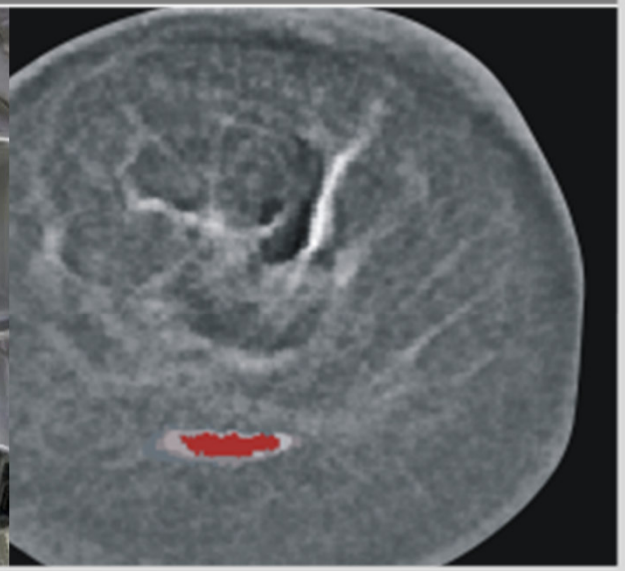
Karlsruhe Institute of Technology

USCT
3D Ultrasound Computer Tomography

3D Ultrasound Computer Tomography for Breast Cancer Diagnosis

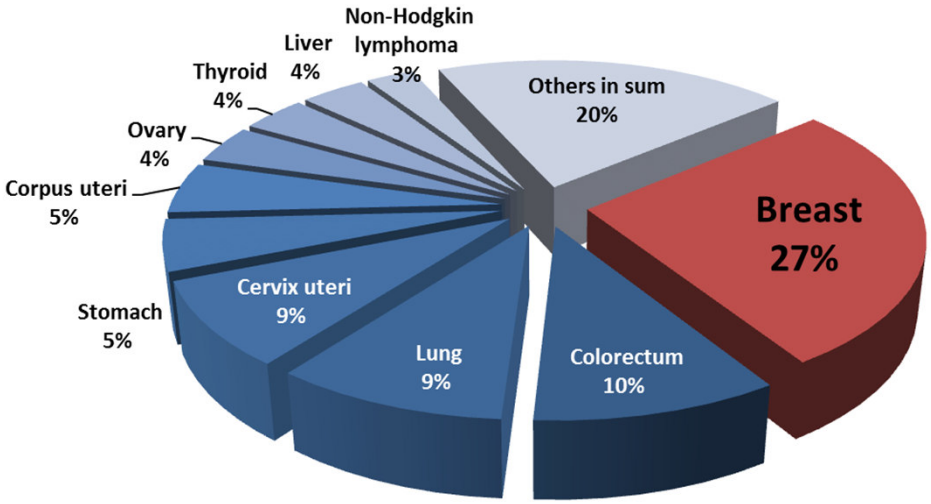
N. V. Ruiter, M. Zapf, T. Hopp and H. Gemmeke

INSTITUTE FOR DATA PROCESSING AND ELECTRONICS



Breast cancer

- Most common cancer of women in western world (every 10th woman)

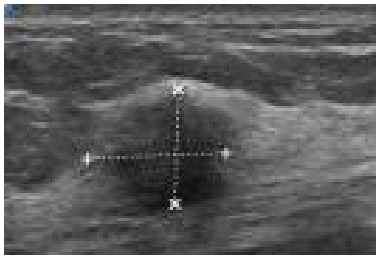


WHO cancer statistics 2012 (GLOBOCAN 2012)

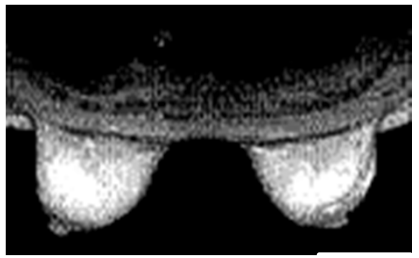
- Challenge: Early diagnosis

X-ray mammography

Screening



Sonography



MRI

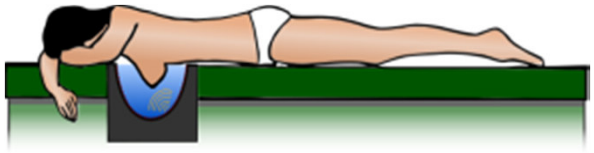
...

Symptomatic patients

What is USCT?

Basic idea

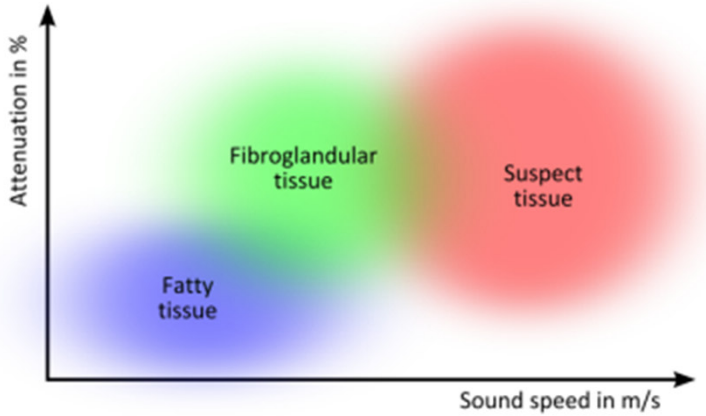
- Surround object with (unfocused) ultrasound transducers in a fixed setup



Breast imaging in fixed setup

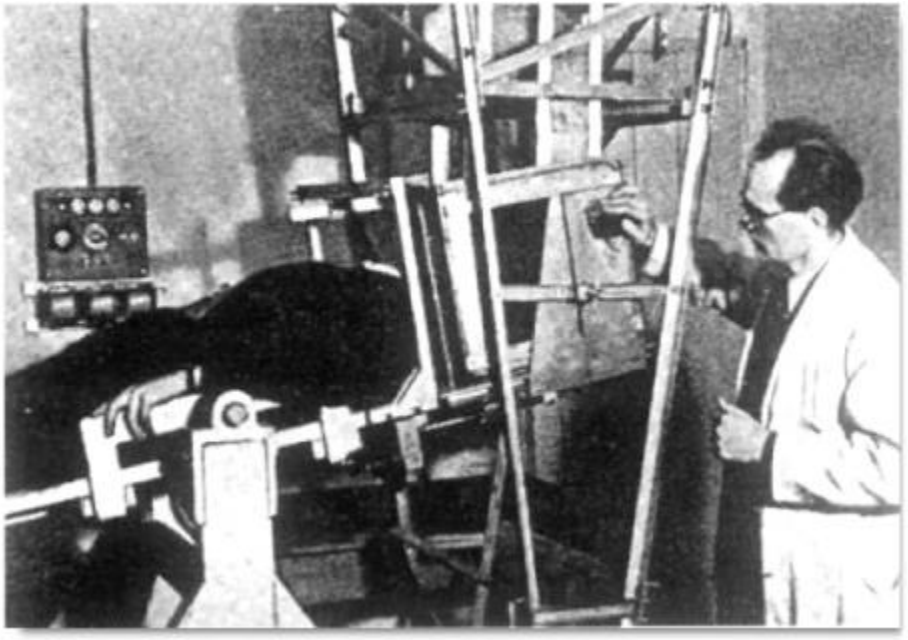
Diagnostic value

- Reproducible 3D images with ultrasound
- Images three modalities concurrently:
  - **Reflection**
    High quality “B-scans”
  - **Speed of sound** and **attenuation**
    Quantitative information

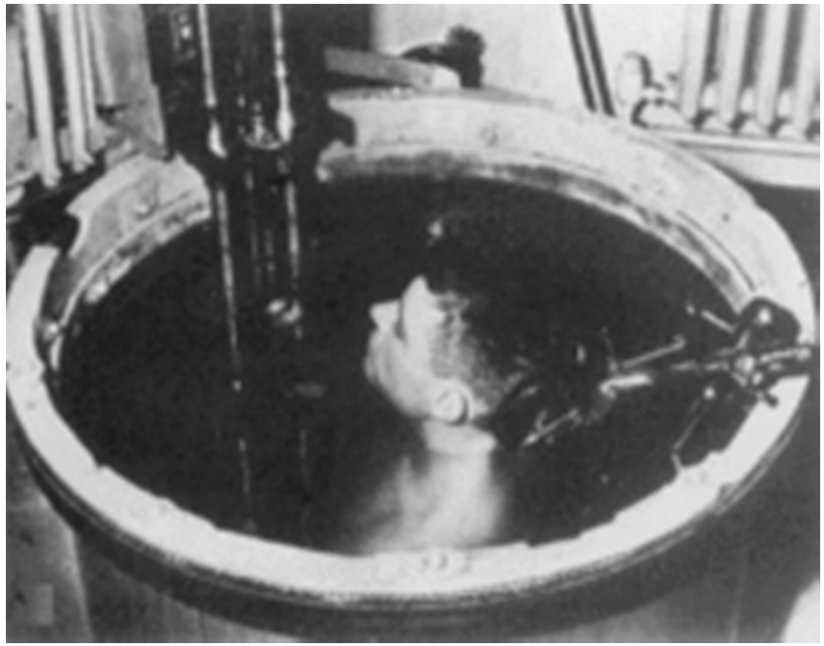


Simplified from Greenleaf et al., 1981

The beginnings



First attenuation imaging (Dussik, 1946): Not so successful imaging of brain ventricles



First “USCT“ device (Holmes et al., 1954): Slice image of the neck, compounding device

Image sources: ob-ultrasound.net, Szabo: Diagnostic Ultrasound: Inside out.

KIT 3D USCT

KIT 3D USCT system

3D aperture

Vision for 3D USCT …

- as harmless as diagnostic ultrasound
- as affordable as X-ray mammography
- as good as MRI

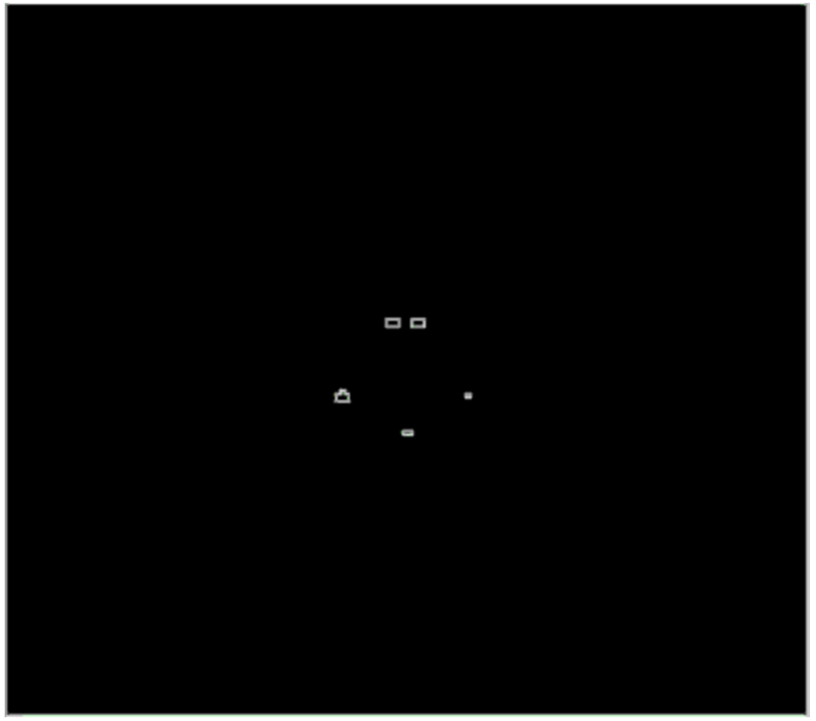
Schwarzenberg, Ruiter et al.: Aperture optimization for 3D ultrasound computer tomography, 2007.

How does it work? Ultrasound and soft tissue

- Wave equation for inhomogeneous water like materials:

$$\nabla^2 p(\vec{x}) + k_0^2 \left(\sqrt{\frac{K_0}{\rho_0}} \sqrt{\frac{\rho(\vec{x})}{K(\vec{x})}} + i \frac{\mu(\vec{x})}{k_0} \right)^2 p(\vec{x}) - \frac{1}{\rho(\vec{x})} \nabla \rho(\vec{x}) \nabla p(\vec{x}) = 0$$

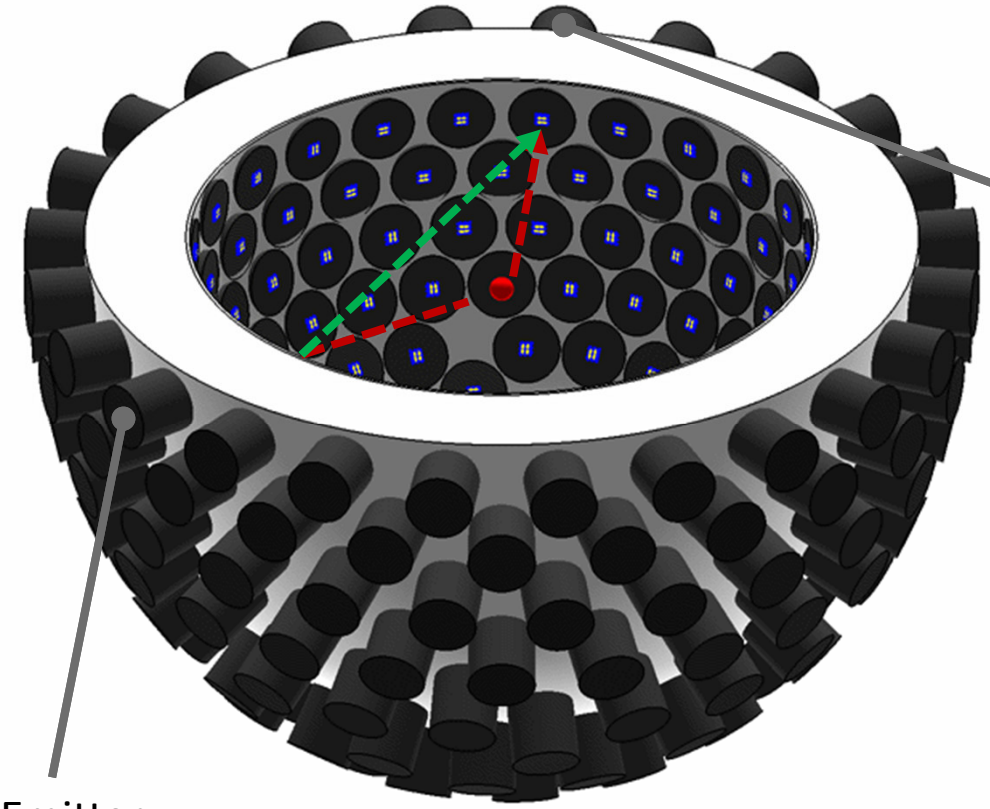
- Three physical properties influence wave propagation:
  - Density ρ, compressibility K and absorption μ
- Typically reconstructed in USCT:
  - qualitative acoustical impedance $\mathrm{Z} = \rho c$,
  - speed of sound $\mathrm{c} = \sqrt{\frac{K}{\rho}}$,
  - attenuation $\alpha = \mu + \mu_s$

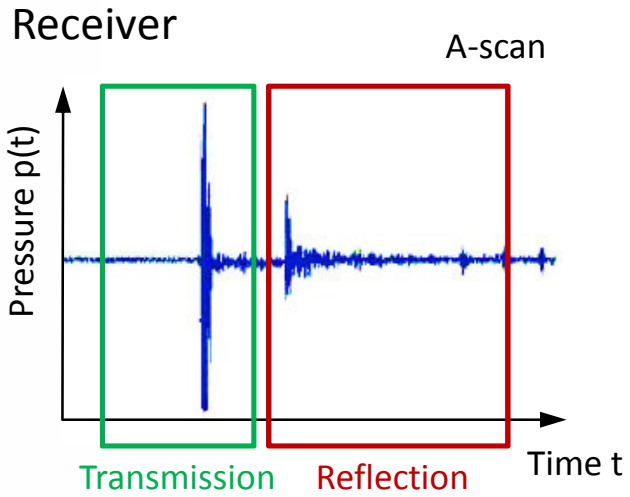


2D simulation of interaction with point scatterers

p: ultrasound pressure, k: wave number, μ_s: scatter

How does it work? Data acquisition



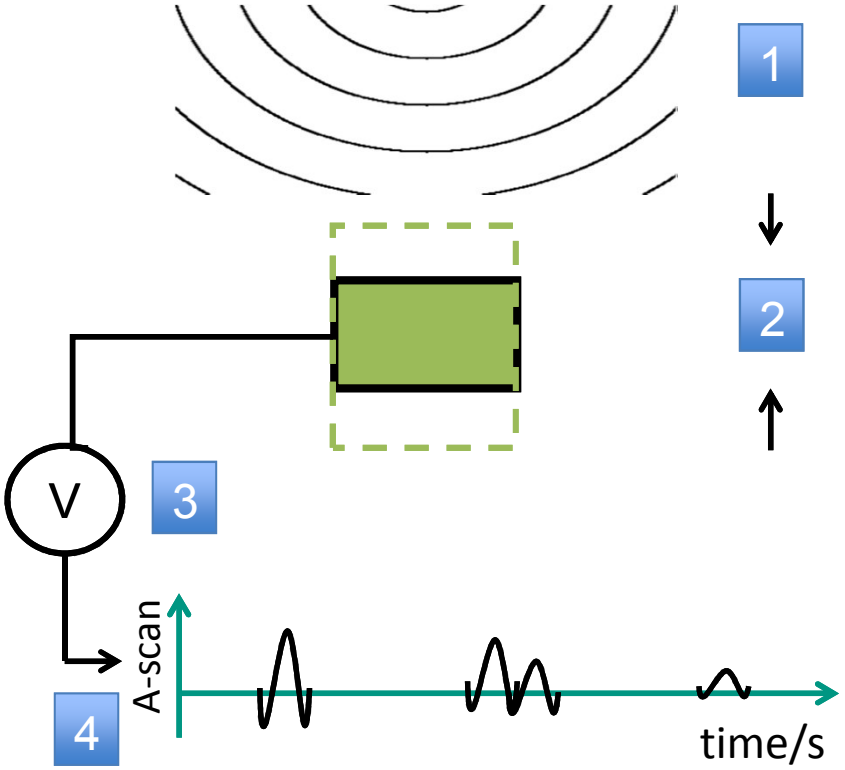


Acquired information

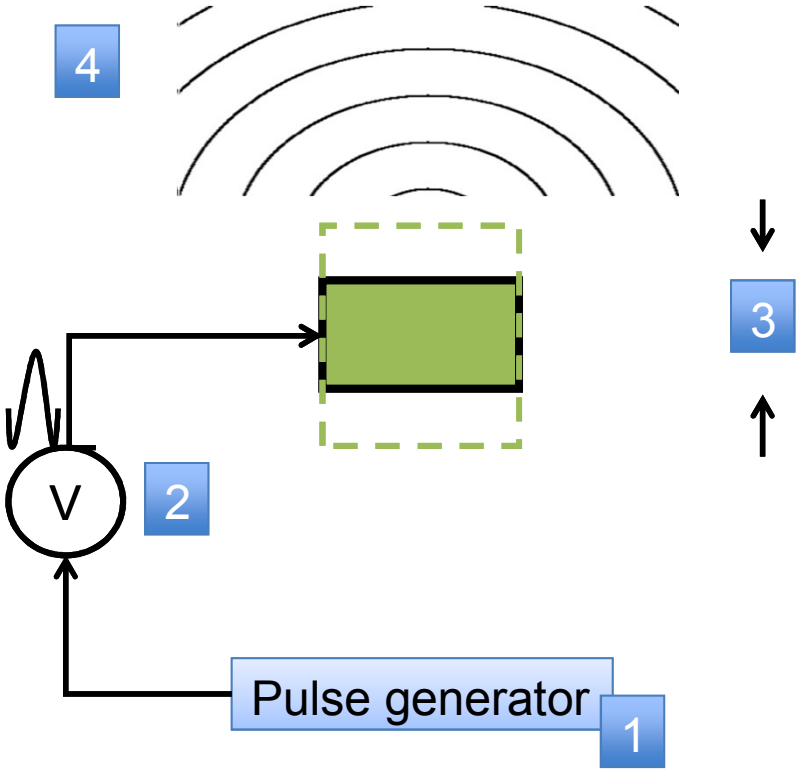
- **Sound speed**
- **Attenuation**
- **Reflection**

How does it work? Ultrasound transducers

Convert ultrasound (mechanical wave) to electrical signals and vice versa



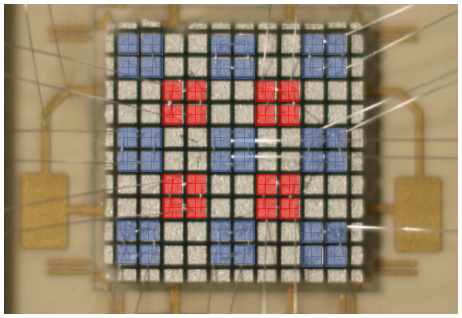
Reception: Piezoelectric effect



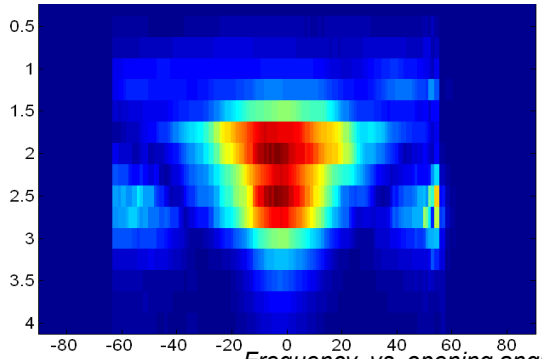
Emission: Inverse piezoelectric effect

Transducer array systems (TAS)

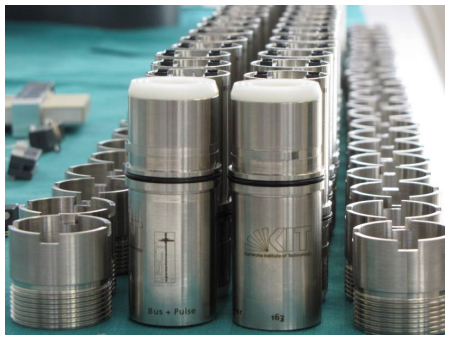
Center frequency (bandwidth)	2.5 MHz (1.5 MHz)
Opening angle	38° at -6dB (± 1.5°)
Structured Piezo composites	0.64 mm²
Emitters / receivers per TAS	4 emitters and 9 receivers



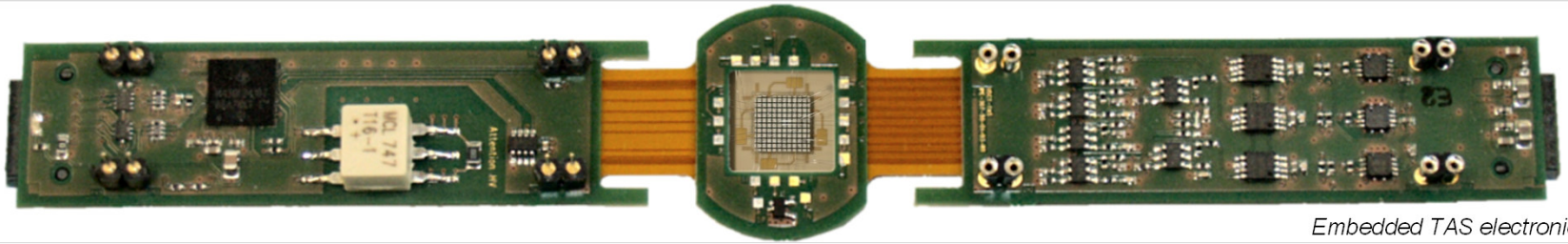
Emitters (red) and receivers (blue) per TAS



Frequency vs. opening angle



TAS

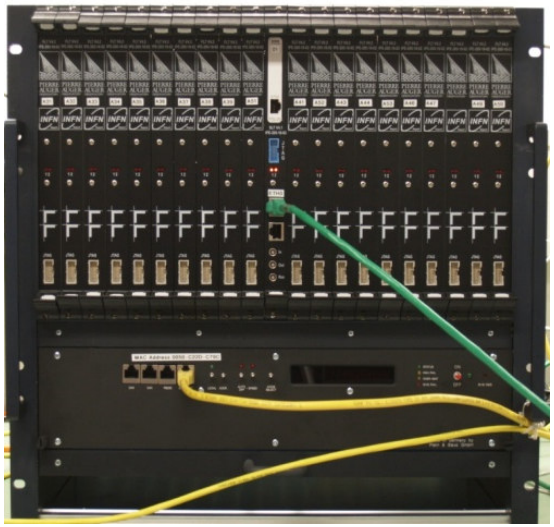


Embedded TAS electronics

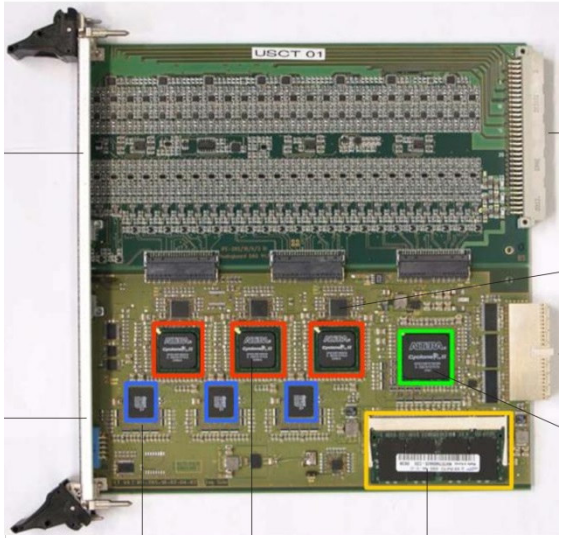
Kohout, Ruiter et al.: Simulation und Entwicklung von Ultraschallwandlersystemen für die 3D-USCT, 2012.
Zapf, Ruiter et al.: Evaluation of chirp and binary codes as excitation pulses for 3D USCT transducers, 2009.

Data acquisition system

Number channels	480
AD conversion	12 Bit @ 20 MHz
Memory	80 GB
Measurement time	10 s – 4 min



IPE-DAQ-V4



First Level Trigger Board

Cabling

Menshikov et al.: RTM-modules for waveform digitization, 2015.
Kopmann et al.: FPGA-based DAQ system for multi-channel detectors, 2008.

Listen to USCT data

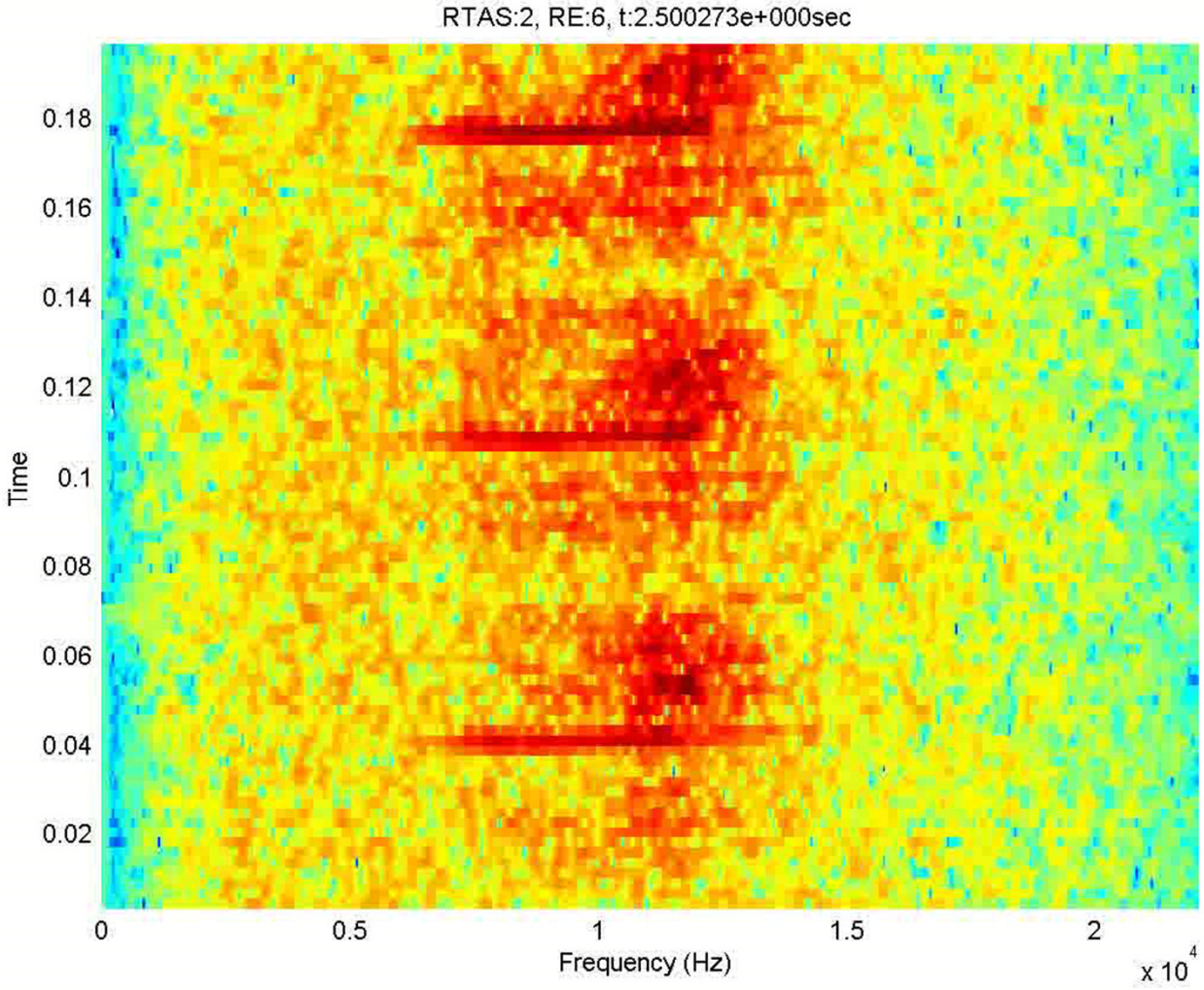
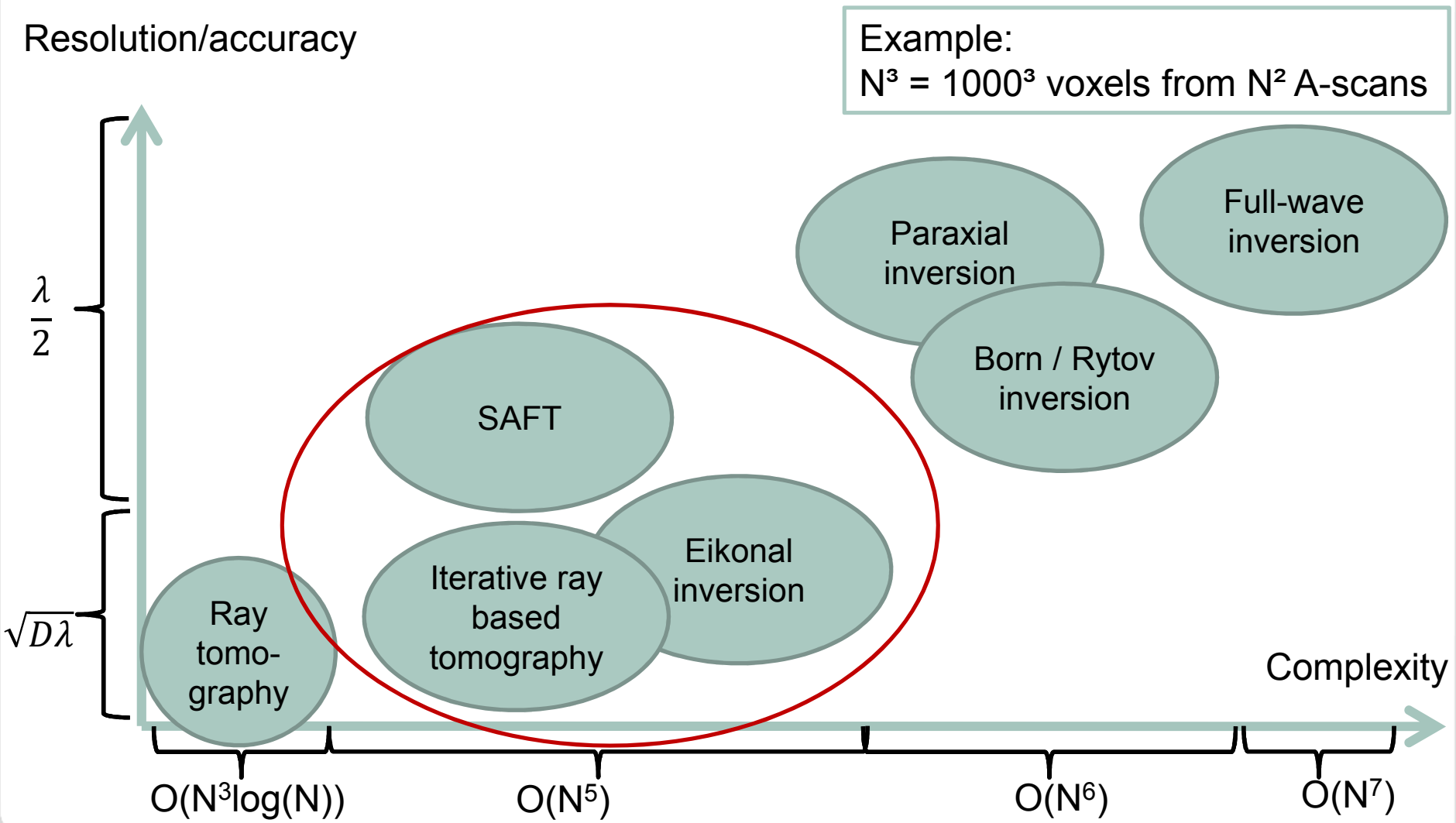


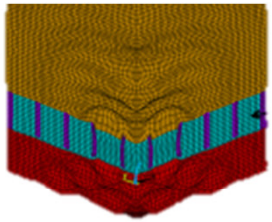
Image reconstruction



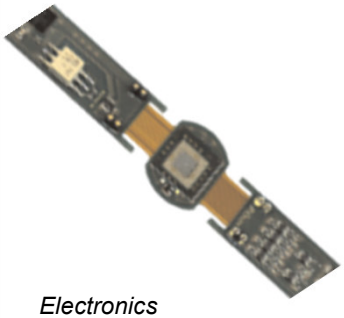
Althaus: On acoustic tomography using paraxial approximations, 2015.
Özmen: Ultrasound Imaging Methods for Breast Cancer Detection, 2015 (TU Delft).
Dapp: Abbildungsmethoden für die Brust mit einem 3D-Ultraschall-Computertomographen, 2013.
Hardt: Distributed Simulations for 3D USCT. Acoustic wave simulations for a new breast cancer imaging device, 2012.

Challenges

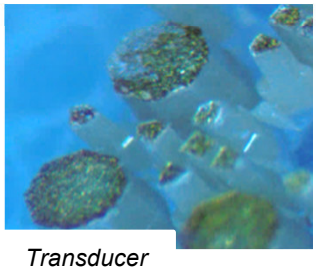
Transducer development



Transducer design

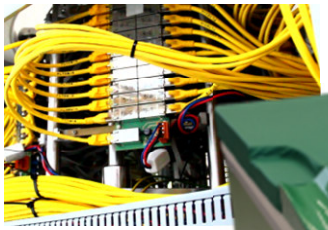


Electronics

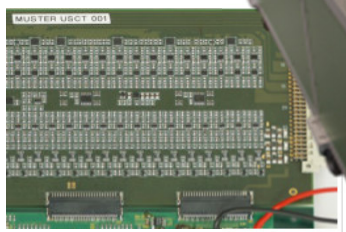


Transducer

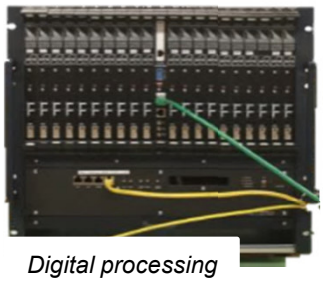
Parallel data acquisition



Parallel channels

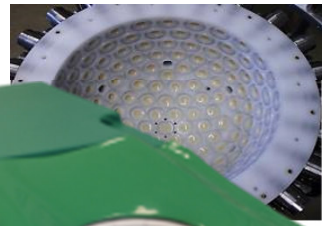


Electronics



Digital processing

Clinical applicability



Biocompatibility

3D reconstruction

Ultrasound physics

orithms

Acceleration

Medical analysis

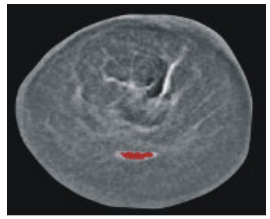
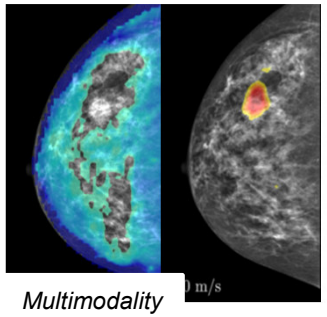
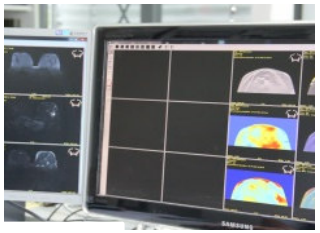


Image fusion



Multimodality



Analysis

Patents: PCT/EP2012/000640 (pending), EP 2539870 A2 (2011), EP 2 056 124 (2009), EP 1 755 837 (2004), US.6.786.868 (2003).

Clinical study Jena

- Universitätsklinikum Jena
  (Prof. W. A. Kaiser)

- Aim: Test device in clinical setting
  → prepare larger study

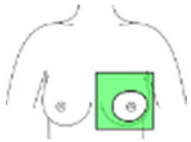
- 10 patients, all with suspicious lesions
  - 2 implants
  - 4 cancers
  - Papilloma, fibroadenoma, mastopathy, cyst

- End of clinical trial: September 2014

Prof. Kaiser in Jena

Ruiter et al.: First results of a clinical study with 3D Ultrasound Computer Tomography, 2013.

Patient 1: Healthy

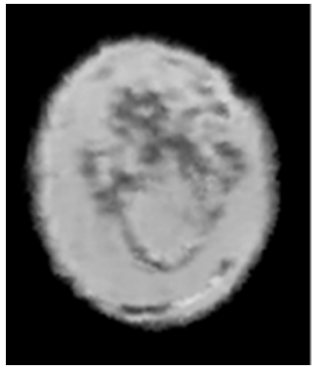


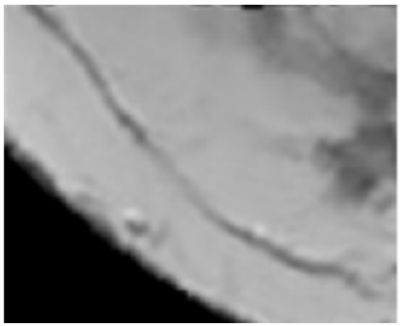
Coronal plane

Transversal plane

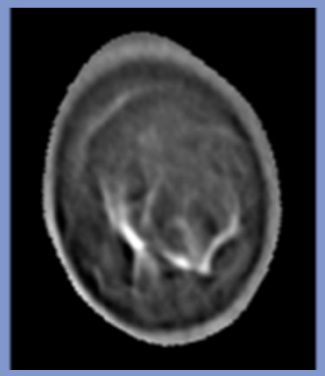
(detail view)

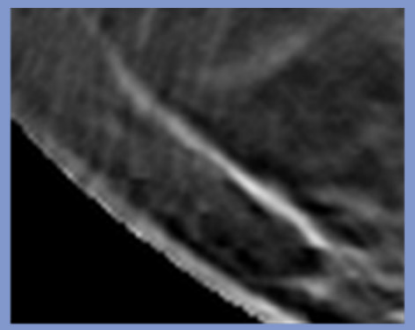
Registered MRI
T1-weighted





USCT
Reflectivity





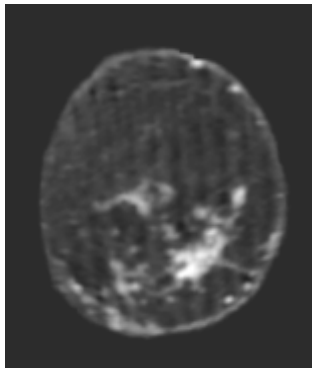
Patient 2: Inflammatory carcinoma

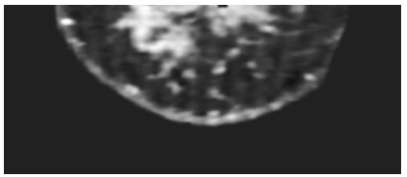
Coronal plane

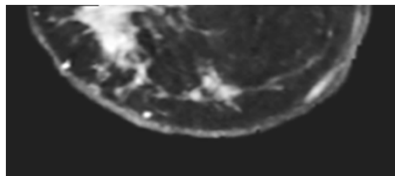
Sagittal plane

Transversal plane

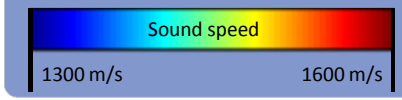
Registered MRI
T1 contrast enhancement

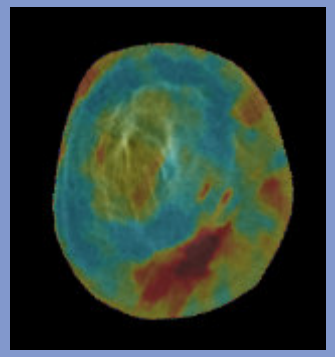


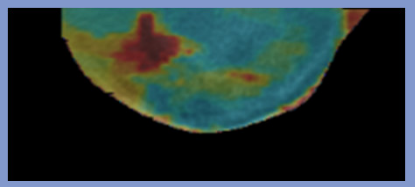


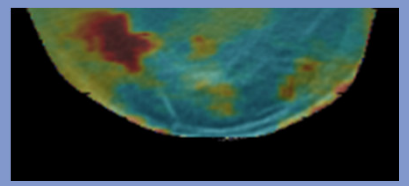


USCT image fusion:
Reflectivity + sound speed (color-coded)









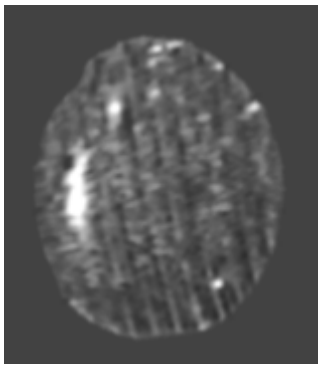
Patient 3: Multicenter carcinoma

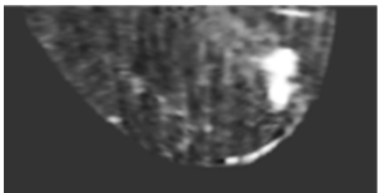
Coronal plane

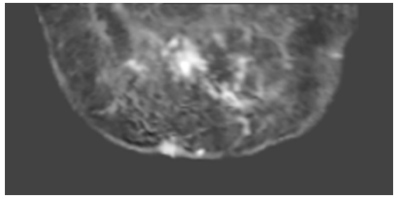
Sagittal plane

Transversal plane

Registered MRI
T1 contrast enhancement

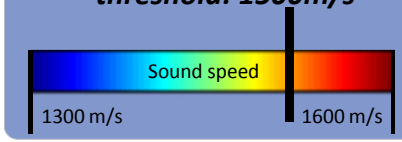


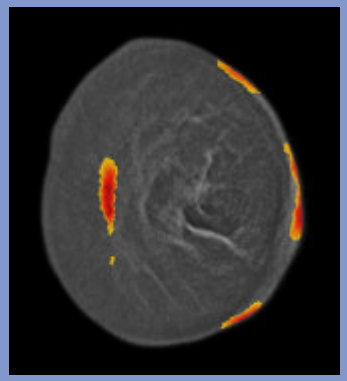


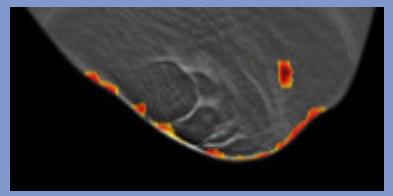


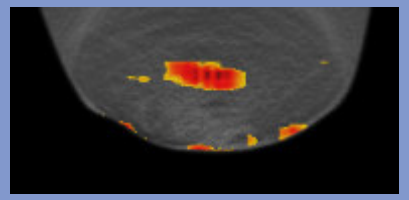
USCT image fusion:
Reflectivity + sound speed (color-coded)

threshold: 1500m/s

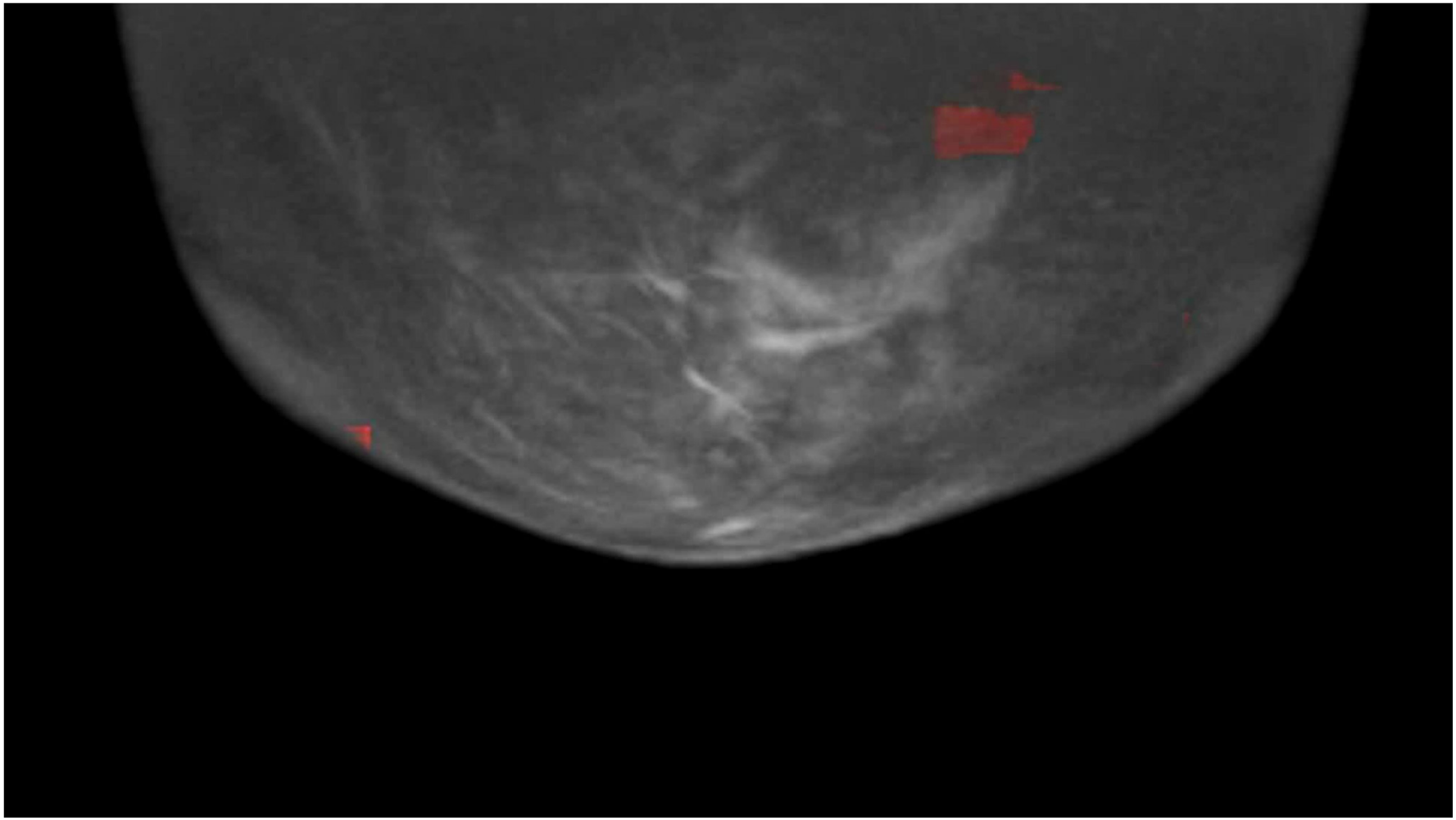








3D data



Summary pilot study in Jena

- 3D USCT was applicable in clinical setting (~ 1 patient/h)
- First images very were encouraging
- Speed of sound seem to give best cancer detection

- Mean patient movement: 3 mm
- Breast positioning critical

Major system updates:

- Data acquisition time: 8 min → 4 min
- New patient interface: + 1 cm

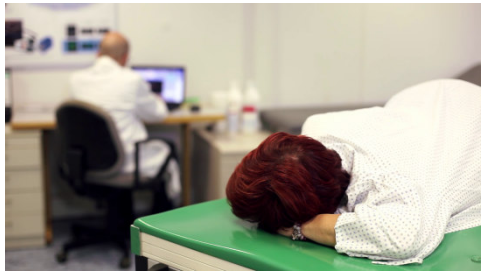
USCT in Jena

Image analysis

Ruiter, et al: First Results of a Clinical Study with 3D Ultrasound Computer Tomography, 2013.

Clinical study Mannheim

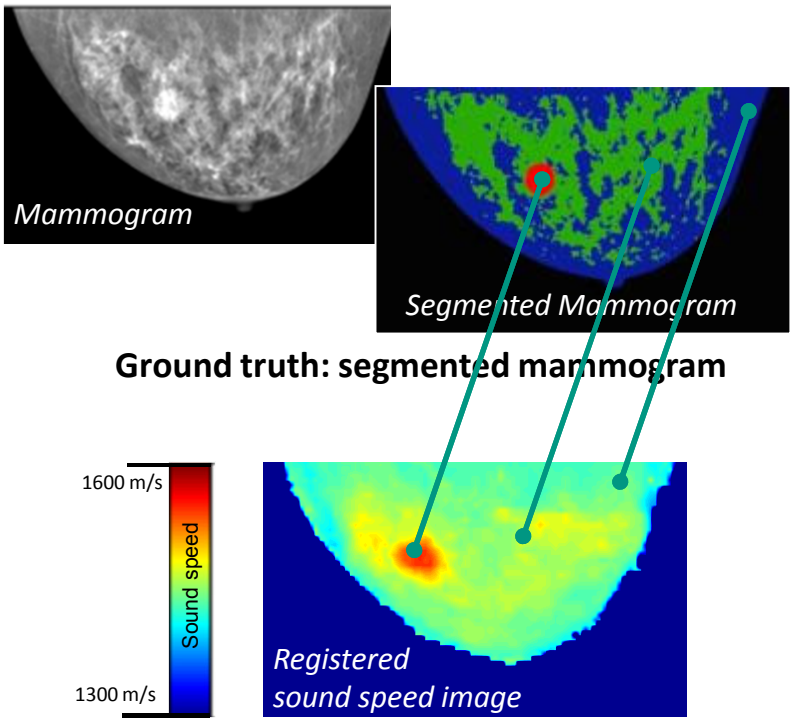
- Universitätsmedizin Mannheim (Prof. S. Schönberg)
- Aims of study
  - Does USCT give comparable diagnoses to MRI?
  - Analyze different lesion types
- 200 patients
- Start: October 2015

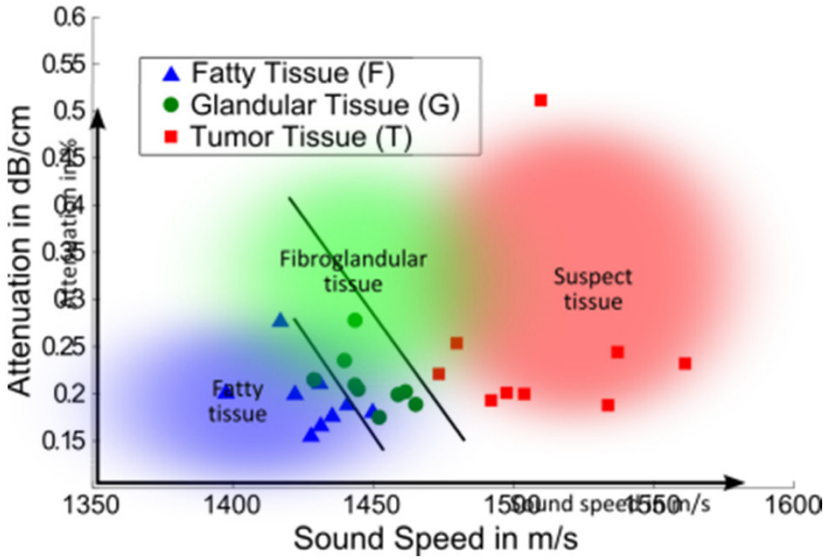


USCT in Mannheim

Multimodal imaging and classification

- Was Greenleaf right?



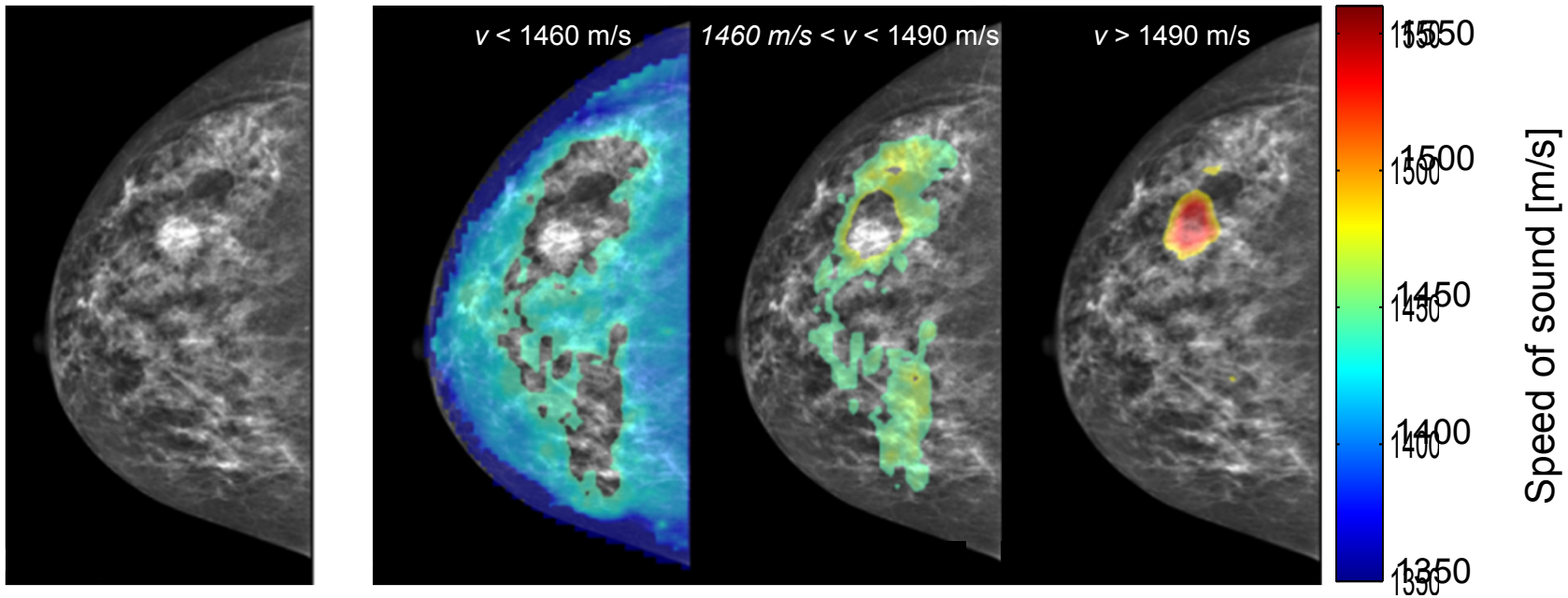


Classification by Support Vector Machine
(9 patients, sound speed and attenuation averaged)

Data from Karmanos Cancer Institute

Hopp, Ruiter et al.: Image fusion of Ultrasound Computer Tomography volumes with X-Ray mammograms using a biomechanical model based 2D/3D registration, 2014.

USCT tissue classification in X-ray mammogram



Mammogram | Fatty tissue | Glandular tissue | Lesion

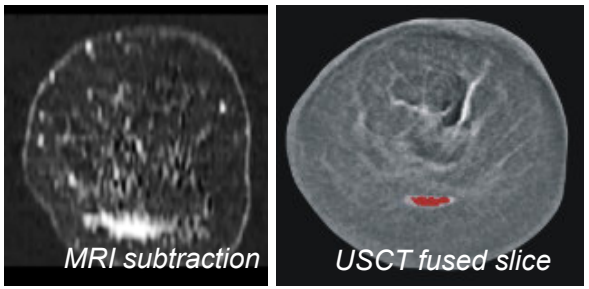
Data from Karmanos Cancer Institute

Hopp, Ruiter et al: Evaluation of breast tissue characterization by ultrasound computer tomography using a 2D/3D image registration with mammograms, 2013.

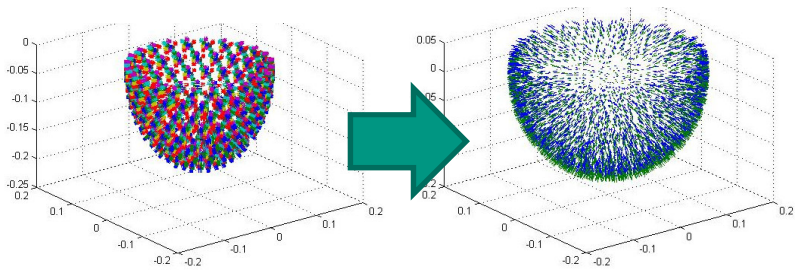
Summary

- USCT is a new imaging method for at early breast cancer diagnosis
- KIT 3D USCT:
  first clinically applicable full 3D USCT
- First pilot study successful,
  second study started
- 3D USCT III:
  - Faster DAQ
  - Optimized image quality

3D USCT during pilot study


MRI subtraction

USCT fused slice



Ruiter et al.: Optimization of the aperture and the transducer characteristics of a 3D Ultrasound Computer Tomography System, 2014.

Thank you!

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Deutsche Forschungsgemeinschaft (DFG)