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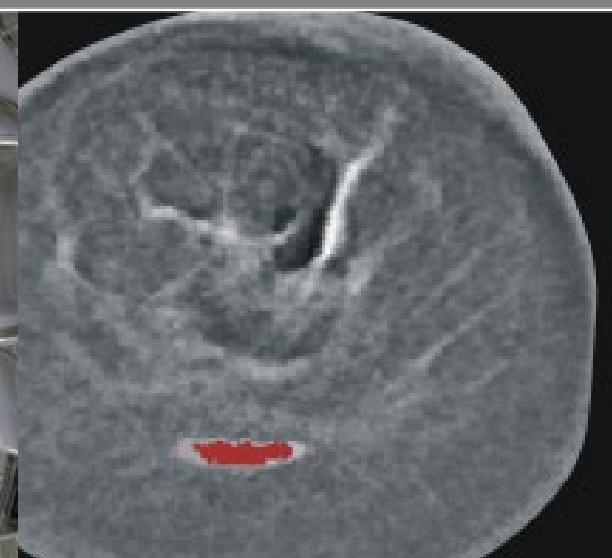
3D Ultrasound Computer Tomography

KIT 3D Ultrasound Computer Tomography – a data & computing intensive approach at multimodal ultrasound imaging

M. Zapf, T. Hopp, H. Gemmeke, N. V. Ruiter, et al.

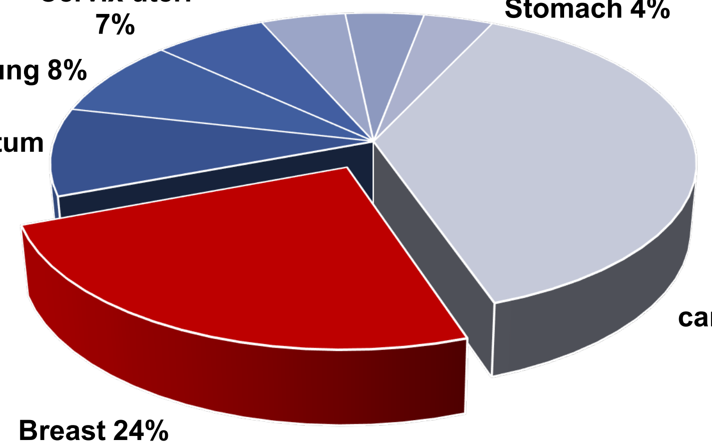
INSTITUTE FOR DATA PROCESSING AND ELECTRONICS



Background: Medical situation

- Motivation: Breast cancer
  - Most common cancer of women in western world (every 10th woman)
  - Deadly, despite not being a non-vital organ
  - Challenge & solution: Early diagnosis
  - Current diagnosis and screening methods have disadvantages

New cancer cases in 2020, females



Source: International Agency for research on cancer, https://gco.iarc.fr
Data source: WHO cancer statistics 2020, GLOBOCAN 2020

Background: Medical situation

Screening

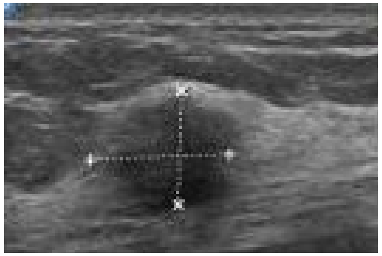
X-Ray Mammography

Symptomatic patients

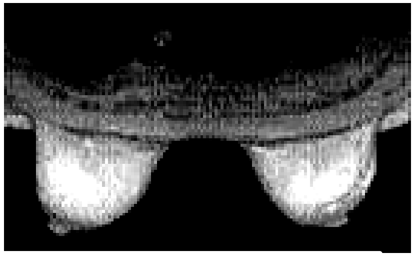
Ultrasound (US) Sonography

Magnetic Resonance Imaging (MRI)

X-ray mammography image



Sonography B-Scan image



MRI image (transversal cut)

- Current diagnosis and screening methods have disadvantages
  - Uncomfortable, ionizing (harming), 2D, non-reproducible, expensive, specificity problems ("false positives"), requires contrast agents…

Vision

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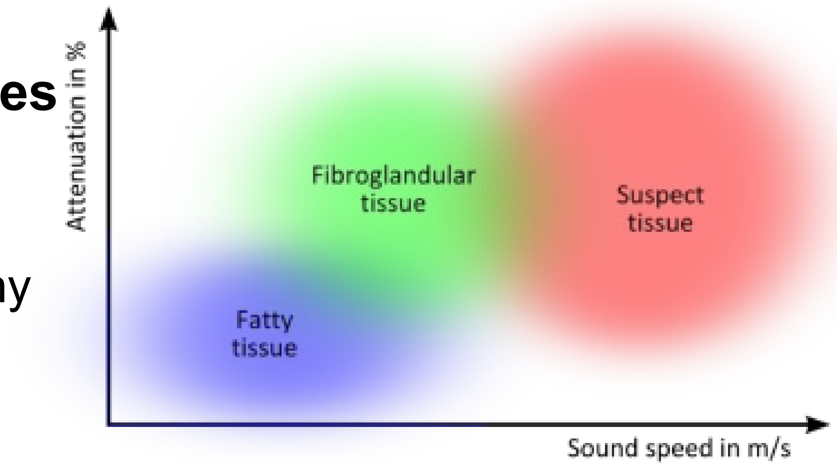
Basic idea: why not combining the best of these methods?

- As sensitive as XR mammography
- 3D like MRT
- Non-ionizing like ultrasound sonography

Diagnostic value: Specificity

- Ultrasound can contain **three modalities** concurrently:
  - **Reflection / morphology** information
    High quality “B-scans” from sonography
  - **Speed of sound** and **attenuation**
    Quantitative information

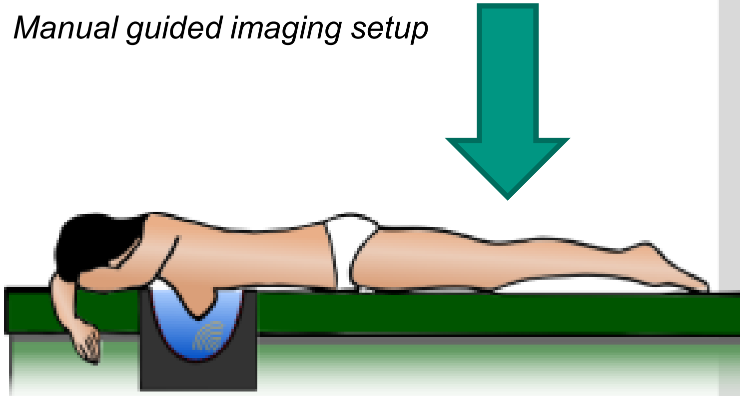


Simplified from Greenleaf et al., 1981

Vision (2)

- Technical properties
  - Fixed and reproducible measurements
    - Surround object with (unfocused) ultrasound transducers
  - Milimeter to sub-mm resolution
    - Water as imaging medium
    - MHz ultrasound
  - Multimodal
    - Measure reflection and transmission signals
  - **Object surrounding aperture**
    - **Many ultrasound transducers surround the object hemishere**

Manual guided imaging setup



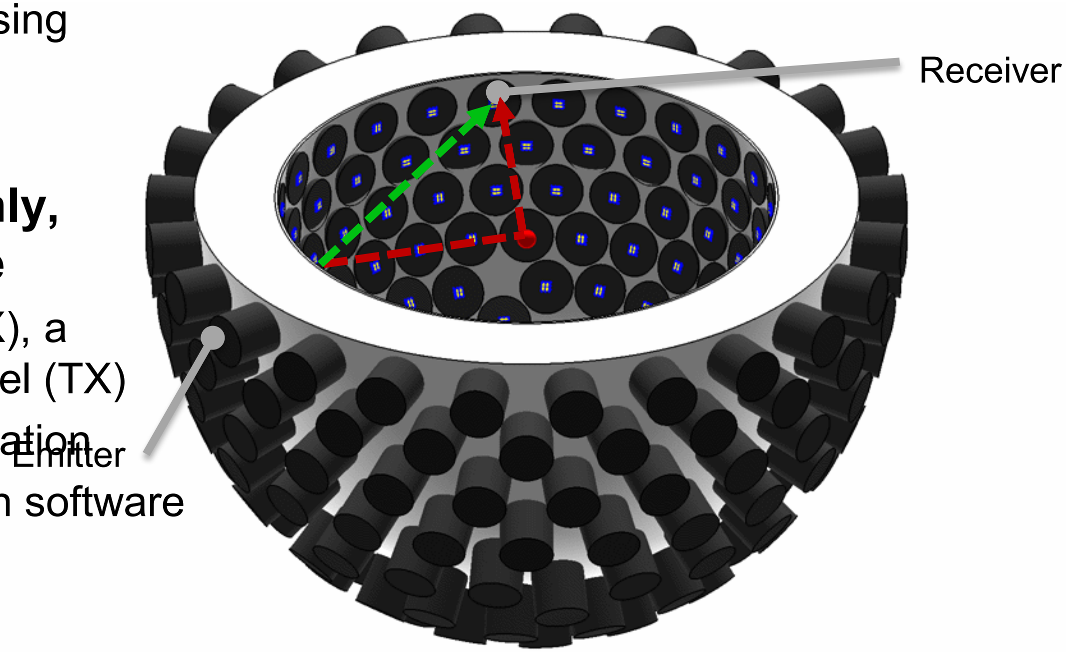
Breast imaging in fixed setup

Vision (3)

- Operation principle
  - 3D phased array imaging like sonography takes too long

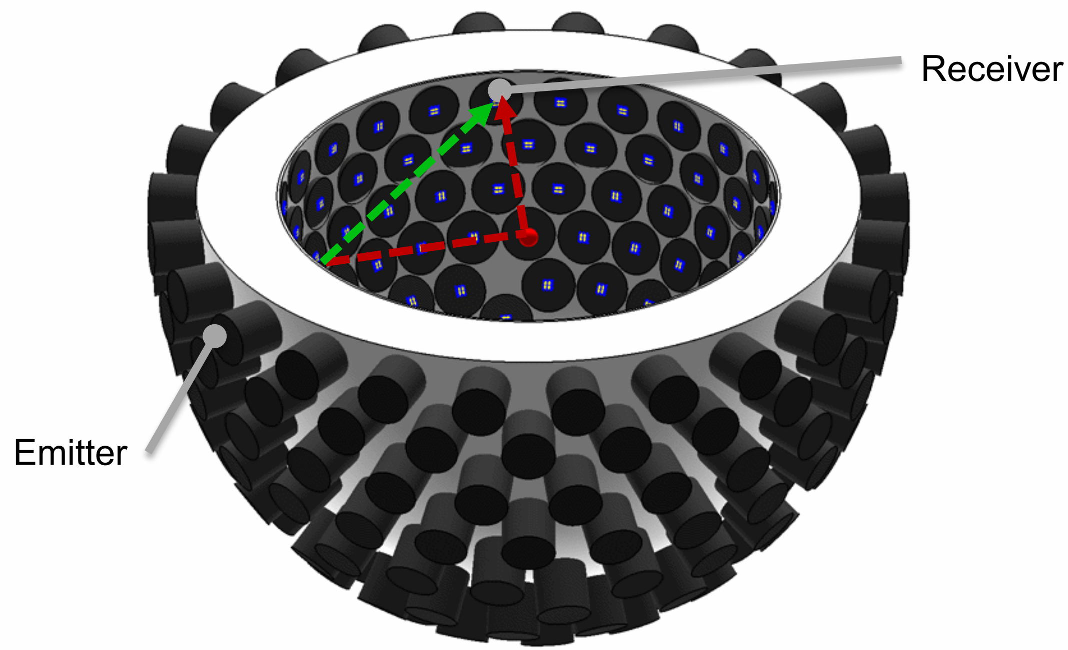
    ⇒ shifting to software

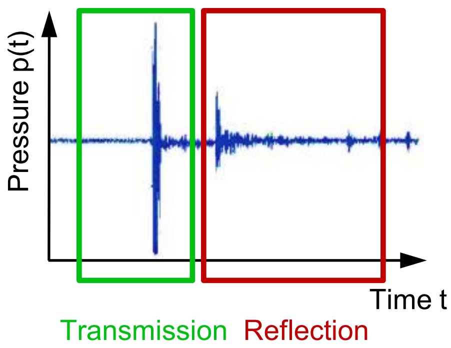
    ⇒ Synthetic aperture focussing technique (SAFT)
  - **One transducer emits only, many transducer receive**
    - Many DAQ channels (RX), a singular excitation channel (TX)
    - Iterative, sequential excitation
    - Focussing and imaging in software on raw data
    - Not a real time system



3D USCT: measurement principle and signals

- Separation of **measurement phase + imaging phase**

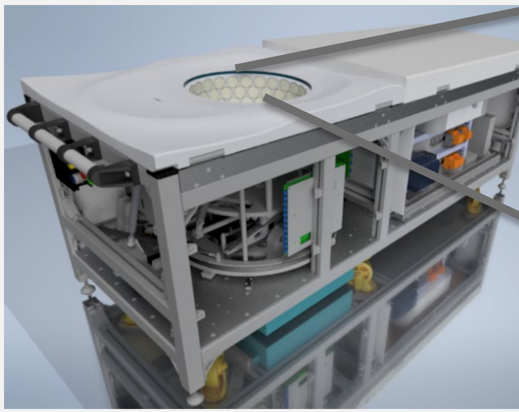




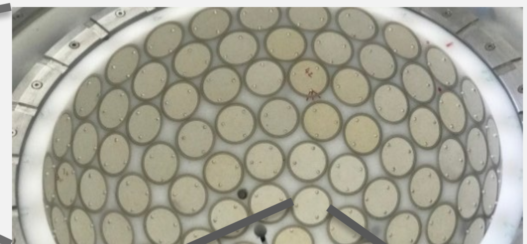
Pressure over time ultrasound signal, so called AScan

Multimodal imaging:
- **Sound speed**
- **Attenuation**
- **Reflection**

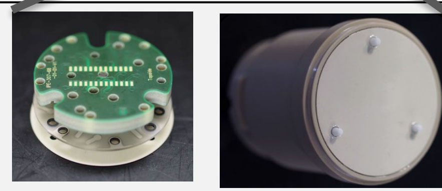
Realization: KIT 3D USCT III



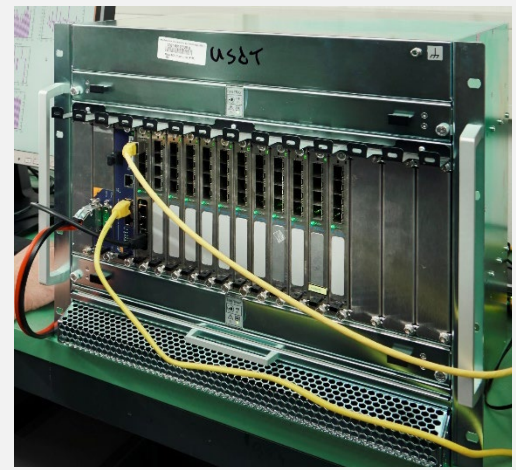
KIT 3D USCT III patient bed



Measurementcontainer



Transducer Array System



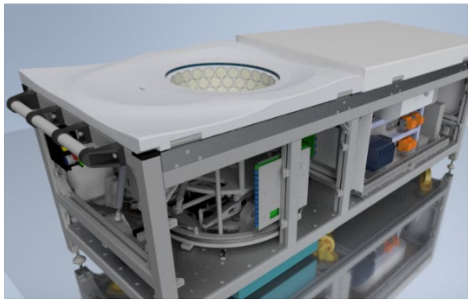
Detail view of DAQ system

- 3D hemisphere
- Diameter: 35 cm

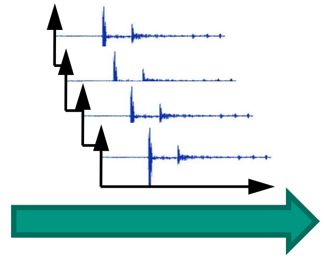
- 2304 US transducers (TX + RX), pseudo-random
- 2.6 MHz center freq (3.4 MHz bandwidth @ -10dB)

- 384 channels 20MHz sample rate
- 96 GB memory buffer

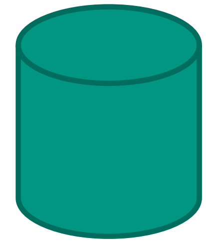
3D USCT III: Measurement time and data



3D USCT III system



Parallel data



Data sink (server)

- Measurement process
  - 2304 emitters are excited individually and iteratively
  - Measurement window: 400µs

  => 1 to 10 minutes (parameter dependend)
- DAQ
  - 384 channels, 6x time muxing (2304 channels)
  - 10 MHz sample rate, 400µs window, 16 bit datatype

  => 80GByte

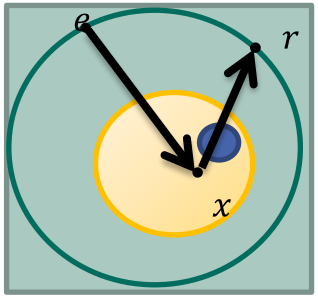
=> Clinical applicable with ~ 10 min

Image reconstruction: reflectivity

- „Weakly scattering assumption“: first reflection only
- **Ellipsoid backprojection: Synthetic Aperture Focusing Technique (3D SAFT)**

$$I(x) = \sum_{e,r} A_{e,r}(t) \quad \text{with } t = \frac{|e - x| + |x - r|}{c}$$

  - Extensions:
    - Sound speed correction $c_{water} \rightarrow c_{path(e,x,r)}$[1]
    - Attenuation correction [2] $A_{e,r}(t) \rightarrow a_{path(e,x,r)} \cdot A_{e,r}(t)$



I: *image*
x: *voxel position*
A: *amplitude scan*
e: *emitter position*
r: *receiver position*
c: *sound speed*
t: *time of flight*

- „Ridiculous easy paralizeable“: over data, over image
  - ….But on modern systems bandwidth limited
- Typical use case:
  - Data: 10^6 Ascans, length 4096 samples (10MHz), datatype double (8Byte)
  - Image: ROI 20x20x20cm^3, 0.2mm resolution => 1024^3 voxel ,

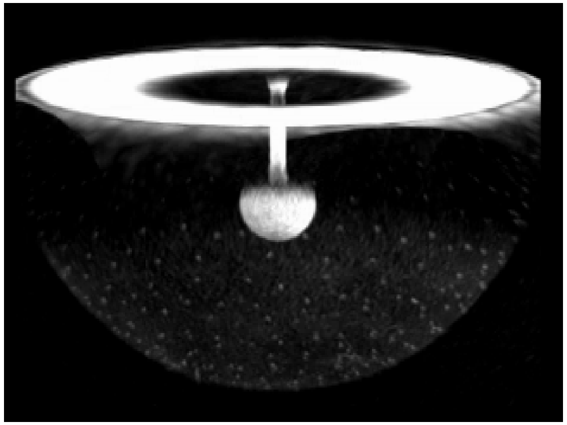
    => data read bandwidth: (4096*2304*128*18*2*8)/1024^3 = 324 GByte
    => Image write bandwidth: ((2304*128*18*2*8)*1024^3)/1024^5 = 81 PetaByte
    => Reconstruction time (8x RTX 2080 TI GPUs): ~30 min.

=> Clinical applicable with ~ 30min

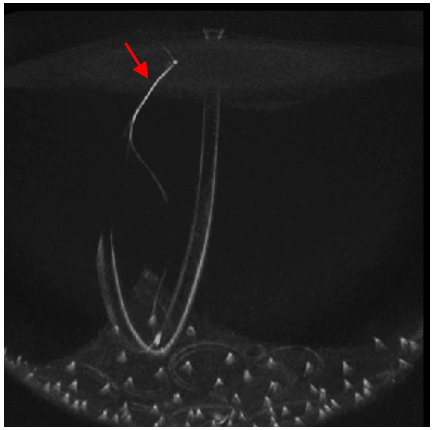
[1] E. Kretzek, N. V. Ruiter, "GPU based 3D SAFT reconstruction including phase aberration," Proc. SPIE 9040, Medical Imaging 2014: Ultrasonic Imaging and Tomography, 90400W (2014)
[2] E. Kretzek, T. Hopp, N. V. Ruiter, "GPU-based 3D SAFT reconstruction including attenuation correction," Proc. SPIE 9419, Medical Imaging 2015: Ultrasonic Imaging and Tomography, 94190E (2015)

Results: 3D Reflectivity imaging (1)

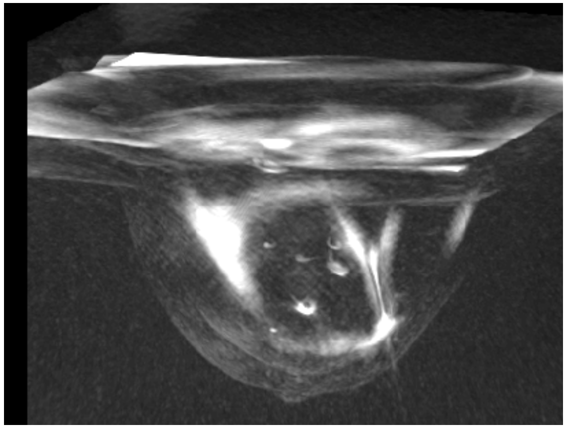
- Phantom images
  - Maximum intensity projection from 3D volume



Steel sphere



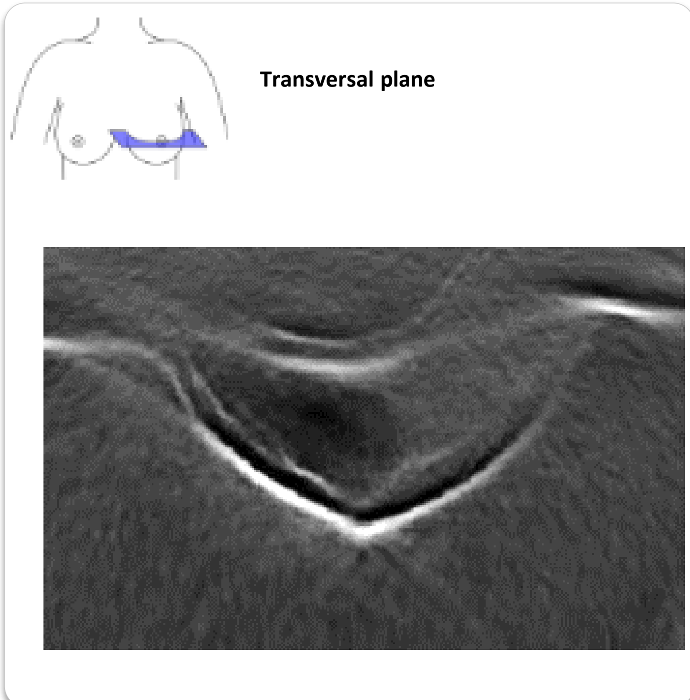
0.2 mm soldering tin wire

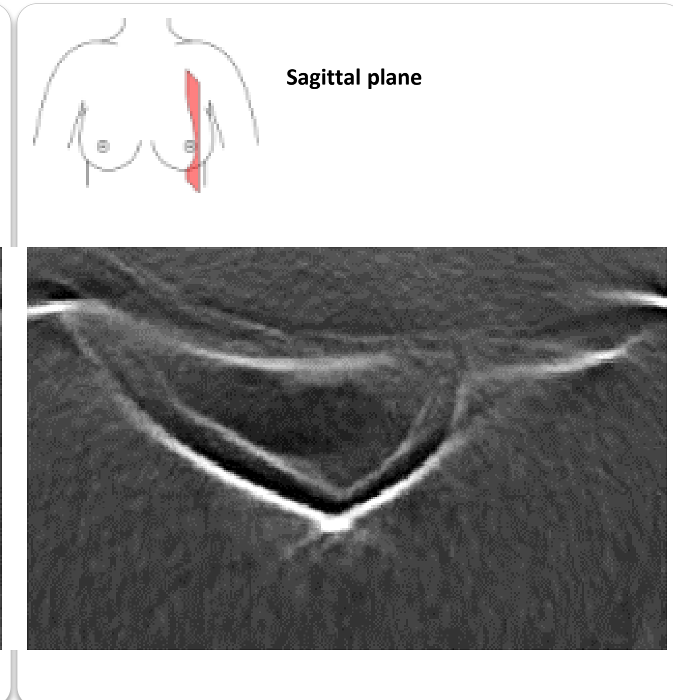


CIRS triple modality phantom

Results: 3D Reflectivity imaging (2)

- Healthy volunteer reflectivity images
  - 2D slices out of 3D volume





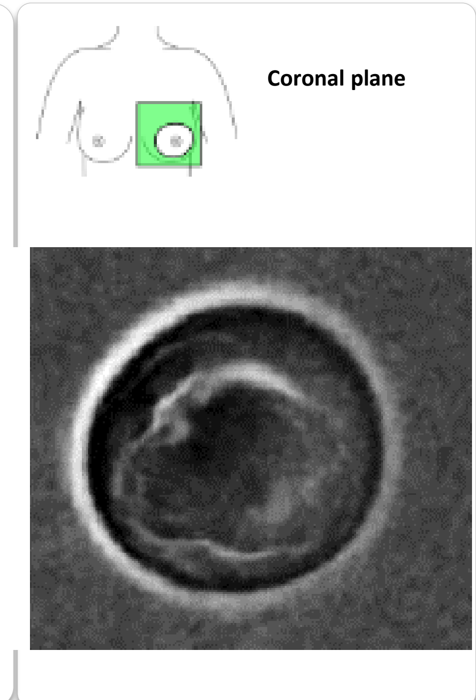


Image reconstruction: transmission

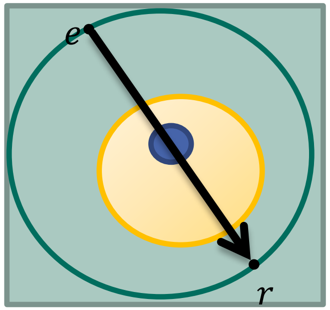
- Ray based back-projection for quantitative soundspeed or attenuation images
  - Not trivial paralizable
- Bent ray reconstruction
  - Fast marching method to update M [1]
- Algebraic Reconstruction Technique (ART)

$$t = M \cdot {}^{1}/_{c}$$

Matrix Size: 128³ voxels x 10⁷ measurements x 8 Byte => 153 PetaByte (dense)

  - Total variation minimization (TVAL3)
- Reconstruction time: ~15 min.

=> Clinical applicable with ~ 15min



M: *system matrix*
e: *emitter position*
r: *receiver position*
c: *sound speed*
t: *time of flight*

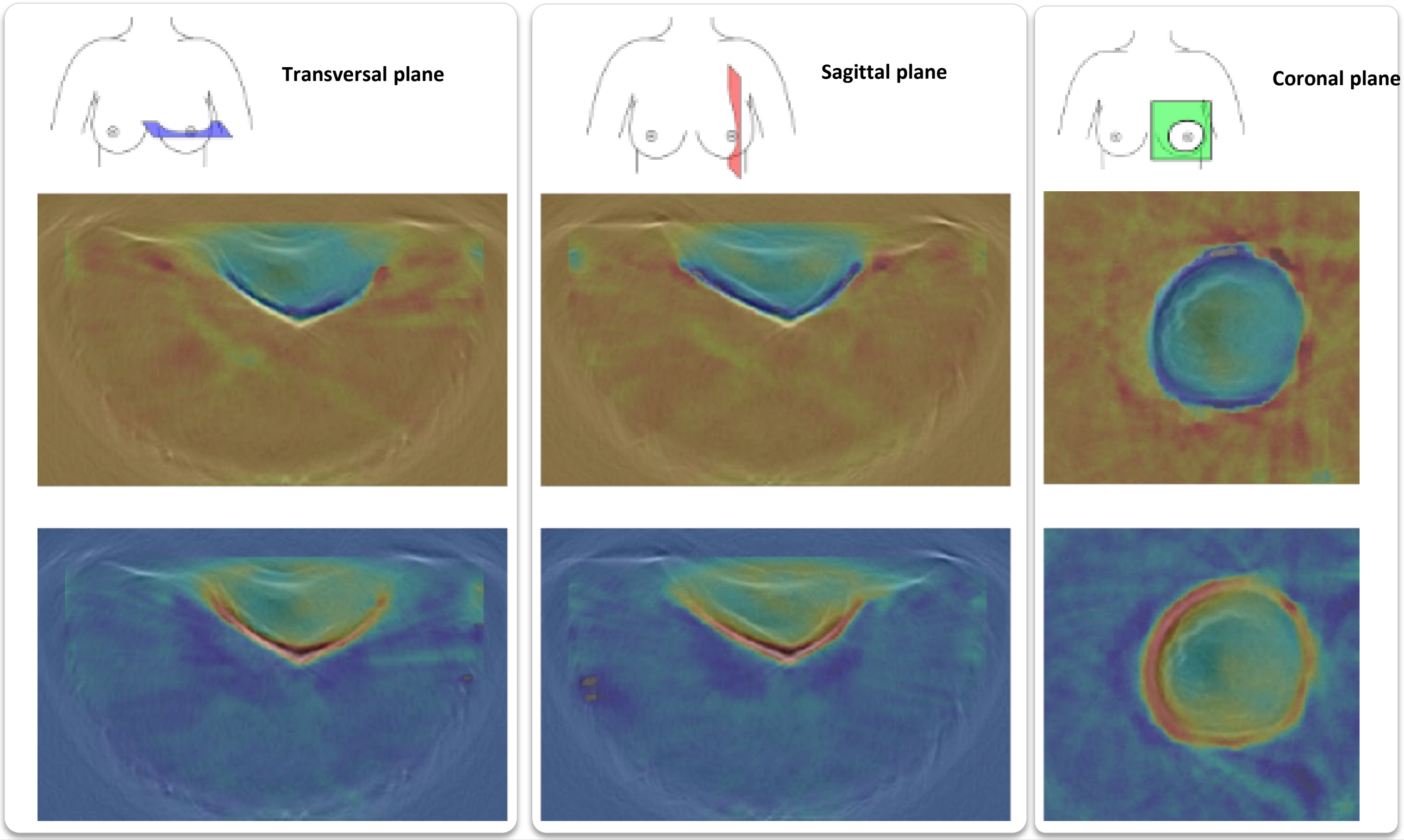
[1] R. Dapp: Abbildungsmethoden für die Brust mit einem 3D-Ultraschall-Computertomographen, Dissertation, KIT, 2013

Results: transmission image

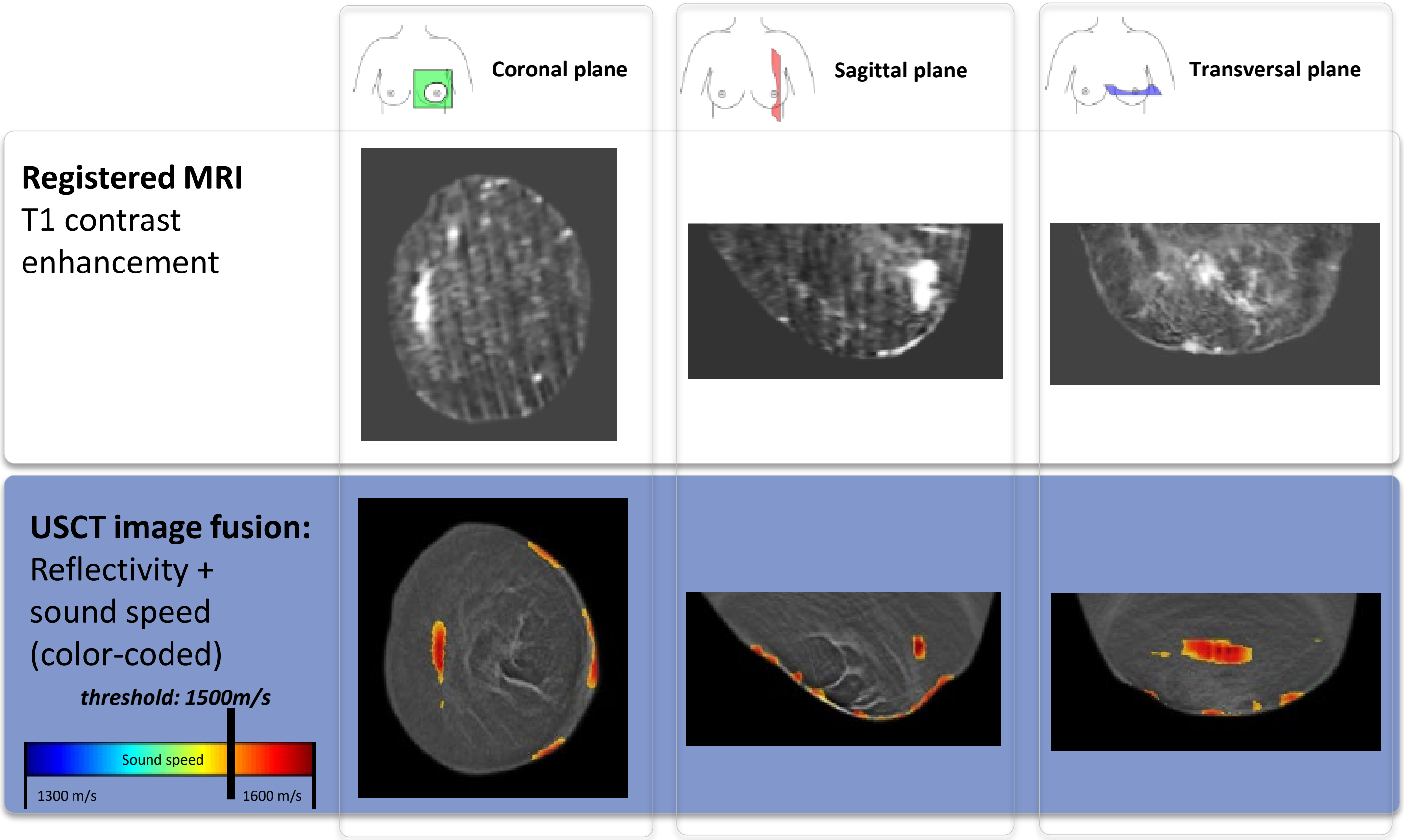
- Healthy volunteer
- Image fusion with transmission images

Reflectivity + Sound speed

Reflectivity + attenuation



Results: Clinical use case: Multicenter carcinoma



KIT 3D USCT: Status – finished?

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- Not in market yet
- Collaborations and ongoing work

European Innovation Council

瑞康医药股份有限公司
Realcan Pharmaceutical Co., Ltd.

UMM UNIVERSITÄTSMEDIZIN MANNHEIM

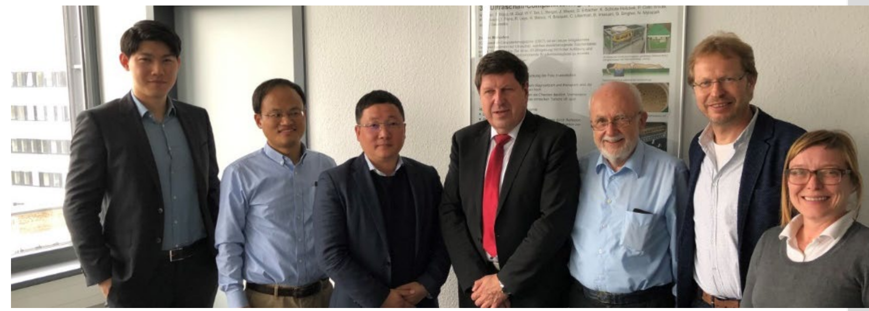
  - EIC QusTom: Kick off February 2024
    - Open goals:
      - Showing clinical viability of the method
      - Showing viability of full waveform image reconstruction methods
  - Equilibirium 9 Technology Transfer project (2024-25)
    - Open goals:
      - Passing chinese regulatory process and entering the Chinese Market
      - Showing viability via Multicenter study

USCT 2024: USCT Technology transfer project

瑞康医药股份有限公司
Realcan Pharmaceutical Co., Ltd.

- Aim: 3D USCT for multi-center study in China, five USCT III, approx. 1000 patients
- Current status:Technology transfer finished (end 2023), first pre-trial in Hangzhou

- In-process 2024:
  - CFDA approval and fabrication site in Hangzhou (near Shanghai)
  - KIT supports EQ9 for study and built up of USCTs and commercialization



Zhejiang Equilibrium Nine Medical Equipment Co., Ltd

EQ9 in hospital in Hangzhou

Status USCT 2024: QusTom Project

KIT Karlsruhe Institute of Technology

European Innovation Council | QUSTom | Imperial College London | BSC | FrontWave Imaging | Vall d'Hebron Barcelona Campus Hospitalari

- EIC Pathfinder Grant: QusTom
  - Aim: 60 patient study for for full 3D wave inversion reconstruction imaging
  - Status: Preparations for „Kick off in Hospital“: Crunch from Nov. 23 to 9th of Feb. 2024

Preparation and packaging for transport to Spain, Barcelona

Status: QusTom Project

- Kick off: Arrival at Barcelona: 13th February 2024
  - Handover at 15th of February

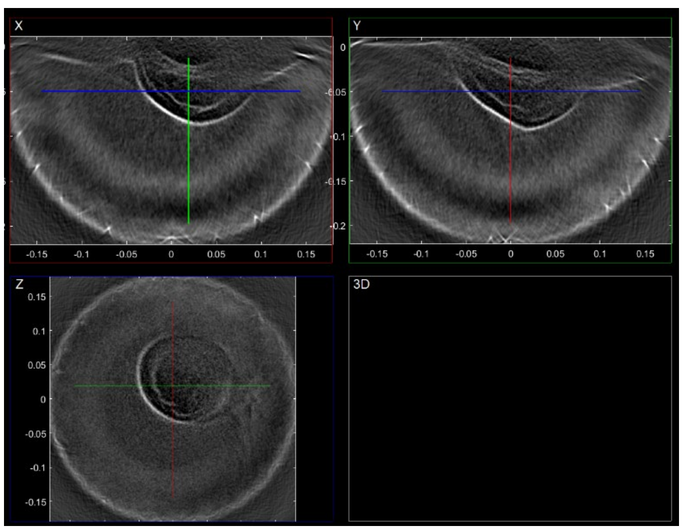
Transportbox arrives at Val'd Hebron

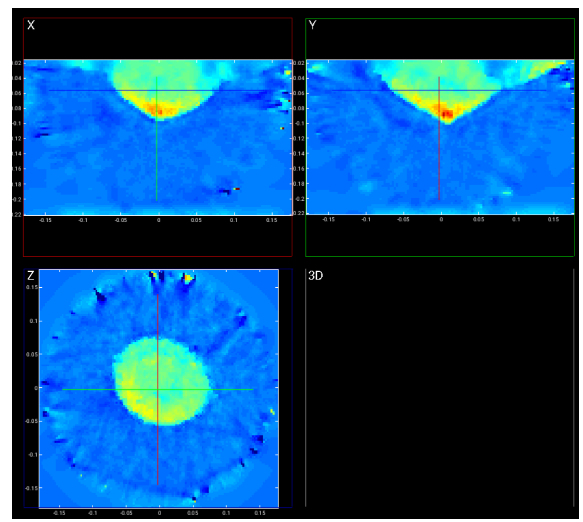
Built up and comissioning of the system

Handover to the hospital and trial coordinators

KIT 3D USCT: Status

- Current project status
  - Realizatibility?
    - Done
  - Clinical Viability?
    - Measurement time: 5-20min,
    - Imaging time : 30min
    - Ongoing patient & hospital studies
  - Fully realized imaging potential?





Left: 2D cuts of reflectivity imaging, Right: soundspeed of healthy volunteer P1 (2023)

Image reconstruction: Future

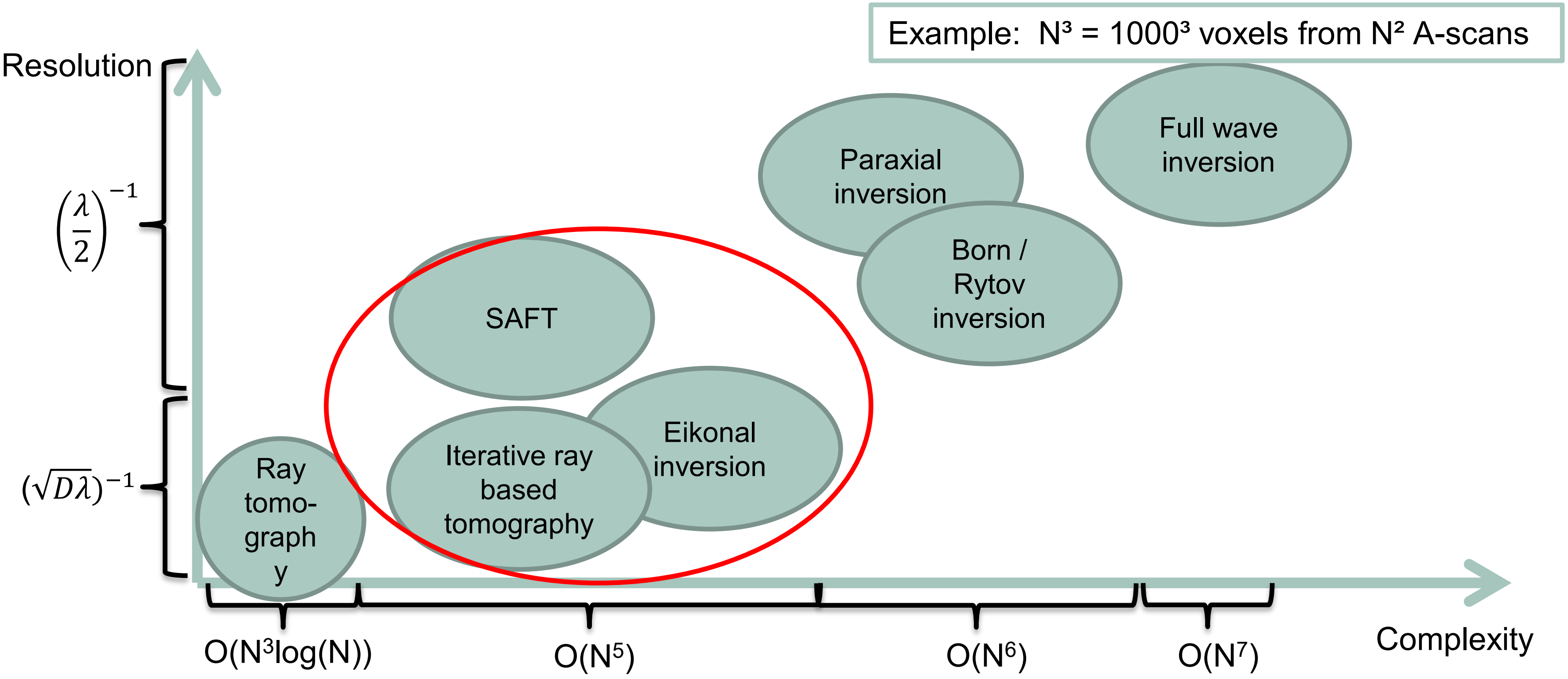


Image reconstruction: Future

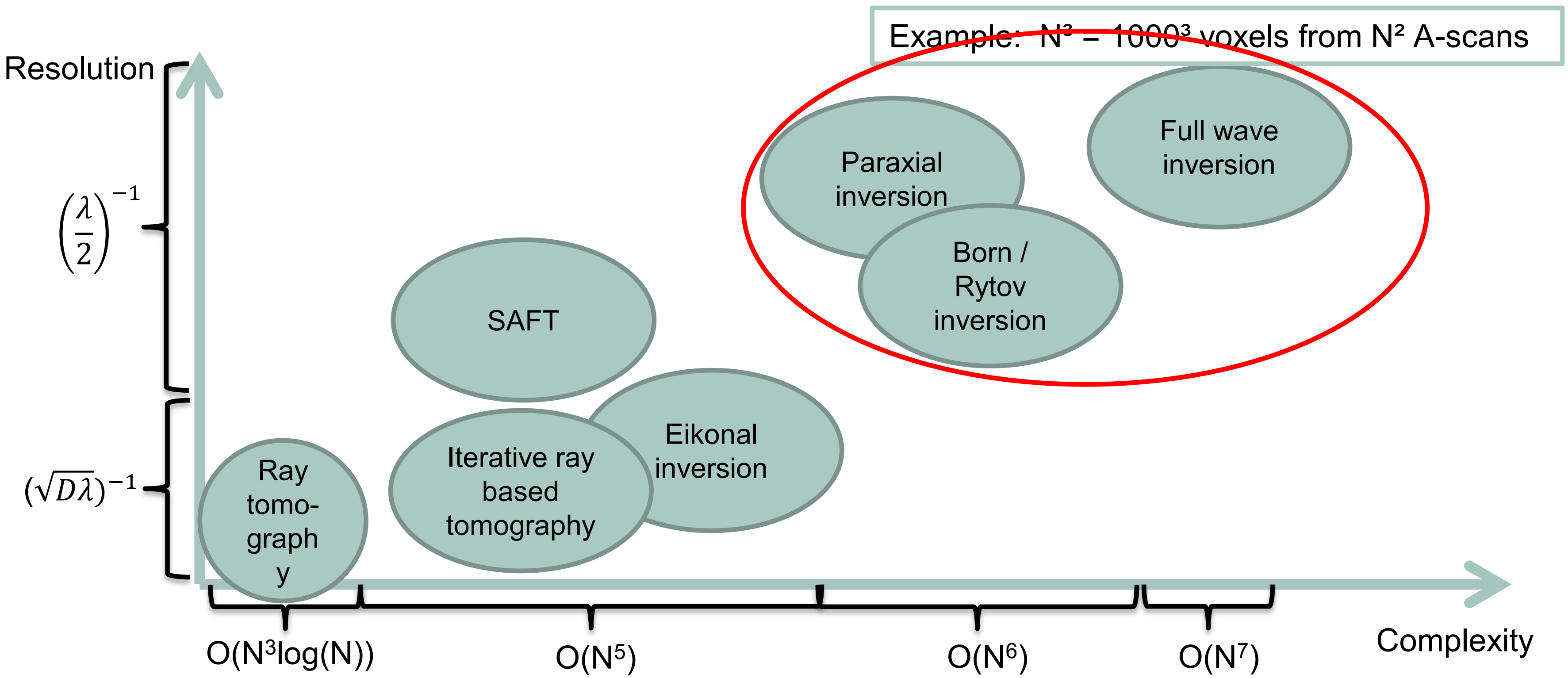
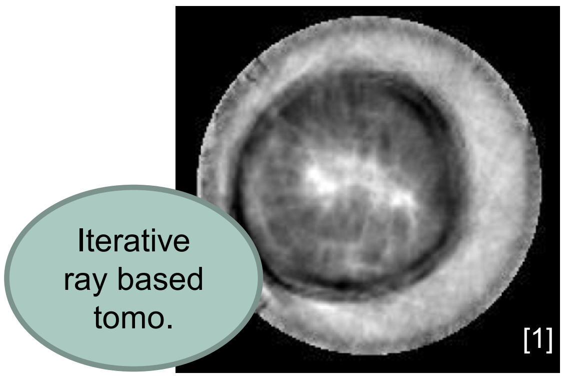
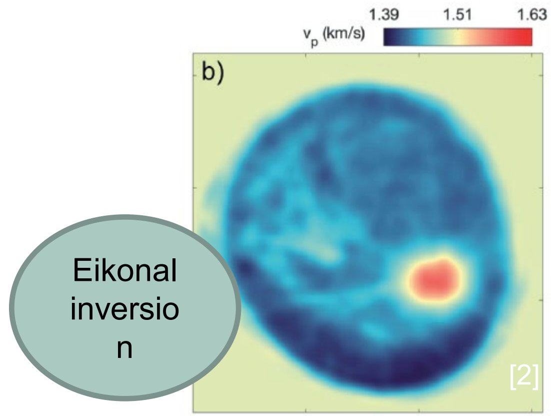
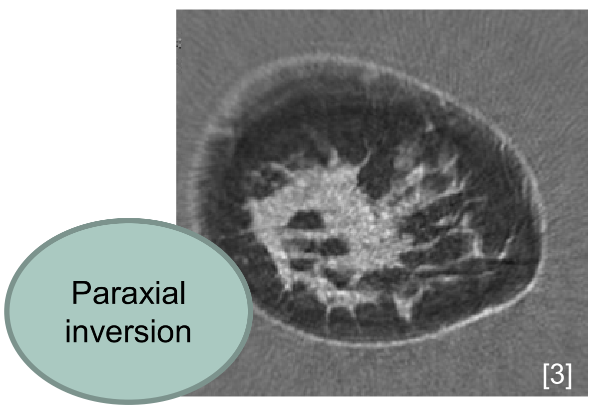


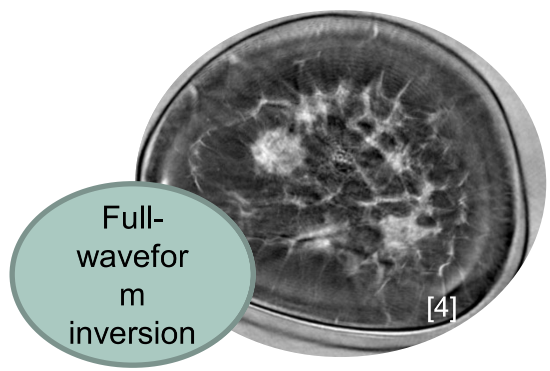
Image reconstruction: Future: 2D Speed of Sound

- More advanced methods…for quantitative imaging
  - Examples from 2D systems









[1] Li et al. Proc. SPIE Medical Imaging, 2008
[2] Agudo, et al. *Proc. of MUST,* 2017
[3] Wiskin et al. Proc. SPIE Medical Imaging, 2020
[4] Littrup, Duric, et al. *Proc. of MUST,* 2017.

Image Reconstruction: Full wave form inversion – paraxial approximation

- The sperical wave in the forward direction can be approximate by a plane wave.

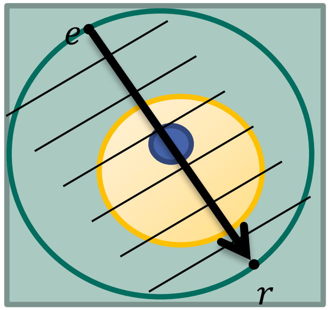
$$p = \frac{e^{-ikr}}{r}$$

$$r = \sqrt{x^2 + y^2 + z^2} = z\sqrt{1 + \frac{x^2+y^2}{z^2}}$$

Taylor series: $\sqrt{1+b} = 1 + \frac{1}{2}b + O(b^2)$

$$\Rightarrow r \approx z + \frac{x^2+y^2}{2z} \approx z \quad \text{for} \quad x, y \ll z$$

$$\Rightarrow p_{\text{paraxial}} = \frac{e^{-ikr_{\text{paraxial}}}}{r_{\text{paraxial}}} \approx \frac{e^{-ikz}}{z}$$



M: *system matrix*
e: *emitter position*
r: *receiver position*
c: *sound speed*
t: *time of flight*

Approximation: Up to an angle of 25° between wave vector and z-axis the deviation for the amplitude is under 10 %.

Image Reconstruction: Full wave form inversion – paraxial approximation (2)

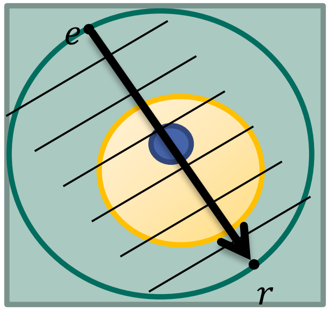
- Iterative method

$$p(x,y,z+\Delta z) = e^{-\mathrm{i}\,k_0 \eta \Delta z}\; \boldsymbol{F}^{-\mathbf{1}}\left\{ e^{-\mathrm{i}k_0\sqrt{1-\frac{\xi_{x,y}^2}{{k_0}^2}}\Delta z}\, \boldsymbol{F}\{p(x,y,z)\}\right\}$$

phase　　　propagator

- Forward model, backward, update…
- Initial pressure p_0 can be calculated analytical in homogeneous medium:

  spherical wave, piston model, …



M: system matrix
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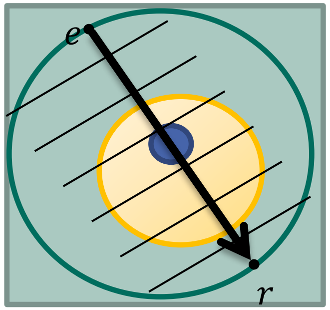
Image Reconstruction: Full wave form inversion – paraxial approximation (3)

- Iterative Scheme, sequential (not trivial parallizeable):
  - Per emission, per frequency,
    - forward projection 2D plane, along Z, to receiver
      => Many fourier transformations
  - Per emitter: Rotation & interpolation of image domain
    => many rotations in image domain required
  - Matrix Inversion



M: *system matrix*
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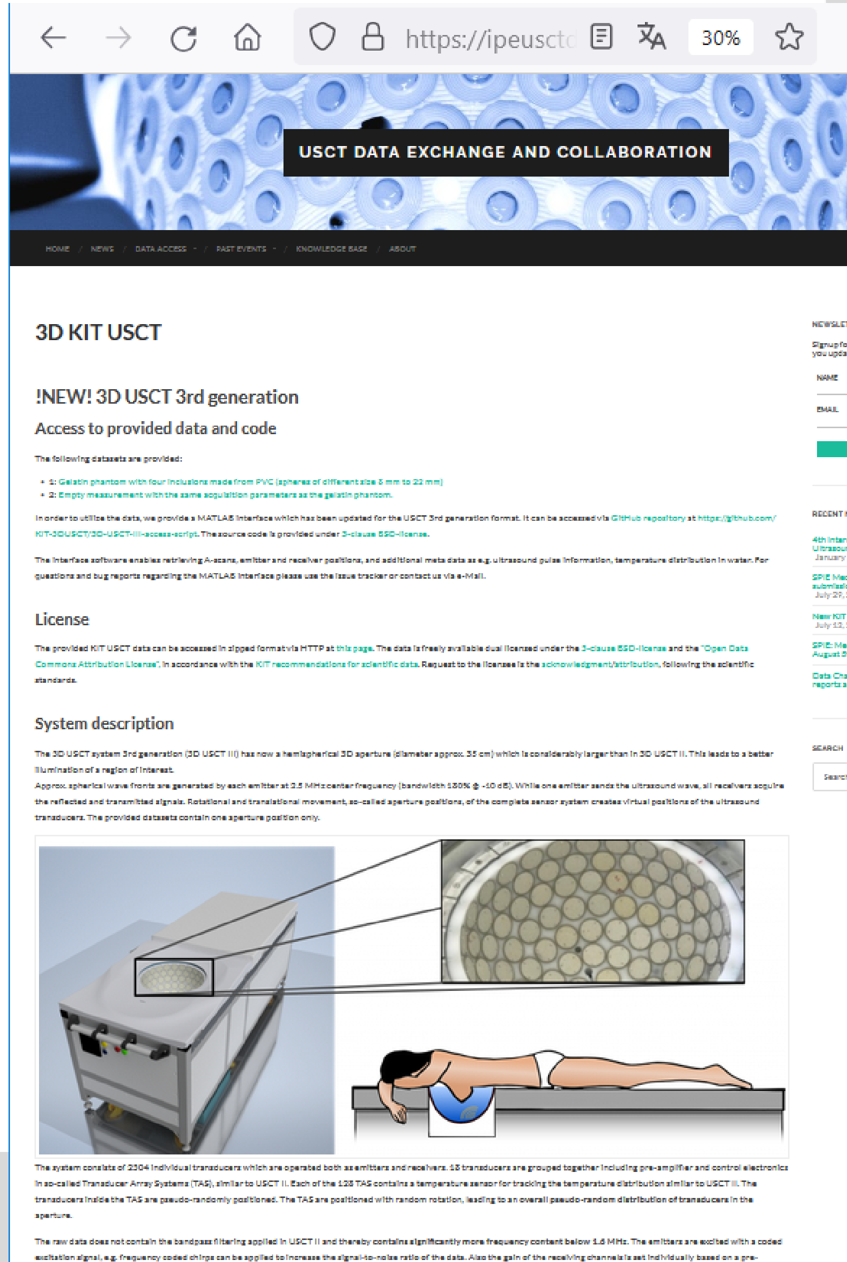
- Applicability:
  - Runs for 2D subsets and < 1MHz center frequency ~ 30min
  - 3D not realized, applicability currently limited by: Memory, bulk calculation time in the many fourier transformations & rotations

Solution: Open data and open access to 3D USCT data

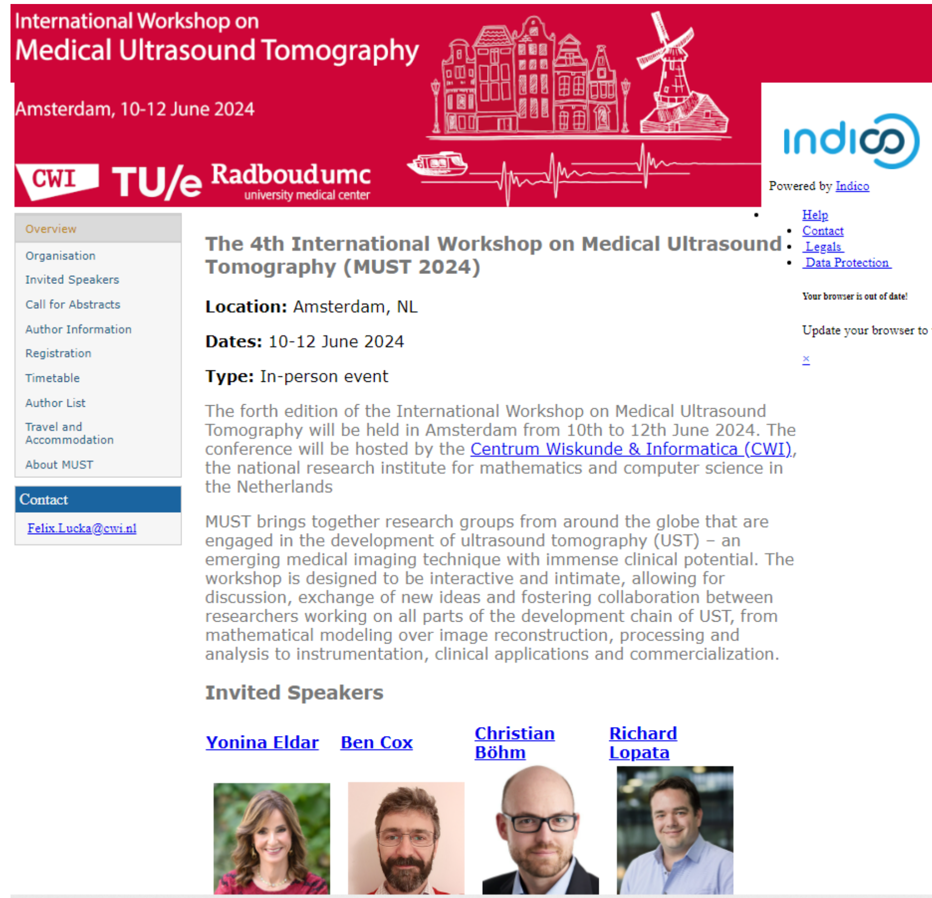
- 3D KIT USCT – USCT data exchange and collaboration
  - A MATLAB script with some reference imaging and visualization code:
  - „3D-USCT-III-access-script“ KIT-3DUSCT/3D-USCT-III-access-script (github.com)
  - The following datasets are provided:
    1. Gelatin phantom with four inclusions made from PVC (spheres of different size 8 mm to 22 mm)
    2. Empty measurement with the same acquisition parameters as the gelatin phantom.



Meet us at MUST 2024

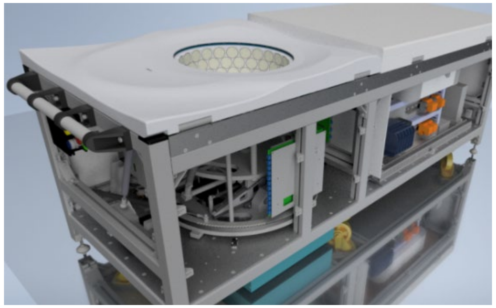
Karlsruhe Institute of Technology

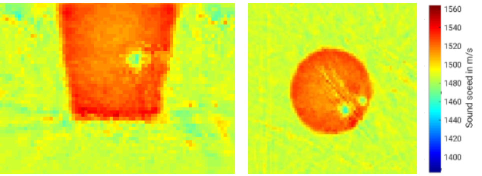
- Workshop on Medical Ultrasound Tomography (MUST) at 10-12 June 2024, in Amsterdam, Amsterdam Science Park, Centrum Wiskunde & Informatica (CWI)
- https://www.cwi.nl/en/events/must-2024/

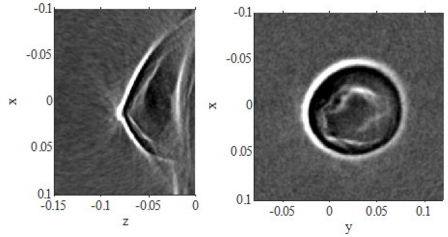


Summary

- Realizability:
  - Successful realization of KIT 3D USCT III as full 3D and multimodal ultrasound computertomography device
- Clinical viability:
  - Promising first images with phantoms and volunteers
    - Measurement time: 5-20min
    - Imaging time: 30min
    - Ongoing multicenter study
    - Ongoing steps into Chinese and European market
- Full realization of imaging potential:
  - Computational and ressource wise challenging due to **3D approach** and **high frequency system**
    - Paraxial currently 30min (2D), to days (3D) with low frequencies (<1MHz)







Join our data challenge!

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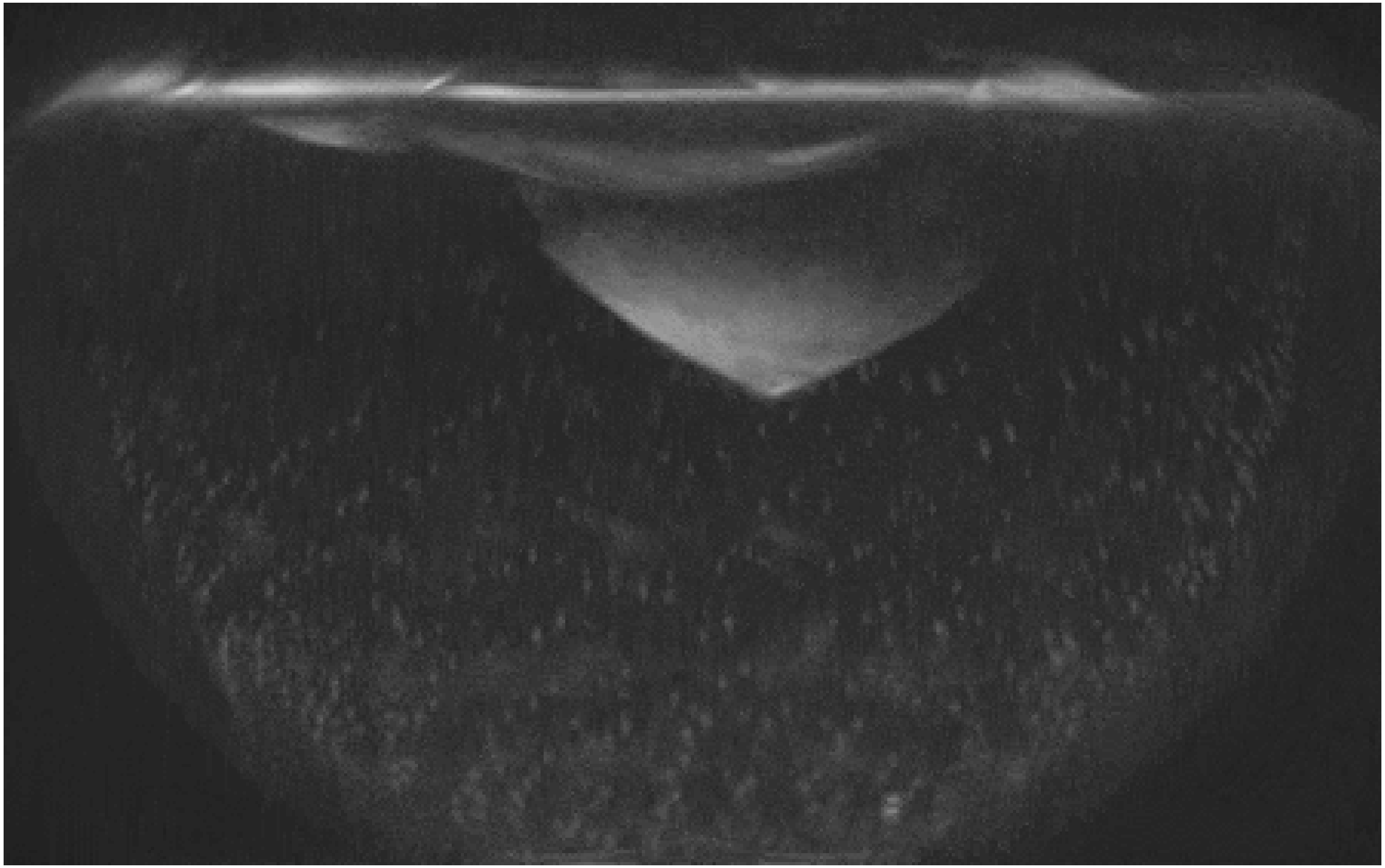

http://ipeusctdb1.ipe.kit.edu/~usct/challenge/

or contact me: **michael.zapf@kit.edu**