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A first approach to the registration error assessment in Quality Controls of Color Doppler ultrasound diagnostic systems

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***Abstract* – Color Doppler Imaging (CDI) is widely used in diagnostic imaging, although the Quality Control procedures for Doppler testing have not been standardized yet. Therefore, in the present study, a novel parameter, called Doppler Image Registration Error (DIRE), for the quantification of the color flow superimposition in duplex imaging of CDI diagnostic systems has been proposed. According to the definition, the registration error is expected to be 0% when no colored pixels associated to the flow are outside the flow region. Its estimation has been carried out through a novel semi-automatic method based on the post-processing of ultrasound (US) images from a flow phantom tube. Two new US diagnostic systems, equipped with a linear array probe each, have been used to collect data at different settings. Based on the promising outcomes, further studies are going to be carried out, mainly to make the results independent on the operator subjectivity.**

I. INTRODUCTION

Nowadays, Color Doppler Imaging (CDI) is used routinely in diagnostic imaging and it plays a key role by allowing the real-time visualization of the blood flow overlaid on the grayscale anatomical image [1,2]. The Doppler signal is codified into velocity values according to a color map and displayed as a color inside a region of interest, known as color box. Although in some cases CDI is still assumed to provide qualitative rather than quantitative information [3], to date, a shared worldwide standard on Doppler equipment testing is lacking. The professional organizations involved, e.g., [3,4], disagree about the ultrasound (US) system configuration settings, as well as how many and which performance parameters have to be included in a Quality Control (QC) program for Doppler testing [5]. On the other hand, in literature the demand of proper performance tests has been highlighted in the last years [5-10], also due to the continuous improvement in the technology of the ultrasound equipment. Among the performance tests for CDI proposed by the Institute of Physics and Engineering in Medicine (IPEM), Color/Power Doppler Duplex priority control function is considered [4]. Such test takes into account the action of a specific US system control, usually adjustable by the operator, known as color write priority (CWP) [1,11,12]. This function allows to set a threshold below which Doppler information is displayed in the flow region and above which it is not displayed. When a high CWP is set, color data override the grayscale data (i.e., higher color flow sensitivity), otherwise, when a low CWP is set, the grayscale data override the color data (i.e., lower color flow sensitivity). In the first case, the lumen of the vessel is totally filled but some color bleeding may occur outside the flow region, while in the second case, a poor filling of the blood vessel can be observed [1,11,12].

By considering the degree of color bleeding when CWP setting is maximum, it is possible to determine a novel parameter useful to monitor the US probe color flow sensitivity over time or to compare it among different systems. In literature, the positioning of color flow information at an incorrect location (e.g., outside the vessel lumen) within the color box is defined as misregistration [1]. No recent studies known to the authors have investigated this positioning error with the aim to implement a QC procedure for CDI systems testing. In this regard, the present study would give a contribution by introducing the Doppler Image Registration Error (DIRE) to objectively assess this specific component of the CDI diagnostic systems, through the implementation of a semi-automatic method based on the analysis and processing of US images from tissue mimicking phantoms. In particular, two new ultrasound diagnostic systems, equipped with a linear array probe each, have been used to collect Color Doppler videos from the tube of a flow phantom at different settings. After the description of the method, first experimental results are shown and discussed.

II. REGISTRATION ERROR ASSESSMENT

The assessment of the registration error proposed in the present study has been carried out by post-processing a Color Doppler video acquired on a flow phantom. As a first step, the implemented semi-automatic method excludes all

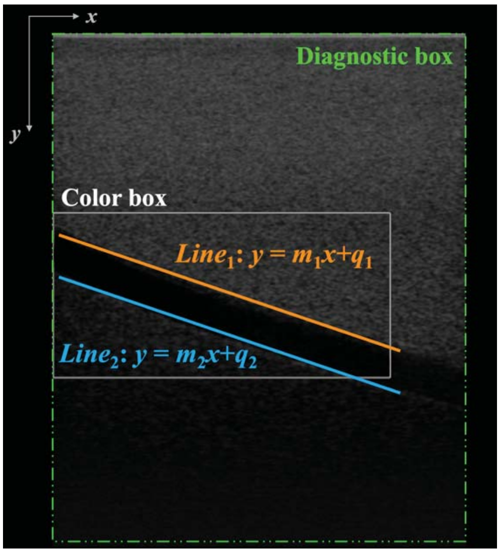

Fig. 1. Example of the straight lines drawn on the upper and lower boundaries of the displayed tube walls. The image $\bar{I}_{gray}$ provided to the operator contains the grayscale-coded information.

the US settings details surrounding the diagnostic box (shown in Fig. 1) through an automatic masking [13], and separates the color-coded information from the grayscale-coded one through a saturation filter [14] based on a threshold th_{sat}, obtaining two distinct images, I_{color} and I_{gray}, respectively. Such procedure is repeated for each frame (j = 1, …, N) of the collected video. Afterwards, the average images $\bar{I}_{color}$ and $\bar{I}_{gray}$ are obtained by averaging all the N frames, and the normalized square sum of the RGB components of $\bar{I}_{color}$ is computed. In the next step, the implemented method provides the operator with the image $\bar{I}_{gray}$ allowing her/him to manually draw a straight line following the upper and lower boundaries of the displayed tube walls ($Line_1$ and $Line_2$ in Fig. 1), to determine the corresponding slope (m_1 and m_2) and y-intercept (q_1 and q_2) values.

The coordinates of the intersecting points between the two lines and the color box (Fig. 1) are retrieved to subdivide the color box into two different sub-boxes: the endpoints of the latter are then used to crop the average image $\bar{I}_{color}$, as shown in Fig. 2. The intensity K of the pixels included in the two sub-boxes is compared with a specific threshold th. If $K \geq th$ the corresponding pixel is assumed as a colored pixel outside the tube walls. Finally, the percentage Registration Error ($RE_{\%}$) is computed as follows:

$$RE_{\%} = \frac{n_{out}}{n_{tot}} \cdot 100 \qquad (1)$$

where n_{out} is the number of colored pixels detected outside the tube walls, while n_{tot} the total number of colored pixels in the entire color box which intensity $K \geq th$. According to the definition proposed, $RE_{\%}$ is expected to be 0%. In this case, no colored pixels associated to the flow are positioned outside the tube.

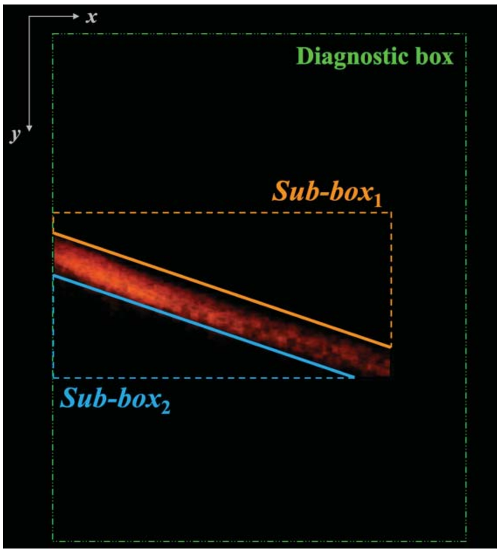

Fig. 2. Example of the average image $\bar{I}_{color}$ cropping according to the endpoints of the two sub-boxes.

III. MATERIALS AND METHODS

CIRS, Model 069 Doppler phantom has been used in this study to collect Color Doppler videos. The simulator [15] is an easy-to-assemble reference test device able to provide constant or pulsatile flows from 0.5 to 12.5 ml·s^{-1}. It consists of a Tissue-Mimicking Material (TMM) and a sloped echogenic tube with an inner diameter of 4.8 mm, filled with a Blood Mimicking Fluid (BMF).

The tube simulating the blood vessel can be scanned in two configurations (at 70° and 45°) since the simulator has both a top and bottom scan surface. In Table 1 the main characteristics of the US flow phantom are reported together with the specification of the configuration used.

Table 1. CIRS Model 069 flow phantom specifications [15].

Parameter	**Characteristics**
Scan surface	Saran laminate membrane
TMM	Zerdine®
TMM attenuation coefficient	0.7 dB·cm^{-1}·MHz^{-1}
TMM sound speed	1540 ± 10 m·s^{-1}
BMF sound speed	1570 ± 30 m·s^{-1}
Flow range	0.5 – 12.5 ml·s^{-1}
Nominal tube inner diameter	4.8 mm
Tube slope	70°

Table 2. B-mode and Color Doppler settings and specifications for ultrasound systems A and B.

Parameter	**set 1**	**set 2**
B-mode frequency	Penetration	
Field of view (cm)	7	
Nominal Doppler frequency (MHz)	A: 5.5 , B: 5.3	
Color write priority	Maximum	
Wall filter	Minimum	Medium
Color smoothing	Minimum	Medium
Persistence	Minimum	Medium
Line density	Minimum	A: Minimum B: Medium
Transmission power (%)	100	A: 100 B: 90
Acquisition duration (s)	2	
Number of acquired frames	A: 61 , B: 65	A: 62 , B: 59
Frames resolution (px×px)	A: 768×1024 , B: 924×1232	
Color box size (px×px)	A: 223×459 B: 295×400	A: 206×461 B: 268×351

In this study, a constant flow rate Q = 6.0 ml·s^{-1}, corresponding to a nominal average flow velocity v_a = 33.7 cm·s^{-1}, has been set on the simulator. Data acquisition has been carried out on two intermediate technology level US diagnostic systems (namely A and B), equipped with a linear array probe each. A single Color Doppler video lasting 2 s has been acquired at the lowest Doppler frequency of the probes and for two US system settings, i.e., set 1 and set 2 (Table 2). In set 1, pre- and post-processing settings have been reduced, while in set 2 the best settings provided by each US specialist have been maintained.

As a preliminary approach, a semi-automatic method for the registration error assessment has been implemented through an *ad hoc* algorithm developed in MATLAB environment. The processing steps described in the previous section have been applied to each acquired video according to the following specifications. The threshold used to process each frame and separate the color- from the grayscale-coded information has been set to th_{sat} = 0.35 [13,14], and the images $\bar{I}_{color}$ and $\bar{I}_{gray}$ have been obtained by averaging N = 55 consecutive frames. After the action of an operator, required to manually draw two straight lines on the boundaries of the tube walls into the US image, the corresponding slope and y-intercept values have been computed. The threshold used to detect the colored pixels, inside the two sub-boxes and in the whole color box, has been selected on the basis of the minimum gray level difference the human eye may distinguish [16], i.e., th =

Table 3. Monte Carlo Simulations settings.

Parameter	**Symbol**	**Distribution**	**Mean ± SD**
Threshold on color saturation	$th_{sat} \pm \sigma_{sat}$	Uniform	0.35 ± 0.01
Number of averaged frames	$N \pm \sigma_N$	Uniform	55 ± 2
Upper line slope	$m_1 \pm \sigma_{m1}$	Normal	A1: 0.36 ± 0.01 A2: 0.36 ± 0.01 B1: 0.43 ± 0.01 B2: 0.44 ± 0.01
Upper line y-intercept	$q_1 \pm \sigma_{q1}$	Normal	A1: 251 ± 3 px A2: 246 ± 2 px B1: 219 ± 4 px B2: 213 ± 3 px
Lower line slope	$m_2 \pm \sigma_{m2}$	Normal	A1: 0.36 ± 0.01 A2: 0.36 ± 0.01 B1: 0.43 ± 0.01 B2: 0.45 ± 0.01
Lower line y-intercept	$q_2 \pm \sigma_{q2}$	Normal	A1: 309 ± 3 px A2: 308 ± 3 px B1: 280 ± 4 px B2: 275 ± 4 px
Threshold for colored pixels detection	$th \pm \sigma_{th}$	Uniform	10 ± 1

A1 = ultrasound system A in set 1; A2 = ultrasound system A in set 2; B1 = ultrasound system B in set 1; B2 = ultrasound system B in set 2.

10. Finally, the percentage registration error has been computed by applying Eq. (1).

IV. MONTE CARLO SIMULATION

Monte Carlo Simulation (MCS) has been widely used in literature for the measurement uncertainty estimation of image analysis-based methods [17-21]. In this study, a MCS with 10^4 iterations has been carried out for each probe and US system setting to estimate the uncertainty of the $RE_{\%}$ parameter. In Table 3, the distributions assigned to the main parameters involved in the registration error assessment are listed and expressed as mean ± standard deviation (SD). Both the thresholds th_{sat} and th, as well as the number of averaged frames N have been set as uniform distributions. On the other hand, normal distributions have been assigned to the slopes and y-intercepts of the lines drawn on the upper and lower tube walls. In particular, since the implemented semi-automatic method requires the action of an operator, six independent observers without medical expertise were asked to manually select two pairs of lines on the tube walls sixteen times to test and estimate subjects' inter- and intra-variability [22]. The test has been repeated by the same operators providing them with the average image $\bar{I}_{gray}$ obtained for each US system (A and B) and configuration setting (set 1 and set 2).

V. RESULTS AND DISCUSSION

The percentage registration errors $RE_{\%}$ obtained for the two new US systems, both set with two different configuration settings (set 1 and set 2), are reported in Table 4. Mean and standard deviation values have been estimated from the MCSs. By considering the US system A, the results for set 1 and set 2 are compatible. As per the US system B, the $RE_{\%}$ obtained in set 2 is rather low, and the closest to 0% among all 4 US system-set pairs. The latter outcome suggests that the proposed semi-automatic method is quite sensitive to the quantification of the $RE_{\%}$, even if the results are affected by a high uncertainty source likely due to the action of the observers required to manually draw the straight lines on the boundaries of the tube walls. This consideration is supported by the estimation of the percentage error between the nominal tube diameter, reported in Table 1, and the measured one, computed by considering the slopes and y-intercepts of the two lines reported in Table 3. In this case, for the US systems A and B, this error varies between 12% and 19%. Therefore, this overestimation can be considered as one of the causes of the high measurement uncertainties obtained in this study.

Table 4. Percentage registration error outcomes for each US system and configuration setting.

US system	US setting	$RE_{\%} \pm SD_{RE\%}$ (%)
A	set 1	8 ± 5
	set 2	9 ± 5
B	set 1	9 ± 6
	set 2	3.3 ± 2.3

VI. CONCLUSIONS

In the last years, the demand of proper performance tests for Color Doppler imaging has been highlighted, since a shared QC program for Doppler testing is still lacking. In this regard, the present study would give a contribution in the field by proposing a first approach to the assessment of a novel parameter for the monitoring of the US probe color flow sensitivity in CDI diagnostic systems. This parameter named Doppler Image Registration Error (DIRE), has been derived from a performance test already proposed by the IPEM, and assessed as the degree of color bleeding when color write priority setting is maximum. According to the definition, the registration error is expected to be 0% when no colored pixels associated to the flow are positioned outside the flow region.

A novel semi-automatic method based on the post-processing of a Color Doppler video, acquired from the tube of a flow phantom, has been implemented in MATLAB environment. As a first attempt, two new ultrasound diagnostic systems, equipped with a linear array probe each, have been used to collect data at different US settings. Although the implemented method requires the external action of an operator, the results obtained are promising, suggesting that further improvements of the method are needed. In fact, to test and estimate subjects' inter- and intra-variability six independent observers without medical expertise were asked to manually draw the straight lines on the boundaries of the tube walls: their action has been identified as one of the main uncertainty sources in the assessment of the percentage registration error. Therefore, the improvements of the semi-automatic method that are going to be carried out will include: the shift towards a fully automatic method removing the need of the subjective action of an operator, and the introduction of some weights in the computation of the registration error parameter in order (a) to exclude or reduce from its quantification any isolated colored pixel outside the flow region (e.g., due to noise) and (b) to accentuate any groups of pixels detected outside the flow region, for instance on the basis of their distance from the tube lumen. Finally, further studies should be carried out on a higher number of ultrasound diagnostic systems and probe models.

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