Flow Assessment Using the Doppler Spectrum

5

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5.1 Methodology of Spectrum Analysis

After the so-called demodulation of the ultrasonic waves reflected back to the transducer, the low Doppler frequency 1–20 kHz shift mentioned in Sect. 4.1 remain. These frequencies are converted into digital signals with the aid of an analog-digital (AD) converter and can then be further processed in any standard PC.

The detection of the frequency components of the Doppler spectrum is usually done by the method of **Fast Fourier Transformation** (FFT). As already mentioned in Sect. 4.1.4 above, the frequency-time spectrum, that is, the representation of the individual frequency components on the y-axis over time (x-axis), has become the standard in medicine. The incidence of the individual frequency components ("power") can be "coded" in color or brightness levels.

5.1.1 Fast Fourier Transformation (FFT)

As shown in Fig. 3.7, any complex curve function can be decomposed into numerous sinusoidal oscillations and thus analyzed in its frequency components. This finding is connected with the name of the French mathematician Jean Baptiste Fourier (1768–1830). The "FFT" is merely a special calculation rule for the rapid decomposition of the individual frequency components. The frequency resolution is usually given in "points." A 128-point FFT means nothing else than that, for example, a Doppler spectrum with a maximum frequency of ±3.2 kHz can be decomposed into 2 × 64 individual frequency components with a resolution of 50 Hz each. The FFT point values of 64, 128, 256, 512, etc. have a compelling mathematical background, which needs not be discussed in detail here.

Summary
Doppler signals can be analyzed in their individual frequency components using spectrum analysis and displayed graphically over time (frequency time spectrum). The Fast Fourier Transformation (FFT) is used mathematically for this purpose.

5.2 Diagnostic Parameters of the Doppler Spectrum

Starting from Sect. 4.3, this chapter provides a detailed description of the various parameters of the Doppler frequency time spectrum ("Doppler spectrum"), as it can be detected with the single pencil probe as well as with duplex devices.

5.2.1 Detection of Flow Direction

All Doppler and duplex devices available today automatically detect the direction of flow toward or away from the Doppler sound beam and display it on the monitor above or below the zero line. Usually there is a graphic symbol (icon) at the edge of the screen, which indicates which direction of flow is displayed above and below the zero line. Problems with directional differentiation only occur if the Doppler frequencies are higher than the pulse repetition frequency in pulsed Doppler applications (**Alias effect** Sect. 5.3.4).

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Practical Tips

If the sound beam is directed largely perpendicular to the vessel, amplitudes in the frequency spectrum can be derived in both directions of flow, almost equal to each other on both sides (Mirroring). "This is due to the fact that the Doppler sound beam is, physically speaking, not a narrowly defined line," but also has a lateral extension, as explained in the Sect. 3.1.1. Similar artifacts (cross talk) can also be found if the amplification of the Doppler or duplex device (gain) is set too high (Fig. 5.1).

5.2.2 Detection of Flow Velocity

First of all, it should be noted that the Doppler spectrum alone permits only **statements** about flow velocities, but no **measurement** in the narrow sense. The measurement of flow velocities always requires additionally the presence of imaging techniques that can be used to determine the angle between the sound beam and the vessel (insonation angle). For details see Sect. 5.3.2.

Background Information

When using the "simple" Doppler pin probe without the possibility of assessing the insonation angle between the sound beam and the vessel, it must always be remembered that changes in the position of the sound probe as well as curved vessels can simulate changes in flow velocity (Fig. 5.2). If, for example, a maximum systolic frequency of 4 kHz is used at the extracranial carotid artery as the limit between "normal" and "pathological," which usually leads to correct results at a transmission frequency of 4 MHz and at the usual insonation angle of 60°, completely different Doppler frequencies can be measured if the vessel passes in the medial or lateral direction (Fig. 1.8). When using standard values, these angle problems must therefore always be taken into account by using Doppler probes without additional B-mode imaging.

Assessment Parameters

The description of the Doppler spectrum is generally based on three parameters (Fig. 5.3).

Systolic Maximum Frequency

It is measured at the apex of the systole and represents the maximum flow velocity occurring in a vessel. ◀

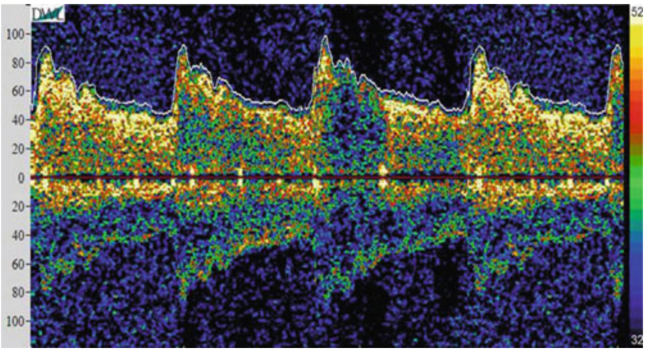

Fig. 5.1 Artifacts caused by "crosstalk" to the other channel of the Doppler device when the gain is set too high

End Diastolic Maximum Frequency

It is measured in the cardiac cycle immediately before the start of the next systole. It is a complex measure of the elasticity of the vascular system and of the peripheral resistance. ◀

Mean Value

The mean value describes the intensity-weighted average of the Doppler frequencies at any point in the spectrum. It correlates best with the actual amount of blood flow volume through the vessel. ◀

Diagnostic Significance

Systolic Maximum Frequency

Due to physiological circumstances (continuity law, Sect. 2.3), there is a quadratic relationship between the degree of stenosis and the systolic maximum frequency, which can usually be detected without major problems in the Doppler spectrum (Fig. 5.4). However, the increase in flow velocity is additionally determined by the length of the stenosis (Fig. 13.7). Of particular practical importance is the fact that the systolic (and enddiastolic) maximum frequency decreases again in subtotal stenoses. There are two reasons for this:

- According to the law of Hagen-Poiseuille (Sect. 2.3), the flow resistance increases drastically for very high grade stenoses and leads to a decrease in flow velocity.
- With increasing degree of stenosis, the proportion of the remaining high flow components becomes increasingly smaller due to turbulence effects. Their backscattered intensity is then no longer sufficient to be detected.

◀

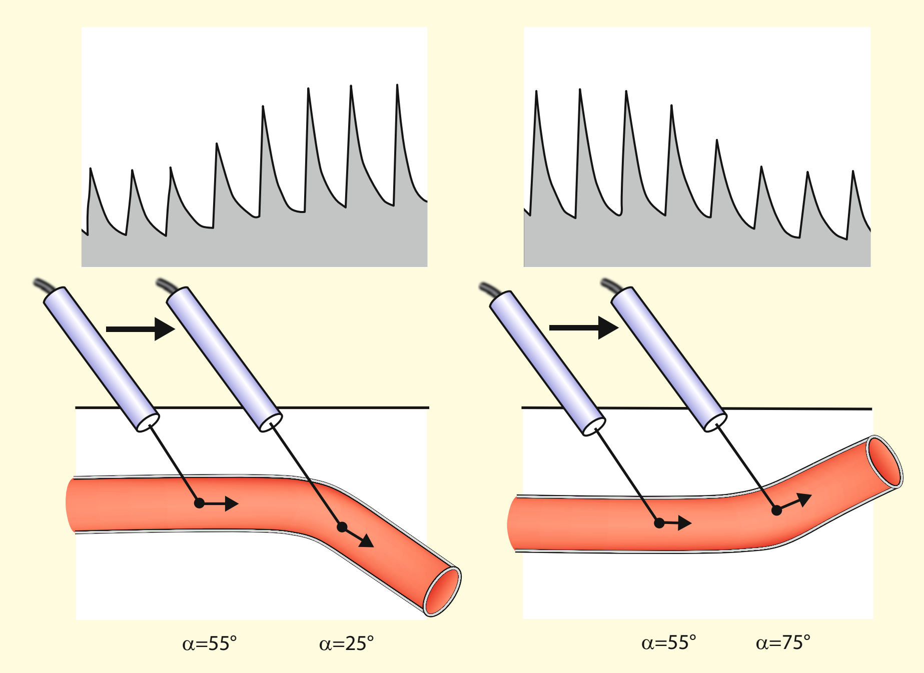

Fig. 5.2 Changes in Doppler frequencies induced by vessel bending at constant vessel diameter. Medial bends (left) lead to an apparent "flow acceleration," a lateral bend (right) results in an apparent "flow reduction"

End Diastolic Maximum Frequency

A similar relationship to the degree of stenosis exists for the end-diastolic maximum frequency. However, due to its greater variability, it has never gained importance for the diagnosis of stenosis. However, this value is indispensable for the measurement of pulsatility (Sect. 5.2.4). ◄

Mean Value

Due to its close relationship with the total amount of blood flowing through a vessel, it is particularly important for determining flow volume (Sect. 5.3.3). ◄

Possible Errors

The detection of systolic maximum frequency can lead to misinterpretations if the sound transmission power and/or the Doppler gain are set too high or too low (Fig. 5.5). If the setting is too high, device artifacts (**crosstalk**) are displayed faking a flow signal; if the setting is too low, less powerful frequency components no longer reach the threshold value of the spectrum display and are "cut off." In case of doubt, an attempt should be made to adjust the spectrum display optimally by slowly increasing or decreasing the Doppler gain. This requires a certain "sure instinct," fixed rules cannot be given.

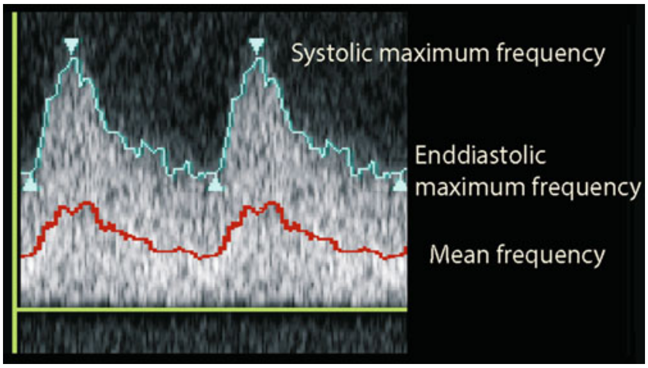

Fig. 5.3 Measurement parameters of the Doppler frequency time spectrum

Practical Tips

For optimal power or Doppler gain adjustment, in non-pathological cases the observation of the systolic window is recommended (Fig. 5.7). If this is just visible, the signal adjustment is usually correct.

5.2.3 Flow Disturbances

Acoustically, flow disturbances in the loudspeaker of the Doppler and duplex device impress as hissing or rather bubbling noises reaching into the diastole. They are often compared with "steps in the gravel" or "snowball crunching."

Assessment Parameters

Spectrum analysis enables a differentiated assessment of the degree of flow disturbances on the basis of typical changes in the Doppler spectrum (Fig. 5.6). A distinction is made between three forms of manifestation and one special case:

1. **Minor flow disturbances** can be recognized by the disappearance of the so-called systolic window. This is the

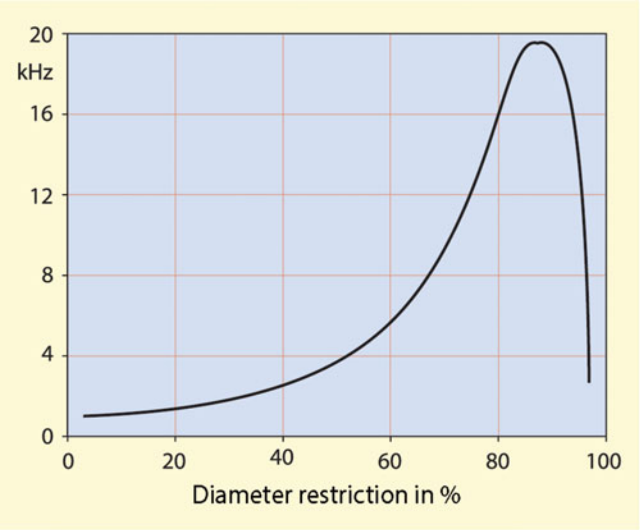

Fig. 5.4 Quadratic relationship between the degree of stenosis and the maximum systolic Doppler frequency (peak frequency) with respect to an ultrasonic transmission frequency of 5 MHz in a flow model. (According to Spencer and Reid 1979)

"empty" area below the systolic peak caused by the predominance of higher-frequency flow components in the laminar flow profile. The disappearance of this window is caused by the occurrence of low-frequency Doppler frequencies. In this case one also speaks of spectral broadening (Fig. 5.7).

2. **Moderate flow disturbances** show a predominance of low-frequency components during systole.
3. **High-grade flow disturbances** also show flow components running retrograde to the flow direction. In extreme cases, only the portion of the flow disturbance and no longer the undisturbed high-frequency "jet flow" can be detected in the Doppler spectrum.

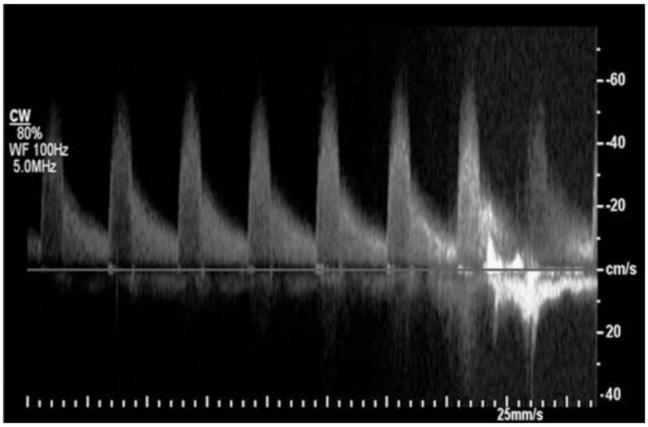

Fig. 5.5 Problems in assessing the systolic maximum frequency due to different settings of the Doppler gain. Example with continuously increased gain from left to right. In addition, at the end of the curve a swallowing artifact

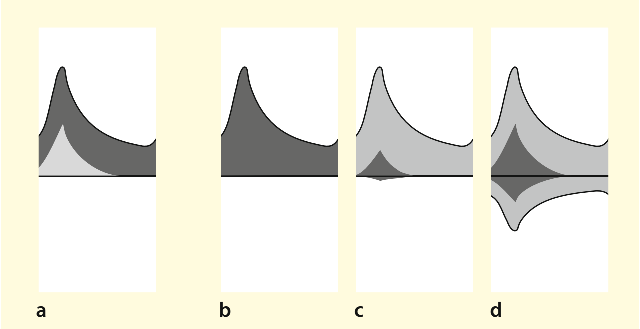

Fig. 5.6 (**a**–**d**) Characteristics of flow disturbances in the Doppler spectrum. Normal pulse curve (**a**), minor flow disturbance with disappearance of the "systolic window" (**b**), moderate flow disturbance with predominance of low frequency components (**c**), high-grade flow disturbance with additionally apparent retrograde flow components (**d**)

4. **Seagull crying:** A special form of high-grade flow disturbances are harmonic frequencies, which are recognizable in the Doppler spectrum as band-shaped stripes with (approximately) uniform frequency during systole (Fig. 5.8). In the loudspeaker of the Doppler device they impress as "whistling" or "squeaking" signals, which are often vividly compared with the cries of seagulls. This noise is probably caused – similar to the transverse flute or panpipe – by a rapid flow of blood "whistling" over a cavity (e.g., vessel outlet). Experience has shown that such signals are more frequent in stenoses of the external carotid artery, which has numerous branches.

Diagnostic Significance

As already mentioned in Sect. 2.4, flow disturbances are basically non-specific and can occur physiologically in the case of vessel bends, branches and dilatations (e.g., carotid bulb) as well as in the pathological case of stenoses, hyperperfusion or aneurysms. The non-specificity, however, only applies to minor and moderate flow disturbances, while pronounced flow disturbances occur almost exclusively in the vicinity of high-grade stenoses. Thus, they are to be used as an essential diagnostic criterion if the diagnostically more significant flow velocity in the maximum of the stenosis cannot be detected reliably.

This situation is given in three constellations:

1. **Insufficient sound window:** Transcranial Doppler/duplex sonography often is limited by an inadequate sound window, which does not allow low-energy, higher Doppler frequencies due to a high-grade stenosis to pass through sufficiently (Fig. 5.9).
2. **Perpendicular insonation angle:** If, as for example in the area of the carotid siphon, the insonation angle is regularly more than 70° for anatomical reasons, the systolic

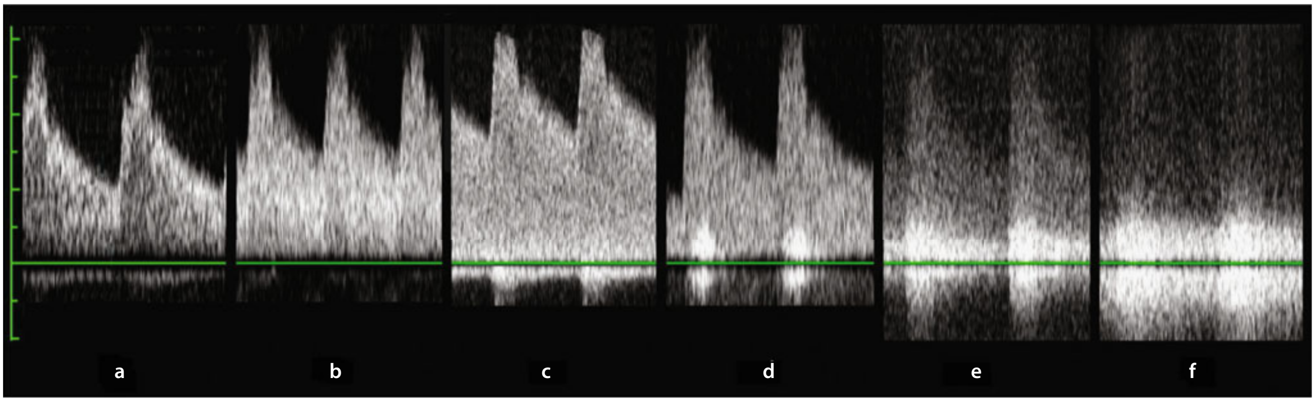

Fig. 5.7 (**a**–**f**) Examples of flow disturbances. Normal Doppler frequency time spectrum with recognizable "systolic window" (**a**); minor flow disturbance with loss of the "systolic window" (**b**); transition to medium flow disturbance with increasing low-frequency components (**c**, **d**); high-grade flow disturbance with still recognizable maximum frequencies (**e**); maximum frequencies can no longer be reliably detected (**f**)

maximum frequency can no longer be used as a valid parameter for the detection of stenoses. In this case the diagnosis must be based on the occurrence of flow disturbances (Fig. 5.10).

3. **Non-assessable stenosis maximum:** If the stenosis is located in an area that is inaccessible by sonography (e.g., when the internal carotid artery passes through the base of the skull) or if the maximum stenosis is obscured by calcification (Fig. 5.11), stenosis detection must be indirectly based on the occurrence of poststenostic flow disturbances.

Note

Severe flow disturbances in a vessel must always be considered pathological.

Possible Errors

False-negative results in stenoses only occur if for some reason the flow velocity in the stenosis is lower than expected (e.g., tandem stenoses, Sect. 13.1.6). False-positive misinterpretations are more frequent and are possible in the following cases:

1. **Vascular superpositions** can lead to an apparent broadening of the frequency density spectrum. This is particularly important in transcranial Doppler sonography, where several vessel sections are often derived due to the relatively large sample volume (Fig. 5.12).
2. **Vessel branches and bends** physiologically lead to locally circumscribed flow disorders (Fig. 5.12) and should not be misinterpreted as stenoses. The decisive factor for differentiation from stenoses is the fact that physiological flow disturbances immediately distal to a vessel junction or bend are detectable over a distance of at most twice the vessel diameter and then disappear, whereas flow disturbances distal to higher-grade stenoses regularly persist over a longer distance.
3. **Hyperperfusion** is often associated with the characteristics of a slight flow disturbance. The long-distance involvement of the entire vessel is indicative of this.
4. **Anemia** lead to turbulence due to their influence on the Reynolds number (Sect. 2.4). Typically, however, they affect all the vessels investigated, but are increasingly found in the area of vessel branches and bends.

5.2.4 Flow Characteristics (Pulsatility)

As already described in the previous Sect. 2.5, skin and muscle arteries with high peripheral resistance (e.g., subclavian and external carotid arteries) show low diastolic blood flow, while vessels supplying the brain and those leading to parenchymatous organs (e.g., thyroid) also show considerable diastolic blood flow due to their low peripheral resistance.

Practical Tips

The relationship between systolic and end-diastolic flow velocity is not only important for the differentiation of vessels, but also represents a quantitative criterion suitable for side comparison.

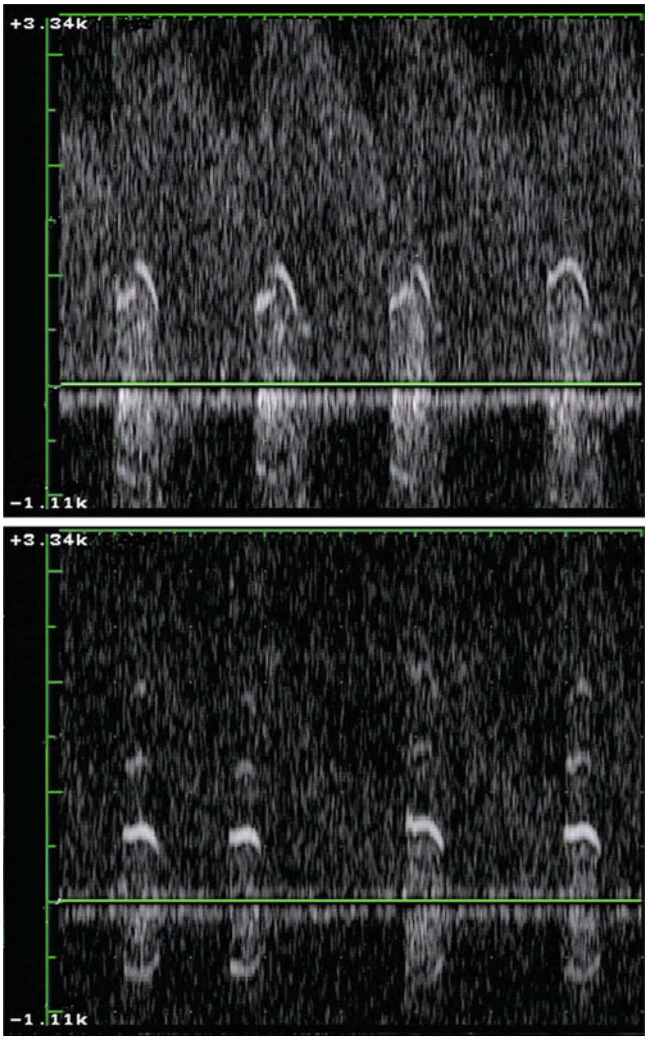

Fig. 5.8 Examples of harmonic "seagull crying" in the Doppler spectrum of the middle cerebral artery in 2 patients with high-grade stenosis in the main stem of the middle cerebral artery. In the upper picture "Seagull crying" subordinated to the just visible flow signal of a high-grade stenosis. Below as a special feature multiple harmonics (in addition irregularity of the pulse curve caused by cardiac arrhythmia)

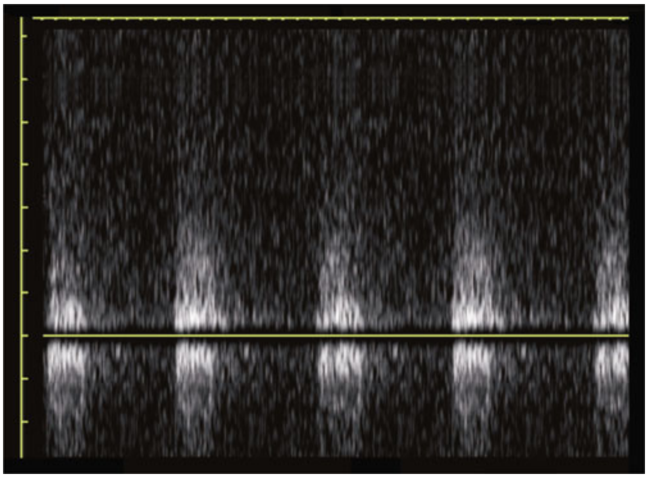

Fig. 5.9 High-grade stenosis of the middle cerebral artery. Since the temporal sound window is insufficient, the maximum systolic flow velocity cannot be defined and the stenosis can only be recognized by the pronounced flow disturbance

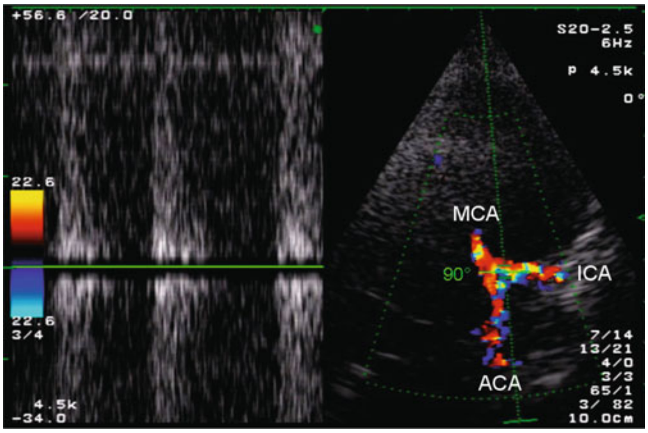

Fig. 5.10 Due to the almost 90° insonation angle, a high-grade stenosis in the distal course of the internal carotid artery (ICA) can only be verified on the basis of the pronounced flow disturbance immediately before division into the cerebral media (MCA) and anterior (ACA)

Assessment Parameters

For the acquisition of pulsatile flow characteristics, usually abbreviated as **pulsatility**, there are three approaches described in the literature (Table 5.1).

Resistance Index (RI)

The pulsatility index described by Pourcelot (1974) and therefore also called Pourcelot index is calculated as the difference between the systolic and end-diastolic maximum divided by the systolic maximum (Fig. 5.3). ◄

Pulsatility Index (PI)

The index introduced by Gosling and King (1974), which can be used as an alternative, requires knowledge of the mean frequency by which the difference between systole and diastole is divided. ◄

Diastolic Ratio

For daily use, qualitative assessment of the relative proportion of diastole in the systolic amplitude ("diastolic ratio") appears to be the easyest reference for pulsatility. If the systole is assumed to be 100%, diastolic flow fraction is less than 1/3 of the systole for skin- and muscle-supplying vessels and more than 1/3 of the systole for brain-supplying arteries. ◄

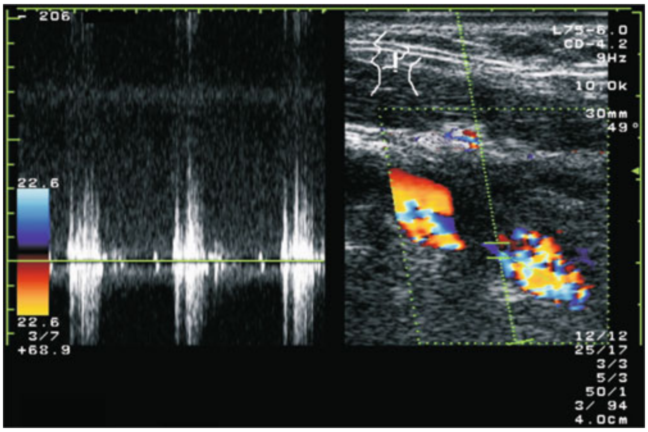

Fig. 5.11 Maximum of a higher degree carotid stenosis hidden by "sound shadow" due to a calcification. The pronounced poststenotic flow disturbance, however, indicates the stenosis

Practical Tips

Unfortunately, the Resistance (RI) and Pulsatility Index (PI) are often used synonymously in studies without more detailed information, which can lead to misunderstandings.

Diagnostic Significance

The assessment of pulsatility not only allows statements about possibly pathologically altered peripheral vascular resistance (e.g., with increased intracranial pressure), but also provides important indirect indications of occlusive cerebrovascular diseases. Thus, pulsatility typically increases proximal to a high-grade stenosis augmenting the peripheral resistance (Fig. 5.13). Conversely, distal to high-grade stenoses, pulsatility is characteristically reduced, since in this case the peripheral resistance vessels are dilated and thus the peripheral resistance is reduced in order to maintain blood supply. Together with an increased flow velocity, however, abnormally reduced pulsatility can also indicate a cerebral arteriovenous malformation (Table 5.2).

Possible Errors

Misinterpretations of pulsatility can occur if the wall filter of the device at low Doppler frequencies is more than approx. 10% of the detected maximum systolic frequency (Fig. 5.14). The task of the wall filter is to suppress artifact signals due to radial pulsations of the vessel wall. An electronic high-pass filter is used for this purpose, which eliminates low frequency components in the Doppler spectrum and is usually set to 50–200 Hz.

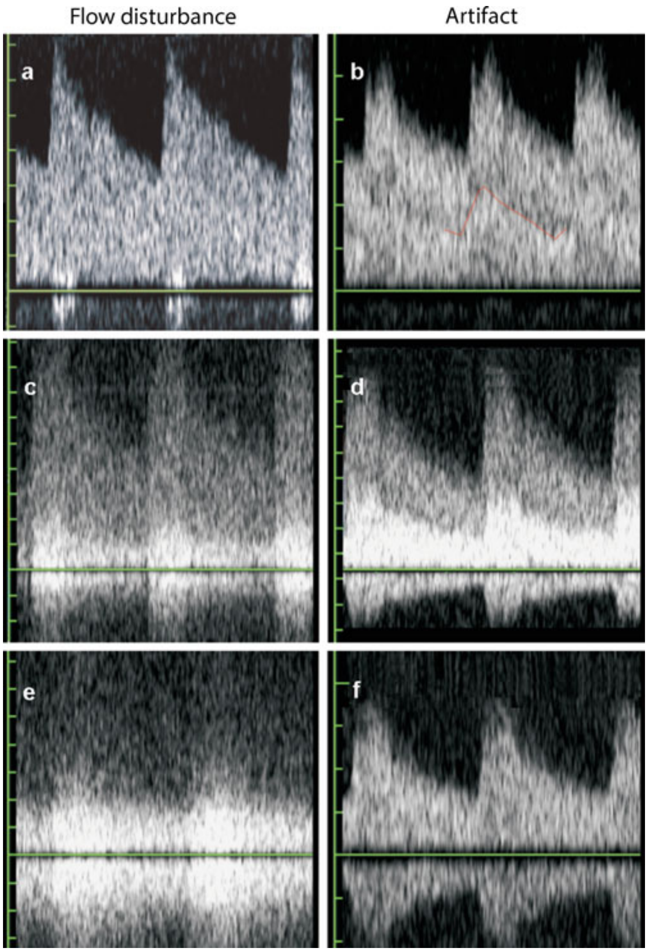

Fig. 5.12 (**a**–**f**) Real (left) and false (right) flow disturbances in the Doppler spectrum. Superposition of 2 vessels flowed through in the same direction (**b**, **d**) deceives a missing "systolic window" (**a**) or a pronounced flow disturbance (**c**, **e**); simultaneous representation of two vessels with opposite flows (**f**)

Practical Tips

When detecting low Doppler frequencies <1 kHz, care should be taken to set the wall filter as low as possible (<100 Hz) to avoid misinterpretation of pulsatility.

Special Case "flattened systolic increase"

A further flow characteristic that is important in individual cases is the systolic increase in the pulse curve. Due to the rapid contraction of the left ventricle, the pulse curve reaches its (largely) maximum after only about 0.1 s in healthy individuals. Behind very high grade stenoses there is a flattened systolic rise, which in extreme cases can lead to the image of a **delta signal** with an almost identical rise and fall

Table 5.1 Possibilities to describe the pulsatility of Doppler flow curves

Parameters	Calculation	Normal values	
		Brain supplying vessel	Muscle vessel
Resistance index (RI)	(systole – diastole)/systole	<0.75	>0.75
Pulsatility index (PI)	(systole – diastole)/mean	<1	>1
Diastolic ratio	Diastole/systole	>1/3	<1/3

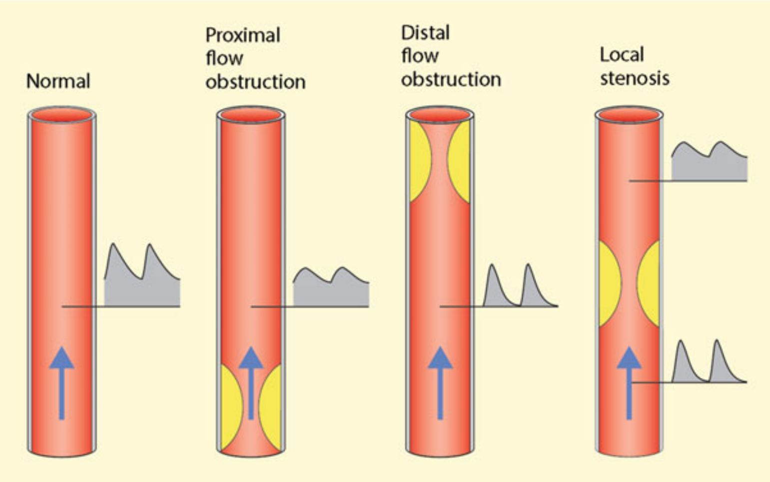

Fig. 5.13 Changes in pulsatility in proximal and distal to a high-grade vascular stenosis of the brain supplying arteries

Table 5.2 Significance of pathologically altered pulsatility values in the brain supplying arteries

Pulsatility compared to normal values	Cause
Diminished pulsatility	Upstream high level flow obstruction Arteriovenous malformation at further vascular course Hyperperfusion through other causes (e.g., to ischemia) Aortic stenosis
Increased pulsatility	Downstream high level flow obstruction Increased intracranial pressure Cerebral microangiopathy Aortic insufficiency

of the systole (Fig. 13.22). However, a flattened systolic increase is also to be expected with reduced heart contractility and aortic stenosis. Accordingly, side comparison is of importance here.

Summary
The diagnostic assessment of the Doppler spectrum is based on few parameters: The measured Doppler shift is proportional to blood flow velocity and shows a quadratic relationship to the degree of stenosis. Although flow disturbances are an unspecific phenomenon, pronounced flow disturbances characteristically only occur with higher degrees of stenosis and can then be used diagnostically. The pulsatility of the Doppler spectrum over the systolic-diastolic cycle is chances in the case of upstream and downstream stenoses. Various pulsatility indices are available for quantification.

5.3 Special Features of Pulsed Doppler Technology

Compared to CW technique, pulsed Doppler and duplex applications have some special features, which mainly have an advantageous effect on the diagnostic possibilities, but also have a typical disadvantage (**Aliasing effect**).

5.3.1 Flow Assessment at Defined Tissue Depths

As already described in the previous Sect. 3.1.2, the use of pulse-echo technique in Doppler sonography makes it possible to search for the presence of blood flow at tissue depths

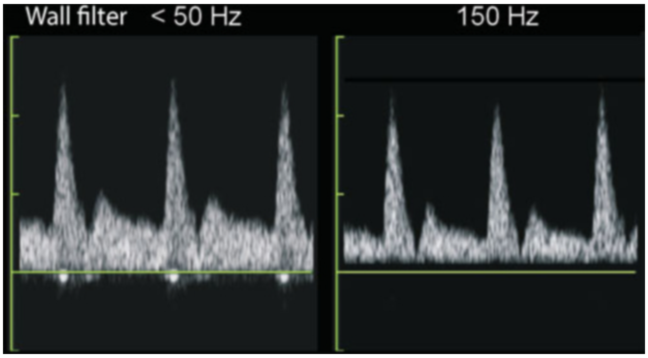

Fig. 5.14 Possible misinterpretation of pulsatility with wall filter set high (right)

defined by the examiner. This possibility is defined by two parameters that can be set on the device.

Depth

The **depth** of the Doppler measurement can either be selected directly for Doppler devices without imaging, or, for duplex sonography, it can defined using "trackball".

Sample Volume

The **sample volume** characterizes the distance along the Doppler sound beam within which a Doppler sonographic flow measurement is to be performed. Knowledge of two physical principles is important for the optimum setting of the measuring volume.

Size of the Sample Volume

As the size of the sample volume decreases, the "total quantity" of ultrasound signals available for Doppler spectrum analysis also decreases (Fig. 5.15), so that a sufficient Doppler signal may no longer be detected, especially in deeper-lying vessels or in cases of transmission difficulties through the skull. In addition, the probability of "dropping out" of the vessel increases even with small movements of the ultrasound probe or the patient. Accordingly, larger measurement volumes should be preferred when examining deep-lying vessels and in restless patients (Table 5.3). ◄

Practical Tips

If it is not possible to recognize a vessel either in B-mode or color-coded imaging, a "blind" attempt can be made to obtain a flow signal in the examined area setting the sample volume to a maximum value. By gradually reducing the size of the sample volume, it can then be localized step by step.

3D-Extension of the Sample Volume

Due to the clear-cut limits on the device screen, the sample volume is often considered to comprise a sharply defined area. For physical reasons, however, the sensitivity of the measurement volume does not break off sharply along the sound axis, but shows a relatively slow decrease toward both sides (Fig. 5.16). In addition, the sample **volume,** as the name suggests, has a three-dimensional shape and

Fig. 5.15 Influence of different sample volumes on the Doppler spectrum in transtemporal Doppler insonation of the middle cerebral artery

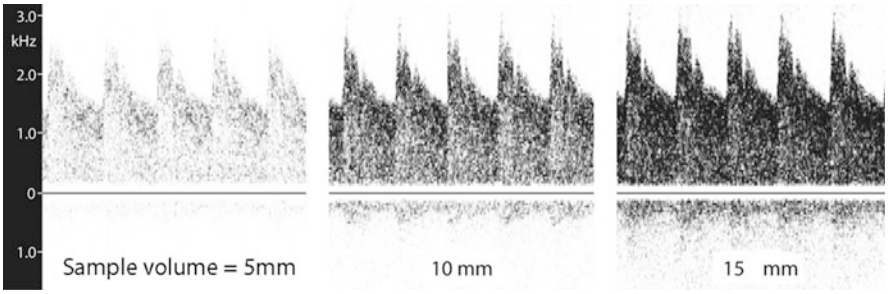

Table 5.3 Basic principles for setting the sample volume in pulsed Doppler and duplex sonography

Sample volume compared to the examined vessel diameter		
Larger	Comparable size	Smaller
Deep lying vessels Insufficient temporal window in the transcranial Doppler/duplex sonography "Blind" search for blood flow with the duplex device Restless patient	Standard setting	Distinguishing vessels lying close together

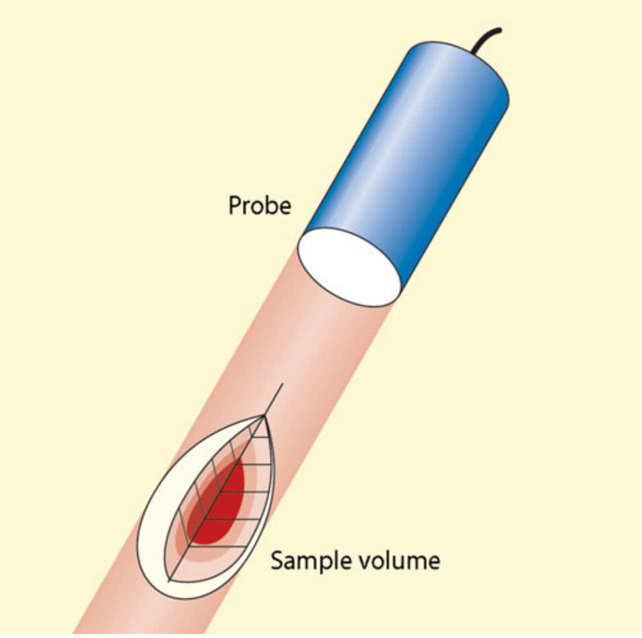

Fig. 5.16 Three-dimensional expansion of the sample volume in pulsed Doppler and duplex sonography. (After von Reutern et al. 2000)

therefore also has a certain lateral extension. If the Doppler gain is set very high, it is therefore possible that vessels lying next to the actual sample volume are also recorded and can cause confusion, especially when differentiating between an occlusion and a still open vessel. ◄

5.3.2 Measurement of Flow Velocity

In contrast to the simple Doppler pin probe, where only frequencies can be assessed, the combination of B-mode image and Doppler sound beam used in duplex sonography allows concrete measurements of flow velocity in cm/s or m/s. A prerequisite for this is the determination of the angle between the Doppler sound beam and the vessel axis (so-called insonation angle). Every duplex device offers the possibility performing such an angle correction by means of a rotatable bar (Fig. 5.17). After setting the angle, the velocity can usually be read directly on the monitor in cm/s or m/s.

Diagnostic Significance

In addition to the possibility of recording a physiological parameter instead of the purely technical criterion of Doppler frequency shift, the angle-corrected measurement of flow velocity offers further significant diagnostic advantages:

1. In the case of a medial or lateral bend of the vessel, false negative and false positive results can occur without knowledge of the insonation angle (Fig. 5.2).
2. If a sufficiently reproducible setting of the angle correction is technically possible (see below), the determination of the flow velocity leads to a more reliable assessment of the degree of stenosis.

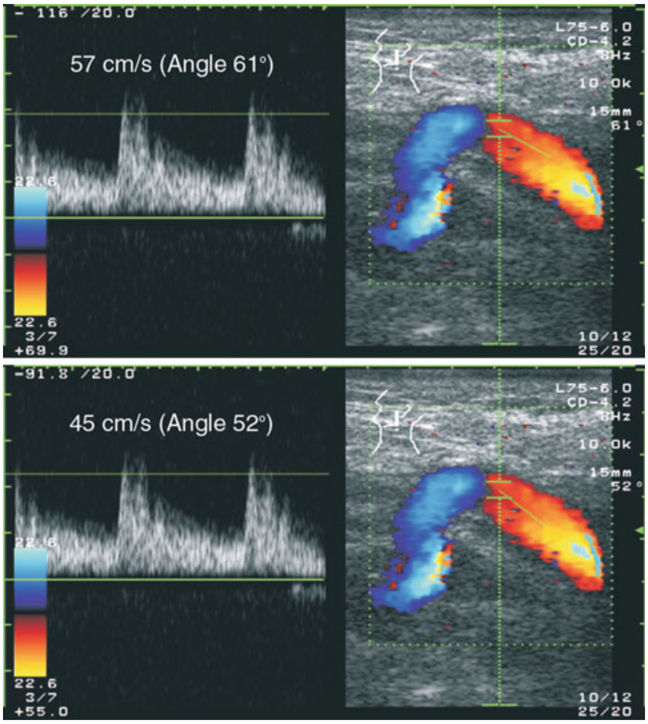

Fig. 5.17 Determination of the flow velocity in the internal carotid artery at different settings of the insonation angle. Note the different measured values even with relatively small fluctuations of the angle setting

Note
When duplex sonography is used, an angular correction of the angle between the Doppler beam and the vessel axis should always (!) be performed.

Possible Errors

Various sources of error must be taken into account in angle-corrected measurements of flow velocity.

"Unfavorable" Insonation Angle

Due to unavoidable inaccuracies in the setting of the angular correction insonation angles of 70° and more should be avoided, otherwise unacceptable measurement errors may occur (Fig. 5.18). This is due to the already mentioned cosine function in the Doppler equation (Sect. 4.1.2). ◄

Vessel Displayed Too "short"

A measurement error which is not obvious at first glance can occur if the correct angle is set in the insonated plane but the vessel runs across this plane, resulting in an angular error in the plane perpendicular to the B-mode section

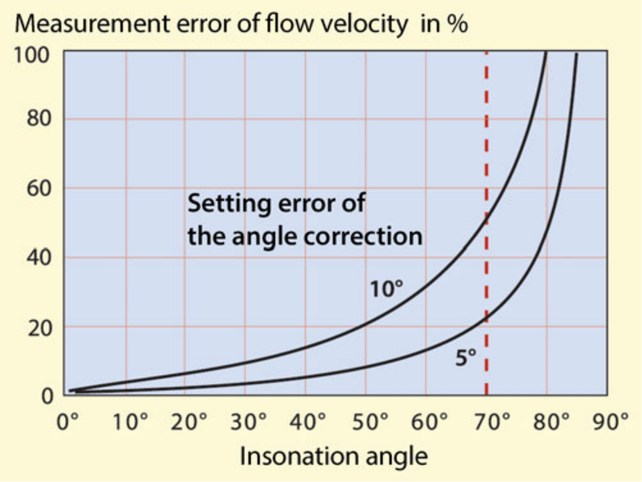

Fig. 5.18 Disproportionate increase of the measurement error when determining flow velocity due to the cosine function in the Doppler relationship. Unavoidable inaccuracies in the adjustment of the insonation angle in the order of 5–10° are only moderately relevant at small angles between the Doppler sound beam and the vessel <60°, whereas pronounced incorrect measurements are obtained from an insonation angle of 60–70°

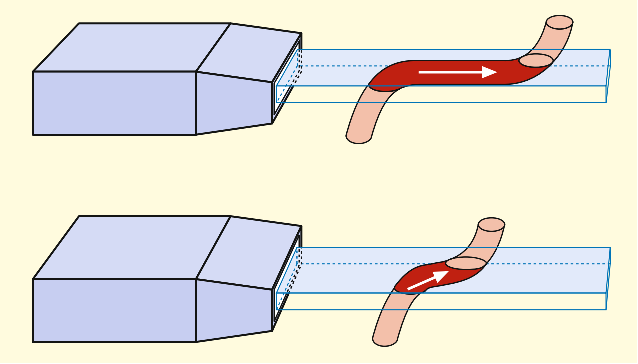

Fig. 5.19 Possible measurement errors when determining the flow velocity through a vessel running across the sectional image plane. If the vessel can only be traced briefly in the sectional image, this can result in an unpredictable angle between the axis of the sound beam and the vessel axis (bottom)

(Fig. 5.19). Such an angle error is to be avoided if the vessel can be represented “band-shaped” from the area of the measuring at least over a distance corresponding to twice the diameter of the vessel on both sides (e.g., in the case of internal carotid artery ± 1 cm) with clearly distinguishable vessel walls. ◀

Note
The reliable determination of blood flow velocity requires an insonation angle of $< 70°$ and a “band-shaped” display of the vessel course over a length of ± 1 cm proximally and distally to the measuring point.

Poststenotic Flow Disturbances

Immediately behind higher grade stenoses, considerable flow disturbances are regularly found, in the case of short-distance stenoses not infrequently combined with a helically twisted blood flow (**helix flow**, Fig. 13.13). Poststenotic determination of flow velocity should therefore always be carried out as far as possible distal to the stenosis to avoid incorrect measurements. ◀

Note
Measurements of the poststenotic flow velocity should not be taken immediately behind a stenosis, but as far as possible away from it.

Elongations and Kinkings

In cases of with elongations and kinkings problems can occur, since the setting of the angle correction leaves variation possibilities, which may result in considerably different measured velocities (Fig. 5.20). ◀

Eccentrically Running Stenoses

Problems with the adjustment of the insonation angle cannot be avoided either in the case of eccentric residual lumina in stenoses (Fig. 5.21). ◀

Practical Tips
If measurement errors cannot be avoided in the case of elongations and eccentric stenoses, the examiner should at least know the “bandwidth” of the measurement error. This can be done by measuring flow velocity at various insonation angles.

5.3.3 Measurement of Flow Volume

If the mean flow velocity and the vessel cross section are known, duplex sonography is also a suitable method for determining flow volume. The calculation is based on the formula

$$I = F \cdot v_m$$

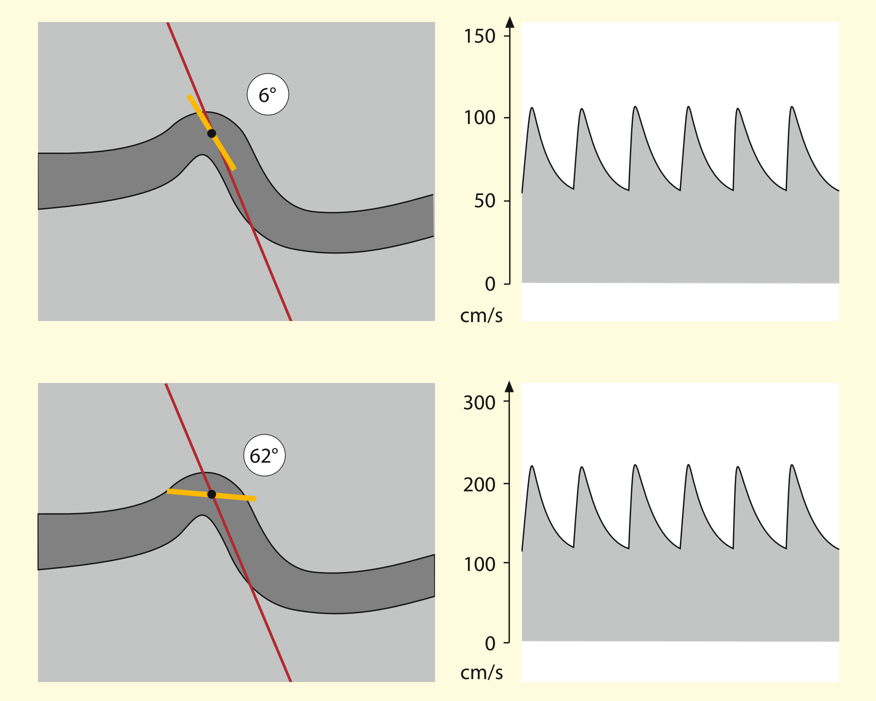

Fig. 5.20 Problem of angle-corrected measurement of flow velocities in kinking. In this case, there are considerable variation possibilities in the setting of the angle correction with considerably variable flow velocity values. In the schematic example shown, maximum systolic velocity has a range from 105 cm/s (angle 6°) to 220 cm/s (angle 62°)

I Flow volume
F Cross-sectional area (= $\pi/4\ d^2$)
v_m Intensity weighted average flow velocity (mean)

As a measure of flow velocity, the intensity-weighted average **mean velocity** correlates best with the total number of "flow threads" in the vessel. A prerequisite for correct determination, however, is a sufficiently large sample volume over the entire cross section of the vessel (Fig. 5.22).

Background Information
As far as the mean velocity is not automatically output by the device, the arithmetically averaged flow velocity can be used as an alternative after angle-corrected conversion of the Doppler frequencies according to the formula.

$$v_m = 1/3\ (v_s + 2v_d),$$

where v_s is the maximum systolic velocity and v_d represents the enddiastolic velocity. Taking the vessel diameter d in mm and the flow velocity v_m in cm/s flow volume I is calculated as

$$I = 0{,}47 \cdot d^2 \cdot v_m [\mathrm{ml/\min}]$$

In clinical routine it is sufficient to estimate the average flow velocity by optical interpolation of the Doppler spectrum on the screen. The area above the movable measuring bar (systole) should be equal to the area below the measuring bar (diastole) (Fig. 5.23).

Diagnostic Significance

The determination of flow volume is particularly important in two situations.

Alternative to rCBF Measurements

Sonographic determination of blood volume is a cost-effective, non-invasive alternative to other methods, for example, nuclear medical measurements of cerebral blood flow (CBF). Indications for this are, for example, the estimation of the cardiac load due to the shunt flow in the case of an arteriovenous malformation, but also the assessment of flow volume after extra-intracranial bypass surgery. ◀

"Abnormal" Vessel Diameters

Sonographic vascular diagnostics is generally based on the comparison of measured flow velocities with reference values and/or with the conditions on the contralateral side. However, this only makes sense in "normal" vessel diameters on both sides. This is not the case with congenital hypoplasia or acquired constrictions of individual vessels (e.g., "normal" flow velocity in a highly constricted vessel in the case of a long-distance dissection). ◀

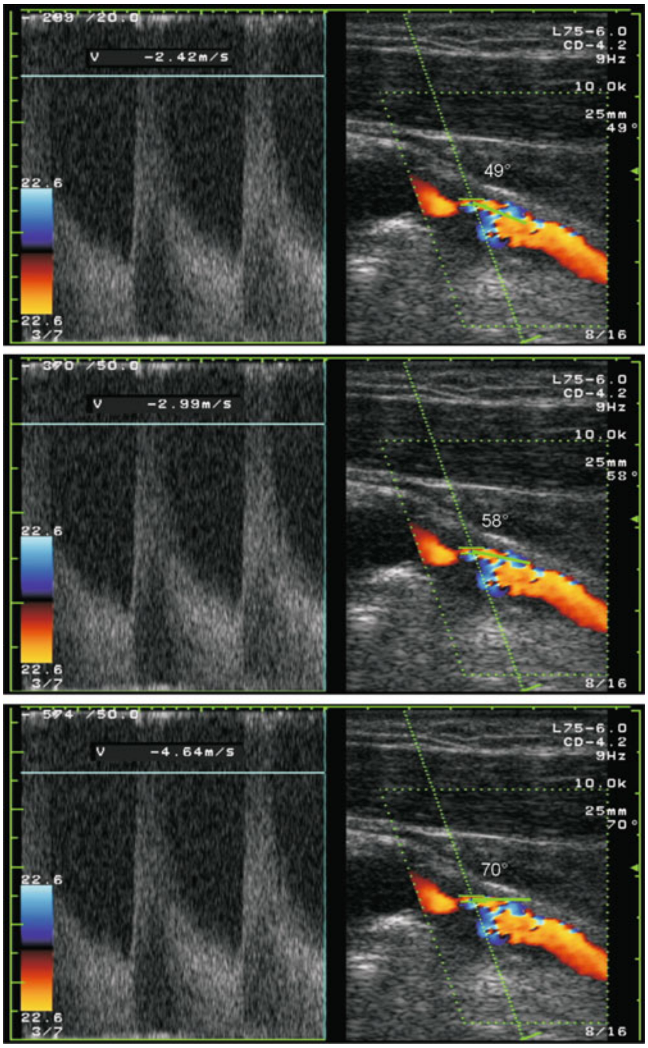

Fig. 5.21 Measurement of flow velocity at the maximum of a short-distance, eccentric stenosis of the internal carotid artery at different settings of the angle correction. Depending on the positioning of the insonation angle, systolic flow velocities between 240 and 460 cm/s result!

Note
In all cases of "abnormal" vessel diameter in B-mode imaging, a determination of flow volume should be carried out, as the determination of flow velocity does not allow reliable statements in this case.

Possible Errors

The main source of error when assessing flow volume concerns the determination of the vessel diameter. Since this is entered quadratically into the calculation formula of flow volume, even small inaccuracies become considerably noticeable (Fig. 5.24). These can occur in several ways (see following overview):

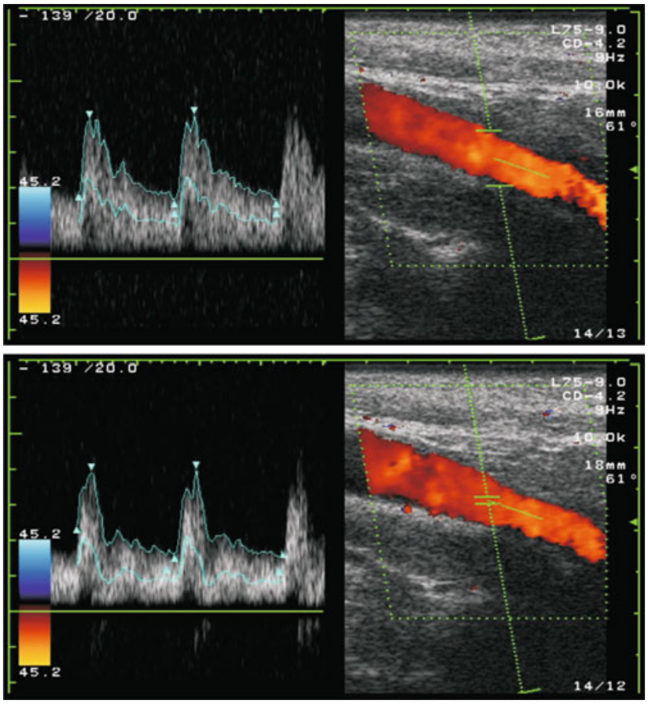

Fig. 5.22 The recording of the flow spectrum in a vessel cross section requires a sample volume that covers the entire lumen (top) otherwise the derived "mean velocity" is incorrect (bottom)

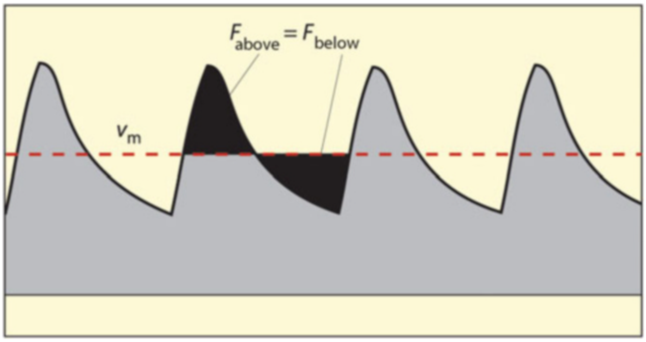

Fig. 5.23 Estimation of average flow velocity on the screen. Further explanations in text

Sources of error in the sonographic determination of flow volume

1. Measurement error of the vessel diameter
   1. Systolic-diastolic diameter fluctuations
   2. Vessel borders not clearly recognizable in B-mode imaging
   3. Vessel has no ideal circular cross section
   4. Determination of the vessel diameter only by means of the color coded display
2. Measurement error of the average flow velocity
   1. Sample volume smaller than the vessel diameter
   2. Angle between the sound beam and the vessel ≥70°
   3. Presence of flow disturbances in the measuring range

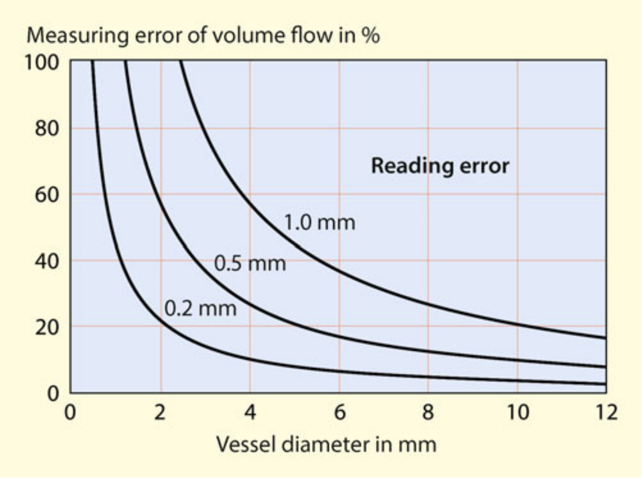

Fig. 5.24 Possible measuring errors in the determination of flow volume as a function of vessel diameter and its measuring (in)accuracy

Problem of Vascular Pulsations

In the systolic-diastolic cycle, radial vascular pulsations result in fluctuations of the vascular diameter in the order of usually about 10%. There is no consensus in the literature on the point in time in the cardiac cycle at which the diameter should be determined. The most correct method would be ECG-triggered averaging, but this has not become established for reasons of practicability. The alternative by using the M-mode image (Fig. 5.25) is only possible if the vessel runs parallel to the transducer (e.g., common carotid artery). ◀

Problem of Vascular Borders

While the vessel wall can usually be clearly defined on the side away from the transducer by means of the intima-media complex, this is often only approximately possible for the vessel wall near the transducer. ◀

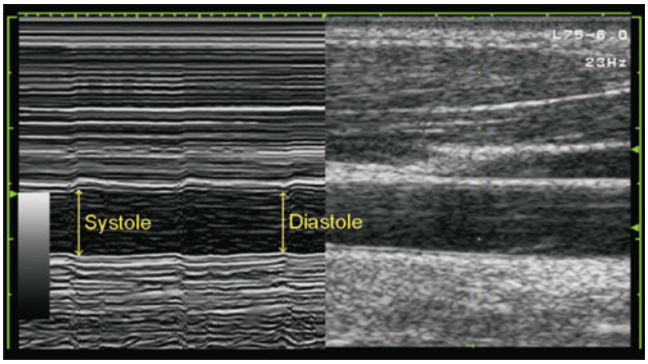

Fig. 5.25 Evaluation of systolic-diastolic vessel pulsations by M-mode imaging

Problem of Cross Section Calculation

The calculation of the area based on the diameter of the vessel requires a circular cross section. Outside the carotid bulb, this situation in arteries is normally present with sufficient accuracy. However, problems arise when eccentric changes in the vessel wall are present. In this case, the cross section may have to be calculated on the basis of the transverse cross-sectional image. ◀

Problem of the Resolution

Compared to B-mode imaging, the resolution of the color coded image is significantly worse. This must be taken into account if, as is often the case in the internal carotid artery, the course of the vessel cannot be adequately defined in the B-mode image and the diameter must be determined using color coded representation. Intracranially, the resolution of color coded duplex sonography is completely inadequate anyway, so that flow volume determinations are not possible here. ◀

Note

As far as technically possible, B-mode (or B-flow) imaging rather than the color coded image should be used to determine the vessel diameter when determining flow volume.

In addition to the above mentioned problems in determining the vessel diameter, there are further sources of error resulting from the measurement of flow velocity. If there are more pronounced flow disturbances in the area of the measuring point, the averaging of flow velocity is only roughly appropriate due to the no longer laminar and rotationally symmetrical flow conditions in the vessel. Other avoidable sources of error are a 70° or more angle between the sound beam and the vessel as well as a too small measuring volume.

Note

In and immediately behind stenoses with flow disturbances no determination of flow volume should be performed.

Due to the inaccuracies mentioned, it goes without saying that flow volume determinations are only relatively rough estimates. Especially when measuring smaller vessel diameters, considerable errors must be expected, which can

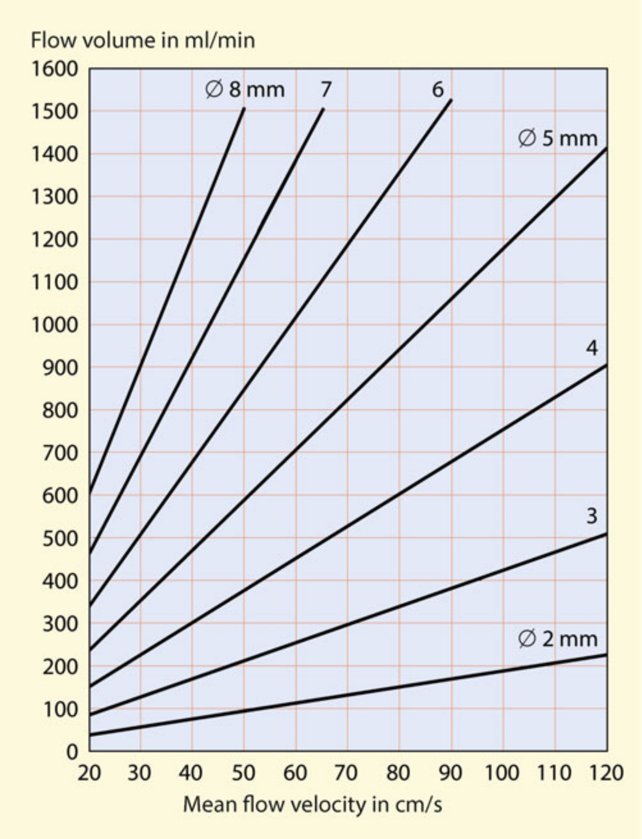

Fig. 5.26 Nomogram for determining flow volume in vessels from mean flow velocity and vessel diameter

reach 50–100%(!) (Fig. 5.24). In the common and internal carotid artery, however, the flow volume can usually be estimated with an accuracy of ±20–30%, which corresponds to the measurement accuracy of other methods (e.g., MRI, SPECT). As far as the existing duplex device does not include the possibility of flow volume determination, the nomogram in the Fig. 5.26 can be used to quickly estimate flow volume.

Practical Tips
Due to the unavoidable inaccuracies in the determination of flow volume, it should be avoided to simulate an apparent accuracy by giving exact calculation values. Rather, relatively coarse subdivisions, for example, 250, 300, 350 ml/min, appear to be more appropriate.

5.3.4 Problems with the Aliasing Effect

The advantages of the selective flow investigation in pulsed Doppler sonography are bought by a physically caused disadvantage called **Aliasing**. This effect is well known from cinema films, for example, when the spoked wheels of moving carriages seem to turn in the wrong direction. The reason is that film recordings consist of individual frames that are recorded and played back at a “frame rate” above the limit of 16 Hz, which is characteristic of the temporal resolving power of the eye. Correspondingly, rotational movements are equally divided into individual images (Fig. 5.27). At a certain speed of rotation, the wheels seem to stand still, and as they increase further, the impression of a wheel turning in the opposite direction is created.

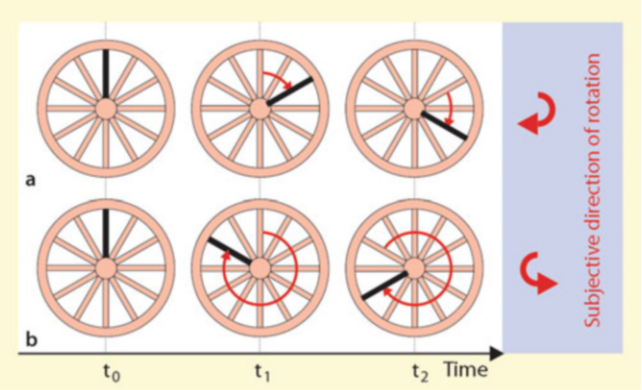

Fig. 5.27 Aliasing effect using the example of spoked wheels rotating clockwise at different speeds in a TV or cinema film with the display. Individual images shown at times t_0, t_1 and t_2. While at slow rotational speed (**a**) the direction of rotation of the wheel appears to be correct, a faster movement results in the subjective impression of a wheel turning in the opposite direction (**b**)

A similar situation exists in pulsed Doppler sonography. Here, the relatively low-frequency Doppler shift in the range of a few kHz with oscillation durations of around 1 ms must be developed from very short consecutive ultrasonic pulses whose oscillation period is 1000 times shorter (Fig. 5.28). This requires very frequent ultrasonic pulses enabling the electronic device to correctly detect the Doppler shift. The measure for this is the so-called **Pulse repetition frequency** (PRF) (Sect. 3.3.1). According to the so-called **Nyquist Theorem** however, only Doppler frequencies that do not exceed half of the PRF can be displayed correctly (**Aliasing threshold**). If Doppler frequencies greater than PRF/2 are to be displayed, the aliasing effect described above will occur.

In Doppler spectrum analysis, aliasing is characterized by the fact that frequency peaks are cut off and reappear on the screen with apparently opposite flow direction (Fig. 5.29). If the Doppler frequency to be derived is above the pulse repetition frequency, the pulsatility of both the acoustically audible Doppler signal and the spectrum image may be lost, or a flow signal may be produced that can no longer be interpreted.

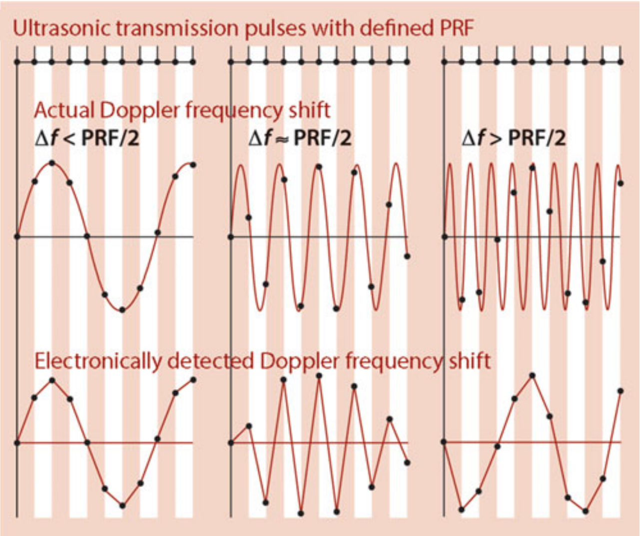

Fig. 5.28 Reconstruction of sinusoidal oscillations of different frequencies (Doppler shift) from single ultrasonic pulses with a defined pulse repetition frequency (PRF). If the Doppler frequency shift Δf to be displayed exceeds half of the PRF (right), a misinterpretation of the measured Doppler frequency (aliasing effect) occurs with an apparently slower frequency, which seems to go in the other direction due to phase inversion

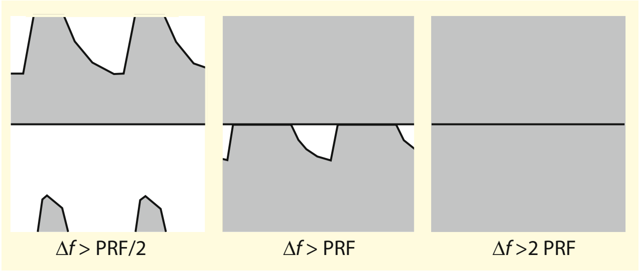

Fig. 5.29 Display of a Doppler spectrum with frequency shift Δf for different pulse repetition frequencies (PRF)

> **Note**
>
> **"Aliasing" means a physically induced phenomenon where the displayed Doppler frequency shift may be misrepresented in the opposite direction of flow.**

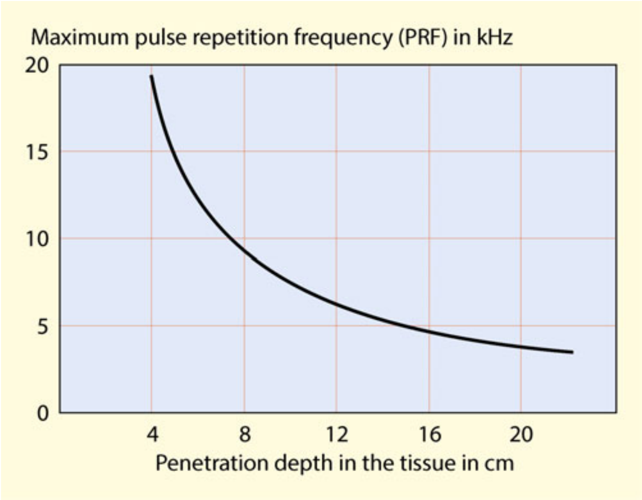

Fig. 5.30 Maximum achievable pulse repetition frequencies depending on the required depth of insonation in the body

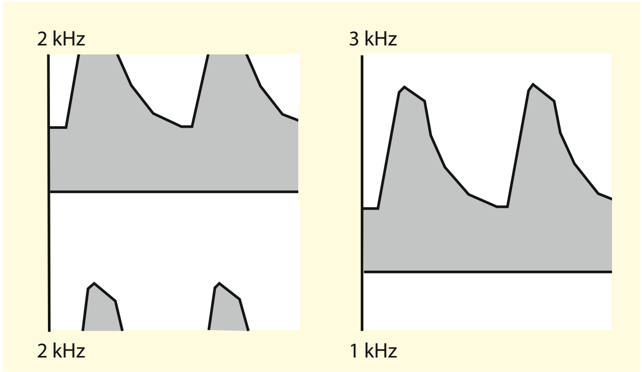

Fig. 5.31 Improved display of higher Doppler frequencies using pulsed Doppler technique by shifting the zero line

Maximum PRF Versus Penetration Depth

The desire to increase the pulse repetition frequency is limited by the fact that the emission of a new sound pulse must be waited until the echoes from the maximum tissue depth to be examined have reached the transducer (Fig. 5.30). This can lead to problems, especially when examining intracranial vessels, since in this case an insonation depth of 8–10 cm is regularly required. The only way to increase the imaging quality is to shift the zero line of the device (Fig. 5.31).

High-PRF Mode

The limitations of the Nyquist theorem on the representability of Doppler frequencies can be partially overcome in most duplex devices by the so-called **High-PRF mode**. Here, the emission of a new ultrasonic pulse does not wait until all reflections have reached the transducer again, but halfway through the time a new pulse is already emitted. Thus a doubling of the displayable Doppler frequency up to the level of the pulse repetition frequency can be achieved. However, this is bought by setting up another sample volume in the middle between the transducer and the measuring volume set on the screen. If a vessel "randomly" runs in this further sample volume, its flow signal is also displayed. Accordingly, the High-PRF mode should not be used, for example, in the diagnostics of vessel occlusions.

Summary

The pulsed Doppler technique enables blood flows to be selectively detected at freely selectable tissue depths by positioning a defined sample volume. If the Doppler examination is carried out in combination with B-mode imaging (duplex sonography), flow velocities and flow volumes can be measured quantitatively after determining the angle between the sound beam and the vessel (insonation angle) and, if necessary, also the vessel diameter. A disadvantage of pulsed Doppler and duplex sonography is the occurrence of the aliasing effect with apparently reversed flow direction if the Doppler frequencies to be displayed exceed half the frequency at which ultrasonic pulses are emitted (pulse repetition frequency).

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