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Proceedings of Symposium on Ultrasonic Electronics, Vol. 34 (2013) pp. 513-514
20-22 November, 2013

Vector Projectile Imaging (VPI): A New Quantitative Framework for High-Frame-Rate Complex Flow Tracking

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1. Introduction

With the advent of spectral Doppler and color flow imaging (CFI), ultrasound has been clinically assisting numerous vascular diagnoses in the past 30 years. This modality has generally been well acknowledged for its real-time applicability under bedside diagnostic settings – an important feature that MRI and CT have yet to match. However, the under-impressive quality of blood flow information rendered by current ultrasound scanners is one major demerit factor that has been hampering ultrasound's popularity amongst vascular clinicians. In particular, although spectral Doppler can more or less provide accurate estimates of flow velocity (provided that Doppler angle correction is properly done), it can only render such information at a single spatial position (or range gate). On the other hand, albeit CFI can offer image-level information about vascular flow, it is known to be susceptible to numerous sources of estimation errors, and thus the results are rather unintuitive for clinicians to properly understand, especially in complex flow situations. Unless there is a fundamental change in the way ultrasound offers flow information, it would be difficult to foresee an expansion of ultrasound's present role in vascular diagnostics.

2. Statement of Contribution

We have formulated a new framework called vector projectile imaging (VPI) that can provide quantitative visualization of complex flow patterns. VPI has the following key features that distinguish itself from conventional CFI:

1) Can readily offer imaging frame rates well beyond video display range (e.g. >1,000 fps);

2) Provides estimates of flow velocity vectors to account for multi-directional flow components;

3) Projectile-based rendering of flow vectors to highlight their spatiotemporal dynamics.

These features are made possible through a unique marriage of broad-view data acquisition principles, flow vector analysis algorithms, and novelties in computer vision.

3. Technical Principles

A system-level schematic of the stages involved in VPI is illustrated in **Fig. 1**. The essential parts of the technique are briefly summarized as follows.

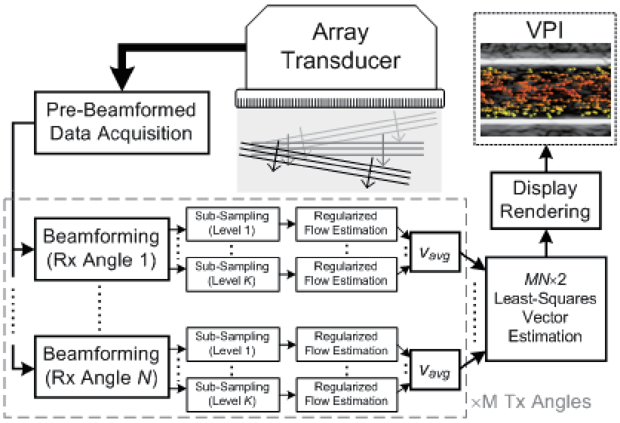

Fig. 1 Overview of key stages involved in VPI.

Data Acquisition: VPI is based on the use of M steered plane waves[1] on transmission (Tx). For each Tx angle, parallel beamforming for a 2-D image grid is performed over N dynamic receive (Rx) steering angles. The M-Tx pulsing scheme is looped repeatedly as analogous to slow-time sampling in Doppler. The effective frame rate for VPI is then simply equal to $FR = f_{PW}/M$, where f_{PW} is the rate of each plane wave firing event (i.e. equal to the pulse repetition frequency, or PRF). By simply adjusting PRF, the FR can be boosted to >1,000 fps as needed to track fast-changing flow. Note that, for each pixel P_o within the 2-D image grid, there are MN beamformed ensembles along slow-time (i.e. MN number of 1-D slow-time signal arrays; each corresponding to one combination of Tx-Rx angle).

Regularized Flow Vector Estimation: This process is performed independently for individual pixels. In every realization, the process can be divided into two stages: (i) velocity estimation for each of the MN slow-time ensembles for that pixel; (ii) vector computation via least-squares fitting of MN velocity estimates derived from all Tx-Rx angle pairs.

In ***Stage 1***, for each of the MN slow-time ensembles (matrix notation $\mathbf{x}_{mn}$), multi-level sub-sampling is first performed to attain finer slow-time resolution.

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For this set of sub-sampled ensembles constructed for $\mathbf{x}_{mn}$, three steps are performed: (i) clutter filter (to suppress tissue echoes); (ii) velocity estimation (based on lag-one autocorrelation: the classical CFI estimator); (iii) aliasing correction. After that, the sub-sampled ensembles are averaged to arrive at the mean flow estimate for that Tx-Rx angle pair. After doing the same for all angle pairs, *MN* raw velocity values (matrix notation **u**) would become available.

In ***Stage 2***, a flow vector $\mathbf{v}=(v_x, v_z)$ is derived from **u** as follows. First, based on cross-beam Doppler principles[2], an $MN\times2$ angle matrix **A** is formed from all *MN* Tx-Rx angle combinations. It is known that $\mathbf{u} = \mathbf{A}\mathbf{v}$. Hence, **v** is computed by carrying out the least-squares fitting operation $\mathbf{A}^{\dagger}\mathbf{u}$.

Dynamic Visualization: For the **v** estimate of each pixel, a single-hue, color-coded arrow is formed. For high velocity magnitude, its corresponding arrow would be brighter in color and longer in length. Arrows for different VPI frames are compiled, and they are displayed as moving projectiles to enable quantitative visualization.

4. Experimental Methods

System Hardware: To experimentally demonstrate the efficacy of VPI, this new framework has been implemented on our lab's research scanner that is equipped with these advanced functionalities: (i) channel-domain control of transmit operations of an array transducer (as modified from a SonixTouch system); (ii) multi-channel pre-beamformed data acquisition (SonixDAQ); (iii) fast data processing throughput based on GPU technology. An L14-5 linear array has been used for this work.

Imaging Parameters: As a proof of concept, we implemented a 3-Tx, 3-Rx VPI configuration. Also, for each Tx-Rx angle pair, a 3-level sub-sampling was imposed during flow estimation. **Table I** summarizes other key data acquisition parameters.

Table I. Summary of Experimental Parameters

Parameter	Value
Imaging Specifications	
Imaging frequency	5 MHz
# of array channels	128
Pulse duration	3 cycles (0.429 μs)
Pulse repetition frequency	10 kHz
Tx-Rx steering angles	–10°, 0°, +10°
Flow Pattern Specifications	
Peak inlet flow rate	6 ml/s
Pulse cycle frequency	1.2 Hz

Anthropomorphic Flow Models: VPI was tested on anatomically realistic flow models that resembled healthy and stenosed carotid bifurcation. These are suitable geometries as flow dynamics within them are known to be multi-directional and significantly time-varying. The phantoms are wall-less designs based on lost-core casting with polyvinyl alcohol gel. Pulsatile flow is supplied through the use of a gear pump with programmable flow rates.

5. Results and Discussion

VPI allowed us to quantitatively track highly complex flow patterns inside the carotid arteries. **Fig. 2** shows examples of VPI in rendering long-axis views of two bifurcation models: (a) healthy; (b) with 50% eccentric stenosis at the entrance to the ICA branch. Results at peak systole are shown. In the healthy case, VPI accurately projected the main transit path of blood flow. In the stenosis case, VPI quantitatively highlighted the high velocity jet emerging at the stenosis site, curvy transit path downstream from the stenosis, and significant recirculatory flow in the ICA bulb. These observations, cineloops of which to be shown at the meeting, are of significance in that they cannot be visualized using conventional CFI.

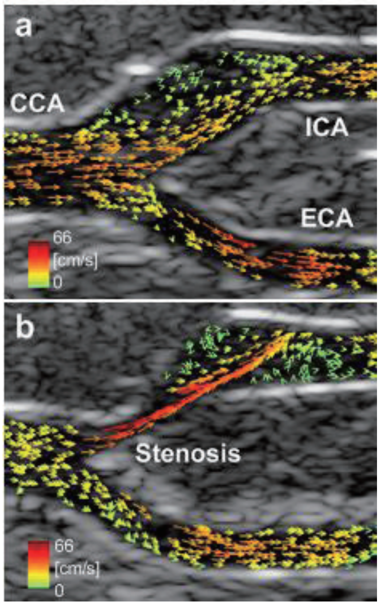

Fig. 2 Examples of VPI taken at peak systole for two carotid bifurcation models: (a) healthy; (b) with 50% eccentric stenosis at the entrance to ICA.

Acknowledgement

Funding support from the Research Grants Council of Hong Kong (GRF 785113M) is gratefully acknowledged.

References

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