Coupling Myocardium and Vortex Dynamics in Diverging-Wave Echocardiography

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***Abstract*— Echocardiography is widely used to provide critical left ventricular indices describing myocardial motion and blood inflow velocity. Tissue motion and blood flow are strongly connected and interdependent in the ventricle. During cardiac relaxation, rapid filling leads to the formation of a vortical blood flow pattern. In this paper, we introduce a high-frame-rate method to track vortex dynamics alongside myocardium motion, in a single heartbeat. Cardiac triplex imaging (B-mode + tissue Doppler + color Doppler) was obtained by insonating the left ventricle with diverging waves. We used coherent compounding with integrated motion compensation to obtain high-quality B-mode images. Tissue Doppler was retrieved and the septal and lateral velocities of the mitral annulus were deduced. A rate of ∼80 triplex images/s was obtained. Vortex dynamics was analyzed by Doppler vortography. Blood vortex signature maps were used to track the vortex and compute core vorticities. The sequence was implemented in a Verasonics scanner with a 2.5-MHz phased array and tested *in vivo* in 12 healthy volunteers. Two main peaks appeared on the vorticity curves. These peaks were synchronized with the mitral inflow velocities with a small delay. We observed a relationship between the tissue and vortex waveforms, though also with a delay, which denoted the lag between the wall and the flow motion. Clinical diastolic indices combining basal and mitral inflow velocities (E/A ratio and E/e' ratio) were determined and compared with those measured using a conventional ultrasound scanner; a good correlation was obtained ($r^2 = 0.96$). High-frame-rate Doppler echocardiography enabled us to retrieve time-resolved dynamics of the myocardium and vortex flow within the same cardiac cycle. Coupling wall-flow analysis could be of clinical relevance for early diagnosis of filling impairment.**

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I. Introduction

ECHOCARDIOGRAPHY is the most widely used cardiac imaging modality owing to its low cost and high accessibility. It is the only technique that allows real-time imaging and analysis of the myocardium and blood motion. Information obtained from the mitral inflow is extensively used by clinicians to assess diastolic function [1]. Examination of the intraventricular vortex dynamics has also been shown to potentially be of clinical relevance for diastology [2], [3]. This vortex forms during early diastole and is reactivated by the atrial contraction during late diastole [4]. Since the intracavitary blood flow pattern is most likely sensitive to small geometric or dynamical changes, any impairment in filling can significantly impact the vortical arrangement [5], [6]. Quantifying the intracardiac vortices could thus lead to clinical clues for an early diagnosis of diastolic function [7]. It is indeed well accepted that the cardiac wall dynamics and intraventricular flow are interconnected [5]. A disturbance of this interdependence can denote a cardiac dysfunction. By way of example, the combination of the mitral inflow velocity and the mitral annulus tissue Doppler is commonly used during an echocardiographic examination [1], [8]. We likewise hypothesized that joining wall motion data with quantitative information on the vortices could be of clinical interest.

To retrieve indices related to the myocardium wall and intracardiac flow, an echographer must complete distinct ultrasonographic examinations: 1) tissue Doppler imaging (TDI) to evaluate mitral annulus velocities and/or myocardial strains; 2) color Doppler imaging (CDI) to visualize intracardiac blood flows; and 3) pulsed-wave Doppler (PWD) to get the mitral inflow velocities. In clinical practice, these modalities cannot be joined into one single acquisition due to the limited frame rate of conventional echography. Not only these separate acquisitions make the examination longer, but it may also add some bias due to heart beat variation when it comes to mix blood and tissue indices. To complicate matters, CDI is a duplex modality which requires interleaving B-mode and Doppler scans. In conventional duplex transthoracic echocardiography, the left ventricle cannot be scanned at image rates greater than 10 to 20 fps. This typically yields 7 to 15 frames/heart cycle for an average 80-bpm subject, which is much too low to decipher the whole diastolic

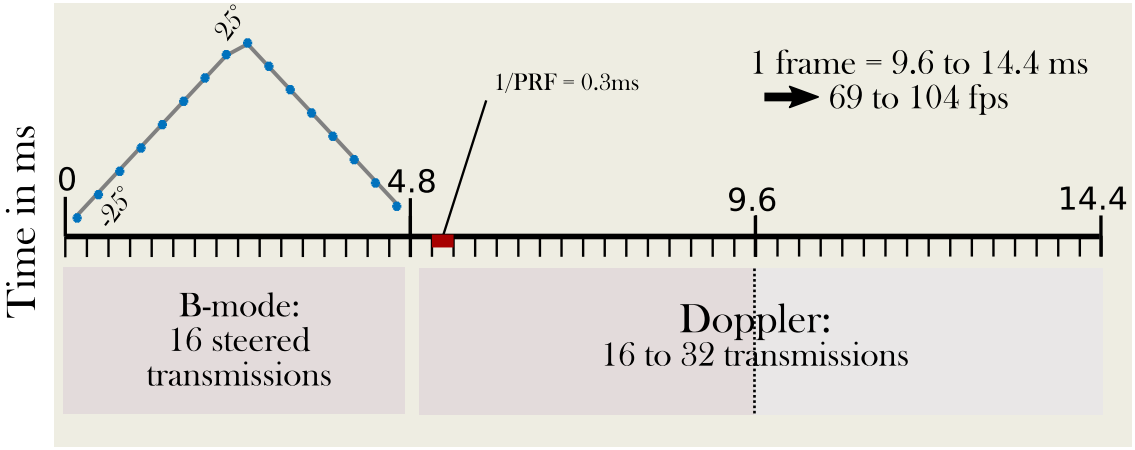

Fig. 1. Timing of the triplex sequence.

blood flow in a single heartbeat. As clinical routine would ideally require simultaneous real-time imaging of these above-mentioned modalities, high-frame-rate echocardiography could be an appropriate solution to address these issues. Ultrafast ultrasound imaging already opened the possibility of multiple modes, for example, in: 1) blood flow analysis with local spectral analysis in addition to color Doppler [9]; or 2) simultaneous quantification of blood flow and arterial wall in the carotid [10]. Several methods have been introduced [11] to reach high frame rates in cardiac ultrasound imaging: the multiline transmit approach [12], [13] and the transmit of plane or circular waves [14]–[17]. In a previous work, we implemented a high-frame-rate Doppler sequence for vortography, i.e., for the analysis of the vortical patterns in the left ventricle [18]. By transmitting wide circular waves, we reached frame rates enabling time-resolved investigation of diastolic core vorticities. In this study, we used a multimodal ultrasound sequence to retrieve myocardial tissue motion alongside intracardiac blood flow dynamics. These sequences allowed us to produce synchronized high-quality B-mode and tissue Doppler images [17], in addition to color Doppler fields. An image rate of ∼80 images/s could be attained with this triplex (an extension of the so-called duplex imaging with B-mode + TDI + CDI) modality. To quantify the vortex dynamics from CDI, we detected the vortex cores by using Doppler vortography and determined the core vorticities during diastole. From this time-resolved triplex imaging, we also derived standard cardiac indices from mitral annulus motion (e', a', and S' peak velocities) and mitral blood inflow (E and A) in a single heartbeat.

II. Methods

A. High-Frame-Rate Triplex Imaging

The ultrasound data were acquired with a Verasonics scanner (V-1-128, Verasonics Inc., Redmond, WA, USA) and a 2.5-MHz phased-array transducer (ATL P4-2, 64 elements, pitch = 0.32 mm). We insonated the left ventricle of 12 volunteers (33 ± 7 y/o) from the apical window with 60° wide diverging waves to acquire three, four, and five-chamber-view images at high frame rates. To assist the clinicians in scanning, we used the real-time beamformed cine loops given by the Verasonics (at low frame rate). We then processed the in-phase and quadrature I/Q components offline. A delay-and-sum approach with integrated motion compensation (MoCo) was applied to generate high-quality compound images of the left ventricle [17]. Briefly, this innovative MoCo method is based on tissue Doppler and adjusts the phase delays induced by the motion of the scatterers. In the MoCo process, the tilt angles of the transmitted wavefronts are organized in a specific triangular arrangement. This ensures the coherent summation of the moving main lobes, while the side lobes are summed incoherently to eliminate their negative effects [17]. MoCo enabled better quality of B-mode diastolic images mostly during active and passive filling. From this technique, both the high-quality B-mode and tissue Doppler images of the whole ventricle were available at a high-frame-rate. In this study, the compounding angles were equally spaced between −25° and 25°, with a triangle arrangement similar to that reported in [17] and a pulse length of two wavelengths at a central frequency of 2.5 MHz. The ensemble size for the B-mode + tissue Doppler images was set to 16. Long pulse (eight wavelength) transmissions were interleaved (without compounding, i.e., tilt angle = 0°) to obtain color flow imaging. The Doppler signals were high-pass-filtered through a principal component analysis [19], using a global method. The cutoff was experimentally fixed at 30% of the greatest energy values. The Doppler packet size was between 16 and 32, depending on the heart rate of the subjects, to approximately obtain a constant intersubject image sampling per cardiac cycle. The Doppler velocities were computed by using a slow-time autocorrelator [20], with a spatial averaging window of 4.5 mm in depth and 1° in width. The acquisition times lasted between 2 and 3 s with a pulse repetition frequency (PRF) set to 3300 Hz. Therefore, a total of ∼10 000 ultrasound transmissions were saved. The triplex images rate was an average of 80 ± 14 fps for all the acquisitions (Fig. 1).

B. Blood Vortex Dynamics

Doppler vortography was used to quantify the intraventricular vortex formation during diastole [21]. This technique

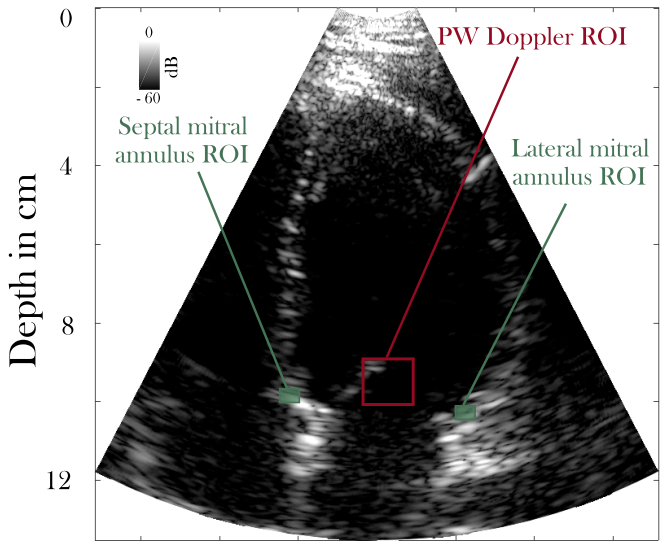

Fig. 2. B-mode of a four-chamber view with selected regions of interest to compute mitral inflow velocities and mitral annulus motion (septal and lateral).

enables location of the main diastolic vortex in a non-scan converted color Doppler image by detecting antisymmetric patterns. High-frame-rate color Doppler sequences returned a series of blood vortex signature (BVS) maps at an average of 80 images/s (depending on the framerate of the sequence). As explained in [18] and [21], BVS reaches an extremum, where a major vortex core exists. Knowing its location, the core vorticity of the vortex can then be derived from the surrounding Doppler velocities [21]. Applying vortography to each color Doppler frame of the diverging-wave sequence yielded evolution of the core vorticity at high temporal resolution.

C. Mitral Annulus Motion

Mitral annulus motion was assessed by high-frame-rate TDI in the same way a physician would do with conventional TDI during a routine echocardiographic examination [22]. Peak Doppler velocities were determined at both the septal (except for three subjects) and lateral annulus during early (e') and late (a') diastolic filling and systole (S') (a total of $9 + 12$ samples). The peak basal velocities were derived by spatially averaging the Doppler velocities within a small region of interest (2.5 mm in depth, 1.5° in width, Fig. 2).The clinical recommendation is to use a sample volume with a gate range of 5–10 mm. We analyzed the basal motion as it returns the only recommended myocardium-based parameter for the evaluation of left ventricular diastolic function [22]. Combining Doppler vortography and TDI in a single ultrasound series thus produced quasi-simultaneous waveforms (with a delay of 4.8 ms) of both the myocardial and vortical dynamics at high frame rates.

D. Mitral Inflow Velocities

To evaluate diastolic dysfunction in echocardiographic routine, clinicians switch to a spectral Doppler mode to measure the mitral inflow peak velocities (E and A, during early and late filling) [22]. With the triplex sequence, we derived these indices by implementing a spectral analysis of the Doppler signals. The mitral inflow region was selected manually on the B-mode images (Fig. 2), similarly as a conventional PWD measurement. Mitral inflow velocities were then deduced by using the clutter-filtered I/Q Doppler series. Because of the interleaved B-mode and Doppler transmissions, the PWD sample sizes were limited to the Doppler packet size between 16 and 32 slow-time samples. Spectrograms were estimated for each packet using a fast Fourier transform (FFT) with a Hamming taper. E and A peaks were finally determined manually from the Doppler spectrograms (Fig. 3). E/A and E/e' ratios were calculated to obtain two markers of diastolic function.

E. In Vivo Study and Comparison Against Conventional Echocardiography

The triplex sequence and vortography processing were tested on 12 healthy volunteers with the Verasonics scanner. This enabled comparing the dynamics of the vortex core vorticity to that of the mitral inflow and mitral annulus (septal + lateral). None of the participants reported cardiac events. In addition to the Verasonics acquisitions, we acquired the mitral inflow velocities and mitral annulus motion by PWD with a Vivid-q scanner (General Electrics, GE, Fig. 3). The acquisitions were performed with a 2.5-MHz phased-array transducer (M4S-RS), at a PRF of 6400 Hz and a window range of 5 mm. The Vivid-q data were synchronized with the Verasonics-derived tissue and color Doppler acquisitions as follows: the T (R) waves of the Vivid-q electrocardiogram were matched with the opening (closing) of the mitral valve, both visible on the B-mode images [23, p. 398]. The Verasonics sequences were all acquired and processed in three different chamber views (3-, 4-, and 5-chamber views). The E- and A-peaks (during early and active filling) of the mitral inflow estimated from the Verasonics acquisitions were compared with those determined with the Vivid-q scanner. The e' (ventricular relaxation), a' (atrial contraction), and S' (systolic) peaks of the mitral annulus were analyzed in like manner. Fig. 4 displays the triplex acquisition for one subject and the blood-tissue derived indexes. The velocity peaks derived by Vivid and Verasonics were compared through a robust linear regression (Theil–Sen estimator). The protocol was approved by the CRCHUM ethic committee and each participant gave a written consent.

III. Results

A. Vortex and Tissue Dynamics

The mitral inflow velocities are known to follow a biphasic waveform related to the ventricular relaxation and atrial contraction (E and A waves) [22]. In concordance with our previous study [18], the maximal vorticity adopted a similar biphasic pattern in healthy subjects. The triplex sequence allowed us to measure the time elapsed between the mitral inflow velocity (E and A) and vorticity peaks (noted Ev and Av). The E- and A-peaks slightly preceded the

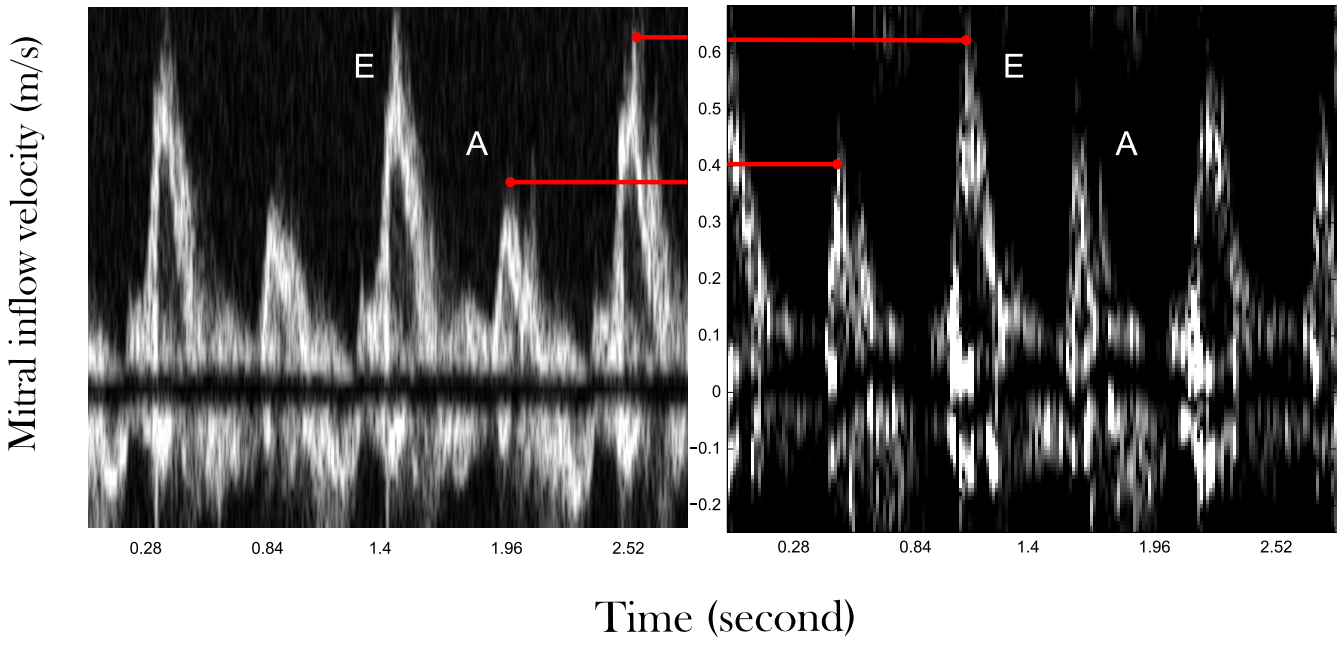

Fig. 3. Conventional PWD [with a GE Vivid scanner (left)] and triplex-derived PWD [with a Verasonics scanner (right)], in the same subject.

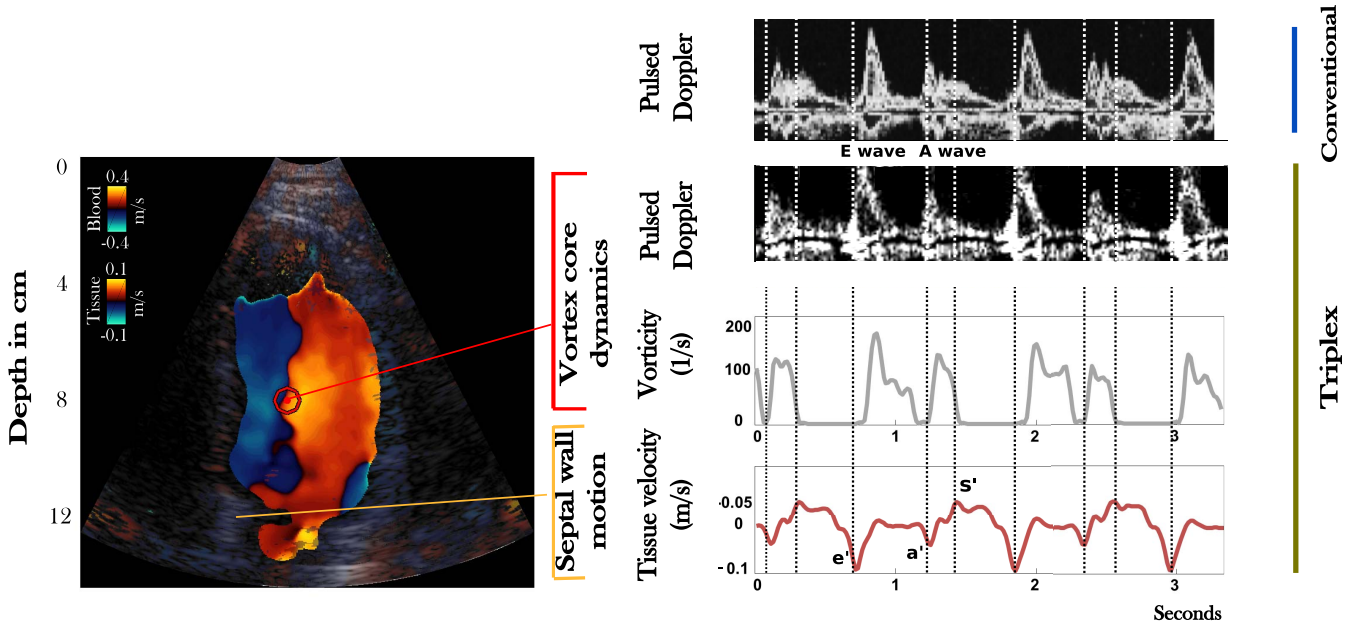

Fig. 4. Triplex color Doppler and TDI of the left ventricle (four-chamber view) (left). Dynamics of the 1) mitral inflow (conventional versus triples), 2) core vorticity (triplex), and 3) mitral annulus (triplex) (right).

corresponding vorticity peaks. Consistent with these observations, short delays occurred between the base (mitral annulus) and vortex dynamics (see Table I), which was due to the time it takes for blood to enter the left ventricle and reach its highest velocity (and vorticity).

TABLE I

TIME DIFFERENCES BETWEEN THE Ev/Av VORTICITY PEAKS AND SEPTAL BASE MOTION $e'/a'/S'$

	Tissue-Vortex Time Difference (ms)					
	e' to E_v		A' to A_v		A_v to S'	
	septal	*lateral*	*septal*	*lateral*	*septal*	*lateral*
3ch	81 ± 40	79 ± 40	42 ± 20	43 ± 20	180 ± 50	180 ± 60
4ch	81 ± 30	80 ± 20	40 ± 20	42 ± 20	150 ± 40	150 ± 30
5ch	75 ± 40	72 ± 20	41 ± 20	34 ± 20	140 ± 50	140 ± 30

B. Diverging Wave (Verasonics) Versus Conventional (Vivid) Data

The E- and A-peaks estimated in the 12 subjects with the triplex sequence (Verasonics) were in agreement [$y = 0.88\ x + 0.05, r^2 = 0.92$, Fig. 5(a)] with those determined by conventional echocardiography (Vivid). The limited Nyquist velocities observed with the Verasonics sequences were due to the PRF set to 3.3 kHz (see Section II). A good

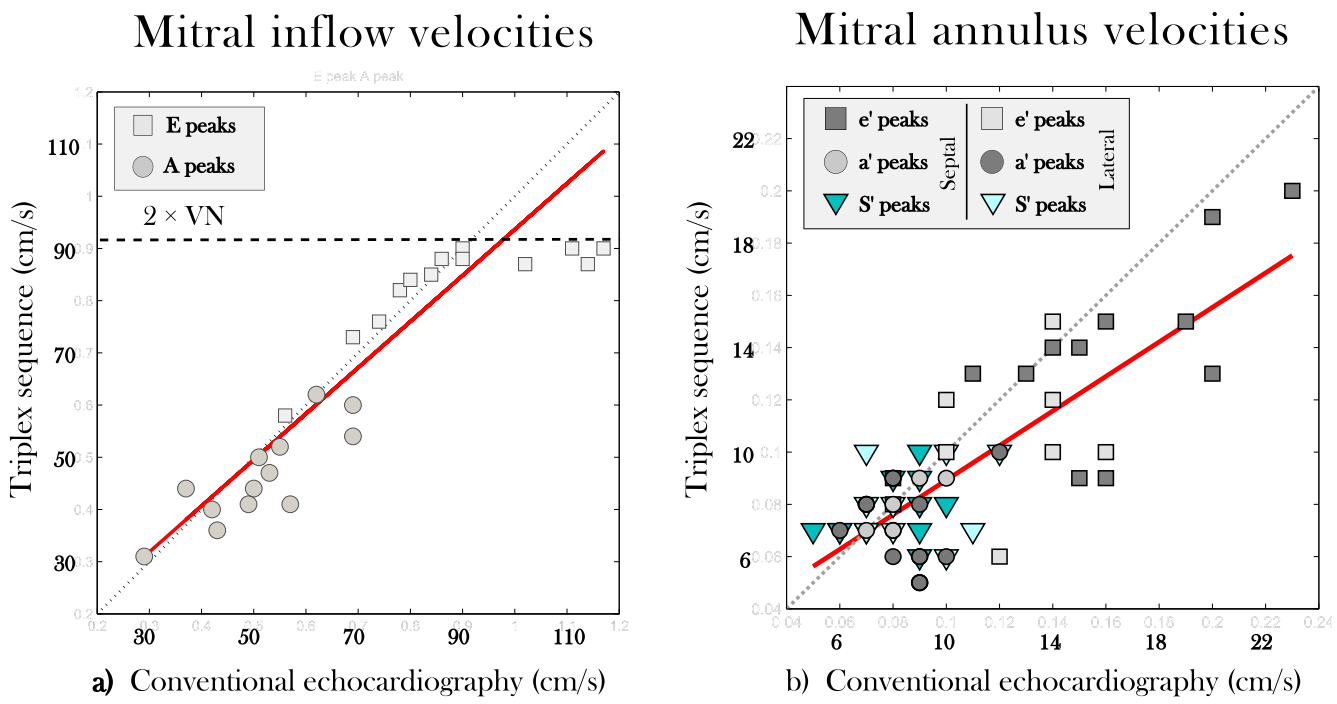

Fig. 5. Triplex sequence versus conventional echocardiography for (a) E- and A-peaks and (b) e', a', and S' peaks. VN = Nyquist velocity.

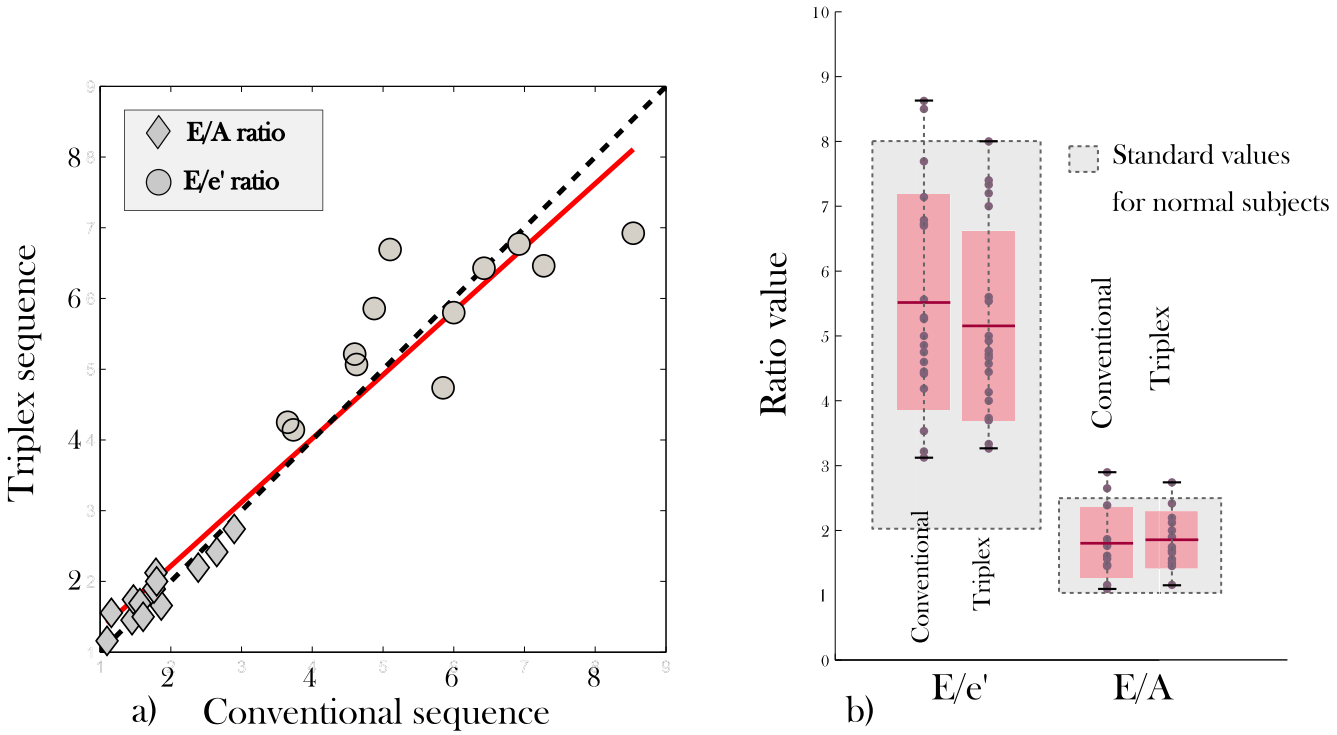

Fig. 6. Markers of diastolic function (E/A and E/e'). (a) Correlation triplex sequence versus conventional echocardiography. (b) Mean and standard deviation for normal subjects.

concordance was also observed for the e', a', and S' peaks of the septal mitral annulus [$y = 0.66\ x + 0.02, r^2 = 0.79$, Fig. 5(b)], which is in line with our former observations [17]. In clinical practice, E-over-A and E-over-e' ratios are both widely used to assess diastolic function [22]. A good agreement was obtained between the two ultrasound methods [$y = 0.90\ x + 0.42, r^2 = 0.96$, Fig. 6(a)]. The E/A and E/e' ratios were both within normal ranges [Fig. 6(b)].

IV. Discussion

We proposed a high-frame-rate echocardiographic sequence combined with data processing methods to quantify myocardium and vortex dynamics. This led to the opportunity of deriving blood and tissue physiological indexes, all acquired within the same cardiac cycle. A single-heartbeat multimodality sequence can potentially improve cardiac diagnosis and save examination time. It also opens new possibilities for evaluation of diastolic function by bringing new indexes integrating vortex formation, mitral inflow, and left ventricular base dynamics concurrently.

A. Scheme of the Triplex Sequence

The design of the triplex sequence was adapted and customized according to the objectives. In this study, we were interested in analyzing the relationship between vorticity and wall dynamics. The Doppler packet size was adjusted to obtain a roughly constant number of frames during diastole (52 ± 14) for 12 subjects, despite the wide range of heart rate, leading to different frame rates (from 60 to 100 fps per modality). For technical (memory) reasons, we chose a PRF of 3300 Hz, thus yielding a Nyquist velocity of 0.5 m/s, i.e., a 1-m/s limit for mitral spectral Doppler with the shifted baseline. Indeed as we aimed at acquiring two full cardiac cycles for each subject, a compromise had to be found to manage the memory issue, some cycle being as long as 1.5 s. For long-axis imaging of the left ventricle, the PRF could theoretically be increased up to $\sim$6000 Hz (for an average range of 12 cm in a human adult), which could provide a mitral inflow velocity limit of $\sim$1.8 m/s with a 2.5-MHz transducer. Although conventional color Doppler uses 8 to 16 slow-time samples, we worked with packet sizes between 16 and 32 (depending on the heart rate). Indeed, increased Doppler packet sizes eased high-pass filtering for clutter mitigation. Multimodality imaging limits the use of larger packet sizes due to the interlaced B-mode/Doppler transmissions; a compromise must be made between the increase in packet size and its impact on image rate. The choice of the clutter filter was also of utmost importance as clutter removal in the heart cavity is a major challenge with diverging waves (mostly due to the mitral valve and wall motion). Though the principal component analysis provided acceptable results, there is still room for improvement by using block processing and adaptive thresholding [24] or by taking advantage of multilinear singular value decomposition [25]. Regarding B-mode and tissue Doppler (combined in the MoCo process), the number of compounding transmits (16) was chosen based on the findings reported in [17] and dropped to its minimal acceptable value in terms of grating lobes and contrast [17, Fig. 6, Sec. 2]. This lower bound helped us to achieve a relatively high image rate (80 ± 14 fps). Finally, the use of diverging waves inherently implies some limitations. Unlike conventional focused imaging, the energy of diverging waves is widely spread. This acoustic dissipation results in reduced SNR and also limits the use of harmonics, which can be penalizing for some patients (e.g., obesity or hypertrophic myocardium).

B. Vortex and Tissue Dynamics

Intracardiac vortex analysis has emerged over the past few years in echocardiography and MRI. Several vortex characteristics have been shown of interest; among them, vorticity, which reflects vortex strength, is being investigated to identify its relationship with cardiac function. A recent clinical study revealed a reduced vorticity during early diastole in subjects with chronic pulmonary disease and no signs of left ventricular diastolic dysfunction given by standard echographic indexes. Those results suggest that early changes in the flow pattern could be reflected in vorticity before deeper changes associated with diastolic impairment appear [26]; vorticity thus could be used as an early predictor of diastolic dysfunction. We recently introduced high-frame-rate Doppler vortography based on diverging wave imaging to quantify the vortex that forms during diastole in the left ventricle [18]. We showed that this imaging modality can yield measures of core vorticities similar to those obtained by 4-D flow MRI or vector flow mapping [18]. As it is known that the interplay of intracavitary blood flow and wall motion can reflect cardiac function, a sequence that allows assessment of the fluid-wall interaction, such as the triplex sequence introduced in this paper, could be diagnostically relevant. In line with our previous results [18], the echocardiographic measures showed that peak vorticities (E_v and A_v) and peak mitral velocities (E and A) are slightly delayed (Fig. 4) in normal subjects. And consistent with other previous analyzes [17], we obtained a good concordance between the mitral annulus peak velocities (e' and a') measured with the triplex sequence and those determined by the conventional PWD with a clinical scanner. In addition, tissue Doppler with a triangular sequence returned errors less than 5% *in vitro* conditions within physiological ranges [17]. Further testing could be undertaken to compare with a nonsteered sequence. Regarding wall and blood dynamics, they obviously have some parallel with each other, but with a small time delay observable between the blood and tissue peaks. This time gap between the mitral inflow and annulus peak velocities is potentially a biomarker of diastolic function. This has been documented in [27], whose authors observed a prolonged delay in patients with impaired relaxation. In conventional echocardiography, because tissue and blood velocities are not measured simultaneously, time delays are determined with respect to ECG R-peak. This indirect method can result in biases due to the changes in heart rhythm. It is noticeable that the retrieved values of the time gap were small (from 40 to 160 ms) and could only be obtained with a high temporal resolution; in the case of our triplex sequence, we reached a resolution up to 9 ms. If it is confirmed that wall-blood dynamics delay has some diagnostic significance, echocardiographic sequences combining blood and tissue Doppler at high frame rates should be promoted. Furthermore, *in vivo* studies should be undertaken to deeply investigate these issues.

C. Mitral Inflow and Derived Cardiac Indexes

The mitral inflow velocities have long been used by clinicians and are part of routine cardiac evaluation. Indexes derived from these velocities are of paramount importance for

TABLE II
TIME DIFFERENCES BETWEEN THE Ev/Av VORTICITY PEAKS AND E/A VELOCITY PEAKS

	Time Difference (ms)	
	E to E_v	A to A_v
4ch	71 ± 30	32 ± 30

the assessment of diastolic function [22]. Benefiting from the relatively high-frame-rate of our triplex sequence, we used the I/Q Doppler signals to perform local spectral analyzes and retrieve E- and A-peak velocities. When compared with conventional PWD, we obtained good concordance despite noisier spectra, which confirms that the mitral inflow velocities could be retrieved directly from the triplex sequence. Note, however, that the E-peak velocities determined by the triplex sequence were bounded by $\sim$0.9 m/s due to the limited PRF (3.3 kHz). In the absence of technical (memory) limitation, higher PRFs ($>$5 kHz) should be recommended. The E/A and E/e' ratios were both normal since we examined healthy subjects exclusively. A good concordance between the two ultrasound modalities was also obtained (Fig. 5), and no statistical difference was observed when comparing the respective distributions (Fig. 6). It is noticeable that the E/e' dispersion was narrower with the triplex sequence [Fig. 6(b)]; this could be explained by the use of E and e' values measured in the same heartbeat. The triplex sequence made it possible to measure accurate time delays between the different peaks (e'-E-E_v and a'-A-A_v) on the same cardiac cycles (Tables I and II). This sequence highlights the chain of events, namely, tissue relaxation, valve opening, rapid filling, and vortex formation. It all occurred in an average time of 80 ms in the healthy volunteers.

D. Potential Hints for the Next Steps

In our study, we focused the spectral analysis on well-established and routinely used clinical indexes (E and A peaks). But high-frame-rate echocardiography might open the way to new indexes and a more thorough analysis of the intraventricular blood flow. Reference [9] showed the possibility for a full spectral analysis of the 2-D Doppler field in the carotid. In our case, the analysis could be widened to the whole ventricle instead of solely the mitral inflow. As another example, in accordance with our previous studies, we showed that it is possible to evaluate the dynamics of the intraventricular vortex by Doppler vortography. An alternative for a more complete analysis of the intraventricular vortices (e.g., size and circulation) would be the use of the global and regularized approach that we recently introduced for intraventricular vector flow mapping [28]. Although there is a tendency in the recent literature to demonstrate the pathophysiological interest of intraventricular vortices, the clinical impact of these vortices has yet to be demonstrated in large cohorts. Intracardiac blood flow analysis could be further broadened according to the clinical needs. Though infrequently used amongst cardiologists, color M-mode could also be derived from high-frame-rate CDI to provide other markers of cardiac function such as E/Vp, with Vp being the propagation velocity [29], or pressure gradients [30]. Spectral analysis was carried out using a standard FFT despite a limited Doppler packet size. An increased PRF would provide an opportunity to increase the packet size and in turn achieve better spectral results. Spectral analyzes could also be improved by using spectral estimators better adapted for small samples, such as blood amplitude and phase estimation [31].

V. CONCLUSION

High-frame-rate ultrasound imaging is able to overcome some limitations of conventional ultrasound imaging by reaching higher temporal resolution and allowing multimodality imaging. It opens up new possibilities for thorough blood and tissue analysis and better understanding and assessment of cardiac function. In this study, triplex echocardiographic imaging (B-mode, tissue Doppler, and CDI) was obtained at a high-frame-rate in 12 volunteers. This modality allowed us to compare the blood vortex dynamics (core vorticity) alongside the basal wall motion (mitral annulus velocity) in a single heartbeat. Our findings highlight the dynamical relationship between the intracardiac flow and the myocardium by showing the chain of events during early and late diastole (the successive e'-E-Ev peaks and a'-A-Av peaks). Using a single B-mode and Doppler sequence at high frame rates, it was possible to compute the time delays between the myocardial peak velocities and intraventricular peak vorticities, during early and active filling. It was also possible to obtain mitral pulsed-wave-Doppler waveforms and retrieve the routinely used E and A peak velocities. The introduced tools could decipher the interconnection between the vortex and wall dynamics and could thus be of clinical relevance for early assessment of diastolic function.

REFERENCES

[1] S. F. Nagueh *et al.*, "Recommendations for the evaluation of left ventricular diastolic function by echocardiography," *Eur. J. Echocardiogr.*, vol. 10, no. 2, pp. 165–193, 2009.
[2] G. Pedrizzetti, G. L. Canna, O. Alfieri, and G. Tonti, "The vortex—An early predictor of cardiovascular outcome?" *Nature Rev. Cardiol.*, vol. 11, no. 9, pp. 545–553, 2014.
[3] P. M. Arvidsson *et al.*, "Vortex ring behavior provides the epigenetic blueprint for the human heart," *Sci. Rep.*, vol. 6, Feb. 2016, Art. no. 22021.
[4] M. S. Elbaz, E. E. Calkoen, J. J. Westenberg, B. P. Lelieveldt, A. A. Roest, and R. J. van der Geest, "Vortex flow during early and late left ventricular filling in normal subjects: Quantitative characterization using retrospectively-gated 4d flow cardiovascular magnetic resonance and three-dimensional vortex core analysis," *J. Cardiovascular Magn. Reson.*, vol. 16, no. 1, p. 78, 2014.
[5] M. Tanaka *et al.*, "Blood flow structure and dynamics, and ejection mechanism in the left ventricle: Analysis using echo-dynamography," *J. Cardiol.*, vol. 52, no. 2, pp. 86–101, 2008.
[6] D. J. Penny, M. L. Rigby, and A. N. Redington, "Abnormal patterns of intraventricular flow and diastolic filling after the fontan operation: Evidence for incoordinate ventricular wall motion," *Heart*, vol. 66, no. 5, pp. 375–378, 1991.
[7] P. P. Sengupta *et al.*, "Emerging trends in CV flow visualization," *JACC, Cardiovascular Imag.*, vol. 5, no. 3, pp. 305–316, 2012.
[8] S. R. Ommen *et al.*, "Clinical utility of Doppler echocardiography and tissue Doppler imaging in the estimation of left ventricular filling pressures: A comparative simultaneous Doppler-catheterization study," *Circulation*, vol. 102, no. 15, pp. 1788–1794, 2000.

[9] J. Bercoff *et al.*, "Ultrafast compound Doppler imaging: Providing full blood flow characterization," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 58, no. 1, pp. 134–147, Jan. 2011.

[10] I. K. Ekroll, A. Swillens, P. Segers, T. Dahl, H. Torp, and L. Lovstakken, "Simultaneous quantification of flow and tissue velocities based on multi-angle plane wave imaging," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 60, no. 4, pp. 727–738, Apr. 2013.

[11] M. Cikes, L. Tong, G. R. Sutherland, and J. D'Hooge, "Ultrafast cardiac ultrasound imaging: Technical principles, applications, and clinical benefits," *JACC, Cardiovascular Imag.*, vol. 7, no. 8, pp. 812–823, Aug. 2014.

[12] D. P. Shattuck, M. D. Weinshenker, S. W. Smith, and O. T. von Ramm, "Explososcan: A parallel processing technique for high speed ultrasound imaging with linear phased arrays," *J. Acoust. Soc. Amer.*, vol. 75, no. 4, pp. 1273–1282, 1984.

[13] L. Tong, A. Ramalli, R. Jasaityte, P. Tortoli, and J. D'Hooge, "Multi-transmit beam forming for fast cardiac imaging—Experimental validation and *in vivo* application," *IEEE Trans. Med. Imag.*, vol. 33, no. 6, pp. 1205–1219, Jun. 2014.

[14] C. Papadacci, M. Pernot, M. Couade, M. Fink, and M. Tanter, "High-contrast ultrafast imaging of the heart," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 61, no. 2, pp. 288–301, Feb. 2014.

[15] L. Tong, H. Gao, H. F. Choi, and A. J. D'Hooge, "Comparison of conventional parallel beamforming with plane wave and diverging wave imaging for cardiac applications: A simulation study," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 59, no. 8, pp. 1654–1663, Aug. 2012.

[16] H. Hasegawa and H. Kanai, "High-frame-rate echocardiography using diverging transmit beams and parallel receive beamforming," *J. Med. Ultrason.*, vol. 38, no. 3, pp. 129–140, 2011.

[17] J. Porée, D. Posada, A. Hodzic, F. Tournoux, G. Cloutier, and D. Garcia, "High-frame-rate echocardiography using coherent compounding with Doppler-based motion-compensation," *IEEE Trans. Med. Imag.*, vol. 35, no. 7, pp. 1647–1657, Jul. 2016.

[18] J. Faurie *et al.*, "Intracardiac vortex dynamics by high-frame-rate Doppler vortography—*In vivo* comparison with vector flow mapping and 4-D flow MRI," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 64, no. 2, pp. 424–432, Feb. 2017.

[19] A. C. Yu and L. Lovstakken, "Eigen-based clutter filter design for ultrasound color flow imaging: A review," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 57, no. 5, pp. 1096–1111, May 2010.

[20] T. Loupas, J. T. Powers, and R. W. Gill, "An axial velocity estimator for ultrasound blood flow imaging, based on a full evaluation of the Doppler equation by means of a two-dimensional autocorrelation approach," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 42, no. 4, pp. 672–688, Jul. 1995.

[21] F. Mehregan *et al.*, "Doppler vortography: A color Doppler approach to quantification of intraventricular blood flow vortices," *Ultrasound Med. Biol.*, vol. 40, no. 1, pp. 210–221, Jan. 2014.

[22] S. F. Nagueh *et al.*, "Recommendations for the evaluation of left ventricular diastolic function by echocardiography: An update from the american society of echocardiography and the European association of cardiovascular imaging," *J. Amer. Soc. Echocardiogr.*, vol. 29, no. 4, pp. 277–314, Apr. 2016.

[23] E. P. Widmaier, H. Raff, K. T. Strang, and A. J. Vander, *Vander's Human Physiology*. New York, NY, USA: McGraw-Hill, 2014.

[24] P. Song, A. Manduca, J. D. Trzasko, and S. Chen, "Ultrasound small vessel imaging with block-wise adaptive local clutter filtering," *IEEE Trans. Med. Imag.*, vol. 36, no. 1, pp. 251–262, Jan. 2017.

[25] M. Kim, C. K. Abbey, J. Hedhli, L. W. Dobrucki, and M. F. Insana, "Expanding acquisition and clutter filter dimensions for improved perfusion sensitivity," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 64, no. 10, pp. 1429–1438, Oct. 2017.

[26] M. Schäfer *et al.*, "4D-flow cardiac magnetic resonance-derived vorticity is sensitive marker of left ventricular diastolic dysfunction in patients with mild-to-moderate chronic obstructive pulmonary disease," *Eur. Heart J.-Cardiovascular Imag.*, vol. 19, no. 4, pp. 415–424, 2017.

[27] C. Rivas-Gotz, D. S. Khoury, M. Manolios, L. Rao, H. A. Kopelen, and S. F. Nagueh, "Time interval between onset of mitral inflow and onset of early diastolic velocity by tissue Doppler: A novel index of left ventricular relaxation: Experimental studies and clinical application," *J. Amer. College Cardiol.*, vol. 42, no. 8, pp. 1463–1470, 2003.

[28] K. C. Assi *et al.*, "Intraventricular vector flow mapping—A Doppler-based regularized problem with automatic model selection," *Phys. Med. Biol.*, vol. 62, no. 17, p. 7131, 2017.

[29] P. Brun *et al.*, "Left ventricular flow propagation during early filling is related to wall relaxation: A color M-mode Doppler analysis," *J. Amer. College Cardiol.*, vol. 20, no. 2, pp. 420–432, 1992.

[30] R. Yotti *et al.*, "Noninvasive estimation of the rate of relaxation by the analysis of intraventricular pressure gradientsclinical perspective," *Circulat., Cardiovascular Imag.*, vol. 4, no. 2, pp. 94–104, 2011.

[31] K. L. Hansen, F. Gran, M. M. Pedersen, I. K. Holfort, J. A. Jensen, and M. B. Nielsen, "*In-vivo* validation of fast spectral velocity estimation techniques," *Ultrasonics*, vol. 50, no. 1, pp. 52–59, 2010.

Authors' photographs and biographies not available at the time of publication.