Phlébologie ANNALES VASCULAIRES 2019, 72, 2, p. 69-77

SOCIÉTÉ FRANÇAISE DE PHLEBOLOGIE

Chapter 1

Pulsed and Color Doppler: General Technical Considerations

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Abstract

For many of us, it often seems daunting to look at the physical principles that govern ultrasound and its use in the medical field.

However, it is illusory to consider optimizing the machine settings and thus the diagnostic performance of our examinations without knowing a minimum. This chapter therefore aims to address in the most attractive way possible, the general technical considerations of Doppler Ultrasound and the immediate practical applications that flow from it.

Introduction

Vascular ultrasonography studies vessels and blood flows using several modalities: B mode, color and power Doppler modes, spectral Doppler mode and other modes depending on the manufacturer.

For many of us, addressing basic physical principles often seems daunting.

However, it is illusory to consider optimizing the machine settings and thus the diagnostic performance of our examinations without knowing a minimum.

In order to make this chapter attractive, we will make some reminders on the properties of ultrasound and then the plan will follow the different points of optimization of the B, color Doppler, power Doppler and spectral Doppler modalities, while addressing the general technical considerations. We will end with the specificities of adjustments in the context of superficial venous insufficiency (SVI) and deep venous thrombosis (DVT) assessments.

Properties of ultrasound

Characteristics of ultrasonic waves and their propagation

Ultrasound is a mechanical wave that propagates through elastic and deformable material media, and whose frequency is within a range of 20,000 and 1,000,000 Hertz (beyond the range of frequencies audible by the human ear).

Traditionally, the frequencies used are in Mega Hertz (in millions of cycles per second). Ultrasound can be produced and detected, among other things, by the mechanical oscillations of piezoelectric crystals placed on the probes (these are the direct and indirect piezoelectric effects). The gel applied to the patient's skin avoids a 99% ultrasound beam reflection generated by a soft tissue-air interface.

Some definitions:
- Wavelength = length of an oscillating cycle; it is expressed in mm. The frequency of the sound wave f and the wavelength λ are linked by the relationship $\lambda = c/f$, c corresponding to the speed of propagation of the wave in the environment. The average propagation rate in soft tissues is about 1540 m/s.
- Acoustic impedance = the "resistance" of a material to the passage of sound.
- Interface= boundary area between fabrics of different acoustic impedances.

Ultrasound will spread and interact with tissues during the to and fro trip.

There are different forms of interaction with tissues:

- ***Reflection:*** **considering the case of waves at normal incidence (angles close to 90°) and an interface larger than the wavelength, it is accepted that when the wave reaches an interface between two media, a part crosses the medium (the wave "transmitted") and a part is returned (the "reflected" wave). The reflected beam leaves with an angle identical to the angle of incidence.**

- In most tissues, only 1 to 2% of the beam is reflected. NB: The more the acoustic impedances on either side of the interface are different, the more important the reflection is.
- Refraction: the transmitted beam retains its initial direction only if the incident beam arrives perpendicular to the interface. In all other cases, it is partially deviated, this is called refraction.
- Diffusion: it corresponds to the re-emission in all directions of space of a minimal fraction of the ultrasonic energy when the ultrasounds encounter a particle. Scattering depends on the size of the particle encountered and the ratio of this size to wavelength. For a particle smaller than the wavelength, such as a red cell, the scattering of the incident wave is identical in all directions.
- Absorption: it is due to the transformation of mechanical energy into heat by internal friction phenomena (related to the viscosity and relaxation time of the molecules). The highest frequency waves are more easily absorbed and scattered than the lowest frequency waves.
- Attenuation: during its propagation within the tissue, the wave energy is attenuated by the multiple interactions described above. It is characterized by an exponential decrease or a reduction in intensity in decibels (dB).

Interaction of ultrasound with circulating flow: the Doppler effect

When a source emits sound waves, the frequency of the reflected wave from a moving object in the path of the wave beam increases or decreases respectively as the object approaches or moves away from the source. This is the Doppler effect **(Fig. 1)**.

The delta of frequency is called Doppler frequency. The latter is in the audible frequency range for circulating red blood cells. A relationship links blood velocity to this frequency such that:

$$V = (\Delta F \times c) / (2 \times F0 \times \cos\theta)$$

ΔF: Doppler frequency
c: ultrasound velocity in soft tissue F0 : emission frequency
θ: angle formed by the incident beam and the direction of flow

The only data that the operator will have to provide to his device during a speed measurement via the angular correction will be the angle θ. If the operator makes a mistake on that correction, the speed calculation will be completely wrong.

An angular correction less than or equal to 60° is allowed.

If θ = 90° then cos θ = 0, the device does not record any signal. The device extrapolates the result in its entirety and the error will be maximum.

If θ = 60° then cos θ = 0.5; when calculating speeds, the maximum estimation error will be about 50% (1-0.5).

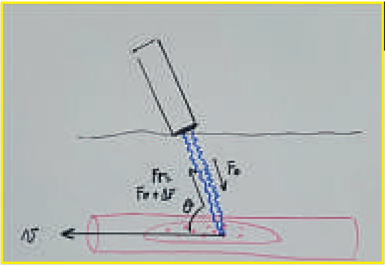

Fig 1: The Doppler effect.

If θ = 0° then cos θ = 1; when calculating speeds, the maximum estimation error will be about 0 %. In other words, the closer θ is to 0°, the closer the calculated speed is to the speed in presence.

How to adjust your monitor

- Do not saturate towards the whites.
- Adjust the brightness and contrast properly.

Choosing the probe

- The axial resolution depends on the emission frequency of the sensor (a high transmission frequency is associated with an excellent resolution).
- The explorable depth is inversely proportional to the emission frequency of the sensor (when the emission frequency is high, the absorption is high so the penetration and the explorable depth are low).

Optimization of the 2D image

- The operator always aims for a compromise between the highest possible frequency for good resolution and the lowest possible frequency for high penetration.

Notion of image rate:

The highest possible image rate should always be sought **(Fig. 2 and 3)**, for this purpose, it is necessary to:

- Position the region of interest in the lower third of the explored field.
- Minimize the width of the exploration field (this reduces the number of lines that the device must "manufacture").
- Position a single focus area opposite the region of interest (if 2 focal lengths are positioned, the camera will have to "pass" twice per line).
- If necessary, zooming in, in digital zoom (writing zoom, see concept below), will focus on the region of interest.

For more information:
Image Rate = (Speed / (2x number of shots per image)) x (1/depth)

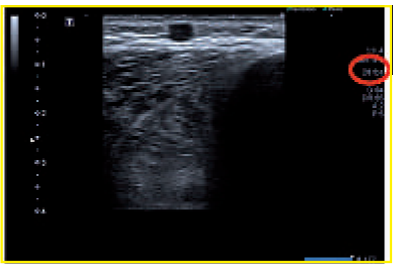

Fig. 2: The image rate here is 28 images/ seconds.

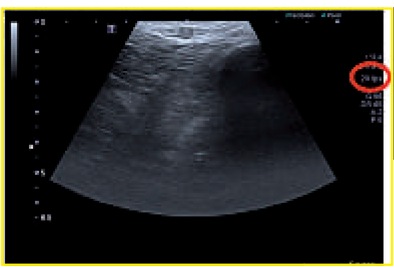

Fig. 3: Increasing the depth and widening the field to areas that are sometimes even uninteresting degrades the image rate at 20 images/seconds.

Some definitions:
- *Focusing a beam:* an ultrasonic beam is focused towards a socalled focal point where the intensity of said beam is maximum; this near field is called the Fresnel zone. Beyond this focal point, the beam diverges (its diameter increases and its intensity gradually decreases); this far field is called the Fraunhofer zone. Acoustic lenses (mechanical focusing) and piezoelectric crystal activation sequences (electronic focusing) are used for this purpose.
- *Axial resolution:* it defines the ability to distinguish two echoes in the beam axis. High frequencies and short pulses improve it.
- *Lateral resolution:* it defines the ability to distinguish two echoes in the beam width. The electronic focusing of the phased array probes makes it possible to improve it.
- *Temporal resolution:* it defines the ability to distinguish two events at different times. A high image rate indicates a good temporal resolution.

Notions of optical zoom and acoustic zoom:

- **Optical zoom (or "post processing" zoom) refers to a pixel magnification that involves distortion and denaturation of information.**
- **Acoustic zoom (or digital or writing), "at acquisition" (i.e. in pre-processing) corresponds to a focus of machine power on a user-defined area that implies increased precision and clinical relevance.**

Notion of smoothing:

- **Smoothing: Smoothing reflects a spatial «averaging» called spatial interpolation defining the «acutance» of the image (for example: pixelized or smoothed).**

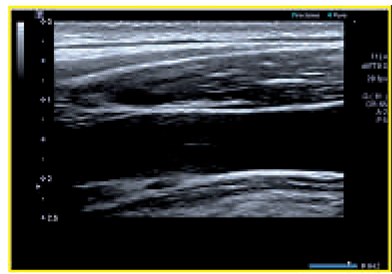

Fig. 4: On this jugular, the clear visualization of the venous wall as well as the valve is possible with ideal perpendicular ultrasonic incidence (90°). In areas exposed at angles other than 90° (i.e. at the left end of the image) the wall rendering is much less clear.

*The importance of the ultrasonic incidence **(Fig. 4)**:*

- **The detection efficiency of a reflected energy varies with the angle, ideally a 90° angle. That ideal perpendicular incidence to the structure being explored must be achieved with a probe angulation on patient's skin and/or with a use of possible electronic angulation of shot.**

*Notion of dynamic range **(Fig. 5)**:*

- **It is usually expressed in dB (or compression). It acts directly on tissue differentiation. It therefore intervenes on the contrast of the image and defines the visualization of the information according to our wishes.**

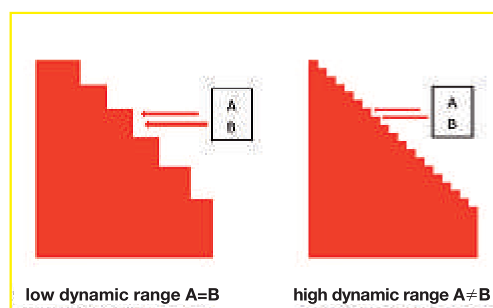

Fig 5: Notion of dynamic range.

*What about the 2D Gain / TGC / Grey Scale settings **(Fig. 6 and 7)**: their objectives are:*

- **Not to saturate the screen.**
- **To accept a grey image that is more informative than a white image.**
- **To accept some background noise in the vascular light. Nb1 : the grey scale does not modify the dynamic range: there is therefore no loss of information). Nb2: Time Gain Compensation will be set differently for a superficial venous study and for a deep venous study.**

For more information:
- *The dynamic range* allows us to increase or decrease the scale of the brightness levels of the echoes generated. With a low dynamic range, the low echoes level are hidden which creates a greater contrast of the highest int*ensity signals.*

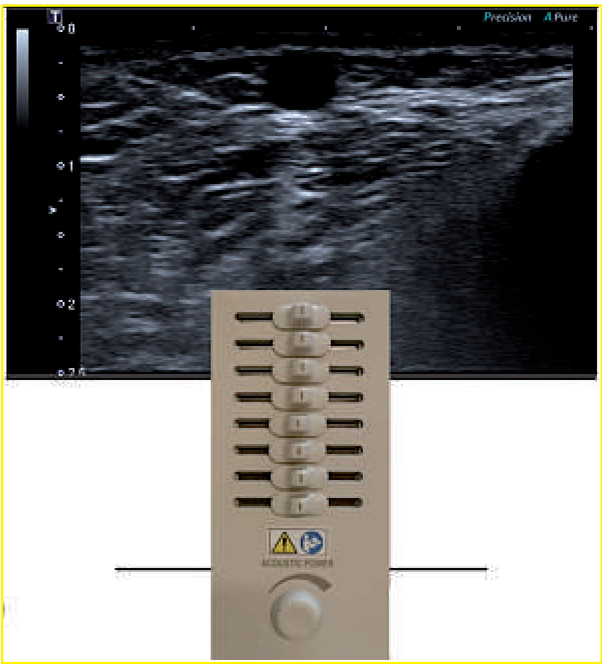

Fig. 6: Gains from the most superficial echoes insufficiently raised (i.e. poorly adjusted TGC).

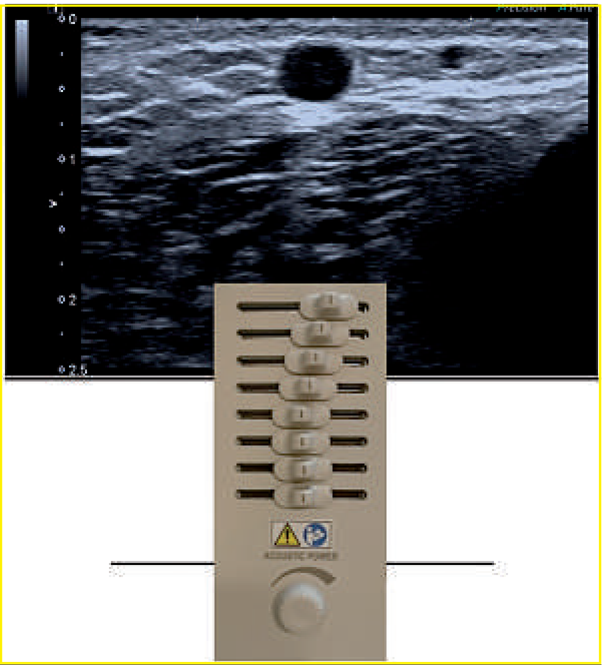

Fig. 7: 2D gain and TGC well adapted to superficial venous study.

- The TGC: Time Gain Compensation: in order to obtain a identical brightness over the entire depth of field, echoes from areas of different depths can be deleted or on the contrary enhanced. For example, the enhancement of deep signals usually attenuated will make it easier to visualize them.

Doppler optimization, basic principles (Fig. 8, 9, 10, 11, 12)

Impact of Sensor Frequency / Exploration Depth / Pulse Repetition Frequency (PRF):

- **The depth sensitivity is inversely proportional to the emission frequency of the sensor (i.e. a deep circulating structure is studied with a low frequency probe).**
- **How to adjust the PRF: a fast circulating structure is studied with a high PRF (cf. notion of aliasing) // a slow circulating structure is studied with a low PRF // a deep structure is studied with a low PRF (cf. notion of spatial ambiguity).**

Some definitions:

- *Pulse Repetition Frequency (PRF):* it corresponds to the time it takes for a doppler pulse to return to the probe. It defines the pulse emission frequency of the probe and it is expressed in kilohertz.

- *Nyquist limit notion:* it defines the upper limit of the measurable Doppler frequency without ambiguity. This maximum explorable frequency is equal to PRF / 2.
When the explored speed exceeds our PRF, the device transcribes it by a color mosaic called aliasing; it is the frequency ambiguity.
A relationship also links the maximum explorable depth to the PRF, such as Max. depth = Speed / (2.PRF).
This is because a new ultrasonic pulse cannot be emitted until all the information from the previous pulse has been received.
The study of a deep structure with a too high PRF will expose to spatial ambiguity (i.e. difficulty in locating the signal at depth).

Angular correction: (cf. Interaction of ultrasound with the circulating flow: the Doppler effect)

- **V= (ΔF x c)/ (2 x F0 x Cos θ)**
- **θ must be less than 60° and tend towards 0°.**
- **In color Doppler, it is advisable to tilt the color box**
- **In pulsed Doppler, it is advisable to tilt the angle of shot**

For more information:

- *Duplex or triplex modes:* the same probe is used to combine two to three modes (B mode, color Doppler and spectral Doppler). The device can switch very quickly from one modality to another, giving the impression of real-time imaging combining the different desired modalities.

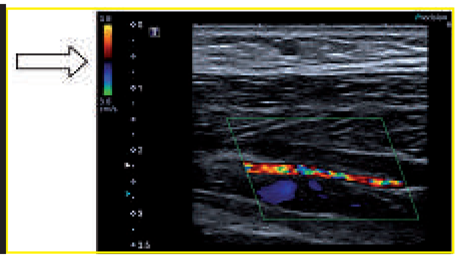

Fig. 8: PRF too low, not suitable for this posterior tibial artery study, resulting in an aliasing/ mosaic color.

(i.e. PRF too low compared to studied speeds).

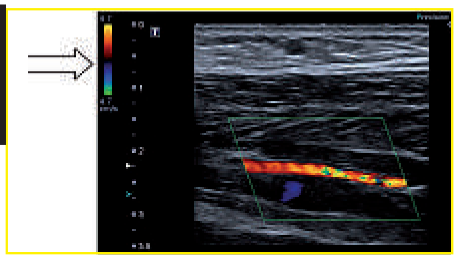

Fig. 9: PRF still too low and unsuitable for the study of this posterior tibial artery.

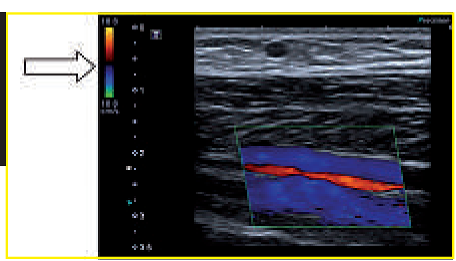

Fig. 10: PRF well set, aliasing disappears. Homogeneous red color over the entire artery.

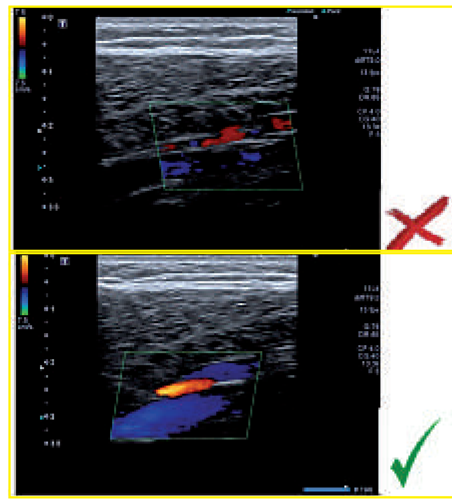

Fig. 11: In longitudinal section, for a well inclined color box, the largest axis of the parallelogram is placed in the axis of the vessel. This inclination of the color box corresponds to an inclination of insonation that allows the Doppler signal to be picked up.

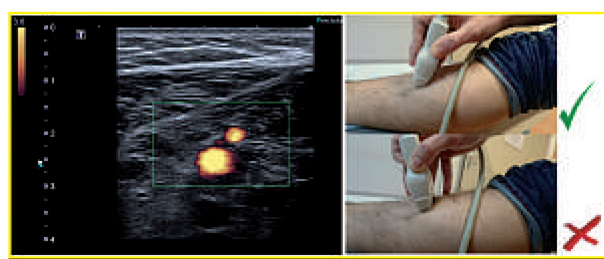

Fig 12: In cross-section the color/power box is positioned in "rectangle". or "square". In these conditions, it is up to the operator to carry out on the patient a good incidence with the probe in order to obtain an angulation conducive to effect/sensitivity Doppler.

- ***Continuous Doppler:*** **it uses 2 crystals (one in transmission and one in reception). The analyzed signal results from the summation of all the flows encountered on the path of the incident beam.**
- **B mode (brightness): This mode provides twodimensional images in real time and in grayscale. While the probe scans the cut plane, an image is recreated from the information obtained by each firing line.**
- ***Color Doppler:*** **Color Doppler analyzes average speeds. It is a multi-portal pulsed Doppler for qualitative analysis of hemodynamic events. Average speeds, not instantaneous speeds, are analyzed. This Doppler information is superimposed on 2D imagery. The Doppler effect is then represented in color coding to define the direction of the effect. The color Doppler setting meets the same conditions and rules as the pulsed Doppler.**
- ***Power Doppler:*** **it allows to visualize the concentration of red blood cells. By integrating the color Doppler signal, this mode also called energy mode is made less dependent on the angle of incidence. It allows a better visualization of slow and permanent flows. It is also less prone to color interference when the PRF is low. However, this mode is more subject to movement artifacts. Thanks to modern ultrasound scanners, it can now be directional like color Doppler.**
- ***Spectral Doppler:*** **a gate is used to calculate the time interval between the transmission and reception of the feedback signals. The depth at which sampling is performed is thus determined. This mode is used to study the spectrum and direction of the Doppler frequency. The velocities are obtained after a manual angular correction and then by calculation using the Doppler effect formula.**

Optimization of the color Doppler

Transmission frequency:

- **The color Doppler transmission frequency of the probe can be varied. The higher the frequency, the better the Doppler definition, but the greater its absorption; the penetration depth is then reduced.**

Gain / PRF **(Fig. 13)***: the objectives are:*

- **To obtain maximum color sensitivity: the gain must then be adjusted until some background noise appears in the region of interest.**
- **To obtain as much information as possible: the PRF must then be adapted to the expected speed range, the territory studied and the suspected pathology.**

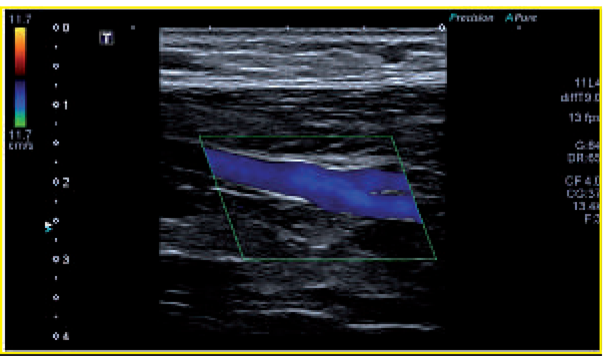

Fig. 13 : Example of a well set gain and PRF.

Size of the color box:

- **Color Doppler is a multi-line, multi-gate Doppler.**
- **The creation of a color encoding requires a large number of shots per line (i.e. a lot of data, a lot of calculations).**
- **It is advisable to optimize the color filling by a correct angulation of the box.**
- **To optimize the image rate, the width and height of the box must be selected accordingly (Figs. 14 and 15).**

Colour priority / 2D gain / number of shots per line:

- **The priority corresponds to the grey levels from which we want the device to put color on it. It can be adjusted to be high, low or intermediate.**
- **The 2D gain modifies the overall grayscale of the image; therefore, lowering the 2D gain will also have the advantage of increasing the appearance of the color (Fig. 16).**
- **It should always be kept in mind that a high number of shots will have a direct impact on the image rate.**

Notion of persistence:

- **It corresponds to a "temporal averaging" of the color assigned to the different pixels on more than one image; it can be compared to retinal persistence. Persistence must be be used in moderation because the color image is improved apparently and to the detriment of dynamic information, the temporal resolution being reduced.**

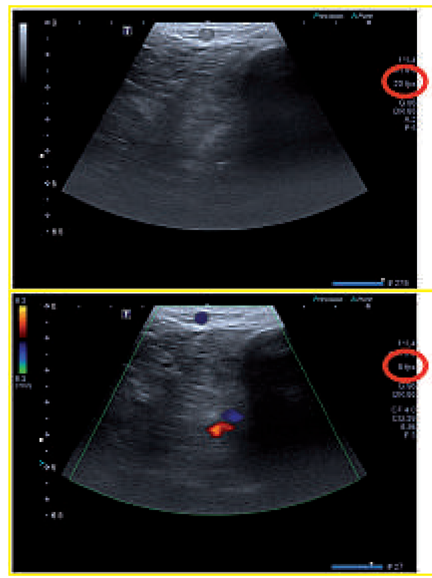

Fig. 14 and 15 : An extended color box, even on areas without circulating vessels, results in a very quickly degraded image rate, 6 frames per second in this case compared to 20 before the color box was installed.

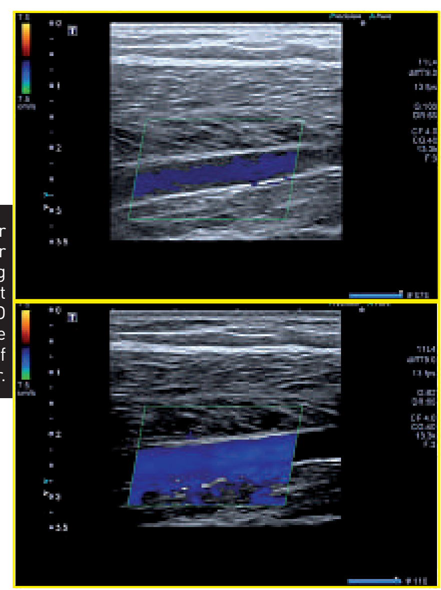

Fig. 16: Even for identical color settings including color priority, just the decrease in 2D gain favors the appearance of color.

Optimization of spectral Doppler

Gain / dynamic range / grey scale: the objectives are:

- **Not to saturate the spectrum**
- **To obtain a good distinction between neighbouring speeds, for this we will use:**
  - **moderate pulsed Doppler gain**
  - **a high dynamic range**
  - **an adapted post-treatment curve**

The choice of the spectral scrolling speed:

- **Fast or slow depending on the area studied, the speeds involved, the desired calculations (Fig. 17 a and b).**

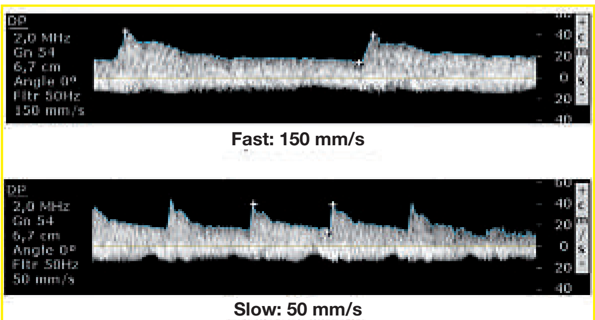

Fig. 17a: For example, a fast scrolling speed facilitates the calculation of the acceleration/rise time on a renal artery.

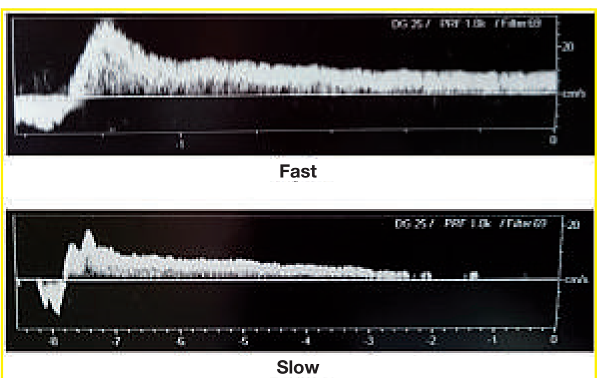

Fig. 17b: On the other hand, a slow scrolling speed facilitates the characterization of venous reflux.

High pass filter:

- **It eliminates all frequencies or speeds below the selected threshold.**
- **It can be useful to eliminate wall noise (low frequencies**
- **of high energy).**
- **Be careful not to mask, for example, a continuous diastolic flow with a high-pass filter that is too high. Example on this jugular. (Fig. 18 a, b and c)**

Notion of ambiguous door: **(Fig. 19)**

- **The increase in PRF beyond the theoretical limit for recording depth creates uncertainty about the topographic origin of the signals (several “gates” are then positioned along the Doppler firing line)**
- **The signal remains interpretable if there are only vessels in one of the gates.**

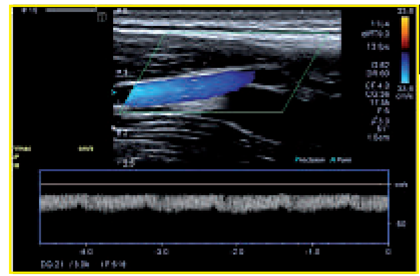

Fig. 18a : High pass filter too high (loss of information).

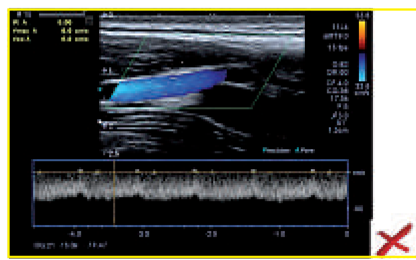

Fig. 18b : High pass filter too low (wall noise).

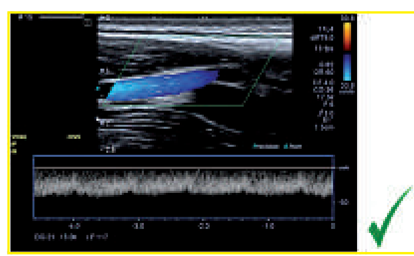

Fig. 18c : High pass filter well adjusted.

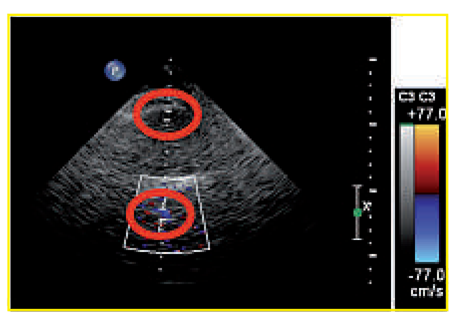

Fig. 19 : Notion of ambiguous door.

In total:
Settings in B mode:
- **Choice of suitable probe and preset**
- **B mode color**
- **Grey scale**
- **2D Gain**
- **Sector width**
- **Depth of exploration**
- **TGC curve**
- **Position and number of focal zones**
- **Optical or acoustic zoom**
- **Dynamic range**
- **Smoothing**

Settings in Color Doppler Mode:
- Range/color chart
- Colour scale
- Base line
- Reverse color encoding
- Colour gain
- Filter
- Position, angulation, box size
- Priority
- Persistence

Settings in spectral Doppler mode:
- Spectrum color
- Scrolling speed
- Speed scale (controlled by PRF)
- Base line
- Spectrum inversion
- Spectral gain
- High pass filter
- Position, angulation, sample volume size
- Angular correction

Settings in power Doppler mode:
- Range/color chart
- Gain / scale
- Base line
- Position, angulation, box size
- Filter
- Priority
- Persistence

Optimization of settings in phlebology: superficial venous insufficiency assesment

B Mode

- We will generally use a linear probe of medium to high frequencies (5-12 MHz) for the thigh and leg and a convex probe of low to medium frequencies (2-7 MHz) for the abdominal vessels. High resolution / high frequency ultrasound (> 15 MHz) may be useful on a case-by-case basis, particularly for the management of telangiectasia and reticular veins.
- Gain and power must be low (i.e. do not saturate the image).
- The TGC curve can be shifted to enhance the most superficial echoes.
- The dynamic range will be adapted:
  - low to visualize the venous walls during distal manual augmentation
  - high to visualize venous stasis.

Color Doppler mode

- The speed scale will be set to around +10 to -10 cm/s, to be increased if there are too many artifacts or if the image rate is too low.
- Colour gain and priority will be optimized to fill the vessels correctly and without burr (i.e. without "overpainting").
- Tilt the probe well to avoid insoning the vessels at 90°.

Spectral Doppler mode

- The speed scale will be set to around +100 to -100 cm/s for the search for reflux, to be reduced for the study of slow flows.
- The high-pass filter is set to the minimum so as not to suppress slow flows.
- The sampling volume is open to cover the entire diameter of the vessel.
- The scrolling speed must be low in order to identify the different types of reflux.
- The angular correction must be optimal.

Optimization of settings in phlebology: deep venous thrombosis assessment

B Mode

- We will generally use a linear frequency probe (5-12 MHz) for the thigh and leg and a convex probe of low to medium frequencies (2-7 MHz) for the abdominal vessels. This convex probe may also be useful in case of difficult examination conditions in the thigh and/or leg; in case of severe oedema for example.
- Gain and power must be low (i.e. do not saturate the image).
- The dynamic range will be adapted:
  - low to visualize the venous walls during venous compression manoeuvres
  - high to view/characterize-date the thrombus.

Colour Doppler mode

- The speed scale will be set to around +10 to -10 cm/s, to be increased if there are too many artifacts or if the image rate is too low.
- Colour gain and priority will be optimized to fill the vessels correctly and without burr (i.e. without "overpainting").
- Tilt the probe well to avoid insoning the vessels at 90°.

Spectral Doppler mode

- The speed scale will be set to around + 50 to - 50 cm/s, to be reduced for the study of slow flows.

Power mode

- On a case-by-case basis, for example, for a distal manual augmentation study in case of impossible direct compression with the probe.

Optimization of settings in phlebology: abdominal vessels

B mode

- We will use a convex probe with low to medium frequencies (2-7 MHz).

- **Gain and power must be high enough without overloading the image.**
- **An appropriate width and depth of field should be used to avoid imposing unnecessary calculations on the machine.**
- **The dynamic range must be quite high.**
- **It is preferable to work with a single focal length.**

Color Doppler mode

- **It is necessary to adapt the width of the color box to optimize the image rate.**
- **The speed scale will be set to around +10 to -10 cm/s.**
- **Colour gain and priority will be optimized to fill the vessels correctly and without burr (i.e. without "overpainting").**
- **It must be ensured that the insoning**

Spectral Doppler mode

- **The speed scale will be set to around +100 to -100 cm/s.**
- **The high-pass filter is set to minimum or medium level.**
- **The sampling volume is open to cover the entire diameter of the vessel.**
- **It must be ensured that the insoning angle is satisfactory (i.e. not too high).**

For more information:
High resolution/high frequency ultrasound:
- High resolution ultrasound defines an ultrasound imaging system with an axial resolution of less than 100 µm. Such a level of resolution requires the use of high ultrasonic frequencies, higher than 15 MHz.
The very superficial venous study is well suited to the use of these high frequency probes. In depths less than 1 cm, all Doppler echo modes are better; this is the case for 2D resolution (i.e. image quality) and Doppler sensitivity.
The identification of small caliber veins, reticulars feeding telangiectasia areas is thus facilitated.
This is also the case when identifying adjacent structures such as nerves and arterioles. The best Doppler sensitivity is associated with better sensitivity in the study of venous reflux appreciation.
High-resolution ultrasound is therefore of diagnostic interest. But its interest is also therapeutic.
Treatment at the source of reflux is made more effective by identifying reticulars feeding a range of telangiectasias.
Also, during therapeutic procedures, the identification of adjacent structures such as nerves and arterioles and the improved visualization of needles provide greater safety.
The available probes should become more miniaturized.
This tool should take its place in our routine clinical practice for the support of C1 of the CEAP classification alongside vein illumination, transluminescence and polarized light.

Books for further study (non-exhaustive list):

[1] Bases physiques et technologiques de l'échographie ultrasonore. M. Boynard. EMC Radiologie et imagerie médicale : Principes et techniques – Radioprotection. 2015.
[2] Kursbuch Doppler- und Duplexsonografie. B. Amann-Vesti, C. Thalhammer. Editeur : Thieme 2015.
[3] L'écho-Doppler en pratique clinique. P. Allan, P. Dubbins, M. Pozniak, N. McDicken, M. Hassan. Editeur : Elsevier 2008.
[4] Échographie. P. Legmann, P. Bonnin-Fayet, J.P. Convard, G. Seguin. Editeur : Elsevier/Masson 2008.
[5] Comprendre l'écho-Doppler Vasculaire. A. Clough, K. Myers. Editeur : Masson 2007.

We thank Pierre Boismain for his critical review of this chapter.