SUper-Resolution ultrasound imaging using the Erythrocytes (SURE)

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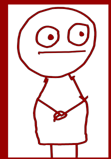
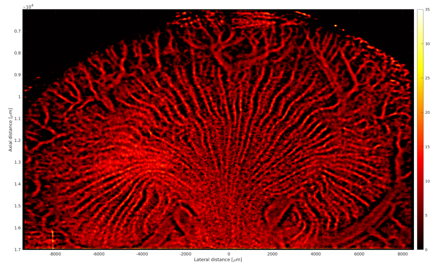


Outline

- Limitation of super resolution ultrasound imaging with MB (ULM)
  - Current approach
  - Limitations for clinical use
- SURE: SUper Resolution ultrasound imaging using the Erythrocytes
  - Processing pipeline
  - Field II simulated phantom
  - 3-D Printed phantom
  - In vivo rat experiments
  - Comparison to micro-CT and ULM
  - Human studies
- Summary

5 Seconds of SURE



Advantages of SRI with microbubbles:

- Sparse distribution of microbubbles ➔ Easy isolation

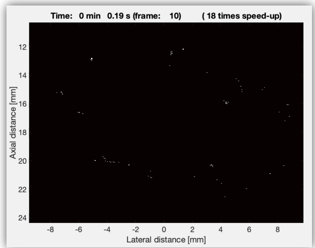
Disadvantages of SRI with microbubbles:

1- Time limitation:

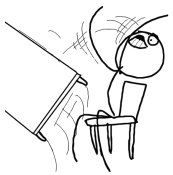
- Long acquisition in minutes (ex. 1-10 mins)
- Movement of probe and organ
- Blood flow and pressure changes over time so organ volume can vary

2- Bubble trouble:

- Fragile microbubbles
- Enough but not too many
- Bubbles are lost over time
- Bubbles are killed by the emission pressure from the probe
- Low MI gives low SNR for image

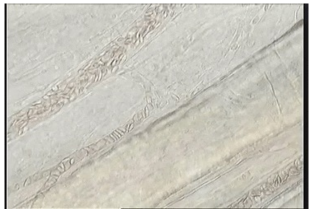


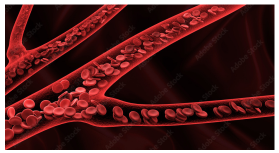
10 min Super Resolution Image



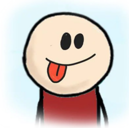
Super-resolution without contrast agents

SUper Resolution ultrasound imaging using Erythrocytes (SURE)



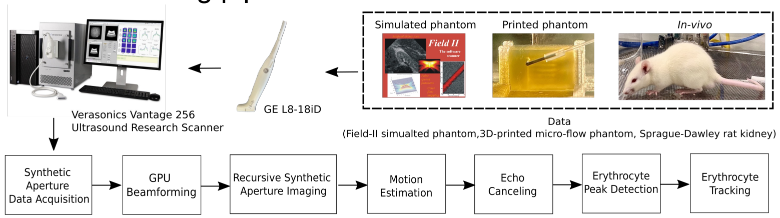


- Using Erythrocytes (red blood cells) as the target instead of fragile MBs.
- Abundance of targets (5 million cells per mm3)
- Non-invasive, contrast free ultrasound
- Fast Imaging, Real time (seconds)
- Full MI can be used (1.9 below FDA, 0.05-0.2 for SRI)



- J. A. Jensen et. al, "Fast super resolution ultrasound imaging using the erythrocytes," SPIE Medical Imaging 2022
- J. A. Jensen et al., "In Vivo Super Resolution Ultrasound Imaging using the Erythrocytes - SURE," IUS 2022

SURE tracking pipeline



- 10 MHz GE L8-18i Hockey stick probe
- SA sequence: 12 emissions
- Frame rate: 416.7 Hz
- Verasonics Vantage 256 scanner

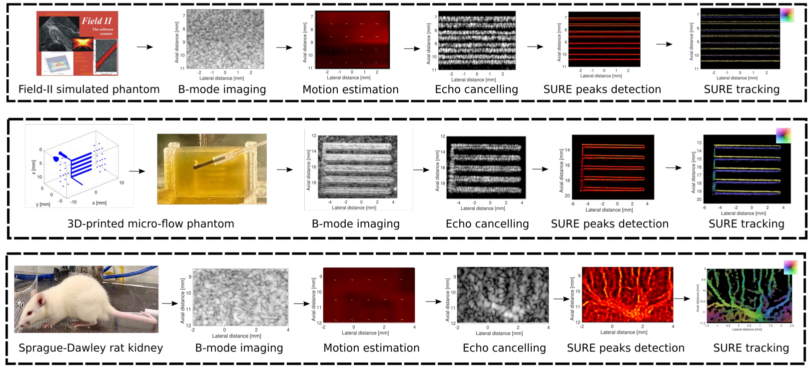
J. A. Jensen et al., "Fast super resolution ultrasound imaging using the erythrocytes," SPIE Medical Imaging 2022

J. A. Jensen et al., "In Vivo Super Resolution Ultrasound Imaging using the Erythrocytes - SURE," IUS 2022

M. Amin-Naji et al., "Super Resolution Ultrasound Imaging Using the Erythrocytes: II: Velocity Images", TUFFC 2024.

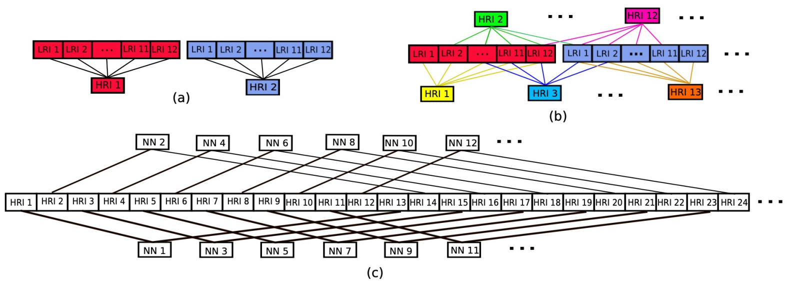
J.A. Jensen et al., "Super Resolution Ultrasound Imaging Using the Erythrocytes: I: Density Images", TUFFC 2024.

SURE validation setup



M. Amin-Naji et al., "Super Resolution Ultrasound Imaging Using the Erythrocytes: II: Velocity Images", TUFFC 2024.

Recursive SA Imaging Recursive Nearest Neighbour (NN) tracker



LRI: Low-Resolution Image

HRI: High-Resolution Image

(a) Normal Synthetic Aperture (SA) imaging

(b) Recursive SA imaging

Frame rate from 208.3 to 2500 Hz

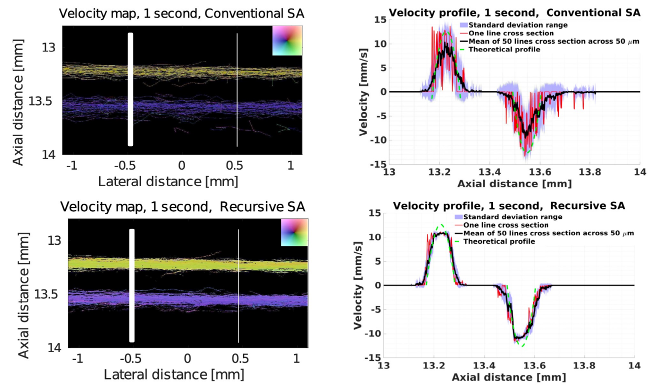
M. Amin-Naji et al., "Super Resolution Ultrasound Imaging Using the Erythrocytes: II: Velocity Images", TUFFC 2024.

M. Amin-Naji et. al, "Super Resolution Ultrasound using Recursive Imaging of Highly Dense Scatterers," IUS 2022.

M. Amin-Naji et. al, "Recursive Imaging for Tracking High Density Scatterers in Super-Resolution Imaging", IUS 2023.

J.A. Jensen, "Recursive ultrasound imaging", *Proc. IEEE Ultrason. Symp.*, vol. 2, pp. 1999.

Recursive SA Imaging Recursive NN tracker



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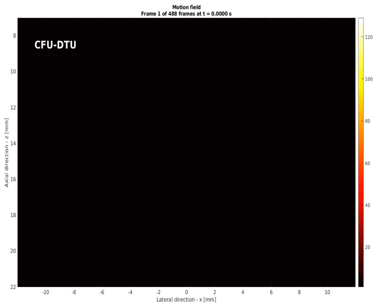
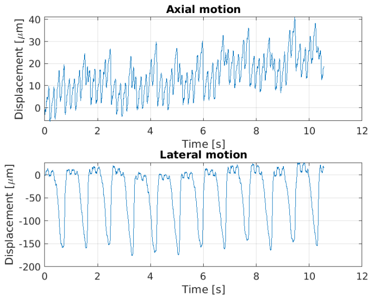
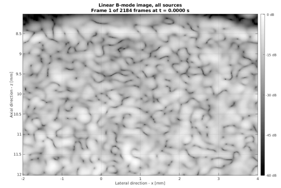
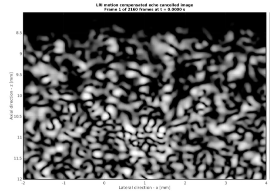
Motion estimation





Tissue signal removal

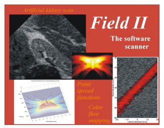




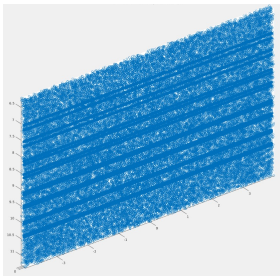
- Spatial Align all images to a reference frame
- Singular value decomposition (SVD) made
- First singular values removed as tissue
- Middle values are kept; the rest is noise
- SVD is applied on every 400 frames with SVD
- Accumulation of peak positions

Field II simulated phantom

Actual tube distance (wall-to-wall)	Actual tube distance (center-to-center)	Estimated tube distance (center-to-center)
125 µm (0.81λ)	150 µm (0.97λ)	146 µm
125 µm (0.81λ)	150 µm (0.97λ)	146 µm
75 µm (0.48λ)	100 µm (0.65λ)	103 µm
75 µm (0.48λ)	100 µm (0.65λ)	99 µm
45 µm (0.29λ)	70 µm (0.45λ)	70 µm
45 µm (0.29λ)	70 µm (0.45λ)	67 µm
25 µm (0.16λ)	50 µm (0.32λ)	54 µm
25 µm (0.16λ)	50 µm (0.32λ)	50 µm



Distances <λ/2
=
Super Resolution



- Eight tube pairs (r=12.5 µm) were simulated using Field-II
- The flow directions are in the same and opposite directions
- wavelength of 154 µm.
- 250,000 scatterers for moving tissue
- 200,000 scatterers inside the tubes
- 11,400 scatterers per resolution cell.

M. Amin-Naji et. al, "Super Resolution Ultrasound using Recursive Imaging of Highly Dense Scatterers," IUS 2022.
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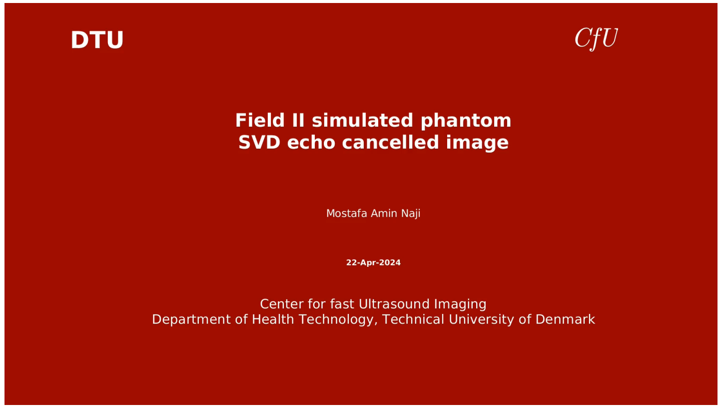
Field II simulated phantom



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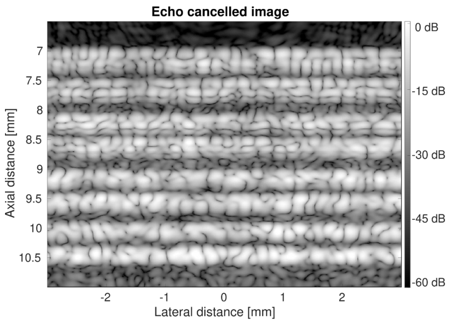
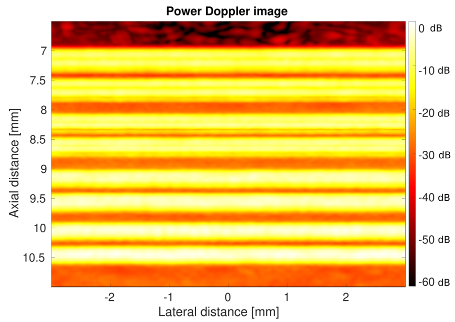
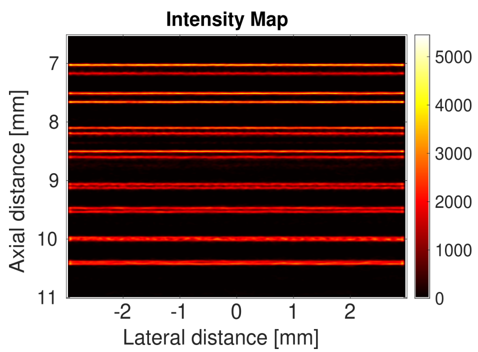
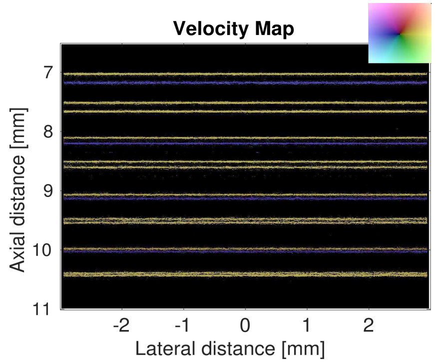




Field II simulated phantom





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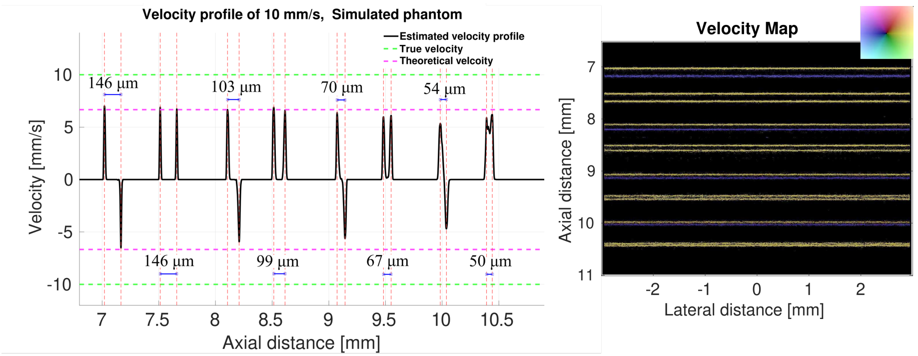
Field II simulated phantom



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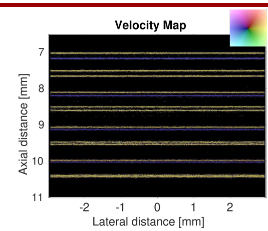
Field II simulated phantom



Actual tube distance (wall-to-wall)	Actual tube distance (center-to-center)	Estimated tube distance (center-to-center)	Distance error	Estimated peak velocity		Velocity underestimation	
125 µm (0.81λ)	150 µm (0.97λ)	146 µm	4 µm	+7.0 mm/s	-6.5 mm/s	30%	35%
125 µm (0.81λ)	150 µm (0.97λ)	146 µm	4 µm	+6.9 mm/s	+6.7 mm/s	31%	33%
75 µm (0.48λ)	100 µm (0.65λ)	103 µm	3 µm	+6.7 mm/s	-5.9 mm/s	31%	41%
75 µm (0.48λ)	100 µm (0.65λ)	99 µm	1 µm	+6.9 mm/s	+6.6 mm/s	31%	34%
45 µm (0.29λ)	70 µm (0.45λ)	70 µm	0 µm	+6.4 mm/s	-5.6 mm/s	36%	44%
45 µm (0.29λ)	70 µm (0.45λ)	67 µm	3 µm	+6.0 mm/s	+6.1 mm/s	39%	36%
25 µm (0.16λ)	50 µm (0.32λ)	54 µm	4 µm	+5.3 mm/s	-4.7 mm/s	47%	53%
25 µm (0.16λ)	50 µm (0.32λ)	50 µm	0 µm	+5.9 mm/s	+6.2 mm/s	39%	38%

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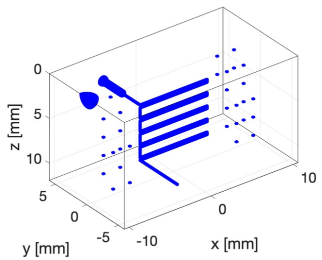
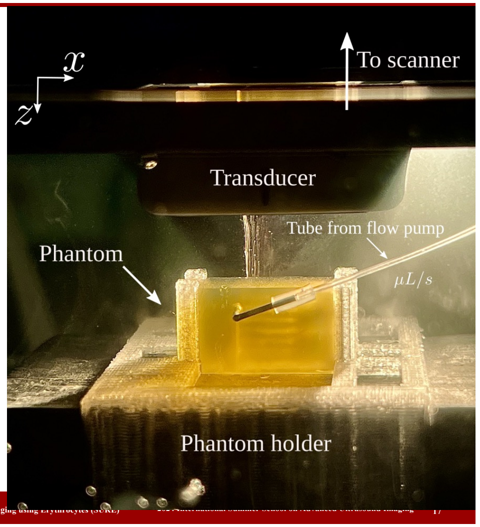
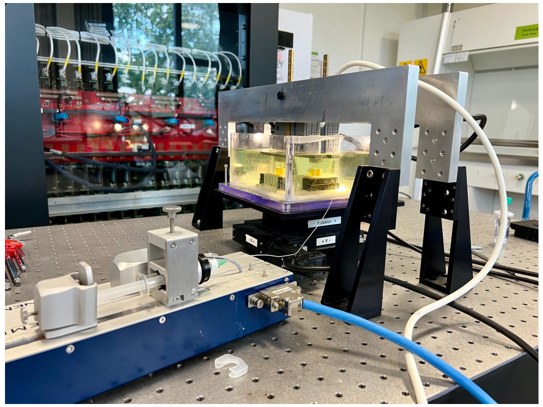
3-D hydrogel Printed Phantom

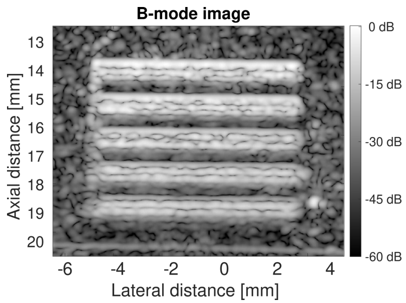


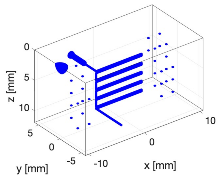


3-D hydrogel Printed Phantom



3-D hydrogel Printed Phantom





Actual tube distance (wall-to-wall)	Actual tube distance (center-to-center)	Estimated tube distance (center-to-center)
100 µm (0.64 λ)	300 µm	305 µm
90 µm (0.58 λ)	290 µm	298 µm
80 µm (0.51 λ)	280 µm	289 µm
70 µm (0.45 λ)	270 µm	274 µm
60 µm (0.38 λ)	260 µm	265 µm

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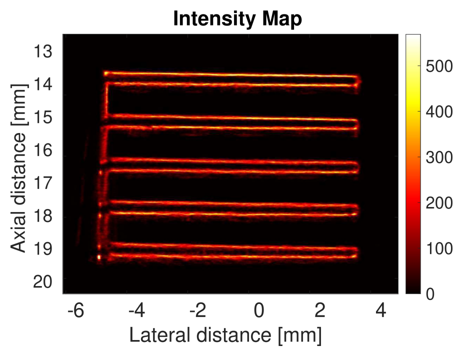
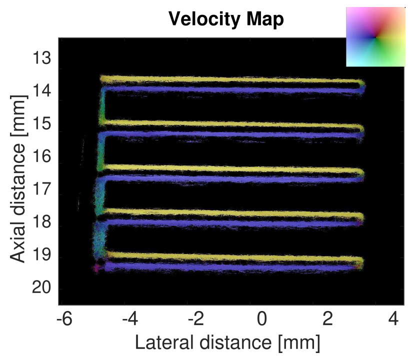
3-D hydrogel Printed Phantom





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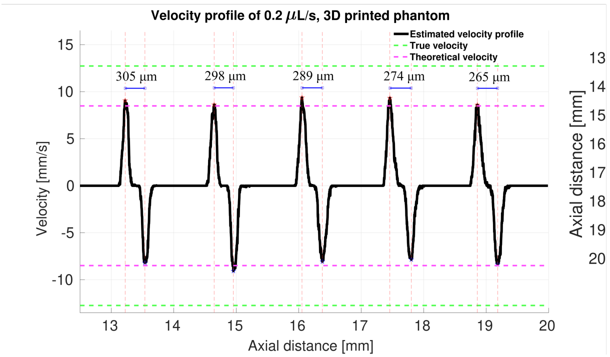
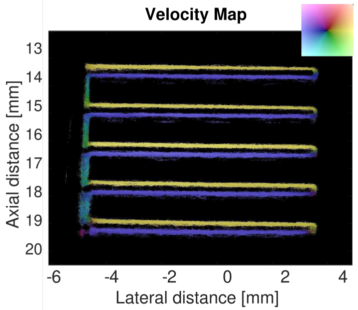
3-D hydrogel Printed Phantom





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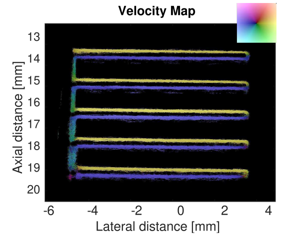
3-D hydrogel Printed Phantom



Actual tube distance (wall-to-wall)	Actual tube distance (center-to-center)	Estimated tube distance (center-to-center)	Distance error	Estimated peak velocity		Velocity underestimation	
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75 µm (0.45λ)	100 µm (0.60λ)	103 µm	3 µm	+6.7 mm/s	-5.9 mm/s	31%	41%
75 µm (0.45λ)	100 µm (0.60λ)	99 µm	1 µm	+6.9 mm/s	+6.6 mm/s	31%	34%
45 µm (0.27λ)	70 µm (0.42λ)	70 µm	0 µm	+6.4 mm/s	-5.6 mm/s	36%	44%
45 µm (0.27λ)	70 µm (0.42λ)	67 µm	3 µm	+6.0 mm/s	+6.1 mm/s	39%	36%
25 µm (0.15λ)	50 µm (0.30λ)	54 µm	4 µm	+5.3 mm/s	-4.7 mm/s	47%	53%
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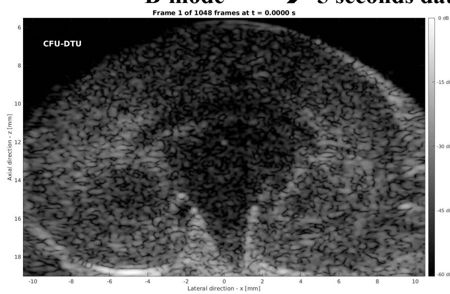
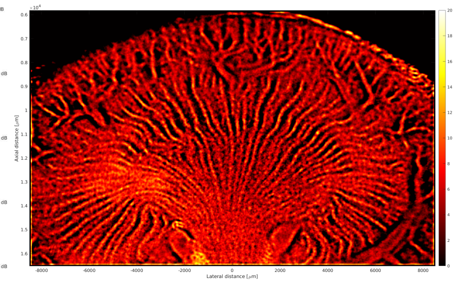
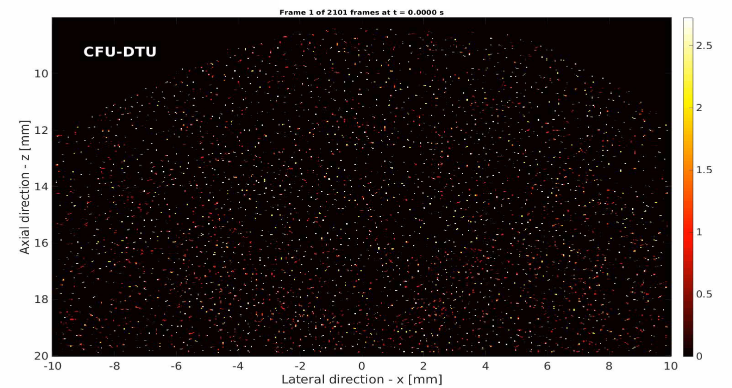
Sprague-Dawley rat kidney

B-mode ➔ 5 seconds data collection ➔ SURE



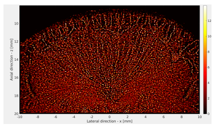


Time evolution of SURE images

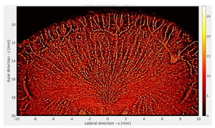


Time evolution of SURE images

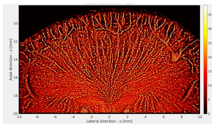
0.1 seconds



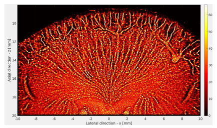
0.3 seconds



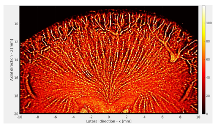
0.5 seconds



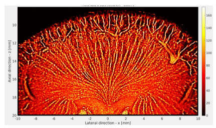
1 seconds



2 seconds

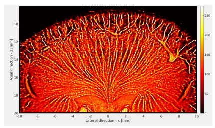


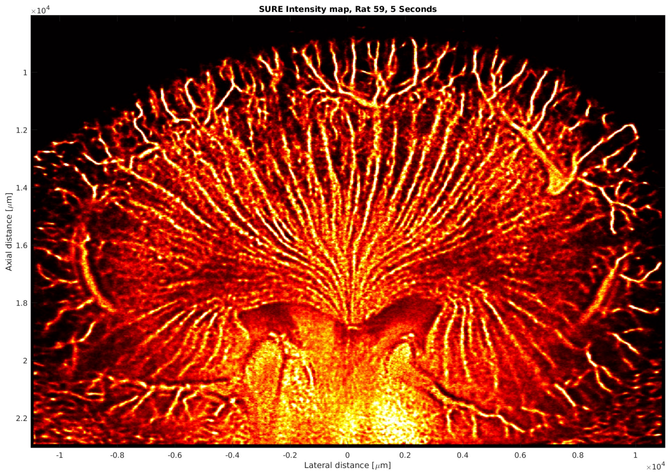
3 seconds



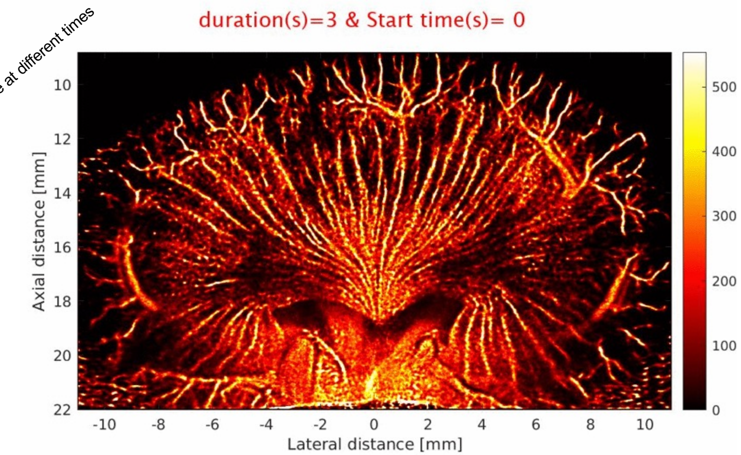
4 seconds

5 seconds

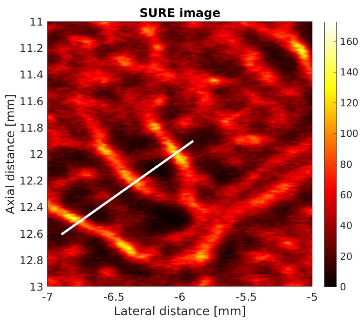


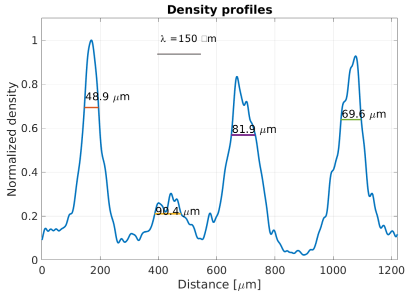


SURE in reliable at different times



Resolution *in vivo*





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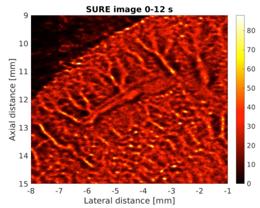
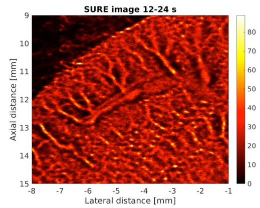
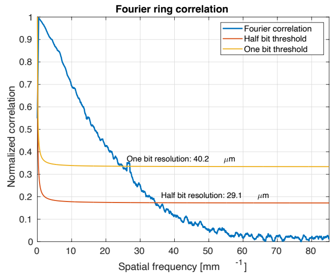
Fourier Ring Correlation: Correlation between two independent images

Resolution of 29 □m, wavelength 150 □m





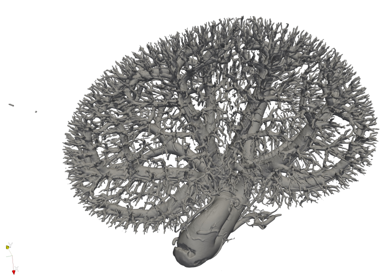


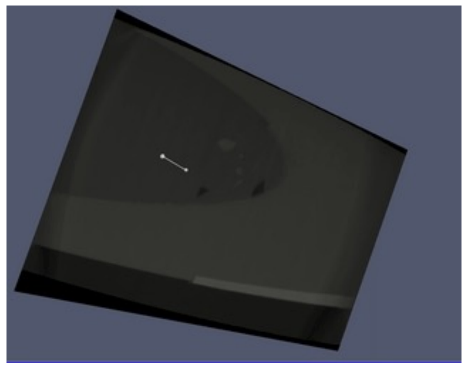
J.A. Jensen et al., "Super Resolution Ultrasound Imaging Using the Erythrocytes: I: Density Images", TUFFC 2024.

Micro-CT scans of Kidneys

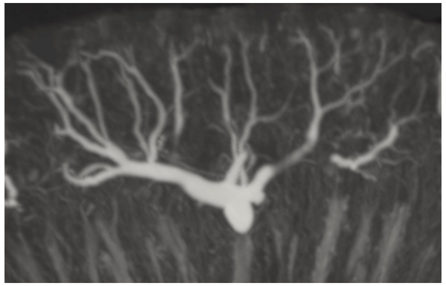
- Kidney excised, decapsulated, fixated in formaldehyde, and embedded in paraffin in custom-made cylinder-shaped holder.
  - Zeiss XRadia 410 Versa □CT scanner
  - Isotropic voxel sizes 22.6 and 5 □m
  - 360°scan around vertical axis with 3,201 different projections
- Scanned for 11 and 20 hours

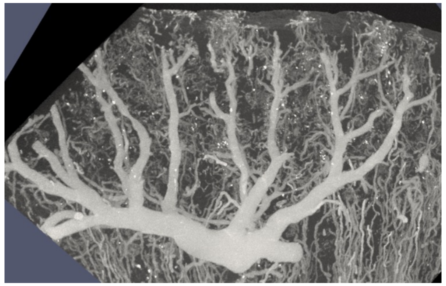
Micro-CT of Sprague-Dawley rat kidney





Micro-CT 26.5 μm & 5 μm
11 hours & 20 hours

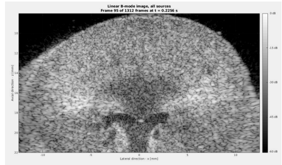




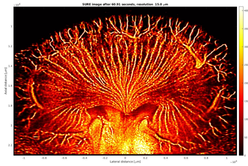
M. Amin-Naji et al., "Super Resolution Ultrasound Imaging Using the Erythrocytes: II: Velocity Images", TUFFC 2024.

SURE vs SRI vs micro-CT

B-mode

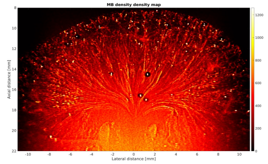


SURE intensity map (5 Sec)

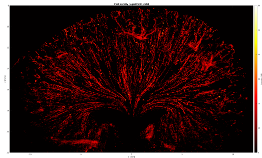


Micro-CT (10 h)

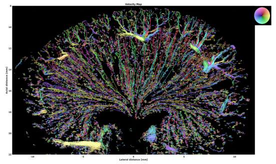
SRI MB density map (26 Sec)



SRI track density map (32 Sec)



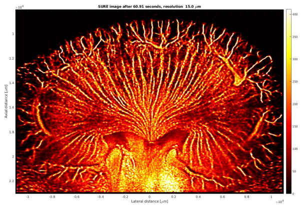
SRI velocity map (32 Sec)



M. Amin-Naji et al., "Super Resolution Ultrasound Imaging Using the Erythrocytes: II: Velocity Images", TUFFC 2024.

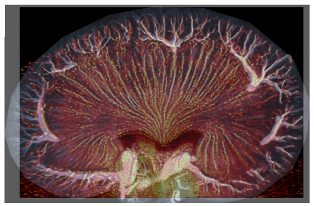
SURE vs micro-CT

SURE intensity map



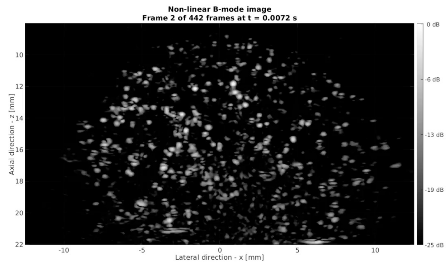
Micro-CT

SURE & micro-CT overlay

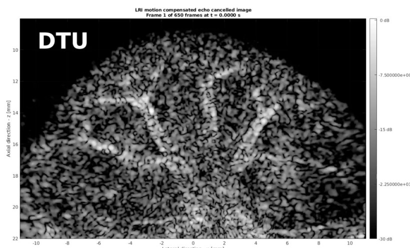


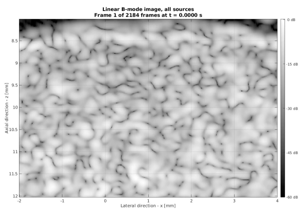
Rat 82, same rat, same plan, same position of probe

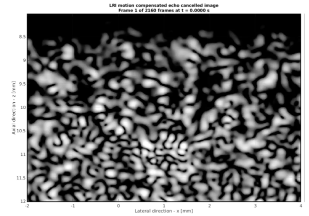
Microbubbles
(Non linear B mode)

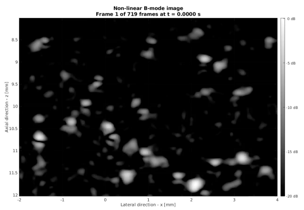


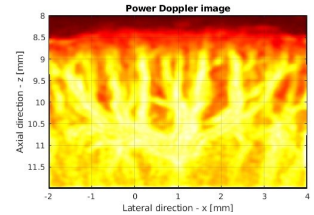
Erythrocytes
(After motion compensation and echo chancelling)



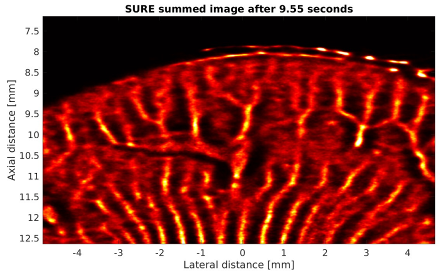


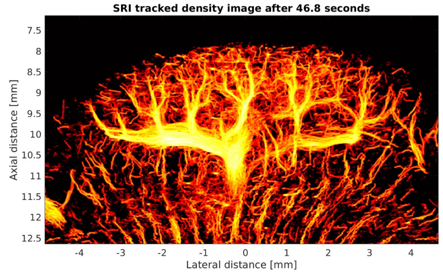






SURE vs ULM





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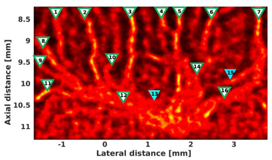
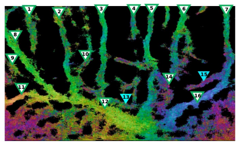
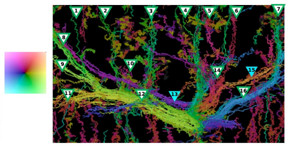
SURE, ULM, and micro-CT comparison



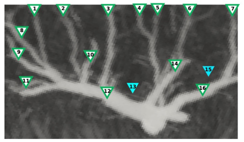
SURE intensity map, 3 seconds



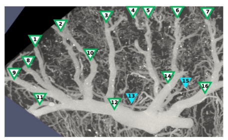
SURE velocity map, 3 seconds



ULM velocity map, 32 seconds



micro-CT, 26.5 µm, 11 hours



micro-CT, 5 µm, 20 hours

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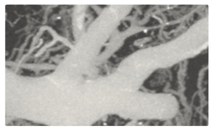
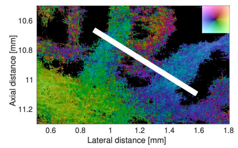
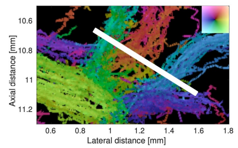
SURE, ULM, and micro-CT comparison



micro-CT, 5 µm

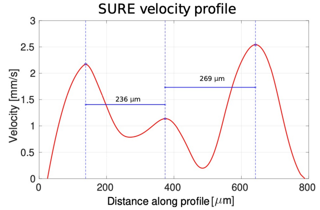


SURE velocity map

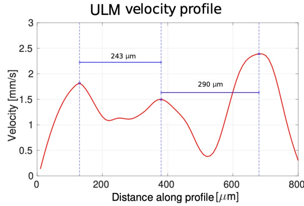


ULM velocity map

SURE velocity profile



ULM velocity profile



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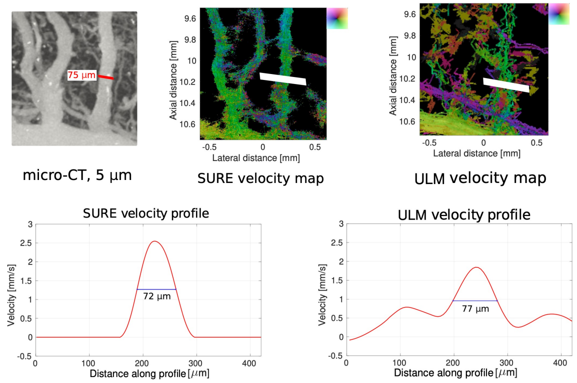
SURE, ULM, and micro-CT comparison



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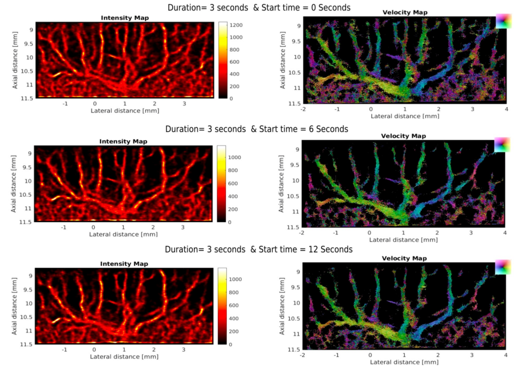
SURE consistency



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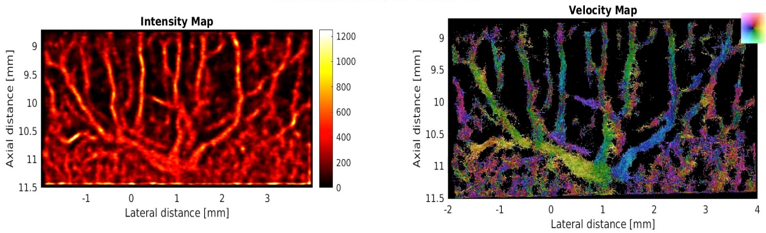
SURE consistency

duration(s)=3 & Start time(s)= 0



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Human study

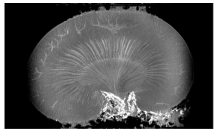
It will be included …

Conclusion

- Using Erythrocytes in SURE instead of microbubbles in SRI
- Don't have to inject anything
- Just 1-5 seconds is enough for SURE (not 10 minutes in SRI)

B-mode

MRI



Micro-CT

SRI

SURE

Do you want to ask questions?

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