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Color-Encoded Speckle Imaging (CESI): A Novel High Frame Rate Approach to Coherent Visualization of Complex Flow Dynamics

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1. Introduction

For many years, ultrasound color flow imagng (CFI) has been used in clinical practice to conduct diagnosis of vascular health. Its main technical features include: 1) display of mean flow velocity using color codes (usually bidirectional flow can be shown through a red-blue color palette); 2) parallel showing of a B-mode background image of the anatomy in the field of view; 3) provision of frame rate in the real-time range, typically up to 20 frames per second (fps). These features generally suffice in applications where the sonographer is searching for the presence of blood flow in the field of view. Nevertheless, they are not sufficient for obtaining detailed insights on blood flow dynamics inside the circulation. One particular issue lies with the frame rate: 20 fps is simply inadequate to track blood flow that may change significantly over a cardiac pulse cycle. Also, CFI is prone to false coloring artifacts due to velocity aliasing and beam-flow angle variations. New engineering innovations are thus needed to revamp the way in which ultrasound is used to obtain images of blood flow.

2. Statement of Contribution

In this work, we present a novel way that uses ultrasound to achieve visually intuitive rendering of complex flow dynamics. Our new technique, which we will refer to as color-encoded speckle imaging (CESI), has the following technical features that outperform conventional CFI:

1) Provision of high frame rates of >1,000 fps;

2) Simultaneous display of flow speckles and velocity color codes to enhance flow visualization quality.

To our knowledge, CESI is amongst the first of its kind in terms of rendering both flow speckles and velocity color codes at very high frame rates. This effort should also be the first to demonstrate that, with sufficient temporal resolution such as that provided by CESI, complex flow patterns may be consistently visualized using ultrasound imaging.

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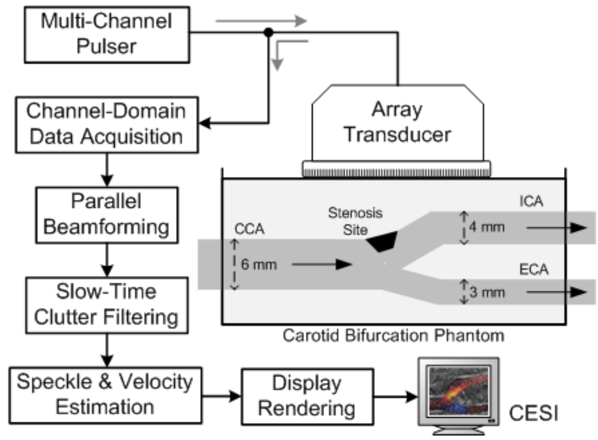

Fig. 1 System-level blocks involved in CESI and the experimental scenario considered in this study.

** CCA: common carotid artery; ICA: internal carotid artery; ECA: external carotid artery.*

3. Technical Principles

A system-level schematic of the stages involved in CESI is illustrated in **Fig. 1**. The following is a description of the major stages.

Data Acquisition: CESI achieves high frame rate through the use of broad-view data acquisition schemes that can in principle obtain an image from each pulse firing. Plane wave compounding[1] is used here, and pre-beamformed data from the transducer array channels are used to perform parallel beamforming. Note that a compounded image frame is typically formed from M steered plane wave images that may be computed at very high speed using graphical processing units (GPU)[2].

The compounded image frame rate can be expressed using the relation $FR = f_{PW} / M$, where f_{PW} is the rate in which steered plane wave images are acquired. In reality, f_{PW} is essentially equal to the pulse repetition frequency (PRF) since an image may be obtained from each firing when performing broad-view data acquisition. Therefore, FR can be readily set to over 1,000 fps by balancing between the choice of PRF and the compound group size M.

Signal Processing: Flow speckle and mean flow velocity is estimated in the CESI techniuqe by processing each pixel's slow-time ensemble (i.e. the set of beamformed signal values over multiple compounded frames). This can be considered as a two-stage process. First, clutter filtering is applied to the slow-time ensemble to attenuate unwanted tissue echoes[3]. Standard digitial highpass filtering methods like finite impulse response filtering may be used here. This operation is performed on all pixels in the image frame, and we can denote $F_k(P_o)$ as the filtered signal for the k^{th} frame at pixel P_o.

In the second stage, estimation of speckle pattern and velocity map is carried out based on processing of $F_k(P_o)$. For the k^{th} frame and at pixel P_o, the flow speckle is estimated as the filtered slow-time power $S_k(P_o)$ over a data window of L samples, i.e. $[F_k(P_o), F_{k+1}(P_o), \ldots, F_{k+L-1}(P_o)]$. Concurrently, the mean velocity $V_k(P_o)$ is estimated over the same M-sample window using the autocorrelation algorithm that is standard in CFI[3].

Display Rendering: After performing this operation for all pixels, flow speckles and mean velocitiy estimates are combined into a visually integrative form. Flow speckle pattern is obtained by converting $S_k(P_o)$ into grayscale pixels (assuming a given dynamic range), while velocity color codes are obtained by mapping $V_k(P_o)$ onto a hot-cold color hue. They are then overlaid onto the B-mode image $B_k(P_o)$ using alpha compositing.

4. Experimental Methods

System Hardware: CESI has been implemented experimentally in our laboratory using a composite imaging platform. The front-end pulser core is modified from a SonixTouch research scanner. We have customized the operation of this pulser to work in the plane wave compounding mode, and it is used to drive an L14-5 linear array. On reception, we have used a custom-made pre-beamformed data acquisition system[4] to acquire raw data samples for CESI processing on a high-speed parallel beamformer developed by our team using GPUs[5].

Table I. Summary of Experimental Parameters

Parameter	Value
Imaging Specifications	
Imaging frequency	7 MHz
# of array channels	128
Pulse duration	3 cycles (0.429 μs)
Pulse repetition frequency	10 kHz
# of steering angles	5
Flow Phantom Specifications	
Inlet flow rate	5 ml/s
Pulse cycle frequency	1.2 Hz

Flow Phantom Design: Since complex flow patterns usually emerge in-vivo inside diseased vasculature, the technical merit of CESI can be suitably assessed with a stenosed arterial flow phantom. As such, we have fabricated a carotid bifurcation phantom with 25% eccentric stenosis at the inlet to the internal carotid artery (depicted in **Fig. 1**). It is a wall-less phantom design. Carotid-like flow is supplied to the phantom using a computerized gear pump system.

Technical Parameters: As an illustration, we have conducted CESI imaging at 2,000 fps frame rate. The key technical parameters used in our experiments are listed in **Table I**.

5. Results and Discussion

CESI was found to be potent in capturing how flow patterns progress over a pulse cycle. **Fig. 2** shows a bifurcation image example of CESI with schematic labels of key flow events in the imaging view included. We found that CESI's high temporal resolution, flow speckle display, and velocity encoding collectively allowed us to monitor how flow jets and recirculation develop downstream from the stenosis site. This is appealing as it enables us to obtain insights on specific flow dynamics details in different parts of a pulse cycle. Cineloops of these observations will be shown at the meeting.

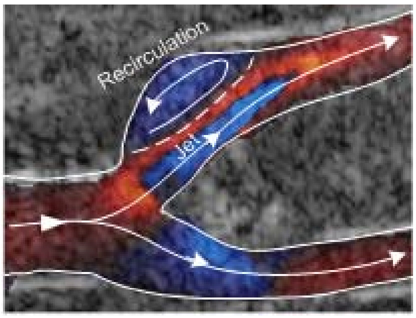

Fig. 2 CESI screenshot when imaging a bifurcation with stenosis at the inlet to upper branch. Flow directions and key flow events have been labeled.

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