Part 1

Objective
The use of Doppler sonography in prenatal medicine and obstetrics to analyze flow rates in different maternal and fetal blood vessels has become extremely important. This is largely the result of extensive worldwide studies and the application of this knowledge in daily clinical practice thanks to the DEGUM-certified courses offered over the last 25 years. Doppler sonography is used for screening, assessing fetal health, and monitoring complicated pregnancies, and serves as a tool for making obstetric decisions. It has a broad range of uses in hospitals and physician’s offices during all three trimesters [1–5]. As in all areas of medicine, correct application of the method is a prerequisite for ensuring good quality of resulting clinical decisions [1, 4]. The first step...
Technical Principles and Methods

Equipment

The ultrasound device used for Doppler sonography in obstetrics provides color Doppler and spectral Doppler ultrasound images as well as B-mode images and is approved for use in obstetrical examination.

Technical Principles and Methods

Setting: Pulsed Doppler sonography (pulsed wave, PW-Doppler) is used for imaging in pregnancy. The color Doppler signal makes it possible to locate the vessel on the B-mode image and to position the Doppler window (sample volume) more quickly and easily. The Doppler signal can be derived in duplex or triplex mode, but duplex mode is preferable because the quality of the resulting Doppler sonogram (Doppler curve, spectral curve, envelope, Doppler effect curve) is better and the energy load is lower.

The default setting should emphasize the Doppler sonogram and not the B-mode image (2/3 vs. 1/3) (Fig. 1).

Angle. Based on the Doppler equation \( f_d = 2f_0 \cos \alpha \cdot v/c \), the following parameters are significant. The insonation angle \( (\alpha) \) in the direction of the blood flow should be as small as possible to achieve the highest Doppler shift frequencies \( (f_d) \). The angle setting helps to adjust the insonation angle appropriately. When measuring absolute velocities, the insonation angle should be as close to 0° as possible; at angles ≥ 30°, velocity measurements are subject to greater errors because of the cosine function of the Doppler equation.

Flow rate. An average flow rate should be selected when plotting the Doppler curve so that ideally 3 to 6 cycles are shown when measuring fetal and maternal vessels. This makes it possible to measure the Doppler curves exactly and to assess their uniformity.

Gain. The gain should be selected so that the signal can be clearly differentiated from background noise and the Doppler spectrum is distinctly displayed against the background. In addition, the intensity of the individual Doppler shift frequencies within the spectrum should be visible.

High-pass filter. The movements of the vessel walls produce low-frequency interference signals that a high-pass filter can suppress. It should be set to ≤ 60 Hz to ensure that low end-diastolic Doppler shift frequencies are recorded.

Display of the Doppler signal. The recorded Doppler sonogram represents the measured frequency shift (Doppler shift frequency). The devices report either frequencies (Hz) or velocities \( (\text{cm/s}) \). The latter assumes an optimal insonation angle of 0° or 180°. Blood flow towards the transducer produces positive Doppler shift frequencies, while blood flow away from the transducer results in negative frequencies. In color Doppler sonography, these flows are coded red and blue, respectively.

Aliasing. If the Doppler shift frequency exceeds the Nyquist limit (maximum pulse repetition frequency (PRF)/2), the higher frequencies erroneously appear in the reverse channel (aliasing effect). There are multiple ways to correct aliasing. The first approach is to increase the PRF and/or adjust the baseline. If that does not work, the transducer can be used at a lower frequency in duplex mode because it allows a higher PRF. Using a CW Doppler transducer is yet another alternative.

Doppler window (sample volume). In pulsed Doppler sonography, the measurement site is precisely defined by the positioning of the sample volume. The size of the sample volume can vary depending on the case and is normally 2 – 3 mm. When measuring blood flow volume, the sonographer must ensure that the sample volume captures the entire cross-section of the vessel.

Transducer frequency. Transducer frequency is differentiated into B-mode and Doppler mode. Higher frequencies in Doppler mode lead to higher Doppler shift frequencies at the same blood flow velocities. Higher Doppler frequencies are therefore better at capturing lower velocities.

Continuous wave (CW Doppler). In continuous wave Doppler, all Doppler shift frequencies in the overall ultrasound beam are recorded. It therefore is not possible to precisely define a measurement range. However, the aliasing effect poses no limitations, even permitting measurement of extremely high velocities.

Vascular areas

Both arterial as well as venous vessels can be examined via Doppler sonography, whereby maternal-placental, feto-placental, and fetal vessels are differentiated (Table 1, 2).

The arterial vessels exhibit a biphasic, pulsatile flow pattern with a systolic and a diastolic phase (Fig. 1).

The velocities vary between the arteries and increase over the course of the pregnancy. The pulsatility of the blood flow pattern also depends on gestational age. Pathological changes are accompanied by an increase in pulsatility. Pulsatility decreases only in the cerebral arteries.

Depending on the cardiac cycle, there is a triphasic flow pattern in the veins surrounding the heart, with a systolic and early
diastolic peak as well as a nadir during the late diastolic atrial contraction (▶ Fig. 2).

In the umbilical vein, the blood flow is uniform and hence monophasic (▶ Fig. 3). Pathological changes are accompanied by an increase in pulsatility in the veins near the heart. In the umbilical vein, the blood flow then becomes pulsatile. Reference curves based on gestational age should be consulted to evaluate pulsatility and velocities.

In practice, the following vessels are of particular importance:

**Uterine arteries** The blood flow in the uterine arteries is largely determined by the downstream maternal-placental vasculature, especially the shape of the spiral arteries. Owing to the expansion of the vascular lumina caused by the trophoblast invasion, the flow resistance drops and the pulsatility decreases as an expression of altered impedance. Accordingly, the pulsatility in the uterine arteries falls in the first and early second trimester [6]. An early diastolic notch is also an expression of increased impedance. A notch arises from a pulse wave reflection when vascular continuity changes; it then disappears when the spiral arteries are fully dilated. It is found bilaterally at the end of the first trimester (▶ Fig. 4) in approximately 50% of pregnant women but almost always disappears by the 24th week (▶ Fig. 5, 6). Bilateral notching is therefore detectable after the 24th week of pregnancy only in fewer than 5% of normal pregnancies [6–9]. The further from the placenta, the higher the pulsatility. It is measured near the cervix in the respective main branch of the right and left uterine arteries in the absence of contractions.

**Umbilical artery** The blood flow in the umbilical arteries is largely determined by the downstream feto-placental vasculature, the number and width of the small arteries, arterioles, and especially the sinusoidal end segments of the placental villi. It therefore reflects the degree of villi maturation, which persists throughout the entire course of the pregnancy. Accordingly, the pulsatility in the umbilical arteries decreases over the course of the pregnancy [10–14]. Within the umbilical cord, the pulsatility decreases in the direction of the placental insertion [13]. It is therefore recommended to measure the middle section of the free umbilical cord (▶ Fig. 1).

**Middle cerebral artery (MCA)** The pulsatility of the middle cerebral artery is qualitatively assessed during Doppler sonography examination. Its pulsatility is largely determined by the flow resistance of the downstream cerebral vasculature. Pulsatility increases slightly during pregnancy and drops again around the 34th gestational week [10, 15–17].

A quantitative measurement of the peak systolic velocity (PSV or Vmax) is performed in the MCA to diagnose anemia [18]. In this context, particular quality standards apply: Color Doppler sono-
Doppler Sonography during Fetal Ultrasound Imaging

Graphy is used to locate the circle of Willis in the transverse cerebral section. It is best to visualize the full length, rather than specific points or short stretches, of the MCA near the transducer. This also ensures that the azimuthal angle is close to 0°. The image is enlarged to nearly maximum such that the MCA takes up more than 50% of the image. The Doppler signal is derived from a 1–3 mm sample volume 1.0–1.5 cm from the branch of the MCA from the circle of Willis or the internal carotid artery. The insonation angle should be 0° if possible; an insonation angle < 15° is tolerable (Fig. 6), while insonation angles ≥ 30° cannot be used [19, 20], because major errors in absolute velocity measurement are unavoidable even when the angle is adjusted (Fig. 7). The peak systolic velocity (PSV), i.e., the highest point of the Doppler sonogram, is measured. Measurements should be performed three times; the highest PSV is evaluated [19, 20]. If the position is unfavorable, the measurement can also be performed in the MCA of the cerebral hemisphere remote from the transducer [19]. Phases of fetal heart rate acceleration should be avoided particularly in the third trimester, because the PSV of the MCA decreases at that time [21].

**Descending aorta** The fetal aorta is no longer measured because it provides no additional information compared with the above-named vessels and also presents methodological difficulties. In particular, the pulsatility depends on the measurement site, and the insonation angle is almost always unfavorably large due to the position. These conditions adversely affect the reproducibility of this measurement.

**Pulmonary arteries** Measurements of the pulmonary arteries are reserved for special issues, especially for evaluating the pulmonary arterial vascular bed to predict pulmonary hypoplasia or pulmonary hypertension.

**Ductus venosus** The pulsatility of the ductus venosus (DV), like other systemic veins near the heart, is largely determined by fluctuations in central venous and right arterial pressure. It conti-
nually decreases over the course of the pregnancy [22, 23]. After the first trimester, there is an antegrade flow in all phases. The DV differs from other veins near the heart in that its blood flow velocities are significantly higher, which makes it easy to identify with color Doppler owing to the aliasing effect (▶ Fig. 8). The measurement is performed in a longitudinal parasagittal section, with the full length of the DV being visualized at a minimal insonation angle (<30°). The sample volume should not exceed 2 mm to avoid recording the pulsatile flow pattern with the negative a-wave of the adjacent liver veins (▶ Fig. 2).

**Umbilical vein** The blood flow pattern of the umbilical vein is determined in the free umbilical cord. It is monophasic with a consistent antegrade flow, like in the intra-abdominal section of the umbilicus vein (▶ Fig. 3). Only a marked increase in the pulsatility in the ductus venosus will result in flow patterns in the umbilical vein with biphasic, or rarely triphasic, pulsatility [24].

**Pulmonary veins** The pulmonary venous blood flow pattern is best derived in the vein near the transducer close to where the vein enters the left atrium.

The pulsatility in the pulmonary veins reflects the left atrial pressure, which equals the right atrial pressure when the foramen ovale is open. Therefore, the pulsatility in the pulmonary veins usually changes in line with that of the systemic veins. The blood flow pattern is triphasic with a constant positive flow [25, 26]. Regardless of the right atrial pressure, only severe diastolic dysfunction of the left ventricle will result in a poor or absent antegrade or retrograde flow during left atrial systole, which is particularly pronounced in the case of a highly restrictive or intact atrial septum [27, 28].

**Evaluating the Doppler Sonogram**

The Doppler curve can be evaluated qualitatively and quantitatively.

Qualitative evaluation means assessing the shape (e.g., retrograde flow or notching) and pulsatility of the Doppler curve.

Pulsatility is characterized by the impedance indices, the resistance index (RI), and pulsatility index (PI) (▶ Table 3). In general, the PI is favored because it contains more information about the blood flow. To qualitatively assess the uterine arteries, the average of the left and right PIs is used.

Quantitative evaluation involves recording absolute blood flow velocities and is reserved for specific indications such as anemia diagnostics in the middle cerebral artery.

Most modern devices can analyze the Doppler curve via automatic curve tracing. This requires flawless recording of the Doppler curve (see ▶ Fig. 1, 2, 6). If the curve is not perfect, the measurement can be done manually. But it is better to repeat the measurement (▶ Fig. 9).

**Sources of error**

As with every examiner-dependent method, a number of errors are possible in Doppler sonography. Most errors occur when the above-described measurement techniques are not observed.

The following possible errors should also be kept in mind:

**Uterine arteries** – Measurement during a uterine contraction results in a decrease in the diastolic blood flow or even flow reversal, measurement of smaller uterine vessels (arcuate arteries);

**Umbilical artery** – Measurement during fetal body or respiratory movements (▶ Fig. 10);

**Table 3 Indices for arterial and venous vessels**

<table>
<thead>
<tr>
<th>Index</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>RI = (S-D)/S</td>
</tr>
<tr>
<td>Pulsatility</td>
<td>PI = (S-D)/TAmax</td>
</tr>
<tr>
<td>Pulsatility</td>
<td>PIV = (S-a)/D</td>
</tr>
<tr>
<td>Peak velocity</td>
<td>PVIV = (S-a)/TAmax</td>
</tr>
</tbody>
</table>

RI = resistance index, PI = pulsatility index, PIV = pulsatility index for veins, PVIV = peak velocity index for veins, TAmax = average velocity of the envelope or maximum velocities of a cycle.
Middle cerebral artery – Too much transducer pressure causes a loss of diastolic blood flow.

Ductus venosus (see ▶ Fig. 2) – Mix-up with adjacent vessels (e.g., liver veins) (▶ Fig. 11), resulting in incorrect Doppler spectrum, measurement during fetal respiration.

Documentation
Images of every Doppler sonographic examination should be documented to show the envelope and its measurement.

Patient Safety
Ultrasound waves generate mechanical and thermal energy in biological tissues. Sonographic examinations should therefore follow the ALARA principle (as low as reasonably achievable). The default settings of modern ultrasound devices are adjusted specifically for use in fetuses. The examiner is required to check the thermal index (TI) and mechanical index (MI) settings. In B-mode ultrasound, the TI should be lower than 1.0 and the MI under 0.7. In pulsed Doppler sonography, in particular, these limits are exceeded to keep the examination time as brief as possible (ALARA principle). Especially in early pregnancy, the indications for Doppler sonography should be determined on a very strict basis [29].

Certification and Quality Management
Authorization for medical practices in Germany to use and bill for Doppler examinations in obstetrics and gynecology is regulated by the Ultrasound Agreement (Agreement on Quality Assurance Measures in accordance with § 135, paragraph 2 of Social Code Book V (SGB V) on ultrasound diagnostics (Ultrasound Agreement of October 31, 2008 in the currently valid version effective October 1, 2017). The Agreement differentiates between Doppler in prenatal diagnosis (application area = AB 22.1, duplex procedure – fetal cardiovascular system; AB 22.2, duplex procedure – fetomaternal vascular system) and Doppler examination of the vessels of the female genital system (AB 20.11 duplex procedure – vessels of the female genital system). Authorization must be obtained for each of these application areas.

There are currently multiple options for obtaining Doppler sonography certification. These are likewise specified in the Ultrasound Agreement (§ 4: Acquisition of technical skills in accordance with the Regulation on Continuing Education; § 5 Acquisition of technical skills through regular activity; § 6 Acquisition of technical skills through ultrasound courses) (www.kbv.de/html/ultraschall).

Beyond the course specifications contained in the Ultrasound Agreement, the DEGUM also developed and specified quality standards for the content of these courses (www.degum.de).

The courses also cover the use of Doppler sonography on the uterine arteries, ductus venosus, and tricuspid valve during first-trimester screening. The use of these Doppler parameters in algorithms to identify the risk of aneuploidy and to predict the risk of preeclampsia and IUGR requires primary certification as well as annual auditing (www.fetalmedicine.com, www.fml-deutschland.de).

Conflict of Interest
The authors declare that they have no conflict of interest.

References