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A preliminary study on the blind angle estimation for Quality Assessment of Color Doppler ultrasound diagnostic systems

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***Abstract* – Quality Controls (QCs) for the evaluation of Color Doppler (CD) performance play a pivotal role since CD is one of the most widely used Doppler techniques in medical imaging. Among the recommended test parameters, directional accuracy at 90° is included, even if its assessment is carried out visually. Therefore, in this study, a novel CD test parameter, called blind angle, has been proposed and defined as it allows testing the Doppler frequency shift dependency on the insonation angle. Moreover, a novel automatic method for the estimation of this parameter through the post-processing of CD videos has been proposed. Data have been collected from a single ultrasound diagnostic system equipped with a phased array probe. Tests have been carried out for two probe frequencies and three constant flow rate regimes set on a flow phantom. Based on the preliminary promising outcomes, further studies are going to be carried out.**

I. INTRODUCTION

In diagnostics, Color Doppler (CD) is one of the most widely used Doppler techniques, as it allows the 2D real-time representation of blood flow superimposed on the anatomical image [1,2]. A color map codifies and quantifies the velocity of blood flow inside a region of interest (or color box) adjusted by the operator on the B-mode grayscale ultrasound (US) image depending on the clinical question. Since CD measurement uncertainties reach up to 50% or more [3,4], such technique is often assumed to provide qualitative diagnostic data [5,6], although the scientific community has not reached a definitive consensus on this issue. The low measurement accuracy could be overcome by monitoring a clinical parameter of interest through a series of exams carried out over time. In this way, measurement repeatability can help the clinician prevent diagnostic errors. However, variations in measurement outcomes may be also due to the worsening of the US system performance, resulting in misleading diagnostic information. In this regard, periodic Quality Controls (QCs) for the evaluation of Doppler mode performance are needed and play a key role despite a commonly accepted reference standard on US equipment testing is still lacking [7-9]. Among the performance tests for Color Doppler QC recommended by the American Institute for Ultrasound in Medicine (AIUM), directional accuracy at 90° is included. The latter is qualitatively defined by the professional agency that recommends performing a visual assessment directly on the US system monitor [5]. This test parameter takes into account the Doppler frequency shift dependency on the insonation angle ϑ, i.e., the angle between the US beam path and the flow direction [1].

The angle can change because of variations in the orientation of the probe or the vessel, and consequently, the detected Doppler shift varies according to the cosine function: it is maximum for $\vartheta = 0°$, while it is minimum for $\vartheta = 90°$. The latter condition can be avoided by combining the probe angulation and the beam steering to keep the insonation angle in the range between 40° and 70° at which an adequate CD flow and B-mode display of the vessel walls can be obtained [1]. Since the flow detection depends on the insonation angle, as well as on the flow velocity, and it is strictly related to the sensitivity of the US probe, a novel QC parameter can be defined as the range of beam angles around 90° for which the US system is not able to detect moving reflectors, and it can be denoted as blind angle. In this regard, the present study is a preliminary attempt to propose a novel automatic method for the estimation of the blind angle parameter through the post-processing of CD videos. Data have been acquired from a single US diagnostic system equipped with a phased array probe. Moreover, because of the Doppler shift dependency on both the transmitted frequency and the flow velocity, tests have been repeated for two different probe Doppler frequencies and three constant flow rate regimes set on a flow phantom model available on the market.

II. BLIND ANGLE ESTIMATION

The estimation of the blind angle can be carried out through Doppler flow phantoms that allow displaying a portion of the vessel perpendicularly to the US propagation

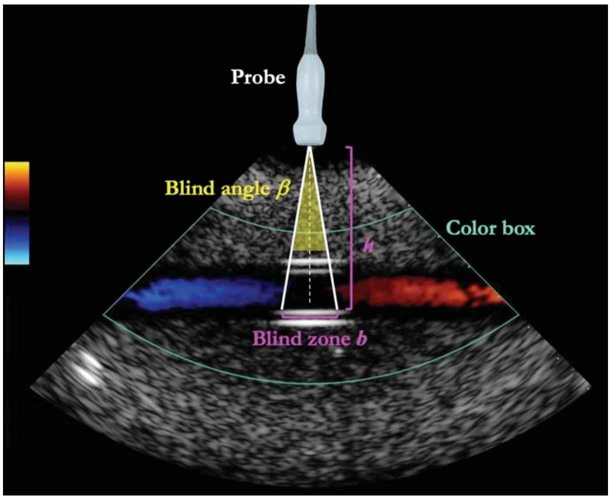

Fig. 1. Color Doppler blind angle in a straight tube parallel to the scanning surface.

axis. In particular, when the insonation angle approaches 90° the Doppler shift is almost zero, therefore in the corresponding area inside the color box, no color-coded flow is shown [1,2]. For a sector scanner, preferred for echocardiography, the displayed velocity inside a straight tube parallel to the scanning surface decreases by approaching the center of the image, and then it rises again. This effect is due to the variation of ϑ, and it is shown in the color box as a change in the flow color.

From this consideration, the blind angle can be defined as the range of beam angles at which a flow area in the image is black due to the incapacity of the probe to detect flow velocities at around $\vartheta = 90°$. By considering the US image shown in Fig. 1, the blind angle β can be estimated as follows:

$$\beta = 2\arctan\left(\frac{b}{2h}\right) \tag{1}$$

where b is the blind zone in which no Doppler shifts are detected, while h is the tube depth from the scanning surface. Since the distribution of the moving reflectors determines the Doppler signal power, the blind zone can narrow or widen in different temporal instants. Therefore, the evaluation of the blind angle in the present study has been carried out through the post-processing of a video rather than a single image. In the following, the main steps of the proposed automatic method are reported.

Firstly, the text boxes surrounding the diagnostic box are excluded through automatic masking [10,11], and a saturation filter based on a threshold th_{CD} is applied to extract the color-coded information only, removing the gray-scale coded B-mode information [12]. After that, an average image A_i is obtained from the CD video by averaging K consecutive frames at a time, for a total of N average images ($i = 1, \ldots, N$). The latter are filtered through a median filter with a n_{px}-by-n_{px} kernel to remove the color noise that can be shown as isolated color pixels within the black zone and the normalized square sum of the RGB components is computed. At this point, the flow central axis is automatically assessed on A_1, as in [13], and its coordinates are used to determine the endpoints of M parallel flow axes placed at a fixed distance Δd, above and below the central one, therefore obtaining a total of M+1 axes. The coordinates retrieved for the M+1 axes are kept fixed for all the N average images.

In the next step, the intensity I_{px} of the pixels that intersect the M+1 axis in the area at around $\vartheta = 90°$ is compared with a color threshold th_{blind} to determine the length of the blind zone b_j (j = 1, …, M+1) on each axis. If $I_{px} \leq th_{blind}$, the corresponding pixel is assumed to be a blind pixel and b_j is computed as the distance between the first and the last blind pixel. Finally, the blind angle β_j is calculated for each flow axis by applying Eq. (1), assuming h_j as the mean depth from the scanning surface of the j-th axis. Afterwards, the blind angle β_i for each average image can be computed as follows:

$$\beta_i = \frac{1}{M+1}\sum_{j=1}^{M+1}\beta_{ij} \tag{2}$$

The procedure as described until now allows the estimation of the blind angle value on the i-th average image, therefore, the overall blind angle $\bar{\beta}$ is computed as:

$$\bar{\beta} = \frac{1}{N}\sum_{i=1}^{N}\beta_i \tag{3}$$

while the corresponding standard deviation $\sigma_{\bar{\beta}}$ can be estimated as follows:

$$\sigma_{\bar{\beta}} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\sigma_i^2} \tag{4}$$

where σ_i is the equivalent standard deviation (SD) assessed on each average image.

III. MATERIALS AND METHODS

Color Doppler videos have been collected by means of Doppler 403™ flow phantom [14], a self-contained reference test device (Table 1) able to provide repeatable flows from 1.7 to 12.5 ml·s^{-1} in constant or pulsatile mode. It consists of a Tissue-Mimicking Material (TMM) and a hydraulic circuit to simulate the acoustic properties of the biological tissues and blood vessels, respectively. In particular, the hydraulic circuit is constituted by a horizontal and a diagonal tube segment of 5 mm inner diameter filled with a Blood Mimicking Fluid (BMF).

Data have been collected through a phased array probe on a portion of the horizontal tube segment that simulates a carotid artery at a depth of 2 cm from the phantom

Table 1. Doppler 403TM flow phantom specifications.

Parameter	Characteristics
TMM	Patented High Equivalence (HE) GelTM
Scanning surface	Patented composite film
TMM sound speed	1540 ± 10 m·s^{-1}
BMF sound speed	1550 ± 10 m·s^{-1}
Flow measurement range	(1.7 – 12.5) ± 0.4 ml·s^{-1}
Tube inner diameter	5.0 ± 0.2 mm
Attenuation coefficient	0.70 ± 0.05 dB·cm^{-1}·MHz^{-1}
Dimensions	28.0 × 30.5 × 22.0 cm

scanning surface. The US diagnostic system used has been set in raw CD working conditions, reported in Table 2. A single video clip lasting 12 s has been acquired for two Doppler frequencies and three constant flow rates (i.e., Q_1 = 6.0 ml·s^{-1}, Q_2 = 8.5 ml·s^{-1} and Q_3 = 11.0 ml·s^{-1}) set on the flow phantom in order to guarantee at least 110 frames per video.

Table 2. B-mode and Color Doppler settings.

Parameter	Setting
Nominal B-mode frequency (MHz)	H4.0(*)
Field of view (cm)	6
TGC(**) – slide controls	Medium position
Nominal Doppler frequency (MHz)	f_1 = 2.0 , f_2 = 2.5
Wall filter	Minimum
Persistence	Minimum
Line density	Medium
Video clip duration (s)	12

(*) H = harmonic frequency; (**) TGC = Time Gain Compensation.

The proposed automatic method for blind angle estimation has been implemented through a custom-written algorithm using MATLAB routines. Each acquired video has been processed by applying the steps described in the previous section with the following specifications. The color-coded information has been extracted through the saturation filter with th_{CD} = 0.35 [12], and N = 15 images have been obtained from each video by averaging K = 6 consecutive frames. Color noise has been removed through a median filter with a 4-by-4 px kernel. Afterwards, M = 2 parallel flow axes have been placed above and below the central one at a fixed distance Δd = 7 px (corresponding to about 1 mm). In this study, the color threshold used to detect the blind pixels on each axis has been chosen as th_{blind} = 10, i.e., about the minimum gray level difference the human eye may distinguish [10,11,15]. Finally, the results obtained from each average image have been used to estimate the overall blind angle $\bar{\beta}$ and corresponding SD value by applying Eq. (3) and (4), respectively.

IV. MONTE CARLO SIMULATION

Monte Carlo Simulation (MCS) is a proper tool for both measurement uncertainty estimation and software-based method robustness assessment, as already experienced in several fields [16-21]. Therefore, a MCS with 10^4 iterations has been carried out for each Doppler frequency and flow rate acquired. Uniform distributions, whose characteristics are reported in Table 3, have been assigned to the main parameters influencing the blind angle assessment.

Table 3. Monte Carlo Simulations settings.

Parameter	Symbol	Distrib.	Mean ± SD
Threshold on color saturation	$th_{CD} \pm \sigma_{CD}$	Uniform	0.35 ± 0.01
Number of averaged frames	$K \pm \sigma_K$	Uniform	6 ± 1
Median filter kernel	$n_{px} \pm \sigma_{px}$	Uniform	4 ± 1 px
Distance from the central flow axis	$\Delta d \pm \sigma_d$	Uniform	7 ± 1 px
Blind pixel threshold	$th_{blind} \pm \sigma_{blind}$	Uniform	10 ± 1

Distrib. = distribution.

V. RESULTS AND DISCUSSION

The blind angle outcomes retrieved at different flow rates (Q_1, Q_2 and Q_3) and Doppler frequencies (f_1 and f_2) are reported in Table 4 and shown in Fig. 2. Standard

Table 4. Blind angle outcomes (mean ± SD) for each flow rate and Doppler frequency.

Flow rate	Doppler frequency	Blind angle $\bar{\beta}$ (°)
Q_1	f_1	15.9 ± 1.9
	f_2	13.1 ± 1.6
Q_2	f_1	5.4 ± 1.2
	f_2	5.8 ± 1.6
Q_3	f_1	2.6 ± 0.7
	f_2	1.4 ± 0.5

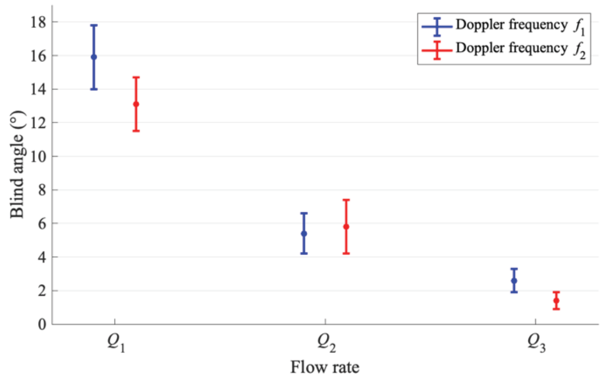

Fig. 2. Blind angle outcomes for f_1 and f_2 Doppler frequencies at Q_1, Q_2 and Q_3 flow rates.

deviation values have been computed by combining the SD obtained by applying Eq. (4) with the corresponding one estimated through the MCS.

The outcomes obtained are always compatible at the same flow regime and, as expected, they show a decreasing trend for increasing flow rate values, almost independently of the probe frequency.

VI. CONCLUSIONS

The present study aims at giving a contribution to Color Doppler QC tests by investigating a novel parameter, called blind angle, derived from a performance test recommended by the AIUM, i.e., directional accuracy at 90°. The latter has been defined only qualitatively by the professional agency that recommends a visual assessment directly on the monitor. The blind angle parameter, defined as the range of beam angles around 90° at which moving reflectors cannot be detected, has been retrieved to test the Doppler frequency shift dependency on the insonation angle. In fact, such parameter is strictly related to the US probe sensitivity and to the performance of the diagnostic system. Moreover, to overcome the limitations of the subjective procedure, a novel automatic method for the estimation of the blind angle parameter through the post-processing of CD videos has been proposed. In this preliminary attempt, data have been collected from a single US diagnostic system equipped with a phased array probe. Because of the further dependence of the detected Doppler shift on the transmitted frequency and the flow velocity, tests have been repeated for two probe frequencies and three constant flow rate regimes (i.e., 6.0, 8.5 and 11.0 ml·s^{-1}) set on a flow phantom. The promising results obtained provide the basis for further studies to be carried out on a higher number of (a) ultrasound diagnostic systems, (b) phased array probes, (c) probe models, and (d) phantom settings.

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