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„Knobology“ in Doppler Ultrasound

Axel Löwe[1], Christian Jenssen[2], Sebastian Hüske[3], David Zander[3], André Ignee[4], Adrian Lim[5], Xin-Wu Cui[6], Yi Dong[7], Beatrice Hoffmann[8], Christoph F Dietrich[1]

[1]Department Allgemeine Innere Medizin (DAIM) Kliniken Hirslanden Beau Site, Salem und Permanence, Bern, Switzerland, [2]Department for Internal Medicine, Krankenhaus Märkisch Oderland GmbH Strausberg/ Wriezen and Brandenburg Institute of Clinical Ultrasound (BICUS) at Medical University Brandenburg „Theodor Fontane“, Neuruppin, Germany, [3]Ruprecht Karls University Heidelberg Medical School, Heidelberg, Germany, [4]Department of Internal Medicine 2, Caritas Krankenhaus, Bad Mergentheim, Germany, [5]Imaging Department, Imperial College Healthcare NHS Trust, Charing Cross Hospital, Fulham Palace Road, London UK, [6]Department of Medical Ultrasound, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, China, [7]Department of Ultrasound, Zhongshan Hospital, Fudan University, Shanghai, China, [8]Harvard Medical School, Department of Emergency Medicine, Beth Israel Deaconess Medical Center, Boston, USA

Abstract

Ultrasonography is a ubiquitous and indispensable diagnostic and therapeutic tool in medicine. Due to modern equipment and automatic image optimization, nowadays the introduction of ultrasound imaging requires only little technical and physical knowledge. However, profound knowledge of the device function repertoire and underlying mechanisms are essential for optimal image adjustment and documentation. From a medical as well as an aesthetic point of view, the goal should always be to achieve the best possible image quality. This article provides an overview of handling of ultrasound systems, fundamental adjustments and their optimization in Doppler ultrasound.

Keywords: guideline; Doppler; ultrasound; perfusion; vascularity

Introduction

The authors recently introduced a series of papers on how to perform certain techniques [1,2] including “knobology” [3,4]. Doppler ultrasound is an indispensible imaging tool that is usually employed in addition to conventional B-mode sonography. It allows for non-invasive and non-ionizing evaluation of cardiac or vascular blood flow. Compared to other imaging procedures such as Magnetic Resonance Imaging (MRI) or Computed Tomography (CT), ultrasound (US) imaging, and even more Doppler ultrasound, largely depends on the examiner’s skills and expertise. Adequate knowledge of anatomical structures and topographies, as well as optimal device and image settings, are crucial requirements to obtain high quality and reliable US diagnoses.

In this publication, we aim to illustrate optimal US device settings in a structured and practically applicable form, focusing on Pulsed Wave Doppler (PWD) US and colour Doppler ultrasound (CDUS) [5]. PWD provides information on the blood flow characteristics at a defined point in a vessel, while CDUS displays the architecture of the blood vessels in a given field of view within the US image as well as direction of flow. When US waves hit moving objects (e.g., blood cells), the wavelengths and frequencies of reflected US waves change depending on the flow direction and velocity (Doppler effect). A blood flow towards the US probe increases US frequency (positive frequency shift), while blood flow away from the US probe decreases the US frequency (negative frequency shift).

The magnitude of the detected frequency shift is directly dependent on the transmission frequency and the velocity of the blood flow, but according to the Doppler equation it is also influenced by the insonation angle.

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Corresponding author: Prof. Christoph F. Dietrich
Department Allgemeine Innere Medizin (DAIM),
Kliniken Hirslanden Beau Site,
Salem und Permancence, Bern, Switzerland
Phone: +41798347180
E-mail: c.f.dietrich@googlemail.com

$$\text{frequency shift} = \frac{2 \times \text{blow flow velocity} \times \text{transmission frequency} \times \cos(\text{insonation angle})}{\text{speed of sound in tissue}}$$

The frequency shift caused by blood flow velocities is in the kilohertz range. It can be displayed acoustically and visually. Doppler US imaging requires high intensity ultrasound pulses due to the low echogenicity of blood cells.

1. Spectral Doppler US

Spectral Doppler modalities (PWD and continuous wave Doppler, CWD) average the differences between transmitted and incoming frequencies over a defined time period by Fast Fourier Transformation and display these frequency shifts as a velocity spectrum (hence, the expression "spectral Doppler").

CWD systems transmit and receive sound waves continuously with separate piezoelectric crystals in a synchronous fashion, registering every Doppler shift along a predefined path. In contrast, PWD systems transmit and receive series of pulses with the same crystal. In PWD, the user defines a small "sample volume" or "Doppler gate" in the B-mode image, which is opened after the sound waves have travelled through the respective tissue. As a consequence, only Doppler shifts from the sample volume area are recorded. PWD is a method for the targeted and selective measurement of flow velocities in vessels where the exact location of evaluation can be determined. The nature of intermittent sampling makes PWD measurements vulnerable to artifacts (i.e., "aliasing") at higher velocities, especially at target structures that are further away from the transducer [6]. CWD allows detection of very high peak flow velocities (e.g., in cardiac evaluations) without the ability of pin-pointing the location of the actual flow [7]. PWD and CWD can both be activated on the ultrasound scanner console.

Parameter adjustment in PWD

The following important parameters must be considered in PW Doppler sonography for optimal image adjustment.

Transmission Frequency

The spectral Doppler frequency is independent of the B-mode or colour Doppler frequency. By its adjustment the examiner maintains spectral Doppler flow sensitivity in vessels located in the near, mid or far field. Settings are transducer- and preset-dependent. For deep-seated vessels lower transmission frequencies should be used than for vessels located close to the transducer. As a rule, low Doppler frequency settings should be used to map deep blood flow with very high velocities to circumvent aliasing (explained in detail below).

Pulse Repetition Frequency / Scale

Pulse repetition frequency (PRF) describes the number of sound pulses that are emitted from the transducer in one second. The PRF is not related to the transmission frequency. On ultrasound devices, the PRF is often denoted as the (velocity) scale, since the PRF determines the velocity range or scale (in cm/s) in which flow can be represented without aliasing. Flow velocities can only be displayed correctly if their Doppler frequency shift is not greater than half the PRF, the so-called "Nyquist limit". When the frequency shift of the maximum flow velocity in a given Doppler gate exceeds half the PRF, "aliasing" occurs, a phenomenon whereby portions of the spectral curve with fast velocities are "truncated" and displayed below the base line in the reverse flow direction (fig 1). Accordingly, the optimal PRF setting is accomplished if the maximum flow velocities do not exceed the velocity range shown on the screen. However, the maximum PRF is limited by the depth localization of the sample volume.

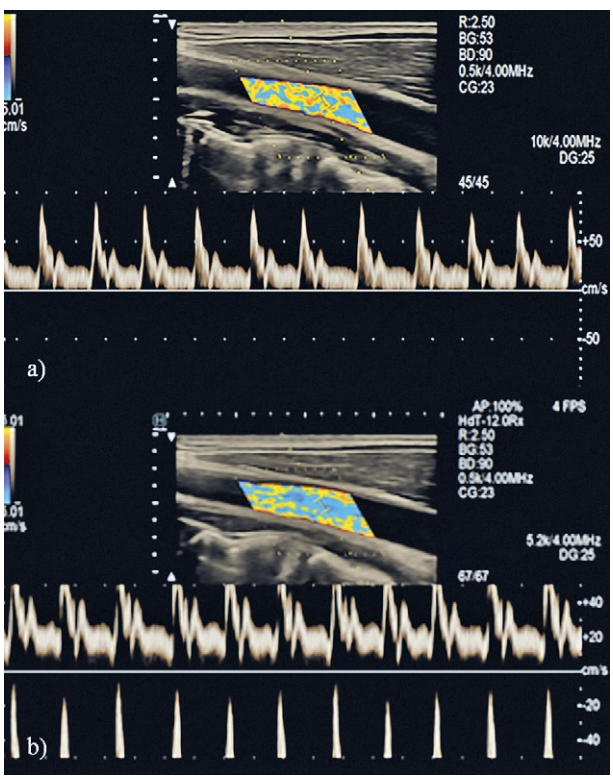

Fig 1. Pulse repetition frequency (PRF) of pulse wave Doppler (PWD) too low (a) and optimized (b). In both images the PRF is set much too low with aliasing in both.

Some flow velocities are so high that their measurement is not possible with standard machine settings. In these cases, options for improving the exam are:

- optimization of the probe position to shorten the distance between the vessel and the probe
- selecting a lower transmission frequency
- increasing the scale
- applying a larger angle between vessel and Doppler beam
- shifting the baseline with loss of retrograde flow components or working with the setting “High Pulse Repetition Frequency (HPRF)” which is possible in certain ultrasound machines.

With HPRF, the US system does not wait for the first Doppler pulse to arrive back at the transducer after reflection; instead, one or more additional pulses are sent beforehand, and “ghost gates” are created for each additional Doppler pulse. This extends the velocity scale at the expense of the display of slow flow components and the spatial allocation of the Doppler signal. In order to avoid a mixed signal, it must be avoided that further vessels are located in the “ghost gates”.

Baseline

The baseline must be set with the objective to display an adequate velocity scale and to make full use of the image.

Wall Filter

The wall filter eliminates interfering movements (e.g., pulsations) from the vessel wall. At the same time, however, slow blood flow components of the spectral curve (e.g., low end diastolic velocities or a slow reverse flow) may not be displayed as the corresponding signals are cut out by the filter settings (fig 2). Image optimization can thus increase the aesthetics but may conceal underlying information. Accordingly, wall filters should be used only if necessary to display weak high-frequency signals within high-grade stenoses. The wall filter should be turned off or set low to display very slow flow, e.g., in leg veins, splanchnic veins or diastolic flow components in arterial vessels. Otherwise, a false “no flow” diagnosis may be the result. Motion artifacts should be minimized by optimization at the level of the incoming information, e.g., by asking patients to hold their breath.

Sweep speed

Sweep speed adjusts the scrolling speed of the Doppler spectrum. A lower sweep speed displays more heart cycles, which can be helpful to illustrate certain pathologies. However, increasing the sweep speed leads to fewer cycles where each is outlined in greater detail. Sweep speed can typically be adjusted after recording several heart cycles; thus, it can be performed after freezing the image (“post-processing”).

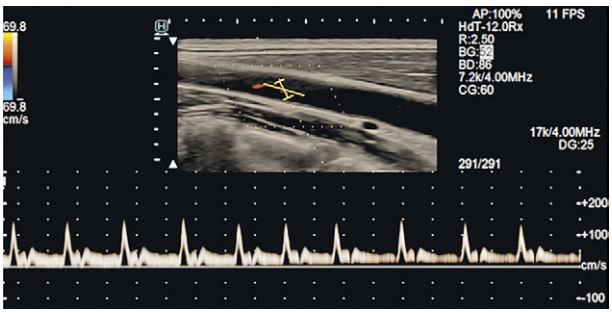

Fig 2. The influence on the Doppler spectrum by enhanced wall filter settings. The filter blanks out signals corresponding to slower flow.

Gate

The size of the gate (Doppler window) should be selected with the objective to display the entire available speed range. The size should ideally be at least two thirds of the vessel diameter. In very small vessels it should be as small as reasonably applicable.

Doppler angle

The Doppler angle must be aligned with the course of the vessel by use of the respective rotary control or toggle switch. This adjustment is crucial for enabling the system to calculate the maximum flow velocity and calibrate the scale according to the Doppler equation. For Doppler angles between 0° and 30°, adjustments are negligible as the resulting correction of flow velocity is very small. Between 30° and 60°, the Doppler angle should be corrected on the device. Since the cosine of 60° is 0.5, omitting the angle correction may result in an erroneous doubling of the measured flow velocity. With Doppler angles above 60°, exact measurements are no longer possible. When exceeding 60°, velocity measurements become inaccurate despite angle correction. The US devices often use a marker to indicate that an adequate angle correction is not possible. In those cases, the examiner should try to find a probe position enabling a Doppler angle of 60° or below (fig 3). Another option is electronic Doppler beam steering, which is possible with modern US systems.

Since breathing movements must be avoided during velocity measurements, the examiner should be aware that angle corrections could be performed as part of post-processing on most US machines, i.e., after freezing the image.

A flow parameter independent of the Doppler angle is the Pourcelot Resistance Index (RI) which is calculated from the systolic peak velocity and end diastolic velocity [RI = (peak systolic velocity – end diastolic velocity) / (peak systolic velocity)]. It quantifies the pulsatility of blood flow and illustrates the flow resistance downstream within the subsequent arterial system and capillary bed. Another index for the indirect measurement of blood

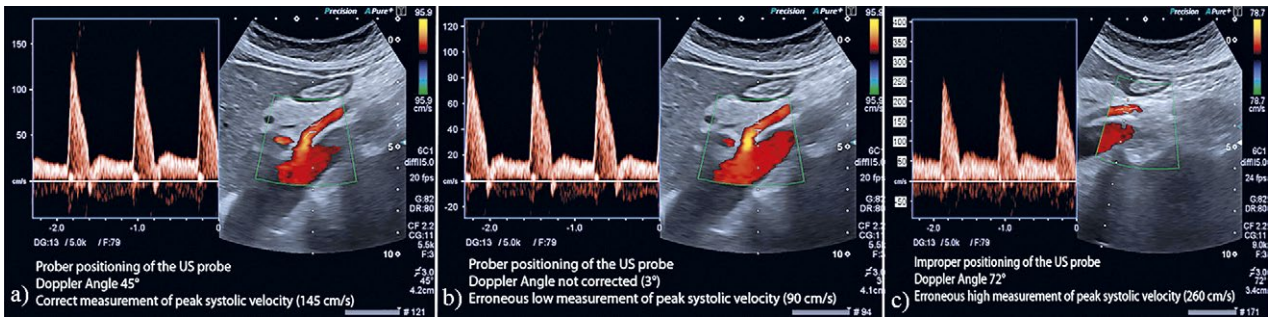

Fig 3. Measurement of flow velocities in the superior mesenteric artery (SMA): Following adjustment of scale to the velocity range typical for superior mesenteric artery (95.9 cm/s) and a correction of the Doppler angle to 45° correct measurement of the normal peak systolic velocity is possible: 145 cm/s (a); in case of no correction of Doppler angle an erroneous low peak systolic velocity is measured (b; 90 cm/s); improper positioning of the US probe results in a Doppler angle of 72° (c), and correct measurement of flow velocity is impossible (erroneous measurement of a high peak systolic velocity in the range of mild stenosis)

flow downstream, which is also independent of the angle of insonation, is the Pulsatility Index [PI = (peak systolic flow – peak diastolic flow) / (mean flow)]. If it is not feasible to adjust the Doppler angle below 60°, one should refer to Doppler angle independent measurements like RI or PI [8-10].

Inversion

The "Inversion" function interchanges the mapping of the flow direction as part of the Doppler spectrum. Values are displayed above or below the baseline depending on the flow towards or away from the probe.

Post-Processing

As part of post-processing, the brightness of the image can be varied by adjusting the Doppler gain, which allows for better noise suppression. For arteries, the gain should be set in a way that a frequency-free window is recognizable. In post-processing, the colour of the image can also be changed (e.g., monochromatic or polychromatic illustration), and the angle correction can be carried out as described above. In newer machines, the user can edit sweep speed and baseline as well. The knowledge of post-processing alterations is essential particularly in measurements acquired in breath hold while examining abdominal vessels.

Automatic Image Optimization

Most high-end ultrasound devices can automatically adjust the Doppler settings by changing the parameters outlined above. Nevertheless, optimum image settings are best achieved manually.

2. Colour and Power Doppler US

CDUS integrates B-scan and colour-coding of flow information. It is often complemented by PWD. CDUS is therefore primarily used for targeted vascular diagnostics. Two modes are distinguished. In velocity mode, the flow direction in relation to the transducer is coded by different colours (usually red and blue) and colour brightness and shading convey different flow velocities. A third colour (green) displays the velocity dispersion. Thus, turbulences are visualized. In contrast to the modality mentioned above, the intensity mode (Amplitude-Doppler / Power-Doppler / Angiomode) displays only the flow amplitude without flow direction. This allows for a higher sensitivity in detecting low-velocity blood flow [11].

There are two main objectives of CDUS. The first is to detect the presence of flow, its direction and accelerations within larger vessels (macro-CDUS). The second is to visualize perfusion of organs or tumors by detecting low-velocity flow in small parenchymal vessels (micro-CDUS). Micro-CDUS techniques close the gap to contrast-enhanced ultrasound (CEUS). Different settings and modalities are used for macro- and micro-CDUS [12,13]. CDUS must be distinguished from other flow imaging modalities. Microvascular Flow Imaging (MFI) for example displays blood flow in real-time on the B-scan image. Echoes are encoded, decoded and filtered in such a way that the significantly weaker echoes of blood cells are visualized. By comparing successive frames, these weaker echoes are displayed as a flow. Currently, manufacturers have established this technology to varying degrees. The advantages are significantly better spatial resolution similar to B-scan sonography and better representation of slow flow with fewer artifacts than CDUS. Owing to limitations such as a lack of velocity measurement and penetration depth, it is likely that microflow imaging will increasingly complement CDUS in the future without replacing it [14,15].

Other types of MFI make use of traditional Doppler ultrasound techniques with enhanced filters and higher frame rates improving the discrimination between slow flowing signals and background noise. These advanced Doppler techniques have acronyms such as Superb Microvascular Imaging (SMI) (Canon Medical systems)

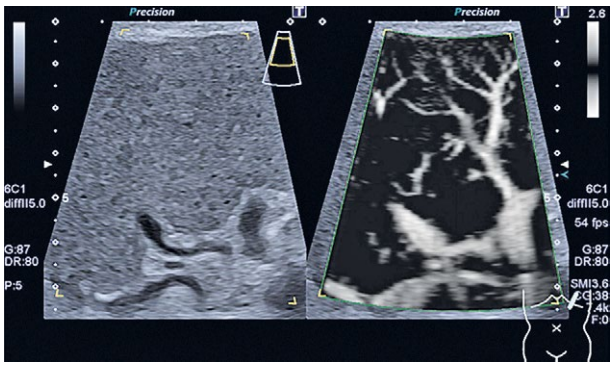

Fig 4. Low flow Doppler modality (superb microvascular imaging, SMI) nicely depicting intrasplenic vessel tree

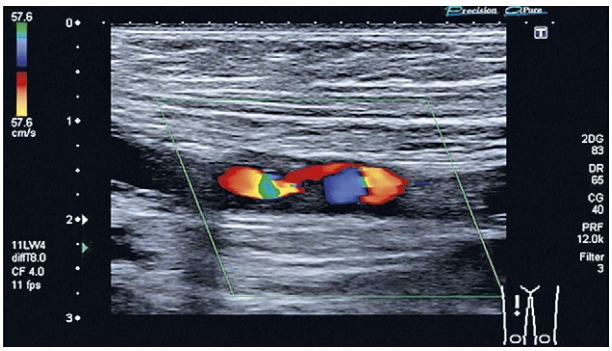

Fig 5. CDUS aliasing in femoral artery: scale is properly adjusted to the normal velocity range of femoral artery blood flow. Aliasing indicates stenosis.

or Microvascular Imaging (MVI) (Philips Medical Systems). They are more sensitive than CDUS and become increasingly relevant in the field of contrast-enhanced ultrasound, which owing to constraints of this article cannot be explained in detail [16] (fig 4).

Parameter adjustment in CDUS

The following important parameters must be taken into consideration using CDUS.

Transmission Frequency

The colour Doppler frequency can be adjusted independently of the B-scan. Due to the proportionality between the transmission frequency and the Doppler frequency, the transmission frequency is important for the sensitivity of flow detection. A compromise between sufficient penetration and adequate sensitivity must be found since penetration depth decreases as frequency increases.

Pulse Repetition Frequency / Scale

The PRF defines the velocity range on display. If the maximum flow velocity on the scale is exceeded, aliasing artifacts occur. If the scale is correctly adjusted to the flow velocity that can be expected in a given vessel [8-10], aliasing on CDUS is a “red flag” signal for stenosis [6] (fig 5, fig 6).

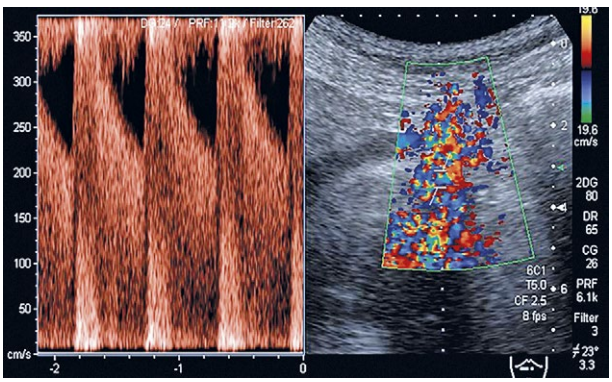

Fig 6. Aliasing with CDUS and PWD in celiac trunk stenosis

In micro-CDUS a low PRF is used to avoid false negative results of vascularization, while with macro-CDUS, higher PRF settings would prevent aliasing (fig 7, fig 8).

Baseline

The baseline alters the display of the flow velocity range as it is moved up or down. On CDUS, baseline adjustment is of no clinical value.

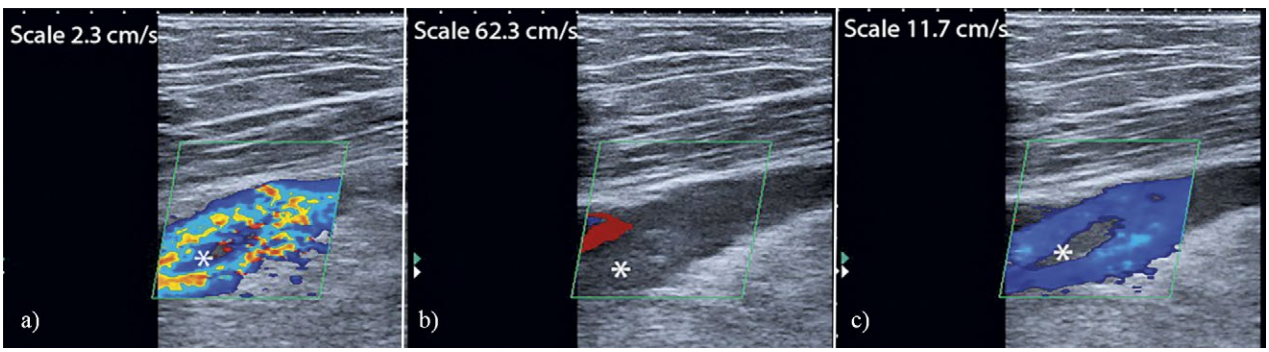

Fig 7. Adjustment of velocity scale in colour Doppler of a focal thrombus of the femoral vein: low scale (2.3 cm/s), aliasing with thrombus (*) poorly visibly (a); high scale (62.3 cm/s), nearly no flow is visible and complete thrombosis is feigned (b); adequate scale (11.7 cm/s) showing venous blood surrounding the focal thrombus (c)

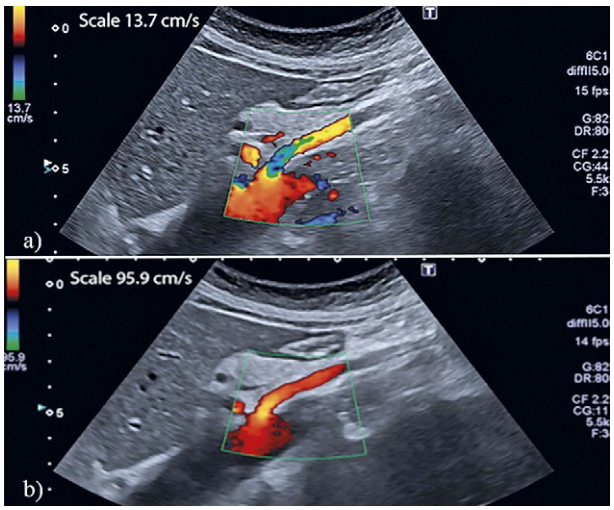

Fig 8. Influence of scale adjustment in CDUS of superior mesenteric artery (normal velocity range 100 – 200 cm/s): alias phenomenon due to improper low selection of scale (13.7 cm/s) simulates stenosis (a); Correction of scale to the velocity range typical for superior mesenteric artery (95.9 cm/s) shows normal blood flow (b)

Colour Doppler box

The sampling box, in which the flow is displayed, should be as small as possible and as large as necessary. A smaller box size increases temporal resolution and frame rate. Using the trackball or touchpad and the "set" button can optimize the size and position of the box. When using linear array transducers, the examiner can steer the insonation angle. The smaller the Doppler angle between the transducer and the vessel of interest, the better and more accurate the retrieved flow information (fig 9).

Doppler angle and steering

The Doppler angle should be at or below 60° as angles above this threshold will compromise the colour display of blood flow, owing to the fact that the cosine of an insonation angle above 60° in the Doppler equation leads to erroneous flow velocities and cannot be compensated by manual or technical corrections. In the case of linear arrays, steering of the Doppler angle is possible but reduces the sensitivity of flow detection. Therefore, it is preferable to position the transducer carefully in the first place with the objective of acquiring a smaller Doppler angle between 0 and 30°.

Inversion

The colour spectrum is interchangeable by pressing the "invert" button. Since colours are selected individually, the flow pattern on display should be interpreted with the colour bar on the right or left edge of the screen. By default, flow towards the transducer is coded in red, and flow away from the transducer is depicted blue. Inversion can be helpful to display arteries in red and veins in blue but this can lead to confusion if not all providers use the same inversion option.

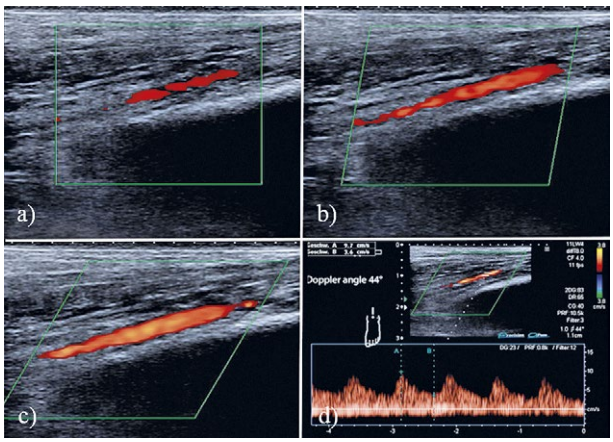

Fig 9. Influence of beam steering on visualization of slow post-occlusive flow in tibial artery. Scale was adjusted to low flow velocities (3.8 cm/s): no beam steering with poor visibility of flow (a). Beam steering (b: 15°; c: 30°) improves visibility and allows correct PWD measurement of the peak systolic velocity (9.7 cm/s) with an acceptable Doppler angle of 44° (d)

Gain

The gain of colour Doppler should be initially increased until so-called "blooming" artifacts occur followed by a gradual gain reduction until these artifacts disappear (fig 10).

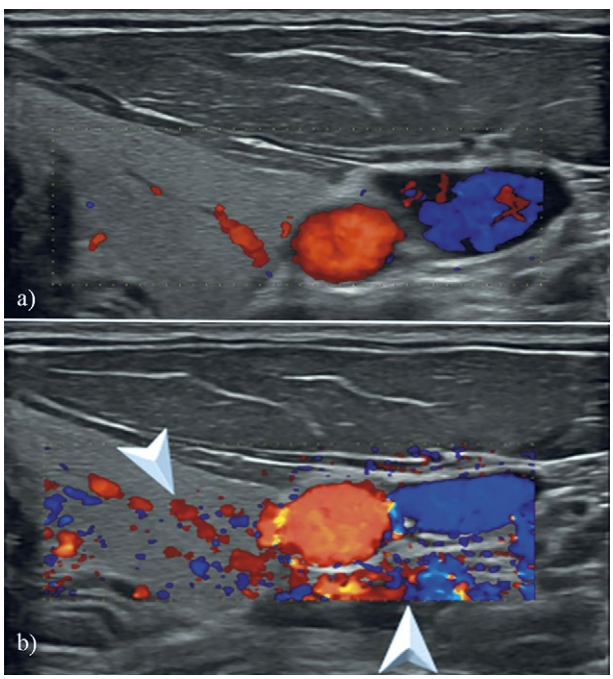

Fig 10. Gain optimized (a), and too high with additional colour artifacts, so-called "blooming" phenomenon, around the actual vessels (arrows) (b).

Duplex- and Triplex-Mode

CDUS and PWD may be used together with B-mode imaging. While “Duplex imaging” incorporates grey-scale imaging and either CDUS or PWD, the examiner makes use of all three modalities in what is termed “Triplex imaging”. This modality can be applied to detect the vessel of interest by first using CDUS and then perform an additional flow measurement by pressing the “Update” button. Here, only PWD is active in real time while the CDUS image is frozen. Newer devices can also display B-scan, CDUS and PWD simultaneously in real time in Triplex mode. However, as this is accompanied by a loss of image quality and a significantly reduced frame rate, Duplex mode is generally preferred.

3. Contrast enhanced Doppler ultrasound

The introduction of US contrast agents (USCA) has improved the potentials of colour Doppler US in difficult situations, e.g., to visualize the renal arteries [17,18], and to reduce the number of equivocal examinations [19]. The same is true for other organs including pancreatic vessel evaluation for the important differential diagnosis of chronic pancreatitis and ductal adenocarcinoma [20,21].

Conclusion

The article summarizes knowledge, handling and recommendations for colour and spectral Doppler ultrasound parameter adjustment to achieve the best possible image quality. The most important parameters include transmission frequency, pulse repetition frequency (scale), baseline, wall filter, gain, sweep speed, size of gate, Doppler angle, inversion mode, post-processing parameters, automatic image optimization, colour Doppler box size and angle steering as well as duplex- and triplex-mode.

Conflict of interest: none

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