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Comparison of Ultrafast Color Doppler and High-frame-rate Vector Flow with Pulsed Wave Doppler: A Phantom Study

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Abstract: The aim of this work is to compare the in vitro performance of two new Doppler techniques with pulsed wave Doppler (PW). Ultrafast color Doppler (UFCD), high-frame-rate vector flow (HiFR-VF), and PW methods were compared on a standardized phantom. The time-averaged maximum (TAmax) velocity measured by three different ultrasound systems was compared with the nominal values, namely 35, 70 and 106 cm/s, displayed by the phantom. The accuracy and precision in measuring different velocities were estimated for a continuously fully-developed flow in a 5 mm diameter straight tube. All the systems estimated TAmax with a relative bias between -10% and +20% with PW, mainly overestimating the expected velocity. The mean velocities and relative biases were significantly different in the three systems at almost all selected velocities ($p<0.0001$). However, the mean velocities and relative biases were not significantly different for UFCD and HiFR-VF methods at all velocities ($p>0.36$) and showed the same accuracy and precision ($p>0.05$). The HiFR-VF, UFCD and PW methods demonstrated an overall mean relative bias of -1.02%, 2.14% and -2.77%, respectively. The HiFR-VF technique resulted in more accurate and precise overall results. HiFR-VF and UFCD were more accurate and precise than PW in the TAmax assessments at various velocities. HiFR-VF showed better performance compared to PW and UFCD which are angle dependent. This may be due to HiFR-VF angle independence. The HiFR-VF findings were achieved with the plane wave multidirectional transmission and reception technique, employed to measure each velocity vector component, which may have affected the positive results.

Keywords: Doppler, Plane Wave Imaging, Vector Flow Imaging, Ultrafast Doppler, Pulsed Wave Doppler

1. Introduction

Pulsed wave Doppler (PW) and color Doppler (CD) have been considered the reference methods for assessing hemodynamics in the cardiovascular medicine. In particular, PW offers excellent temporal and spatial resolution and provides a quantitative assessment of flow characteristics such as peak and mean flow velocity as a function of time [1]. However, the flow is quantified at only one single location at a time. CD shows real-time two-dimensional (2D) Doppler information over an extended area at a limited frame rate, thus estimating only the mean flow velocity [2].

To overcome the limitations of CD, a new technique, referred to as ultrafast color Doppler (UFCD), was suggested. This method achieves a high frame rate during a short period of acquisition. In UFCD, several tilted plane waves are sent into the medium, and the backscattered signals are coherently summed, allowing high frame rates [3]. Moreover, UFCD allows multiple sample volume spectrum calculations over the entire image, using the retrospective row data, thus displaying the peak velocity at a single location [4].

It should be stressed that the angular dependency limits the quantitative evaluations in conventional Doppler ultrasound (CDUS) techniques [2, 5]. The beam-to-flow angle should be kept below 60° to maintain an accurate estimation. When introducing the angle correction to resolve the Doppler formula, the cursor is conventionally aligned to the vessel axis. Nonetheless, this statement is only partially correct, as it assumes that all velocity vectors are axial [6]. Moreover, this statement does not account for the red cells moving in multiple directions during the cardiac cycle even in a straight vessel with laminar flow, such as the common carotid artery. Additionally, a fully developed or axisymmetric flow profile appears to be the exception rather than the rule in a nominally straight vessel [7]. A significant problem with CDUS techniques is that only the velocity component in the beam direction can be found [8]. Therefore, for a more precise measurement of flow velocity, it becomes necessary to evaluate the lateral component of the 2D velocity vector.

Jensen et al. proposed a new method for determining at least two of the three velocity components of velocity vectors [8]. The main advantages are the independence of the method on the beam-flow angle and the ability to assess multidirectional blood flow [9]. Since then, various methods to estimate 2D velocity vectors have been suggested [10, 11]. One of them, named high-frame-rate vector flow (HiFR-VF), represents an implementation of the vector projectile imaging method and derives the 2D velocity vectors at any location from multidirectional transmission and reception of plane waves based on the Doppler technique [12, 13]. This method achieves a high frame rate during a short period of acquisition and provides the visualization and estimation of the flow velocity in all directions [14-17]. HiFR-VF also allows the measurement of the peak and mean flow velocities in a sample volume of selectable size. A wide assessment of the quantitative performance of UFCD and HiFR-VF in comparison with the PW, which is considered a gold standard, is not currently available. This issue limits their application in the staging of stenosis and in vorticity and local wall shear rate quantification.

To our knowledge, this is the first study aiming to evaluate the accuracy and precision of both UFCD and HiFR-VF in the flow velocity estimation at different flow rates. Although only a few systems based on plane wave technology are currently available for vascular applications, some systems will to the best of our knowledge enter the market soon. It is therefore appropriate that in parallel with the clinical validation of these new technologies, the quantitative performance is assessed.

2. Materials and Methods

High-frame-rate ultrasound (US) imaging provides high temporal resolution, of up to tens of thousands of frames per second, by transmitting unfocused US pulses and using parallel receive beamforming. Due to the complexity in implementing ultrafast imaging techniques, only two scanners for clinical use have been introduced on the market before the study. For this reason, we involved the Aixplorer system (SuperSonic Imagine, France) for the UFCD and the Resona 7 system Rev. 2 (Mindray Bio-Medical Electronics Co., China) for the HiFR-VF. The two systems and a third, the recently introduced MyLab 9 (Esaote, Italy) which uses only a conventional line-by-line scanning technique, were tested to obtain a reliable analysis with PW, which was considered the reference technique (Table 1).

Linear probes with similar bandwidths were used on the systems. The influence of different frequency bandwidths on the measurement findings was tested on one system (Resona 7) using two different probes, as described in Table 1.

Table 1. *Systems involved in the study and acquisition parameters.*

Producer	Model	Linear probe (Bandwidth)	PW steering angle	Tilt angle	US technique	Correction angle
SuperSonic Imagine – France	*Aixplorer*	SL10-2 (2-10 MHz)	20°	10°	PW UFCD	60°
Mindray Bio-Medical Electronics Co. – China	*Resona 7*	L9-3U (1.8-9.8 MHz) L11-3U (3.8-11.8 MHz)	30°	-	PW HiFR-VF	60° (not for HiFR-VF)
Esaote – Italy	*MyLab 9*	L11-3 (3-11 MHz)	30°	-	PW	60°

Compared to the in vivo setting, flow phantoms provide a more consistent signal environment in which a spectrum of velocities are produced across the flow profile of a simulated vessel. The acquisitions were performed on a certified phantom, Gammex OPTIMIZER® RMI 1425A (Sun Nuclear Corporation, Gammex Inc, Middleton, WI, US), consisting of a flow system of 5 mm in diameter with horizontal and diagonal vessel orientations, a tissue mimicking gel and a blood mimicking fluid, and an electronic flow controller (Figure 1a, Table 2).

The phantom provides flow at variable rates in a continuous or pulsed mode and ensures that the measured performance closely approximates the scanner performance in a clinical examination. The flow velocity accuracy test evaluates the congruence between the flow velocity displayed on the phantom and the flow velocity displayed on the US system. In both vessels, there is a region where a fully developed laminar flow could be observed (Figure 1b). To ensure an accurate estimation of the velocity within the vessel, we performed the measurements at that site along the horizontal tube. We did not use the available diagonal vessel, because of some limitations in the assignment of the velocity vectors direction with the current release of the HiFR-VF for 45° vessel angulation.

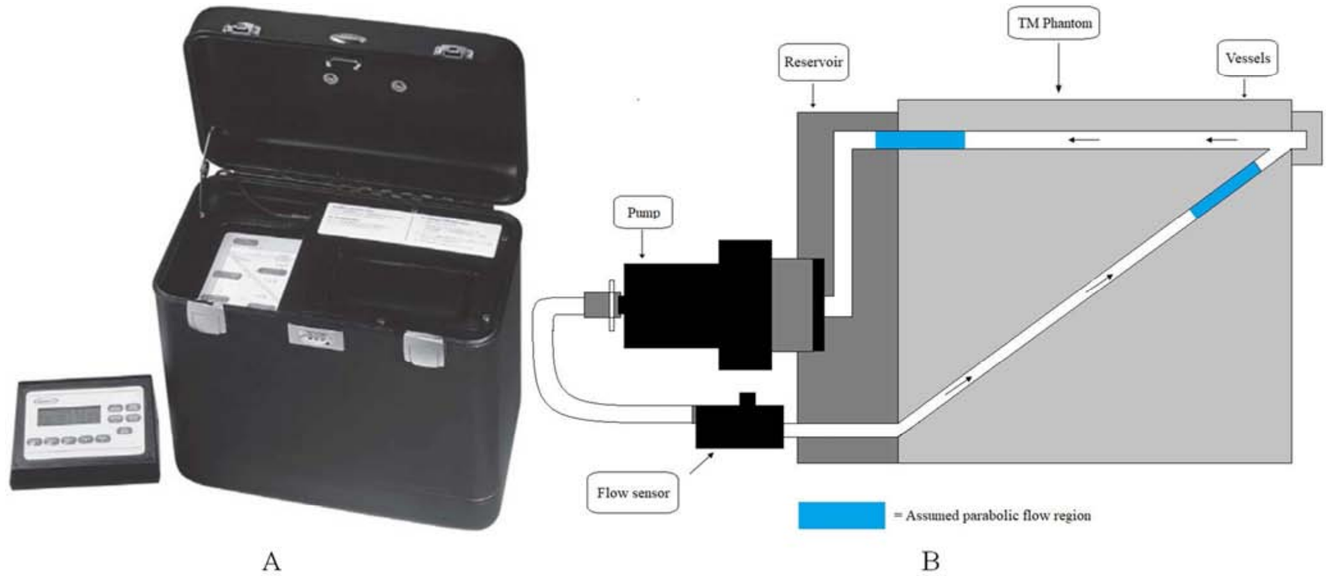


Figure 1. *The Gammex 1425A used for the acquisitions (1a) and its scheme (1b). 1b shows the zones where the flow is assumed to be parabolic by the manufacturer.*

Table 2. *The Gammex 1425A specifications as certified by the manufacturer.*

Tissue Mimicking Background Material	
Speed of sound	1540 ± 10 m/s (22°C)
Attenuation coefficient	0.7 ± 0.05 dB/cm/MHz 0.5 ± 0.05 dB/cm/MHz
Tissue Mimicking Blood Material	
Speed of sound	1550 ± 10 m/s
Density	1,03 g/cc
Particle diameter	4,7 µm
Particle concentration	20 mg/liter
Total Volume	approx. 200 ml
Viscosity	3.8×10^{-3} Pa s
Vessel	
Speed of sound	1550 ± 10 m/s
Density	1,03 g/cc
Diameter	5 mm
Wall thickness	1,25 mm

Measurements were obtained at three continuous flow rates of 3.2, 7.2 and 12 ml/s (estimated Reynolds numbers of 237, 474.5 and 720; estimated velocities 35, 70, and 106 cm/s, respectively). In this first study, we decided to only focus on continuous flow, to compare the performance of the two new Doppler techniques in the most basic flow setting. This study was exempt from obtaining institutional ethical approval and informed consent.

Based on the signal environment allowed by the phantom, a limited number of measurements obtained by fixing the probe on the phantom with a dedicated holder are usually considered sufficient for the performance estimation. To evaluate any bias occurrence that could also affect clinical performance, we decided to include the intra-observer analysis by avoiding the use of a probe-holder. Ten measurements were performed for each reference velocity for a total of 180 datasets. These measurements were performed using the different systems when analyzing the PW technique and using different techniques (PW vs. UFCD vs. HiFR-VF) to obtain significant statistical samples. All the acquisitions and measurements were obtained by A. G., a radiologist with more than 25 years of experience with performing vascular US examinations. In this study, we excluded the inter-operator variability analysis usually considered in clinical evaluations. All analyses were recorded in a raw data format for further evaluations. In particular, retrospective spectrum derivation, angle correction and TAmax calculations for each UFCD acquisition, and TAmax calculation on a selected region of interest (ROI) were processed retrospectively on the stored video clips for each HiFR-VF acquisition.

2.1. UFCD Technique

A series of UFCD acquisitions were obtained at a pulse repetition frequency (PRF) of 15 kHz. A 3-second acquisition time among the three available times (2-3-4 seconds) was selected. There is no change at all in the UFCD acquisition among the three times, except the duration. The Aixplorer allowed a maximum of a 20° steering angle of the CD-region-of-interest (ROI), which was compensated by a 10° probe tilting. On the stored videoclips, a 5 mm axial length sample volume covering the tube diameter was further added at the flow level by positioning the cursor in the midline of the CD-ROI. A spectrum was automatically derived from the retrospective processing of the ultrafast raw data. At the same time, a Doppler angle compensation of 60° was applied to resolve the Doppler equation (Figure 2).

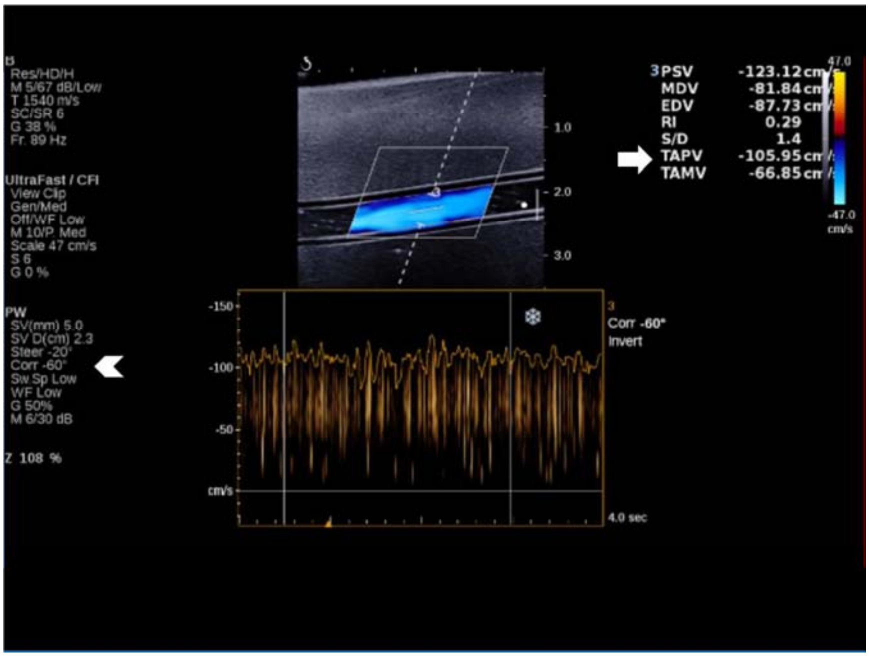
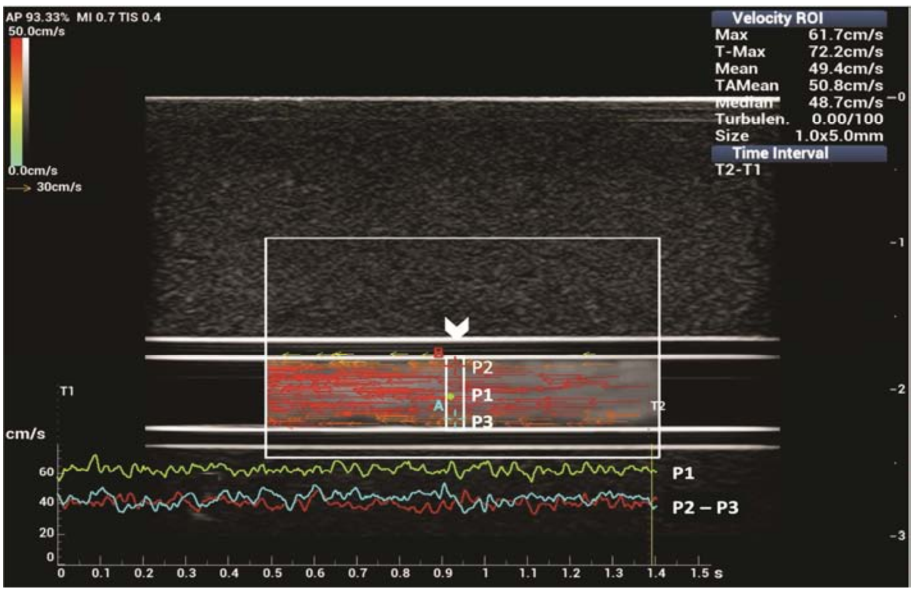


Figure 2. UFCD velocity estimation of a continuous parabolic flow moving at 106 cm/s. In the top, the UFCD map with a 20° CD-box steering angle and a 10° probe tilting angle. In the bottom, the spectrum derived from the retrospective processing of the ultrafast.

2.2. HiFR-VF Technique

For the HiFR-VF, the flow was analyzed over the selected VF-ROI by performing the multidirectional transmission and reception of plane waves with a total PRF of 15 kHz and a frame rate of 600 Hz for 1.5 seconds (the acquisition time defined by the manufacturer). The obtained data were processed by the system, generating a sequence of 900 images, displayed on a 36-second duration videoclip at a frame rate of 25 Hz for further analysis. HiFR-VF detects the speed and direction of all scatterers flowing through every point of the evaluated ROI and uses arrows indicating the flow direction. The length and color of the arrows indicate the velocity magnitude.

The qualitative evaluation of the flow behavior was allowed by analyzing spatiotemporal flow characteristics on the videoclips (Video 3). We particularly evaluated whether the flow profile was well developed for the entire duration of the acquisition, verifying that the vectors at higher speed would be steadily visualized in the central part of the lumen and that lower velocity vectors would slide along both walls of the tube. The quantitative evaluation of flow profiles was obtained retrospectively by measuring the point velocity in the center of the vessel and near the two boundaries (Figure 3a). The TAmax velocity estimation was obtained by setting an adjustable ROI (sample volume of 5 × 1 mm) to cover the tube diameter (Figure 3b).



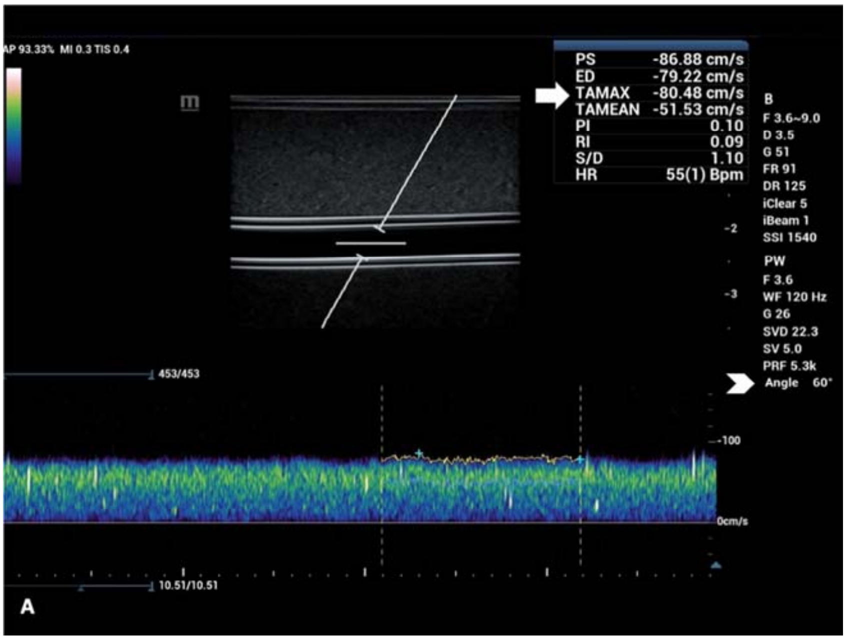
A

B

Figure 3. *HiFR-VF of a continuous laminar flow moving at 70 cm/s. Frames extracted from the 900 images of two cine loops acquired in 1.5 seconds. In the top, the velocity ROIs (arrowhead) positioned over the vessel for the flow quantification. a) Flow profile evaluation. In the bottom, three velocity curves are displayed over time. The green curve corresponds to the maximum velocity measured at a single point in the center of the vessel (P1). The red and light blue curves represent the low velocity flow in the two single points near the boundaries (P2-P3). The velocity curves suggest a well-developed flow profile and show how the instant velocity (time interval about 1.6 msec) varies for the three single points over time (1.5 sec), thus highlighting the variations in the 2D velocity vectors. (The full clip is available as Video 3). b) Velocity estimation. In the velocity ROI, the maximum velocity point (green dot) is automatically detected by the system. Contrary to common belief, this point does not necessarily correspond with the center of the vessel lumen because the flow profile in a real environment is unstable. Moreover, it is not certain that the flow will experience a perfect axisymmetric shape. A time-averaged peak velocity of 70.1 cm/s was measured (arrow).*

2.3. PW Technique

For all the systems, the flow in the PW mode was analyzed with focused waves. The beam direction was the same as the flow direction. PW measurements were performed with a steering angle of 30°, allowed by both Resona 7 (Figure 4a) and MyLab 9 (Figure 4b) systems. Aixplorer allowed a maximum of a 20° steering angle, compensated by a 10° probe tilting (Figure 4c). A correction angle of 60° between the US beam and the tube axis was applied to the stored images in order to obtain measurement accuracy, as explained in the previous section.



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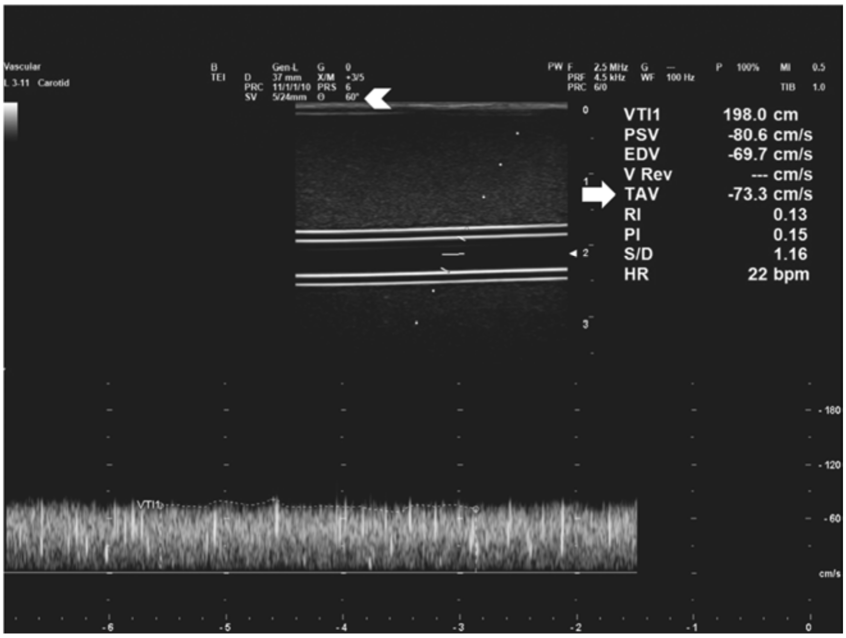

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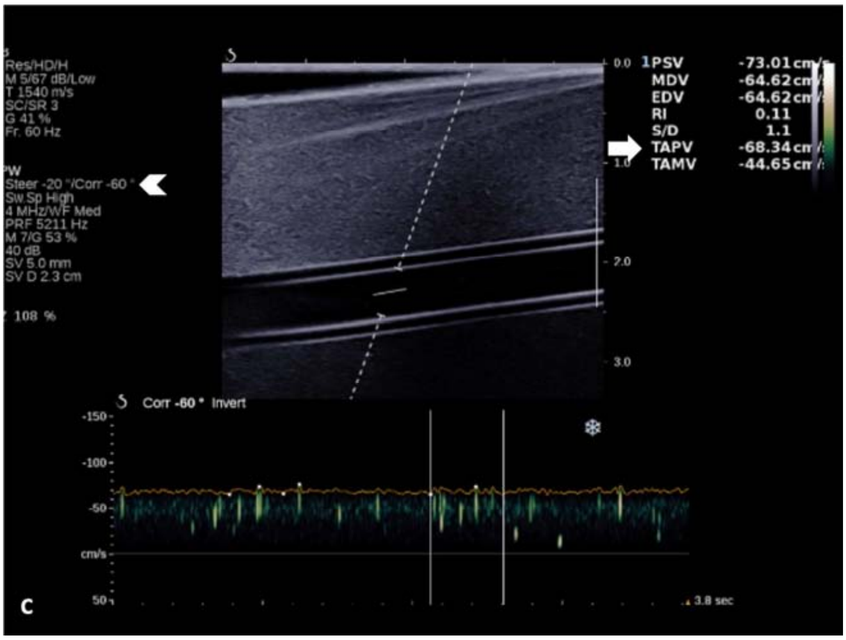

C

Figure 4. *PW velocity estimation with three different systems using focused waves of flow moving at 70 cm/s. a) Resona 7 (probe L9-3U) system: spectral Doppler analysis obtained with a US beam steering angle of 30°. b) MyLab 9 system: spectral Doppler analysis obtained with a US beam steering angle of 30°. c) Aixplorer system: spectral Doppler analysis obtained with a US beam steering angle of 20° and a 10° probe tilting angle. In all measurements, a Doppler angle compensation of 60° was applied (arrowhead). In these single measurements displayed in the pictures, time-averaged peak velocities of 80.48, 73.3, and 68.34 cm/s were measured, respectively (arrow).*

2.4. Velocity Measurements

By considering the continuous characteristics of the steady flow in our study, the different acquisition time applied for the three different techniques does not affect the measurement performance. The performance of systems and techniques was evaluated by comparing the nominal peak phantom velocities with the time-averaged peak velocity values (TAmax). TAmax was automatically measured by the systems on the acquired spectrum for the PW technique and on the retrospectively derived spectrum for the UFCD. In the case of HiFR-VF, the TAmax was obtained retrospectively with a postprocessing tool available on the system. The system automatically detects the maximum velocity point in a selected ROI, independently from their position, and displays the related velocity curve over time (Figure 3b).

Since the phantom manufacturer does not certify a reference value for the time-averaged mean velocity (TAmean), this parameter was not evaluated. Moreover, the instant mean velocity is averaged on space (i.e., sample volume) and is affected by the flow profile development and by the temporal front wave variations and, as a consequence, it does not represent a reliable measure for the study purpose.

2.5. Statistics

The normal distribution of the measures in the samples was verified with the D'Agostino-Pearson t-test. The paired sample t-test was performed by comparing two samples at a time to evaluate if the velocity estimations from the various techniques were comparable. The accuracy of the velocity estimation was evaluated by comparing the mean bias and the mean relative bias to the actual velocity. The paired sample t-test was used to compare the mean relative bias. The precision was investigated by calculating the standard deviation (SD) (the F-test was used for the standard deviations). Moreover, the error factor (EF) and coefficients of variation (CV%) were calculated.

The mean relative biases were compared among the different systems (PW) and techniques (PW vs UFCD vs HiFR-VF) by repeated measures analysis of variance (ANOVA).

The analysis was carried out with MedCalc statistical software version 18.2.1 (MedCalc Software bvba, Ostend, Belgium).

3. Results

The parameters evaluated to assess the performance of systems and techniques in the velocity estimation are summarized in Table 3.

3.1. PW: System Comparison

Comparing the systems for estimating PW velocities, the paired sample t-test showed that the velocity measurements provided significantly different mean velocities and mean relative biases ($p<0.0001$), at almost all three selected velocities. Only Aixplorer and the Resona 7 probe L9-3U at 35 cm/s (38.73 and 39.05 cm/s, $p=0.26$) and both probes of Resona 7 at 106 cm/s (117.89 and 118.73 cm/s, $p=0.23$) were not significantly different. MyLab 9 was the most accurate, with a lower relative bias at all flow velocities than the other systems, even if it increased with velocity (-1.14%, 3.76%, -10.93%).

The SDs (Table 2) were similar for the two Resona 7 probes at 35 cm/s (0.80 vs. 0.53, $p=0.24$) and 70 cm/s (0.53 vs. 0.33, $p=0.17$), while for 106 cm/s, the L11-3U is more precise with respect to L9-3U (SD 0.71 vs 1.83, $p=0.01$). Additionally, Aixplorer and MyLab 9 had similar precision values at 35 cm/s (0.25 vs. 0.25, $p=1.00$) and 70 cm/s (1.56 vs. 1.41, $p=0.77$), while at 106 cm/s, MyLab 9 showed the worst precision (1.91 vs. 3.93, $p=0.04$). Notably, the precision decreased with velocity both for Aixplorer and MyLab 9, while it was constant for each probe of Resona 7 (Table 3).

Table 3. *Parameters assessing the performance of different systems and techniques in the velocity estimation, based on 10 repeated measurements at three peak velocities for parabolic flow (35, 70, and 106 cm/s).*

		Mean ± SD (CV%) [EF]	Velocity bias (%)
35 cm/s			
PW	*Aixplorer*	38.73 ± 0.25 cm/s (0.64%) [1.01]	3.73 (10.66%)
	Resona 7 probe L9-3U	39.05 ± 0.80 cm/s (2.05%) [1.02]	4.05 (11.57%)
	Resona 7 probe L11-3U	37.88 ± 0.53 cm/s (1.4%) [1.03]	2.88 (8.23%)
	MyLab 9	34.60 ± 0.25 cm/s (0.72%) [1.00]	-0.40 (-1.14%)
UFCD	*Aixplorer*	36.06 ± 1.14 cm/s (3.17%) [1.04]	1.06 (3.03%)
HiFR-VF	*Resona 7 probe L9-3U*	35.06 ± 0.44 cm/s (1.26%) [1.02]	0.06 (0.17%)
	Resona 7 probe L11-3U	35.61 ± 0.47 cm/s (1.31%) [1.02]	0.61 (1.74%)
70 cm/s			
PW	*Aixplorer*	69.70 ± 1.56 cm/s (2.24%) [1.04]	-0.30 (-0.43%)
	Resona 7 probe L9-3U	82.11 ± 0.53 cm/s (0.65%) [1.01]	12.11 (17.3%)
	Resona 7 probe L11-3U	79.49 ± 0.33 cm/s (0.42%) [1.01]	9.49 (13.56%)
	MyLab 9	72.63 ± 1.41 cm/s (1.94%) [1.03]	2.63 (3.76%)
UFCD	*Aixplorer*	71.13 ± 1.80 cm/s (2.53%) [1.04]	1.13 (1.61%)
HiFR-VF	*Resona 7 probe L9-3U*	69.81 ± 1.38 cm/s (1.98%) [1.03]	-0.19 (-0.27%)
	Resona 7 probe L11-3U	71.49 ± 0.97 cm/s (1.36%) [1.02]	1.49 (2.13%)
106 cm/s			
PW	*Aixplorer*	127.00 ± 1.91 cm /s (1.50%) [1.01]	21.00 (19.81%)
	Resona 7 probe L9-3U	117.89 ± 1.83 cm/s (1.56%) [1.03]	11.89 (11.22%)
	Resona 7 probe L11-3U	118.73 ± 0.71 cm/s (0.60%) [1.01]	12.73 (12.01%)
	MyLab 9	94.41 ± 3.93 cm/s (4.16%) [1.06]	-11.59 (-10.93%)
UFCD	*Aixplorer*	107.87 ± 2.06 cm/s (1.91%) [1.03]	1.87 (1.76%)
HiFR-VF	*Resona 7 probe L9-3U*	102.87 ± 1.34 cm/s (1.30%) [1.02]	-3.13 (-2.95%)
	Resona 7 probe L11-3U	108.12 ± 1.44 cm/s (1.33%) [1.01]	2.12 (2.00%)

Error factors did not vary at the various velocities ($p>0.05$); only MyLab 9 showed a worsening in EF at increasing velocities ($1.00<EF<1.06$), as previously highlighted.

To obtain a comprehensive view of which systems performed better regardless of the velocity, the mean relative bias and the 95% confidence interval (CI) of all velocities are reported in Figure 5, and their values are summarized in Table 4. MyLab 9 is on average the most accurate system, as it had the lowest mean relative bias, even if its 95% CI is the highest one. For the two transducers of Resona 7, it can be seen that the L11-3U probe had better accuracy than the L9-3U probe (11.27% vs. 13.37%), while the precision did not differ significantly (0.45 vs. 0.60, p=1.00).

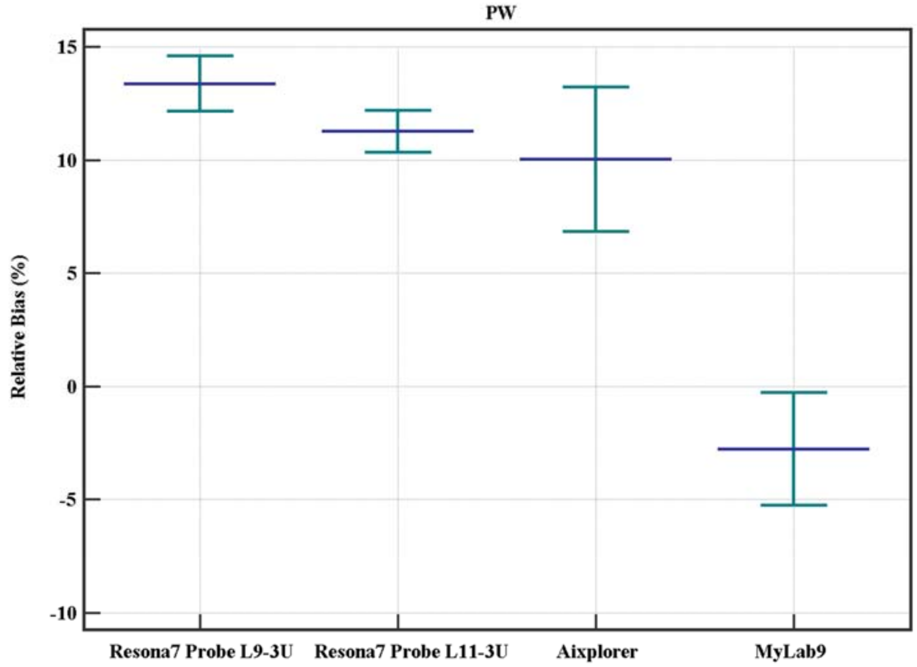

Figure 5. *Parameters assessing the performance of different systems and techniques in the velocity estimation, based on 10 repeated measurements at three peak velocities for parabolic flow (35, 70, and 106 cm/s).*

Finally, it should be noted that the CV% values over the ten repeated measurements were regularly <5% for all techniques and velocities (Table 3); this result may indicate that the velocity biases were related more to the methods' intrinsic differences than to operator variability. The Mean relative error between UFCD and HiFR-VF and PW favors the new techniques, thus suggesting that the missed inter-operator variability probably doesn't affect the final results. Our findings can be considered relevant enough without the inter-operator variability.

Table 4. *Comparison among systems implementing PW, and between UFCD and HiFR-VF techniques.*

	Mean relative error (%) [min-max]	SD	EF
System comparison (PW)			
Aixplorer	10.02 [-2.40 - 21.75]	1.57	1.02
Resona 7 probe L9-3U	13.37 [6.14 - 18.50]	0.60	1.02
Resona 7 probe L11-3U	11.27 [6.57 - 14.49]	0.45	1.02
MyLab 9	-2.77 [-16.42 - 7.14]	1.21	1.03
UFCD and HiFR-VF techniques			
UFCD	2.14 [-2.63 - 6.89]	0.48	1.04
HiFR-VF probe L9-3U	-1.02 [-5.00 - 3.57]	0.37	1.02
HiFR-VF probe L11-3U	1.96 [-0.19 - 4.71]	0.24	1.02

3.2. UFCD and HiFR-VF: Comparison of Techniques

The UFCD and HiFR-VF (both probes) techniques were compared. From the data in Table 3, the mean velocities and relative biases were not significantly different considering UFCD and HiFR-VF performed with the L9-3U probe at all three velocities (p>0.36); however, both Resona 7 probes, as well as the probe L11-3U compared with UFCD, did not provide equivalent results (p<0.05).

The precision (SD) did not differ (p>0.05) at 70 and 106 cm/s, while it did at 35 cm/s (p<0.05, for both probes), with HiFR-VF more precise than UFCD. Indeed, at each velocity, UFCD provided the worst precision. Notably, the SD of UFCD and HiFR-VF with the L11-3U probe increased with increasing velocity (R^2=0.94 and R^2=0.99, respectively); the precision of HiFR-VF with the L9-3U probe decreased as the velocity varied from 35 cm/s to 70 cm/s and then remained approximately constant (R^2=0.71).

It must be emphasized that EF was slightly higher for UFCD, confirming that its precision was worse than that of HiFR-VF. Nonetheless, no trend with increasing velocity was observed.

The graph reported in Figure 6 shows that HiFR-VF with the L9-3U probe gave, on average, the most accurate results in comparison to UFCD and HiFR-VF with the L11-3U probe. Consequently, the L9-3U probe exhibited better accuracy in comparison to the L11-3U probe (Table 4), while the precision did not differ significantly (p=1.00).

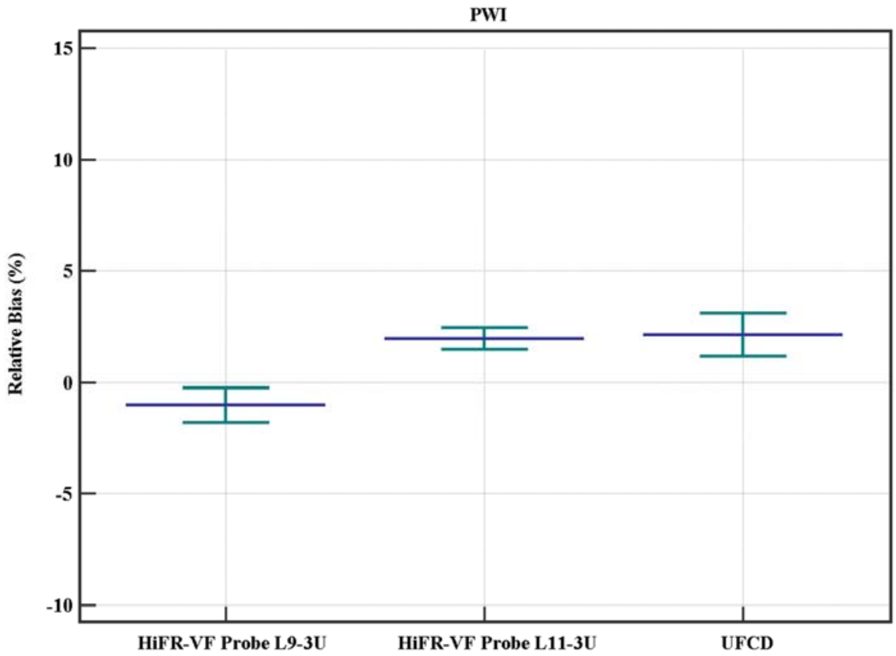

Figure 6. *Comparison of the mean relative biases and 95% CI for the UFCD and HiFR-VF techniques. HiFR-VF (with probe L9-3U) performed better, between the two new techniques (-1.02%).*

The frame-by-frame qualitative analysis of the streamline flow behaviors allowed by HiFR-VF confirmed the expected laminar flow at the different flow rates. The fluid near the boundary has been shown to move at low velocity, thus confirming a well-developed flow profile at the measured site in all the series (Figure 3a).

3.3. Overall Comparison of UFCD, HiFR-VF and PW

To compare the three techniques, the overall mean relative differences regardless of the velocity estimation of the best-performing systems, such as Aixplorer for UFCD, Resona 7 - L9-3U probe for HiFR-VF, and MyLab 9 for PW, were considered (Table 4). In Figure 7, it can be stressed that PW underestimated the real velocity and had a larger CI in comparison to both UFCD and HiFR-VF. UFCD and HiFR-VF slightly overestimated the correct velocity, and HiFR-VF had the best accuracy and precision overall.

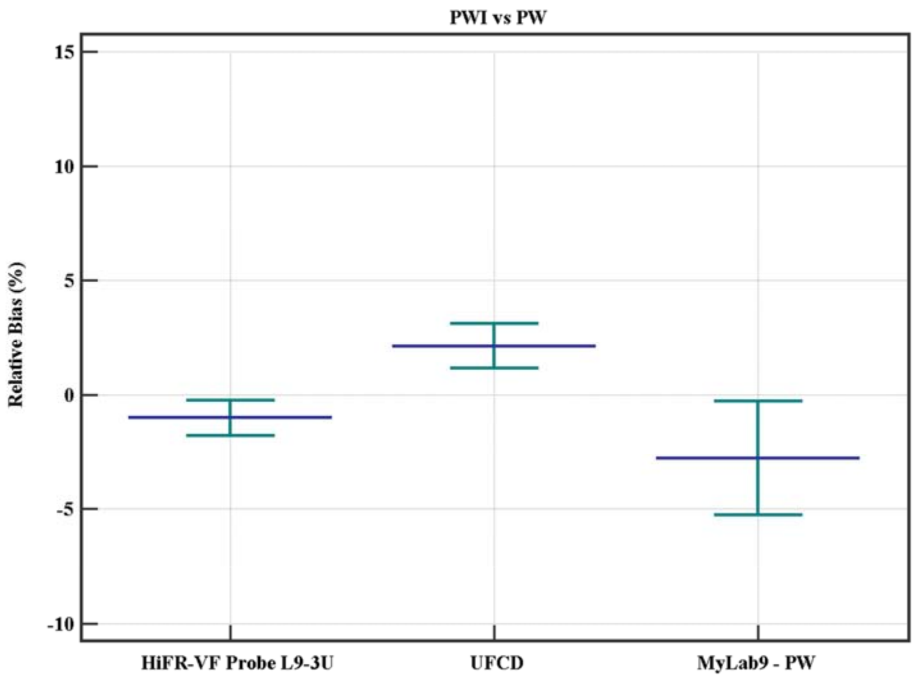

Figure 7. *Comparison of the mean relative biases and 95% CI for the UFCD, HiFR-VF, and PW techniques. HiFR-VF (with probe L9-3U) performed better than UFCD and the best performing PW system.*

4. Discussion

Before analyzing UFCD and HiFR-VF performance, our study evaluated the accuracy of the PW reference technique. The comparison of different systems in the assessment of the TAmax showed a mean relative bias within ±20% (maximum range of relative errors from -10.93% to 19.81%), suggesting a possible limitation in the velocity estimation. Aixplorer showed better performance for 70 cm/s in comparison to the 35 and 106 cm/s, thus resulting in non-uniform biases. This finding is unrelated to the system, which obviously always applies the same formula, but is probably due to the inherent fault of each measurement multiplied for the number of measurements executed by manually handling the probe. In this case, the error measurement might have been further influenced by the necessity to compensate the maximum steering angle of merely 20°, available on the Aixplorer, with a 10° probe tilting. Yet this difference does not influence the overall results as the Mean relative error favors UFCD and HiFR-VF techniques. The overall findings can be explained by considering that the maximum flow velocity measurements using PW are typically assessed from the Doppler spectrum by locating the highest frequency detectable from noise [18]. Moreover, despite the ability to identify a laminar and disturbed flow, PW does not take into account the transverse velocity component of the 2D velocity vectors. This component may vary in laminar flow depending on the nonlinear pressure exerted by the flow controller of the phantom, even in continuous flow rates. This variation results in a spectral broadening and in the oscillating shape of the Doppler spectra, which may influence the velocity estimation.

Our results are aligned with those of previous studies in which an overestimation of velocities was observed with PW. In particular, a study on the PW estimation of maximum velocity using six Doppler US systems showed that the flow velocity in a straight vessel is usually overestimated in all cases (0%-29% error); it was reported that maximum velocity errors ranged from -4% to 47% for all measurements [19]. Moreover, the peak velocity estimation with PW was limited by the manual angle correction, causing high inter-observer variability [5]. With a traditional approach, the flow velocity was underestimated when the beam sweeping direction was opposite the flow direction and was overestimated when the beam sweeping direction was the same as the flow direction [20].

The different performances among the systems and probes (L11-3U versus L9-3U) in our study could be related to the beam geometry transmitted in the focus zone and to the frequency bandwidth, respectively. Since the US beam is usually transmitted into the sample volume from a finite aperture, the Doppler angle does not correspond to the cursor axis displayed but includes a range of angles, resulting in a higher measured velocity than that expected from the flow conditions when a larger aperture is applied. The better performance obtained by MyLab 9 might be related to a narrow beam emitted by the system during the PW acquisition.

UFCD, which estimated the velocity values with a maximum bias of 3.03%, showed the advantages of a high frame rate and the compound-based Doppler technique, which provides flow images at a high temporal resolution and performs accurate quantifications of the flow velocities. UFCD overperformed PW on the same system (mean relative bias of 2.13% for UFCD vs. 10.01% for PW), thus confirming the theoretical power of the ultrafast Doppler technique. However, UFCD also determines a reduction of the PRF, which represents a limitation in high-velocity flows. Due to the lack of other reference papers regarding UFCD, previously published on this item, a literature comparison cannot be made.

The limitations of CDUS explain why efforts have been made to create an angle-independent vector velocity US system capable of measuring vector flow [21-23]. Various methods of estimation have been tested in vitro and sometimes in vivo, demonstrating that vector flow can be used to generate spatial maps of the velocity vectors and to highlight complex flows [7, 11, 24, 25].

The higher precision of vector flow imaging (VFI) based on the transverse oscillation (TO) method compared to conventional methods performed in vivo has previously been reported [26-29]. Despite these premises, a recent study comparing PW and VFI-TO in a phantom at a constant flow velocity of 60.3 cm/s showed a higher accuracy for PW (an average accuracy of 1.7% vs. 5.5%) at four angle positions. VFI underestimated the peak velocity at all but one angle position, i.e., at 60°, which corresponds to the angle used in our study. A relative bias of 3.5% for VFI-TO vs. 0.3% for PW was found. Although the two techniques measured different mean peak velocities at four angle positions, the SDs did not differ significantly, and a similar precision was found [30].

Another study, based on the same TO method, examined the precision of replicated velocity measurements in a phantom with a beam-to-flow angle of 90° for constant and pulsatile flow and showed a strong systematic bias for increasing flow velocities [31]. In contrast to the in vitro studies, a recent in vivo study showed that VFI-TO is more accurate in estimating the peak systolic velocities in a common carotid artery (CCA) compared with PW when magnetic resonance imaging (MRI) was used as a reference [32]. In particular, VFI-TO was more precise than PW in both CCAs, and the correlation between VFI-TO and MRI was slightly higher than the correlation between PW and MRI.

The use of fast plane wave imaging (PWI) was suggested by Jensen et al. to overcome the limitations of the TO method [33]. These researchers combined TO and directional beamforming (DB) based on PWI to analyze a parabolic flow (peak velocity of 0.5 m/s) in straight vessels at beam-to-flow angles from 45° to 90°. The velocities were estimated accurately with a bias of less than 3% for both TO and TO-

DB, and a reduction in SD from 5.7% to 1.1% was found for the 60° beam-to-flow angle, when using TO-DB rather than only TO. However, these authors also reported that TO-DB underestimated the velocities for flow transverse to the US beam.

In our study, HiFR-VF performed better than UFCD and PW at all three velocities, the maximum percentage differences ranging from -2.95% to 2.13%, with the exception of the high TAmax in which UFDC has a lower velocity bias, probably due to the number of plane waves applied for the multiangle transmission and reception by HiFR-VF, i.e. aliasing issue. In general, HiFR-VF had the lowest mean relative errors, resulting in the most accurate and precise technique. This behavior may be explained by the fact that HiFR-VF detects the speed and direction of all scatterers flowing through every point of the ROI exploiting a multiangle approach; in contrast, PW detects the velocity distribution from a fixed angle in a defined sample volume. Moreover, HiFR-VF allows dynamical visualization of all the flow events by showing transient phenomena, which would not be detected otherwise [14]. The slightly different and nonuniform findings between the two linear probes on the same system could be related to the different frequency bandwidths and probe tuning.

In general, the precision result of HiFR-VF is aligned with the findings of previous studies that determined the reproducibility of the vector technique [34]. Some different findings between our study and a previous study [30] that compared VFI-TO with PW may be related to the different acquisition techniques. In fact, in the VFI-TO method, the axial velocity component is obtained as in a conventional velocity estimation, whereas the transverse velocity component is found by changing the apodization of the receiving elements and through a particular estimator [8]. In contrast, in the HiFR-VF method, the axial and lateral components of the flow vectors are derived from the multiangle Doppler analysis principles. This fact allows for a robust estimation by solving an overdetermined system of linear equations, based on least-squared fitting principles, which effectively increase the total number of independent frequency shift estimations [12].

Two other studies were performed with an in vitro investigation to provide quantitative velocity flow measurements using a different HiFR US imaging technique based on a research platform configured to acquire plane wave images. The accuracy of the velocity at different flow rates in steady and pulsatile flow was estimated [35, 36]. This technique was a noninvasive tool to quantitatively measure the spatiotemporal velocity, thus providing a sensitive, accurate and full field of view velocity measurement. A coherent comparison between these studies and our study cannot be performed due to the different study designs and parameters applied. However, their conclusions are in accordance with our UFCD and HiFR-VF findings.

The limitations of our study are the inclusion of operator errors, such as the subtle beam flow angle alignments and deviations of the sample volume from the center of the tube, which can cause a decrease in the measured flow velocity. An angle error of only ±2° at a 60° correction angle can result in a ±6% error in the velocity estimate for PW, which was not included in the phantom study [1]. However, these errors are always present during clinical examinations. Other limitations are the use of only a steady flow and not a pulsatile flow, which will be part of a further study, and the comparison at a fixed angle of 60° between the US beam and the tube axis for PW and UFCD. Moreover, very high-velocity flow, highlighting the inherent limitation of the plane wave techniques, was not considered. The sample size for the velocity measurements was set to a length of 5 mm to comprise the entire tube lumen diameter for all the techniques considered. However, the axial sample size differs among different systems and techniques, which may slightly affect the spectral broadening and consequently, the velocity values.

5. Conclusion

Two promising ultrasound techniques, UFCD and HiFR-VF, both based on high frame rate and compounding technique, have been recently introduced in the market. These methods allow to overcome the limitation of the CDUS, such as the angle dependence and the limited frame rate. HiFR-VF also provides the visualization and quantification of velocity vectors in all directions. Their performance must be compared with the conventional PW one through a well-controlled phantom study to evaluate the clinical implications of these technologies. For this reason, the accuracy and the precision of PW, UFCD and HiFR-VF have been assessed and compared in laminar and continuous flow at three different velocities. The TAmax measured with the PW showed a mean relative bias higher respect to the ones obtained with UFCD and HiFR-VF. This result is due to the ability of UFCD and HiFR-VF to analyze the flow at any angle with a higher temporal and spatial resolution by using many data points, which allows to retrospectively measure the flow velocity with high accuracy. However, the HiFR-VF technique showed better performance compared to PW and UFCD, which are angle-dependent. This result may be due to HiFR-VF angle independence, which eliminates the bias from the operator performing the Doppler angle setting. The HiFR-VF performance is probably the result of the plane wave multidirectional transmission and reception scan sequence, employed to measure each velocity vector component, which may have affected the positive results.

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