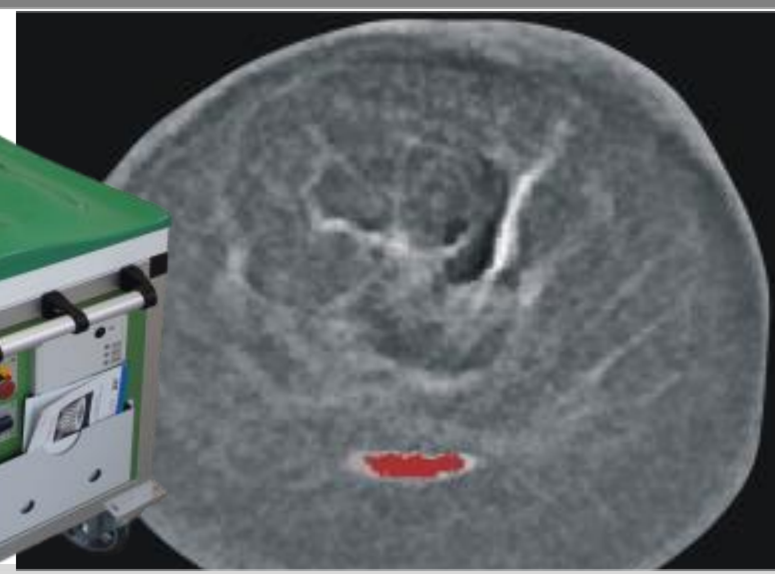
Karlsruhe Institute of Technology

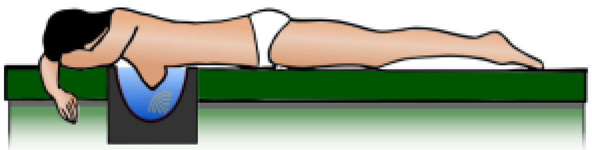
3D Ultrasound Computer Tomography

N.V. Ruiter, M. Zapf, T. Hopp, E. Kretzek, H. Gemmeke



Ultrasound Computer Tomography

- Application: Breast imaging for cancer diagnosis

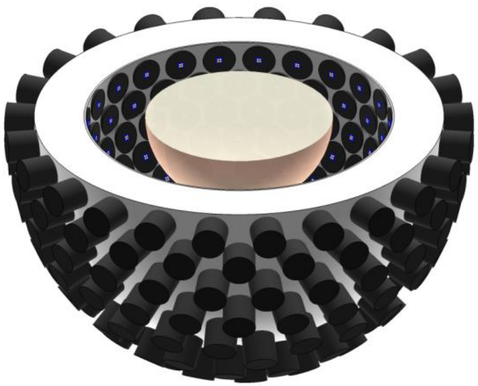


Breast imaging in fixed setup

- Basic idea:
  Surround object with (unfocused) ultrasound transducers in a fixed setup

- Features:
  - Reproducible 3D images with ultrasound
  - Three modalities concurrently
  - Sub-millimeter volumes
  - Fast data acquisition
  - Optimally focused images in 3D (isotropic PSF)

Worldwide unique!



3D USCT imaging setup

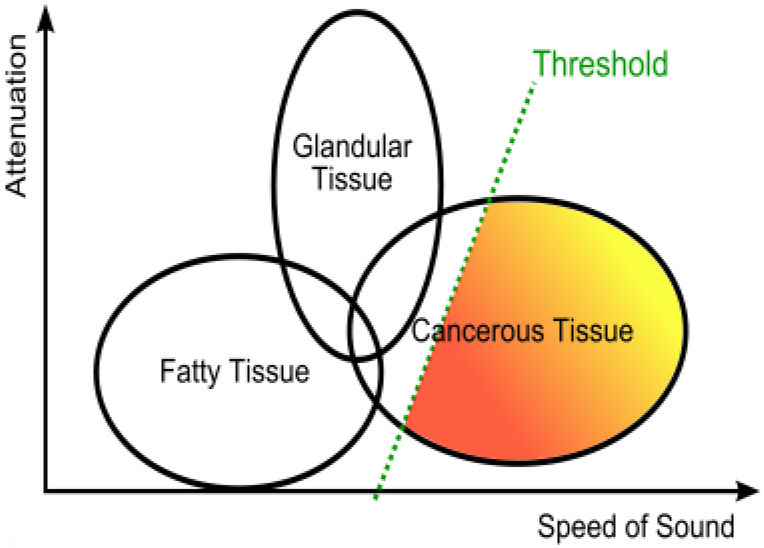
Ideal for Breast Cancer Diagnosis?

- Images three modalities concurrently

- **Reflection**:
  High quality “B-Scans”

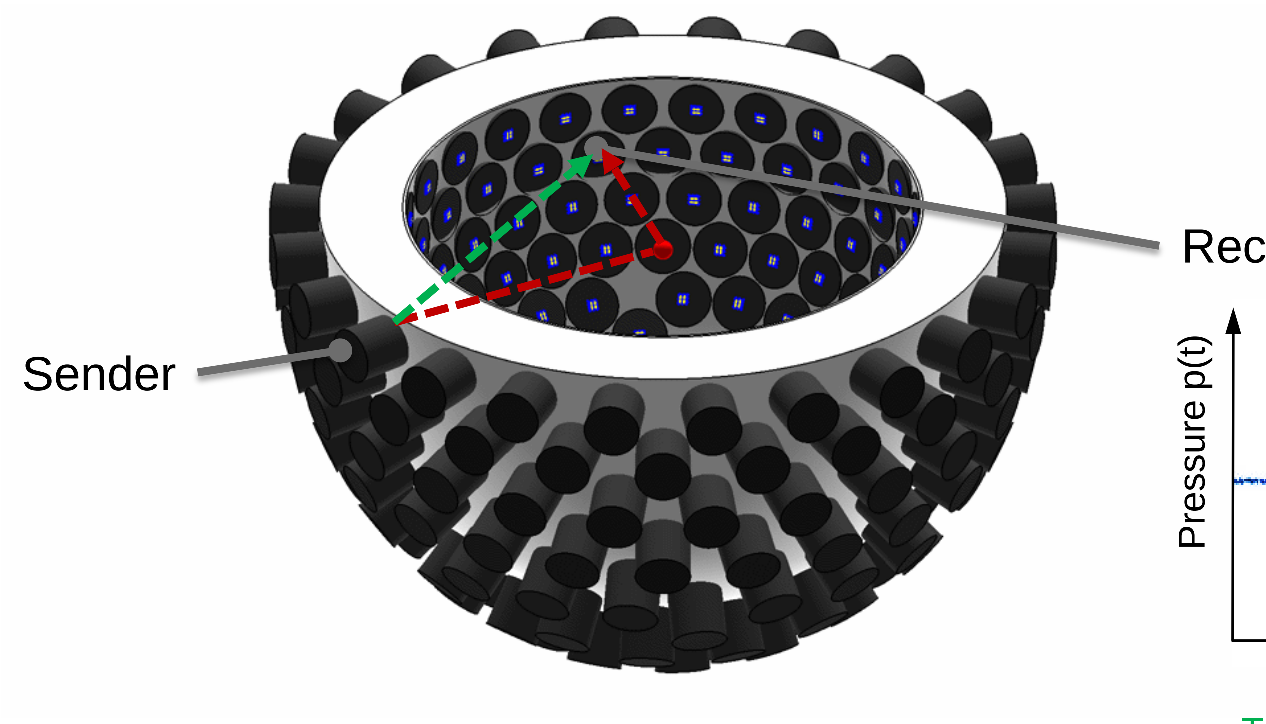
- **Speed of sound** and **attenuation**:
  Quantitative information

- USCT for early breast cancer diagnosis:
  - as good as MRI?
  - as cheap as X-ray mammography?
  - as harmless as diagnostic ultrasound!



[*Simplified from Greenleaf et al.*]

USCT imaging principle



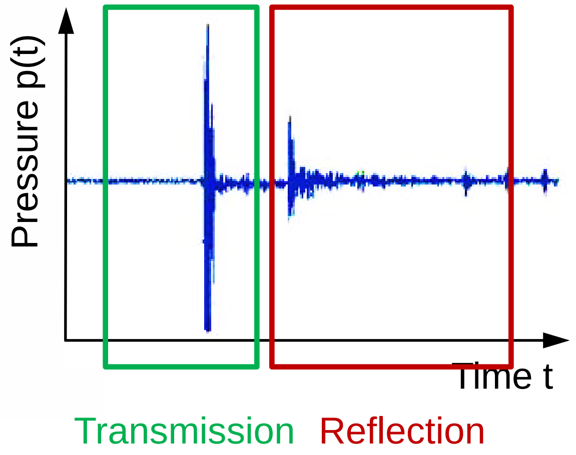


Image reconstruction

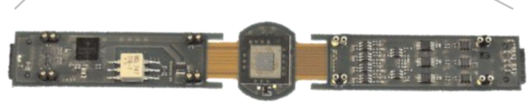
- Sound speed
- Attenuation
- Reflection

KIT 3D-USCT

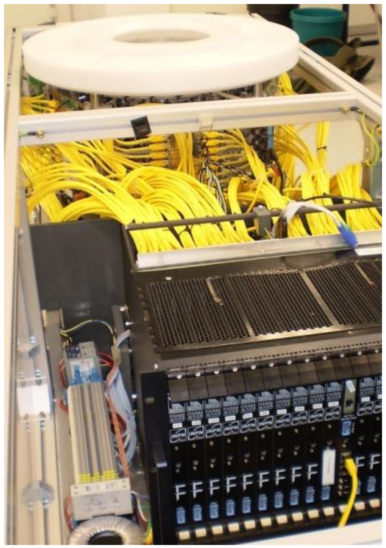
Center frequency	2.5 MHz (~50% bandwidth)
Raw data	Up to 40 GByte per breast
Measurement time	10 s – 8 min (now 4 min)
Maximal resolution	$(0.24\ \text{mm})^3$

KIT 3D USCT patient bed

Measurement aperture



Transducer Array System

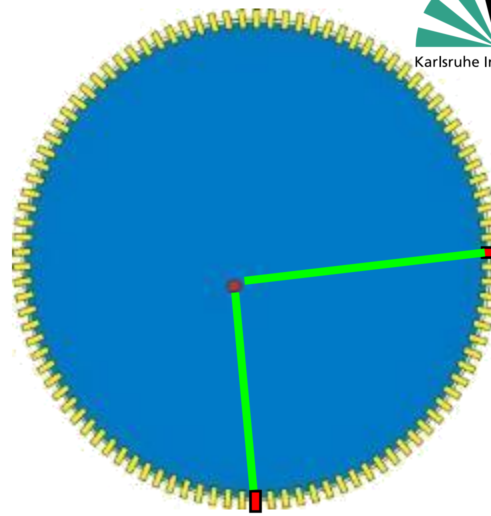


Detail view of DAQ system

Reflection Tomography

- **How it works**:
  - 3D Synthetic Aperture Focusing Technique

$$f(\vec{x}) = \sum_{(i,k)} A_{(i,k)}\left(\frac{\left\|\vec{x}_i - \vec{x}\right\| + \left\|\vec{x} - \vec{x}_k\right\|}{\hat{c}(\vec{x}_i, \vec{x}_k, \vec{x})}\right)$$



- **Approximations and resolution**:
  - Born approximation, no refraction
  - Maximum resolution: $(0.24\ \text{mm})^3$
  - Speed of sound and attenuation correction

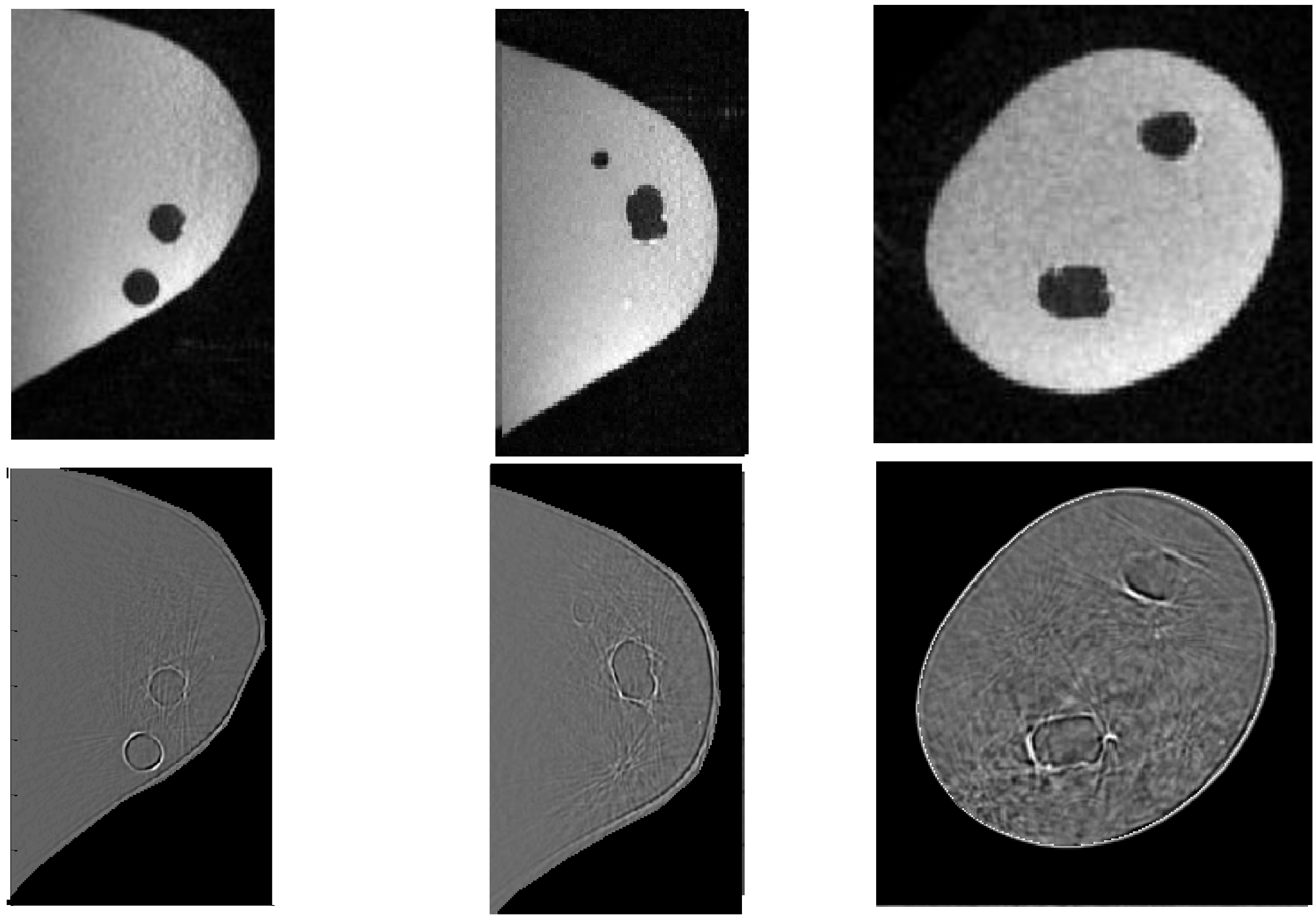
- **Reconstruction load and performance**
  - Realistic scenario: 256^3 voxels using 8 million A-scans (MRI resolution)
  - Using multi CPU and GPU cluster in 2 hours, corrected in 14 hours

Clinical Breast Phantom: Results

Transversal | *Sagittal* | *Frontal*

MRI

USCT

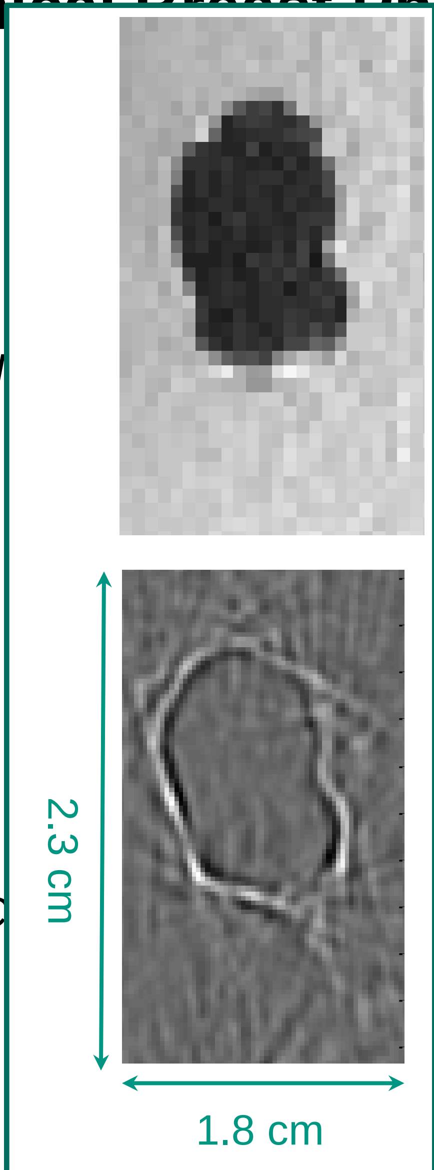


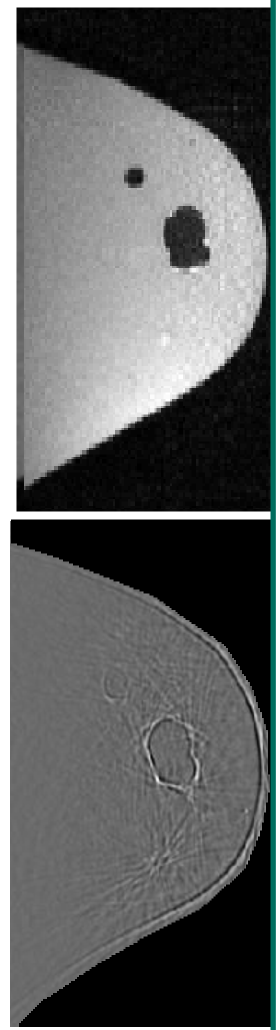
Clinical Breast Phantom: Results

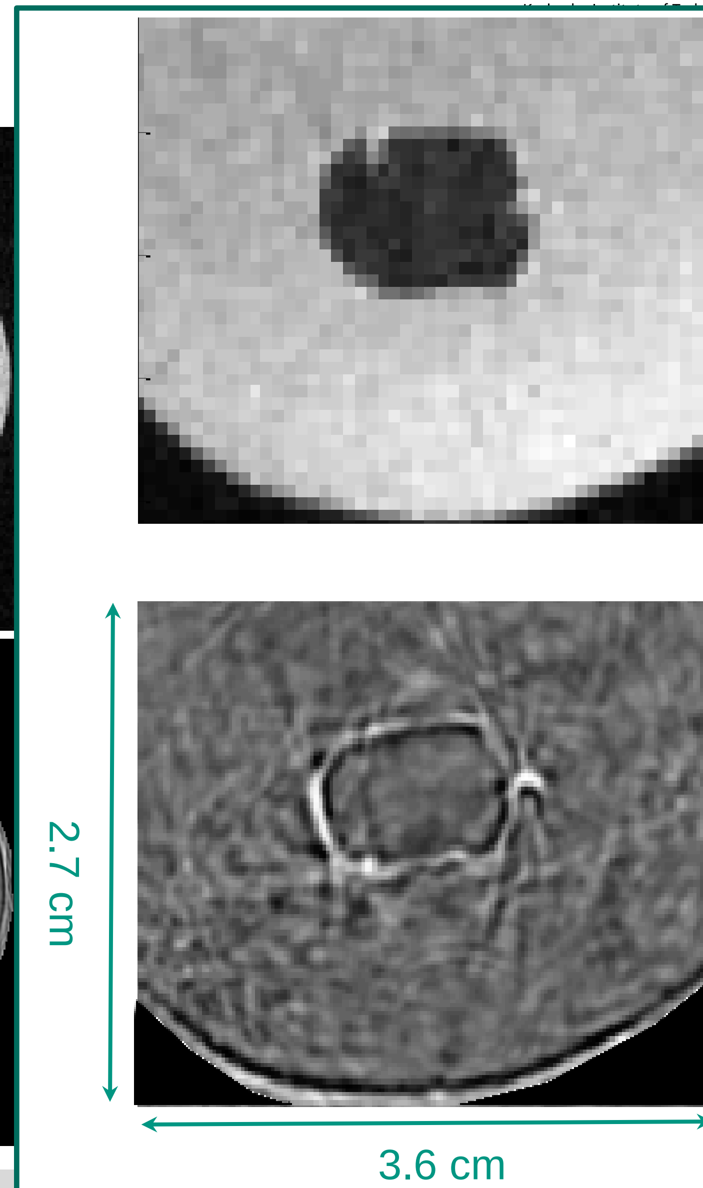
Sagittal

MRI

USC







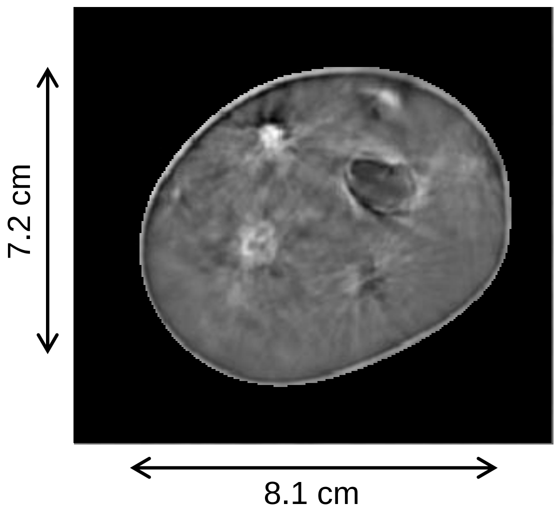
Transmission Tomography

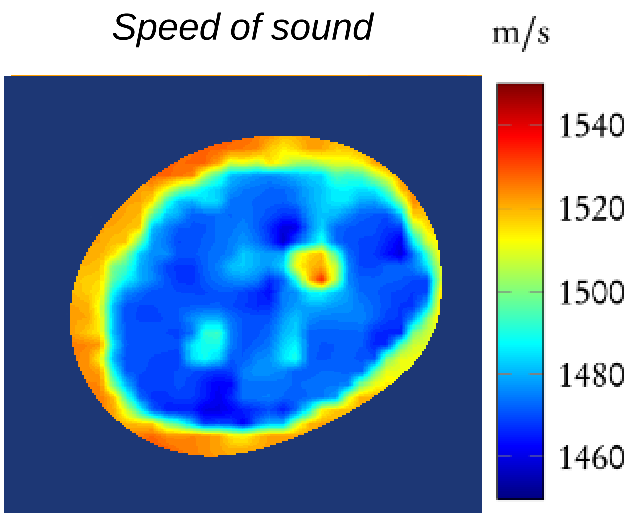
- **How it works** (example for speed of sound)
  - $t = l / c$
  - $$\begin{bmatrix} t_1 \\ \vdots \\ t_n \end{bmatrix} = \begin{bmatrix} l_{11} & \cdots & l_{1m} \\ \vdots & \ddots & \vdots \\ l_{n1} & \cdots & l_{nm} \end{bmatrix} \begin{bmatrix} 1/c_1 \\ \vdots \\ 1/c_m \end{bmatrix}$$
  - Solve linear equation system using Total Variation minimization (TVAL3)

t: time of flight
l: travelled path
c: speed of sound
n: number of measurements
m: number of voxels

- **Approximations and limitations**
  - Straight ray approximation
  - Optimal resolution: $(5\ \text{mm})^3$
  - Refraction correction
- **Reconstruction load and performance**
  - Matrix dimensions of 3 000 000 x 1 500 000
  - Reconstruction in 5 minutes, refraction corrected in 8 hours

Clinical Breast Phantom: Speed of Sound and Attenuation





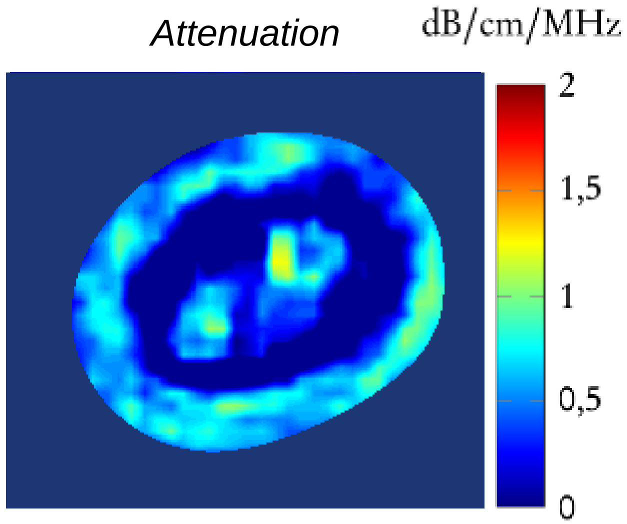


Image Fusion and Display

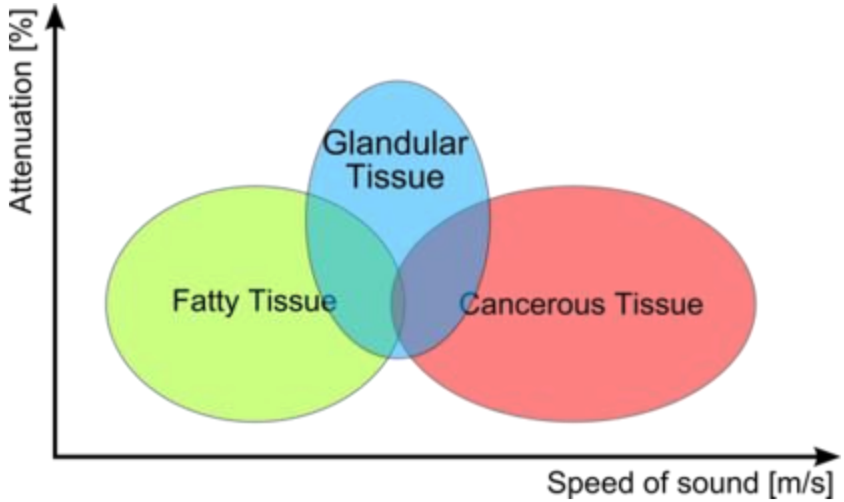
- Three types of images:
  - Reflectivity I_R
  - Speed of sound I_S
  - Attenuation I_A

- Overlaid images I_o:

$$I_O = I_R + I_T$$

- Thresholded fused images I_F*:

$$I_F = \left[I_R + I_{S=a}^{S=b}\right] + \left[I_{S>c} \bullet I_{A>d}\right]$$

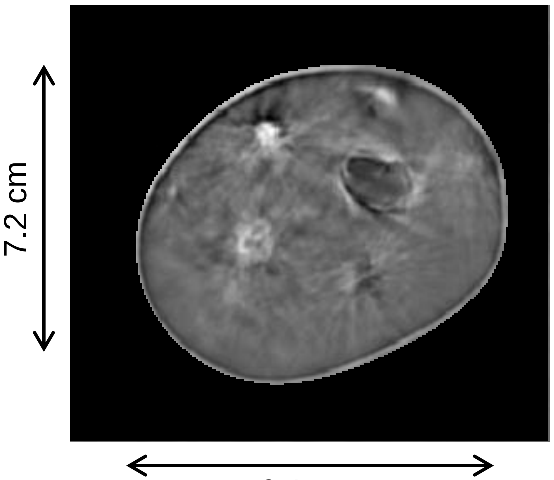


[Simplified, based on Greenleaf et al, Clinical Imaging 1981.]

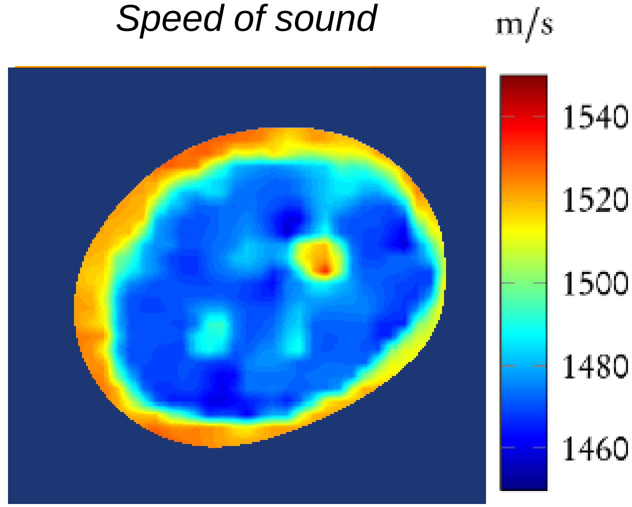
*N. Duric, P. Littrup, et al, "In-vivo imaging results with ultrasound tomography: Report on an ongoing study at the Karmanos Cancer Institute," Proc. SPIE Medical Imaging, 2010.

Clinical Breast Phantom:
Speed of Sound and Attenuation

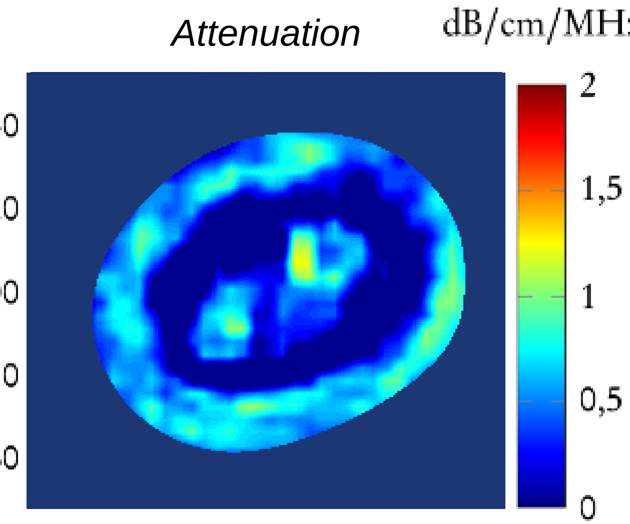
Reflectivity



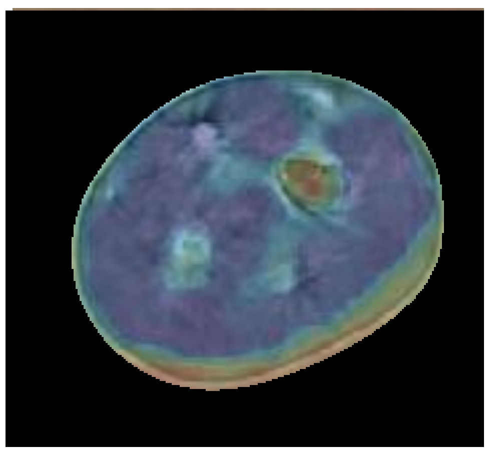
Speed of sound



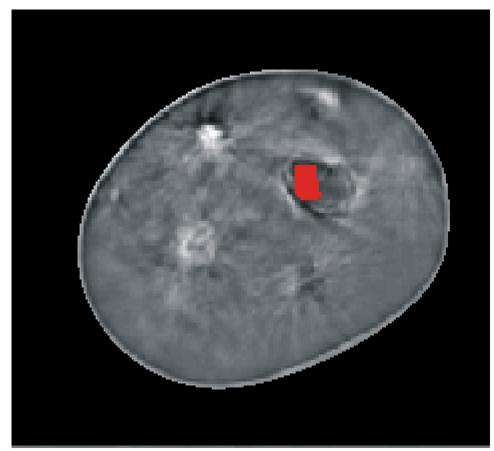
Attenuation



Exemplary image fusion



Fused reflectivity and speed of sound

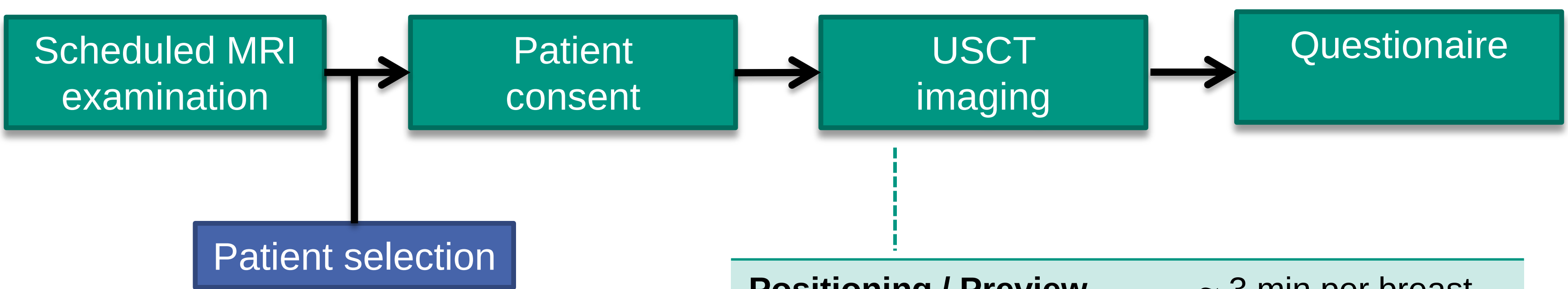


All modalities with thresholding

Pilot in-vivo study

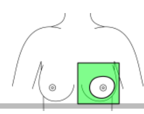
- **Aim:** Test KIT 3D USCT with 10 patients
  1. Test data acquisition and image reconstruction protocols
  2. Test display/combination of multimodal images
  3. Compare tissue structures with established imaging method

- Study performed on 3 days at University Hospital of Jena, Germany
- MRI images as ground truth

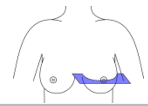


Positioning / Preview	~ 3 min per breast
Data acquisition	~ 8 min per breast

Patient with Implants

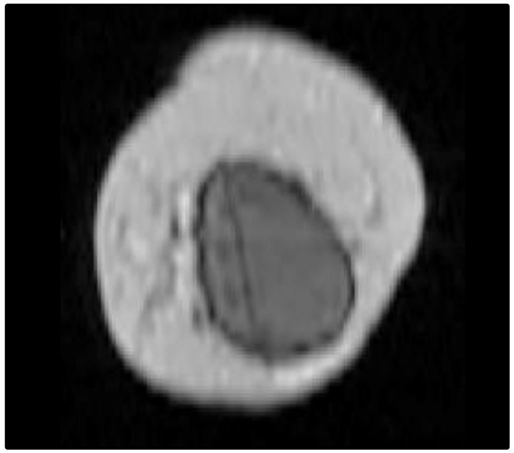


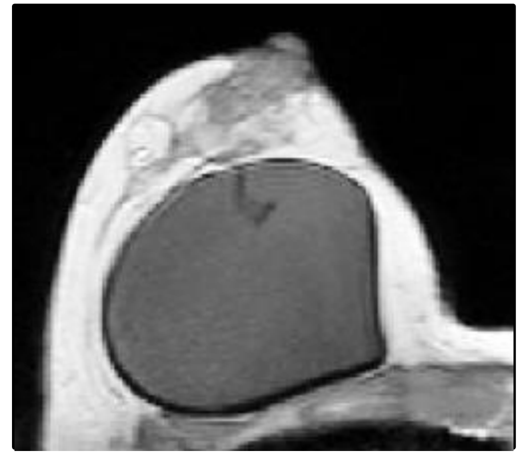
Coronal plane



Transversal plane

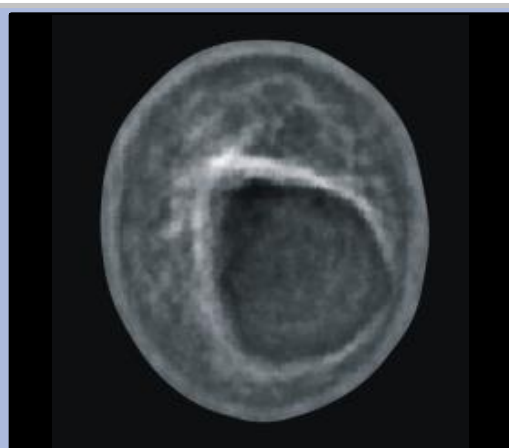
MRI
T1

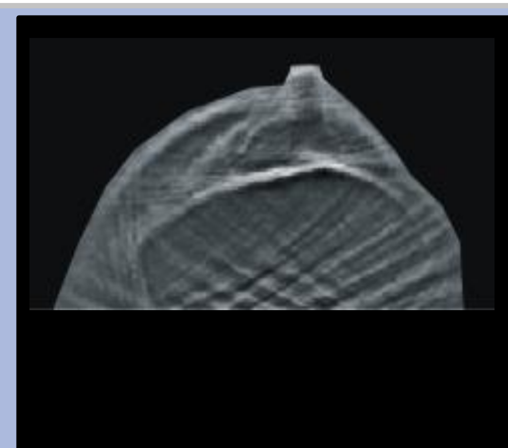




9.4 cm

USCT
Reflectivity



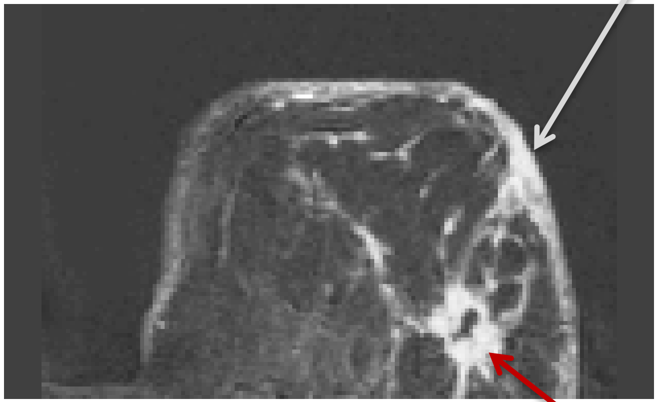


6.4 cm

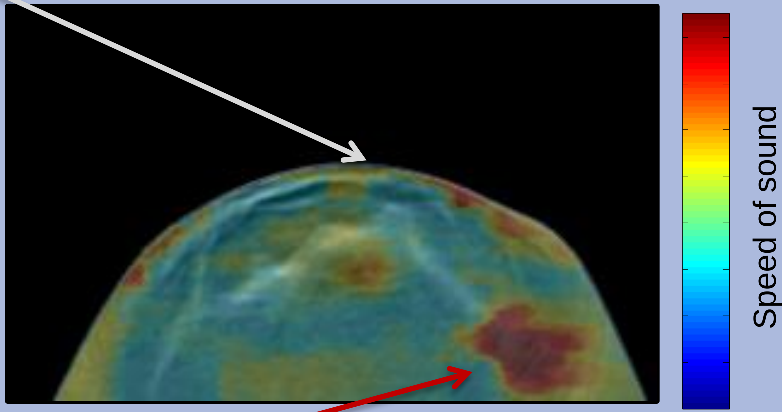
8.7 cm

Patient with carcinoma

MRI: T1 subtraction, 2 min.
after Gd-DTPA contrast agent



USCT: Reflectivity (background) +
speed of sound (colour coded)



~1530 m/s

18 cm

Nipple

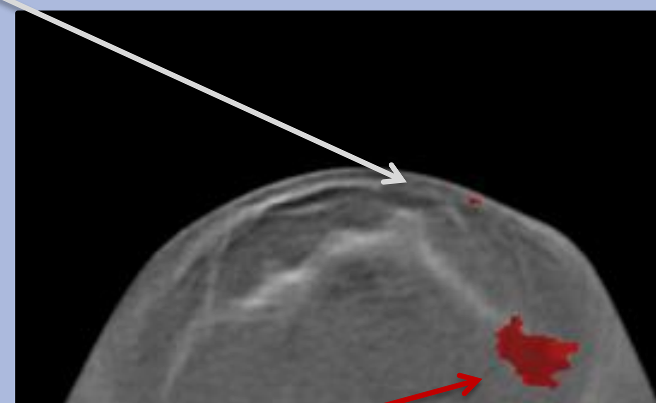
Carcinoma

Patient with carcinoma

MRI: T1 subtraction, 2 min. after Gd-DTPA contrast agent

USCT: Reflectivity (background) + tresholded speed of sound and attenuation (colour coded)

Nipple

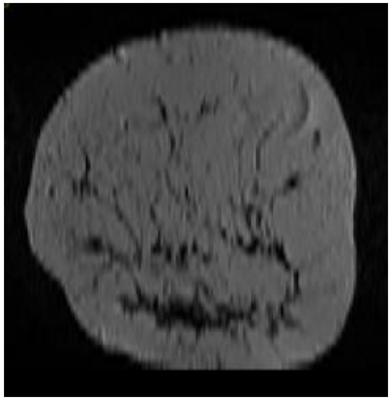


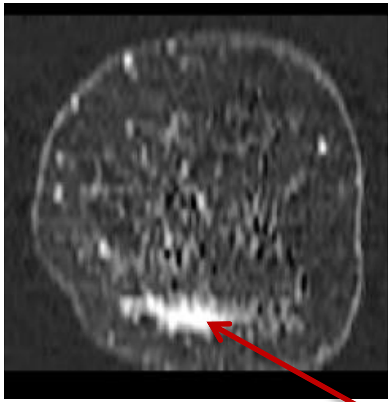
>1520 m/s

Carcinoma

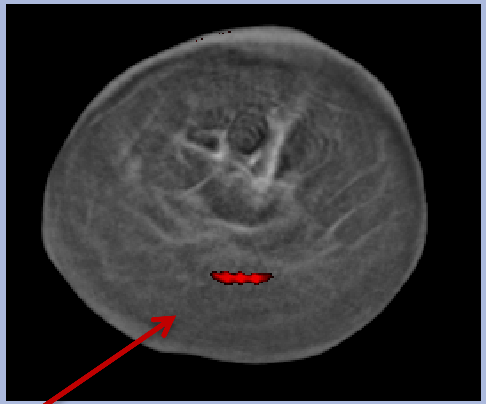
Another Patient with Cancer

MRI: T2 (left) , T1 subtraction, 2 min. after Gd-DTPA contrast agent (right)





USCT: Reflectivity (background) + tresholded speed of sound and attenuation (colour coded)

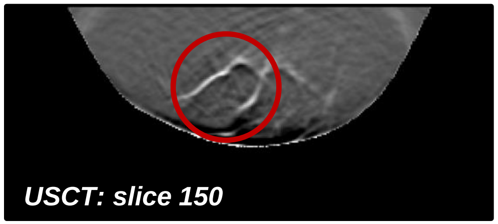


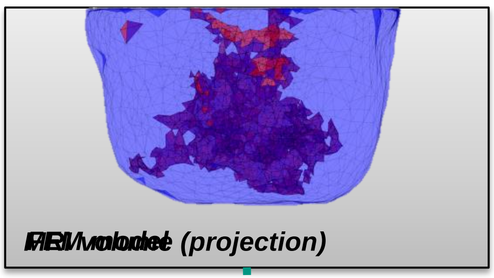
>1520 m/s

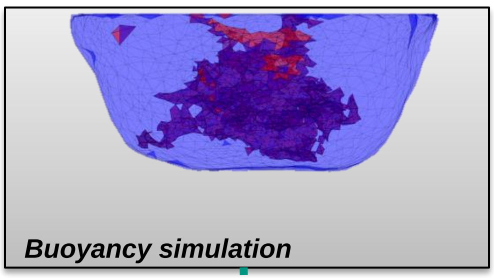
Cancer

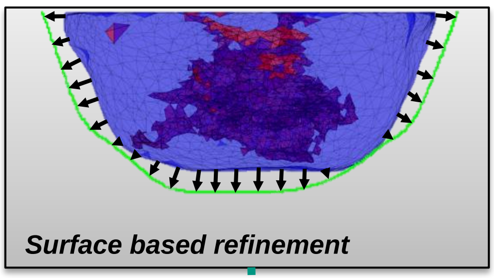
Image registration

- Comparison of USCT and MRI is challenging due to buoyancy
  ➔ Image registration to estimate spatial correspondence









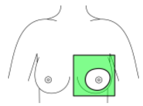
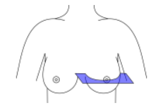
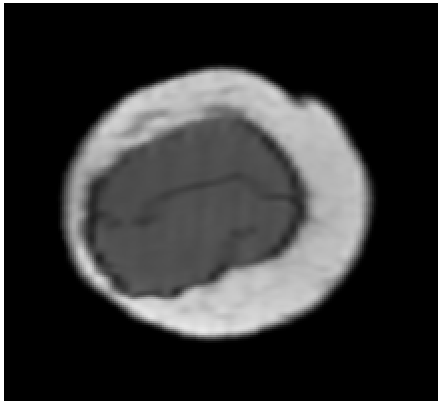
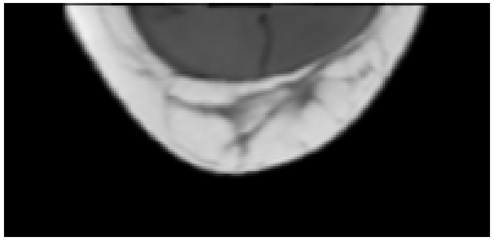
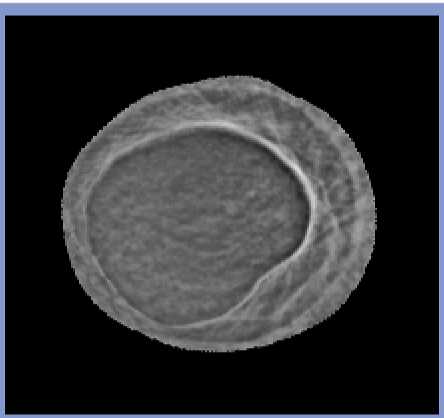
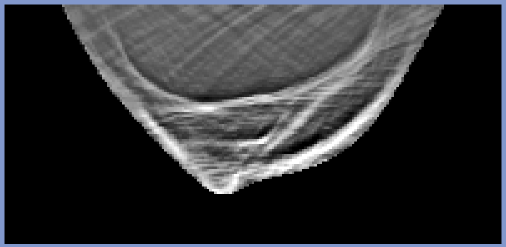
- Preprocessing
- Segmentation of MRI
- Tetrahedral meshing
- Neo-hookean material model

- Inverse gravity load
- Optimization of material parameters

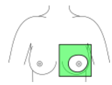
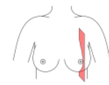
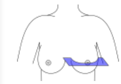
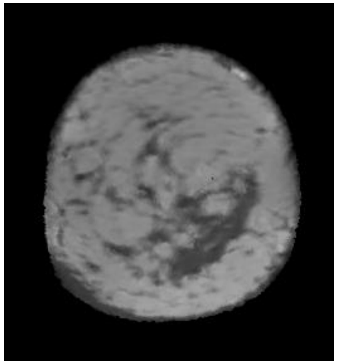
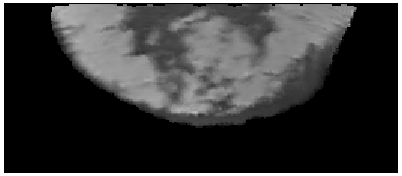
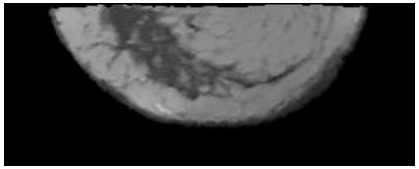
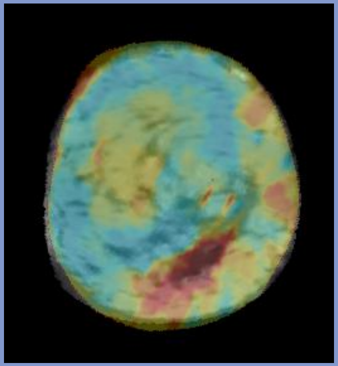
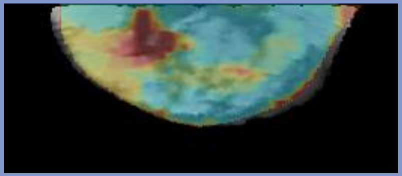
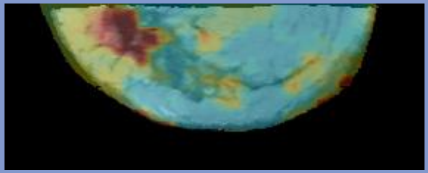
- Segmentation of USCT
- Rigid alignment
- Freeform deformation with cubic B-splines

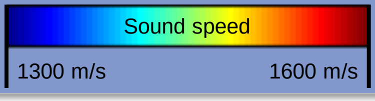
Registered MRI: slice 150

Patient with breast implant

	 Coronal plane	 Transversal plane
MRI T1-weighted		
USCT Reflection		

Inflammatory carcinoma

	 Coronal plane	 Sagittal plane	 Transversal plane
MRI T1-weighted			
Image fusion: T1-weighted MRI + USCT sound speed (color-coded)			



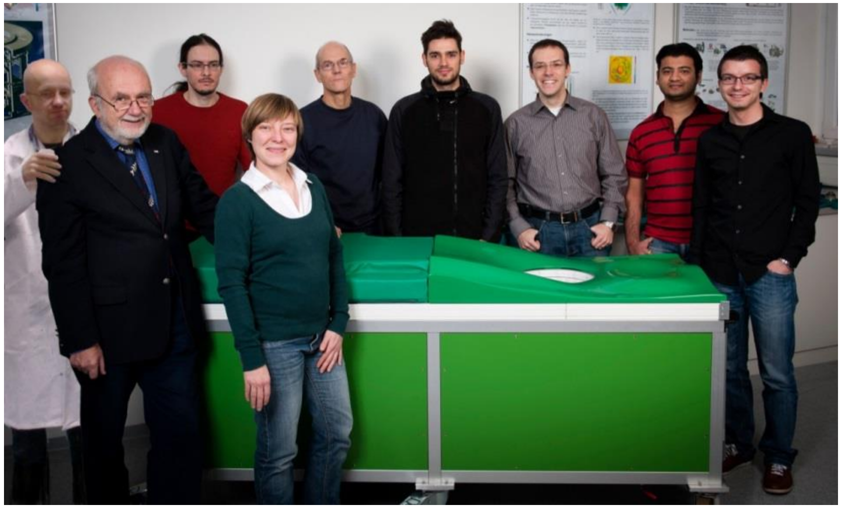
Summary

- **First in vivo images**, it really works!
- Technical challenges could be met
- USCT has the potential to
  be the screening modality of the future

Ready for a larger clinical study at University Hospital Mannheim

Thank you!

We acknowledge support of this project by
Deutsche Forschungsgemeinschaft (DFG)



IPE USCT Group

- Algorithms / Imaging / Image Processing
  N. V. Ruiter, M. Zapf, R. Dapp, T. Hopp, H. Gemmeke, et al.
- Hardware acceleration
  E. Kretzek, M. Balzer, et al.
- Transducers
  M. Zapf, H. Gemmeke, et al.
- DAQ and Hardware
  D. Tscherniakhovski, S. Menshikov, et al.
- Design and Mechanics
  L. Berger, B. Osswald, T. Piller, W. Frank, et al.