2023 International Summer School on Advanced Ultrasound Imaging
Technical University of Denmark

SUper-Resolution ultrasound imaging using Erythrocytes (SURE)

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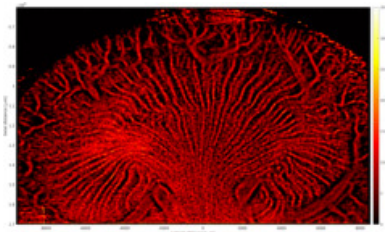
Outline

- Current super resolution imaging and limitations
  - Current approach
  - Limitations for clinical use
- SURE: SUper Resolution ultrasound imaging of Erythrocytes
  - Processing pipeline
  - Simulated phantom
  - Printed phantom
  - In vivo rat experiments
  - Comparison to micro-CT
- Summary

5 Seconds of SURE



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Advantages of SRI with microbubbles:

- Sparse distribution of microbubbles ➔ Easy isolation

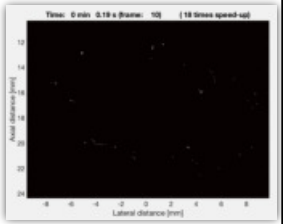
Disadvantages of SRI with microbubbles:

1- Time limitation:

- Long acquisition in minutes (ex. 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

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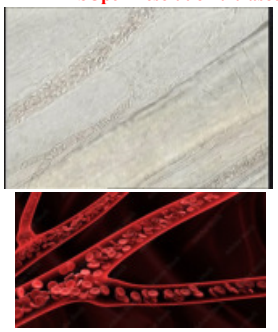
Super-resolution without contrast agents

SUper Resolution ultrasound imaging using Erythrocytes (SURE)



- Using Erythrocytes (red blood cells) as the target instead of fragile MBs.
- Abundance of targets
- Non-invasive, contrast free ultrasound
- Fast Imaging, Real time (seconds)
- Full MI can be used

- 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

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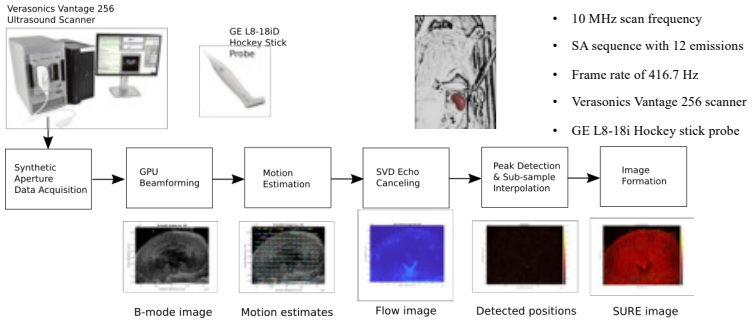
SURE pipeline stages for scanning of Sprague-Dawley rats



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

- 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

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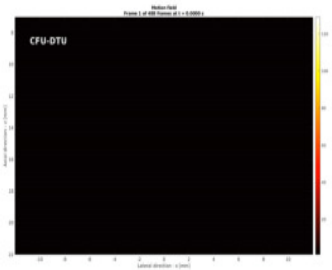
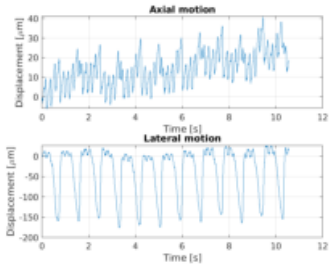
Motion estimation



- Motion field found as a function of space and time
- Speckle tracking (correlation) on envelope data
  3 x 3 mm patches, 50% overlap



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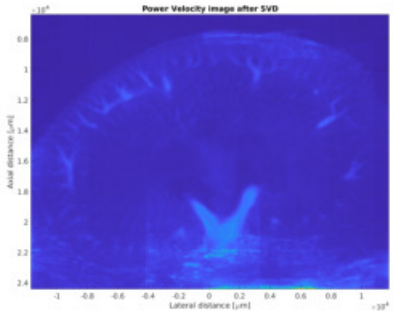
Tissue signal removal and detection



- Align all images to a reference frame
- Singular value decomposition (SVD) made
- First singular values removed (tissue)
- Middle values kept, rest is noise
- Detection of peaks

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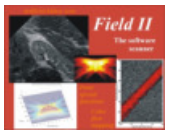
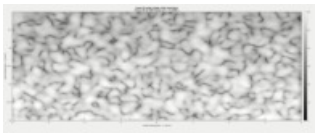
Is it Possible? Phantom Simulations using Field II

Parameter	Value
Time	2 seconds
Scatter density	175 λ^{-3}
Tubes distances #1	200 μm (1.33 λ)
Tubes distances #2	100 μm (0.67 λ)
Tubes distances #3	50 μm (0.33 λ)
Tubes distances #4	25 μm (0.17 λ)

- Four tube pairs (r=12.5 μm) simulated using Field-II
- wavelength of 154 μm.
- 30,000 scatterers for moving tissue
- 1,500 scatterers inside the tubes
- 175 scatterers per resolution cell.

Distances <λ/2
=
Super Resolution





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

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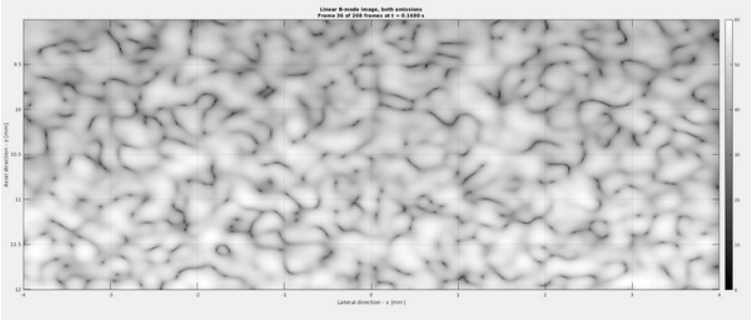
B-Mode images of 2 seconds



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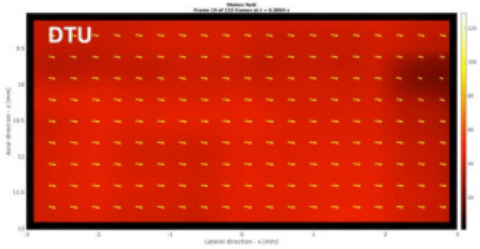
Motion estimation



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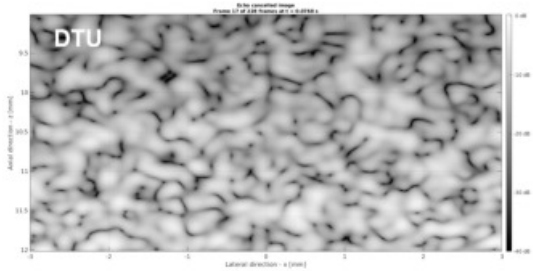
After motion compensation



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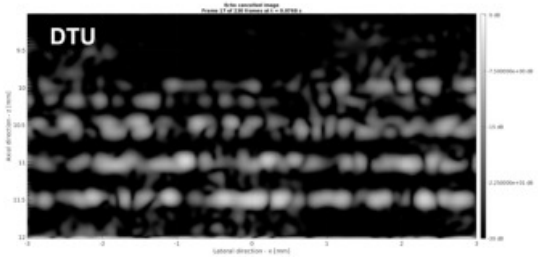
After echo canceling



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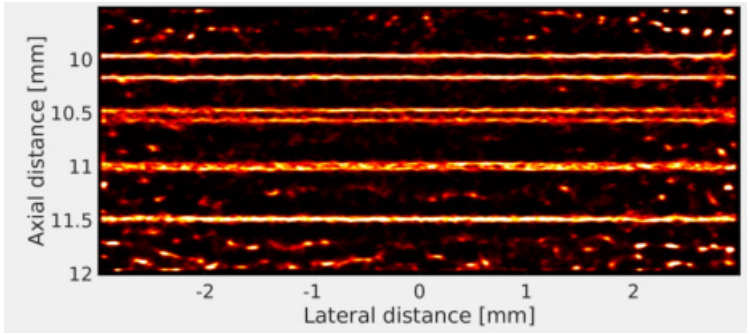
Intensity Map



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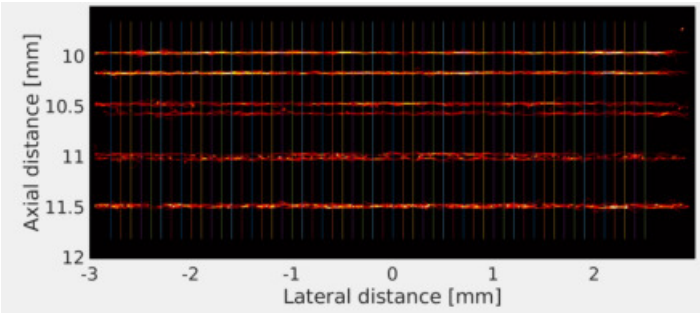
Track Density Map



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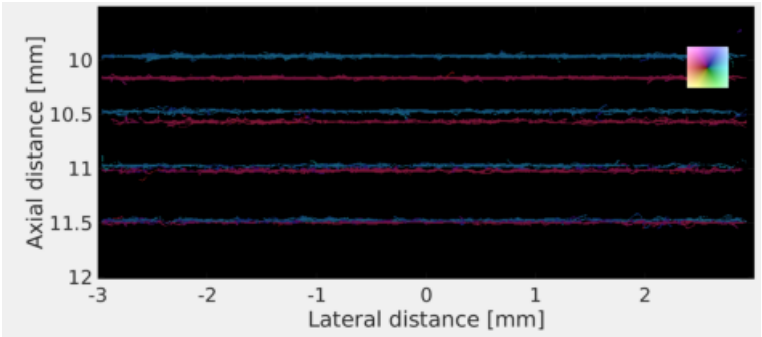
Velcoity Map



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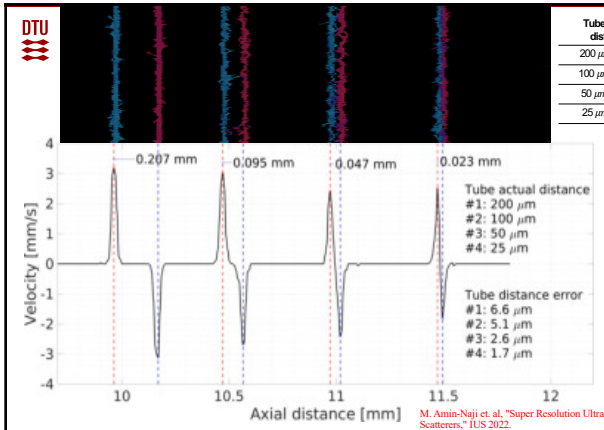

Tubes actual distances	Predicted distance	Error
200 μm (1.33 λ)	206.6 μm	6.6 μm
100 μm (0.67 λ)	94.9 μm	5.1 μm
50 μm (0.33 λ)	47.4 μm	2.6 μm
25 μm (0.17 λ)	23.3 μm	1.7 μm

Time = 2 Seconds

Scatterers density = 175 λ^{-3}

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

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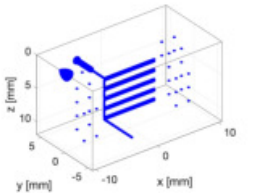
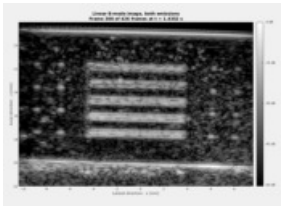
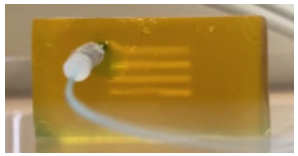
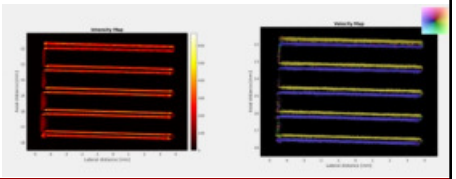
Printed Phantom Validation









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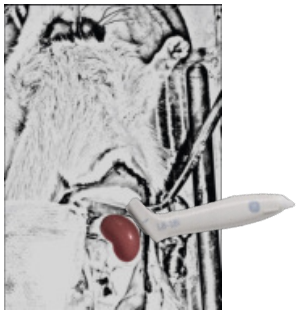
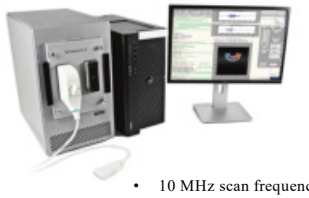
Scanning of Sprague-Dawley rats





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

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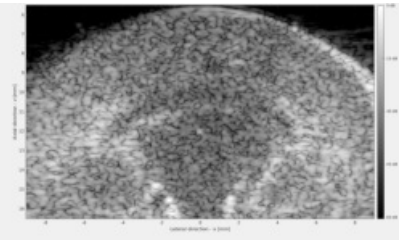
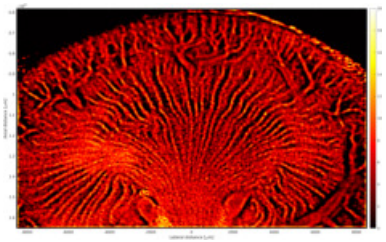
B-mode ➔ 5 seconds ➔ SURE





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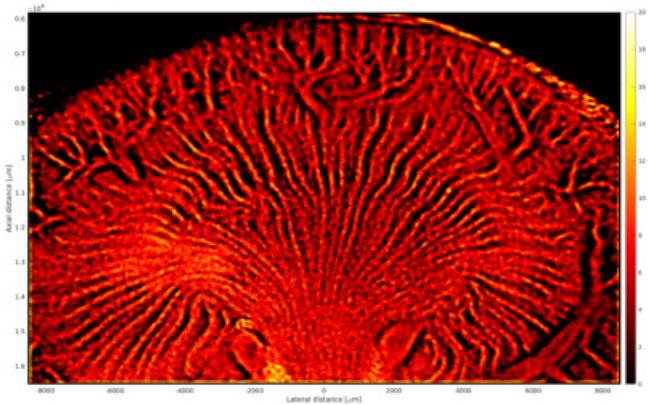

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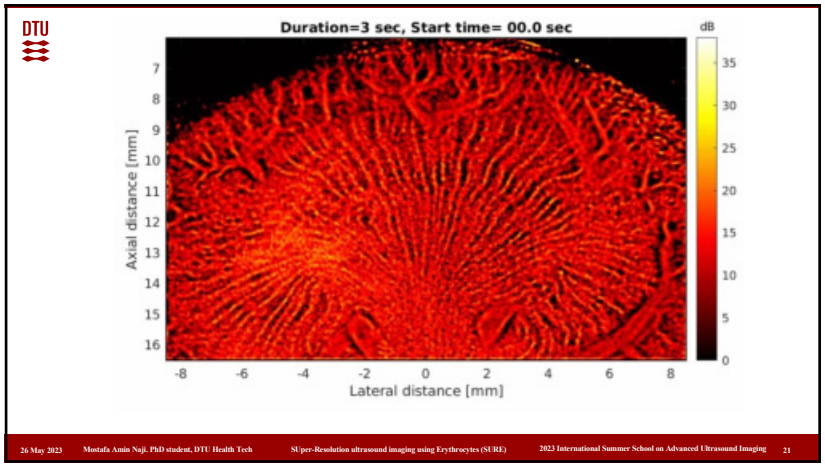
Duration=3 sec, Start time= 00.0 sec
dB
Axial distance [mm]
Lateral distance [mm]
26 May 2023 Mostafa Amin Naji, PhD student, DTU Health Tech SUper-Resolution ultrasound imaging using Erythrocytes (SURE) 2023 International Summer School on Advanced Ultrasound Imaging 21

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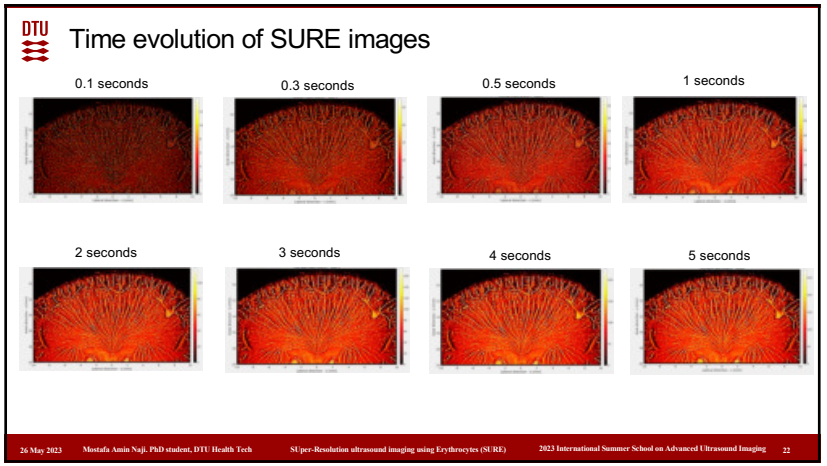
Time evolution of SURE images
0.1 seconds
0.3 seconds
0.5 seconds
1 seconds
2 seconds
3 seconds
4 seconds
5 seconds
26 May 2023 Mostafa Amin Naji, PhD student, DTU Health Tech SUper-Resolution ultrasound imaging using Erythrocytes (SURE) 2023 International Summer School on Advanced Ultrasound Imaging 22

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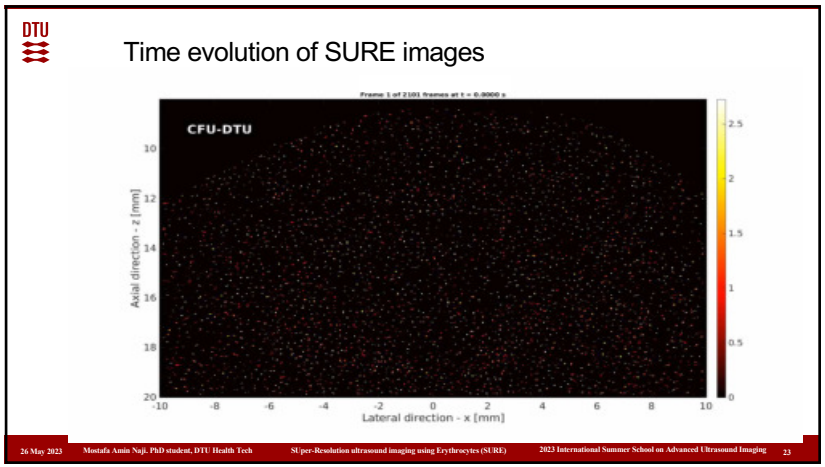
Time evolution of SURE images
CFU-DTU
Axial direction - z [mm]
Lateral direction - x [mm]
26 May 2023 Mostafa Amin Naji, PhD student, DTU Health Tech SUper-Resolution ultrasound imaging using Erythrocytes (SURE) 2023 International Summer School on Advanced Ultrasound Imaging 23

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duration(s)=3 & Start time(s)= 0
Axial distance [mm]
Lateral distance [mm]
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SURE Intensity map, Rat 59, 5 Seconds
Axial distance [μm]
Lateral distance [μm]
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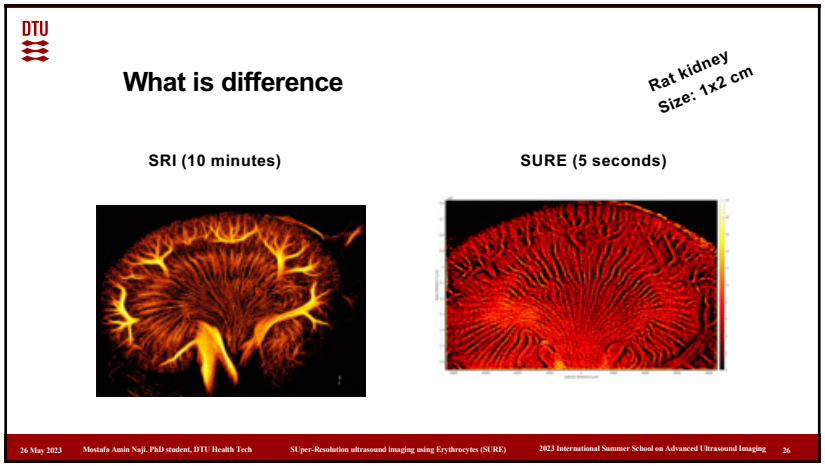
What is difference
Rat kidney
Size: 1x2 cm
SRI (10 minutes)
SURE (5 seconds)
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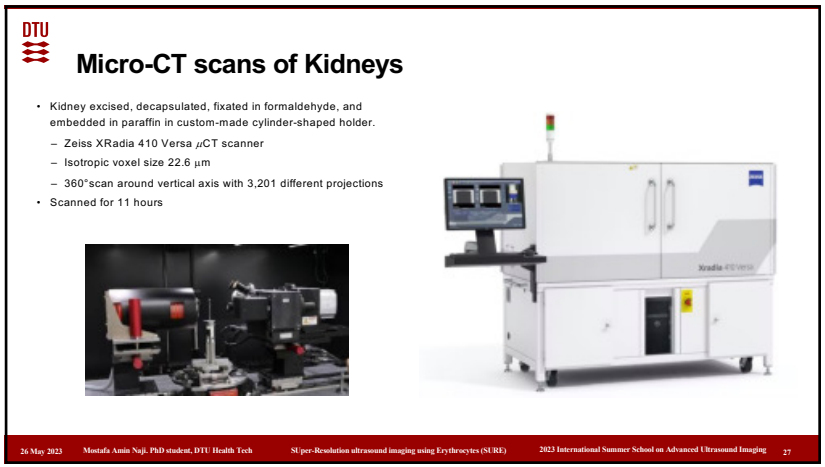
Micro-CT scans of Kidneys
• Kidney excised, decapsulated, fixated in formaldehyde, and embedded in paraffin in custom-made cylinder-shaped holder.
– Zeiss XRadia 410 Versa μCT scanner
– Isotropic voxel size 22.6 μm
– 360°scan around vertical axis with 3,201 different projections
• Scanned for 11 hours
26 May 2023 Mostafa Amin Naji, PhD student, DTU Health Tech SUper-Resolution ultrasound imaging using Erythrocytes (SURE) 2023 International Summer School on Advanced Ultrasound Imaging 27

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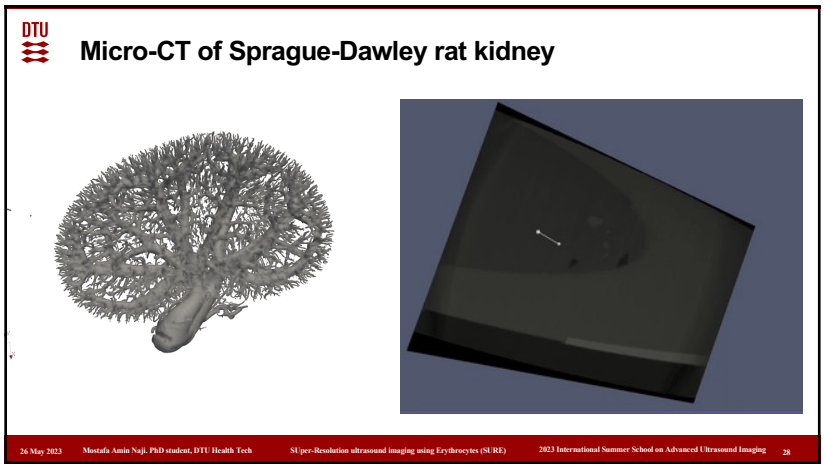
Micro-CT of Sprague-Dawley rat kidney
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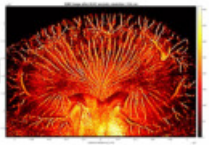
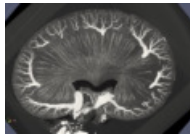
SURE vs micro-CT

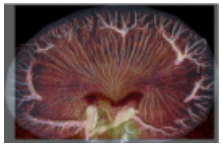
SURE intensity map



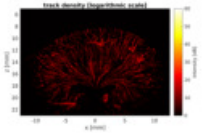
Micro-CT



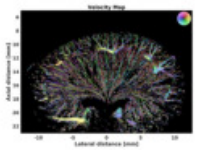
SURE & micro-CT overlay



SRI track density



SRI velocity map



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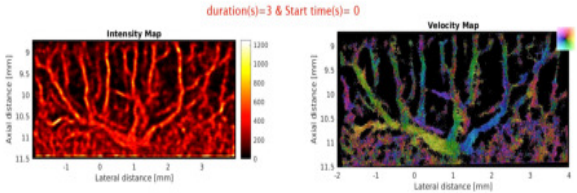

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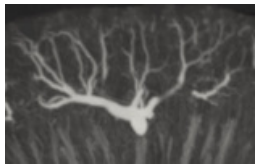
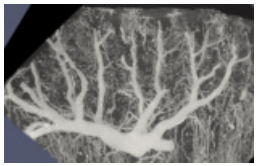
Micro-CT 26.5 μm & 5 μm





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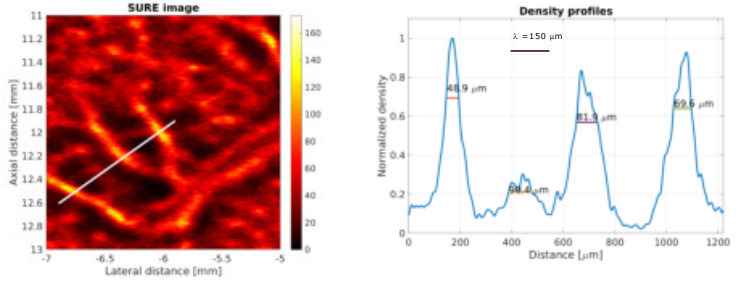
Resolution *in vivo*



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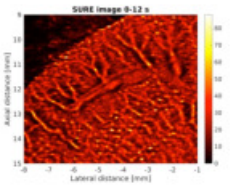
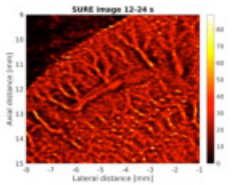
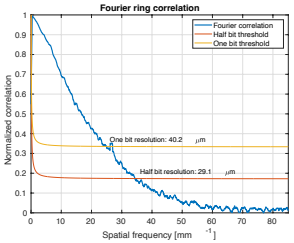
Fourier Ring Correlation:
Correlation between two independent images

Resolution of 29 μm, wavelength 150 μm







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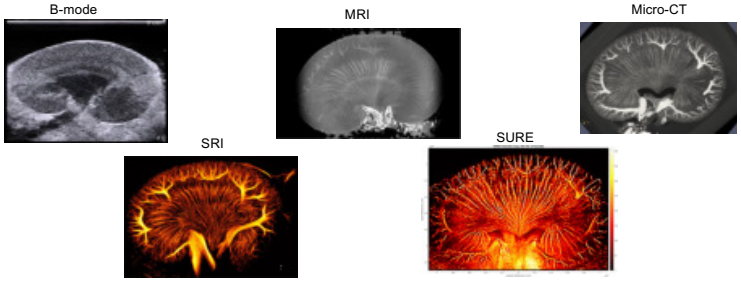
Conclusion

- Using Erythrocytes in SURE instead of microbubbles in SRI
- Don't have to inject anything
- SURE is 20-30 times faster than SRI
- Just 1-5 seconds is enough for SURE (not 10 minutes in SRI)



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