A Radiologist's Guide to the Performance and Interpretation of Obstetric Doppler US

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Abbreviations: ALARA = as low as reasonably achievable, S/D = systolic to diastolic

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- Describe how to sample the umbilical artery and vein, the ductus venosus, the middle cerebral artery, and the uterine artery.
- Recognize normal and abnormal waveforms and the pitfalls in the interpretation of Doppler US findings for these vessels.
- Discuss how Doppler US of the umbilical artery is used in the management of fetal growth restriction.

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Doppler US provides a unique window to the fetoplacental circulation, allowing assessment of fetal well-being. Doppler US of the umbilical artery is an integral component of managing the fetus with growth restriction; and Doppler US of the middle cerebral artery, as a noninvasive means of detecting fetal anemia, has revolutionized the management of pregnancies complicated by alloimmunization. Serial use of amniocentesis, with its attendant risks, has been replaced by serial Doppler US examinations. Invasive procedures are now reserved for the treatment of anemia with intrauterine transfusion. Technique is critical to obtain the best waveforms for ease of shape assessment, velocity measurement, and calculation of various ratios. In this article, the safety of Doppler US is reviewed, the fetal circulation is described, and the role of Doppler US is demonstrated in first-trimester screening and in the evaluation of growth restriction, anemia, and other causes of fetal compromise in the second and third trimesters. Sampling technique is explained, and normal and abnormal waveforms are illustrated for the ductus venosus, umbilical artery, umbilical vein, middle cerebral artery, and uterine artery. Some examples of clinical cases are provided to illustrate how the results are used in clinical practice. Clinical examples of velamentous insertion and vasa previa are also provided to aid the practicing radiologist with recognition of these entities. In particular, vasa previa is considered a critical finding; it alters pregnancy management, requiring hospital admission, administration of steroid therapy, and planned early cesarean delivery.

Introduction

Doppler US was first used in obstetrics when continuous-wave Doppler US allowed the examiner to hear flow in the umbilical cord. With the advent of B-mode US and pulsed-wave Doppler US, it became possible to see specific vessels and to sample waveforms, providing a window into the fetoplacental circulation (1). The addition of color Doppler flow US improved the identification of normal anatomic structures. Depiction of the umbilical arteries on either side of the bladder confirms a three-vessel umbilical cord, use of color Doppler flow US to identify loops of cord that might be mistaken for fluid pockets prevents the overestimation of amniotic fluid volume, and mapping the placental site of insertion of the umbilical cord is much easier with color Doppler flow US than with

TEACHING POINTS

- All fetal imaging, including Doppler US, should be performed only for valid medical indications with use of techniques to decrease fetal exposure to as low as reasonably achievable (ALARA), in accordance with the ALARA principle.
- The results of all spectral Doppler US examinations should be displayed with an appropriate baseline, scale, and sweep speed, to maximize the ease of analysis of the waveform. Technical errors in the angle of insonation and in sample volume size and placement, as well as incorrect selection of the wall filter, may lead to misinterpretation of findings and management errors.
- It important to note that Doppler US examinations of the fetoplacental circulation have no role in screening low-risk pregnancies. Doppler US of the umbilical cord is a relatively crude index of placental health, in that it only becomes abnormal when large amounts of the placental tertiary villous arteries are obliterated.
- Whenever unexplained fetal hydrops is encountered, it is vital to check for fetal anemia as a cause. Transfusion may be lifesaving in this setting.
- Dedicated imaging protocols with endovaginal US and color Doppler flow US have been shown to improve antenatal detection of vasa previa. In turn, antenatal detection results in improved outcomes.

gray-scale US alone. When technically possible, documentation of the placental site of insertion of the umbilical cord is part of standard obstetric US (2,3). In multiple gestations, mapping the placental sites of the umbilical cord insertions is critical, because marginal or velamentous insertions increase the risk of growth restriction, unequal placental sharing, and vasa previa (4). Although many different vessels have been the subject of research studies, only spectral analysis of the umbilical artery has been shown to impact the outcome for pregnancies affected by fetal growth restriction (5). We review the relevant guidelines in the section on "Obstetric Doppler US in the Second and Third Trimesters."

A detailed review of the literature on obstetric applications of Doppler US is beyond the scope of this article, but the interested reader is referred to the guidelines for "Doppler Assessment of the Fetus with Intrauterine Growth Restriction," a publication of the Society for Maternal-Fetal Medicine (5). Another source of detailed technical information is *Doppler in Obstetrics,* a free online textbook (6).

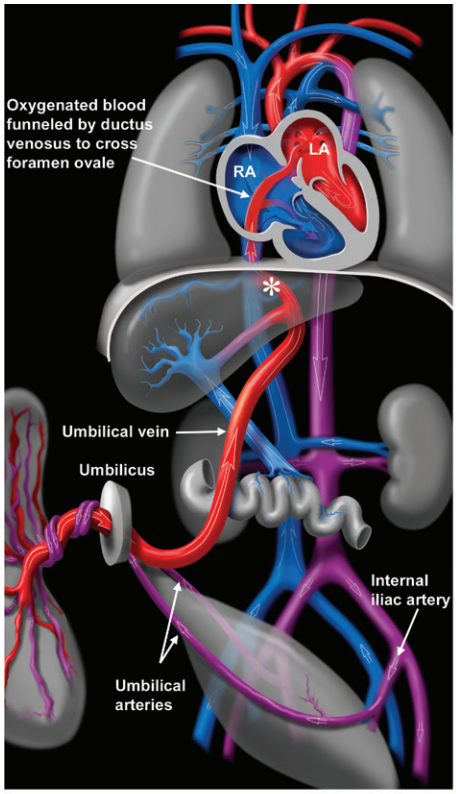
Safety of Obstetric Doppler US

No discussion of imaging in pregnancy is complete without a discussion of safety. Although US does not use ionizing radiation and is considered safe for use at all gestational ages, considerable energy output can occur during the performance of spectral Doppler US.

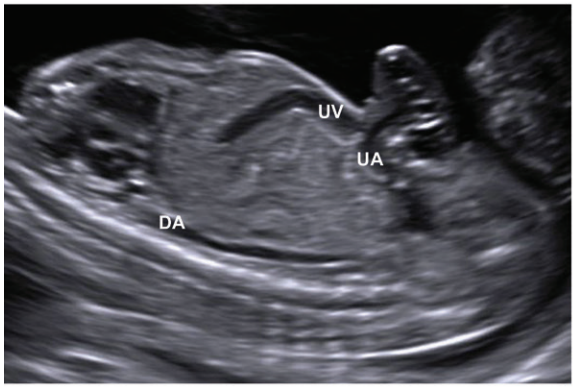
All fetal imaging, including Doppler US, should be performed only for valid medical indications with use of techniques to decrease fetal exposure to as low as reasonably achievable (ALARA), in accordance with the ALARA principle. Fetal exposure to energy during US is affected by many factors, including the power output, the depth and type of structures being interrogated (bone vs soft tissue), the length of the examination, and the type of transducer. When Doppler US is used, particular attention should be paid to safety, because the energy output is higher than that with B-mode US. The mechanical index and the thermal index are on-screen guides to the relative risk of potentially harmful US-induced bioeffects (7). The mechanical index is the relative indicator of potential nonthermal bioeffects, primarily cavitation (ie, interaction of US with gas bubbles), and this index should be 1.0 or less. Evidence suggests that there is a threshold below which no effect is seen and that this threshold varies with different types of tissue (8). Given the lack of gas within a fetus, the mechanical index is believed to be of lesser importance than the thermal index in obstetric imaging.

The thermal index is a relative indicator of temperature rise and potential tissue damage from thermal effects. The thermal risk is related to the amount of energy absorbed, which varies by tissue type (bone > soft tissue > amniotic fluid). A thermal index for soft tissue should be used in the first trimester before bone ossification is seen, and a thermal index for bone should be used when bone ossification is evident (typically after 10 weeks). These indexes fluctuate with varying machine settings and power output and should be monitored closely throughout the examination (8). Color Doppler flow US increases the total power emitted. The power output changes according to the size and depth of the color box, which should be kept as small as possible to include only the area of interest. Spectral Doppler US has an even higher energy output and hence a greater heating potential. This problem is compounded by the transducer being held in a fixed position with the power concentrated along a single line. Current guidelines for use of Doppler US at the time of first-trimester screening (11 weeks to 13 weeks, 6 days) state that the displayed thermal index should be 1.0 or less and that exposure time should be as short as possible, usually no longer than 5–10 minutes and not exceeding 60 minutes (9).

Throughout the remainder of a pregnancy, all imaging should adhere to the ALARA principle. The display of the thermal index and mechanical index varies from vendor to vendor. Many dedicated imaging packages are set up to ensure low energy output, but all operators performing



a.



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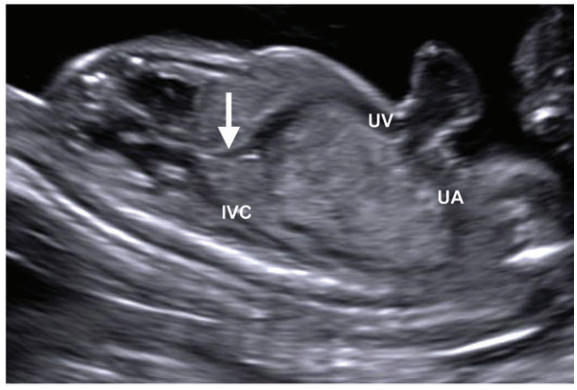


c.

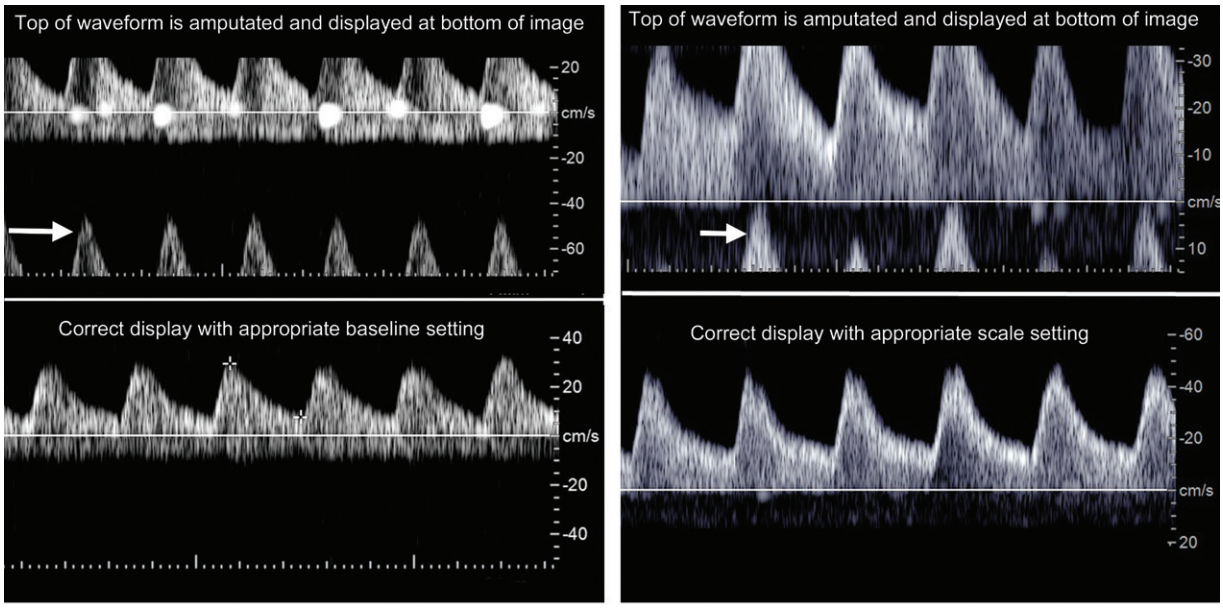
Figure 1. Fetal circulation. **(a)** Anatomic drawing of the fetal circulation from an oblique coronal perspective shows the umbilical arteries arising from the internal iliac arteries and carrying deoxygenated blood (purple) to the umbilicus and onward to the placenta. The umbilical vein carries the oxygenated return (red) from the placenta through the umbilicus, along the free edge of the falciform ligament to the left portal vein. Some of this blood goes to the liver, but a portion is directed to the inferior vena cava and right atrium by the ductus venosus (*). This stream of oxygenated blood crosses the foramen ovale from the right atrium *(RA)* to the left atrium *(LA)* and thence to the aorta to preferentially perfuse the coronary arteries and cranial structures with the most oxygenated blood. (Reprinted from reference 10.) **(b)** Parasagittal gray-scale US image of a second-trimester fetus shows the umbilical artery *(UA),* umbilical vein *(UV),* and descending aorta *(DA).* **(c)** Right parasagittal gray-scale US image of the same second-trimester fetus shows the umbilical artery *(UA),* umbilical vein *(UV),* inferior vena cava *(IVC),* and ductus venosus (arrow).

obstetric US should verify with their application specialists that the operators know where the thermal index and mechanical index are displayed and that they know how to adjust levels. Both indexes should be monitored throughout the examination; begin with a low power level, and adjust to levels just high enough to obtain a diagnostic examination.

Fetoplacental Circulation

In the fetus, deoxygenated blood is carried to the placenta by the umbilical arteries, which arise from the internal iliac arteries. Oxygenated blood returns from the placenta to the right atrium by way of the umbilical vein, left portal vein, ductus venosus, and inferior vena cava. Flow across the trumpet-shaped ductus venosus produces a defined stream of oxygenated blood that preferentially flows through the foramen ovale to the left atrium, left ventricle, and aorta, diverting the most oxygenated blood to the head and neck vessels and the coronary arteries (Fig 1) (10).

The fetal right ventricular output largely bypasses the lungs. Instead, it is diverted by way of the ductus arteriosus to the descending aorta to perfuse the fetal torso. As noted, the umbilical arteries arise from the internal iliac arteries and are responsible for carrying deoxygenated fetal blood to the placenta. When placental resistance increases, the abnormal pressures produce increased afterload, which can impair right ventricular function. The right ventricle accounts for more than 50% of the cardiac output in the fetus; thus, any process that has a negative effect



a. **b.**

Figure 2. Correction of aliasing. **(a)** Baseline selection. Top: Spectral Doppler US image shows that an incorrect baseline causes the waveform to wrap around the baseline, with the highest systolic velocities cut off from the rest of the waveform. The highest systolic velocities (arrow) are confusingly displayed at the bottom of the image. Bottom: Spectral Doppler US image shows that bringing the baseline down results in better waveform display. **(b)** Scale selection. Top: Spectral Doppler US image shows that an incorrect velocity scale (range of ~50 cm/sec) causes the waveform to wrap around the baseline. Again, the fastest velocities (arrow) are displayed at the bottom of the image. Bottom: Spectral Doppler US image shows that increasing the velocity scale to a range of 80 cm/sec results in better waveform display.

on right ventricular function adversely influences fetal well-being (11).

The maternal side of the fetoplacental circulatory unit is represented by the uterine artery. Normal trophoblastic invasion of the maternal spiral arteries in the first half of pregnancy causes maximum vessel distention and impairs sympathetic and parasympathetic responses to ensure arterial dilatation and increased blood flow to the pregnant uterus (12). Thus, the uterine artery waveform changes from relatively high resistance in the nonpregnant state to a low-resistance waveform in pregnancy, with continuous forward flow throughout diastole.

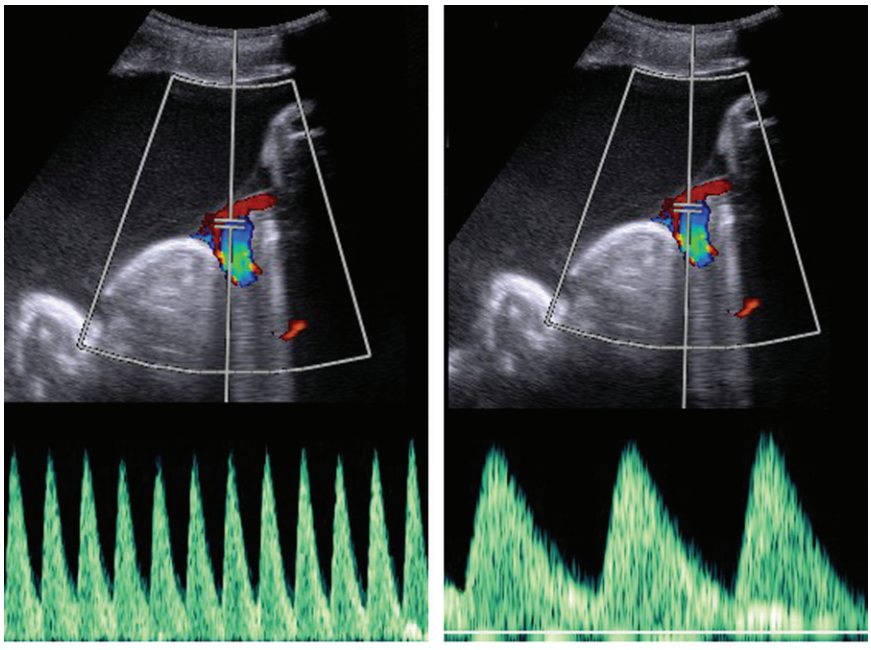
The vessels sampled to assess the fetoplacental unit include the umbilical artery, umbilical vein, ductus venosus, middle cerebral artery, and uterine artery. In the first trimester, the focus of Doppler US is *(a)* detection of aneuploidy and an increased risk for congenital heart disease with evaluation of the ductus venosus waveform, and *(b)* screening for women more likely to develop preeclampsia by evaluation of the uterine artery waveform. In the second and third trimesters, use of Doppler US is targeted toward risk assessment in growth-restricted fetuses, those with high-output conditions, and detection of complications of monochorionic twinning (umbilical artery, middle cerebral artery, umbilical vein, ductus venosus), as well as noninvasive detection of fetal anemia by measurement of the peak systolic velocity in the middle cerebral artery.

The results of all spectral Doppler US examinations should be displayed with an appropriate baseline (Fig 2a), scale (Fig 2b), and sweep speed (Fig 3), to maximize the ease of analysis of the waveform. Technical errors in the angle of insonation (Fig 4) and in sample volume size and placement, as well as incorrect selection of the wall filter (Fig 5), may lead to misinterpretation of findings and management errors. Figure 6 is a composite illustration of normal and abnormal waveforms in the umbilical artery.

Obstetric Doppler US in the First Trimester

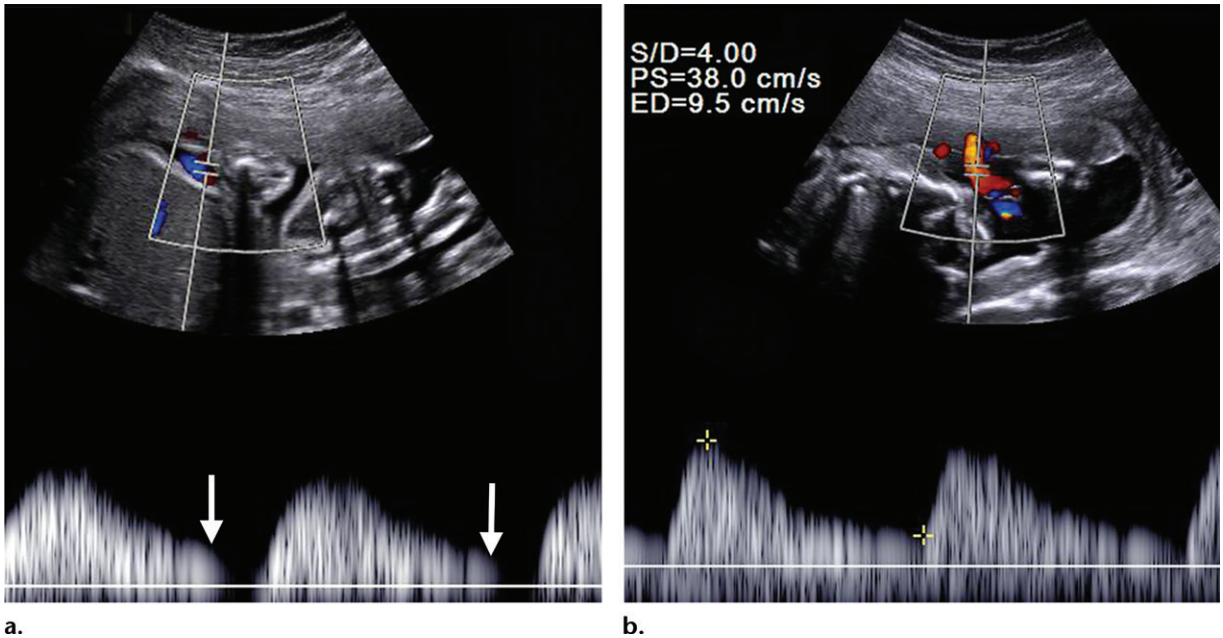
The ductus venosus is a small trumpet-shaped connection between the umbilical/portal system and the inferior vena cava. Its shape effectively funnels the oxygen-rich blood returning from the placenta directly into the right atrium, with flow dynamics that then facilitate flow across the foramen ovale into the left atrium. The ductus venosus has a characteristic waveform and sound. The latter has been likened to the sound of a washing machine. Listening while sampling is helpful to confirm correct cursor placement.

Correct technique is important when sampling the ductus venosus. Use color Doppler flow US to localize the site of aliasing between



a. b.

Figure 3. Sweep speed. **(a)** Color Doppler duplex US image shows that an incorrect sweep speed crowds the waveform and makes it difficult to assess diastolic flow and to place cursors for measurement of end-diastolic flow. **(b)** Color Doppler duplex US image shows that a correct sweep speed opens up the waveform for ease of visual assessment and cursor placement. All vendors have specific imaging packages that are set up to maximize image quality for the area being examined. Use of these presets is the first step in image adjustment; after that, the sweep speed can be manually adjusted so that the waveforms are displayed in the best possible manner for visual analysis of shape and systolic and diastolic components.



a. b.

Figure 4. Angle of insonation. **(a)** Color Doppler duplex US image shows that the angle of insonation for the umbilical artery is 70°–80°, resulting in poor signal. End-diastolic velocities are absent, but the cutoff is abrupt (arrows), indicating a technical problem rather than true absent end-diastolic flow, in which the waveform tapers smoothly to the baseline before the next systolic upstroke. **(b)** Color Doppler duplex US image shows that with a small adjustment in transducer position, the angle of insonation is close to 0°, producing better signal and a complete display of flow velocities throughout the cardiac cycle (calipers mark the peak systolic velocity [PS] and the end-diastolic velocity [ED]). In this case, the systolic to diastolic (S/D) ratio was elevated, but absent end-diastolic flow was not seen.

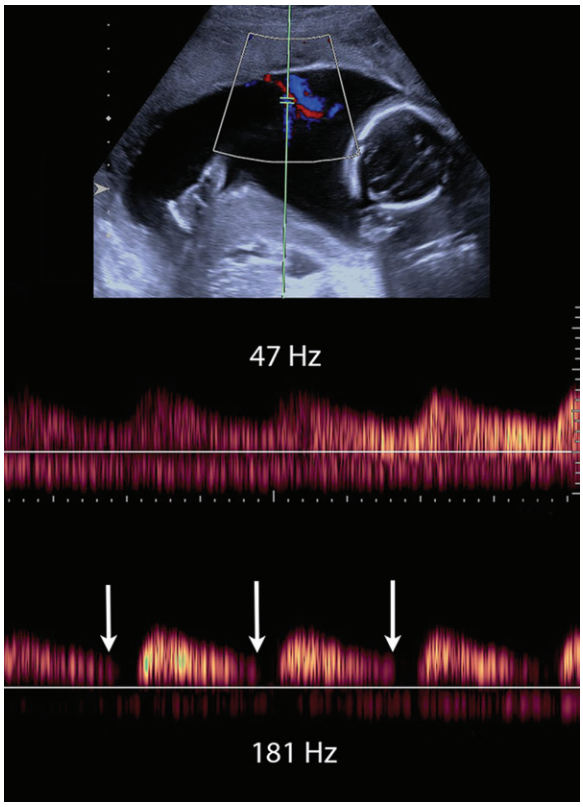


Figure 5. Wall filter selection. Color Doppler duplex US image shows that another pitfall causing confusion with absent end-diastolic flow is an incorrect wall filter setting. High wall filter frequency will cut off velocities below a certain level. At 47 Hz, the waveform is normal, with all flow velocities displayed; at 181 Hz, end-diastolic flow is removed from the display. Note that an abrupt cutoff (arrows) is depicted, rather than a steady taper to the baseline, as is seen with real absent end-diastolic flow.

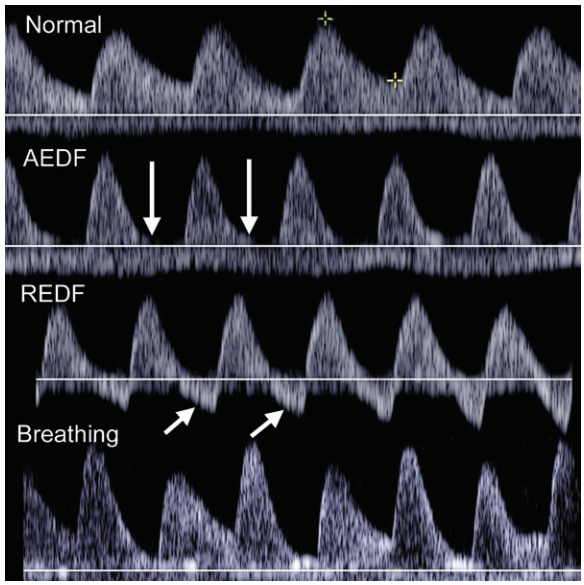
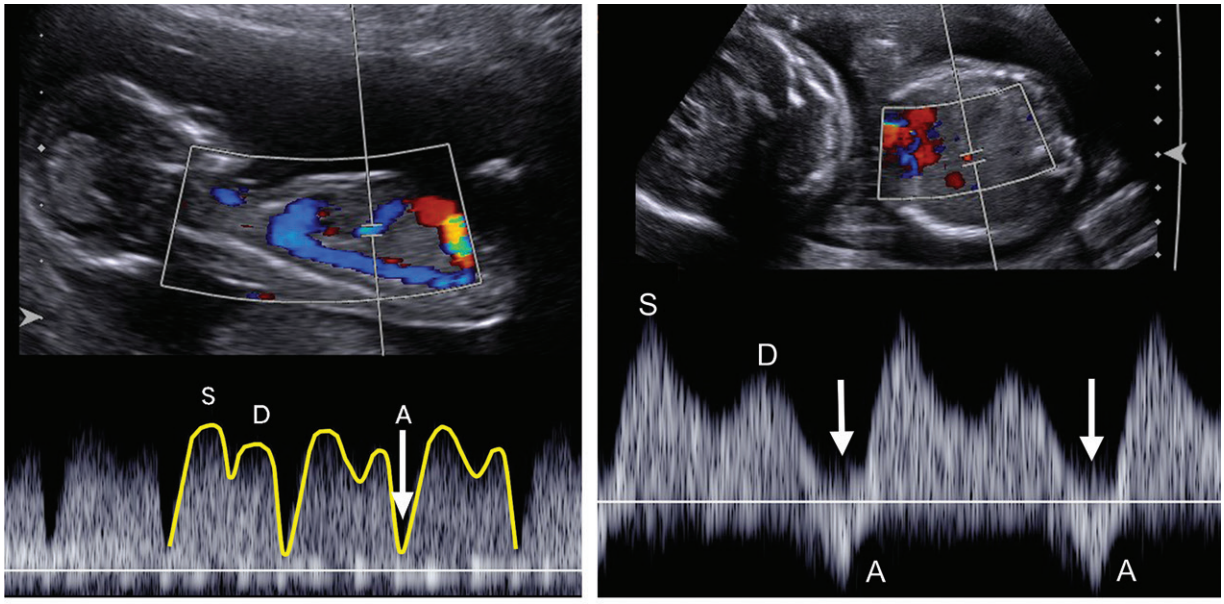


Figure 6. Umbilical artery waveforms. Top to bottom: Spectral US images show a normal waveform, absent end-diastolic flow *(AEDF)* waveform, reversed end-diastolic flow *(REDF)* waveform, and breathing waveform. The normal waveform in the third trimester is low resistance, with continuous forward flow throughout diastole. The S/D ratio was 1.96 (calipers mark the peak and end-systolic velocities), and respiratory undulations are visible in the associated umbilical vein waveform. When there is absent end-diastolic flow (long arrows), the waveform smoothly tapers all the way to the baseline, and there is no forward flow at the end of diastole. Respiratory variation is also depicted in the umbilical vein in this example. With reversed end-diastolic flow (short arrows), flow in the umbilical artery is reversed in diastole and thus is displayed below the baseline. Not only is there lack of antegrade flow in diastole, but also the blood is actually pushed back out of the placenta owing to the high intraplacental pressure from obliteration of chorionic villi. Flow in the umbilical vein is not depicted on this spectral US image. Fetal breathing changes the intrathoracic pressure, resulting in variable systolic and diastolic flow but never absent or reversed end-diastolic flow. This breathing waveform is from a normal fetus.

the left portal vein and the inferior vena cava. This aliasing is best seen in a sagittal plane in the first trimester at the time of nuchal translucency screening. Later in pregnancy, an axial image at the level used for abdominal circumference measurement can be used; color Doppler flow US is useful to identify aliasing in the ductus venosus as it branches from the portal vein (Fig 7).

For the best technique, use a small sample volume (0.5–1 mm) to avoid contamination from the adjacent portal vein, hepatic veins, or inferior vena cava (Fig 8) (10). The angle of insonation should be less than 30° to maximize Doppler shift and obtain a good waveform. As with all Doppler US examinations, avoid interrogating the ductus venosus at a 90° angle (ie, perpendicular to the vector of flow), because this angle results in zero Doppler shift and no flow information. Set the filter at the lowest possible frequency (50–70 Hz) so that the A wave is not obscured, and use a high sweep speed (2–3 cm/sec) to spread the waveform, to allow assessment of the shape (5,6).

Observe the waveform, and identify the three components: the S wave, the D wave, and the A wave. The S wave reflects ventricular systole, the D wave reflects ventricular diastole, and the A wave reflects atrial contraction. Reversal of the A wave is always abnormal. Associations include increased risk of aneuploidy (13,14) and congenital heart disease (15); and in twins, reversal of the A wave is a marker for increased risk of developing the twin-twin transfusion syndrome (16). Abnormal findings include the absence or reversal of the A wave (Fig 7b). The venous pulsatility index and other measurements are used in research settings. Doppler US of the ductus venosus for aneuploidy screening is performed between 10 and 14 weeks gestation, often in combination with evaluation of nuchal translucency and first-trimester anatomic structures. Doppler US of the ductus venosus is also performed in the second and third trimesters to assess cardiac function in



a. **b.**

Figure 7. Ductus venosus waveform in two different fetuses. *A* = A wave (atrial contraction), *D* = D wave (ventricular diastole), *S* = S wave (ventricular systole). **(a)** Color Doppler duplex US image of a 13-week fetus: This ductus venosus waveform is partly outlined in yellow to show the S-wave, D-wave, and A-wave components, which are all on the same side of the baseline; flow should be continuously forward throughout the cardiac cycle. The waveform has been inverted to display above the baseline. The small sample volume is placed at the site of aliasing. **(b)** Color Doppler duplex US image obtained in the axial plane in a 25-week fetus with severe growth restriction: This ductus venosus waveform is abnormal, with reversal of the A wave (arrows), which crosses the baseline before the upstroke of the S wave.

fetuses with high-output conditions and to assess cardiac strain in fetuses with fetal growth restriction attributed to abnormal placentation. The fetus should be at rest and not breathing during ductus venosus sampling.

Obstetric Doppler US in the Second and Third Trimesters

In the second and third trimesters, Doppler US is used to assess fetal well-being and to noninvasively monitor the fetoplacental unit. The umbilical artery and the middle cerebral artery are the most important vessels sampled; supplemental information may be obtained from evaluation of the ductus venosus and the umbilical veins.

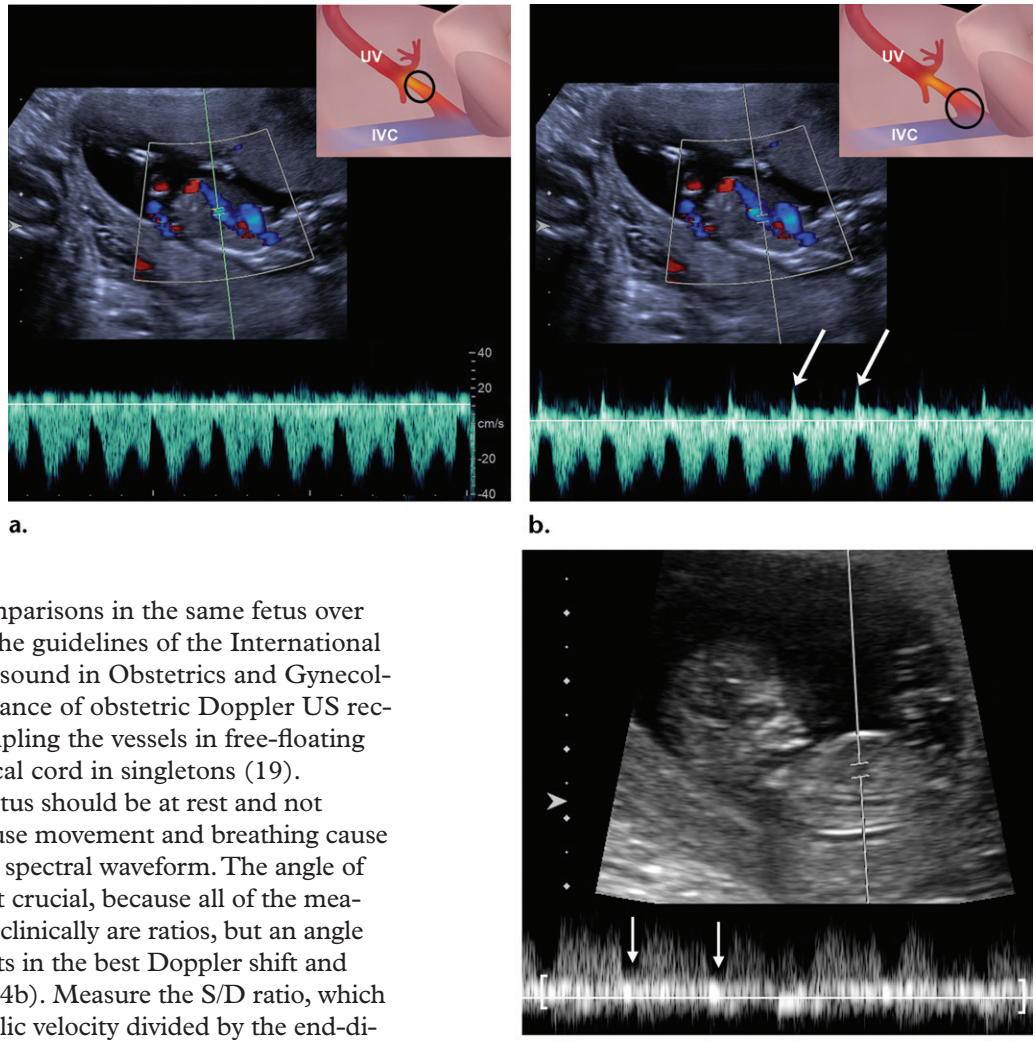
Umbilical Artery

The normal placental vascular bed is low resistance, with continuous forward flow throughout the cardiac cycle. Diastolic flow increases as pregnancy progresses, so the S/D ratio decreases with advancing gestational age. At 20 weeks, the 50th percentile for the S/D ratio is 4. At 30 weeks, the 50th percentile is 2.83; and at 40 weeks, the 50th percentile is 2.18 (17).

In current clinical practice, the S/D ratio and the presence of absent or reversed end-diastolic flow are used to manage fetal growth restriction and to stage the twin-twin transfusion syndrome. In most clinical settings, Doppler US of the umbilical artery is not performed until viability (ie, 24 weeks); but in the twin-twin transfusion syndrome, Doppler US of the umbilical artery is part of the staging system. Therefore, it is performed whenever that diagnosis is suspected, regardless of gestational age. In research studies, investigators use the pulsatility index in an effort to study blood flow throughout the cardiac cycle. The pulsatility index is calculated by dividing the peak systolic velocity minus the end-diastolic velocity by the time-averaged velocity.

Resistance to flow in the umbilical arteries varies along the length of the umbilical cord. Resistance is highest at the abdominal site of insertion of the umbilical cord, is intermediate in free-floating loops of the umbilical cord, and is lowest at the placental site of umbilical cord insertion (18) (Fig 9). Thus, it is important to sample consistently when performing serial evaluations throughout pregnancy. In 2012, the Society for Maternal-Fetal Medicine recommended sampling at the abdominal site of umbilical cord insertion (5), but this site can be challenging in later gestation when it may be obscured by the fetal lower extremities or when there is oligohydramnios limiting acoustic access (as often occurs in association with fetal growth restriction). In multiple gestations, it is essential to sample at, or as close as possible to, the abdominal site of umbilical cord insertion of each fetus to ensure

Figure 8. Sampling of the ductus venosus. **(a)** Color Doppler duplex US image shows a ductus venosus waveform obtained with a correct sample volume and proper cursor location in the ductus venosus at the site of aliasing. Inset: Anatomic drawing shows the correct sampling location (circle). *IVC* = inferior vena cava, *UV* = umbilical vein. (Inset reprinted from reference 10.) **(b)** Color Doppler duplex US image shows a ductus venosus waveform obtained with the cursor placed too cephalad (ie, closer to the heart and not at the site of aliasing) and with use of too large a sample volume, which caused simultaneous sampling of the inferior vena cava with the ductus venosus. This waveform (arrows) can be mistaken for reversed flow in the A wave, but the key observation is that the A wave does not reach the baseline; the apparent reversed flow is, in fact, part of the normal inferior vena cava waveform. Inset: Anatomic drawing shows the incorrect sampling location (circle). *IVC* = inferior vena cava, *UV* = umbilical vein. (Inset reprinted from reference 10.) **(c)** Duplex US image shows a different case in which the sample volume is large and has been placed so that there is simultaneous sampling of the portal vein and the ductus venosus. Portal vein flow (between the square brackets on the waveform) obscures the A wave arrows) and could prevent detection of a diminished or even reversed A wave.



appropriate comparisons in the same fetus over time. In 2013, the guidelines of the International Society of Ultrasound in Obstetrics and Gynecology for performance of obstetric Doppler US recommended sampling the vessels in free-floating loops of umbilical cord in singletons (19).

Ideally, the fetus should be at rest and not breathing, because movement and breathing cause variations in the spectral waveform. The angle of insonation is not crucial, because all of the measurements used clinically are ratios, but an angle close to 0° results in the best Doppler shift and waveforms (Fig 4b). Measure the S/D ratio, which is the peak systolic velocity divided by the end-diastolic velocity; and compare the value to nomograms for flow at specific gestational ages (17). Do not average the values for S/D ratios. Take note of absent end-diastolic flow or reversed end-diastolic flow and whether it is intermittent or sustained.

It important to note that Doppler US examinations of the fetoplacental circulation have no role in screening low-risk pregnancies. Doppler US of the umbilical cord is a relatively crude index of placental health, in that it only becomes abnormal when large amounts of the placental tertiary villous arteries are obliterated. It is thought that as much as 70% of the placental vascular bed has to be obliterated before reversed end-diastolic flow is seen (20,21) (Fig 6). However, Doppler US findings may occur before heart rate changes that manifest as abnormal results of fetal nonstress testing.

In 2012, the Society for Maternal-Fetal Medicine published a clinical guideline for Doppler US assessment of the fetus with growth restriction (5); the recommendations still stand today. In the setting of fetal growth restriction, the guidelines of the Society for Maternal-Fetal Medicine recommend weekly Doppler US of the umbilical artery. If the results of Doppler US remain normal, delivery is recommended at

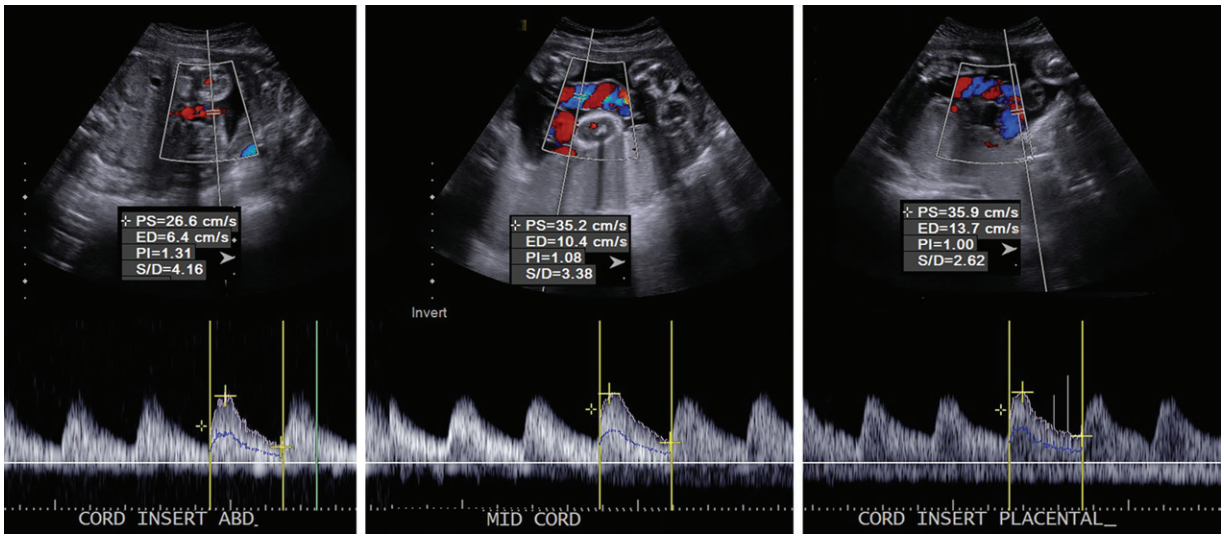


Figure 9. Sampling sites for Doppler US of the umbilical artery. Left to right: Color Doppler duplex US images obtained at different points along the umbilical cord show varying S/D ratios from the abdominal (ABD) cord insertion (left) to the mid cord (middle) to the placental cord insertion (right). For consistency from scan to scan, always sample at the same site. In multiple gestations, sampling is best performed at the abdominal site of umbilical cord insertion to ensure correct twin identification. Even though the S/D ratio may be highest at this site, consistent sampling will allow assessment of trends during the duration of the pregnancy. Some waveforms were inverted to place all above the baseline for ease of comparison. ED = end-diastolic velocity, PI = pulsatility index, PS = peak systolic velocity.

38–39 weeks. When these results are abnormal, management is determined by the severity of the finding. With decreased diastolic flow, antenatal testing (eg, nonstress tests, amniotic fluid measurement, and biophysical profile) is increased in frequency, Doppler US is performed weekly, and delivery is considered after 37 weeks. When absent end-diastolic flow or reversed end-diastolic flow is present, corticosteroid therapy is given in anticipation of preterm delivery, and Doppler US is performed two to three times per week, in addition to standard antenatal tests of fetal well-being (5). Goal gestational ages for delivery are 34 weeks or more with absent end-diastolic flow and 32 weeks or more with reversed end-diastolic flow. The role of umbilical artery Doppler US in the assessment of unequal placental sharing and delivery timing in twins is illustrated in Figures 10 and 11.

Umbilical Vein

Normal flow in the umbilical vein is continuous, returning oxygenated blood from the placenta to the fetus (Fig 12). Fetal breathing is a common observation in the third trimester. The changes in intrathoracic pressure alter flow dynamics in the vein to produce undulations in the umbilical vein waveform that are not linked to the cardiac cycle (Fig 12). Pulsatile flow in the umbilical vein is an ominous finding. When present, it indicates that the abnormal placental pressures have compromised right heart function such that there is back pressure through the right ventricle to the right atrium, back out the ductus venosus (which will show a decreased or reversed A wave) all the way into the umbilical vein, where forward flow decreases during diastole. This process causes a pulsatile waveform with diminished forward flow in the umbilical vein during ventricular diastole (Fig 12).

For the best technique, sample in a free-floating loop of the umbilical cord in singletons. In multiple fetuses, sample close to the abdominal site of umbilical cord insertion to verify which umbilical vein belongs to which fetus (19). The angle of insonation is not critical, because there are no velocity measurements. Ideally, the fetus should be at rest and not breathing. Observe the shape of the waveform, and be sure to differentiate between the normal undulations seen with fetal breathing and pulsatile venous flow.

Ductus Venosus

In contrast to its role in screening for aneuploidy and congenital heart disease in the first trimester, Doppler US of the ductus venosus is used to assess cardiac strain in the second and third trimesters. In normal circumstances, approximately 30% of the incoming placental return bypasses the liver in the second trimester; this percentage drops to about 18% by 31 weeks until term. When placental function is impaired, a larger percentage of umbilical vein blood flow is shunted to the left side of the heart (the head-sparing effect). This shunting decreases flow to the liver, impairing liver growth and limiting fetal weight gain (22).

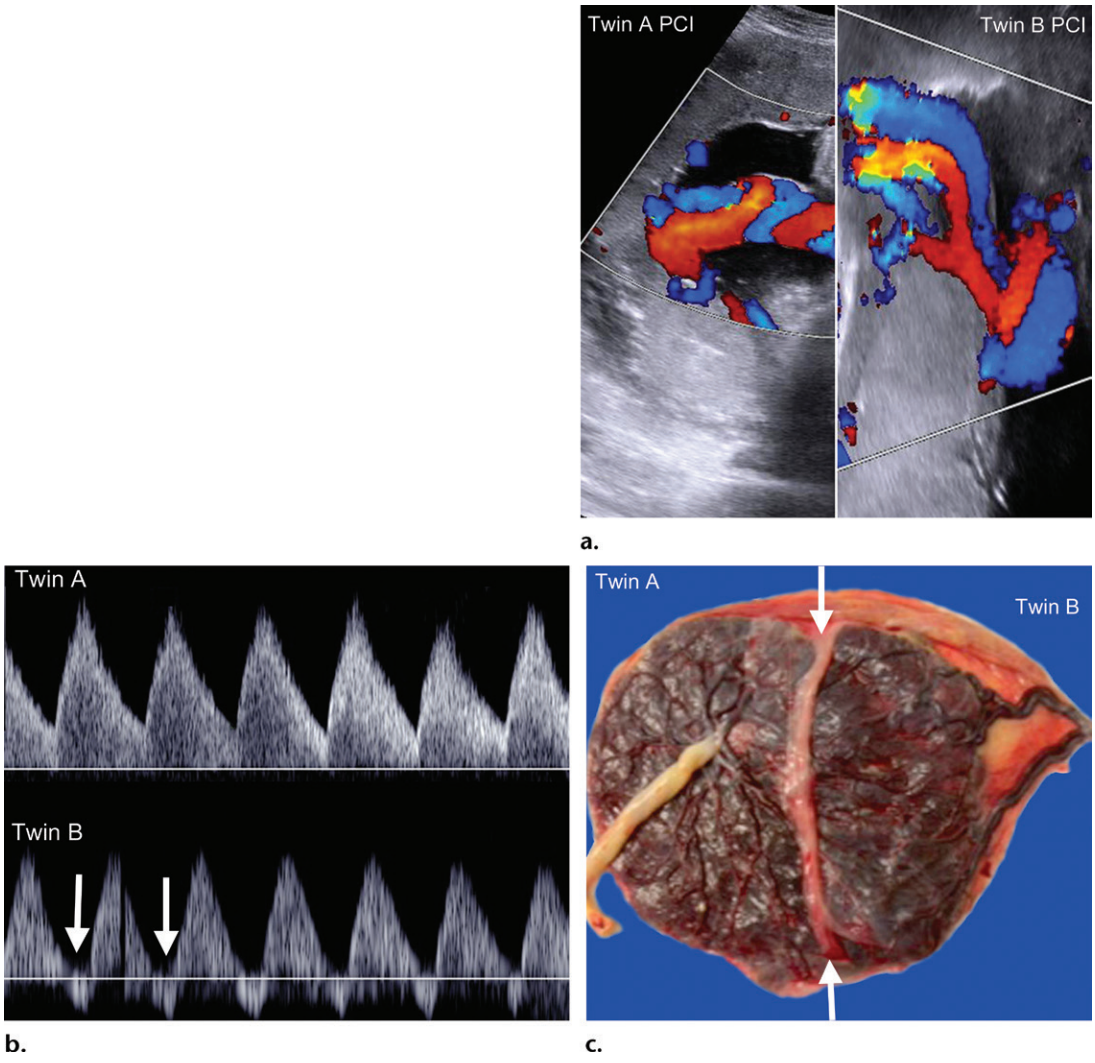


Figure 10. Unequal placental sharing in twins. **(a)** Composite view of color Doppler flow US images of twin A (left) and twin B (right) show the placental cord insertion (PCI) sites in a monochorionic diamniotic pregnancy; twin A's placental cord insertion is central, and twin B's placental cord insertion is velamentous. Twin B had severe growth restriction by 24 weeks. **(b)** Spectral Doppler US images of the umbilical cord at 25 weeks in twin A (top) and twin B (bottom) show normal flow for twin A but reversed end-diastolic flow (arrows) for twin B. The management dilemma in this case was when to deliver, balancing the risk of extreme prematurity for the normally grown twin A against the risk of the death of twin B, with the resultant hypotension in the survivor causing ischemic injury. **(c)** Photograph of the placenta after delivery shows the monochorionic diamniotic placenta with unequal placental sharing. The thin intertwin membrane (arrows) divides the placenta unequally. Twin A has a central cord insertion and a larger share of the single placenta; twin B has a smaller share of the placenta as well as a velamentous insertion.

The parameters that influence cardiac function include afterload (eg, increased placental resistance), myocardial performance (eg, cardiomyopathy), and preload (eg, the recipient twin in the twin-twin transfusion syndrome). Decreased forward flow during atrial systole (ie, diminished or reversed A wave) is the most sensitive and ubiquitous finding when any one of these parameters is affected (23,24).

The US technique is similar to that used in the first trimester, but with a larger fetal size, it may be easier to sample the ductus venosus in an axial plane in the midline, just below the diaphragm (Fig 7). Research studies and protocols in research laboratories use the venous pulsatility index and compare the flow rates and vessel diameters to calculate the volume of shunting to the brain; but in a general setting, A-wave reversal is used as a sign of substantial cardiac compromise. An absent or reversed A wave in the ductus venosus has been shown to be a strong predictor of stillbirth. In particular, when a reversed A wave is depicted in a fetus with fetal growth restriction, this finding seems to indicate that fetal survival is unlikely beyond 1 week (25).

Middle Cerebral Artery

Fetal Doppler US of the middle cerebral artery is used in two situations: *(a)* noninvasive assessment of fetal anemia and *(b)* calculation of the

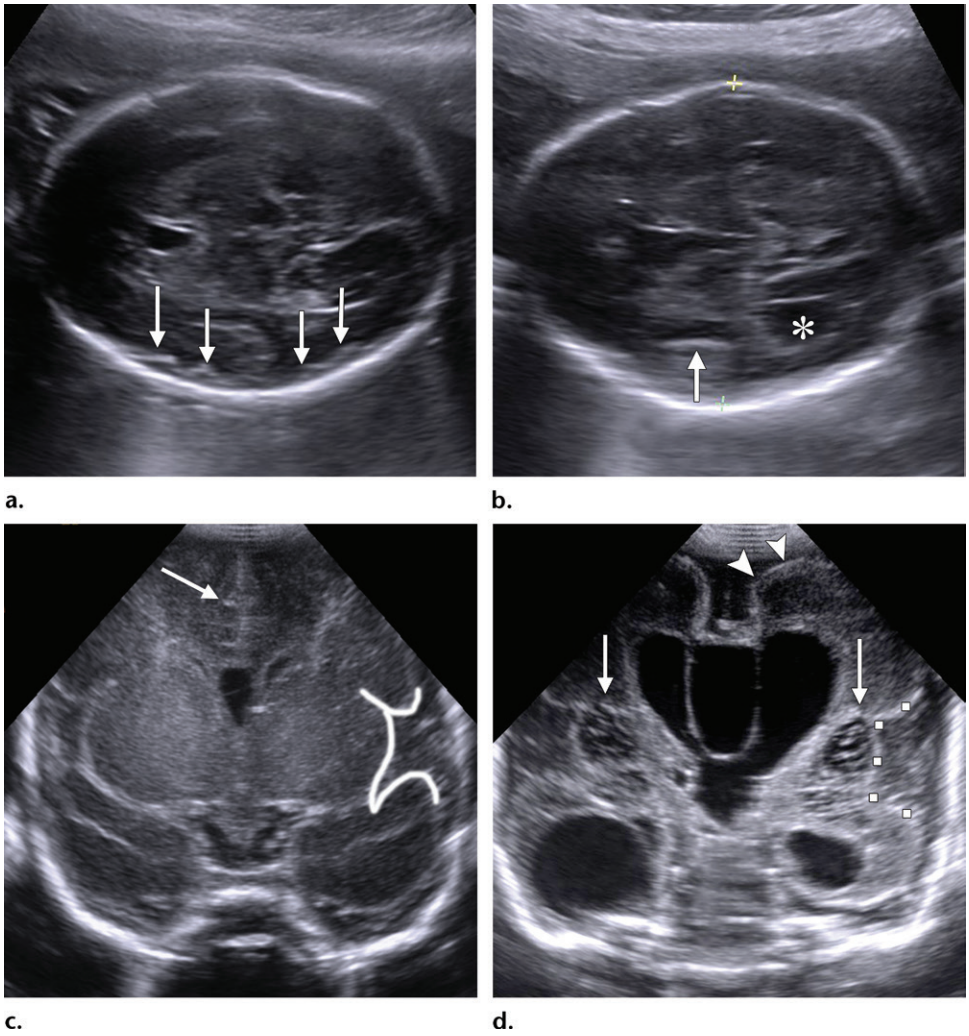


Figure 11. Consequences of unequal placental sharing in the same pregnant patient shown in Figure 10. The patient was admitted at viability (ie, 24 weeks) and given steroid therapy in anticipation of preterm delivery. She was counseled that the likely outcome for twin B was poor, given the early onset of severe growth restriction with reversed end-diastolic flow in the umbilical cord. Daily biophysical profiles and Doppler US of the ductus venosus and the umbilical cord were performed. A-wave reversal at Doppler US of the ductus venosus in twin B was considered a preterminal event, which precipitated delivery at 28 weeks. **(a)** Axial US image of the fetal brain of twin A at 25 weeks shows a normal cavum, normal development of the surface gyri (arrows), and no ventriculomegaly. **(b)** Axial US image of the fetal brain of twin B at 25 weeks shows ventriculomegaly, with the ventricle (*) measuring 13 mm (upper limit of normal, 10 mm), as well as no development of the surface gyri, with a smooth cortex and wide open sylvian fissures (arrow). Calipers indicate biparietal diameter. **(c)** Coronal neonatal US image of the head of twin A at 28 weeks shows a normal appearance, with sylvian fissure operculization (outlined in white) and a visible cingulate sulcus (arrow). **(d)** Coronal neonatal US image of the head of twin B at 28 weeks shows severe diffuse ischemic encephalomalacia, with marked ventriculomegaly, a smooth cortical surface (arrowheads), no sylvian fissure operculization (outlined by squares), and cystic changes in the deep white matter (arrows). The family withdrew support from twin B after review of the neonatal brain findings, which indicated a dismal prognosis for neurologic function. Twin A did well despite premature delivery.

cerebroplacental ratio as a measure of fetal brain sparing. The assessment of fetal anemia by using Doppler US of the middle cerebral artery can start as early as 18 weeks. In calculation of the cerebroplacental ratio, the pulsatility index is preferred over the S/D ratio. The cerebroplacental ratio is a ratio of the middle cerebral artery flow to the umbilical artery flow by using the pulsatility index values; therefore, the angle of insonation is less important than when using Doppler US of the middle cerebral artery for assessment of anemia, where measurement of velocity is angle dependent. The cerebroplacental ratio compares fetal brain perfusion to that of the placenta. In normal circumstances, flow in the middle cerebral artery is fairly high resistance, and flow in the umbilical artery should be low resistance, with continuous antegrade flow and a continuous increase in the diastolic flow as the pregnancy progresses. As a rule of thumb, the S/D ratio in

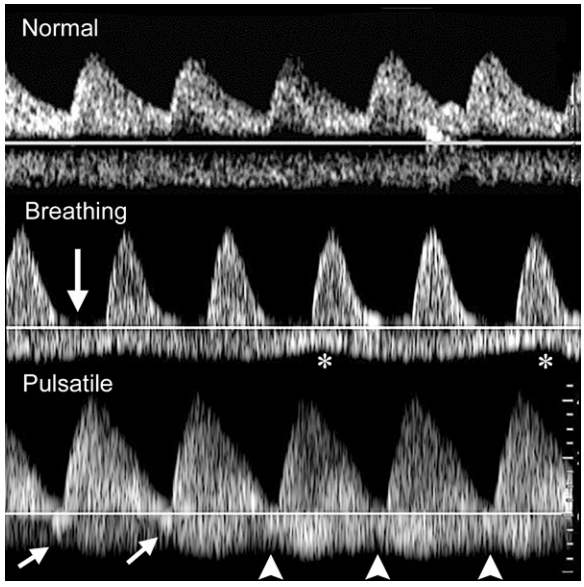
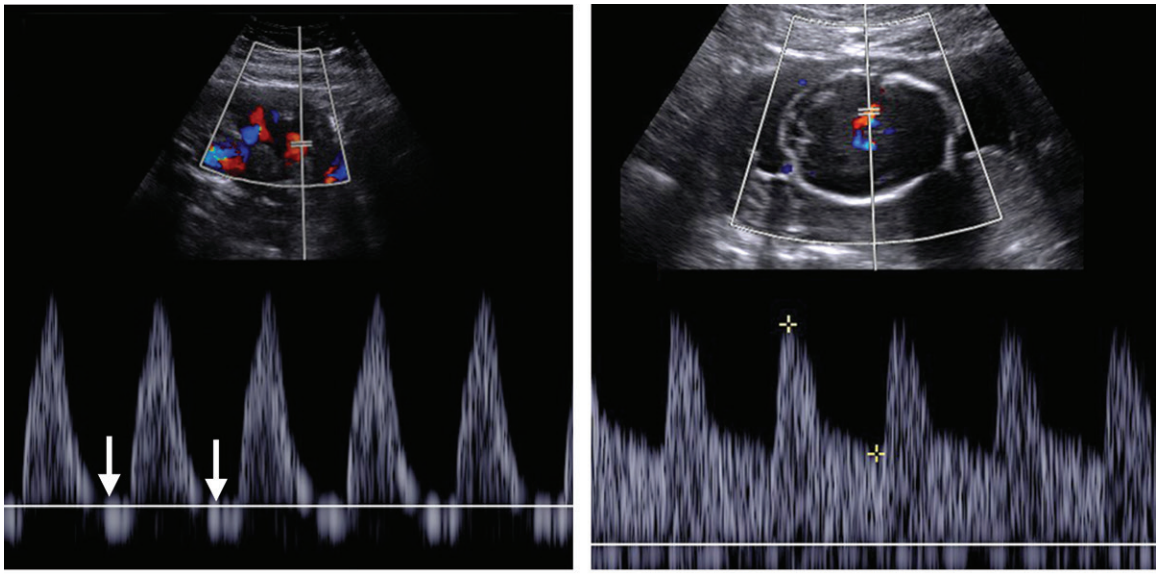


Figure 12. Umbilical vein waveforms. Top: Spectral US image shows a normal umbilical artery waveform above the line and a normal umbilical vein waveform below the line. Note the continuous flow throughout the cardiac cycle. Middle: Spectral US image shows absent end-diastolic flow (long arrow) in the umbilical artery, with undulations in the umbilical vein (*) owing to fetal breathing. The undulations are independent of the fetal heart rate. Bottom: Spectral US image shows mixed absent and reversed end-diastolic flow (short arrows) and a pulsatile umbilical vein waveform (arrowheads). The umbilical vein pulsations occur during diastole at the same time as the absent end-diastolic flow.



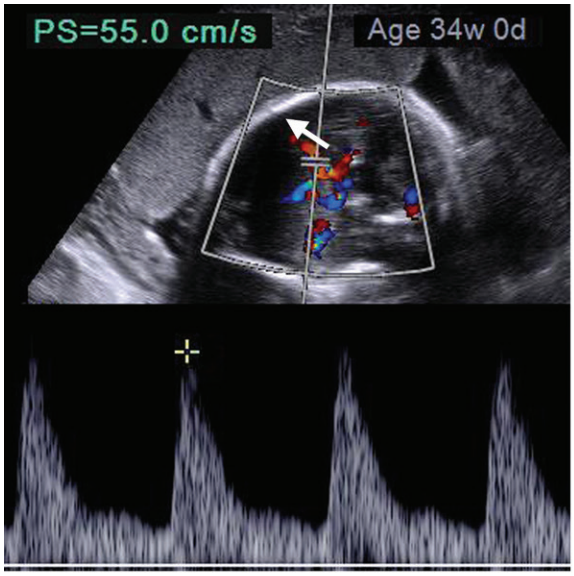
a. **b.**

Figure 13. Abnormal cerebroplacental ratio. **(a)** Color Doppler duplex US image of the umbilical artery shows reversed end-diastolic flow (arrows) at 25 weeks in a fetus with severe early-onset growth restriction. **(b)** Color Doppler duplex US image shows that increased diastolic flow was present in the middle cerebral artery, indicating "head-sparing" flow and an abnormal cerebroplacental ratio. Calipers indicate peak systolic velocity (upper caliper) and end-diastolic velocity (lower caliper). The estimated fetal weight of about 350 g was such that resuscitation was unlikely to be successful if the infant were to be delivered with an emergency cesarean delivery. Intrauterine death occurred at 29 weeks; the measured fetal size was that of a fetus of 21 weeks gestation. The patient declined autopsy and placental histopathologic examination.

the umbilical artery should always be lower than that in the middle cerebral artery. In response to hypoxia, the fetus diverts blood flow to the brain, increasing the middle cerebral artery diastolic flow, thereby decreasing the pulsatility index and altering the ratio of the umbilical artery flow to the middle cerebral artery flow (Fig 13).

Bahado-Singh et al (26) found a significant increase in perinatal morbidity and mortality in fetuses at risk for growth restriction who had an abnormal cerebroplacental ratio—defined as the ratio of the middle cerebral artery pulsatility index divided by the umbilical artery pulsatility index that is less than the 5th percentile for gestational age—but only until 34 weeks gestation. Thereafter, the correlation was lost (26). In the results of other studies, investigators suggested that an abnormal cerebroplacental ratio at more than 37 weeks is strongly associated with adverse obstetric outcomes (27). Although the cerebroplacental ratio appears to hold promise in guiding clinical management of fetal growth restriction,

Figure 14. Doppler US of the middle cerebral artery in a single fetus. The middle cerebral artery should be sampled with a 0° angle of insonation. **(a)** Color Doppler duplex US image obtained with poor technique in a 34-week fetus shows that when the middle cerebral artery is sampled with poor technique, the measured peak systolic velocity (PS; caliper) is 55.0 cm/sec. The vertical white line marks the orientation of the ultrasound beam. The arrow indicates the orientation of the middle cerebral artery. The angle of insonation is the angle between the arrow and the vertical line; this angle should be 0°. **(b)** Color Doppler duplex US image obtained with correct technique in the same 34-week fetus shows that using the correct technique with an angle of insonation of 0° results in a peak systolic velocity (PS; caliper) measurement of 64.5 cm/sec. Note that the orientation of the ultrasound beam (vertical white line) is now directly parallel to the arrow marking the long axis of the middle cerebral artery. At this gestational age (34 weeks), the difference is from 1.1 to 1.25 multiples of the median. **(c)** Color Doppler duplex US image obtained with correct technique compromised by fetal breathing of the same fetus shows that in this case, the angle of insonation is correct, but the waveform is distorted by fetal breathing. Therefore, it is not possible to select an accurate measurement of peak systolic velocity to predict fetal anemia.



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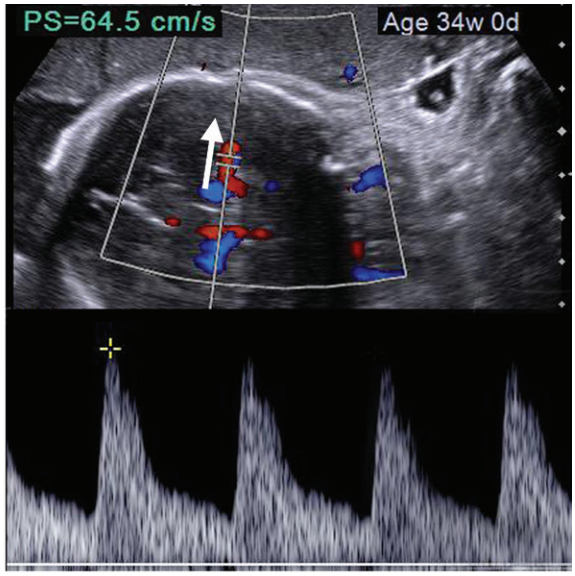

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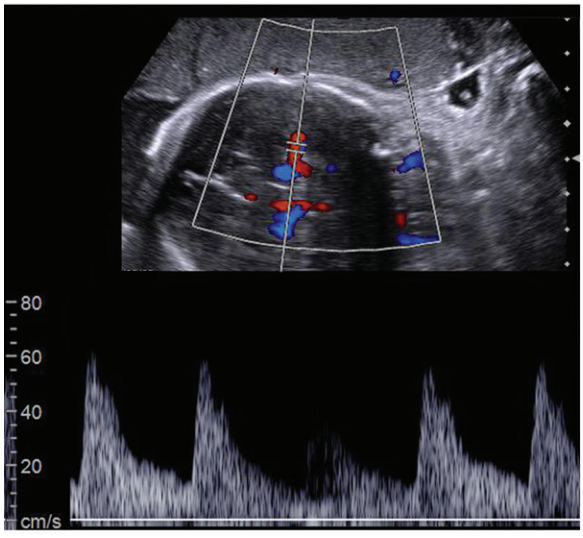

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the investigators in two recent reviews stated that there is insufficient evidence to demonstrate the value of the cerebroplacental ratio as a stand-alone test and that large clinical trials are needed to determine its role (28,29).

In fetal anemia, flow in the middle cerebral artery increases for several reasons. Fluids move faster through a fixed-diameter tube as viscosity decreases; therefore, as the fetal hematocrit reading decreases, middle cerebral artery flow velocity increases. In addition, in a compromised fetus, cerebral vasodilatation diverts blood flow to the brain; because flow velocity in a pipe is proportional to the fourth power of the radius, a small increase of the middle cerebral artery diameter results in a considerable increase in flow velocity (Poiseuille law). Cardiac output also increases in anemic fetuses.

For the best technique to measure the peak systolic velocity in the middle cerebral artery, first use color Doppler flow US to identify the circle of Willis in an axial view of the fetal head. The middle cerebral artery branches off the circle of Willis and runs into the sylvian fissure. Most fetuses in cephalic presentation will thus have the near-field middle cerebral artery running toward the maternal abdominal wall. In real time, the transducer position can be adjusted relative to the fetal head so that the middle cerebral artery is sampled with the beam parallel to the long axis of the vessel, creating a 0° angle of insonation (Fig 14b). The image is magnified such that the color image of the circle of Willis occupies 50% of the image and the middle cerebral artery is depicted for its entire length. The 1-mm sample volume cursor is placed within 2 mm of the origin of the middle cerebral

artery with a 0° angle of insonation while the fetus is at rest and not breathing (30).

The peak systolic velocity is measured; multiples of the median for gestational age are calculated and followed over time. A useful calculator is available online to quickly calculate the multiples of the median for gestational age (31). The risk of fetal anemia is highest when the peak systolic velocity is more than 1.5 multiples of the median for gestational age (32).

Obviously, technique is critical in the evaluation of fetal anemia, because multiples of the median of the peak systolic velocity in the middle cerebral artery are used to determine surveillance intervals and the timing of intrauterine transfusion. Serial amniocentesis for measurement of blood breakdown products in fetuses with alloimmunization has been replaced by serial Doppler US examinations; invasive procedures are now performed with intent to treat anemia with intrauterine transfusion (Fig 14). Whenever unexplained fetal hydrops is encountered, it is vital to check for fetal anemia as a cause. Transfusion may be lifesaving in this setting (33).

The most common application of middle cerebral artery peak systolic velocity measurement is in tracking patients at risk for fetal anemia owing to alloimmunization. This measurement may also be used *(a)* with other potential causes of anemia, including viral infection (eg, parvovirus); *(b)* when there is concern for anemia secondary to bleeding into a fetal tumor; and *(c)* in the evaluation of twin anemia-polycythemia sequence, which may complicate monochorionic twin pregnancies (34,35).

Doppler US of the Uterine Artery

Doppler US of the uterine artery is used in the first trimester to screen for early-onset preeclampsia and other adverse pregnancy outcomes such as fetal growth restriction, particularly early-onset disease (36). In the second and third trimesters, Doppler US of the uterine artery may be used in the evaluation of pregnancies complicated by fetal growth restriction.

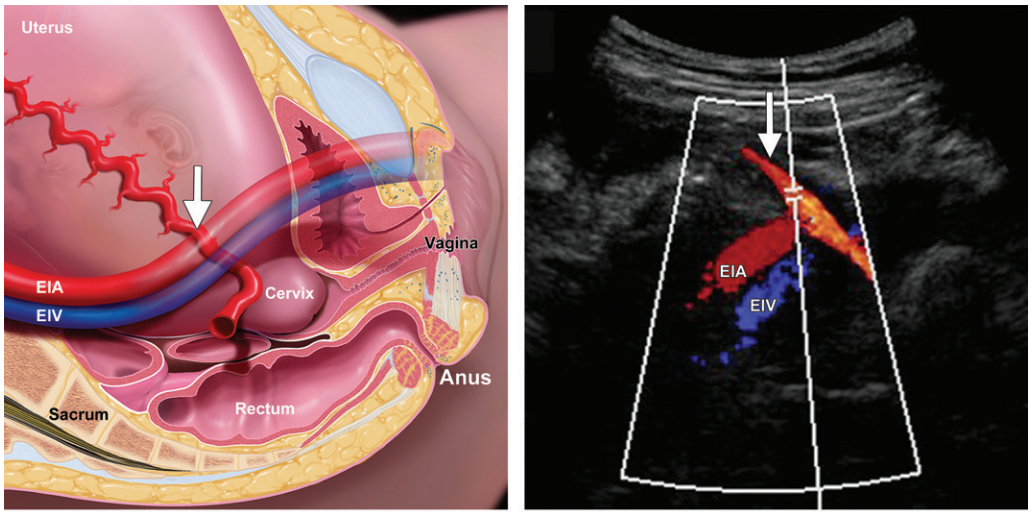
The uterine artery is a branch of the internal iliac artery that runs anteriorly in the pelvis to enter the myometrium at the junction of the uterine corpus and cervix (ie, the cervicoisthmic junction). In the nonpregnant state, the waveform is high resistance with low diastolic flow and early diastolic notching. Remodeling of the uterine artery branches is essential for successful placentation; this remodeling is indicated by a change in the waveform to become low resistance with continuous diastolic flow. This recruitment of placental blood flow is rapid; notching should disappear by 13 weeks (37), and low-resistance flow should be established by 20 weeks at the latest (38). An abnormal waveform is characterized by increased resistance and persistence of a diastolic notch beyond the late second trimester. A *diastolic notch* is defined as a reduction in forward flow at the start of diastole and is thought to represent abnormal uteroplacental flow. A diastolic notch has been associated with adverse outcomes, including fetal growth restriction, maternal preeclampsia, increased risk of preterm delivery, and fetal distress in labor (39–41).

The transducer is placed in the lower lateral quadrant of the abdomen angled medially. Color Doppler flow US is used to identify the uterine artery as it courses anteriorly and appears to cross the external iliac artery (Fig 15) (10). The orientation of the vessel allows for a low angle of insonation, typically 15°–30°; aim for as close to 0° as possible. Fetal activity does not alter the uterine artery waveform, unlike those of the umbilical artery, the umbilical vein, and the middle cerebral artery. Samples can be obtained during normal maternal respiration. The most important observation is the presence of a diastolic notch, but various Doppler US parameters may be measured in a research setting (Fig 16).

Clinical Applications of Color Doppler Flow US

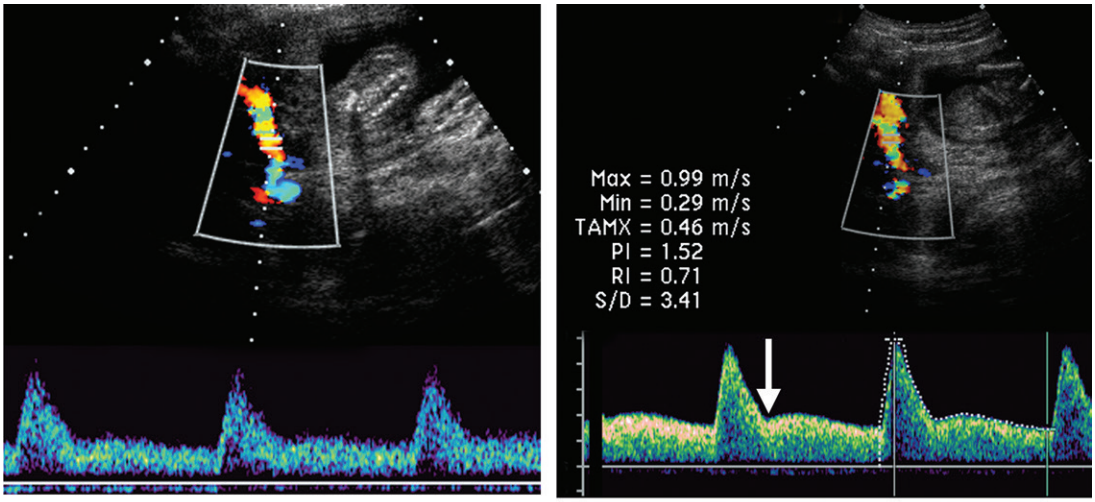
Documentation of the placental site of umbilical cord insertion is part of the standard obstetric US examination. This documentation is easier to do with color Doppler flow US than with gray-scale US alone, especially when the placenta is posterior or when dealing with a multiple pregnancy. Normally, the umbilical cord inserts on the placental disk, but it can have either a marginal or velamentous insertion. *Marginal insertion* is defined as placental attachment within 2 cm of the edge of the placental disk. The placental site of umbilical cord insertion should be documented in longitudinal and transverse planes, because marginal cord insertion may not be apparent if imaged in only one plane.

A velamentous cord inserts on the membranes rather than onto the placental disk. The umbilical vessels then traverse the membranes to reach the placenta and, while doing so, are unprotected by Wharton jelly and the tough coverings of the umbilical cord (Fig 17). If the unprotected vessels traverse the cervix or run within 2 cm of the internal os, this condition is known as vasa previa. Unprotected vessels in the membranes over the cervix are at risk for rupture as the cervix dilates or when membranes rupture. When this situation occurs, fetal exsanguination can occur within minutes. Vasa previa is considered a critical finding. Management of prenatally diagnosed vasa



a. b.

Figure 15. Doppler US technique for the uterine artery. *EIA* = external iliac artery, *EIV* = external iliac vein. **(a)** Anatomic drawing of a third-trimester pregnancy shows the location of the uterine artery (arrow) at the cervicoisthmic junction. Although the lower uterine segment elongates and the fundal height increases, the location of the cervicoisthmic junction does not change in pregnancy. (Reprinted from reference 10.) **(b)** Color Doppler flow US image shows the sample volume placed in the uterine artery (arrow) with an angle of insonation of about 30°. The uterine artery perfuses the myometrium, so flow is toward the transducer, because the uterine artery is a branch of the internal iliac artery deep in the maternal pelvis.



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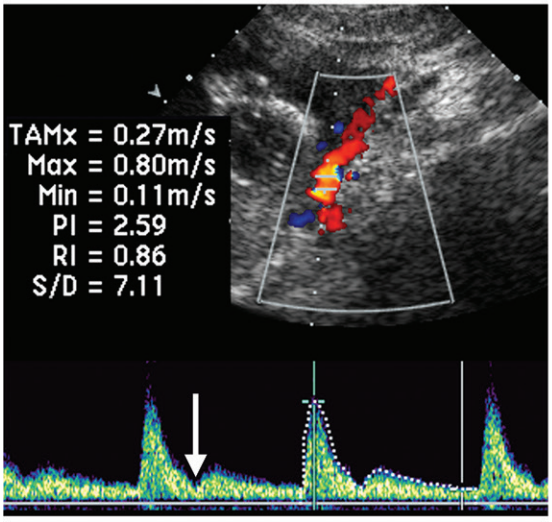

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Figure 16. Uterine artery waveforms. **(a)** Color Doppler duplex US image shows a normal waveform with no notch and continuous diastolic flow. **(b)** Color Doppler duplex US image shows an abnormal waveform with a mild notch (arrow) in diastole but preserved end-diastolic flow. Max = maximum (same as peak systolic velocity), Min = minimum (same as end-diastolic velocity), PI = pulsatility index, RI = resistance index, TAMX = time-averaged maximum velocity. **(c)** Color Doppler duplex US image shows an abnormal waveform with marked notching (arrow) and decreased end-diastolic flow. Max = maximum (same as peak systolic velocity), Min = minimum (same as end-diastolic velocity), PI = pulsatility index, RI = resistance index, TAMx = time-averaged maximum velocity.

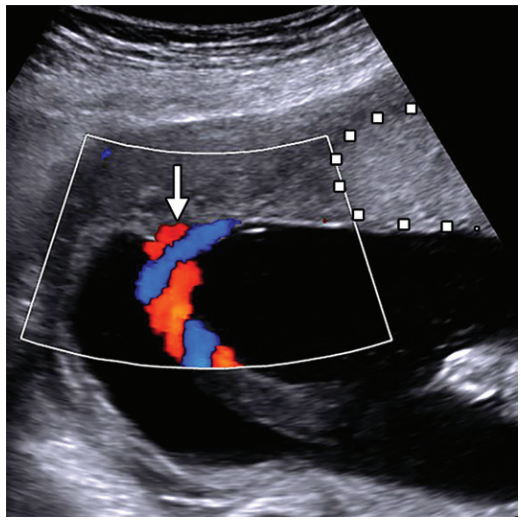
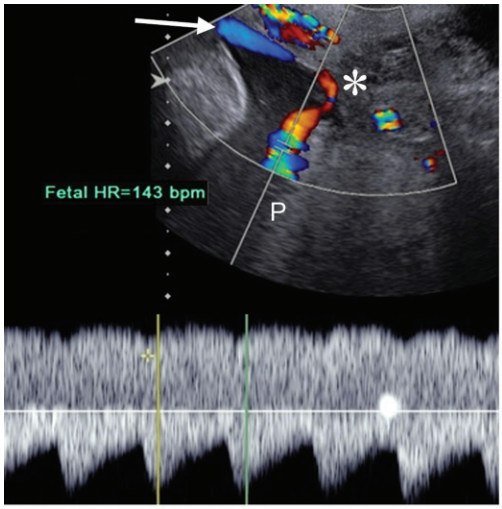


Figure 17. Velamentous insertion. Color Doppler flow US image of a 20-week fetus shows the umbilical cord inserting on the membranes (arrow) some distance from the placental margin (outlined by squares). With color Doppler flow US, it is easier to identify the site of umbilical cord insertion than with gray-scale US alone.

Figure 18. Vasa previa. **(a)** Transvaginal color Doppler duplex US image of a 32-week fetus shows a vessel crossing the internal cervical os (*) and entering the placenta *(P)* from an anterior velamentous insertion. The spectral waveform is an arterial waveform with a fetal heart rate (HR) of 143 beats per minute (bpm), indicating that this vessel is an umbilical artery and helping confirm the diagnosis of vasa previa. The umbilical vein (arrow) is seen separately, in the membranes, anteriorly. **(b)** Intraoperative photograph obtained at the time of cesarean delivery shows the distended umbilical vein (arrows) running in the membranes, which are bulging through the hysterotomy. **(c)** Photograph of the placenta shows the distended umbilical vein (arrows) running in the membranes to the site of the velamentous insertion. The umbilical arteries (arrowheads) are smaller but still vulnerable while running in the membranes.



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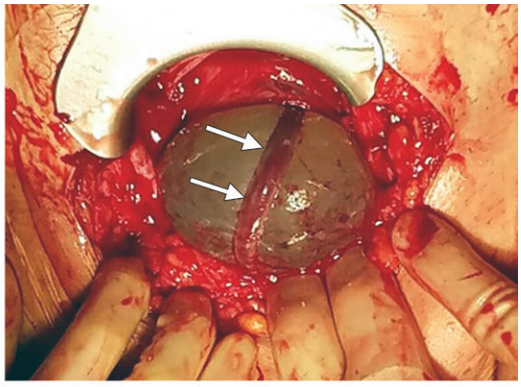

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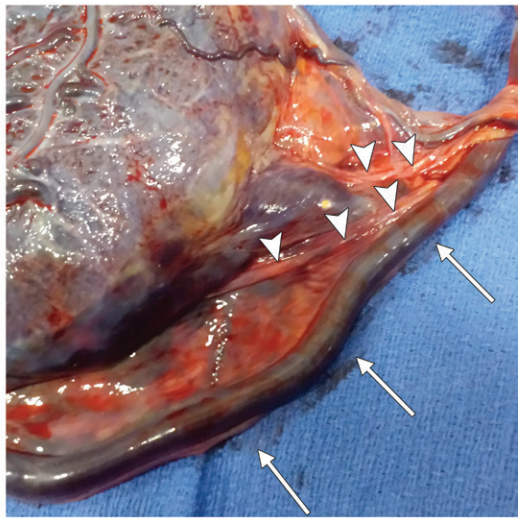

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previa includes antenatal corticosteroid therapy between 28 and 32 weeks of gestation, consideration for preterm hospitalization at 30–34 weeks of gestation, and scheduled cesarean delivery at 34–37 weeks of gestation (Fig 18). Dedicated imaging protocols with endovaginal US and color Doppler flow US have been shown to improve antenatal detection of vasa previa (42,43). In turn, antenatal detection results in improved outcomes. Neonatal survival in cases with antenatal diagnosis was 97%, compared with 44% in those not diagnosed; and the blood transfusion rate in the known group was 3.4%, compared with

58.5% in the undiagnosed cases (44). Velamentous insertion is also associated with fetal growth restriction and with discordant growth in multiple gestations (45,46) (Figs 10, 11).

Conclusion

Doppler US examinations provide a window into the fetoplacental circulation. Technique is critical to obtain the best waveforms for ease of shape assessment, velocity measurement, and calculation of various ratios. Doppler US of the umbilical artery is an integral component of managing the fetus with growth restriction, and Doppler US of the middle cerebral artery allows noninvasive assessment of fetal anemia. Other Doppler US parameters are being investigated and may have niche roles in specific clinical settings.

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