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Pregnancy and Cardiovascular Disease (N Scott, Section Editor)

Imaging of Cardiovascular Disease in Pregnancy and the Peripartum Period

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Opinion statement

Cardiovascular disease is an important cause of morbidity and mortality during pregnancy and the postpartum period. During pregnancy, the cardiovascular system undergoes extensive hemodynamic, hormonal, and microstructural changes which may exacerbate a preexisting underlying cardiovascular condition or predispose to cardiovascular complications not typically seen in young healthy women. Such conditions include spontaneous coronary artery dissection, atherosclerotic coronary artery disease, and peripartum cardiomyopathy. When evaluating this patient population, the diagnostic strategy should be tailored to specifically assess this distinct disease spectrum. The choice of imaging techniques must also consider potential risks to both the mother and child; a unique challenge of diagnostic imaging during pregnancy. The risk of radiation from radiography, computed tomography, and nuclear medicine imaging; iodinated and gadolinium-based contrast media for computed tomography and magnetic resonance imaging respectively; and heat deposition from sonography are of special importance during pregnancy. A thorough understanding of pregnancy-specific cardiovascular complications and the capabilities and risks of available diagnostic imaging modalities is crucial to appropriately manage the pregnant patient.

Introduction

During pregnancy, the cardiovascular system undergoes extensive physiologic changes that have been widely investigated and described in the literature. Compensatory hemodynamic process including increased cardiac output, decreased maternal systemic vascular resistance, and vascular remodeling create an optimal environment for fetal growth and development [1]. While most women adjust to these changes without significant adverse effects, the hemodynamic burden of pregnancy may predispose to unique pregnancy-related pathology, unmask previously asymptomatic cardiac disease, or stress an existing well-controlled condition.

Maternal heart disease remains the leading cause of non-obstetric mortality in pregnancy [2] with cardiomyopathy and cardiovascular disease accounting for at least 26% of all pregnancy-related deaths in the USA during 2011–2013 [3]. Pregnancy-associated cardiovascular risk is predicted to increase due to rising pregnancy rates among women of advanced maternal age (35 years or older); increasing incidence of coronary artery disease secondary to a higher prevalence of obesity, hypertension, and diabetes; and a greater number of patients with congenital and acquired heart disease reaching reproductive age due to medical advances [4–7]. Pre-existing or newly diagnosed cardiovascular conditions during pregnancy often necessitate imaging to further characterize the disease process and guide treatment throughout gestation. Various imaging modalities are available for use, including echocardiography, radiography, cardiac magnetic resonance imaging (MRI), computed tomography (CT), and nuclear imaging. An understanding of modality-specific imaging indications and limitations in the unique physiologic setting of pregnancy is crucial to maximize diagnostic potential and minimize maternal and fetal risk.

Ionizing radiation in pregnancy

Ionizing radiation is electromagnetic radiation produced by X-ray equipment and is utilized in diagnostic tools such as radiography, fluoroscopy, and CT. The application of imaging modalities that use ionizing radiation in pregnancy is often an anxiety-provoking topic for both patients and referring clinicians. Major concerns include radiation-induced teratogenesis, mutagenesis, and malignancy, the probability of which depends on many factors including gestational age at the time of exposure and radiation dose. To our current knowledge, there are no data directly linking diagnostic imaging to fetal harm. Much of existing data regarding the effects of radiation on humans has been extrapolated from in utero exposure to radiation after detonation of the atomic bombs in Hiroshima and Nagasaki [8–10].

The accepted maximum cumulative dose of ionizing radiation in pregnancy is 5 rad (i.e., 50 mSv or 50 mGy) [11, 12]. No fetal risk of anomalies, growth restriction, or abortion has been reported below 5 rad. During the first 2 weeks after conception, the developing embryo is most sensitive to the lethal effects of X-rays, resulting in possible failure of implantation at doses upwards of 5 rad [13]. The most sensitive period for teratogenesis to the central nervous system is between weeks 8 to 15, with the incidence of microcephaly and reduction in intelligence quotient (IQ) increasing in a non-threshold, linear, dose-related fashion [10]. Doses greater than 10 rad can result in some reduction of IQ.

Many of today's diagnostic procedures that employ ionizing radiation carry minimal risk to the fetus. No single radiologic study approaches or exceeds the accepted threshold of 5 rad. For example, a two-view chest radiograph exposes a fetus to 0.02–0.07 mrad, while a typical cardiovascular CT ranges from 0.06 to 0.09 rad [14, 15]. Certain techniques can be implemented to minimize fetal radiation during imaging, such as shielding of the gravid abdomen from scattered radiation, lowering the peak kilovoltage or tube current, and reducing the time of

exposure. Many facilities have radiation safety programs in place that maintain doses according to the ALARA (As Low As Reasonably Achievable) principle.

Advanced cardiovascular imaging modalities

Echocardiography

Echocardiography is an ideal initial study that utilizes high-frequency (2–10 MHz) ultrasound waves rather than radiation to assess the anatomic and hemodynamic changes of the heart in pregnancy. Echocardiograms can provide information on ventricular function, valvular dysfunction, congenital abnormalities, ascending aortic size, and estimation of cardiac pressures. The mild interval enlargement as well as anterior and leftward shift that the heart undergoes in the gravid patient allow for key advantages for sonographic assessment by facilitating the acoustic windows in a transthoracic parasternal and apical approach [16]. Multiple conditions can be initially diagnosed and serially followed with echocardiography, including existing congenital heart disease, peripartum cardiomyopathy, valvular disorders, ascending aortic disease, and other disorders resulting in systolic or diastolic dysfunction. The major theoretical risk of diagnostic ultrasound is that of tissue heating which can be mitigated by optimization of machine scanning parameters and minimization of scan time [17]. To date, there are no documented reports of adverse effects from diagnostic ultrasound [17], making it the preferred diagnostic test in women with a history or physical examination concerning for heart failure.

Transesophageal echocardiography (TEE) is considered relatively safe in pregnancy [6] and can be considered in a case-by-case basis given the need for sedation which may place the pregnant patient at a higher risk for complications, including aspiration. Appropriate patient selection is key and the procedure should be restricted to cases of necessity, such as for women with mitral stenosis in need of percutaneous mitral balloon valvuloplasty, or other cases where findings would alter management, such as the case of suspected aortic dissection [18]. TEE has been shown to have a comparable sensitivity and specificity to CT and MRI for detection of thoracic aortic dissections [19].

Chest radiography

Chest radiography is a useful diagnostic modality for evaluation of cardiovascular disease in the pregnant patient. It is a readily available tool that can quickly assess for cardiopulmonary processes such as pulmonary edema or cardiac enlargement, and should be considered in symptomatic gravid women presenting with new-onset dyspnea [20]. Although radiography uses ionizing radiation, the exposure dose to the fetus is minimal and of likely negligible clinical consequence. Nevertheless, shielding of the gravid abdomen to protect from scattered radiation to the fetus is good practice in keeping with the ALARA principle.

Cardiovascular computed tomography

CT uses X-rays to produce cross-sectional images of the body. Given the use of ionizing radiation, safety concerns predominantly center around fetal radiation exposure, which can vary depending on multiple factors including gestational age and proximity of the uterus to the scan plane. Imaging of the chest results in fetal radiation exposure only via scatter radiation as opposed to direct irradiation via

the primary X-ray beam when imaging the pelvis [21]. As a result, imaging of the chest is often more favorable to imaging of the pelvis in the gravid patient and results in substantially lower radiation exposure, although fetal exposure will increase as the uterus grows and ascends toward the diaphragm. Larger patients will also have greater secondary fetal exposure due to higher peak kilovoltage and tube current requirements to acquire a diagnostic study. Fetal doses have been estimated around 1 mGy for prospective ECG-triggered coronary CT angiography and 3 mGy for retrospective ECG-gated coronary CT angiography compared to >7 mGy for abdominopelvic CT [21–27].

CT pulmonary angiography (CTPA) is the preferred diagnostic test for suspected pulmonary embolism in pregnancy, although ventilation-perfusion nuclear scintigraphy scans are a comparable alternative in select patients [28]. Fetal radiation dose for CTPA can be very minimal, on the order of 0.1–0.4 mSv if performed carefully with dose reduction protocols [29]. Pregnancy poses unique challenges for the successful acquisition of diagnostic quality CTPA images. A common occurrence in pregnancy is a decreased enhancement of the pulmonary arterial tree resulting from transient interruption of contrast material inflow by unopacified blood from the inferior vena cava, an effect heightened by the hyperdynamic state of pregnancy, pregnancy-associated hemodilution, and shunting of maternal blood toward the fetus [30, 31]. Diagnostically inadequate studies have been reported as high as 35.7%, compared to 2.1% in the non-pregnant cohort in one study by Ridge et al. [32]. Potential techniques to circumvent this issue include using bolus triggering with shorter scan delays, a high flow rate of contrast, a high concentration of contrast medium, low kV, and performing imaging acquisition during shallow inspiration or end expiration. Recent data suggest substantial improvement with the utilization of dual-energy CT techniques [33].

Dose reduction techniques in CT

Protocol optimization methods can be implemented to reduce radiation dose. Such techniques include decreasing the peak kilovoltage and tube current, using tube current modulation, increasing pitch, widening the beam collimation, and decreasing the anatomic coverage scan length (reduce *z*-axis) and overall field of view [34, 35]. Use of lead shielding around the gravid abdomen can also reduce fetal dose [36]. Additionally, the omission of CT planning scout views and additional scan phases can help reduce overall radiation exposure (e.g., excluding lower extremity venography when performed in conjunction with pulmonary CTA or omitting non-contrast/calcium scoring scans during coronary CTA). Such dose-modifying strategies adhere to the ALARA principle for radiation safety, provided that they do not compromise diagnostic accuracy. When possible, diagnostic workup with imaging modalities that do not use ionizing radiation can be considered.

Use of CT iodinated contrast in the pregnant and lactating patient

The use of iodinated contrast in CT may also be a source of concern, although the currently used contrast agents are of low osmolality and may be used during pregnancy (category B) [37]. Iodinated contrast agents are known to cross the human placenta and enter the fetus [38]; however, there are no documented

associations between iodinated contrast agent use and teratogenic effects and the risk of neonatal hypothyroidism following injection of newer contrast agents is only theoretical [39]. Although evaluation of risks and benefits of contrast administration must be assessed on a per patient basis, the American College of Radiology (ACR) manual on contrast media recommends that iodinated contrast should not be omitted solely due to pregnancy if contrast is otherwise indicated [17, 22, 39].

For nursing mothers, current ACR guidelines do not require the cessation of breastfeeding after iodinated contrast administration [39–41]. The plasma half-life of IV CT contrast agents is 2 h, with approximately 100% excreted in a 24-h period. The total contrast dose absorbed by the infant is negligible (< 0.01% of the maternal contrast dose) since less than 1% of the administered maternal contrast dose enters breast milk due to poor lipid solubility and less than 1% of that dose is absorbed by the infant's gastrointestinal system [42, 43]. Thus, iodine accumulation in the breast milk is considered too low to warrant interruption of the breastfeeding schedule [38]. Theoretical risks to the infant include allergic reaction, sensitization, or chemical toxicity, although none have been reported to date. This understanding should be communicated to the mother and, should concern persist, the mother may choose to abstain from breast feeding for up to 24 h, after which, there is no further benefit [39].

Cardiovascular magnetic resonance imaging

MRI uses the properties of hydrogen proton excitation in a strong magnetic field to produce images of the body without the use of ionizing radiation that are both high in spatial and temporal resolution. MRI is a powerful problem-solving tool that can be used for both quantitative and qualitative cardiac assessment and characterization of numerous other disease processes. In the case of suspected cardiomyopathy or myocarditis, MRI can assess both right and left ventricular function as well as evaluate for the presence of tissue infiltration or scar. MRI is superior to CT for tissue characterization in the setting of neoplasms and pericardial disease [44, 45] and can accurately assess the aorta in suspected cases of dissection without the use of contrast by utilizing time of flight sequences. MRI has also been used to assess for significant coronary artery stenosis, although CT has been shown to have both higher sensitivity and specificity for stenosis evaluation comparatively [46].

MRI has routinely been used to diagnose conditions in the fetus and mother for more than a quarter century, with no reported deleterious effects on the fetus to date [40, 47–49]. Although several investigations have demonstrated no evidence of harm in pregnancy [50, 51], the safety of MRI during pregnancy has yet to be definitely established. Theoretic concerns include teratogenesis and fetal acoustic damage, although no cases of hearing damage have been found [52]; most studies show a favorable safety profile overall [50, 53–55]. MRI performed at 1.5 T is preferable to higher field strengths for the pregnant patient given that the majority safety data comes from research involving magnetic fields of 1.5 T or less, although MRI strength up to 3 T appears to be safe throughout pregnancy [56].

Use of MRI gadolinium-based contrast in the pregnant and lactating patient

Gadolinium-based contrast agents have been shown to readily cross the placenta, upon which they are filtered by the fetal kidney and excreted by amniotic fluid.

High or repeated doses of intravenous gadolinium have been demonstrated to have teratogenic effects in animal studies [57], although there are currently no data reporting any deleterious effects on the human fetus at the doses used in diagnostic imaging. Given the paucity of data, gadolinium-based agents are considered a category C drug and should only be used during pregnancy if the benefit outweighs the potential fetal risk [47]. Gadolinium is excreted into breast milk in extremely small amounts, with less than 0.04% of the administered dose detected in breastmilk. Of that amount, only 0.8% is actually absorbed by the baby's gastrointestinal tract [58]. As a result, current ACR 2017 guidelines suggest that "it is safe for the mother and infant to continue breast-feeding after receiving a gadolinium-based contrast medium" [59].

Pregnancy-associated cardiovascular disease-specific imaging considerations

Anomalous coronary artery

Anomalous coronary artery describes the group of anatomic abnormalities of coronary artery origin, course, and termination. While uncommon, affecting 0.99% to 5.8% of people, anomalous coronary artery is a significant cause of sudden cardiac death in young, otherwise healthy, patients [60–62]. While limited data exist for pregnant women with underlying coronary artery anomalies, they appear to be at increased risk for adverse cardiovascular events [63].

Numerous permutations of anomalous coronary artery origin exist including a coronary artery arising from the non-coronary cusp, the opposite cusp (i.e., right coronary artery arising from the left cusp), or the pulmonary artery [64, 65]. Of concern, are cases in which a coronary artery, in particular the left, arises from the opposite coronary cusp, has a prolonged intramural segment, and takes an inter-arterial course (between the aorta and pulmonary artery) [65, 66]. As the anomalous coronary artery passes obliquely within the aortic wall, it has a slit-like coronary orifice and coronary stenosis [65]. This configuration substantially increases risk of sudden cardiac death [60, 61, 65].

The inter-arterial course must be differentiated from the benign trans-septal course in which the coronary artery courses inferior to the crista supraventricularis and is surrounded by myocardium as shown in Fig. 1 [65]. Since delineating these subtle anatomic relationships by catheter angiography may be challenging, multidetector cardiac-gated CT and MR angiography are preferred to evaluate the vessel origin and course with respect to the aorta, pulmonary artery, and myocardium [65–68].

Also of clinical significance is the rare situation of anomalous left coronary artery from the pulmonary artery (ALCAPA) seen in only 1 of 300,000 people [62]. Infant mortality from ALCAPA is high (approximately 90% within the first year of life); however, those that survive to adulthood often develop extensive intercoronary collaterals which can ultimately result in flow reversal, coronary artery steal, and ischemia [62]. Most other anatomic variants are asymptomatic and of little clinical consequence.

Coronary artery disease

Myocardial infarction during pregnancy is uncommon, 3–6 cases per 100,000 [6, 69]; however, it remains one of the leading cardiac causes of death in

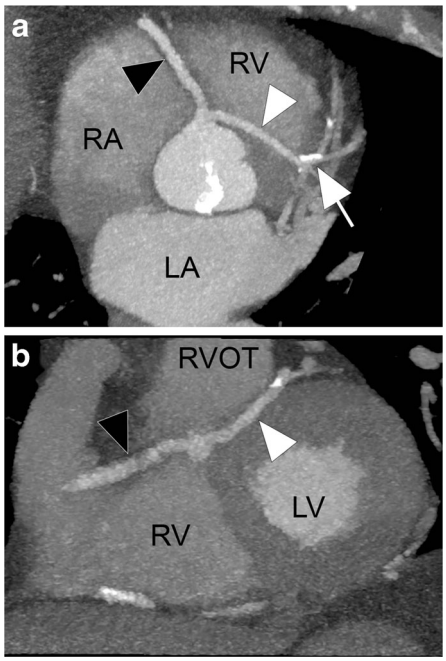

Fig. 1. Anomalous origin of the left main coronary artery and coronary artery calcification. **a** Axial oblique maximum intensity projection (MIP) image of the aortic root demonstrates a single coronary artery arising from the right coronary cusp which bifurcates into the right coronary artery (black arrowhead) and the anomalous left main coronary artery (white arrowhead). The white arrow identifies coronary artery calcification within the proximal left anterior descending coronary artery, a sign of coronary artery atherosclerosis. **b** Coronal oblique MIP image of the aortic root depicts the proximal course of the right coronary artery (black arrowhead) and the anomalous left main coronary artery (white arrowhead). The left main coronary artery travels within the interventricular septum (transseptal course) at the level of the right ventricular outflow tract (RVOT), well below the level of the pulmonic valve (beyond the field of view). *RA* right atrium, *RV* right ventricle, *LA* left atrium, *LV* left ventricle.

pregnant women [70]. Predisposing factors include hypertension, diabetes, advanced age [5], family history of coronary artery disease, and hyperlipidemia [6]. Additional pregnancy-specific risk factors such as pre-eclampsia, eclampsia [5], thrombophilia, transfusion, and postpartum infection may explain the three to four times increased risk that pregnancy confers [71]. Likewise, increased cardiac workload during pregnancy may exacerbate the impact of flow-limiting lesions [69]. Given the greater number of women becoming pregnant at advance age and increased prevalence of atherosclerosis risk factors such as diabetes, hypertension, and obesity, acute coronary syndrome incidence during pregnancy is likely to increase [5, 6].

Between 27 and 40% of pregnancy associated myocardial infarction is related to atherosclerotic disease and plaque rupture [69, 72] while spontaneous coronary artery dissection (SCAD) is the underlying causative factor in at least 43% of cases [72]. Other less common causes of myocardial infarction include in situ thrombosis, possibly related to hypercoagulability, embolism (Fig. 2), and vasospasm [69]. While older reports suggest maternal mortality from myocardial infarction may be as high as 37% [73], recent reports estimate mortality to be between 5 and 11% [5, 69, 71], likely related to improvements in diagnosis and treatment.

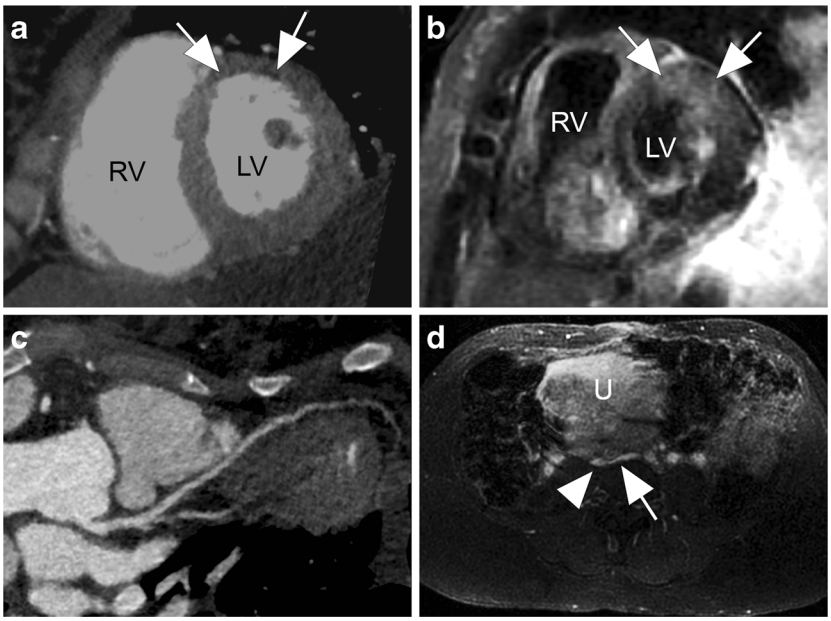

Fig. 2. Suspected coronary artery embolus of a 36-year-old woman 2 days post-partum with chest pain and elevated cardiac biomarkers. Differential diagnosis included coronary artery dissection, vasospasm, atherosclerosis, and embolism. The constellation of May-Thurner anatomy, patent foramen ovale diagnosed by transesophageal echocardiography with intravenous injection of agitated saline (not shown), and findings of coronary artery territorial ischemia in the absence of coronary atherosclerosis and dissection raises the concern for coronary artery embolus. **a** Short axis multiplanar reformatted post contrast computed tomography image demonstrates a subendocardial perfusion defect in the mid anterior segment of the left ventricle demarcated by arrows. **b** T2-weighted double inversion recovery left ventricular short axis image at the mid ventricular level shows corresponding regional signal hyperintensity in the anterior wall suspicious for recent territorial ischemic insult. **c** A curved planar reformation of the left anterior descending coronary artery shows a patent vessel without significant stenosis, atherosclerosis, nor dissection. No intraluminal filling defect was identified, presumably due to resolution of the embolus. **d** Axial fat suppressed post contrast image of the lower abdomen demonstrates severe narrowing of the left common iliac vein (arrow) as it crosses the spine beneath the right common iliac artery (May-Thurner anatomy) and joins the right common iliac vein (arrowhead). This is exacerbated by mass effect from the recently post-partum uterus. *RV* right ventricle, *LV* left ventricle, *U* uterus.

In addition to invasive coronary angiography, numerous non-invasive imaging modalities play a role in diagnosis and management of coronary artery disease. Non-contrast cardiac-gated CT is able to identify and quantify coronary artery calcification which is closely related to total coronary artery disease burden [74]. Non-contrast CT is unable to identify non-calcified atherosclerotic disease and is not associated with coronary stenosis [74]. Coronary CT angiography reliably identifies coronary artery stenosis and accurately grades the severity of the stenosis when compared with invasive angiography [75]. In addition to identifying calcified atherosclerotic plaque (Fig. 1), contrast-enhanced CT can identify and characterize vulnerable non-calcified atherosclerotic plaques, those lesions that are felt to be responsible for plaque rupture-associated myocardial infarction [75–77]. When CT images of multiple phases of the cardiac cycle are acquired, images can be reconstructed and viewed in sequential time points throughout the cardiac cycle in order to assess global and regional left ventricular function; agreement with both MRI and echocardiography is good [75]. In a similar manner, function can be assessed by MRI by

obtaining cine steady-state free precession (SSFP) images of the left ventricle [78]. Administration of contrast will demonstrate reduced perfusion to ischemic areas of myocardium as seen by reduced enhancement on first pass perfusion images [78]. Areas of prior myocardial infarction are evident as segments of the left ventricular myocardium showing delayed gadolinium enhancement in a subendocardial or transmural distribution in an expected epicardial coronary artery territory [79]. The thickness of affected myocardium compared with the total wall thickness predicts the probability of improvement following revascularization [80]. Given the paucity of data to support fetal safety with gadolinium-based contrast agents, the post contrast techniques would be reserved for the postpartum patient.

Spontaneous coronary artery dissection

Coronary artery dissection in the absence of a predisposing factor such as iatrogenic causes, extension of aortic dissection, or thoracic trauma is termed spontaneous coronary artery dissection or SCAD. The majority of SCAD cases arise in women with approximately 30% of cases in pregnant and peripartum women [81, 82]. While previously felt to be rare in the general population (2–3 cases per million) [83], newer estimates suggest SCAD as the etiology of up to 1.7–4% of all acute coronary syndrome cases [84, 85], at least 43% of myocardial infarctions in pregnant patients [72], and 50% when recently postpartum [69]. Mortality may be as high as 38% [86].

Coronary artery dissection results when blood products accumulate within the wall of the coronary artery (between the intima and media or the media and adventitia) with or without an associated intimal tear [87, 88]. As the hematoma within the vessel wall grows, the true vascular lumen can narrow, ultimately to the point of ischemia and/or infarction [88]. Multivessel involvement is common [69, 89]. The relatively higher incidence observed during the course of pregnancy may be a sequela of vessel wall weakening secondary to complex pregnancy-related hormonally mediated biochemical changes as well as hemodynamic alterations such as increased blood volume and cardiac output leading to increased shear forces upon the vessel wall [87].

The intramural hematoma of SCAD is directly identified as a low to intermediate density intimately associated with the affected coronary artery wall on cardiac-gated CT (Fig. 3); a discrete dissection flap may not be appreciated [87, 88]. Identification of these findings by coronary angiography can be challenging and the only finding may be smooth vessel narrowing [89]. Intravascular ultrasound and optical coherence tomography are useful adjuncts to assist interventionists identify intimal tears and intramural hematoma [89]. While cardiac-gated MRI is not routinely employed for the purpose of identifying SCAD, a coronary artery dissection may be detected as a focal T1 hyperintensity along a coronary artery [90].

Aortic dissection

Aortic dissection occurs when blood products accumulate within the aortic wall, disrupting the medial layer, creating a true and false lumen [91]. Population-wide, incidence of aortic dissection is estimated at 6 per 100,000, rarely occurring in women of child-bearing age [92]; however, half of cases under age 40 occur during pregnancy [93]. In addition to myocardial infarction, thoracic

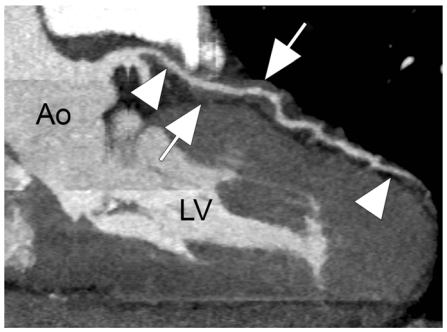

Fig. 3. Spontaneous coronary artery dissection. A curved planar reformation of the left anterior descending coronary artery (white arrowheads) shows subtle luminal irregularity with distinct adjacent soft tissue attenuation (white arrows) reflecting intramural blood products in a 32-year-old G1P1 woman presenting 2 weeks postpartum with acute onset chest pain. *Ao* aorta, *LV* left ventricle.

aortic dissection is a second major cause of pregnancy-associated maternal death [70].

Pregnancy-associated hemodynamic changes result in increased aortic wall stress and shearing forces which reach their zenith during the third trimester and peripartum period [93]. As with the coronary arteries, pregnancy-related hormonal changes may lead to microstructural changes within the aortic wall leading to weakening and predisposing to dissection or rupture [94]. Likewise, patients with underlying aortic dilatation or aortopathy from conditions such as Marfan syndrome, Ehlers-Danlos syndrome, or other conditions are also at increased risk of aortic dissection [93]. To mitigate the risk of aortic dissection, certain patients with dilated aortas may require prophylactic surgery, ideally prior to pregnancy. For select high-risk patients, a rapidly enlarging ascending aorta greater than 50 mm in size may warrant intrapartum surgery, although this is controversial [6].

Aortic root and ascending aortic size is best monitored by echocardiography during pregnancy. When abnormal, the aortic arch, descending aorta, and abdominal aorta are preferentially examined with non-contrast MRI rather than CT [93]. The role of imaging for acute aortic dissection, whether by echocardiography, CT, or MRI, is to identify the presence and extent of the dissection flap [91]. On echocardiogram, M-mode will demonstrate the intraluminal dissection flap, while color Doppler can identify flow acceleration in the region on an intimal tear or differential flow within the aortic true and false lumens [91]. While non-contrast CT has limited sensitivity for detection of aortic dissection, displaced intimal calcifications can be suggestive [91]. Furthermore, identification of a hyperdense crescent within the aortic wall is indicative of an intramural hematoma [91]. Contrast-enhanced CT clearly delineates the dissection flap as a low-density linear filling defect upon a background of bright contrast within the two separate resulting lumens [95]. The false lumen may demonstrate a network of thin linear filling defects (cobweb sign) reflecting residual medial fibers [95]. As assessed by MRI, the intimal flap can be identified by black-blood spin echo sequences as a linear luminal filling between the two dark lumens, although the false lumen may demonstrate relatively increased signal due to slow flow and turbulence [96, 97]. Bright blood sequences, such as SSFP, allow the identification of the dissection flap as a dark filling defect, direct visualization of turbulent blood flow within the false lumen, and aid in the detection of

communication sites between the true and false lumen [98]. Furthering imaging with phase contrast MRI permits direct measurement of blood flow in the true and false lumens [98].

Peripartum cardiomyopathy

Peripartum cardiomyopathy is a rare cause of left ventricular dysfunction occurring near the end of pregnancy or the months following delivery in previous healthy women without another identifiable cause [99, 100]. This entity differs from a preexisting dilated cardiomyopathy unmasked by pregnancy-associated hemodynamic changes in that the latter typically presents earlier when hemodynamic changes peak in the late second trimester [100, 101]. Incidence of peripartum cardiomyopathy has been estimated at 1 in 3000–4000 live births; however, there is substantial geographic variability both within the USA and across the world [101].

The etiology of peripartum cardiomyopathy is poorly understood; however, potential causative or modifying factors include increased myocardial oxidative stress, pathologic inflammatory cascades, viral infection, autoantibodies, and genetic predisposition [100]. Additional risk factors that have been described include hypertension, advanced age, African descent, multiparity, tocolysis, twin gestation, and malnutrition [100–102]. Reduced left ventricular systolic function can predispose these patients to left ventricular thrombus formation and subsequent thromboembolism including the possibility of stroke [100].

Imaging findings will commonly demonstrate left ventricular cavitary dilatation and concomitant systolic dysfunction, typically with an ejection fraction less than 45% [100]. Left ventricular volume and function can be estimated by echocardiography; however, MRI is more accurate [100]. MRI also permits more definitive evaluation for left ventricular thrombus which will appear as an intracavitary mass with low signal intensity [103]. While role of late gadolinium enhancement and myocardial T2 hyperintensity is yet to be fully elucidated [104], diagnostic imaging with echocardiography, CT, and MRI may be helpful to exclude other confounding diagnoses such as pulmonary embolism, ischemic heart disease, or other forms of non-ischemic cardiomyopathy.

Takotsubo cardiomyopathy

Takotsubo cardiomyopathy, or more broadly “stress cardiomyopathy”, is a transient non-ischemic cardiomyopathy in which the left ventricular apex becomes dyskinetic resulting in apical ballooning, or less commonly midventricular or basal ballooning [105, 106]. Presenting symptoms are those of acute onset chest pain or dyspnea, classically in association with a stressful life event [99]. Incidence is estimated as high as 2.2% of patients presenting with acute coronary syndrome [107]. There is a strong female predilection and most cases present after age 50 [108]. As a result, presentation during pregnancy is exceedingly uncommon; however, when present, differentiation from coronary artery disease, pulmonary artery thromboembolism, and peripartum cardiomyopathy is crucial as management of these conditions varies greatly [105, 109, 110].

Pregnant women seem to be at greatest risk for takotsubo cardiomyopathy at the time of delivery, particularly via cesarean section [111]. Limited reports suggest that outcomes in pregnancy are favorable with complete recovery being the norm [110, 111]. The exact cause is unknown; however, considerations

include coronary artery vasospasm or emotional stress mediated by excessive catecholamine levels resulting in the transient myocardial stunning which is characteristic [99]. Notably, atherosclerotic coronary artery disease is often minimal or absent [108].

Cardiac imaging demonstrates a characteristic rounded left ventricular cavity with a narrow base similar in shape to a Japanese octopus trap (tako tsubo) for which the disease is named [108]. Functional imaging shows dynamic apical ballooning [99]. Tissue characterization by MRI typically shows apical T2 signal hyperintensity with absent abnormal late gadolinium enhancement, the latter of which distinguishes takotsubo cardiomyopathy from myocarditis or myocardial infarction [112].

Congenital heart disease

Congenital heart disease is a broad category of developmental cardiac anomalies encompassing entities that include atrial and ventricular septal defects, congenital valvular dysfunction, and great vessel anomalies such as aortic coarctation and transposition [113]. This group of disorders comprises the most common preexisting cardiac conditions in pregnant women in the western world [114, 115]. The prevalence of adults with congenital heart disease has increased with improving childhood treatment and now is approximately 6 per 1000 [7]. The substantial hemodynamic changes that occur during pregnancy can unmask or exacerbate problems related to underlying structural abnormalities, the exact mechanism of which relies upon the individual patient's anatomy [116]. As a result, these patients are at increased risk for cardiac-related pregnancy complications which occur in 5–20% of such pregnancies [115]. In particular, maternal mortality rates approach 1 in 200 compared with 0.007% for normal pregnancies [113].

The imaging appearance of congenital heart disease varies considerably based upon the underlying abnormality and any subsequent corrective surgical procedures. While both MRI and CT are excellent for characterization of patient anatomy in the setting of congenital heart disease, typically such an evaluation occurs long before pregnancy is considered and may not be required in the peripartum period. MRI may be useful in select circumstances for complex congenital disease [6]. Ultrasound is the preferred modality during pregnancy for cardiac re-evaluation when possible [6].

Cardiac valvular disease

Valvular dysfunction is a common cause of cardiac disease, particularly in the developing world where 80% of patients with heart disease have valvular dysfunction from rheumatic heart disease [115]. Valvular stenosis, especially involving the left heart, confers a substantially higher risk of complications during pregnancy compared with regurgitant lesions since transvalvular gradients across stenotic valves are exacerbated by the pregnancy-related increase in cardiac output [6]. Regurgitant valves are typically well tolerated since valvular regurgitation decreases during pregnancy owing to the reduction in systemic vascular resistance [115].

For valvular heart disease, echocardiography is a key diagnostic tool with which valvular area, peak flow velocity, mean pressure gradient, left ventricular size, and left ventricular function can be measured [117]. Cardiac MRI is

typically reserved for patients with poor acoustic windows or unreliable echocardiographic measurements [117]. ECG-gated cardiac MRI with cine SSFP images and phase contrast images can help to quantify regurgitant volumes when necessary [118, 119].

Conclusion

The spectrum of cardiovascular diseases plays an important role in peripartum complications. Pregnancy-associated hemodynamic, hormonal, and microstructural changes dramatically alter cardiovascular disease incidence and pathophysiology compared with other patient populations. When deciding upon imaging strategies in pregnancy, the risks and benefits to both mother and fetus must be carefully weighed with particular attention to the ALARA principle and a preference for modalities that avoid ionizing radiation and protocols that avoid exposure to gadolinium-based contrast agents when possible. A thorough understanding of these nuances are required for optimal care of the gravid patient with pre-existing, new, or suspected cardiovascular disease.

Compliance with Ethical Standards

Conflict of Interest
Theodore Pierce, Meline Hovnanian, and Sandeep Hedgire each declare no potential conflicts of interest. Brian Ghoshhajra is a consultant for Medtronic and a consultant for Siemens.

Human and Animal Rights and Informed Consent
This article does not contain any studies with human or animal subjects performed by any of the authors.

References and Recommended Reading

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