Spectrally Resolved Super-Resolution Ultrasound for Microvascular Imaging and Quantification

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Background, Motivation and Objective

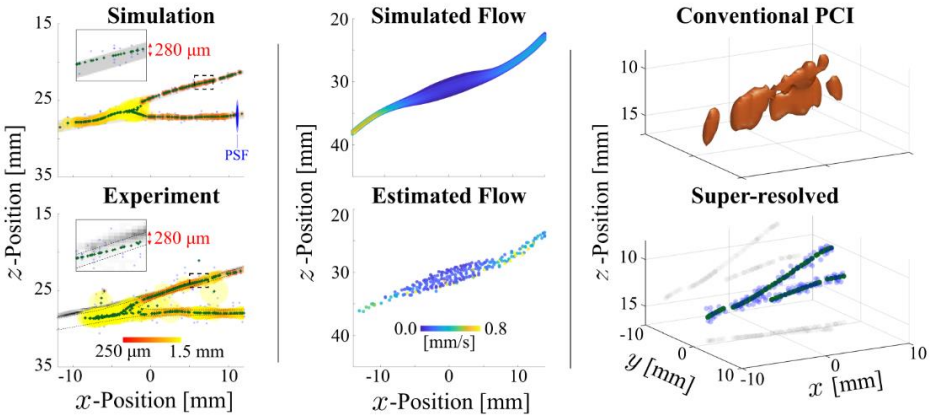
The super-localization of echoes generated by ultrasonically excited microbubble vibrations within vessels can enable the quantification of microvascular structure and flow at an unprecedented level of detail. However, tradeoffs between spatial and temporal resolution, which are more severe for volumetric reconstructions, together with the limited bubble selectivity of current methods, hinder the abilities of this technology to reveal microvasculature's molecular, anatomical, and functional characteristics. Here we propose a spectrally resolved super-resolution ultrasound (SRS-US) method towards quantifying microvasculature characteristics.

Statement of Contribution/Methods

The proposed method employs angular spectrum beamforming and has three key features: first, it provides frequency selectivity to enable the detection of microbubbles' nonlinear echoes with respect to mostly linear tissue. Second, due to the extensive use of 1D and 2D FFTs, the computational expense scales favorably for higher imaging depths and dimensions (3D/4D). Third, by combining a morphological image processing with deconvolution methods after beamforming, multiple microbubbles with different signal-to-noise ratio can be super-localized within the same frame. In addition to a new super-resolution computation, we devised methods for bubble tracking, vessel segmentation, and velocimetry using statistical methods based on Euclidian minimum spanning tree.

Results/Discussion

Our experimental and simulation results indicate recovery of vessel structures with radii tenfold below the diffraction limit and flow velocities 0.1 to 1 mm/s with error less than 10%. An effective resolution limit of 210 µm was established, compared with 3 mm for the diffraction-limited case. On a standard desktop, frame reconstruction was performed in 10.6 ± 1.1 ms (2D) and 220 ± 77 ms (3D), super-localization of the points required 7.6 ± 1.0 ms (2D) and 701 ± 54 ms (3D), and analysis of the points took less than 50 ms in all dimensions. These advancements were demonstrated across a range of geometries, including microvessels separated by distances smaller than the diffraction limit, having continuous variations in diameter, bifurcations, and 3D helical structures, and provide a quantitative framework towards real-time imaging of microvascular physiology and pathophysiology.



Left: Experimental validation of a birfurcated vessel phantom. **Center:** Flow velocities were recovered from spatiotemporal association between super-localized points. **Right:** Algorithm efficiency enables nearly tenfold resolution improvement in 3D, with total processing of a few minutes.