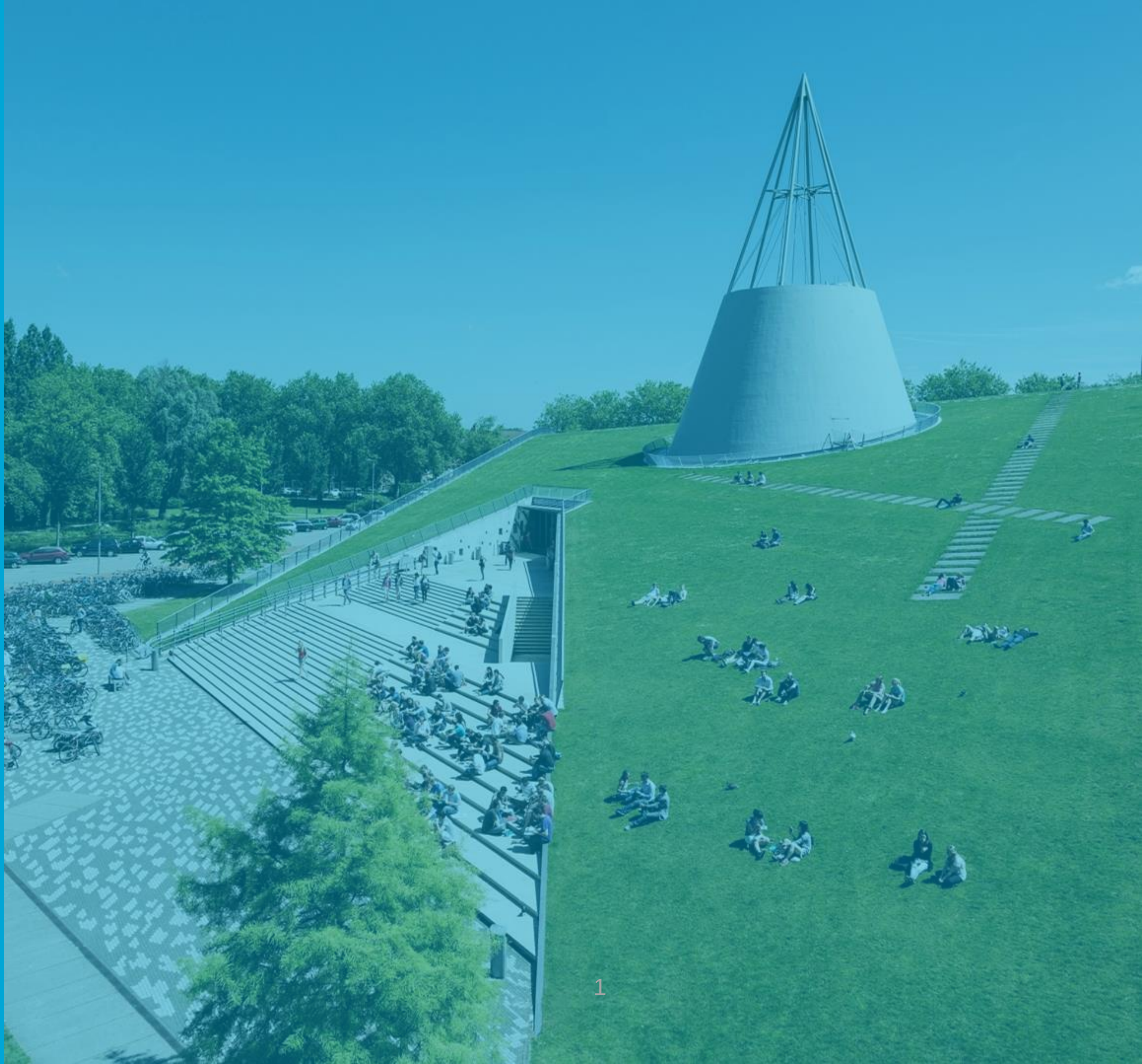
Ultrasound imaging inside and behind bone

Gabrielle Laloy-Borgna

Guillaume Renaud

TU Delft

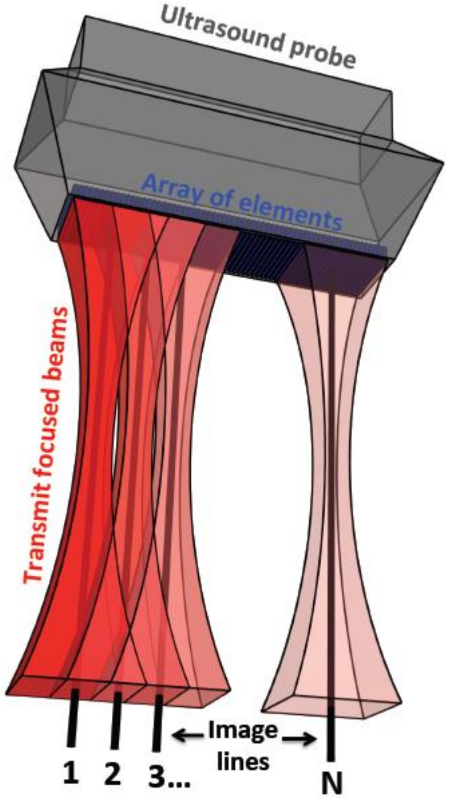


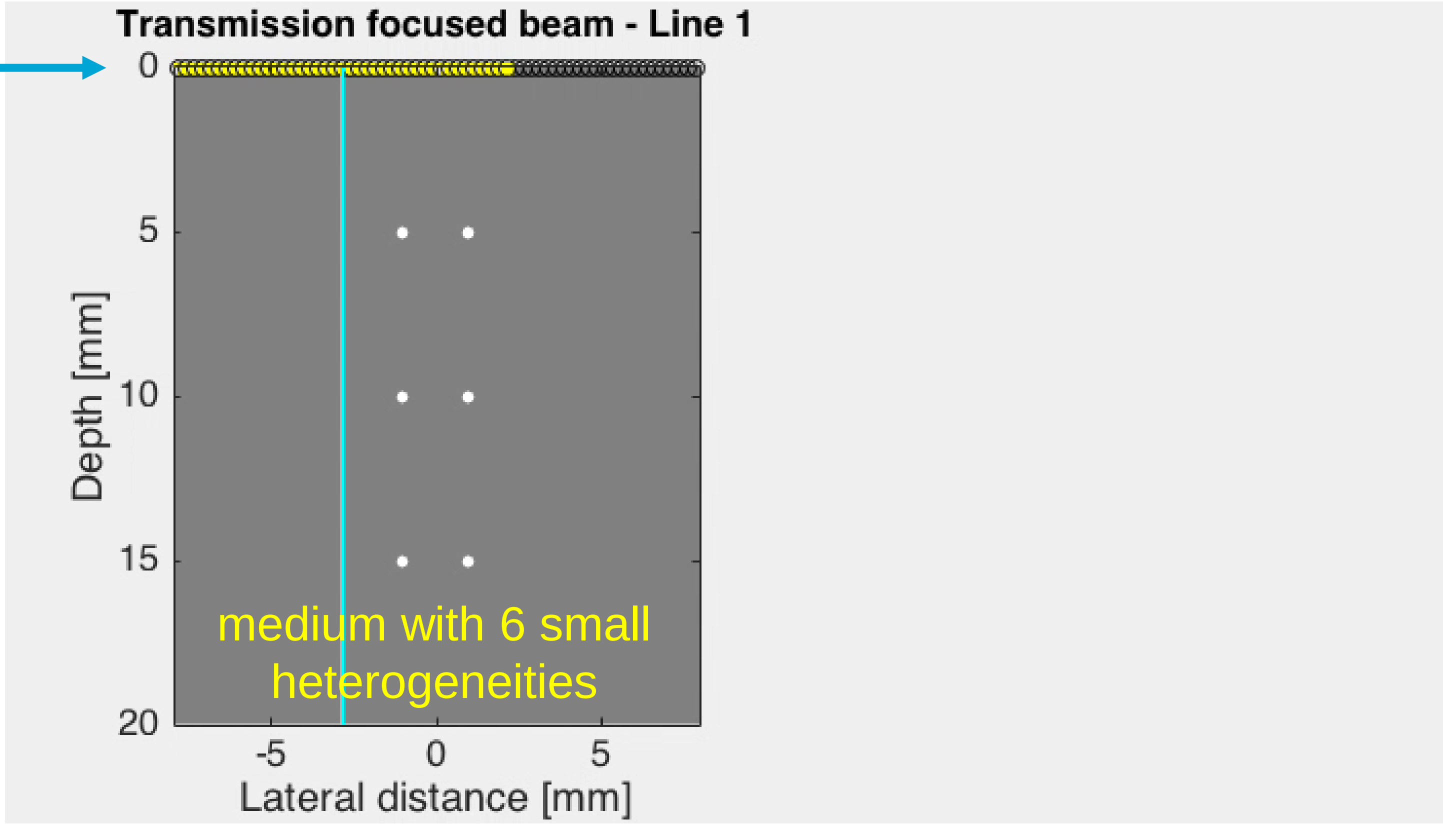
Traditional ultrasound imaging (best image quality but slow)

Line-by-line image formation with focused transmit beams

Any local variation in mass density or compressibility scatters the transmitted ultrasound wave

Each element is used as an emitter and receiver (piezoelectric material)



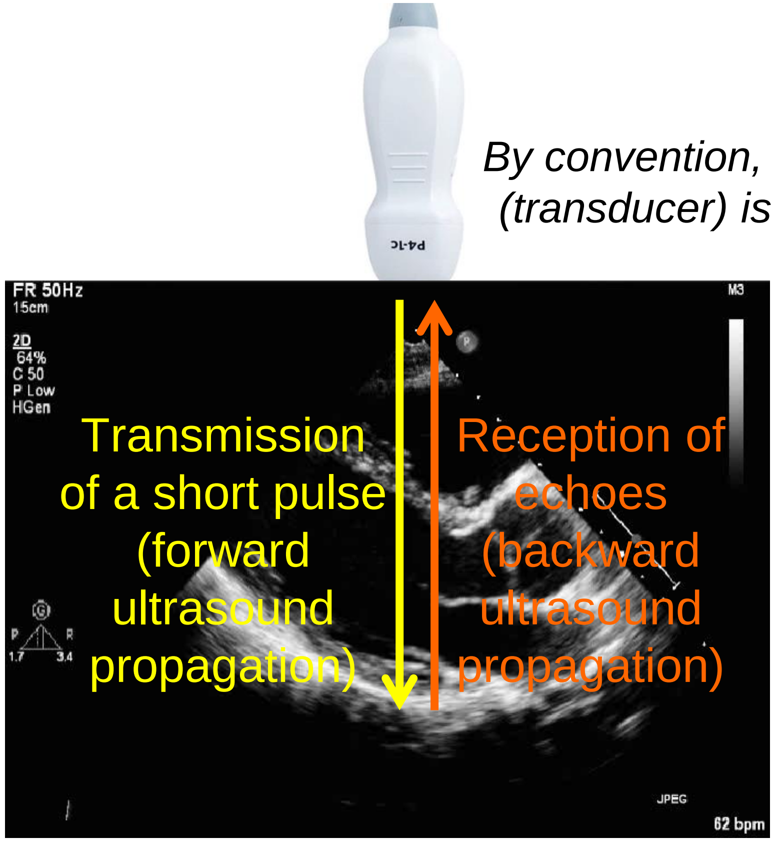


Traditional ultrasound imaging (best image quality but slow)

Line-by-line image formation with focused transmit beams

Limited to 50 images per second

By convention, ultrasound probe (transducer) is on top of image



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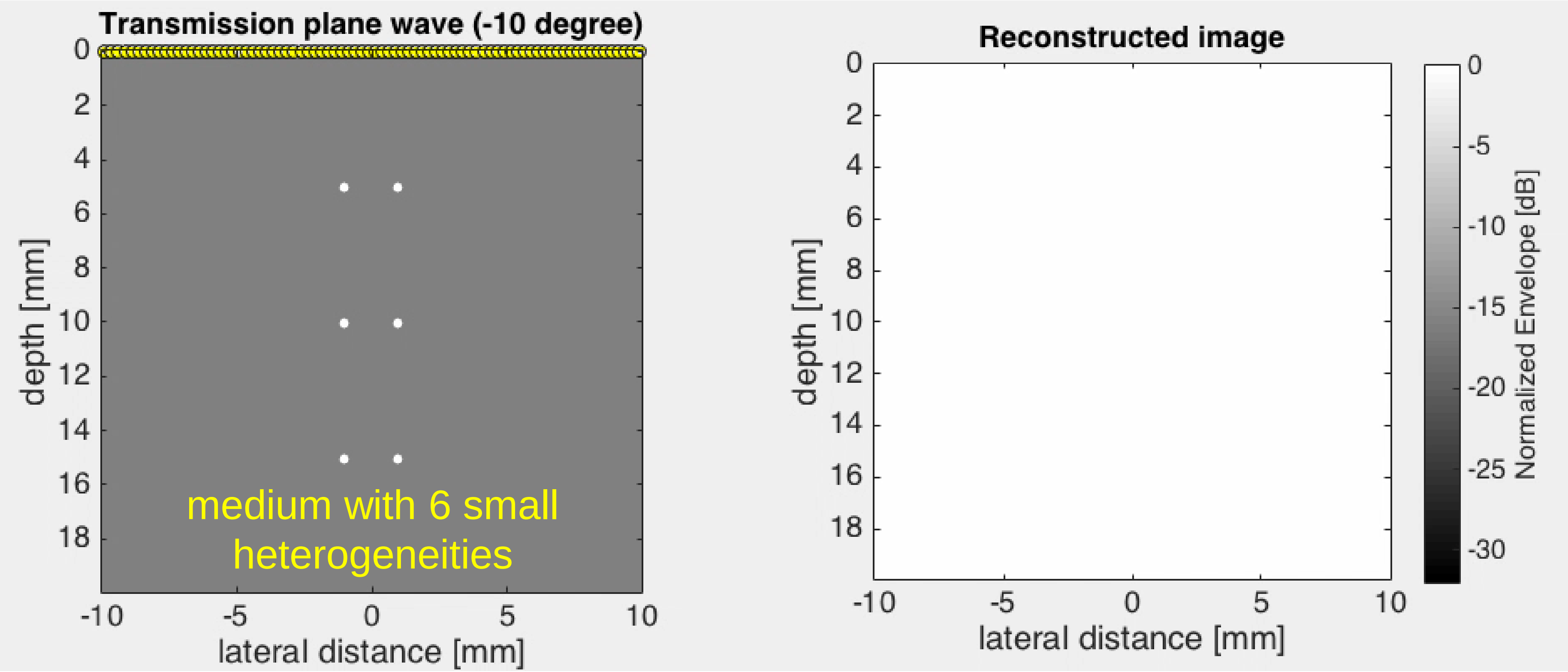
Modern ultrasound imaging (fast)

Full-image synchronous formation with unfocused transmit beams

Up to thousands of images per second



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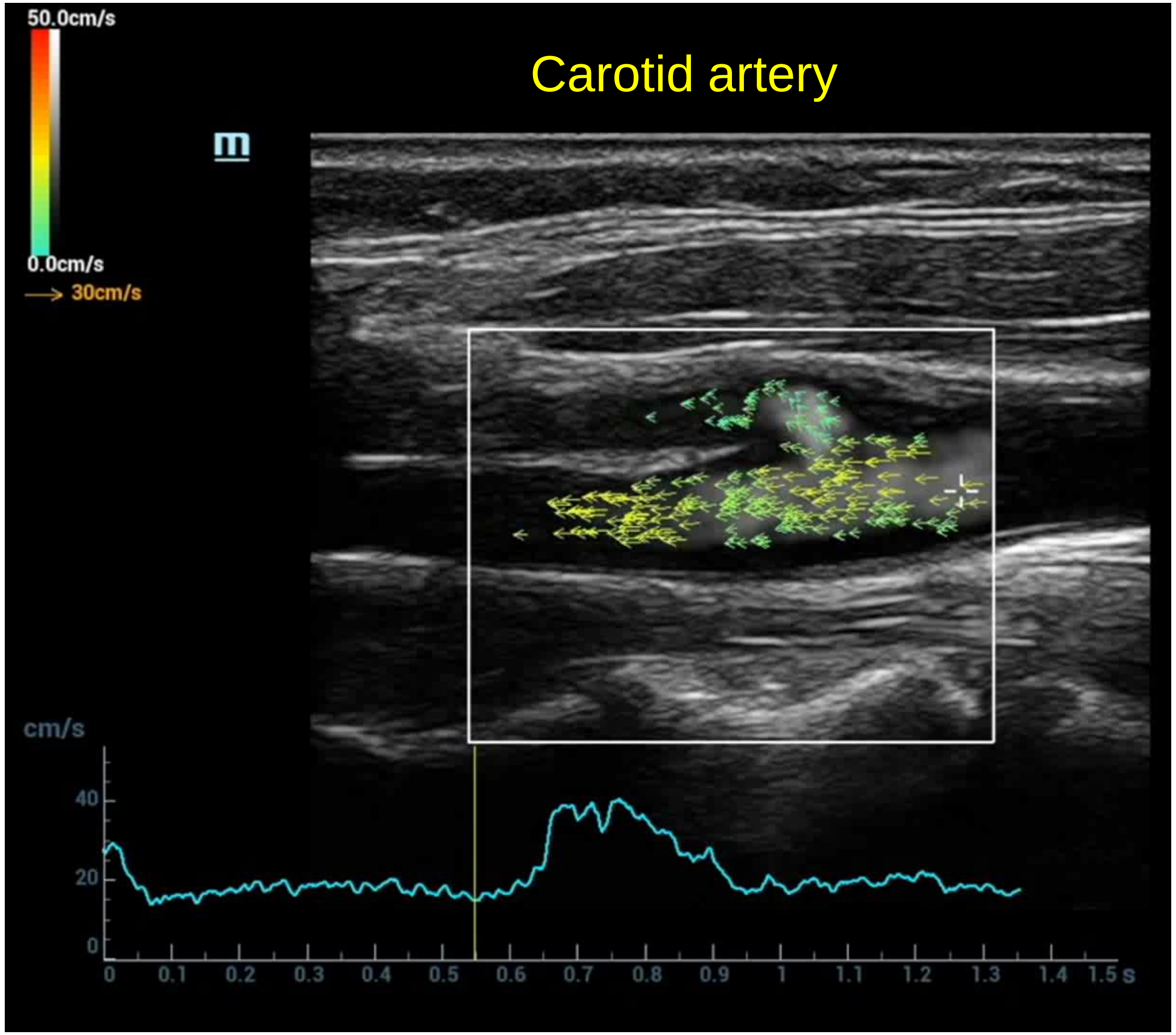
Modern ultrasound imaging (fast)

Full-image synchronous formation with unfocused transmit beams



Instantaneous **velocity** and **direction** of blood flow

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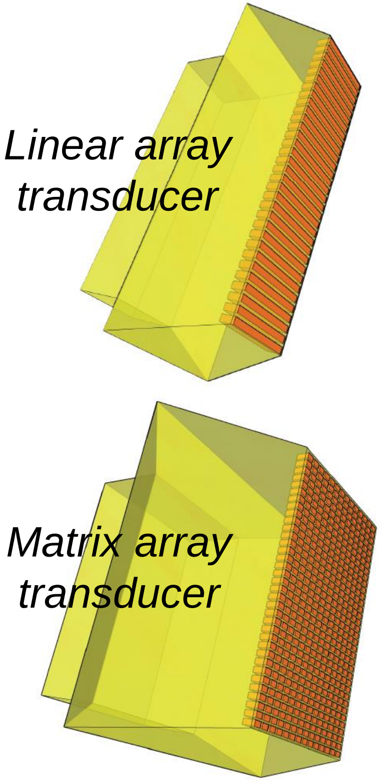
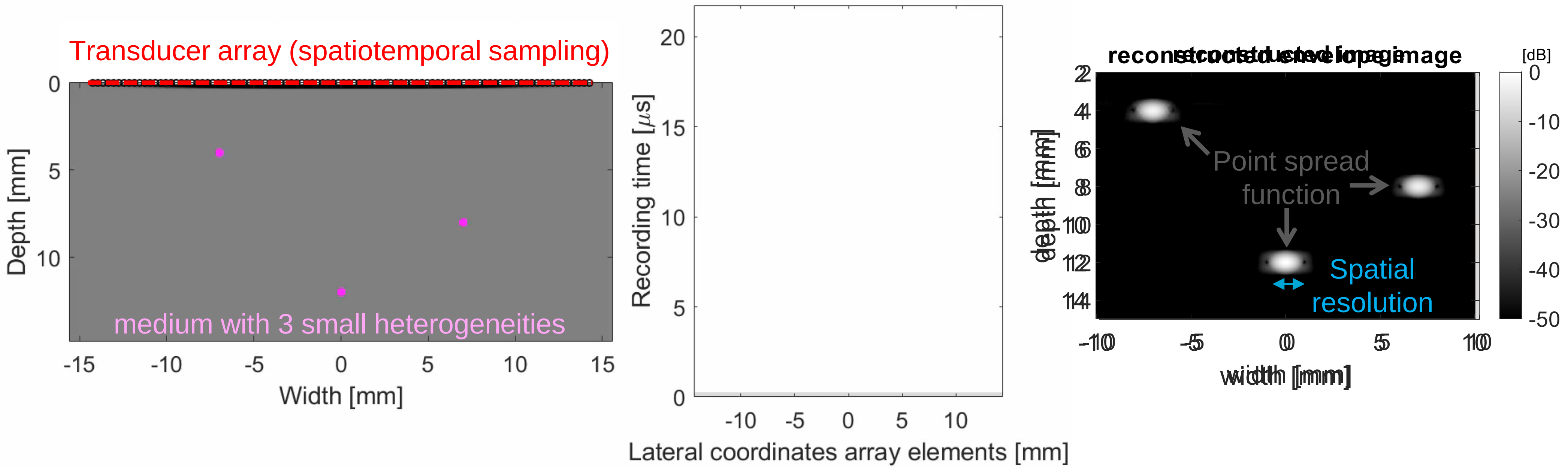
Image reconstruction relies on “synthetic” back-propagation

Back-propagation of recorded echo signals, back to each image pixel (high intensity if heterogeneity exists)

Echo arrival time converted to distance based on knowledge of sound speed (wave field extrapolation)

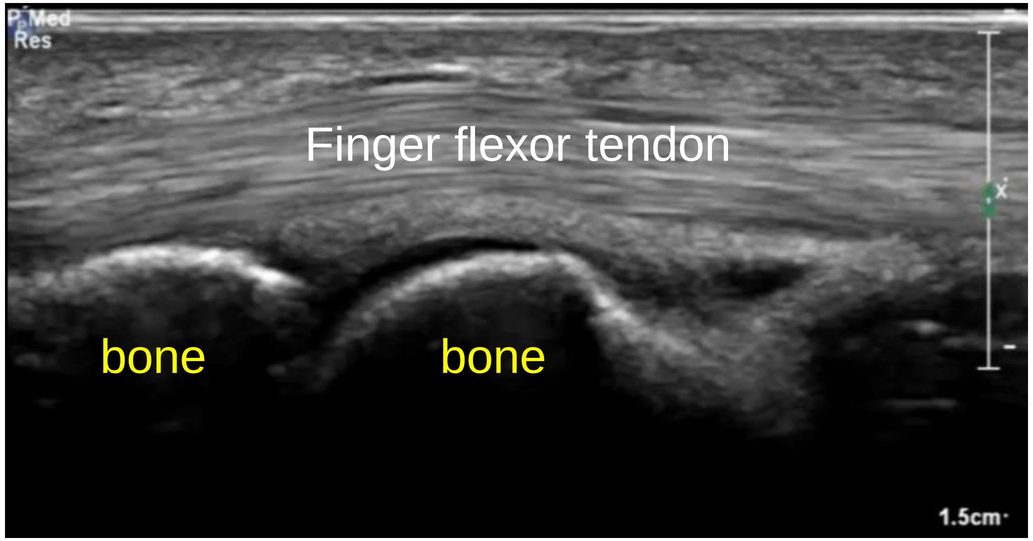


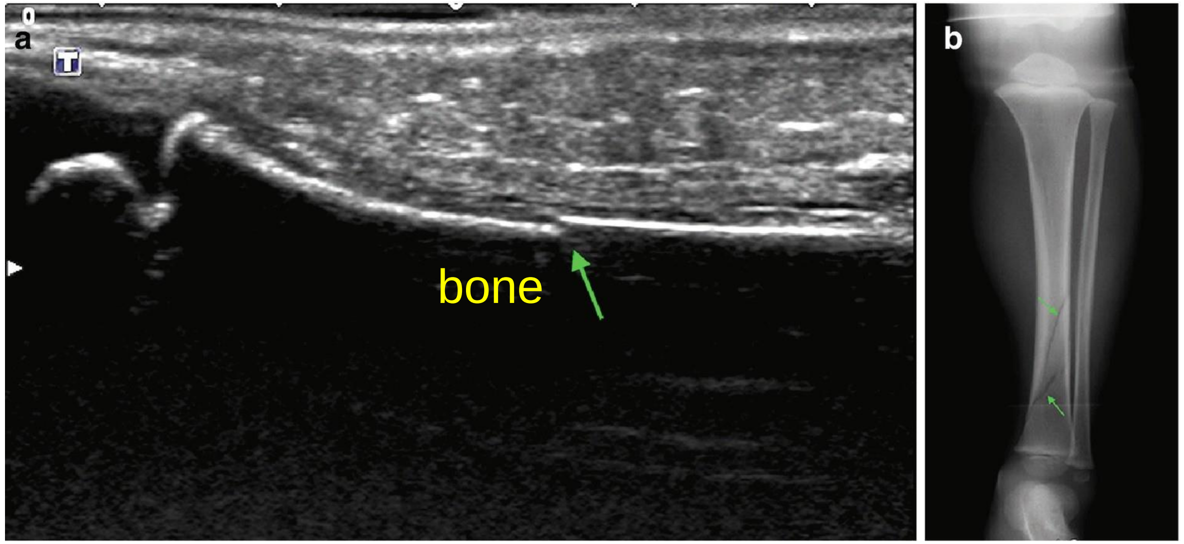


Nyquist–Shannon sampling theorem

- Spatial sampling period = half ultrasound wavelength
- Temporal sampling period < half ultrasound temporal period

Ultrasound imaging inside bones?





"Ultrasound is not good for imaging bones"
website National Institutes of Health (NIH)

"Ultrasound cannot penetrate into regions of the body that contain bones"
Diagnostic Ultrasound, K Kirk Shung, book for engineers, 2005

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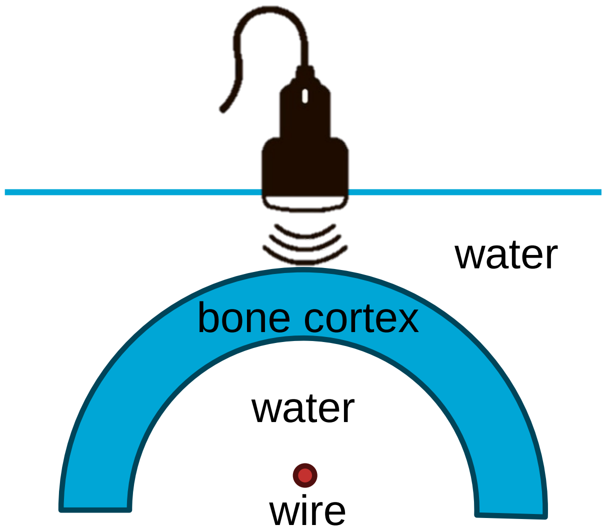
Why does traditional imaging fail to image inside bone?

1. High attenuation of ultrasound
   - State-of-art ultrasound hardware provides excellent signal-to-noise ratio
   - Using low ultrasound frequency reduces attenuation
2. Strong phase aberration (sound speed in cortical bone is larger)
   - Mapping sound speed enables accurate image reconstruction
   - Modern hardware enables unfocused beam transmission and synthetic transmit focusing
3. Multiple scattering and mode conversion
   - Future work…

Demonstration



	Sound speed [m/s]	Ultrasound attenuation [dB/cm/MHz]
Soft tissues (excluding lungs and tendons)	1400-1700	0.2-2
Cortical bone tissue	2600-4200	3-15

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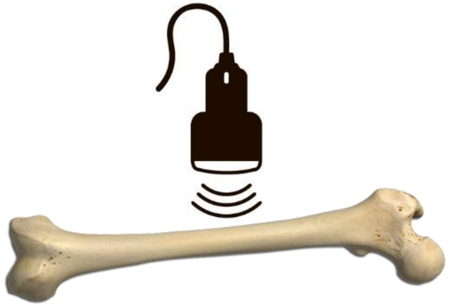
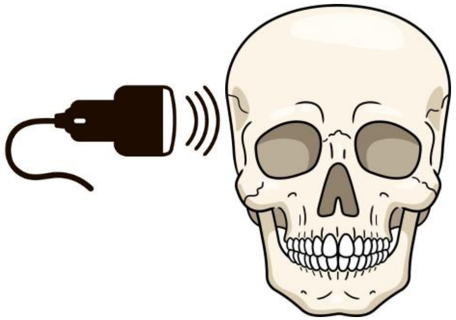
Unlock ultrasound imaging inside bones





Learn the medium (map sound speed)

Tissue structural assessment

Accurate blood flow quantification

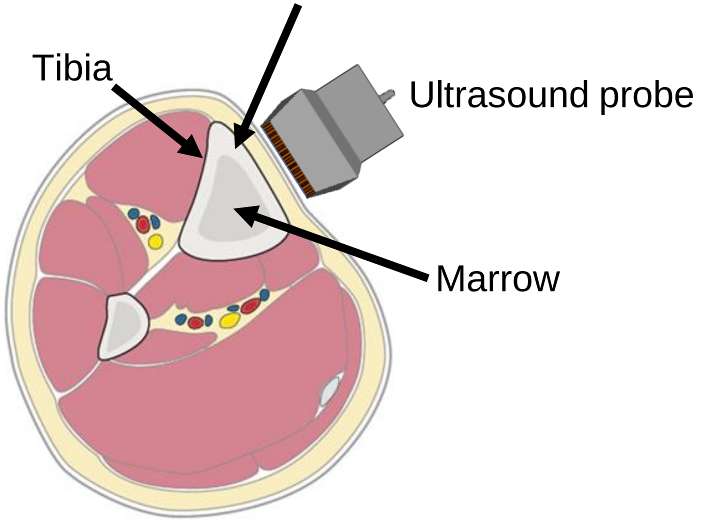
Accurate anatomical image

Learn the medium / map sound speed

Our method:

Medium described with **multiple homogeneous layers**

1. Cutaneous tissue
2. Cortical bone
3. Marrow
4. Cortical bone



Transverse section of the lower leg

Estimation of sound speed layer by layer, starting near the ultrasound probe, with **autofocusing**

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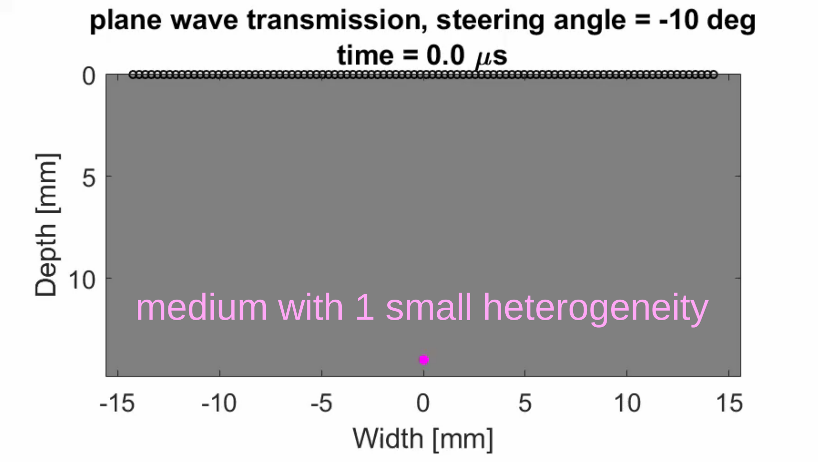
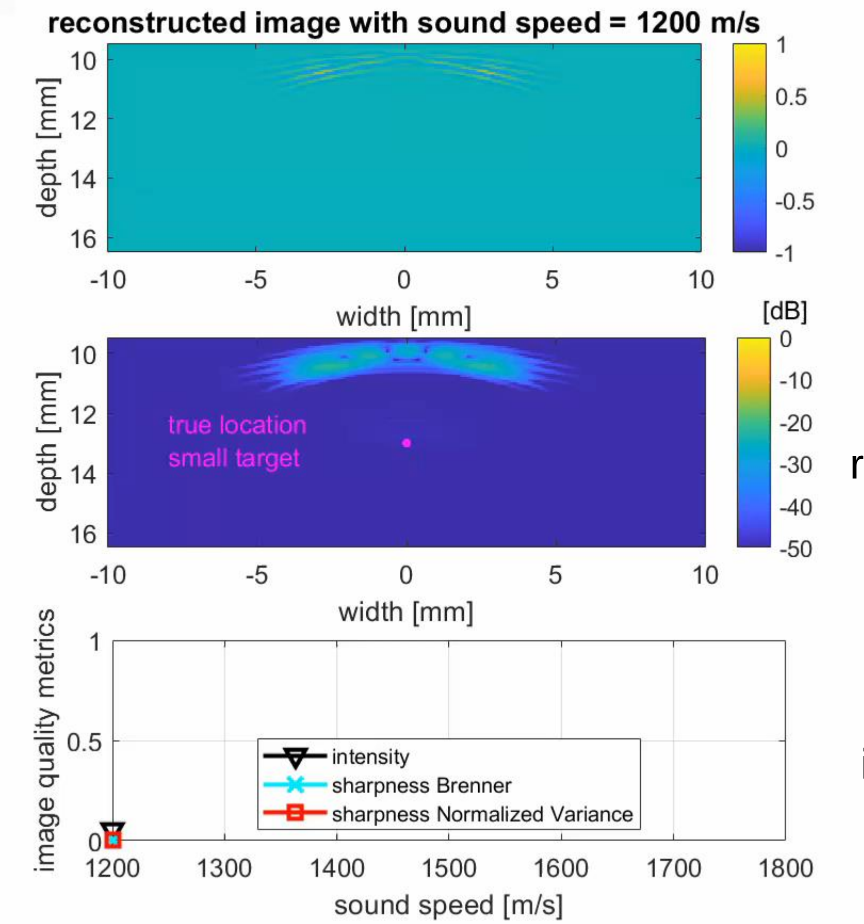
Learn the medium / map sound speed
Autofocusing - principle

Searching for maximum image intensity/sharpness enables the estimation of sound speed

Testing different values of sound speed

Transmission of 5 steered plane waves
Small heterogeneity





Reconstructed image

Envelope of reconstructed image

Image intensity/sharpness

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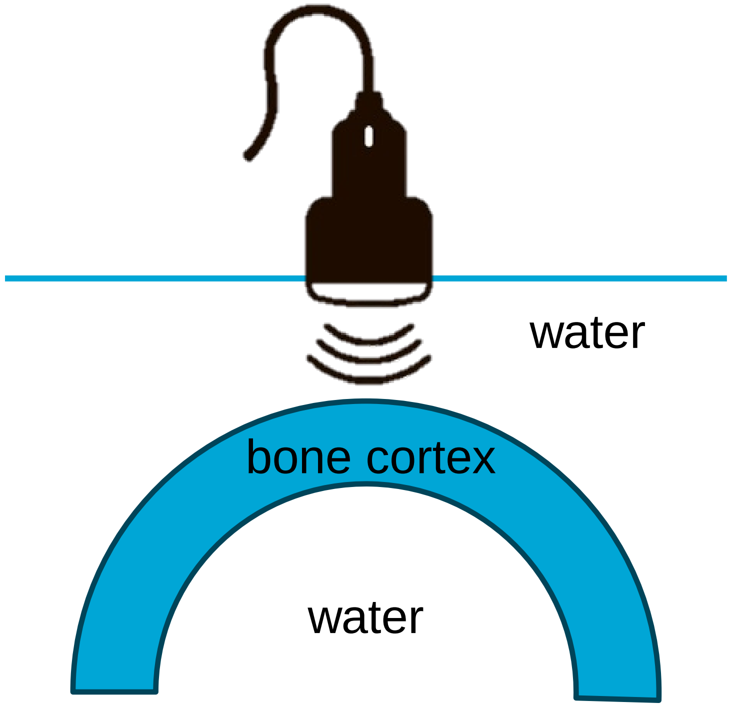
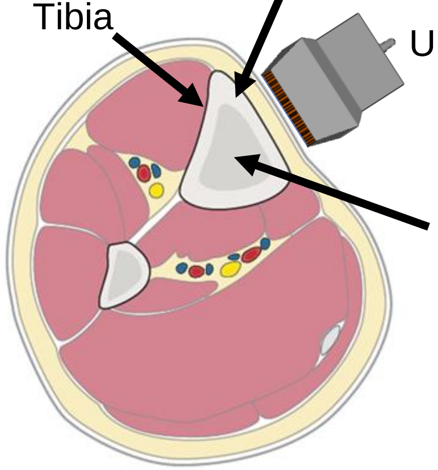
Learn the medium / map sound speed
Autofocusing - demonstration



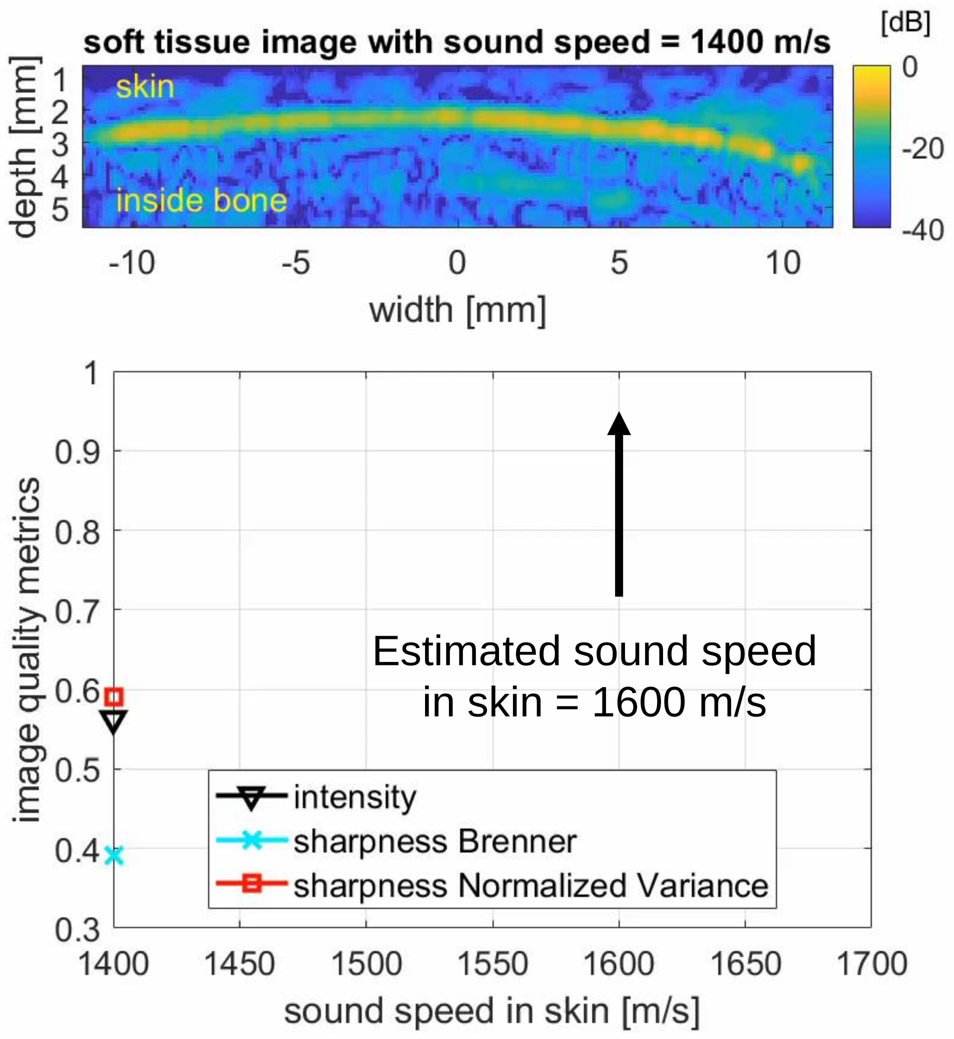
Estimation of sound speed in **water**

Learn the medium / map sound speed
Autofocusing in vivo

Estimation of sound speed in **cutaneous tissue**



Transverse section of the lower leg



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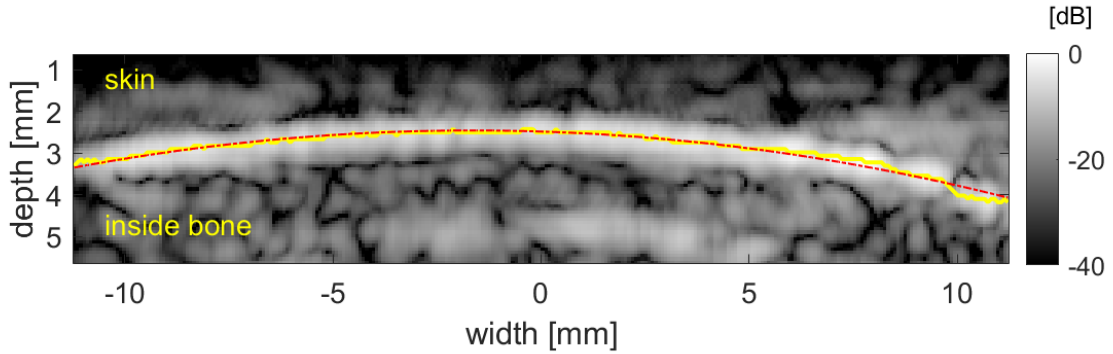
Learn the medium / map sound speed
Autofocusing in bone cortex

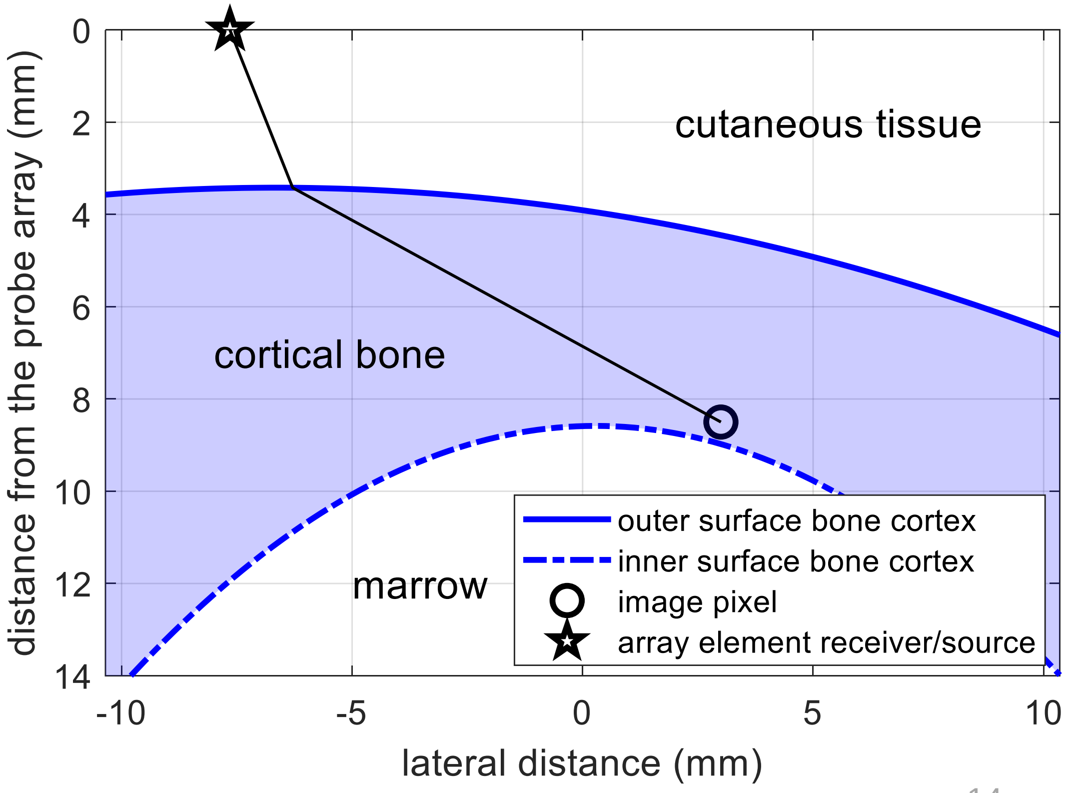
Estimation of sound speed in **bone cortex**

1. Sound speed in first layer (skin) is now known
2. Segmentation of outer surface of bone
3. Autofocusing in bone cortex

Segmentation:
Dijkstra algorithm finds path with maximum cumulative intensity
Raw segmentation approximated by a polynomial function



Two-point ray tracing to account for wave refraction (search for minimum travel time)



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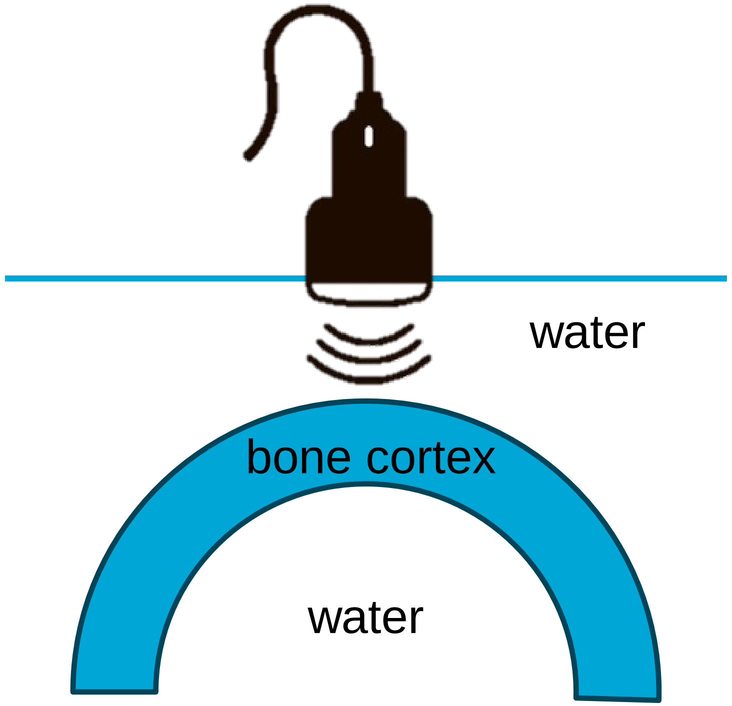
Learn the medium / map sound speed
Autofocusing in bone cortex - demonstration

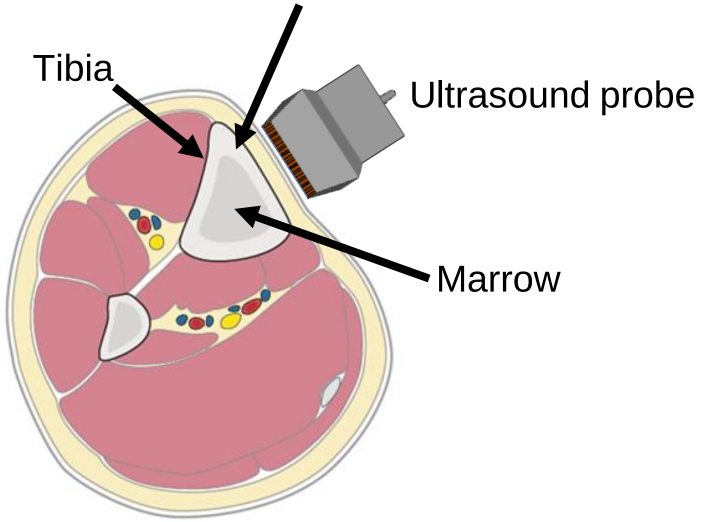


Estimation of sound speed in **bone cortex**

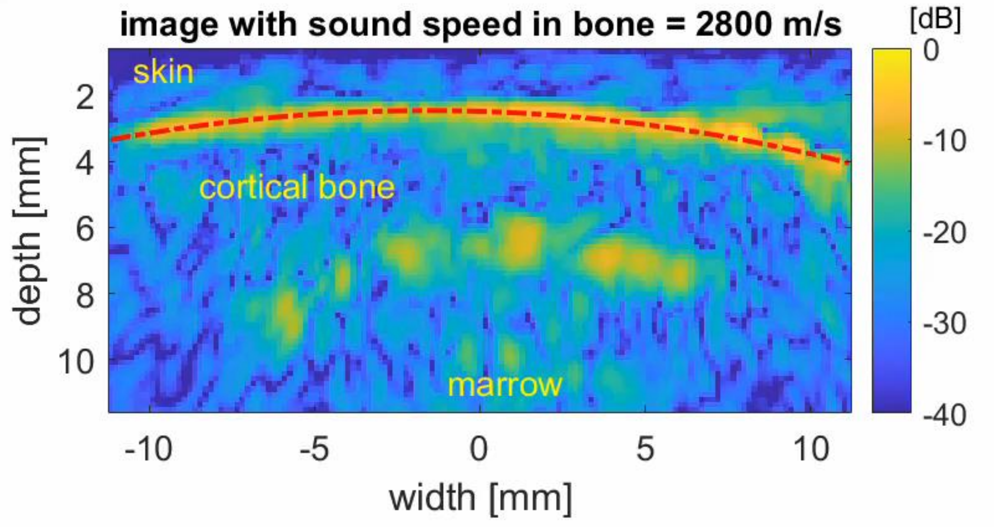
1. Segmentation of outer surface of bone
2. Autofocusing in bone cortex

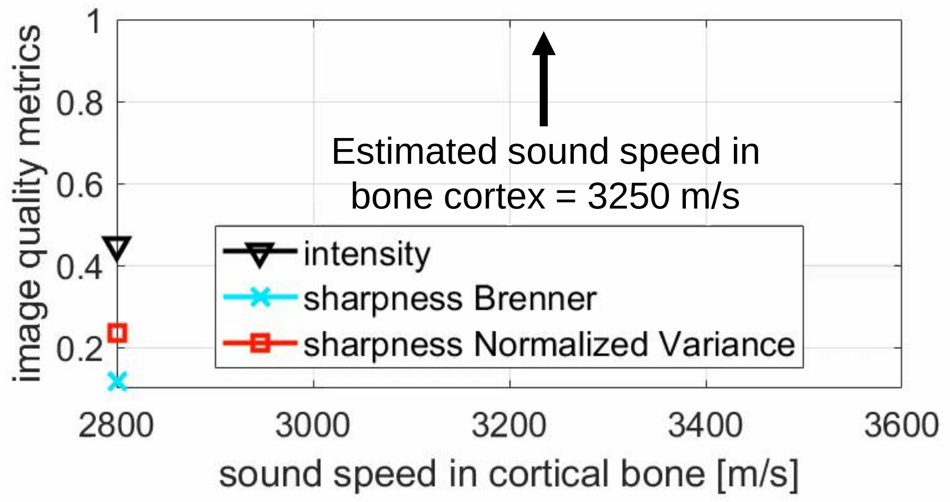
Learn the medium / map sound speed
Autofocusing in bone cortex – In vivo

Estimation of sound speed in **bone cortex**



Transverse section of the lower leg





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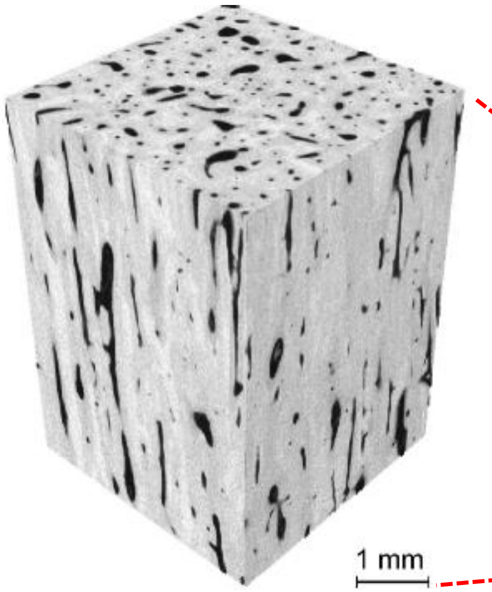
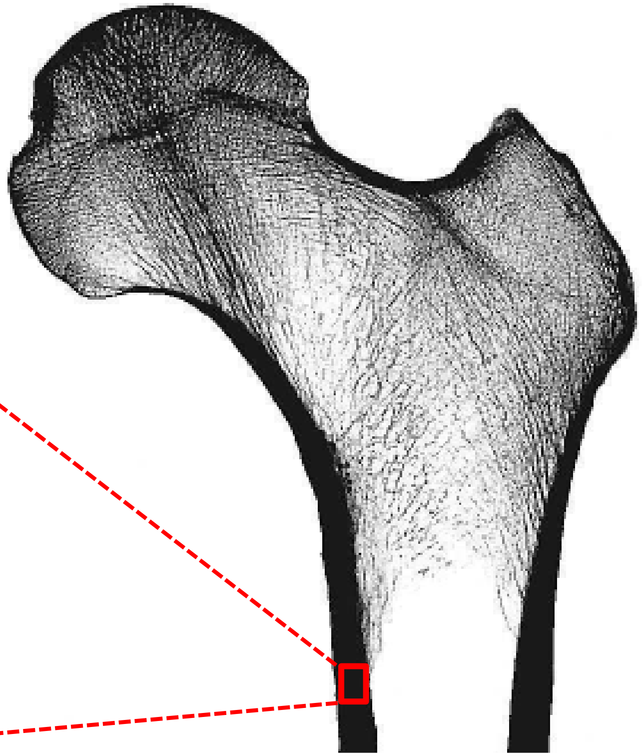
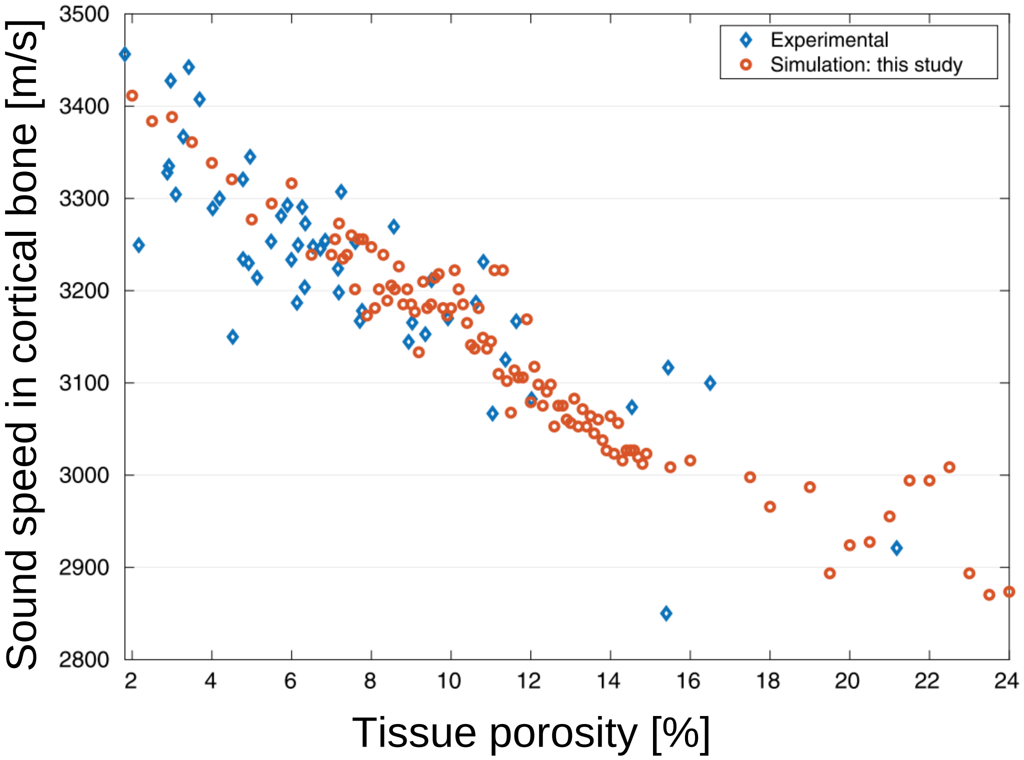
Tissue structural assessment

Sound speed in cortical bone is well correlated with tissue **porosity**

Porosity = 2-25%
Median pore diameter = 40-100 μm







X-ray Computed Tomography
(10-μm voxel size)

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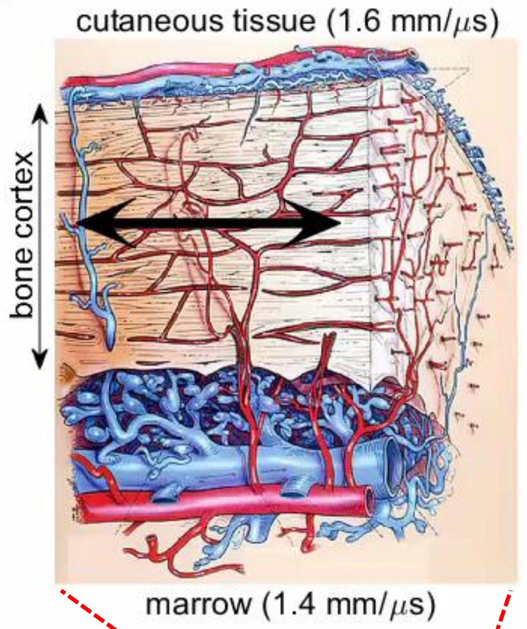
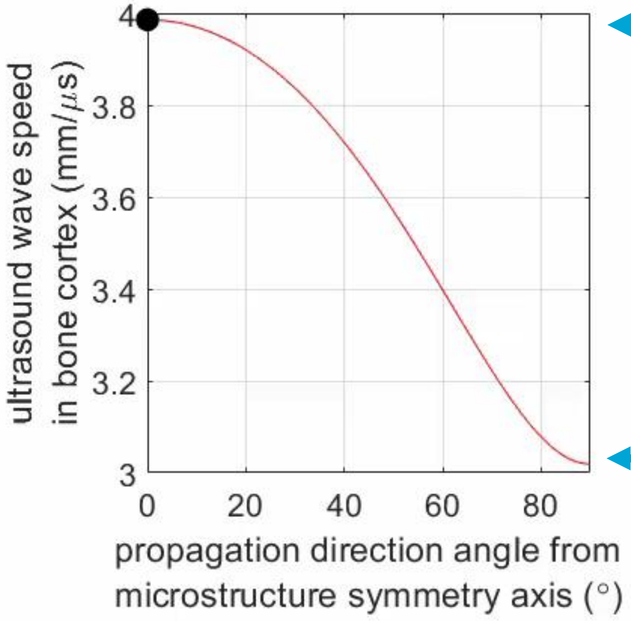
Tissue structural assessment

Tissue structural organization can be assessed with sound speed **anisotropy** (depends on direction)

Mineralized collagen fiber matrix with nearly cylindrical pores (Haversian canals)

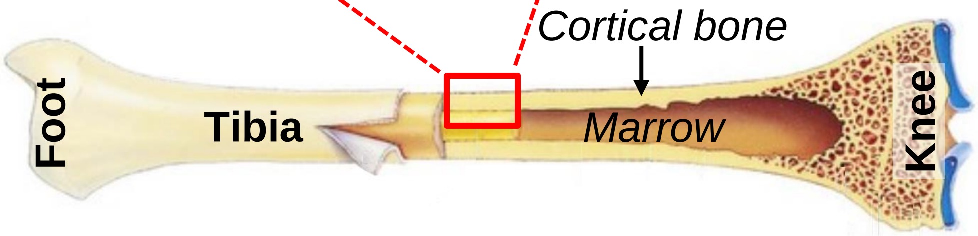
Collagen fibers and pores are nearly aligned along bone axis





← Sound speed in axial direction

← Sound speed in radial direction



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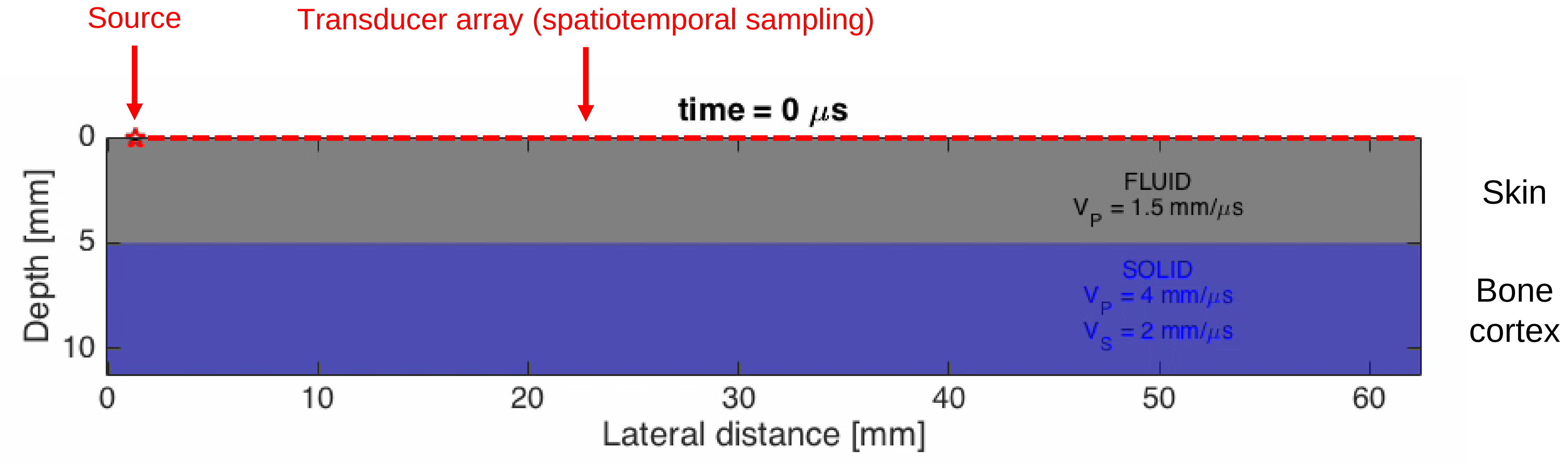
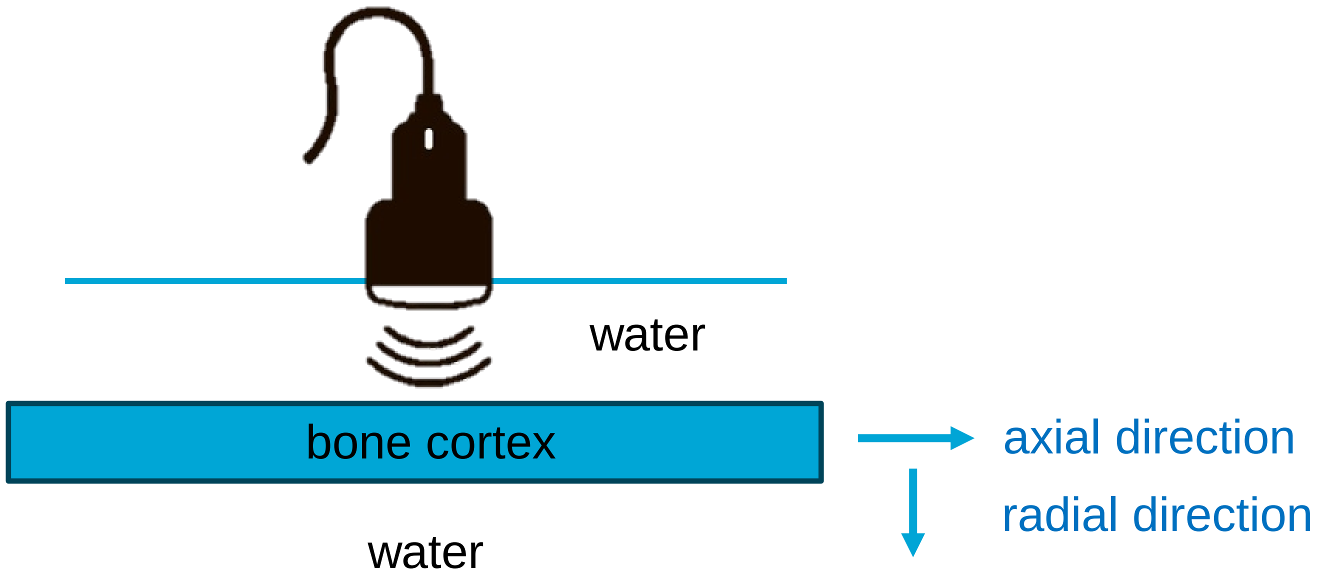
Tissue structural assessment

Measurement of sound speed in cortical bone in axial direction with the **head wave velocity**



Tissue structural assessment
Demonstration

Measurement of sound speed in cortical bone in axial direction with the **head wave velocity**

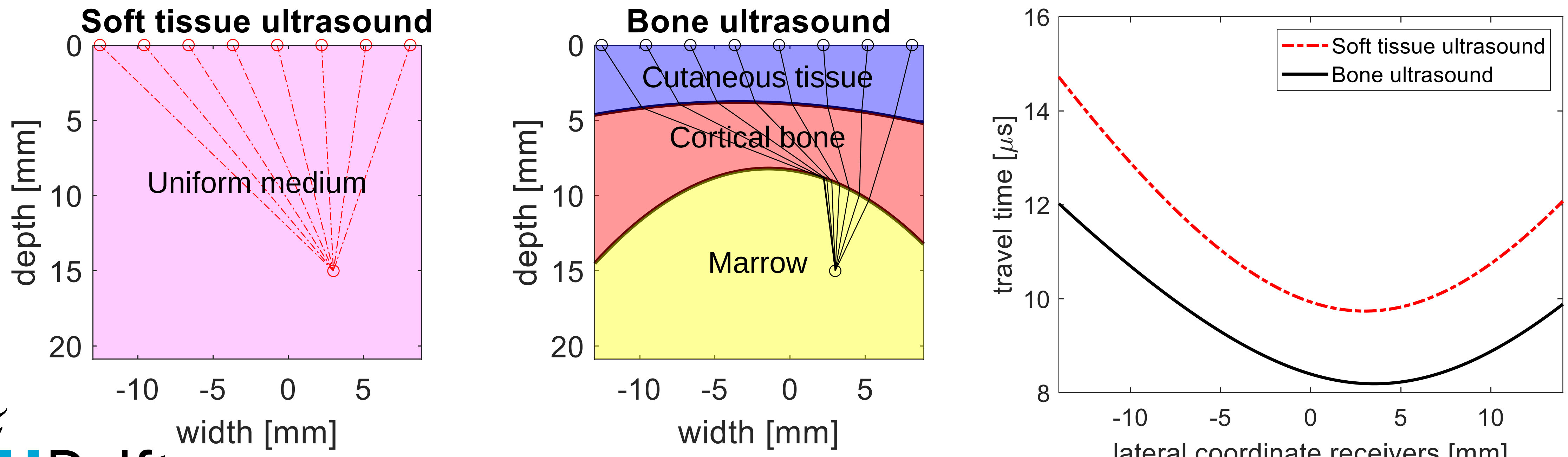


Accurate anatomical image

Image reconstruction relies on the back-propagation of recorded echoes

It requires to calculate the travel time of ultrasound waves back to each pixel

Once a map of the sound speed is available, accurate image reconstruction is possible



Two-point ray tracing

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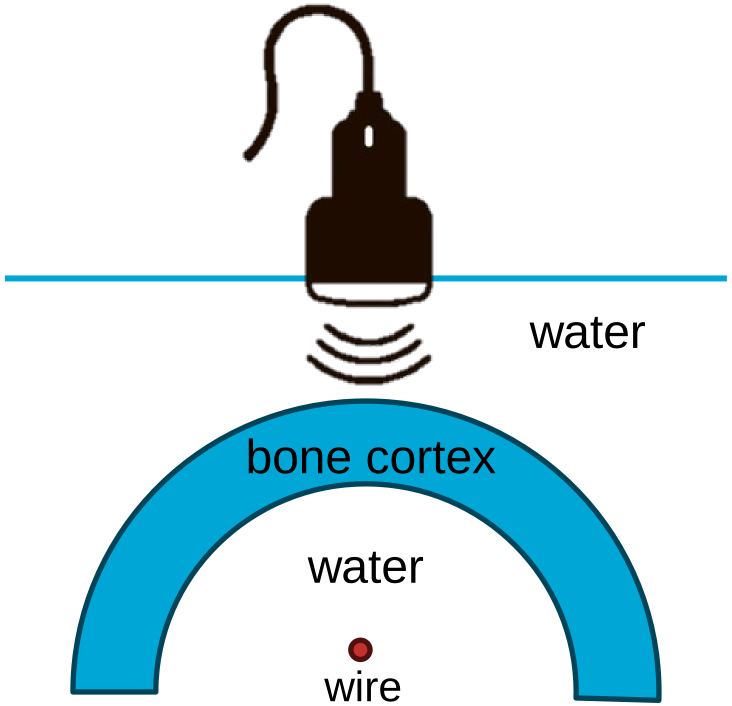
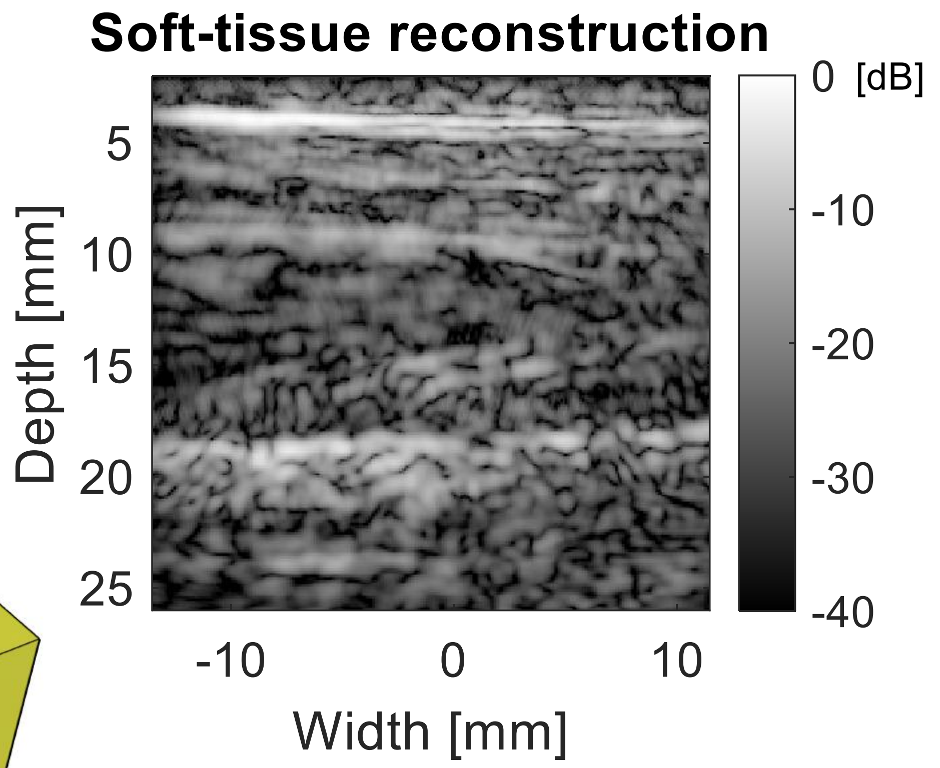
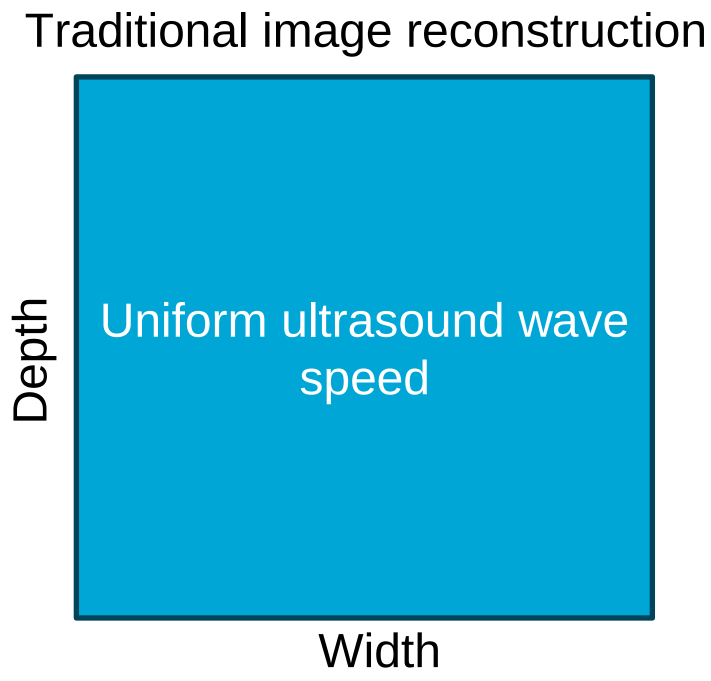
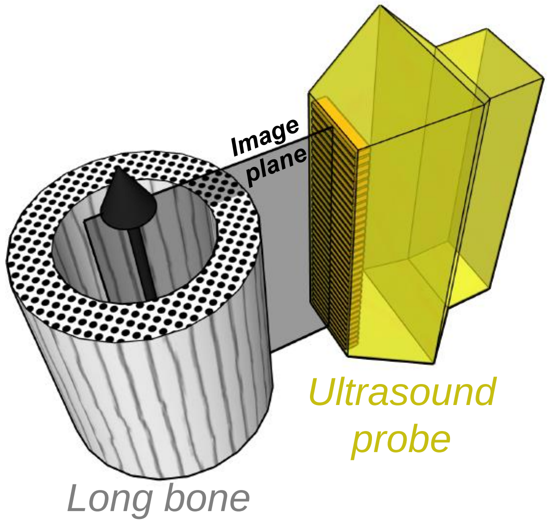
Accurate anatomical image
Demonstration

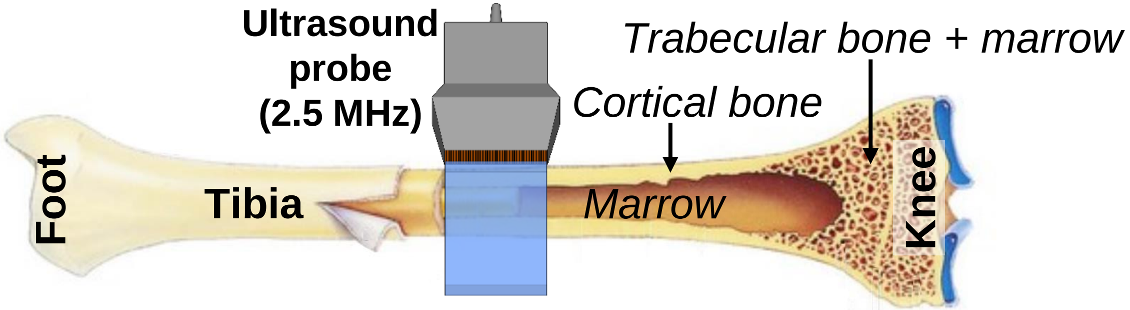


Accurate anatomical image
In vivo – Human tibia



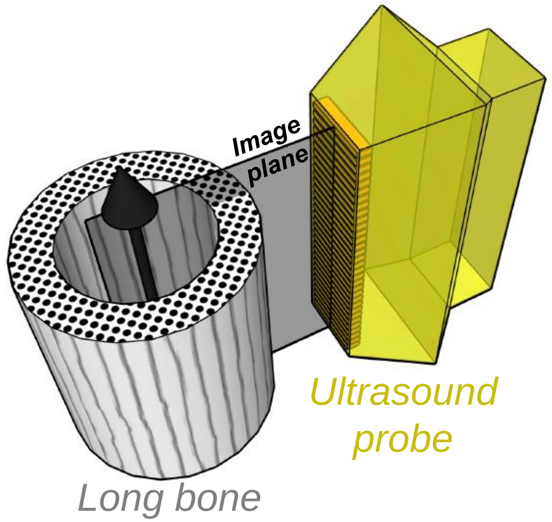


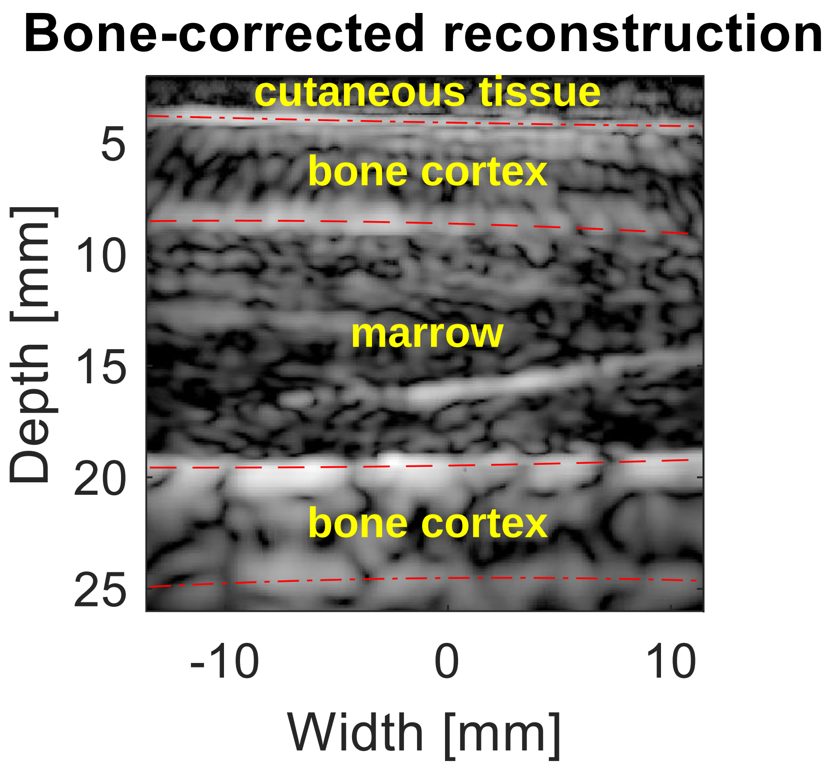


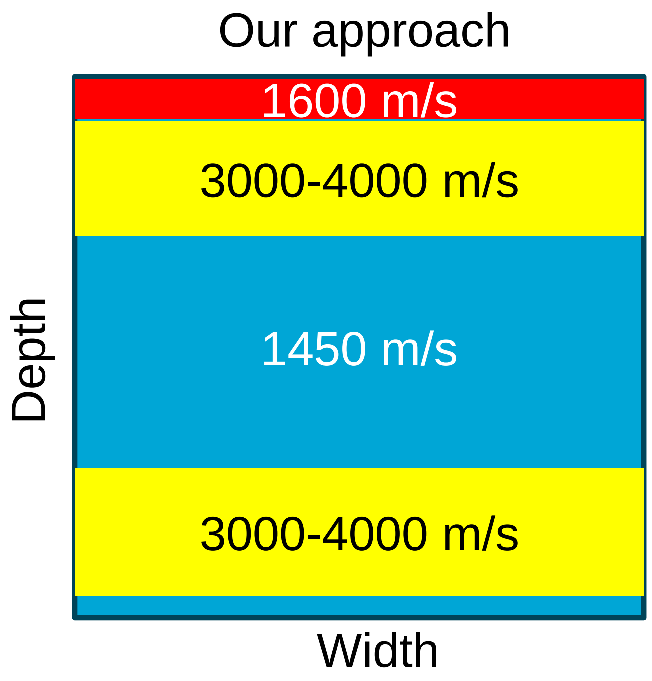


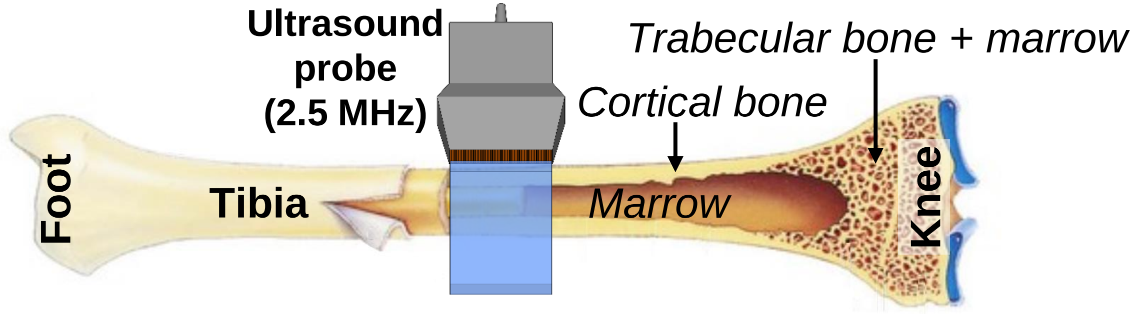
Accurate anatomical image
In vivo – Human tibia

Phase aberration correction

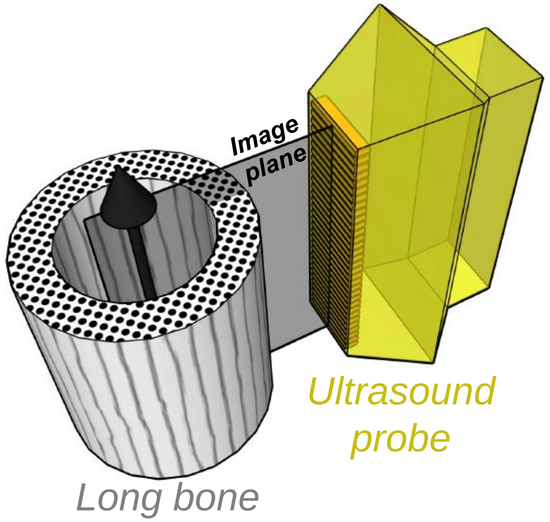






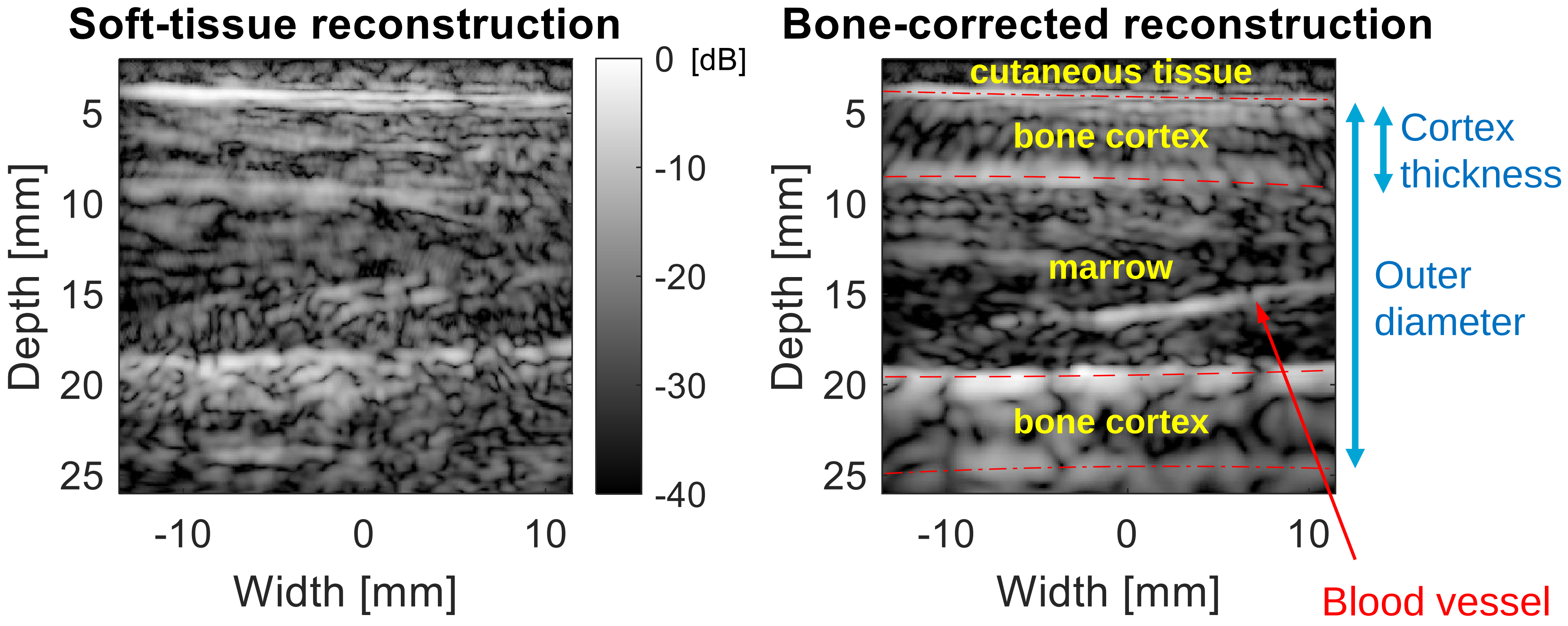


Accurate anatomical image
In vivo – Human tibia

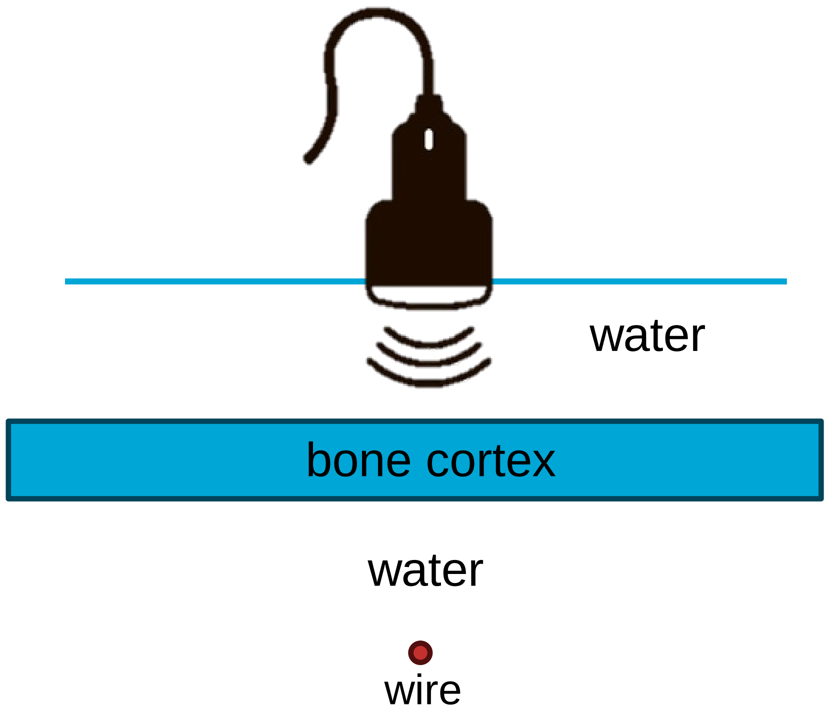


Without phase aberration correction

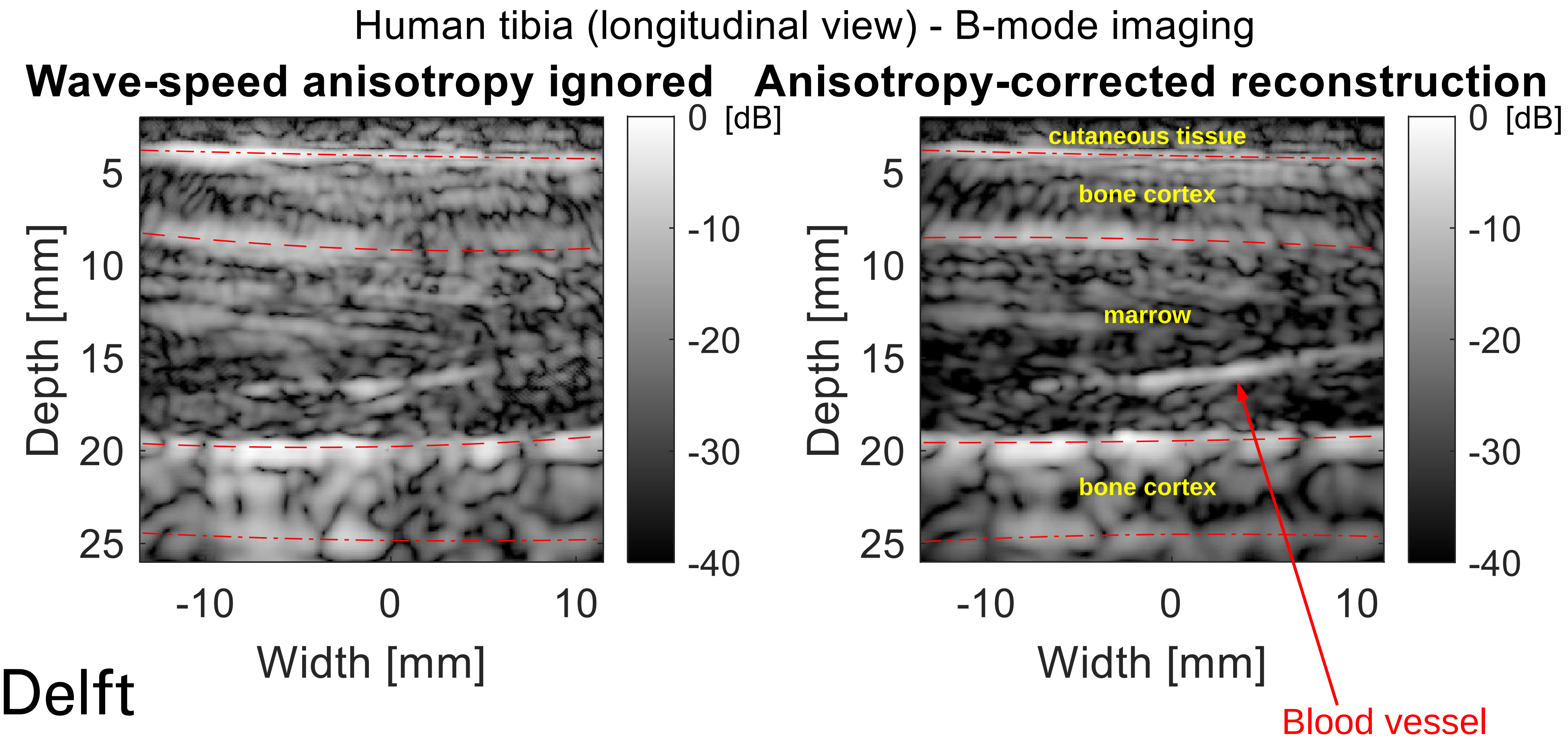
With phase aberration correction



Accurate anatomical image
Sound speed anisotropy - Demonstration



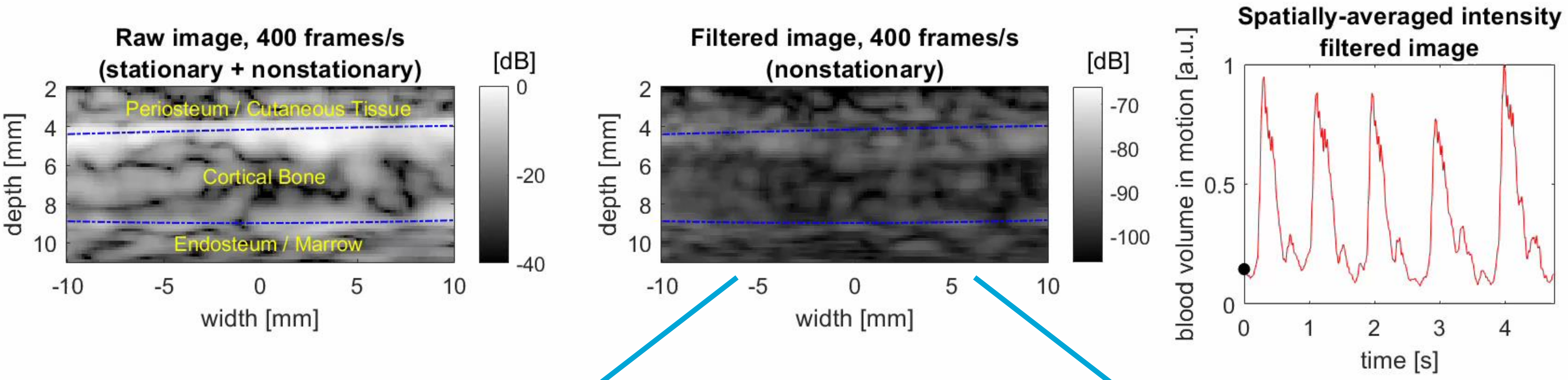
Accurate anatomical image
Sound speed anisotropy – In vivo



Accurate blood flow quantification

Fast repetition of image acquisition (400 images per second)

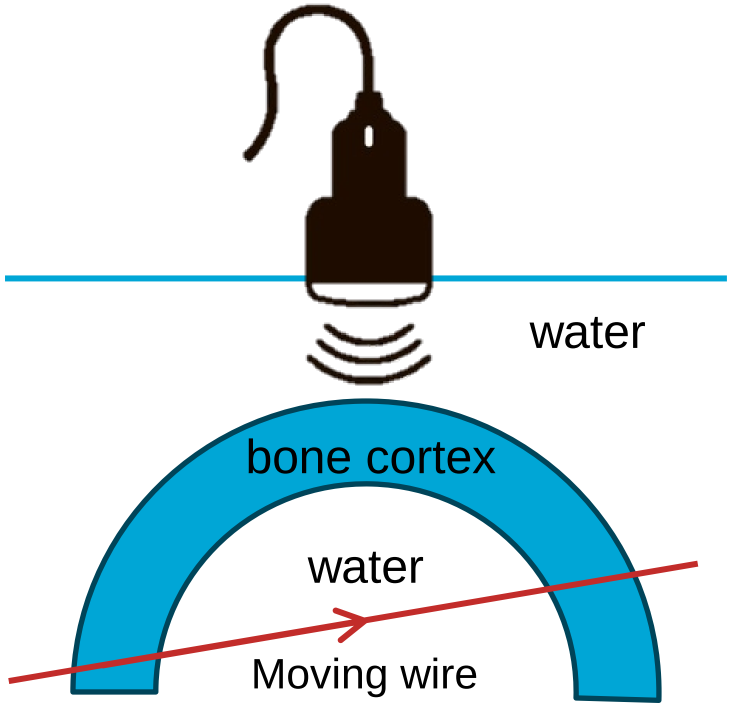
Extraction of blood signal (non-stationary component)



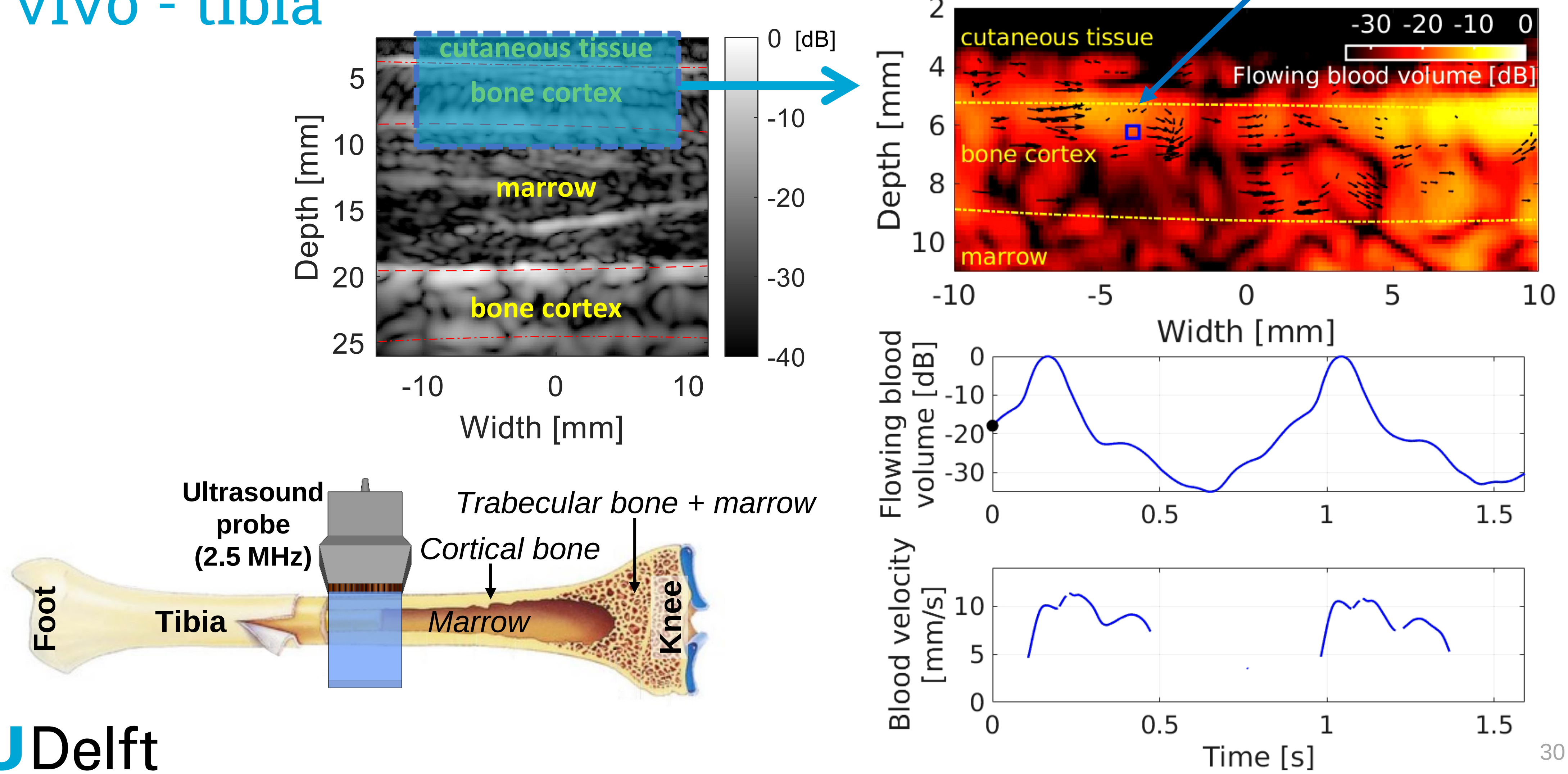
Power fluctuations:
Flowing blood volume

Phase fluctuations:
Blood flow velocity and direction

Accurate blood flow quantification
Demonstration



Accurate blood flow quantification
In vivo - tibia



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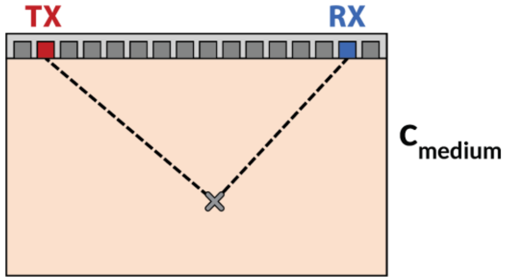
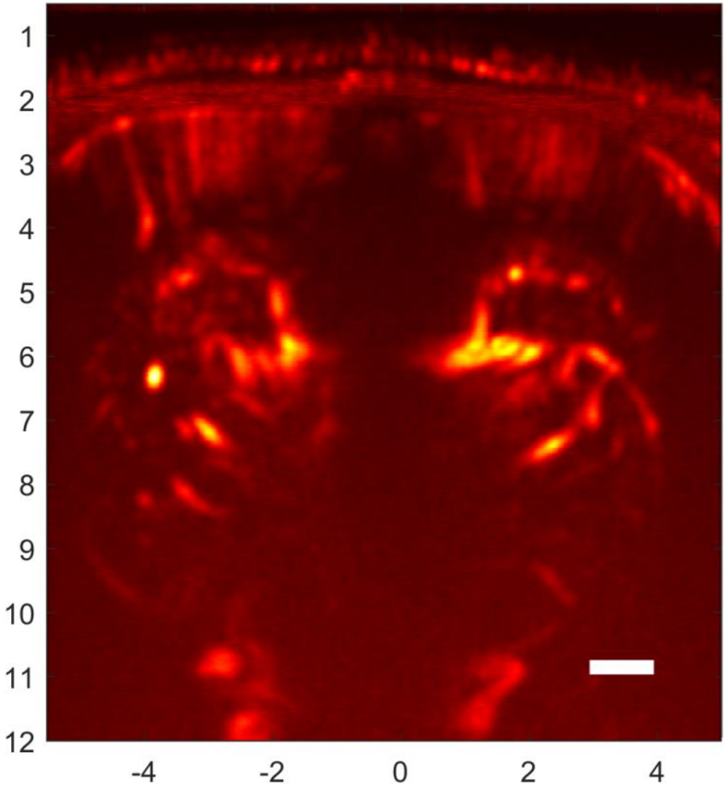
Accurate blood flow quantification
In vivo – brain vasculature (transcranial imaging)

David Maresca
(TU Delft)

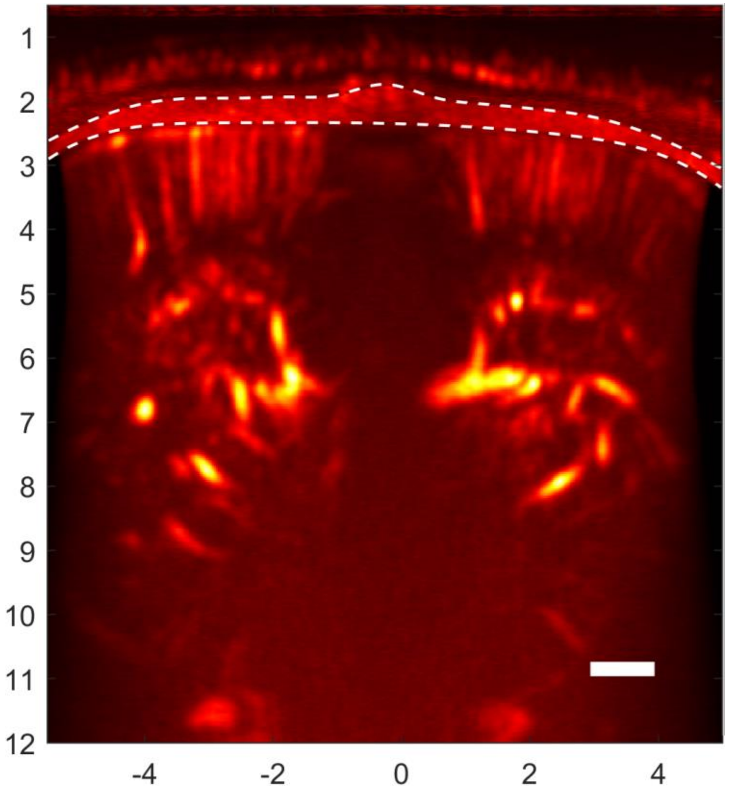


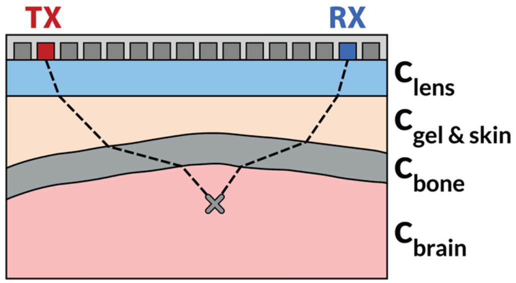
Uniform medium assumption

No skull correction



Skull corrected





Multi-layer medium sound speed model

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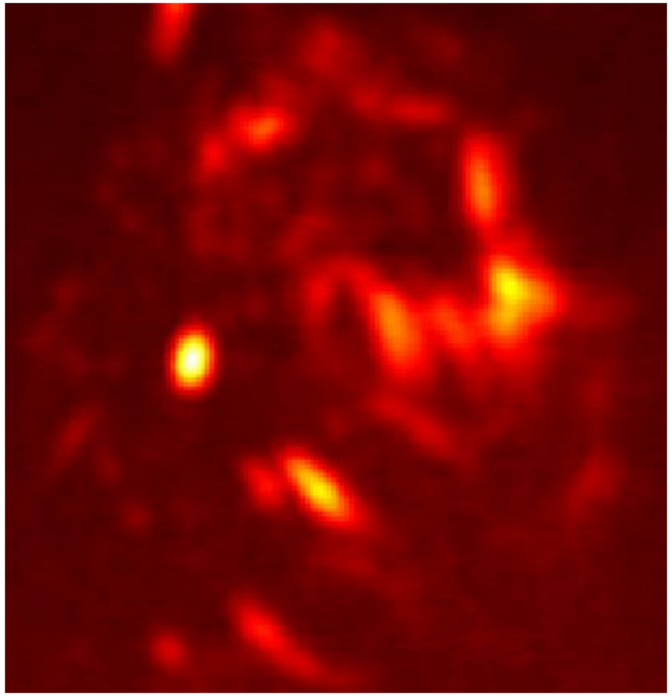
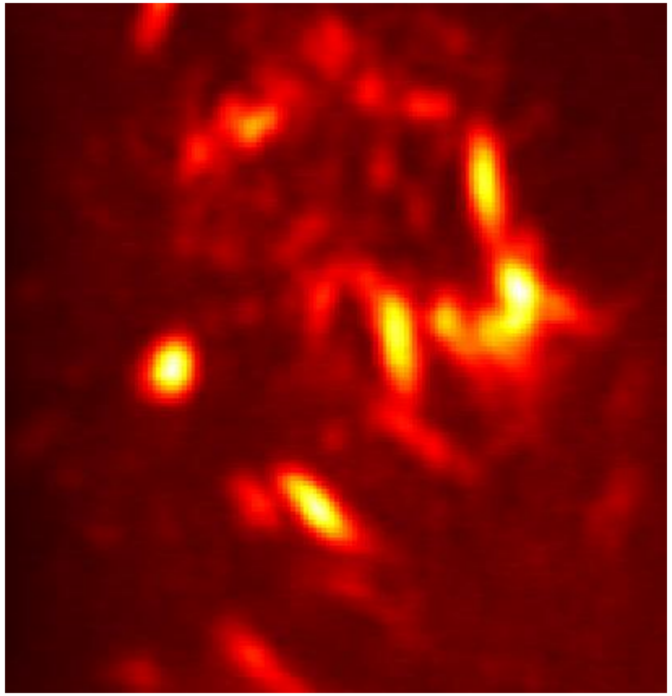
Accurate blood flow quantification
In vivo – brain vasculature (transcranial imaging)

No skull correction



Skull corrected



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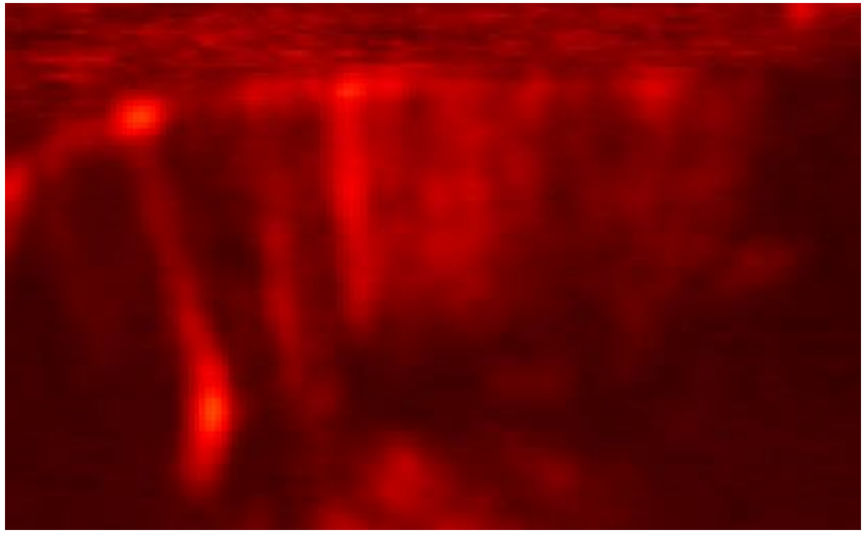
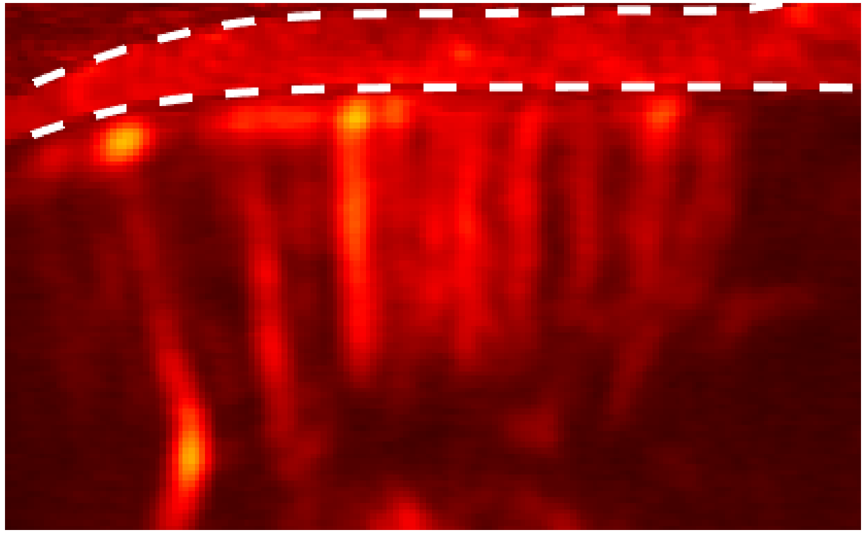
Accurate blood flow quantification
In vivo – brain vasculature (transcranial imaging)

No skull correction



Skull corrected



Thank you for your attention!

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