

Supplementary Materials for

Enhanced Ultrasound Particle Image Velocimetry (E-uPIV)

Enables Fast Flow Mapping of Microvasculature

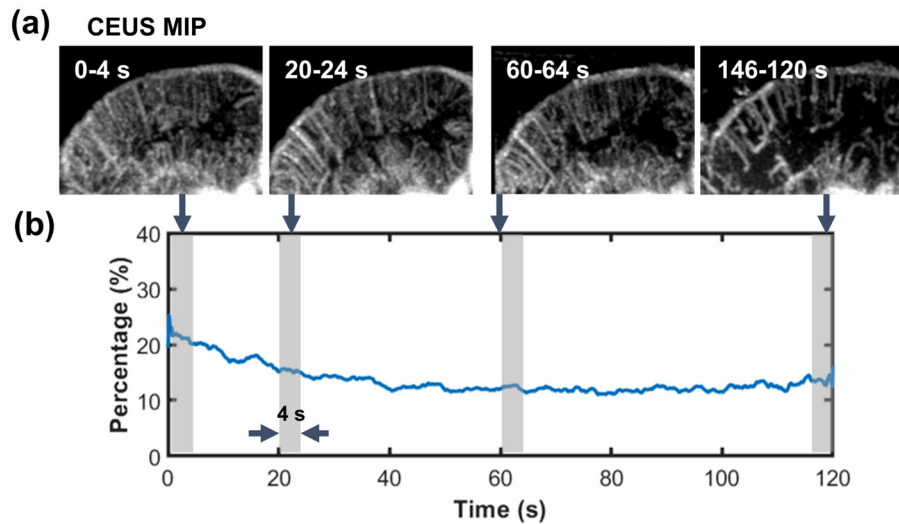
This PDF file includes:

Supplementary Figures 1 to 4

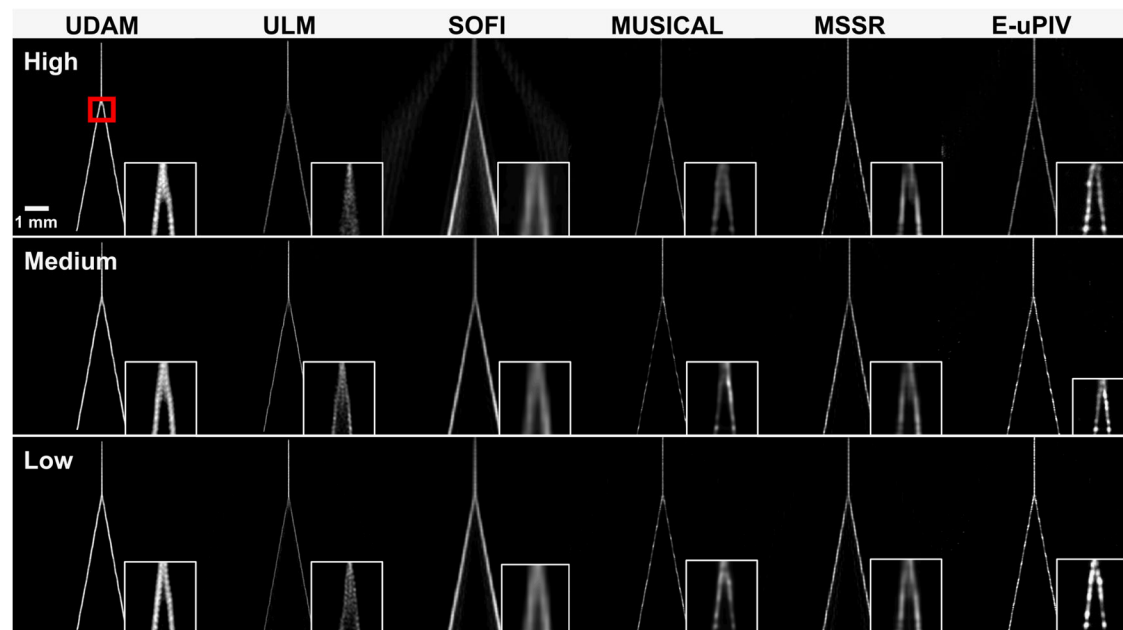
Supplementary Tables 1 to 2

Supplementary Note 1

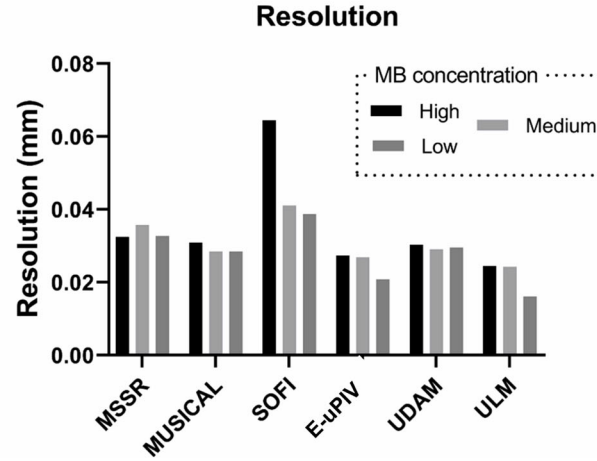
Supplementary Videos 1 to 2



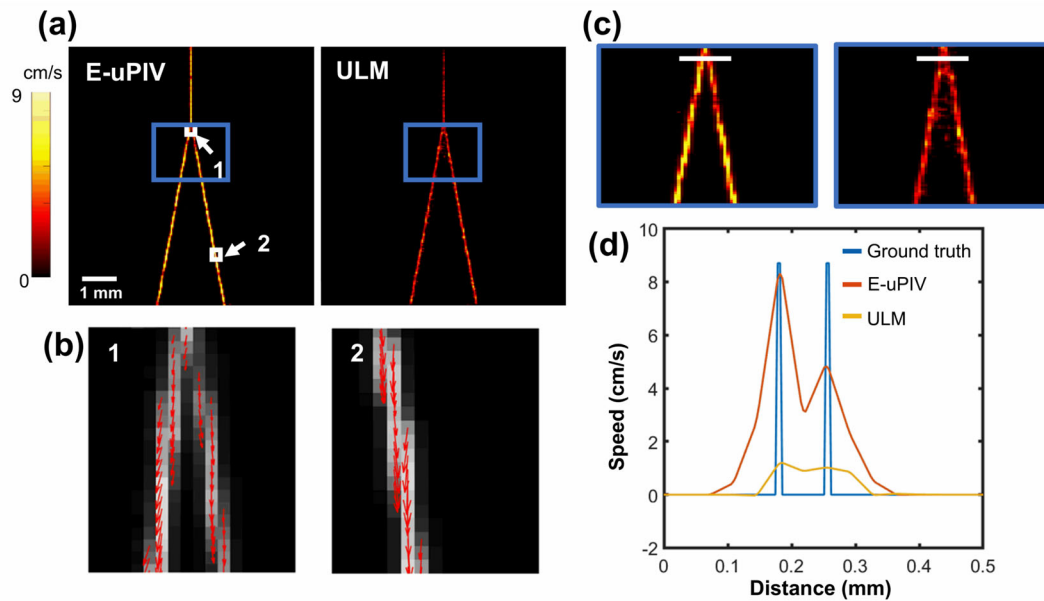
Supplementary Figure 1. Changes in microbubble perfusion for in vivo CEUS data. (a) Maximum intensity projection (MIP) of the CEUS image sequence over a typical period (4 s); (b) Variation of microbubble perfusion area ratio over time.



Supplementary Figure 2. Comparative analysis of super-resolved streamlines in simulation data under different microbubble concentrations (High, Medium, and Low). UDAM, ultrasound diffraction attenuation microscopy; ULM, ultrasound localization microscopy; SOFI, super-resolution optical fluctuation imaging; MUSICAL, multiple signal classification algorithm; MSSR, Mean-shift super resolution; E-uPIV, enhanced ultrasound particle image velocimetry.



Supplementary Figure 3. Spatial resolution estimation of resolved streamlines in simulation data under different microbubble concentrations (High, Medium, and Low). UDAM, ultrasound diffraction attenuation microscopy; ULM, ultrasound localization microscopy; SOFI, super-resolution optical fluctuation imaging; MUSICAL, multiple signal classification algorithm; MSSR, Mean-shift super resolution; E-uPIV, enhanced ultrasound particle image velocimetry. The spatial resolutions of super-resolved images are estimated through Fourier ring correlation (half bit).



Supplementary Figure 4. Comparison of flow velocity measurements in simulated data. (a) Flow velocity distribution maps from E-uPIV and ULM; (b) Vector flow distribution of the sampling region within the white box in (a) using E-uPIV, where arrow directions represent the measured flow direction and arrow lengths are normalized for display, with the vector flow image overlaid on the streamline structure reconstructed by E-uPIV (grayscale image); (c) Enlarged flow velocity distribution at the bifurcation, with the local area marked by the blue box in (a); (d) Flow velocity distribution along the white line in (c).

Supplementary Table 1. Parameters in the Verasonics simulator

Parameter	Value
Central frequency	7.8 MHz
Excitation pulse	Sinusoid
Pulse cycles	2
Sound velocity	1540 m/s
Sampling frequency	270 μ m
Pitch	0.3 mm
Kerf	30 μ m
Imaging mode	Plane wave
Number of frames	1000

MHz=megahertz

Supplementary Table 2. Fourier ring correlation resolution estimates

	Mouse brain (half bit)	Mouse brain (Fixed 1/7)
uPIV	193.171	127.385
E-uPIV	42.352	29.303

Unit: μ m; uPIV: ultrasound particle image velocimetry; E-uPIV: enhanced ultrasound particle image velocimetry.

Supplementary Note 1

For the separation of signal subspace $\mathbf{R}$ and null subspace $\mathbf{N}$, the optimal σ_0 for all sliding windows need to be determined. In this study, σ_0 is chosen to be slightly less than the value where a knee feature is observed in the logarithmic plot of singular values (x axis: the i th singular value, y axis: $\log_{10}\sigma_i$) of all the sliding windows. This knee feature is characterized by the point before which singular values show a fast-decaying characteristics and after which the singular values decay slowly. The exact σ_0 based on all logarithmic plots of singular values is empirically determined.

Supplementary Movie 1: Simulated data with different concentrations.

Supplementary Movie 2: Dynamic flow measurement results of E-uPIV in the mouse brain.