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Ultrasound Microvessel Imaging: A Step Toward Clinical Integration in Image-guided Radiotherapy

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ABSTRACT

Ultrafast ultrasound imaging, enabled by plane-wave acquisition, achieves frame rates over 10,000 frames per second, which is more than 100 times faster than conventional clinical ultrasound. This high temporal resolution allows for visualization of microvascular flow, opening new opportunities in tumor localization and treatment response monitoring for radiotherapy. In this study, we evaluated the feasibility of ultrafast ultrasound microvessel imaging using a controlled phantom model. A vessel-mimicking tube was submerged in a water tank, and intermittent water flow with air gaps was introduced to simulate sparse flow dynamics. Data were acquired using a Verasonics Ultrafast Ultrasound system with a P4-2v phased array probe at a frame rate of ~800 Hz. Beamformed IQ data were processed with rigid motion correction to reduce tank-induced disturbances, followed by singular value decomposition (SVD) filtering to isolate flow signals from noise and background motion. The resulting images demonstrated significantly enhanced visibility of air bubble motion and sparse flow features, confirming the ability of this method to detect low-amplitude flow. Local adaptive thresholding and Gaussian filtering further improved image quality. These findings validate the use of ultrafast ultrasound with SVD filtering and motion correction as a microvascular imaging technique. Future work will focus on translating this technique to in vivo imaging and integrating it into the radiation therapy workflow to further improve image-guided adaptive radiotherapy. A clinical study is planned to evaluate its potential for real-time tumor visualization and monitoring treatment response during radiotherapy.

Keywords: Ultrafast Ultrasound, Vascular Imaging, Motion Correction, SVD Filtering, label-free ultrasound

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1. INTRODUCTION

Ultrasound imaging has long been used in medical diagnostics as a safe, portable, and low-cost imaging modality [1]. However, conventional ultrasound is limited to frame rates of approximately 50-100 frames per second [1,2]. The low frame rate limits the ability to visualize fast physiological processes such as microvascular flow. Recent advances in ultrafast ultrasound imaging have addressed these temporal limitations. By leveraging ultrafast ultrasound imaging, frame rates exceeding 10,000 frames per second can be achieved, which is over 100 times faster than conventional systems [2]. These higher frame rates increase sensitivity to subtle blood motion and allow for detection of slow or sparse flow that would otherwise be obscured by tissue and noise clutter. This dramatic improvement in temporal resolution allows for imaging of more rapid and dynamic physiological processes and enables visualization of the underlying microvasculature [3].

Though higher frame rates enable the system to capture rapid dynamic physiological changes, there are still challenges that remain for reliable microvascular imaging. With these ultrafast frame rates, increased sensitivity to noise and motion artifacts can clutter the weaker flow signals. Small probe movements or bulk tissue motion can produce signals that are stronger than blood flow and therefore mask the signals of interest. To mitigate these issues, a clutter-based filtering technique, singular value decomposition (SVD), can be used to separate low-rank tissue signals, mid-rank blood flow signals, and high-rank noise signals, and thereby enabling the isolation of vascular flow dynamics [4-7]. By decomposing the spatiotemporal data into these different ranks, distinguishing between tissue motion and blood flow becomes possible. When combined with motion correction and adaptive thresholding, SVD filtering can significantly improve the visualization of lower velocity, microvessel flow [8,9].

Vascular imaging is particularly valuable in radiation therapy, where tumors are supported by rich and dense microvascular networks. Tumors shift position during treatment due to respiratory motion, cardiac activity, and involuntary patient movement^[10]. This creates uncertainty in dose delivery precision and increases the likelihood of healthy tissue being irradiated. An ultrasound-based technique capable of visualizing these vascular dynamics could improve tumor localization and guide adaptive radiotherapy by providing immediate feedback during treatment delivery. This breakthrough allows for new applications of ultrasound imaging in treatment monitoring for radiotherapy, where high-resolution vascular imaging is critically needed^[10].

The purpose of this study is to develop and validate a microvascular imaging pipeline that combines ultrafast ultrasound, motion correction, and SVD filtering. We demonstrate the feasibility of this approach in a phantom model, laying the foundation for future in vivo studies and clinical integration into radiotherapy workflows^[5]. This study validates the technique under controlled conditions and establishes a framework that can ultimately be translated into patient imaging and incorporated into image-guided radiotherapy workflows.

2. METHODS

2.1 Ultrafast Acquisition

The ultrafast ultrasound data were obtained using a Verasonics Vantage system with a P4-2v phased array, 64-element transducer that runs at a frequency of 2.7 MHz (Figure 1). The system was configured to achieve a frame rate of approximately 800 Hz to allow for higher temporal resolution for flow imaging of the phantom vessel. We used a transparent cylindrical tube submerged in a water bath to mimic a vessel environment. A syringe was used to manually introduce sparse air gaps within the tube to simulate signal variation in blood flow. The ultrasound transducer was placed approximately 1 inch away from the phantom and aligned perpendicular to the tube's axis to image the flow region on the 2D plane. We recorded a total of 1800 beamformed IQ (in-phase and quadrature) frames and stored the data in a $240 \times 65 \times 1 \times 1800$ matrix ($N_z \times N_x \times N_y \times N_t$), where the first 2 dimensions are the axial (depth) and lateral (width) resolution and the 4th dimension representing time. The third dimension does not encode additional image information as data was collected in a 2D imaging plane.

The ultrafast imaging process is outlined in Figure 1. This method is used for collecting flow data such as movement of air gaps in the phantom vessel and will be essential in applications in vivo. We collected 1800 individual IQ frames with a 65 mm depth of imaging. Each frame captures a moment (1.25 ms) in time and all frames compiled together represent a temporal dataset of the phantom vessel. The system transmits plane waves at multiple steering angles (-15, -8, 0, 8, 15), beamforms, and combines them to enhance resolution before further processing. The data acquisition system collects and organizes the frames into super-frames (1-200), with each super-frame containing a batch of 9 acquisitions. Multiple frames allow for sufficient spatial and temporal data for the SVD decomposition. The processing pipeline involves 5 steps beginning with transmission of ultrasound pulse sent out from the transducer, signals received and digitized, beamforming of the raw IQ data, processing and saving the data into the system, and updating the data in MATLAB.

2.2 Motion Correction

To mitigate the issue of rigid tissue motion demonstrated as movement of water in the bath, the first step in this approach involves aligning all frames to a stationary reference frame. The reference frame was taken as the median of the first ten IQ frames. Following this, for each frame, a geometric transformation was approximated using MATLAB's `imregcorr` function. This estimated transformation was then applied via MATLAB's `imwarp` function to yield a motion corrected dataset with dimensions $N_z \times N_x \times N_t$ ^[14-16].

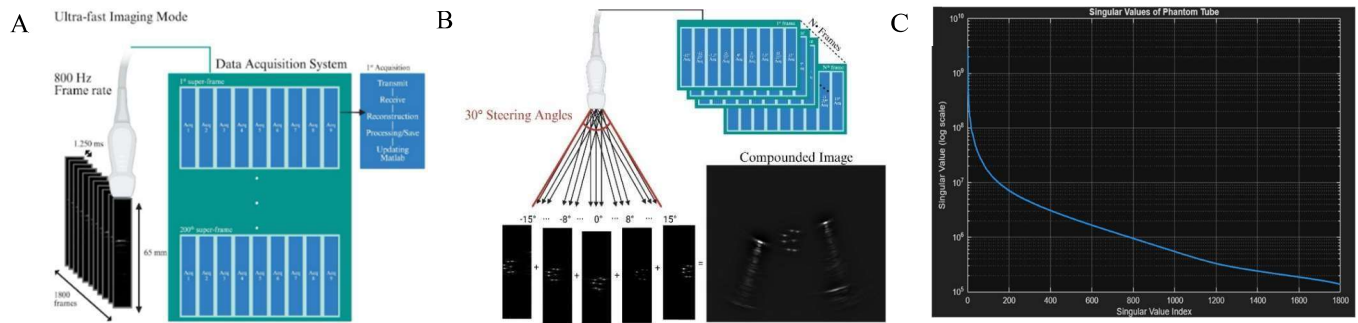


Figure 1. Ultrafast ultrasound acquisition and processing workflow. **(A):** A P4-2v phased array transducer captures 1800 IQ frames at ~800 Hz. Frames are grouped into super-frames (9 frames each). **(B):** Multiple steering angles ($\pm 15^\circ$), are transmitted, beamformed, and compounded to enhance resolution for processing through motion correction and SVD filtering for flow visualization. **(C):** Singular values of the IQ dataset plotted on a logarithmic scale. Selected components (5–20) are retained to suppress background noise and motion artifacts, isolating true flow signals in the phantom vessel.

2.3 SVD Decomposition and Flow Isolation

The motion corrected data were reshaped into a 2D matrix (M) [M of size $(N_z \times N_x) \times N_t$; each row represents the temporal signal of one pixel] to be decomposed by SVD [6-9].

$$M = U \times S \times V^T \quad (1)$$

Where U contains the left singular vectors representing spatial modes, S is a diagonal matrix containing the singular values, which quantify the energy of each mode, and V^T contains the right singular vectors representing the corresponding temporal modes [7-9, 12, 13]. To isolate and enhance the flow related signals, only the singular components 5 through 20 were kept. Singular values were chosen through visual analysis of the singular value data plotted on a logarithmic scale (Figure 1) and empirically optimized.

The filtered matrix was reconstructed as

$$M_{\text{filtered}} = U_{(:,5:20)} \times S_{(5:20, 5:20)} \times V_{(:,5:20)}^T \quad (2)$$

and reshaped back into a 3D matrix for further analysis.

2.4 Adaptive Flow Enhancement and Visualization

Each reconstructed frame was post-processed to improve the visualization of the flow using a local adaptive thresholding strategy [12]. A moving average and local standard deviation were calculated within a window (7×7), and a dynamic threshold was generated and scaled by a low sensitivity factor of $k = 0.1$ per pixel to bring our threshold slightly below the mean. Only pixels exceeding this threshold were kept flow-related signals. To further improve clarity of results, a gentle Gaussian filter was applied (kernel size 3, sigma 0.7) [11,17-18]. Each frame was normalized and visualized using a jet colormap.

3. RESULTS

The processed ultrafast ultrasound data showed substantial improvement in the visualization of sparse flow features. SVD filtered images revealed clear and sharply defined air gaps in the phantom vessel, which were previously obscured in raw grayscale images. Frames at multiple time points (e.g., 0.095s, 0.8776s, and 0.9181s) demonstrated consistent enhancement of flow signals (Figure 2).

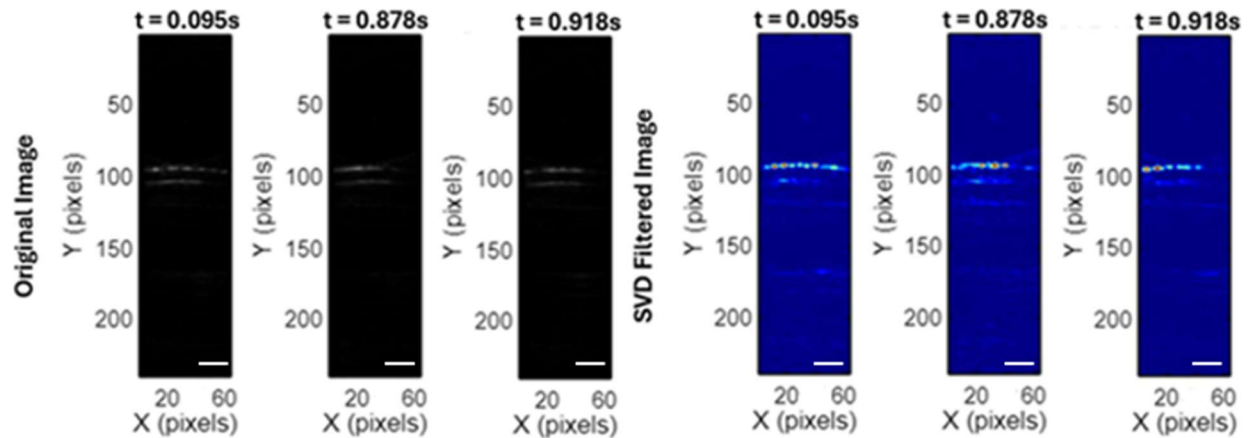


Figure 2. Comparison of original beamformed images and SVD-filtered results at three time points: $t = 0.095$ s, $t = 0.8776$ s, and $t = 0.9181$ s. Frames are arranged in a single row, with raw grayscale images shown on the left and the corresponding SVD-filtered images on the right. Motion correction and SVD filtering enhance visualization of sparse flow within the phantom vessel. Scale bar: 5 mm.

Quantitative analysis using intensity histograms of flow versus background regions showed significant contrast separation, supporting the method's ability to isolate true flow from noise (Figure 3). This validates the effectiveness of motion correction, SVD filtering, and adaptive thresholding for vascular imaging in a controlled environment^[4].

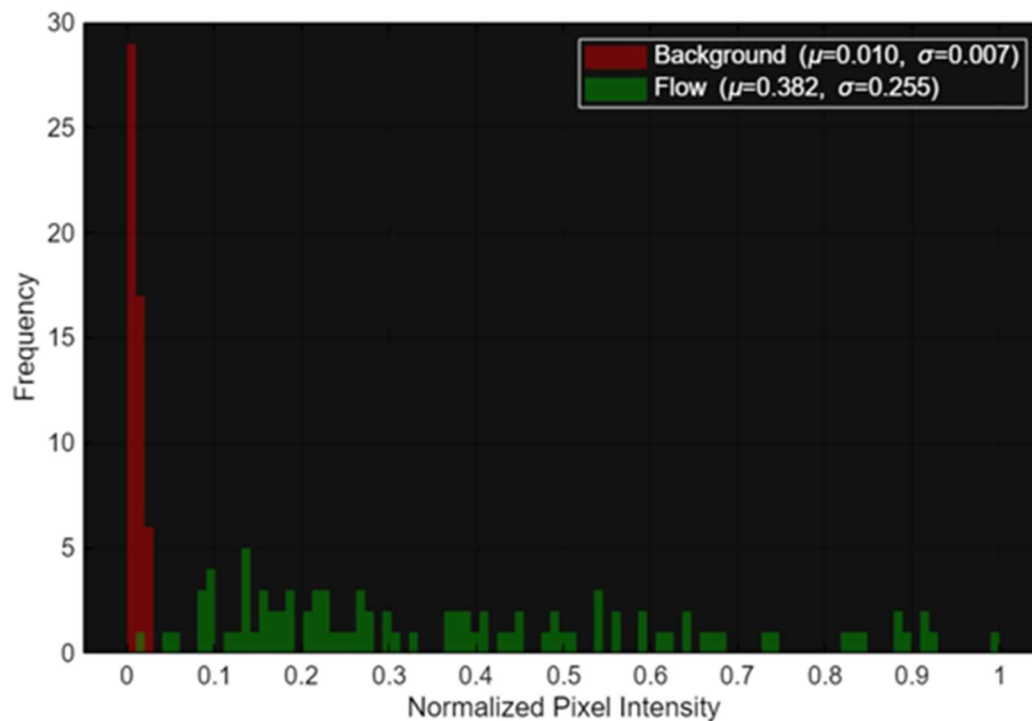


Figure 3. Normalized intensity histograms comparing flow and background regions in the enhanced SVD-reconstructed image. Green bars indicate pixel intensity distribution within a high-signal (flow) region, while red bars represent a neighboring background region. The clear separation between the two histograms demonstrates strong contrast and effective isolation of true flow signals following motion correction and SVD filtering.

4. CONCLUSIONS

This study demonstrates a robust pipeline for ultrafast ultrasound microvessel imaging, combining motion correction and SVD filtering to enhance flow visibility. The method shows strong potential for clinical translation, especially in radiotherapy, where real-time vascular imaging could support tumor localization and treatment monitoring^[10, 12, 19]. Future work will apply this pipeline in patient studies and explore its integration into clinical radiotherapy workflows.

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7. CONFLICT OF INTEREST

Liangzhong Xiang has financial interest in SoundDose, Inc., which, however, did not support this work. The remaining authors declare no conflict of interests.

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