A PRELIMINARY STUDY ON A NOVEL PHANTOM BASED METHOD FOR PERFORMANCE EVALUATION OF CLINICAL COLOUR DOPPLER SYSTEMS

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***Abstract* – Ultrasound Colour Flow is an imaging technique that combines velocity with anatomical information obtained by means of ultrasonic Doppler techniques and pulse-echo methods respectively to generate colour coded maps of the blood flow velocity superimposed on grey-level images of the tissue anatomy. Ultrasound Colour Flow Imaging (CFI) has been found to be effective in assessing blood flow in many clinical conditions and its use is widespread in many diagnostic applications. Although this technique for obtaining the blood velocity information is technically demanding and requires specific tests for its assessment, a shared worldwide standard on CFI equipment testing is not published yet and in the scientific literature there is no agreement on the choice of parameters to be tested, measurements methods and the timing of the test. After a brief introduction to the main principles and main methods in the scientific literature for quality assessment of CFI systems, a novel phantom based method is proposed and applied for a quantitative analysis of the performances of a commercial ultrasound scanner. Finally first results are shown and commented.**

Keywords* – *Ultrasound, Colour Doppler, quality assessment, Colour Flow Imaging, phantoms, velocity measurement

I. INTRODUCTION

Owing to its great usefulness and versatility, diagnostic ultrasounds are among the most important diagnostic imaging technologies in the world: according to [1-3] the global diagnostic ultrasound market value is estimated between $4 and $7 billion in 2016 where Asia-Pacific and Europe areas cover 75% of the world market (almost equally distributed) [3]. The diagnostic ultrasound technology can be segmented in three main classes: 2D imaging (the largest technology segment), the 3D&4D imaging and Doppler. In particular Doppler ultrasound is used to detect the presence, direction, velocity and properties of blood flow in vessels and today Colour Flow Imaging (CFI) is one of its most typical applications: a scanning mode that combines gray-scale imaging with two-dimensional colour mapping of flow information in real-time, superimposing different colours on the bidimensional gray scale image [4]. Therefore performances evaluation of diagnostic ultrasound equipment is a widespread and actual issue for the scientific community [5-15], as well as for manufacturers and end users (i.e. physicians, technicians), and it can be used for technological development and maintenance purposes, whose costs per scanner may range between 10% and 50% of the equipment value each year. Nevertheless, as for other biomedical fields [16-24] a shared worldwide standard on ultrasound equipment testing is not available yet and, despite the great number of publications in literature [25-29], there is a lack also on CFI testing. Perhaps it may be also due to the two different points of view in the scientific community about CFI diagnostic capabilities: in particular scientists are divided between those who think that CFI should be considered a purely qualitative diagnostic technique and those who think that CFI technology is in continuous evolution and improvement and its diagnostic potential can be used to perform also objective and repeatable measurements of flow quantities [4,25,30]. Nevertheless the CFI is much more technical demanding than B-mode [8] and its quality assessment can be useful both for maintenance and research purposes by means of repeatable and objective measurements: the overall CFI image quality is related to motion discrimination, temporal resolution, spatial resolution and uniformity [4]. To this aim in this paper a preliminary study on a tool for performance evaluation of CFI diagnostic equipment is proposed: after a brief overview on main quantities used in CFI quality assessment, some theoretical elements of the tool developed are illustrated and its application to a commercial ultrasound scanner is proposed: measurement results are reported and commented. Future developments are finally discussed.

II. RELATED RESULTS IN THE LITERATURE

The velocity v of blood reflectors (i.e. rouleaux) can be obtained from the well-known physical model (1) used by most of the CFI diagnostic equipment [29, 31]:

$$f_D \cong 2 f_0 \cdot \frac{\mathrm{v}}{c} \cdot \cos\gamma \qquad (1)$$

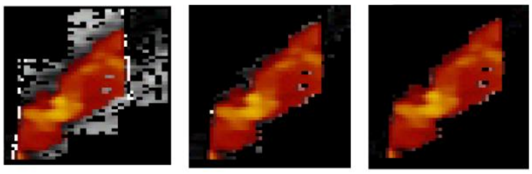
Where the Doppler Shift f_D is related to the frequency f_0 of the transmitted ultrasounds radiation and to the speed v and direction γ of the reflectors in the anatomical districts (i.e. Rouleaux). Since the (1) is an approximate model, the estimation of speed v is usually affected by an intrinsic uncertainty between 0.1% and 3.5% of the actual value [31], such an uncertainty must be combined with other sources of error (e.g. angle correction, propagation speed in tissues, estimation algorithm [32, 33], artifacts, operator, etc.): therefore accuracy in speed measurements can be affected by expanded uncertainties higher than 20% in Spectral Doppler measurements (e.g. Puled Wave Doppler, Continuous Wave Doppler) but up to 50% or more for CFI systems [26, 28, 34-37]. With the aim to evaluate the CFI performances, a flow reference should be used and can be achieved by means of Doppler ultrasound Phantoms: these are devices designed to provide variable flow rates at known orientations and with blood mimicking test objects (e.g. blood mimicking fluid or BMF, string, belt, etc.) usually within a tissue mimicking matrix (i.e. Flow phantoms, String Phantoms, Belt Phantoms, etc.). In some cases Doppler Phantoms are electronic devices that generate radio frequency electric signals similar to those provided from the ultrasound probe due to echoes from blood flows [4]. Doppler phantoms are usually used for evaluating a great number of specific quantities related to CFI system performances [38-41]: most of these quantities depend on accuracy in velocity estimation, therefore an analysis tool that allows the quantitative and repeatable measurements of flow velocity in the CFI image is considered worthwhile for both the hospital technician and the manufacturer. In particular the tool should provide measurements from one or more velocity profiles on arbitrary sections of the CFI image or video in order to evaluate spatial and temporal performances of the ultrasound system by means of commercial Doppler phantoms (e.g. Flow Phantoms). To this aim in the follows a novel phantom based method for performance evaluation of CFI systems is proposed with two applications by means of a commercial Doppler Flow Phantom: accuracy in mean velocity estimation and measurement of the minimum angle in the scan plane (critical angle) at which flow with axis perpendicular to the acoustic axis is detectable [39-42].

III. DESCRIPTION OF THE METHOD

The image and video processing tool has been developed in a Matlab® environment and the colour flow analysis is based on the reconstruction of velocity profiles for selected pixels on single images or on sequences of video frames.

A. Removal of non-Colour Doppler information

All the information unrelated to Color Doppler (i.e. B-Mode pixels and text boxes) is removed from the frame, by applying a threshold-based filter on the pixel colour saturation. Because of some problems related to lossy image compression (e.g. in video frames) a threshold higher than zero is preferable, chosen below the minimum saturation value in the CFI colour map (Fig. 1).



th = 0 *th = 0.12* *th = 0.35*

Fig. 1. Results of thresholding on colour saturation

B. Drawing lines for velocity profiles

Conversion from colour to flow velocity is estimated only for selected pixels in the Colour Doppler image. These pixels all belong to one or more segments (Fig. 2) that can be drawn by the user on the image. Anyway segments can be more properly set in terms of position in the image and angle respect to the detected flow, providing more repeatability of the test. To this aim, an automated function has been developed.

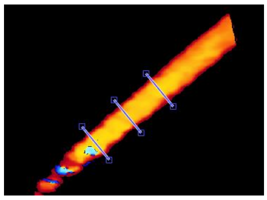


Fig. 2. Example of profile line segments, placed on the analysed image, all segments are normal to the flow axis

C. Colour to velocity conversion

For each pixel of the segment, conversion from colour to velocity is possible with two different algorithms (RGBa and LINa respectively). If the colour map is well fitted to flow, it will be likely to find, for each colour in the flow, a pixel in the map with the same identical colour, whose position along the map can be used in estimating velocity (RGBa). In case of flow pixels without match in the map, the assigned velocities are chosen considering the most similar map pixels. Similarity between two pixel colours is calculated as Manhattan distance, as shown in (2).

$$d_{M,RGB}(a,b) = \sum_{i=R,G,B} |a(i) - b(i)| \qquad (2)$$

An alternative procedure in velocity profile reconstruction is based on linear regression (LINa). A colour feature (e.g. luminance, hue, etc.) varying almost linearly along the Doppler map is selected and the linear fitting coefficients of the relationship between the selected feature and a linear axis of velocities are calculated: mean velocities corresponding to different colours in the flow are therefore quantified. In our study, levels of red, green and blue in all pixels along each map available in the US system under test (Philips IE33 equipped with a phased array probe), have been combined in typical mathematical functions for colour description, like hue, saturation or luminance (fig. 3,a,b,c). Since none of these has been found linear, the selected feature has been the square sum of RGB components, the linearity of which has been considered acceptable for one of the eight maps (fig.3d)

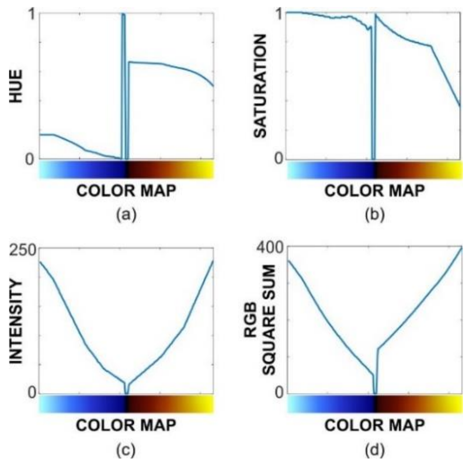


Fig. 3. Feature extraction from colours along a Doppler map, in linear-fitting based algorithm

D. First Results from velocity profiles

Accuracy in mean velocity estimation of the CFI can be evaluated by comparing the mean (or peak) velocity set on the flow phantom with the mean (peak) velocity found on the velocity profile (fig.4). Parameters related to minimum flows detectability [41] are evaluated considering positions of coloured pixels where flow disappears. In static images, for each line segment (fig.2) a velocity profile is determined (fig 4a). In video analysis, the velocity profile of the line segment can be plot for different frames: if the observed area is a single pixel or a quantity evaluated from the whole profile (e.g. mean velocity, peak velocity, etc.), measurement results can be shown in a time-velocity plot, on the other hand if observed area is extended on more pixels, a spectrogram similar to PW or CW Doppler can be provided (fig.4b).

E. Estimation of the tool uncertainty

Velocity measurements above are affected by uncertainty due to (a) the flow phantom, (b) the Color Doppler system and (c) the image processing. The last contribution has been evaluated with a Monte Carlo Simulation, by cycling 100000 times the velocity reconstruction operations on the same area of a same image (Table 1).

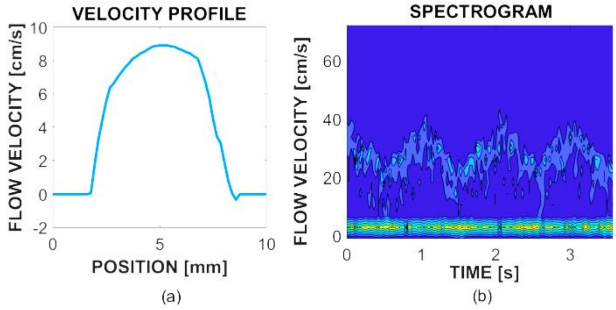


Fig. 4. (a) Velocity profile on a segment line in a static image. (b) Spectrogram of velocities in a section of the phantom in a video at 60 bpm pulsatile flow.

Table 1. Monte Carlo Simulation Settings

Source of Uncertainty	***Distribution***	***Mean***	***Std. deviation***
Flow central axis position (*)	Normal	m=0.822 q=27	σ_m= 0.006 σ_q= 3
LINa - Linear regression coefficients (**) with uncompressed colour map	Normal	A=-5.68 cm s^{-1} B=0.2179 cm s^{-1}level^{-1}	σ_A=0.28 cm s^{-1} σ_B =0.0013 cm s^{-1}level^{-1}
LINa - Linear regression coefficients (**) with compressed colour map		A=-6.70 cm s^{-1} B=0.2228 cm s^{-1}level^{-1}	σ_A=0.35 cm s^{-1} σ_B =0.0017 cm s^{-1}level^{-1}
RGBa - Effect of velocity axis discretization with uncompressed colour map	Uniform	Velocity associated to pixel in the map	σ_{RGB}= 0.11 cm s^{-1}
RGBa – Effect of velocity axis discretization with compressed colour map			σ_{RGB}= 0.17 cm s^{-1}
RGBa - Maximum distance adopted for replacing pixels	Uniform	50 level	14 level
Iteration cycles	10^5		

(*) i=m*j+q is the relation between the column, i, and the row, j, of pixels on the central axis of the detected flow
(**) Y=A+Bx where x is the RGB square sum and Y the velocity associated to each RGB combination.

IV. RESULTS AND DISCUSSIONS

The Monte Carlo Simulation results are uncertainties intrinsic to image and video processing, as shown in Table 2: the relative uncertainties are expressed as the percentage ratio of the standard deviation to the mean [43] and confirm that the two algorithms provide results below 2 percent with a linear map.

Table 2. Relative uncertainties of the image processing tool,

Image type	Algorithm	δV_{peak} (%)	δV_{mean} (%)
Static image	LINa	1.1	1.5
	RGBa	0.4	0.16
Compressed video frame, uncompressed colour map	LINa	1.3	1.6
	RGBa	0.4	0.2
frame and colour map both compressed	LINa	1.6	1.9
	RGBa	0.7	0.4

The tool has been applied in different tests on the Colour Doppler system which model and settings are reported in table 3: results for critical angle and mean velocity estimation (percentage error from phantom flow) are exposed in Table 4 and are compatible with the literature in terms of mean velocity estimation [34-37] and image processing uncertainty [44]. Anyway the developed tool could be used in many other applications by means of commercial phantoms. Interesting results are expected with video analysis, e.g. the application of the tool to a pulsatile flow of known amplitude and frequency in a flow phantom will allow the evaluation of the accuracy in mean velocity estimates associated to different time resolutions.

Table 3. Settings of the Ultrasound system under test (Philips IE33 equipped with phased array probe)

Parameter	*Mean velocity accuracy test*	*Critical angle test*
FOV	15 cm	5 cm
CFI frequency	2.5 MHz	variable
CFI gain	65%	80%
CFI ROI Position	Centre of image	Covering all the flow tube
Wall filter	Minimum	Minimum
Persistence	Disabled	Disabled
Color priority	Half range	Half range
Other processing	Minimum	Minimum
Phantom settings	50° sloping tube, variable velocity	Horizontal tube 21 cm/s (mean)

Table 4. Test results: mean velocity error and critical angle

Mean velocity error	77 % ± 9% @16.9 cm/s	64% ± 4% @36.1 cm/s	54% ± 3 % @51.3 cm/s
Critical angle	12° ± 4° @ 3.0 MHz	14° ± 7° @ 3.3 MHz	17 ° ± 4° @ 4.5 MHz

V. CONCLUSIONS

The proposed method allows to quantitatively evaluate velocities provided by medical CFI systems by means of commercial Doppler phantoms. Its relative uncertainty has been estimated below 2% throughout a Monte Carlo Simulation, on the other hand tests on a commercial machine revealed uncertainties between 23% and 50% for the transducer's critical angle and up to 77% percentage error between estimated and nominal flow velocity. Possible applications of the tool are the quality assessment of CFI systems for research or maintenance purposes.

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