Review

Statement for Doppler waveforms analysis

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Summary: Peripheral artery disease of the lower limbs (PAD) is a common disease. Evaluation of PAD is primarily based on non-invasive examinations with analysis of the arterial Doppler signal being a key element. However, the description of arterial Doppler waveforms morphologies varies considerably across medical schools and from country to country. In order to overcome this issue, the French College of Teachers for Vascular Medicine (Collège des Enseignants de Médecine Vasculaire; CEMV) has summarised the published data on Doppler waveforms analysis and proposes a new "Saint-Bonnet" classification system to describe Doppler waveforms morphologies. The simplified Saint-Bonnet classification comprises eight types and allows taking into account if the Doppler signal does not revert to baseline. This classification, which is based on previous classifications, could improve the descriptions of both physiological and pathological waveforms, recorded in lower limb arteries. According to the reviewed literature, recommendations about the use of Doppler waveforms are proposed. This statement is a preamble to reach an international consensus on the subject, which would standardize the description of arterial waveforms and improve the management of PAD patients.

Keywords: Doppler, peripheral artery disease, waveforms, ultrasound

Introduction

Peripheral artery disease of the lower limbs (PAD) is a common disease affecting more than 200 million people worldwide and is mainly caused by atherosclerosis [1, 2]. In France it is estimated to affect 11% of the population over 40 years of age [3]. This disease generates a significant morbidity-mortality rate with an estimated cardiovascular mortality rate of 15 to 30% within five years [4]. The diagnosis of PAD is primarily based on the use of the resting ankle-brachial pressure index (ABI), an ABI < or = 0.90 defining PAD [5–7].

In the management of PAD, analysis of the Doppler morphologies of transcutaneous arterial Doppler waveforms determines the quality of the arterial flow as well as the level and severity of any arterial lesions [2]. However, although this practice of recording Doppler signal waveforms is extremely widespread, considerable disparity exists nevertheless in the description of the Doppler morphologies of the different signals recorded.

Most specialists concur that a Doppler waveform is either normal or abnormal but the description and precise analysis of the Doppler morphologies remain an important issue. For instance, does a demodulated arterial flow correspond to the loss of a normal triphasic waveform or does it correspond to the terminal pathological type? To what does an "attenuated" flow correspond? This problem has not only emerged in France, where the use of different terminologies is common. In fact, English speakers agree on several types, namely "triphasic", "biphasic" and "monophasic" [8] but several nuances exist leading to difficulties with the terms used to describe "sharp monophasic" waveforms, "flat" waveforms, and "reduced biphasic" waveforms, etc. [9, 10]. A literature review previously highlighted the fact that the terminology used to characterise Doppler waveforms morphology is often inadequately de-

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fined. Out of 94 publications analysed, 81% provided a definition of a triphasic or monophasic Doppler waveforms morphology and 38% defined a biphasic Doppler waveforms morphology [8]. Representations of the various waveforms, when provided, are equally problematic since a Doppler waveform morphology described with the same name may have a different waveforms morphology [11]. It therefore seems necessary to specify the morphological characteristics of the arterial Doppler waveforms (Doppler waveforms morphology) and the various potential classifications proposed.

Methodology

The purpose of this paper is to homogenise and standardise the description of the Doppler waveforms morphology so that caregivers managing PAD patients use the same nomenclature.

The authors of this paper, who belong to the French College of Teachers for Vascular Medicine (CEMV), met to discuss the subject over two working days and summarised the various Doppler waveforms classifications used to date. An expert consensus was achieved at the end of this dialogue and a new classification system was proposed. We decided to follow previous classification to determine the class of recommendation and the level of evidence [12]. The strength of recommendation (Class of recommendations, CoR) of particular options and the level of evidence (LoE) were weighed and graded according to predefined scales, as presented in Table I. The class of recommendation represents the anticipated magnitude and certainty of benefit in proportion to risk. The LoE rates evidence supporting the effect of the intervention on the basis of the type, quality, quantity, and consistency of data from studies.

History of Doppler technique to assess the cardiovascular system

The use of the Doppler technique was first proposed in 1956 by Satomura to study the heart [13]. The same group then showed that arterial and venous blood flows could be analysed using the transcutaneous Doppler method in healthy and diseased vessels [14, 15]. A few years later, other authors showed an interest in further developing the technique, such as Franklin and Pourcelot [15–17]. One of the initial issues was that the direction of the flow could not be detected. In 1966, Kato and Izumi developed the first system capable of detecting flow direction [18]. The continuous Doppler waveform has the advantage of being easy to use with reasonable costs but it cannot determine which vessel is being examined (lack of spatial resolution). Consequently, it was decided to link this to 2D ultrasound imaging (to highlight the vessel of interest). The pulse-wave Doppler ultrasound technique was thus created in the late 1960s, essentially through the work of Baker [19] and Peronneau [20].

Recording methods of Doppler waveforms

Arterial Doppler flow is traditionally measured using a continuous Doppler probe or an ultrasound probe in pulse-wave Doppler mode with a probe ultrasound emission frequency adapted to the depth of the vessel being explored. The deeper the vessel to be investigated, the lower the ultrasound emission frequency, and vice-versa. This measurement, which is mostly recorded in the supine position, can be carried out at rest or following stimulation (exercise, reactive hyperaemia, etc.) [21]. This information (supine position, exercise, etc.) must be mentioned in the report because it determines the way in

Table I. Class of recommendations (CoR) and level of evidence (LoE).

Class of Recommendations	Definition	Suggesting wording to use
Class I	Evidence and/or general agreement that a given procedure is beneficial, useful, effective.	Is recommended/is indicated
Class II	Conflicting evidence and/or a divergence of opinion about the usefulness/efficacy of the given treatment or procedure.	
Class IIa	Weight of evidence/opinion is in favour of usefulness/efficacy.	Should be considered
Class IIb	Usefulness/efficacy is less well established by evidence/opinion.	May be considered
Class III	Evidence or general agreement that the given treatment or procedure is not useful/effective, and in some cases may be harmful.	Is not recommended
Level of evidence	Justification	
Level of evidence A	Data derived from multiple randomized clinical trials or meta-analyses.	
Level of evidence B	Data derived from a single randomized clinical trial or large non-randomized studies.	
Level of evidence C	Consensus of opinion of the experts and/or small studies, retrospective studies, registries.	

which the results are interpreted. The room temperature must be neutral (20 to 25 °C) in order to prevent vasoconstriction if the temperature is too low and vasodilatation phenomena if the temperature is too high.

Arterial Doppler waveforms are recorded at different points along the arterial tree of the lower limbs, with or without 2D-mode imaging when measuring with an ultrasound scanner. The angle of incidence of the Doppler beam must also be taken into account during the measurement, since it is involved in establishing the measurement of blood flow. The Doppler frequency (Δ F), which is obtained when the ultrasound beam hits a mobile element (e.g. red blood cell), is proportional to the cosine of the angle between the Doppler firing angle and the shift axis of the mobile element, according to the following equation [22]:

$$\Delta F = 2 \times F_{emission} \times V \times \cos \theta / C, \text{ where}$$

ΔF corresponds to the Doppler frequency (Hz), $F_{emission}$ to the emission frequency (Hz), V to blood velocity (m/s), cos θ to the angle generated by the Doppler firing beam and the arterial flow axis, and C to the velocity at which the ultrasound wave propagates through the soft tissue (1,540 m/s) [23].

An angle of 0° can have a cosine angle equal to 1 with no error arising in evaluating the speed. The smaller the firing angle, the more likely it is that the estimated speed will be correct, and the bigger the angle, the more likely it is that the estimated speed will be wrong. Thus the ideal Doppler firing angle is less than 60° and preferably between 40° and 60° so that the beam emitted does not lose too much acoustic energy [23].

Morphology of the arterial Doppler waveforms recorded: physiology and physiopathology

In a healthy lower limb artery at rest, the arterial flow is laminar and pulsatile. The normal Doppler waveform morphology presents different aspects which are also known as "phases or modulations" and are described as follows in Figure 1 [16, 24–29]:

1. Ascending branch and its rise time (short)
2. Descending branch and its fall time (short)
3. Negative diastolic component
4. Positive diastolic rebound
5. Return to baseline

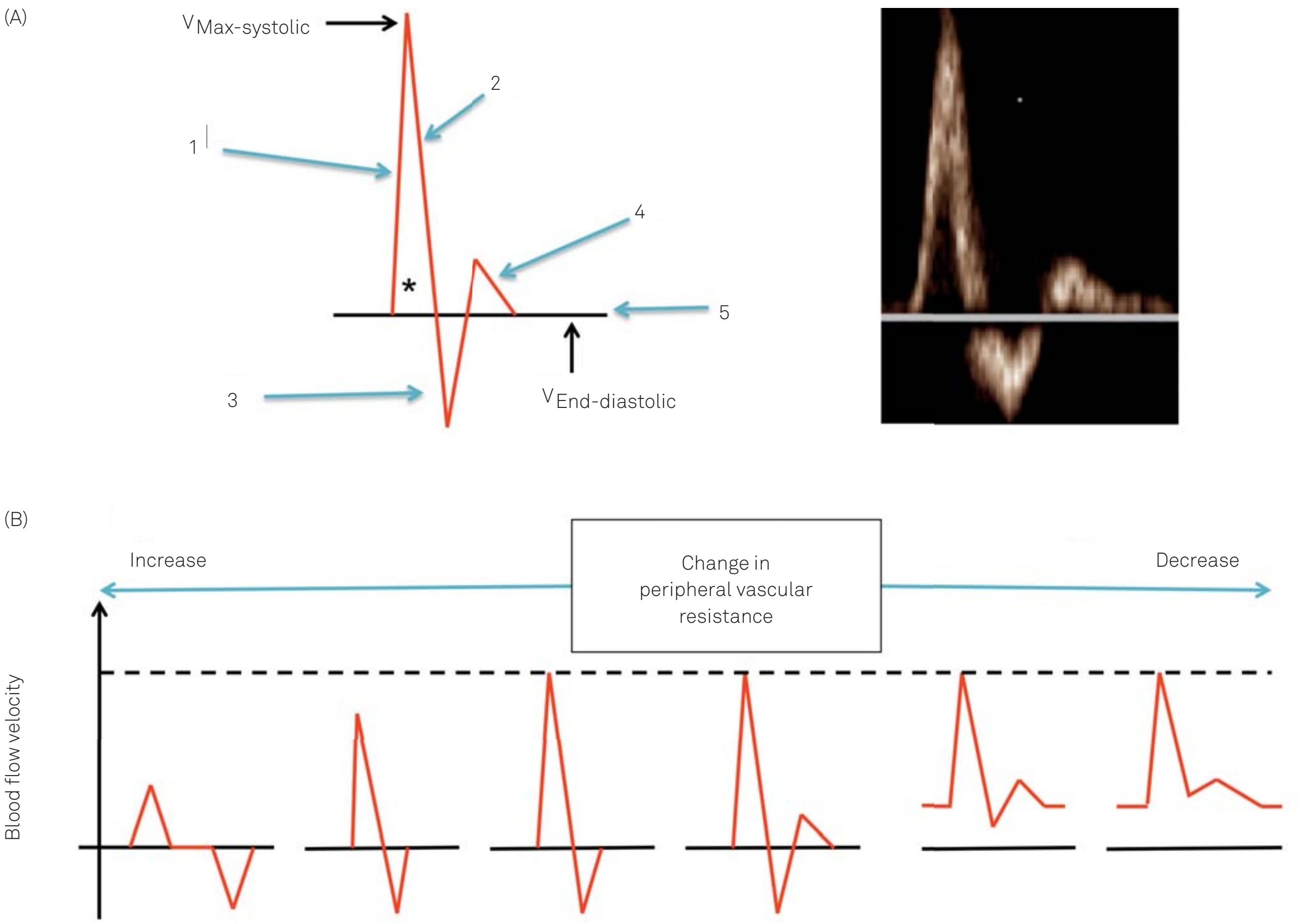


Figure 1. Arterial Doppler waveforms.
(A) Normal Doppler morphology in a lower limb artery at rest in a healthy subject is triphasic and comprises: (1) a rapid ascending branch (systolic rise time less than or equal to 70 ms, (2) a rapid descending branch, (3) a negative diastolic component, (4) a positive diastolic rebound, and (5) a return to baseline. *The spectral window is clear. $V_{Max\ systolic}$ corresponds to the maximum systolic velocity and $V_{End\text{-}diastolic}$ corresponds to the end diastolic velocity. (B): Changes in the arterial Doppler waveforms as a function of changes in circulatory resistance.

In addition to these different phases, the normal Doppler waveform morphology includes a spectral window, which must be clear. This means that all the red blood cells are moving at the same speed. Conversely, when the spectral window is not clear, this means that the red blood cells are not all moving at the same velocity [24].

The various indices and terminology points: "Demodulated" Doppler waveform, "attenuated" Doppler waveform, "reduced", "dampened" or "blunted" Doppler waveform

The following definitions are a consensus proposal of the CEMV group.

A "demodulated" Doppler waveform manifests as a change in or loss of one or more features that make up the normal 'triphasic' arterial Doppler waveform (Figure 2).

An "attenuated" Doppler waveform manifests as a Doppler waveform morphology with an extended systolic rise time, i.e. a systolic rise time >70 ms or 100 ms, depending on the authors [23] (Figure 2).

A "reduced" Doppler waveform manifests as a Doppler waveform morphology comprising a normal systolic rise time but a reduced maximum systolic velocity ($V_{Max\ systolic}$) (Figure 2).

A "dampened or blunted" Doppler waveform manifests as a Doppler waveform morphology with an extended systolic rise time (i.e. a systolic rise time > 70 ms or 100 ms, depending on the authors [23]) and a reduced maximum systolic velocity (Vmax systolic).

Changes in Doppler waveforms morphology depending on the degree of the stenosis and presence of collaterals

The term stenosis must be reserved for lesions causing a haemodynamic change [21].

The arterial flow recorded is altered in the event of constriction following a certain reduction in lumen diameter [16, 30, 31]. Changes in Doppler waveforms morphology with regard to stenosis are known as direct signs. When the stenosis is significant (conventionally ≥ 70 % reduction in diameter), changes in the Doppler waveforms morphology are recorded upstream and downstream from this point. These changes in upstream and downstream flows are called indirect signs. Indirect signs may be absent in the case of good quality/efficient collaterals. Schematically, the flow velocity gradually increases at the point of arterial lumen reduction. The greater the arterial lumen reduction, the more the flow velocity increases. Downstream, indirect signs are visible only when the stenosis is equal to or greater than 70 % (reduction in diameter) and in the absence of good quality/efficient collaterals. A decrease in these changes has also been observed when the distance from the stenosis is increased [32, 33]. The downstream signs observed include an increase in systolic rise time and an increase in the positive diastolic component in relation to the lack of oxygen downstream from the stenosis. This component may, however, be absent if the vasodilatation capacities of the region are exceeded. Finally, the peak systolic velocity decreases significantly. The upstream signs include a loss of triphasic features and a reduced systolic velocity.

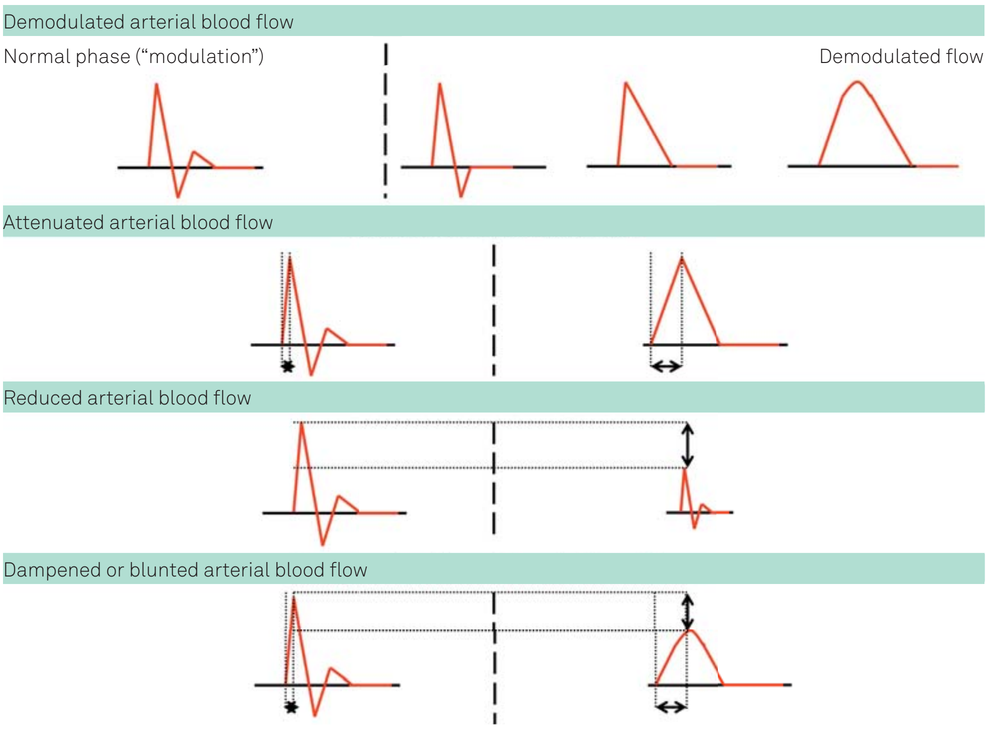


Figure 2. Types of Doppler waveforms. Modifications of the Doppler waveforms.

Circulatory resistance

The diastolic phase (Figure 1) is linked to the circulatory resistance prevailing downstream from the arterial Doppler waveform recording. In fact, the lower the downstream circulatory resistance (e.g. significant exercise-related vasodilatation), the greater the diastolic flow with no Doppler waveforms morphology return to baseline. Conversely, if the circulatory resistance downstream from the arterial Doppler waveform recording is higher (e.g. occlusion of the popliteal artery and recording of the waveform on the superficial femoral artery), the diastolic flow is nil with loss of triphasic features. It is important to note that local or general causes may change circulatory resistance and thus alter the Doppler waveform morphology. Arterial hypertension and heart failure are general causes of increased circulatory resistance whereas stenosis ≥70 % downstream from the recording is a local cause of increased circulatory resistance. Hypoxemia induced by a downstream ischaemic lesion, exertion, all inflammatory processes, and some treatments (calcium channel blockers, sympathectomy, etc.) can reduce circulatory resistance.

The various indices

The Doppler waveforms morphology of the arterial flow presents several specific points (Figure 1) which allow several indices to be determined [2].

The resistance index (RI), also known as the Planiol and Pourcelot index, is calculated as follows [21]:

$$RI = (V_{maximum\ systolic} - V_{end\text{-}diastolic}) / V_{maximum\ systolic} \text{ where,}$$

$V_{maximum\ systolic}$ corresponds to the maximum systolic speed measured and $V_{end\text{-}diastolic}$ corresponds to the end diastolic speed measured. The RI value ranges from 0 to 1. The RI is seldom used in exploration of lower limb arteries because an RI of 1 is recorded when the waveform is normal triphasic.

Gosling's index or pulsatility index (PI) is calculated as shown below [34]:

$$PI = (V_{maximum\ systolic} - V_{minimum\ diastolic}) / V_{mean} \text{ where,}$$

$V_{maximum\ systolic}$ corresponds to the maximum systolic speed measured, $V_{minimum\ diastolic}$ corresponds to the minimum diastolic speed measured, and V_{mean} corresponds to the mean velocity measured over an entire cardiac cycle. The pulsatility index is particularly interesting when studying limb arteries. The PI increases from the aorta as far as the distal arteries in the absence of any atherosclerotic arterial lesion [34]. The abdominal aorta PI generally has a value ranging from 2 to 6, the common femoral artery has a value between 4 and 13, the popliteal artery between 6 and 18 and the posteriortibial artery between 8 and 26. If significant stenosis is present, the PI is lower than the PI upstream.

The RI and PI are independent of the Doppler firing angle [23].

Several physiological and physio-pathological states can modify the appearance of the arterial Doppler morphology (Figure 1).

The various classifications

Various classifications have been proposed in the literature. Amongst these, we refer to the classifications of Descotes and Cathignol [35] and Spronk et al. [36] which offer a clear definition and illustration of the various types, information that are lacking in many publications [8]. However, neither of these two classifications proposes a "no-flow" phase, which may pose problems in the description of arterial haemodynamics.

Classification according to Descotes and Cathignol [35]

This classification was proposed in 1975 and suggests five types in diagnosing an arterial obstruction (Figure 3a). The various types (from 0 or N to type 4) are described as follows in the original publication:

"The N curve or type 0 has the profile of an attenuated oscillating wave used to describe several waveform modifications: 1) a continuous level before the first positive wave, which is taken to be the baseline; 2) a positive wave which indicates a sudden centrifugal acceleration in the blood, the peak amplitude being proportional to the instant speed. The rise and fall times are of the order of 0.1 to 0.2 seconds; 3) a wave located below the baseline known as the reflux wave, even if it does not fully represent a negative wave; this reflux wave is generally 1/3 of the positive wave; 4) finally, a second positive wave, the amplitude of which is 1/6 of the first positive wave. This is followed by a level that is generally set to zero.

Type 1 is characterised by the disappearance of the reflux wave and the second positive wave. Based on our observations, the disappearance of this reflux wave is associated more with a functional alteration (elasticity) in the arterial wall than a change in vessel lumen.

Type 2 is characterised by a greater extension in positive wave fall time.

Type 3 is characterised by a change in all elements of the curve: extended fall time, extended rise time, continuous disappearance of the level between two successive waves, and the curve's adaptation of a sinusoidal dimension.

Type 4 illustrates the most severe deterioration in the speed profile, which often cannot be recorded (only arterial sounds audible). It basically shows that the artery is still patent but there are one or more obliterations below culminating in a very slow blood flow." [35].

Classification by Spronk et al. [36]

This classification (Figure 3b) comprises four waveform categories and is described as follows in the original publication:

"The triphasic waveform corresponds to a Doppler waveform morphology with three "phases". A sharp ascending branch (systolic phase) with a short rise time and then a descending branch comprising a retrograde portion and an anterograde portion during the diastolic phase.

The biphasic waveform corresponds to a Doppler waveform morphology with two "phases". A sharp ascending branch (systolic) with a short rise time and then a descending branch and a retrograde portion during the diastolic phase.

The sharp monophasic waveform corresponds to a Doppler waveform morphology with an ascending branch (systolic phase) with a short rise time, a rapid descending phase (short fall time), and no retrograde portion during the diastolic phase.

The "blunted" monophasic waveform corresponds to an extension of the ascending branch rise time (systolic phase), with no retrograde diastolic portion. This is found downstream from an obstruction." [36].

The Saint-Bonnet Classification [21]

To standardize practices, we are proposing a new classification system (Classic Saint-Bonnet Classification comprising 10 types (Saint-Bonnet N, Saint-Bonnet A, Saint-Bonnet B, Saint-Bonnet C1, Saint-Bonnet C2, Saint-Bonnet D, Saint-Bonnet E, Saint-Bonnet 0, Saint-Bonnet FA, and Saint-Bonnet U) and Simplified Saint-Bonnet Classification comprising 8 types (Saint-Bonnet N, Saint-Bonnet A, Saint-Bonnet B, Saint-Bonnet CD, Saint-Bonnet E, Saint-Bonnet 0, Saint-Bonnet FA, and Saint-Bonnet U)), which aims to provide a more precise analysis of the Doppler waveforms signals (Figure 4). The Doppler curve comprises the following in succession: an ascending branch, a descending branch followed by a negative diastolic component preceding a positive diastolic rebound before a return to baseline. In the presence of reduced peripheral resistance, the flow can be continuous (with no return to baseline).

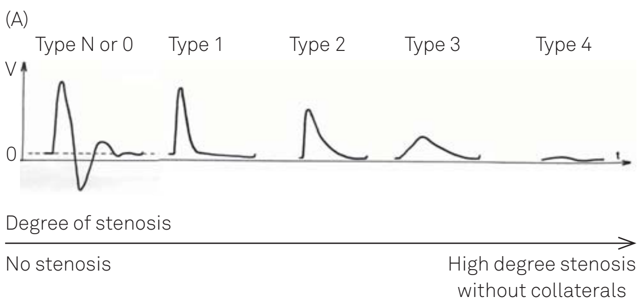
The analysis focuses on a triphasic Doppler waveform morphology on the ascending branch with a short rise time (Figure 1, phase 1), the descending branch with a short fall time (Figure 1, phase 2), the negative diastolic component (Figure 1, phase 3), the positive diastolic rebound (Figure 1, phase 4) and the return to baseline (Figure 1, phase 5; Saint-Bonnet N). The Doppler waveform morphology alters depending on the severity of the arterial lesions (Figure 4):

- Disappearance of the positive diastolic rebound (biphasic Doppler waveform morphology, Saint-Bonnet A)
- Disappearance of the negative diastolic component (symmetrical monophasic Doppler waveform morphology with sharp systolic peak, Saint-Bonnet B)
- Increase in fall time (Figure 1, phase 2; asymmetrical monophasic Doppler waveform morphology with "blunted" systolic peak, Saint-Bonnet C1 if the descending branch does not occupy the entire diastolic phase; Saint-Bonnet C2 if the descending phase occupies the entire diastolic phase)
- An increase in the systolic rise time (Figure 1, phase 1) with the presence of a "blunted" systolic peak (Saint-Bonnet D)
- Loss of signal phase (i.e. modulation) (Saint-Bonnet E)
- No waveform (Saint-Bonnet O)

In case of false aneurysm (FA) with a typical blood flow (ascending branch with a short rise time and descending branch with a short fall time followed by a long diastolic negative component where the area under the curve of the diastolic component is equal to the area under the curve of the systolic component), this is reported as Saint-Bonnet FA (Figure 4, panel B).

Finally, when a blood flow cannot be classified with one of these different types, the undefined blood flow is classified as Saint-Bonnet U.

If the signal does not revert to baseline, the waveform is determined as continuous flow (cf) and can be found in all types (except Saint-Bonnet 0) in the classification. For instance, for a Saint-Bonnet B with a continuous waveform, the waveform is graded "Saint-Bonnet B-cf".



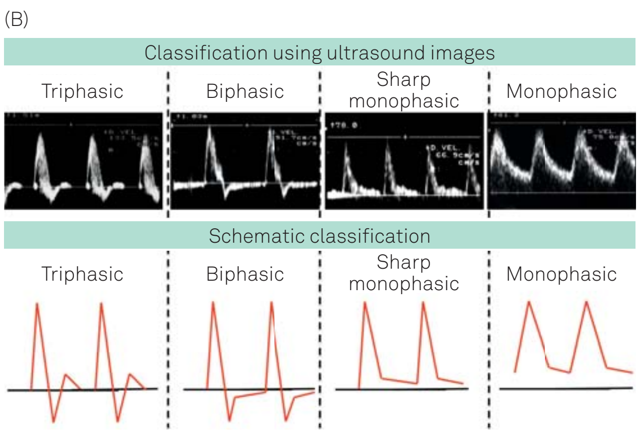


Figure 3. Doppler waveforms classifications.
3a) Descotes et Cathignol [35]; 3b) Spronk et al. [36].

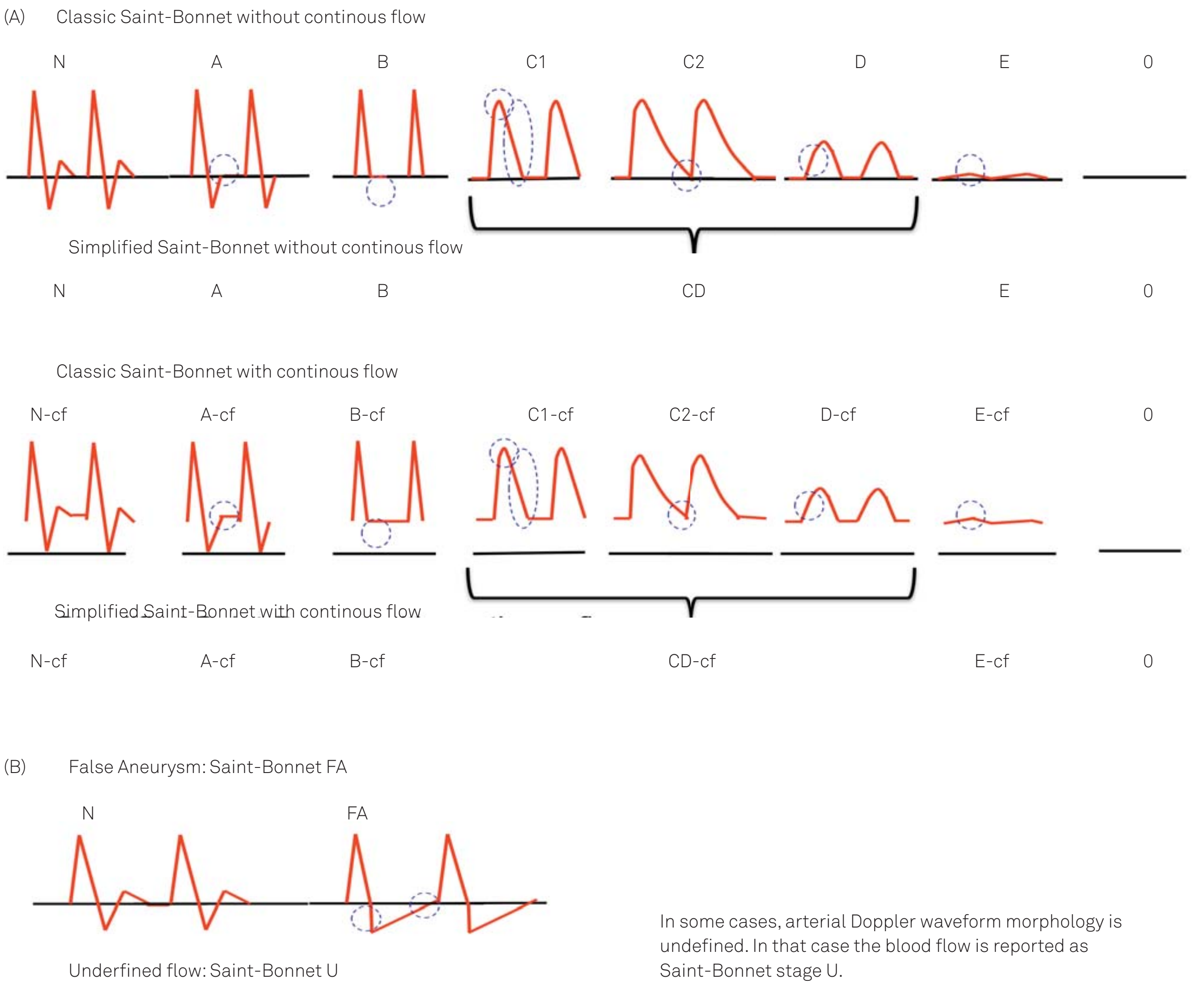


Figure 4. Saint-Bonnet classification (classic and simplified versions).
Panel A: Saint-Bonnet classification according to the severity of the arterial lesions (From type N to 0). cf: continuous flow. The blue circles represent the key elements that change from type to type. It is important to note that the continuous flow may be horizontal or slightly descending. This diagram shows a stable continuous flow and is therefore depicted horizontally. Panel B: Specific arterial Doppler waveforms not linked to the severity of the arterial lesions.

Variability in arterial Doppler waveforms analysis

A literature review previously highlighted the fact that the terminology used to characterise Doppler waveforms morphology is often inadequately defined. Out of 94 publications analysed, 81 % provided a definition of a triphasic or monophasic Doppler waveforms morphology and 38 % defined a biphasic Doppler waveform morphology [8]. Representations of the various waveforms, when provided, are equally problematic since a Doppler waveform morphology described with the same name may have a different waveform [11]. Intra-observer variability was assessed in a study that classified arterial waveforms in three different types, namely triphasic, biphasic, and monophasic [37]. A better waveform classification appears to be generated when a continuous Doppler is used compared to a pulse-wave Doppler [10].

Teaching methods

Given the significant variability in classifying arterial Doppler waveforms morphologies recorded using the Doppler technique [10], attention should be paid to the teaching methods. No specific teaching method has been proposed or validated for Doppler signals, even though analysis of the latter is a key element in vascular practice. A theoretical approach, as adopted by most French Medical Faculties to record the resting ABI, would probably be inappropriate [38]. Regarding ABI, a certain number of measurements must be recorded to build up competence [6, 39, 40]. Studies conducted by Scissons highlight a better system for classifying Doppler waveform morphologies with the person gaining experience with every waveform analysis [8, 10]. Studies should be carried out to establish the best way of teaching arterial waveform analysis and to improve practices for better patient management.

Recommendations and proposals from the CEMV

- Arterial Doppler waveforms show if there is blood flow impairment in the arterial tree (CoR I, LoE B).
- The use of arterial Doppler waveforms morphology classification is recommended to describe Doppler waveforms morphology in patient care and research studies (CoR I, LoE C).
- We recommend that the waveform measurements be recorded after the patient has rested for five to 10 Minutes in the supine position in a room with a neutral temperature (CoR I, LoE C).
- Arterial Doppler waveforms recordings are indicated at rest in patients suspected of peripheral artery disease (CoR I, LoE B).
- If normal Doppler waveforms are recorded for a patient in whom PAD is strongly suspected, we suggest exploration of the arterial waveforms following exercise in order to enhance the reliability of the test and for the same reasons as carrying out a post-exercise ABI (CoR IIa, LoE C).
- We recommend analysing arterial Doppler waveforms morphologies in all patients who should undergo a resting ABI measurement, regardless of whether or not they are symptomatic. These data must be included in the report (CoR I, LoE C).
- We recommend recording arterial waveform measurements, analysing Doppler waveforms morphologies collected along the arterial tree (aorta, common iliac, external iliac, common femoral, popliteal arteries, posterior tibial, dorsalis pedis, and fibular arteries) and including this information in the report (CoR I, LoE B).
- We recommend recording arterial waveforms measurements, analysing Doppler waveforms morphologies in all bypasses and endovascular materials, and including this information in the report (CoR I, LoE C).
- We recommend recording post-exercise measurements as soon as the exercise has been completed, noting the time between cessation of exercise and the recording time (CoR I, LoE C).
- To simplify post-exercise measurements, the use of a felt-tipped pen to mark the point where the resting recording of Doppler waveform was performed is recommended (CoR IIa, LoE C).
- The type of exercise and the symptoms presented by the patient must be reported (CoR I, LoE C).
- Vascular medicine residents/sonographers should be trained for arterial Doppler waveforms analysis (CoR I, LoE C).

Conclusions

Doppler waveforms morphology analysis via the Doppler method is a well-established, straightforward, reasonably priced, risk-free procedure for assessing arterial haemodynamics. However, no consensus has been reached regarding this technique. The Saint-Bonnet classification system proposed by the CEMV could standardise this practice but further clinical validation is required.

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