 1983;287:1654–1656.
  109. Lecarpentier E, Morel O, Fournier T, Elefant E, Chavatte-Palmer P, Tsatsaris V. Statins and pregnancy: between supposed

- risks and theoretical benefits. *Drugs*. 2012;72:773–788. doi: 10.2165/11632010-000000000-00000.
110. Costantine MM, Cleary K; Eunice Kennedy Shriver National Institute of Child Health and Human Development Obstetric–Fetal Pharmacology Research Units Network. Pravastatin for the prevention of preeclampsia in high-risk pregnant women. *Obstet Gynecol*. 2013;121(pt 1):349–353. doi: <http://10.1097/AOG.0b013e31827d8ad5>.
  111. Canobbio MM, Chugh R. Congenital heart disease and pregnancy. In: Wszynski DF, Correa-Villasenor, Graham TP, eds. *Congenital Heart Defects: From Origin to Treatment*. Oxford, UK: Oxford Press; 2011:301–328.
  112. Kahn SR, Lim W, Dunn AS, Cushman M, Dentali F, Akl EA, Cook DJ, Balekian AA, Klein RC, Le H, Schulman S, Murad MH; American College of Chest Physicians. Prevention of VTE in nonsurgical patients: Antithrombotic Therapy and Prevention of Thrombosis, 9th ed: American College of Chest Physicians Evidence-Based Clinical Practice Guidelines. *Chest*. 2012;141(suppl):e195S–e226S. doi: 10.1378/chest.11-2296.
  113. Sayle AE, Savitz DA, Thorp JM, Hertz-Picciotta I, Wilcox AJ. Sexual activity during late pregnancy and risk of preterm delivery. *Obstet Gynecol*. 2011;283–289.
  114. Canobbio MM, Mair DD, van der Velde M, Koos BJ. Pregnancy outcomes after the Fontan repair. *J Am Coll Cardiol*. 1996;28:763–767.
  115. Bryant AG, Grimes DA, Garrett JM, Stuart GS. Second-trimester abortion for fetal anomalies or fetal death: labor induction compared with dilation and evacuation. *Obstet Gynecol*. 2011;117:788–792. doi: 10.1097/AOG.0b013e31820c3d26.
  116. American College of Obstetricians and Gynecologists. ACOG committee opinion no. 560: medically indicated late-preterm and early-term deliveries. *Obstet Gynecol*. 2013;121:908–1010. doi: 10.1097/01.AOG.0000428648.75548.00.
  117. Koos B. Management of uncorrected, palliated, and repaired cyanotic congenital heart disease in pregnancy. *Prog Pediatr Cardiol*. 2004;19: 25–45. doi: <http://dx.doi.org/10.1016/j.ppedcard.2003.09.004>.
  118. Cole PJ, Cross MH, Dresner M. Incremental spinal anaesthesia for elective caesarean section in a patient with Eisenmenger's syndrome. *Br J Anaesth*. 2001;86:723–726.
  119. Wilson W, Taubert KA, Gewitz M, Lockhart PB, Baddour LM, Levison M, Bolger A, Cabell CH, Takahashi M, Baltimore RS, Newburger JW, Strom BL, Tani LY, Gerber M, Bonow RO, Pallasch T, Shulman ST, Rowley AH, Burns JC, Ferrieri P, Gardner T, Goff D, Durack DT. Prevention of infective endocarditis: guidelines from the American Heart Association: a guideline from the American Heart Association Rheumatic Fever, Endocarditis, and Kawasaki Disease Committee, Council on Cardiovascular Disease in the Young, and the Council on Clinical Cardiology, Council on Cardiovascular Surgery and Anesthesia, and the Quality of Care and Outcomes Research Interdisciplinary Working Group [published correction appears in *Circulation*. 2007;116:e376–e377]. *Circulation*. 2007;116:1736–1754. doi: 10.1161/CIRCULATIONAHA.106.183095.
  120. Kjeldsen J. Hemodynamic investigations during labour and delivery. *Acta Obstet Gynecol Scand Suppl*. 1979;89:1–252.
  121. Robson SC, Dunlop W, Moore M, Hunter S. Combined Doppler and echocardiographic measurement of cardiac output: theory and application in pregnancy. *Br J Obstet Gynaecol*. 1987;94:1014–1027.
  122. Zeeman GG, Wendel GD Jr, Cunningham FG. A blueprint for obstetric critical care. *Am J Obstet Gynecol*. 2003;188:532–536.
  123. Capeless EL, Clapp JF. When do cardiovascular parameters return to their preconception values? *Am J Obstet Gynecol*. 1991;165(pt 1):883–886.
  124. Truitt ST, Fraser AV, Grimes DA, Gallo MF, Schulz KF. Combined hormonal versus nonhormonal versus progestin-only contraception in lactation. *Cochrane Database Syst Rev*. 2003;CD003988.
  125. American College Obstetrics Gynecology. ACOG Practice Bulletin No. 121: long-acting reversible contraceptives: implants and intrauterine devices. *Obstet Gynecol*. 2011;118:184–196. doi: 10.1097/AOG.0b013e318227f05e.
  126. Peterson HB, Xia Z, Hughes JM, Wilcox LS, Tylor LR, Trussell J. The risk of pregnancy after tubal sterilization: findings from the U.S. Collaborative Review of Sterilization. *Am J Obstet Gynecol*. 1996;174:1161–1168.
  127. US Food and Drug Administration. 2015 Meeting materials of the Obstetrics and Gynecology Devices Panel. 2015. <http://www.fda.gov/AdvisoryCommittees/CommitteesMeetingMaterials/MedicalDevices/MedicalDevicesAdvisoryCommittee/ObstetricsandGynecologyDevices/ucm463457.htm>. Accessed February 22, 2016.
  128. Silversides CK, Harris L, Haberer K, Sermer M, Colman JM, Siu SC. Recurrence rates of arrhythmias during pregnancy in women with previous tachyarrhythmia and impact on fetal and neonatal outcomes. *Am J Cardiol*. 2006;97:1206–1212. doi: 10.1016/j.amjcard.2005.11.041.
  129. Lydakis C, Lip GY, Beevers M, Beevers DG. Atenolol and fetal growth in pregnancies complicated by hypertension. *Am J Hypertens*. 1999;12:541–547.
  130. Bryerly WG, Hartman A, Foster DE, Tannenbaum AK. Verapamil in the treatment of paroxysmal supraventricular tachycardia. *Ann Emerg Med*. 1991;20:552–554.
  131. Holbrook RH Jr, Gibson RN, Voss EM. Tocolytic and cardiovascular effects of the calcium antagonist diltiazem in the near-term pregnant rabbit. *Am J Obstet Gynecol*. 1988;159: 591–595.
  132. Zipes DP, Camm AJ, Borggrefe M, Buxton AE, Chaitman B, Fromer M, Gregoratos G, Klein G, Moss AJ, Myerburg RJ, Priori SG, Quinones MA, Roden DM, Silka MJ, Tracy C. ACC/AHA/ESC 2006 guidelines for management of patients with ventricular arrhythmias and the prevention of sudden cardiac death: a report of the American College of Cardiology/American Heart Association Task Force and the European Society of Cardiology Committee for Practice Guidelines (Writing Committee to Develop Guidelines for Management of Patients With Ventricular Arrhythmias and the Prevention of Sudden Cardiac Death). *Circulation*. 2006;114:e385–e484. doi: 10.1161/CIRCULATIONAHA.106.178233.
  133. Thaman R, Curtis S, Faganello G, Szantho GV, Turner MS, Trinder J, Sellers S, Stuart GA. Cardiac outcome of pregnancy in women with a pacemaker and women with untreated atrioventricular conduction block. *Europace*. 2011;13:859–863. doi: 10.1093/europace/eur018.
  134. Sbarouni E, Oakley CM. Outcome of pregnancy in women with valve prostheses. *Br Heart J*. 1994;71:196–201.
  135. Meschengieser SS, Fondevila CG, Santarelli MT, Lazzari MA. Anticoagulation in pregnant women with mechanical heart valve prostheses. *Heart*. 1999;82:23–26.
  136. Sadler L, McCowan L, White H, Stewart A, Bracken M, North R. Pregnancy outcomes and cardiac complications in women with mechanical, bioprosthetic and homograft valves. *BJOG*. 2000;107:245–253.
  137. Cotrufo M, De Feo M, De Santo LS, Romano G, Della Corte A, Renzulli A, Gallo C. Risk of warfarin during pregnancy with mechanical valve prostheses. *Obstet Gynecol*. 2002;99:35–40.
  138. Nassar AH, Hobeika EM, Abd Essamad HM, Taher A, Khalil AM, Usta IM. Pregnancy outcome in women with prosthetic heart valves. *Am J Obstet Gynecol*. 2004;191:1009–1013. doi: 10.1016/j.ajog.2004.05.064.
  139. Suri V, Keepanasseril A, Aggarwal N, Chopra S, Bagga R, Sikka P, Vijayvergiya R. Mechanical valve prosthesis and anticoagulation regimens in pregnancy: a tertiary centre experience. *Eur J Obstet Gynecol Reprod Biol*. 2011;159:320–323. doi: 10.1016/j.ejogrb.2011.09.011.



140. Basude S, Hein C, Curtis SL, Clark A, Trinder J. Low-molecular-weight heparin or warfarin for anticoagulation in pregnant women with mechanical heart valves: what are the risks? A retrospective observational study. *BJOG*. 2012;119:1008–1013. doi: 10.1111/j.1471-0528.2012.03359.x.
141. De Santo LS, Romano G, Della Corte A, D'Oria V, Nappi G, Giordano S, Cotrufo M, De Feo M. Mechanical aortic valve replacement in young women planning on pregnancy: maternal and fetal outcomes under low oral anticoagulation, a pilot observational study on a comprehensive pre-operative counseling protocol. *J Am Coll Cardiol*. 2012;59:1110–1115. doi: 10.1016/j.jacc.2011.10.899.
142. Bian C, Wei Q, Liu X. Influence of heart-valve replacement of warfarin anticoagulant therapy on perinatal outcomes. *Arch Gynecol Obstet*. 2012;285:347–351. doi: 10.1007/s00404-011-1962-2.
143. Oran B, Lee-Parriz A, Ansell J. Low molecular weight heparin for the prophylaxis of thromboembolism in women with prosthetic mechanical heart valves during pregnancy. *Thromb Haemost*. 2004;92:747–751. doi: 10.1160/TH04-06-0337.
144. Abildgaard U, Sandset PM, Hammerstrøm J, Gjestvang FT, Tveit A. Management of pregnant women with mechanical heart valve prosthesis: thromboprophylaxis with low molecular weight heparin. *Thromb Res*. 2009;124:262–267. doi: 10.1016/j.thromres.2008.12.005.
145. Quinn J, Von Klemperer K, Brooks R, Peebles D, Walker F, Cohen H. Use of high intensity adjusted dose low molecular weight heparin in women with mechanical heart valves during pregnancy: a single-center experience. *Haematologica*. 2009;94:1608–1612. doi: 10.3324/haematol.002840.
146. McLintock C, McCowan LM, North RA. Maternal complications and pregnancy outcome in women with mechanical prosthetic heart valves treated with enoxaparin. *BJOG*. 2009;116:1585–1592. doi: 10.1111/j.1471-0528.2009.02299.x.
147. Yinon Y, Siu SC, Warshafsky C, Maxwell C, McLeod A, Colman JM, Sermer M, Silversides CK. Use of low molecular weight heparin in pregnant women with mechanical heart valves. *Am J Cardiol*. 2009;104:1259–1263. doi: 10.1016/j.amjcard.2009.06.040.
148. Nelson-Piercy C, Greer IA. Anticoagulation with tinzaparin for women with mechanical valves in pregnancy: a retrospective case series. *Thromb Res*. 2013;131:185–186. doi: 10.1016/j.thromres.2012.11.022.
149. Chan WS, Anand S, Ginsberg JS. Anticoagulation of pregnant women with mechanical heart valves: a systematic review of the literature. *Arch Intern Med*. 2000;160:191–196.
150. Hassouna A, Allam H. Anticoagulation of pregnant women with mechanical heart valve prosthesis: a systematic review of the literature (2000–2009). *J Coagul Disord*. 2010;2:81–88.
151. Vitale N, De Feo M, De Santo LS, Pollice A, Tedesco N, Cotrufo M. Dose-dependent fetal complications of warfarin in pregnant women with mechanical heart valves. *J Am Coll Cardiol*. 1999;33:1637–1641.
152. Nishimura RA, Otto CM, Bonow RO, Carabello BA, Erwin JP 3rd, Guyton RA, O'Gara PT, Ruiz CE, Skubas NJ, Sorajja P, Sundt TM 3rd, Thomas JD; ACC/AHA Task Force Members. 2014 AHA/ACC guideline for the management of patients with valvular heart disease: executive summary: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines [published correction appears in *Circulation*. 2014;129:e650]. *Circulation*. 2014;129:2440–2492. doi: 10.1161/CIR.0000000000000029.
153. Berresheim M, Wilkie J, Nerenberg KA, Ibrahim Q, Bungard TJ. A case series of LMWH use in pregnancy: should trough anti-Xa levels guide dosing? *Thromb Res*. 2014;134:1234–1240. doi: 10.1016/j.thromres.2014.09.033.
154. Bates SM, Greer IA, Middeldorp S, Veenstra DL, Prabulos AM, Vandvik PO; American College of Chest Physicians. VTE, thrombophilia, antithrombotic therapy, and pregnancy: Antithrombotic Therapy and Prevention of Thrombosis, 9th ed: American College of Chest Physicians Evidence-Based Clinical Practice Guidelines. *Chest*. 2012;141(suppl):e691S–e736S. doi: 10.1378/chest.11-2300.
155. Goland S, Schwartzberg S, Fan J, Kozak N, Khatri N, Elkayam U. Monitoring of anti-Xa in pregnant patients with mechanical prosthetic valves receiving low-molecular-weight heparin: peak or trough levels? *J Cardiovasc Pharmacol Ther*. 2014;19:451–456. doi: 10.1177/1074248414524302.
156. Weiss BM, von Segesser LK, Alon E, Seifert B, Turina MI. Outcome of cardiovascular surgery and pregnancy: a systematic review of the period 1984–1996. *Am J Obstet Gynecol*. 1998;179(pt 1):1643–1653.
157. Arnoni RT, Arnoni AS, Bonini RC, de Almeida AF, Neto CA, Dinkhuysen JJ, Issa M, Chacur P, Paulista PP. Risk factors associated with cardiac surgery during pregnancy. *Ann Thorac Surg*. 2003;76:1605–1608.
158. John AS, Gurley F, Schaff HV, Warnes CA, Phillips SD, Arendt KW, Abel MD, Rose CH, Connolly HM. Cardiopulmonary bypass during pregnancy. *Ann Thorac Surg*. 2011;91:1191–1196. doi: 10.1016/j.athoracsur.2010.11.037.
159. Ruys TP, Roos-Hesselink JW, Hall R, Subirana-Domènech MT, Grandó-Ting J, Estensen M, Crepaz R, Fesslova V, Gurvitz M, De Backer J, Johnson MR, Pieper PG. Heart failure in pregnant women with cardiac disease: data from the ROPAC. *Heart*. 2014;100:231–238. doi: 10.1136/heartjnl-2013-304888.
160. Hameed A, Karaalp IS, Tummala PP, Wani OR, Canetti M, Akhter MW, Goodwin I, Zapadinsky N, Elkayam U. The effect of valvular heart disease on maternal and fetal outcome of pregnancy. *J Am Coll Cardiol*. 2001;37:893–899.
161. Yap SC, Drenthen W, Pieper PG, Moons P, Mulder BJ, Mostert B, Vliegen HW, van Dijk AP, Meijboom FJ, Steegers EA, Roos-Hesselink JW; ZAHARA Investigators. Risk of complications during pregnancy in women with congenital aortic stenosis. *Int J Cardiol*. 2008;126:240–246. doi: 10.1016/j.ijcard.2007.03.134.
162. Canobbio MM, Morris CD, Graham TP, Landzberg MJ. Pregnancy outcomes after atrial repair for transposition of the great arteries. *Am J Cardiol*. 2006;98:668–672. doi: 10.1016/j.amjcard.2006.03.050.
163. Guédès A, Mercier LA, Leduc L, Bérubé L, Marcotte F, Dore A. Impact of pregnancy on the systemic right ventricle after a Mustard operation for transposition of the great arteries. *J Am Coll Cardiol*. 2004;44:433–437. doi: 10.1016/j.jacc.2004.04.037.
164. Avila WS, Grinberg M, Snitcowsky R, Faccioli R, Da Luz PL, Bellotti G, Pileggi F. Maternal and fetal outcome in pregnant women with Eisenmenger's syndrome. *Eur Heart J*. 1995;16:460–464.
165. Connolly HM, Grogan M, Warnes CA. Pregnancy among women with congenitally corrected transposition of great arteries. *J Am Coll Cardiol*. 1999;33:1692–1695.
166. Veldtman GR, Connolly HM, Grogan M, Ammash NM, Warnes CA. Outcomes of pregnancy in women with tetralogy of Fallot. *J Am Coll Cardiol*. 2004;44:174–180. doi: 10.1016/j.jacc.2003.11.067.
167. Greutmann M, Von Klemperer K, Brooks R, Peebles D, O'Brien P, Walker F. Pregnancy outcome in women with congenital heart disease and residual haemodynamic lesions of the right ventricular outflow tract. *Eur Heart J*. 2010;31:1764–1770. doi: 10.1093/eurheartj/ehq157.
168. Bowater SE, Selman TJ, Hudsmith LE, Clift PF, Thompson PJ, Thorne SA. Long-term outcome following pregnancy in women with a systemic right ventricle: is the deterioration due to pregnancy or a consequence of time? *Congenit Heart Dis*. 2013;8:302–307. doi: 10.1111/chd.12001.



- 168a. Robertson JE, Silversides CK, Mah ML, Kulikowski J, Maxwell C, Wald RM, Colman JM, Siu SC, Sermer M. A contemporary approach to the obstetric management of women with heart disease. *J Obstet Gynaecol Can.* 2012;34:812–819.
169. Beardmore KS, Morris JM, Gallery ED. Excretion of antihypertensive medication into human breast milk: a systematic review. *Hypertens Pregnancy.* 2002;21:85–95. doi: 10.1081/PRG-120002912.
- 169a. Siu SC, Colman JM, Sorensen S, Smallhorn JF, Farine D, Amankwah KS, Spears JC, Sermer M. Adverse neonatal and cardiac outcomes are more common in pregnant women with cardiac disease. *Circulation.* 2002;105:2179–2184.
- 169b. Ammash N, Warnes CA. Cerebrovascular events in adult patients with cyanotic congenital heart disease. *J Am Coll Cardiol.* 1996;28:768–772.
170. Chambers CE, Clark SL. Cardiac surgery during pregnancy. *Clin Obstet Gynecol.* 1994;37:316–323.
171. Aboulhosn J, Levi DS, Child JS. Common congenital heart disorders in adults: percutaneous therapeutic procedures. *Curr Probl Cardiol.* 2011;36:263–284. doi: 10.1016/j.cpcardiol.2011.04.003.
172. Oylumlu M, Aykent K, Soydinc HE, Oylumlu M, Ertas F, Ozer HO, Sari I. Pulmonary balloon valvuloplasty during pregnancy. *Case Rep Cardiol.* 2012;2012:353168. doi: 10.1155/2012/353168.
173. Silversides CK, Colman JM, Sermer M, Farine D, Siu SC. Early and intermediate-term outcomes of pregnancy with congenital aortic stenosis. *Am J Cardiol.* 2003;91:1386–1389.
174. Avila WS, Hajjar LA, Souza Tda R, Gomex Junior MP, Grinberg M, Zugaib M. Aortic valvuloplasty with balloon catheter in maternal-fetal emergency in adolescence. *Arq Bras Cardiol.* 2009;93:e76–e79, e89–e92.
175. Deleted in proof.
176. Pomini F, Mercogliano D, Cavalletti C, Caruso A, Pomini P. Cardiopulmonary bypass in pregnancy. *Ann Thorac Surg.* 1996;61:259–268.
177. Martin SR, Foley MR. Intensive care in obstetrics: an evidence based review. *Am J Obstet Gynecol.* 2006;195:673–689.
178. Hawkins JA, Paape KL, Adkins TP, Shaddy RE, Gay WA Jr. Extracorporeal circulation in the fetal lamb: effects of hypothermia and perfusion rate. *J Cardiovasc Surg (Torino).* 1991;32:295–300.
179. Chandrasekhar S, Cook CR, Collard CD. Cardiac surgery in the parturient. *Anesth Analg.* 2009;108:777–785. doi: 10.1213/ane.0b013e31819367aa.
180. Parry AJ, Westaby S. Cardiopulmonary bypass during pregnancy. *Ann Thorac Surg.* 1996;61:1865–1869. doi: 10.1016/0003-4975(96)00150-6.
181. Kole SD, Jain SM, Walia A, Sharma M. Cardiopulmonary bypass in pregnancy. *Ann Thorac Surg.* 1997;63:915–916.
182. Arendt K, Abel M. The pregnant patient and cardiopulmonary bypass. In: Cohen N.H. ed. *Medically Challenging Patients Undergoing Cardiothoracic Surgery: A Society of Cardiovascular Anesthesiologists Monograph.* Philadelphia, PA: Lippincott Williams & Wilkins; 2009:215–244.
183. Martin MC, Pernoll ML, Boruszak AN, Jones JW, LoCicero J 3rd. Cesarean section while on cardiac bypass: report of a case. *Obstet Gynecol.* 1981;57(suppl):41S–45S.
184. The confidential enquiry into maternal and child health (CEMACH): saving mothers' lives: reviewing maternal deaths to make motherhood safer 2003–2005. In: Lewis G, ed. *The Seventh Confidential Enquiry Into Maternal Deaths in the United Kingdom.* London, UK; RCOG Press; 2007.
185. Jeejeebhoy FM, Zelop CM, Lipman S, Carvalho B, Joglar J, Mhyre JM, Katz VL, Lapinsky SE, Einav S, Warnes CA, Page RL, Griffin RE, Jain A, Dainty KN, Arafeh J, Windrim R, Koren G, Callaway CW; American Heart Association Emergency Cardiovascular Care Committee, Council on Cardiopulmonary, Critical Care, Perioperative and Resuscitation, Council on Cardiovascular Diseases in the Young, and Council on Clinical Cardiology. Cardiac arrest in pregnancy: a scientific statement from the American Heart Association. *Circulation.* 2015;132:1747–1773. doi: 10.1161/CIR.0000000000000300.
186. Kundra P, Khanna S, Habeebullah S, Ravishankar M. Manual displacement of the uterus during caesarean section. *Anaesthesia.* 2007;62:460–465. doi: 10.1111/j.1365-2044.2007.05025.x.
187. Dijkman A, Huisman CM, Smit M, Schutte JM, Zwart JJ, van Roosmalen JJ, Oepkes D. Cardiac arrest in pregnancy: increasing use of perimortem caesarean section due to emergency skills training? *BJOG.* 2010;117:282–287. doi: 10.1111/j.1471-0528.2009.02461.x.
188. European Heart Rhythm Association; European Association for Cardio-Thoracic Surgery, Camm AJ, Kirchhof P, Lip GY, Schotten U, Savelieva I, Ernst S, Van Gelder IC, Al-Attar N, Hindricks G, Prendergast B, Heidbuchel H, Alfieri O, Angelini A, Atar D, Colonna P, De Caterina R, De Sutter J, Goette A, Gorenek B, Heldal M, Hohloser SH, Kolh P, Le Heuzey JY, Ponikowski P, Rutten FH. Guidelines for the management of atrial fibrillation: the Task Force for the Management of Atrial Fibrillation of the European Society of Cardiology [published correction appears in *Eur Heart J.* 2011;32:1172]. *Eur Heart J.* 2010;31:2369–2429.
189. Tromp CH, Nanne AC, Pernet PJ, Tukkier R, Bolte AC. Electrical cardioversion during pregnancy: safe or not? *Neth Heart J.* 2011;19:134–136.
- 189a. Driver K, Chisholm CA, Darby AE, Malhotra R, Dimarco JP, Ferguson JD. Catheter ablation of arrhythmia during pregnancy. *J Cardiovasc Electrophysiol.* 2015;26:698–702.
190. Miyoshi T, Kamiya CA, Katsuragi S, Ueda H, Kobayashi Y, Horiuchi C, Yamanaka K, Neki R, Yoshimatsu J, Ikeda T, Yamada Y, Okamura H, Noda T, Shimizu W. Safety and efficacy of implantable cardioverter-defibrillator during pregnancy and after delivery. *Circ J.* 2013;77:1166–1170.
191. Natale A, Davidson T, Geiger MJ, Newby K. Implantable cardioverter-defibrillators and pregnancy: a safe combination? *Circulation.* 1997;96:2808–2812.
192. Bao Z, Zhang J, Yang D, Xu X. Analysis of high risk factors for patient death and its clinical characteristics on pregnancy associated with pulmonary arterial hypertension [in Chinese]. *Zhonghua Fu Chan Ke Za Zhi.* 2014;49:495–500.
193. Pieper PG, Lameijer H, Hoendermis ES. Pregnancy and pulmonary hypertension. *Best Pract Res Clin Obstet Gynaecol.* 2014;28:579–591. doi: 10.1016/j.bpobgyn.2014.03.003.
194. Daliotto L, Somerville J, Presbitero P, Menti L, Brach-Prever S, Rizzoli G, Stone S. Eisenmenger syndrome: factors relating to deterioration and death. *Eur Heart J.* 1998;19:1845–1855.
195. Warnes CA. Pregnancy and pulmonary hypertension. *Int J Cardiol.* 2004;97(suppl 1):11–13. doi: 10.1016/j.ijcard.2004.08.004.
196. Zhang XJ, Wang H, Zhang LH, Lin D. Severe idiopathic pulmonary arterial hypertension in pregnancy: a review of 10 cases. *Zhonghua Fu Chan Ke Za Zhi.* 2014;49:419–423.
197. Gleicher N, Midwall J, Hochberger D, Jaffin H. Eisenmenger's syndrome and pregnancy. *Obstet Gynecol Surv.* 1979;34:721–741.
198. Elliot CA, Stewart P, Webster VJ, Mills GH, Hutchinson SP, Howarth ES, Bu'lock FA, Lawson RA, Armstrong IJ, Kiely DG. The use of iloprost in early pregnancy in patients with pulmonary arterial hypertension. *Eur Respir J.* 2005;26:168–173. doi: 10.1183/09031936.05.00128504.
199. Curry RA, Fletcher C, Gelson E, Gatzoulis MA, Woolnough M, Richards N, Swan L, Steer PJ, Johnson MR. Pulmonary hypertension and pregnancy: a review of 12 pregnancies in nine women. *BJOG.* 2012;119:752–761. doi: 10.1111/j.1471-0528.2012.03295.x.

200. Easterling TR, Chadwick HS, Otto CM, Benedetti TJ. Aortic stenosis in pregnancy. *Obstet Gynecol.* 1988;72:113–118.
201. Lao TT, Sermer M, MaGee L, Farine D, Colman JM. Congenital aortic stenosis and pregnancy: a reappraisal. *Am J Obstet Gynecol.* 1993;169:540–545.
202. Leśniak-Sobelga A, Tracz W, Kostkiewicz M, Podolec P, Pasowicz M. Clinical and echocardiographic assessment of pregnant women with valvular heart diseases—maternal and fetal outcome. *Int J Cardiol.* 2004;94:15–23. doi: 10.1016/j.ijcard.2003.03.017.
203. Bhargava B, Agarwal R, Yadav R, Bahl VK, Manchanda SC. Percutaneous balloon aortic valvuloplasty during pregnancy: use of the Inoue balloon and the physiologic antegrade approach. *Cathet Cardiovasc Diagn.* 1998;45:422–425.
204. Mendelson MA. Pregnancy in patients with obstructive lesions: aortic stenosis, coarctation of the aorta and mitral stenosis. *Prog Pediatr Cardiol.* 2004;19:61–70.
205. Gelatt M, Hamilton RM, McCrindle BW, Connelly M, Davis A, Harris L, Gow RM, Williams WG, Trusler GA, Freedom RM. Arrhythmia and mortality after the Mustard procedure: a 30-year single-center experience. *J Am Coll Cardiol.* 1997;29:194–201.
206. Moons P, Gewillig M, Sluysmans T, Verhaaren H, Viart P, Massin M, Suys B, Budts W, Pasquet A, De Wolf D, Vliers A. Long term outcome up to 30 years after the Mustard or Senning operation: a nationwide multicentre study in Belgium. *Heart.* 2004;90:307–313.
207. Dobson R, Danton M, Nicola W, Hamish W. The natural and unnatural history of the systemic right ventricle in adult survivors [published correction appears in *J Thorac Cardiovasc Surg.* 2015;149:950]. *J Thorac Cardiovasc Surg.* 2015;145:1493–1501. doi: 10.1016/j.jtcvs.2013.02.030.
208. Trigas V, Nagdyman N, Pildner von Steinburg S, Oechslin E, Vogt M, Berger F, Schneider KT, Ewert P, Hess J, Kaemmerer H. Pregnancy-related obstetric and cardiologic problems in women after atrial switch operation for transposition of the great arteries. *Circ J.* 2014;78:443–449.
209. Metz TD, Jackson GM, Yetman AT. Pregnancy outcomes in women who have undergone an atrial switch repair for congenital d-transposition of the great arteries. *Am J Obstet Gynecol.* 2011;205:273.e1–273.e5. doi: 10.1016/j.ajog.2011.06.042.
210. Kowalik E, Klisiewicz A, Biernacka EK, Hoffman P. Pregnancy and long-term cardiovascular outcomes in women with congenitally corrected transposition of the great arteries. *Int J Gynaecol Obstet.* 2014;125:154–157. doi: 10.1016/j.ijgo.2013.10.022.
211. Lo Rito M, Fittipaldi M, Haththotuwa R, Jones TJ, Khan N, Clift P, Brawn WJ, Barron DJ. Long-term fate of the aortic valve after an arterial switch operation. *J Thorac Cardiovasc Surg.* 2015;149:1089–1094. doi: 10.1016/j.jtcvs.2014.11.075.
212. Fricke TA, d'Udekem Y, Richardson M, Thuys C, Dronavalli M, Ramsay JM, Wheaton G, Grigg LE, Brizard CP, Konstantinov IE. Outcomes of the arterial switch operation for transposition of the great arteries: 25 years of experience. *Ann Thorac Surg.* 2012;94:139–145. doi: 10.1016/j.athoracsur.2012.03.019.
213. Warnes CA. Transposition of the great arteries. *Circulation.* 2006;114:2699–2709. doi: 10.1161/CIRCULATIONAHA.105.592352.
214. Tobler D, Williams WG, Jegatheeswaran A, Van Arsdell GS, McCrindle BW, Greutmann M, Oechslin EN, Silversides CK. Cardiac outcomes in young adult survivors of the arterial switch operation for transposition of the great arteries. *J Am Coll Cardiol.* 2010;56:58–64. doi: 10.1016/j.jacc.2010.03.031.
215. Aboulhosn JA, Child JS. A blue baby grows up. *Congenit Heart Dis.* 2009;4:378–383. doi: 10.1111/j.1747-0803.2009.00276.x.
216. Aboulhosn J, Child JS. The adult with a Fontan operation. *Curr Cardiol Rep.* 2007;9:331–335.
217. Gewillig M. The Fontan circulation. *Heart.* 2005;91:839–846.
218. Khairy P, Fernandes SM, Mayer JE Jr, Tiedman JK, Walsh EP, Lock JE, Landzberg MJ. Long-term survival, modes of death, and predictors of mortality in patients with Fontan surgery. *Circulation.* 2008;117:85–92. doi: 10.1161/CIRCULATIONAHA.107.738559.
219. Elder RW, McCabe NM, Veledar E, Kogon BE, Jokhadar M, Rodriguez FH 3rd, McConnell ME, Book WM. Risk factors for major adverse events late after Fontan palliation. *Congenit Heart Dis.* 2015;10:159–168. doi: 10.1111/chd.12212.
220. Pundi KN, Johnson JN, Dearani JA, Pundi KN, Li Z, Hinck CA, Dahl SH, Cannon BC, O'Leary PW, Driscoll DJ, Cetta F. 40-Year follow-up after the Fontan operation: long-term outcomes of 1,052 patients. *J Am Coll Cardiol.* 2015;66:1700–1710. doi: 10.1016/j.jacc.2015.07.065.
221. Drenthen W, Pieper PJ, Roos-Hesselink JW, van Lottum WA, Voors AA, Mulder BJ, van Dijk AP, Vliegen HW, Sollié KM, Moons P, Ebels T, van Veldhuisen DJ; ZAHARA Investigators. Pregnancy and delivery in women after Fontan palliation. *Heart.* 2006;92:1290–1294.
222. Nitsche JF, Phillips SD, Rose CH, Brost BC, Watson WJ. Pregnancy and delivery in patients with Fontan circulation: a case report and review of obstetric management. *Obstet Gynecol Surv.* 2009;64:607–614. doi: 10.1097/OGX.0b013e3181b279d6.
223. Gouton M, Nizard J, Patel M, Sassolas F, Jimenez M, Radojevic J, Mathiron A, Amedro P, Barre E, Labombarda F, Vaksman G, Chantepie A, Le Gloan L, Ladouceur M. Maternal and fetal outcomes of pregnancy with Fontan circulation: a multicentric observational study. *Int J Cardiol.* 2015;187:84–89. doi: 10.1016/j.ijcard.2015.03.344.
224. Canobbio MM, Cetta F, Silversides C, Warnes C, Aboulhosn J, Colman J. Pregnancy after Fontan operation: early and late outcomes. *J Am Coll Cardiol.* 2013;61. doi: 10.1016/S0735-1097(13)60427-1.