

## A preliminary study on the Average Maximum Velocity Sensitivity index from flow velocity variation in quality control for Color Doppler

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### ABSTRACT

Color Doppler (CD) is one of the most used ultrasound (US) Doppler techniques as it allows the 2D representation of blood flow. Even if a clarification on whether such technique provides qualitative or quantitative diagnostic information on velocity assessment is still awaited, the necessity of periodic Quality Control (QC) tests is ongoing. Consequently, in the present preliminary study, a previously proposed sensitivity parameter, namely the Average Maximum Velocity Sensitivity (AMVS), has been further investigated for Color Doppler QC. Three diagnostic US systems, equipped with phased array probes, have been used to collect Color Doppler images. Two Doppler phantom flow rate regimes and two US system settings have been employed during data acquisition. Despite the limitations encountered, the AMVS results are promising, therefore further studies should be carried out on CD clips, on a higher number of US systems and probes as well as on a greater number of phantom settings.

### 1. Introduction

Color Doppler (CD) is an ultrasound (US) technique that allows the mean Doppler frequency estimation through the real-time codification of the 2D blood flow velocity in color maps, which is superimposed to the gray-scale coded anatomical image [1]. Nowadays, the scientific community is still discussing whether such technique provides qualitative (i.e., non-repeatable and subjective estimations) or quantitative (i.e., repeatable and objective measurements) diagnostic information on flow velocity [2,3]. In this regard, it should be pointed out that CD velocity measurement uncertainties are higher than spectral Doppler (i.e., Continuous Wave and Pulsed Wave Doppler) ones. In fact, while the latter have been estimated to be higher than 20% [4], the former reach uncertainties up to 50% or more [5,6]. In spite of the above mentioned issues, currently Color Doppler is among the most widely used techniques in medical field [3,7], leading to the necessity of improving the existing performance parameters and/or the definition of novel ones [8–15] for the periodic Quality Control (QC) of both B-mode and Doppler techniques.

This preliminary study is a further investigation of a previously proposed sensitivity index [12], namely the Average Maximum Velocity Sensitivity (AMVS), retrieved from the estimation of the flow velocity variations obtained from Color Doppler velocity profiles. The novelty of the AMVS is the quantitative characterization of a metrological characteristic not considered in QC tests of Color Doppler instrumentation usually suggested in literature. The main advantages of such parameter are (a) the robustness to changes in the setting conditions due to the employment of velocity differences rather than absolute values and (b) its representativeness of the US system ability to display flows of different magnitudes. Color Doppler images have been collected from three intermediate technology level US diagnostic systems, each of them

equipped with a phased array probe, designed for cardiac use. Two constant flow rate regimes set on a Doppler flow phantom as well as two different US scanner settings have been employed for AMVS robustness testing.

### 2. Materials and methods

Data have been acquired using Gammex Optimizer® 1425A [16], a Doppler flow phantom that allows to deliver pulsatile or constant flow in the range of 1.7–12.5 ml·s<sup>-1</sup>. In Table 1 the main phantom characteristics have been reported.

The Doppler flow phantom has been set to provide two constant flow rate regimes: a medium flow rate M (from 7.2 to 8.5 ml·s<sup>-1</sup>) and a high flow rate H (from 10.7 to 12.0 ml·s<sup>-1</sup>). The flow rate has been adjusted to achieve six estimated flow velocity steps of 2 cm·s<sup>-1</sup> for each regime (Table 2).

Three US systems (US<sub>1</sub>, US<sub>2</sub> and US<sub>3</sub>), equipped with a phased array probe, operating at the central Doppler frequency, have been used to collect Color Doppler images. The acquisition protocol, for both B-Mode and Color Doppler (Table 3), has included two different settings (set A and set B) for all the US scanners involved in the study.

A custom-written algorithm developed in MATLAB environment has been employed in the CD image post-processing phase. Firstly, the diagnostic box has been extracted to exclude all the surrounding text boxes, while the gray-scale coded B-mode information has been removed through a threshold-based filter [11], leaving the color-coded information only. Afterwards, the flow central axis has been computed in order to automatically draw on a 100 px portion of it (1.1–1.5 cm), 90° rotated segments spaced of 5 px (0.6–0.8 mm). Since the px/mm conversion factor extracted from the image metadata is almost the same for the three US systems, a total of 16 segments have been drawn in the

**Table 1**  
Ultrasound Doppler phantom characteristics [16].

Parameter	Characteristics
Doppler phantom model	Gammex Optimazer® 1425A
Scanning TMM	Water-based mimicking gel
Nominal tube inner diameter	5.0 mm
Attenuation coefficient	$0.50 \pm 0.05 \text{ dB} \cdot \text{cm}^{-1} \cdot \text{MHz}^{-1}$
TMM sound speed	$1540 \pm 10 \text{ m} \cdot \text{s}^{-1}$
BMF sound speed	$1550 \pm 10 \text{ m} \cdot \text{s}^{-1}$
Flow meter accuracy	$\geq 1.5\%$ full scale

TMM = tissue mimicking material; BMF = blood mimicking fluid.

**Table 2**  
Flow rate regimes and flow velocities settings.

Flow regime	Flow rate $Q$ (ml·s <sup>-1</sup> )	Flow velocity $v_{ph}$ (cm·s <sup>-1</sup> )
M	$7.2 \pm 0.2$	$70.0 \pm 1.7$
	$7.5 \pm 0.2$	$72.0 \pm 1.7$
	$7.7 \pm 0.2$	$74.0 \pm 1.7$
	$8.0 \pm 0.2$	$76.0 \pm 1.7$
	$8.3 \pm 0.2$	$78.0 \pm 1.7$
	$8.5 \pm 0.2$	$80.0 \pm 1.7$
H	$10.7 \pm 0.2$	$96.0 \pm 1.7$
	$10.9 \pm 0.2$	$98.0 \pm 1.7$
	$11.2 \pm 0.2$	$100.0 \pm 1.7$
	$11.5 \pm 0.2$	$102.0 \pm 1.7$
	$11.7 \pm 0.2$	$104.0 \pm 1.7$
	$12.0 \pm 0.2$	$106.0 \pm 1.7$

The nominal flow rate and corresponding estimated velocity values have been found in the phantom datasheet. The flow rate standard deviation has been retrieved from the flow meter accuracy, while the flow velocity standard deviation has been estimated from the latter assuming a rectangular distribution of the tube inner diameter with  $\pm 0.1/\sqrt{3}$  mm standard deviation.

**Table 3**  
B-mode and Color Doppler US system settings.

Parameter	Set A	Set B
Field of View (mm)	90	
Dynamic range (dB)	Max	63–110
Doppler frequency (MHz)	2.3–2.5	
Line density	Min	Min – Med
PRF (kHz)	4.5–5.2 for M, 6.3–7.1 for H	
Wall filter (Hz)	Min for both M and H	136–1100 for M 172–1506 for H

Set A = raw settings; Set B = best settings provided by the US specialist; PRF = pulse repetition frequency; M = medium flow regime; H = high flow regime.

middle of the central axis. The velocity profile for each segment has been reconstructed through the linear regression procedure reported in Ref. [11], as shown in Fig. 1.

From each velocity profile, the peak velocity value  $v_{CD,i}$  has been obtained and, consequently, the mean peak velocity value  $v_{CD}$  has been computed as follows:

$$v_{CD} = \frac{1}{n} \sum_{i=1}^n v_{CD,i} \quad (1)$$

where  $n$  is the number of velocity profiles. Such processing has been repeated for each US system and for each phantom configuration. AMVS has been retrieved based on both  $v_{CD}$ , computed in (1), and  $v_{ph}$ , the estimated phantom flow velocity. As already proposed in Ref. [12], such dimensionless sensitivity parameter is defined as follows:

$$\text{AMVS} = \frac{\Delta v_{CD}}{\Delta v_{ph}} \quad (2)$$

where  $\Delta v_{CD}$  is the difference between two  $v_{CD}$  values obtained from the same configuration setting, at different flow rates set on the phantom,

while  $\Delta v_{ph}$  is the difference between the corresponding estimated flow velocities. Through the uncertainty propagation law, the AMVS standard deviation  $\sigma_{\text{AMVS}}$ , can be computed as follows:

$$\sigma_{\text{AMVS}} = \text{AMVS} \sqrt{\left(\frac{\sigma_{\Delta v_{CD}}}{\Delta v_{CD}}\right)^2 + \left(\frac{\sigma_{\Delta v_{ph}}}{\Delta v_{ph}}\right)^2} \quad (3)$$

where the first and the second contribution in the square sum are the relative standard deviations of  $\Delta v_{CD}$  and  $\Delta v_{ph}$ , respectively. In particular, in the first contribution the uncertainty related to the linear regression procedure for color to velocity conversion, estimated in Ref. [11], has been included.

As already pointed out in Ref. [12], the maximum sensitivity is obtained when AMVS reaches the unity, independently from both  $\Delta v_{ph}$  and US system settings, whereas when it deviates from the unity, a decrease of sensitivity of the US system or the Doppler phantom is implied.

### 3. Results and discussion

The AMVS outcomes for US<sub>1</sub>, US<sub>2</sub> and US<sub>3</sub>, equipped with a phased array probe, in set A and set B configurations, have been reported in Table 4. The AMVS evaluation has been carried out by considering three estimated flow velocity differences  $\Delta v_{ph}$ , i.e., 6 and 8 cm·s<sup>-1</sup>, for which velocities belonging to the same flow regime (M or H) have been subtracted, and 20 cm·s<sup>-1</sup> for differences involving velocities that belong to both M and H. The results have been expressed as mean  $\pm$  SD (SD, standard deviation), where the mean values and the SDs have been computed through (2) and (3), respectively. Furthermore,  $\text{AMVS}_\mu \pm \text{SD}_{\text{AMVS}_\mu}$  has been retrieved as the mean value of all the AMVS values and the corresponding SD for each  $\Delta v_{ph}$  increment (Table 4).

It can be observed that AMVS shows higher standard deviations for flow regime H with respect to the flow regime M at the same  $\Delta v_{ph}$  increment, US system and setting. By considering the  $\text{AMVS}_\mu$  values for set A and set B as well as the three diagnostic systems, a well-defined behaviour cannot be inferred for the distinction of medium and high flow regimes. Moreover, for US<sub>1</sub> and US<sub>2</sub>,  $\text{AMVS}_\mu$  values in set A are closer to the maximum sensitivity (i.e.,  $\text{AMVS} = 1$ ) with respect to the ones in set B, independently from the flow regime, even if  $\text{SD}_{\text{AMVS}_\mu}$  values are always higher in set A than in set B. On the other hand, the behaviour described for the first two US scanners seems to be reversed for US<sub>3</sub>. In Fig. 2 a representative case of such behaviour is shown for flow regime M and  $\Delta v_{ph} = 6 \text{ cm} \cdot \text{s}^{-1}$ .

By considering  $\Delta v_{ph} = 20 \text{ cm} \cdot \text{s}^{-1}$  (Fig. 3), it can be observed that the  $\text{SD}_{\text{AMVS}_\mu}$  values do not significantly differ among the US systems and configuration settings. Therefore, such issue makes it possible to compare the US systems through the inspection of the  $\text{AMVS}_\mu$  values and assess that, independently from the settings, US<sub>3</sub> shows the best sensitivity index, i.e., closest to 1. Conversely, the US system showing the  $\text{AMVS}_\mu$  values that mostly deviate from 1 for the same setting is US<sub>2</sub>.

The results obtained in this preliminary study allow to point out that the AMVS parameter for Color Doppler applications has a reduced significance (i.e., higher uncertainties) for  $\Delta v_{ph} \leq 8 \text{ cm} \cdot \text{s}^{-1}$ , showing a different behaviour with respect to the PW application in Ref. [12]. Such issue is due to the too high uncertainty contribution given both by the phantom flow meter and the linear regression procedure for color to velocity conversion.

### 4. Conclusions

The Average Maximum Velocity Sensitivity, an index already proposed for PW Doppler QC performance test by the Authors, has been investigated, in this preliminary study, for Color Doppler. The maximum velocity values have been retrieved as the peak of the velocity profiles extracted from the Color Doppler images through a custom-written algorithm developed in MATLAB. Data have been acquired from three diagnostic US systems, equipped with a phased array probe each, with

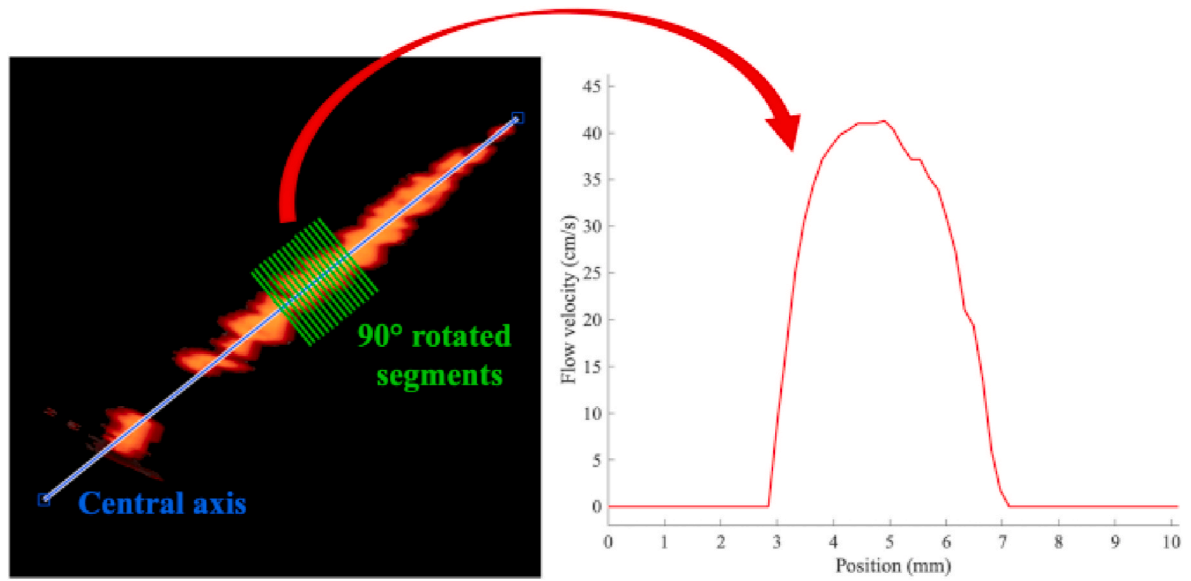


Fig. 1. Example of a segment reconstructed velocity profile for one of the acquired CD images.

Table 4

AMVS results according to US system, setting and estimated velocity difference for flow regimes M and H.

Flow regime	$\Delta v_{ph}$ (cm·s <sup>-1</sup> )		AMVS					
			US <sub>1</sub>		US <sub>2</sub>		US <sub>3</sub>	
			Set A	Set B	Set A	Set B	Set A	Set B
M	76.0–70.0	6	1.2 ± 1.3	1.4 ± 1.4	1.2 ± 1.4	0.1 ± 0.3	0.4 ± 0.7	0.7 ± 0.9
	78.0–72.0		0.8 ± 1.2	−0.2 ± 0.5	1.4 ± 1.6	0.6 ± 1.0	0.6 ± 0.8	0.4 ± 0.8
	80.0–74.0		0.9 ± 1.4	0.3 ± 0.6	1.0 ± 1.3	0.3 ± 0.6	0.4 ± 0.8	1.0 ± 1.1
	AMVS <sub>μ</sub> ± SD <sub>AMVSμ</sub>		1.0 ± 0.8	0.5 ± 0.5	1.2 ± 0.8	0.3 ± 0.4	0.5 ± 0.4	0.7 ± 0.5
	78.0–70.0	8	1.2 ± 1.2	0.3 ± 0.4	1.2 ± 1.2	0.2 ± 0.5	0.3 ± 0.5	0.6 ± 0.8
	80.0–72.0		0.8 ± 1.1	0.4 ± 0.6	0.7 ± 0.9	0.4 ± 0.6	0.5 ± 0.7	0.5 ± 0.7
	AMVS <sub>μ</sub> ± SD <sub>AMVSμ</sub>		1.0 ± 0.8	0.4 ± 0.4	1.0 ± 0.8	0.3 ± 0.4	0.4 ± 0.4	0.6 ± 0.5
H	102.0–96.0	6	2.2 ± 2.7	0.2 ± 0.7	0.3 ± 1.0	1.4 ± 1.0	0.4 ± 1.0	0.4 ± 1.0
	104.0–98.0		2.0 ± 2.3	0.2 ± 0.7	1.7 ± 2.4	1.6 ± 2.1	0.6 ± 1.2	1.0 ± 1.6
	106.0–100.0		−0.1 ± 0.5	0.5 ± 1.1	1.3 ± 2.0	0.4 ± 2.1	0.4 ± 1.0	0.8 ± 1.5
	AMVS <sub>μ</sub> ± SD <sub>AMVSμ</sub>		1.4 ± 1.2	0.3 ± 0.5	1.1 ± 1.1	1.1 ± 1.0	0.5 ± 0.6	0.7 ± 0.8
	104.0–96.0	8	1.5 ± 1.7	0.6 ± 1.0	1.1 ± 1.7	1.2 ± 1.6	0.3 ± 0.8	0.7 ± 1.2
	106.0–98.0		1.3 ± 1.7	0.4 ± 0.8	0.8 ± 1.3	0.4 ± 0.9	0.5 ± 0.9	0.8 ± 1.3
	AMVS <sub>μ</sub> ± SD <sub>AMVSμ</sub>		1.4 ± 1.2	0.5 ± 0.6	1.0 ± 1.1	0.8 ± 0.9	0.4 ± 0.6	0.8 ± 0.9
H – M	96.0–76.0	20	0.5 ± 0.5	0.6 ± 0.6	0.6 ± 0.6	0.7 ± 0.6	0.9 ± 0.7	0.9 ± 0.7
	98.0–78.0		0.4 ± 0.5	1.1 ± 0.7	0.4 ± 0.5	0.6 ± 0.6	0.9 ± 0.6	0.8 ± 0.7
	100.0–80.0		0.8 ± 0.9	0.9 ± 0.7	0.5 ± 0.6	0.7 ± 0.7	1.0 ± 0.8	0.8 ± 0.6
	AMVS <sub>μ</sub> ± SD <sub>AMVSμ</sub>		0.6 ± 0.4	0.9 ± 0.4	0.5 ± 0.3	0.7 ± 0.4	0.9 ± 0.4	0.8 ± 0.4

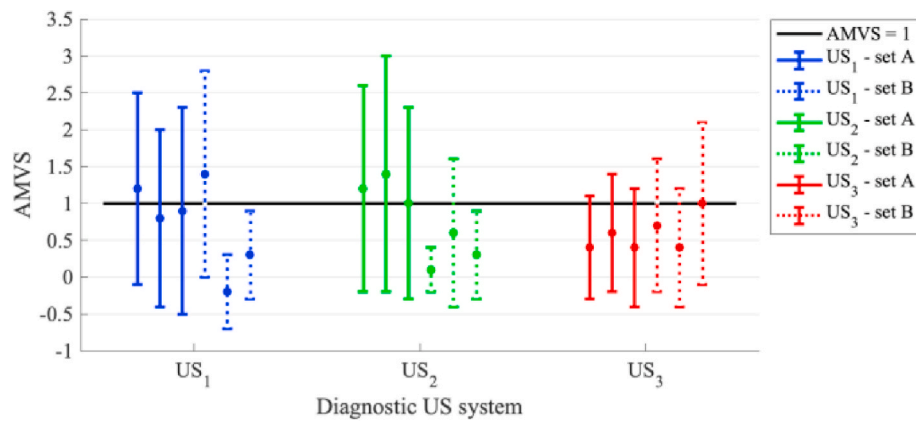
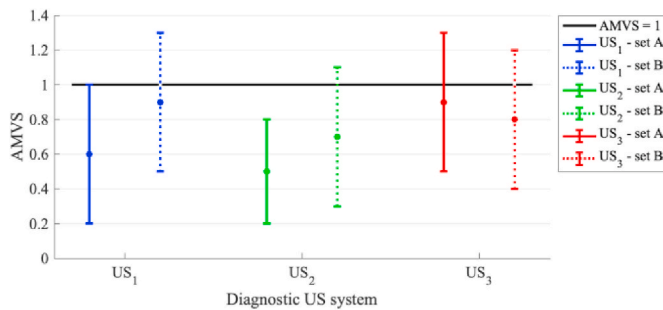


Fig. 2. AMVS with error bars at  $\Delta v_{ph} = 6$  cm·s<sup>-1</sup>, for US<sub>1</sub>, US<sub>2</sub> and US<sub>3</sub>, in set A and set B, for flow regime M.



**Fig. 3.**  $AMVS_i$  with error bars at  $\Delta v_{ph} = 20 \text{ cm} \cdot \text{s}^{-1}$  for  $US_1$ ,  $US_2$  and  $US_3$  in set A and set B.

two scanner configuration settings. The overall outcomes suggest that, for Color Doppler applications, the AMVS index may be representative of the US scanner performance for higher velocity difference increments with respect to the ones applied in PW Doppler applications. Despite the promising results, further studies should be carried out (a) acquiring Color Doppler clips to allow the temporal average in addition to the spatial average of the velocity profiles, (b) for higher differences between the phantom estimated flow velocities, (c) on a wider sample of US systems, (d) on a greater number of phantom settings, and (e) with different probe models.

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