International Workshop on Medical Ultrasound Tomography

1.- 3. Nov. 2017, Speyer, Germany

BOOK OF ABSTRACTS

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Part I Invited talks

Current challenges in breast screening and diagnosis

P. Littrup

Breast cancer screening and diagnosis can save lives through early detection and curative treatments. Continued controversy and publicity arises when potentially life-saving technologies are balanced against epidemiologic and cost-efficacy concerns. Both 2D digital mammography and tomosynthesis (3D) have already established their utility over plain film, while 3D has shown greater cancer detection while reducing unnecessary callbacks. Improved sensitivity and specificity lead to better test performance and potential cost-efficacy. Current breast ultrasound screening efforts for women with dense breasts have improved cancer detection but still suffer from greater total callbacks and lack of color Doppler and/or elastography to potentially improve specificity. A roadmap thus exists for breast ultrasound tomography to overcome the obstacles necessary to produce a paradigm shift in breast imaging.

Medical ultrasound tomography: lessons from exploration geophysics

R. Pratt

University of Western Ontario gpratt2@uwo.ca

The seismic method is a widely-used imaging tool in the geophysical exploration industry. This has led to the development of powerful imaging methods, in some cases inspired by and akin to those used in medical ultrasound tomography. In both exploration seismology and in medical imaging, the experiment involves the propagation of sound waves over distances of a few tens of wavelengths to a few hundred wavelengths. In both cases the transmitters and receiver design is used to control bandwidth and illumination apertures. However, in exploration seismology i) access to the target is unusually restricted, ii) geological targets are often embedded in strongly scattering material, iii) we cannot ignore 3D heterogeneity, elastic wave effects including mode conversions, and anisotropic wave propagation, and iv) we must account for the presence of high amplitude dispersive modes associated with the free surface of the Earth.

In exploration the past decade has seen the emergence of "Full Waveform Inversion" (FWI) as a remarkably successful innovation. Historically, seismic imaging methods have been most successful when applied to back-scattered (aka reflected) waves. FWI, in contrast, has to date been most successful with transmitted (aka refracted) waves. FWI of reflected data is progressing, but significant problems remain. These include i) handling the significant non-linearity and non-uniquenesses that are inherent in the experiment, and ii) convincing skilled interpreters that FWI yields a new type of image that contributes in significant (but unusual) ways. It is suggested that the field of medical ultrasound tomography shares these problems and that there is much to be learned by cross-fertilization in both fields.

Multiscale full-waveform inversion: From the whole earth to the human breast

A. Fichtner

Swiss Federal Institute of Technology (ETH) Zurich andreas.fichtner@erdw.ethz.ch

Seismic tomography using earthquake or explosion data is among the most powerful tools to explore the internal structure of the Earth. The images that it produces are used to study the evolution of our planet, locate and monitor natural resources, constrain the mechanisms of large earthquakes, issue earthquake and tsunami early warnings, and to monitor the Nuclear Test Ban Treaty. In recent years, seismic tomography has been experiencing a shift from classical ray-based methods to full-waveform inversion, built on the combination of numerical wavefield simulations and adjoint techniques. As a result, more of the available waveform data can be exploited, and the resolution of Earth models is increased. The simultaneous emergence of full-waveform inversion in different fields - ranging from whole-Earth tomography to medical imaging - offers new opportunities for interdisciplinary collaboration. In this spirit, I will review recent developments and applications in seismic full-waveform inversion, emphasizing similarities and differences with respect to medical imaging problems. This is intended to serve as the starting point for further discussions that may help to bridge the (language) gap between the medical and seismological communities.

Ultrasound Computed Tomography: Historically Guided Musings

J. Greenleaf

Mayo Clinic Rochester jfg@mayo.edu

Computed Tomography with ultrasound waves, in both through transmission and reflection, has been investigated for over 40 years. In that time investigators have concentrated on the complex interactions of ultrasonic waves with the tissue of the human female breast in an effort to delineate malignant from benign lesions. Over the years the relentless improvement of both electronics and computer power has allowed the inverse solution of more and more complex mathematical models of wave propagation through complex tissue such as the breast. However, the need for complete three-dimensional acquisition of scattering waves from the tissue continues to be a difficult technological problem. In addition to the technical challenges are the challenges of finding where in the flow diagram of breast disease patients traversing the health care system to place ultrasound breast tomography to provide the most effective contribution to the efficacy and efficiency of breast disease detection, diagnosis, and treatment. Meanwhile, other modalities are developing that provide very stiff competition to the field of computed ultrasound tomography of the breast. Historical examples and current implementations will be described and discussed.

Latest developments in ultrasound transducer technology and future directions

N. de Jong

Technical University of Delft Nicolaas.deJong@tudelft.nl

Standard clinical diagnostic ultrasound systems are making cross-sectional (2D planes) views with a linear array transducer consisting of about 100-200 elements. For advanced diagnosis real-time three-dimensional imaging with adequate spatial and high temporal resolution is needed. Three major directions are currently under development: Firstly, the ultrasound systems having matrix array transducers with 10,000+ elements together with embedded electronics (Application Specific Integrated Circuits (ASICs)). Secondly, high frame rate imaging with (volume) frame rates of 100 - 2000 frames per second. Thirdly, the processing of the huge amount of data as received by the individual elements for generating (parametric) images in real-time.

The research focuses on medical acoustical imaging of the heart, liver, kidney, brain, breast and other organs. It includes new ways of measuring the perfusion of the myocardium, developing new accurate three dimensional imaging methods and therapeutic applications. The research lines are the bubble physics for (molecular) imaging and drug delivery, development of matrix transducers with integrated electronics for three dimensional imaging (e.g. catheter based three dimensional ultrasound imaging) and imaging methods like superharmonic imaging and shear wave imaging. It also includes flow pat-terns determination in the left ventricle and development of ultrasound methods for stiffness determination of the septal wall of the left ventricle for heart failure patients, construction of very small ultra-sound transducers with integrated electronics for use in small children and baby's and devices for 3D imaging of the carotid artery for vulnerable plaque determination.

Challenges of breast ultrasound

H. Madjar

DKD HELIOS Klinik Wiesbaden helmut.madjar@web.de

Mammographic screening is used since almost 50 years in menopausal women. However 30% of breast cancers occur in premenopausal women and 30% of menopausal women have dense breasts where mammography fails in up to 50%. Furthermore women with dense breasts have higher risk to develop breast cancer. Diagnostic studies using high quality ultrasound technology (US) have proven a 30-40% increased detection rate of small cancers in young women and women with dense breasts. The problem is that US is operator dependent and requires a systematic examination to cover the whole breast. Reproducibility is problematic with hand-held US. ABUS technology was developed to overcome these problems but requires a number of scan procedures to cover the entire breast, it depends on operator skills and the static scans do not allow to measure vascularity or elastography. A systematic and fast technology which performs whole breast scans in high quality allowing to measure reflectivity as well as other tissue properties could overcome these problems. However, large studies are required to prove its accuracy.

Optoacoustic tomography and the pathway to commercialization

C. Wiest

iThera Medical GmbH christian.wiest@ithera-medical.com \\

Optoacoustic tomography (OAT) is a novel imaging technology that has seen rapid adoption by the biomedical scientific community in the last few years. OAT utilizes the photoacoustic effect to visualize and quantify anatomical, functional and molecular information, in vivo, in deep tissue and in real time. It allows the preclinical study of disease processes on a molecular level as well as the non-invasive analysis of pharmacokinetic and biodistribution properties for new substances. Recently, OAT has been translated for clinical use. Initial patient studies have been conducted in the areas of skin cancer, breast cancer, inflammatory bowel disease, and vascular diseases. While the results of these early clini-cal trials are very promising, the commercial success of the technology will depend on establishing OAT as a diagnostic standard for particular applications and the ability for health care providers to realize sustainable reimbursement for such OAT procedures.

Potential impact of ultrasound tomography in the clinic

P. Littrup

During this conference, many facets of breast ultrasound tomography (UST) have been presented. Focus was made upon the technical specifications needed for many applications of UST, especially for screening in women with dense breasts and improved clinical diagnosis. Improved cancer detection while limiting call-backs and reducing unnecessary biopsies are now possible. Normal, benign and malignant breast tissue characterization is possible from quantitative analyses of multi-parameter UST radiomics. Breast density can be accurately estimated without ionizing radiation or expensive MR, as well as monitoring density modification for chemoprevention. As UST becomes a crucial part in the emerging standard of care, greater use of IV contrast, biopsy and treatment guidance/monitoring is expected.

Part II Oral presentations

One-dimensional Marchenko inversion in stretched space

J. van der Neut¹, J. Fokkema¹, P. van den Berg¹

¹ Delft University of Technology j.r.vanderneut@tudelft.nl

Background, Motivation and Objective

In acoustic inversion, we aim to retrieve the density and compressibility of an unknown medium from single-sided reflection data by solving a nonlinear integral equation. If the wavefield is known throughout the medium, this equation simplifies as a linear map between the medium properties and the reflection data. We aim to realize such a map by substituting the solution of a Marchenko equation into an integral representation in stretched space.

Material and Methods

To acquire the wavefield inside the medium, we propose to use a Marchenko equation. This equation has recently been derived in order to compute a wavefield at an arbitrary location in the medium directly from a single-sided reflection response. To solve the Marchenko equation in physical space, the propagation velocity of the medium must be known a priori. If we transform the wavefields and medium properties to a stretched spatial coordinate system in which the wave speed is constant, we can solve the Marchenko equation in stretched space instead. This solution can be obtained without any information on the medium other than its single-sided reflection response and can be substituted directly into a stretched integral representation.

Results

By substituting the solution of the Marchenko equation into an integral representation in stretched space, we manage to establish an exact and linear map between the medium properties in stretched space and the reflection data. We demonstrate that this map can be used for linear inversion in stretched space without involving any approximation. Once the medium properties are retrieved in stretched space, they can be converted to physical space, if a model of the propagation velocity is available.

Discussion and Conclusion

In conclusion, we have managed to establish a linear relation between the medium properties in stretched space and the reflection data by substituting the solution of the Marchenko equation into an integral representation in stretched space. Our theory is derived for a one-dimensional medium only. In the future, we aim to investigate if this formulation can be extended to three-dimensional media.

Ultrasound imaging from reflection data.

F. Natterer¹

¹ University of Münster nattere@uni-muenster.de

Background, Motivation and Objective

When only reflection data are available, imaging with the wave equation is much more difficult then in the presence of transmission measurements. This is because reflection data are spectrally incomplete due to fact that frequencies close to zero can not be used.

In the talk we describe the mathematical problem and suggest a numerical method of data completion that generates the missing low frequency data by a purely mathematical procedure.

Material and Methods

Our results are based on numerical simulations using data generated by the acoustic wave equation. We model acoustic mammography by using a flat 2D transducer array.

Results

We demonstrate by numerical simulations using a breast phantom patterned after the Salt Lake City phantom that good pictures can be obtained with exactly the theoretically possible spatial resolution. We describe several computing techniques such as plane wave stacking and source encoding to speed up the computations. Our reconstruction algorithm is a nonlinear version of the well known ART algorithm of CT, which instead of line integrals works directly with the wave equation.

Discussion and Conclusion

Our presentation is purely theoretical. It is restricted to 2D and does not discuss practical aspects such as connecting materials. However it demonstrates that reasonable pictures can be obtained in spite of the spectral incompleteness of the reflection data.

Using 2-D approximation of the 3-D incident field for Born inversion

U. Taskin¹, L. Heijnsdijk¹, L. Hoogerbrugge¹, K. van Dongen¹

¹ Delft University of Technology u.taskin@tudelft.nl

Background, Motivation and Objective

In a real ultrasound measurement system, acoustic waves show 3-D propagation characteristics. However, in a majority of recently developed wave based imaging methods, the inverse problem is solved in a 2-D framework due to computational restrictions. This reduction causes problems during inversion. In this work, we use a 2-D approximation for the measured 3-D incident field and show that using this approximated incident field for Born inversion (BI) improves the resulting reconstruction.

Material and Methods

Hankel functions are used as starting point to obtain a 2-D approximation for a given 3-D field as these Hankel functions satisfy the 2-D Helmholtz equation. Consequently, the approximated wave field in cylindrical coordinates reads

$$p_{approx}(r,\phi,\omega) = \sum_{n=-N}^{N} c_n(\omega) H_n^{(1)}(\frac{\omega}{c}r) e^{in\phi},$$
(1)

where $H_n^{(1)}$ is the Hankel function of the first kind. To find the coefficients c_n , we iteratively minimize the L_2 -norm of the mismatch between the measured and approximated field. Once the coefficients are found, the resulting approximated 2-D incident field is used for Born inversion.

Results

To test the proposed approach, we first solve the forward problem in 3-D for a circular array (20 sources and 150 receivers) scanning a cylindrical and a spherical object. Next, we use a 2-D Born inversion method to reconstruct the acoustic medium properties and compare the resulting reconstructions obtained with four approaches. These four approaches are based on computing the incident field using (1) an infinite line source, (2) a point source, (3) a point source followed by a correction to compensate for geometrical spreading, and (4) a point source followed by the proposed method to approximate the field using Hankel functions. It can be clearly observed from the figure that the best result is obtained with our proposed approach.

Discussion and Conclusion

A new approach is proposed for applying 2-D inversion on 3-D measurement data. This new approach approximates the incident field from the original 3-D incident field and uses this approximated incident field in the inversion. Results with Born inversion show that this new approach give better results compared to the currently applied approaches. The proposed method can also be used with other inversion methods.



USCT Image Reconstruction: Acceleration using Gauss-Newton Preconditioned Conjugate Gradient

H. Wang¹, H. Gemmeke², T. Hopp², J. Hesser¹

¹ Heidelberg University hongjian.wang@medma.uni-heidelberg.de ² Karlsruhe Institute of Technology

Background, Motivation and Objective

Ultrasound transmission tomography offers quantitative characterization of the tissue or materials by their speed of sound and attenuation. Reconstruction of such images is an inverse problem which is solved iteratively based on a forward model of paraxial approximation of the Helmholtz equation and thus is time-consuming. Hence, developing optimizers that decrease this time, in particular reducing the number of forward propagations is important for clinical practice.

Material and Methods

We solve the inverse problem of reconstruction in a two-level strategy, by an outer and an inner loop. At each iteration of the outer loop, the system is linearized and this linear subproblem is solved in the inner loop with a preconditioned conjugate gradient (CG). A standard Cholesky preconditioning based on the system matrix is compared with a matrix-free Quasi-Newton update approach, where a preconditioned matrix-vector product is computed at the beginning of every CG iteration. We also use a multigrid scheme with a multi-frequency reconstruction to firstly get a convergent rough reconstruction at a lower frequency and then refine it on a higher-resolution grid as the starting solution of higher frequency reconstruction.

Results

The Cholesky preconditioning reduces the CG iteration by approx. $70\% \sim 85\%$; yet the computation time for determining the system matrix as the input for the matrix factorization function is dominating, offsetting the gains of the reduction of iterations. The matrix-free preconditioning method saves approx. 30% of the computation time on average for single-frequency reconstruction and the multi-frequency reconstruction. For the stable multi-frequency reconstruction, we test three breast-like numerical phantoms resulting in a deviation of 0.13 m/s on average in speed of sound reconstruction and a deviation of 5.4% on average in attenuation reconstruction from the ground truth.

Discussion and Conclusion

Compared with the Cholesky preconditioning, the matrix-free preconditioner via Quasi-Newton updating can actually save computation time. More effective problem-dependent spatial preconditioning techniques will be studied for our USCT image reconstruction. Especially for the multigrid reconstruction framework, the nonuniform convergence rates for coarse scale features and fine scale features should be taken into consideration.

3D time-domain spectral-element ultrasound waveform tomography

C. Boehm¹, N. Korta Martiartu¹, I. Jovanovic Balic², A. Fichtner¹

¹ ETH Zurich christian.boehm@erdw.ethz.ch
² SonoView Acoustic Sensing Technologies

Background, Motivation and Objective

Waveform inversion for ultrasound computed tomography is a promising tool to image the acoustic properties of breast tissue. We present a technique for time-domain 3D acoustic waveform inversion that combines the spectral-element method with source encoding strategies and a quasi-Newton trust-region method. The key objective is to reduce the computational cost of waveform inversion by randomly encoding the emitters in space and by introducing time lags based on the acquisition geometry.

Material and Methods

The spectral-element method is a high-order numerical scheme to efficiently simulate the wave equation. Our approach combines source encoding strategies with a special implementation of the so-called "lazy spectralelement method". In addition to randomly encoding the transducers in space to emit simultaneously, we introduce time lags to overlap the simulation in time. This method dynamically adjusts the computational domain and computes the wavefield only inside the region of influence of the emitting transducers intersected with the domain of dependence of the receiving transducers. We combine this approach with an adaptive trust-region method based on the LBFGS approximation of the inverse Hessian to image the acoustic properties.

Results

We demonstrate how the geometry of a scanning device can be modeled accurately with conforming hexahedral meshes by extending a cubed sphere approach. This is a prerequisite for employing the spectral-element method. By overlapping the simulation of multiple scans in time we can reduce the computational cost by up to 40%.

Furthermore, the trust-region method is well suited for adaptively changing the encoding weights and the number of sources during the inversion.

We analyze different misfit functionals and regularization terms and their ability to reconstruct the acoustic properties of breast tissue. All numerical experiments are carried out with Salvus, a high-performance package for full-waveform modeling and inversion.

Discussion and Conclusion

We present a novel approach to reduce the computational cost of 3D time-domain waveform inversion with a large number of ultrasound scans. We combine the spectral-element method with source encoding strategies that overlap the simulation of multiple events in time. Numerical results for a synthetic phantom demonstrate that this approach is well suited for typical acquisition geometries in USCT and significantly reduces the computational cost of the recurring simulations of the wave equation.

Joint reconstruction of ultrasound and photoacoustic tomography images

M. Anastasio¹, T. Matthews¹

¹ Washington University in St. Louis anastasio@wustl.edu

Background, Motivation and Objective

Photoacoustic computed tomography (PACT) is a bioimaging modality that seeks to reconstruct an estimate of the absorbed optical energy density within an object. We propose a joint reconstruction problem in which the speed-of-sound (SOS) distribution is concurrently estimated along with the sought-after absorbed optical energy density from the photoacoustic measurement data.

Material and Methods

We will investigate the numerical properties of the JR problem for two cases: 1) only PACT data are available and 2) PACT and few-view USCT data are available and combined into a single data set. In the latter case, the SOS information in both the PACT data and the USCT data can be exploited. Realistic numerical phantoms that accurately model the geometry and acoustic heterogeneity of a rat or mouse will be employed. The results will be evaluated on the basis of accuracy when compared with the numerical phantoms. The impact of regularization, acoustic heterogeneity, and model mismatch (e.g. neglecting attenuation, impulse responses of the transducers, etc.) will be investigated.

Results

We will present the results of a systematic study of the joint PACT-USCT image reconstruction problem. The study will address the impact of regularization parameters and data noise.

Discussion and Conclusion

Because variations in the SOS distribution induce aberrations in the measured PA wavefields, certain information regarding an object's SOS distribution is encoded in the PACT measurement data. The purpose of this work was to contribute to a broad understanding of the extent to which the JR problem can be accurately and reliably solved under realistic conditions. This was accomplished by conducting numerical experiments that elucidated important numerical properties of the JR problem.

Non-linear Ultrasonic Computed Tomography (USCT) for soft and hard tissue imaging

P. Lasaygues¹, J. Rouyer¹, S. Mensah¹, E. Franceschini¹, G. Rabau¹, R. Guillermin¹, S. Bernard¹, V. Monteiller¹, D. Komatitsch¹

¹ Aix Marseille Univ, CNRS, Centrale Marseille, Laboratory of Mechanics and Acoustics, Marseille, France lasaygues@lma.cnrs-mrs.fr

Background, Motivation and Objective

This paper presents the theoretical, numerical and experimental frameworks for breast and bone imaging. The difficulties raised are somewhat different as, in soft tissues, the very small fluctuations to be quantified suffer from their very low values. This poor echogenic index generally induces low detection probability, for instance in the case of large diffuse masses. In bone imaging, the difficulties arise from the very high contrast that alters the propagation of the ultrasonic waves.

Material and Methods

Solutions consist in optimally assessing these non-linear effects in an iterative approach aiming at local linearization. The Near-Field USCT method based on the use of the first-order Born approximation, applied to the case of an homogeneous and constant background is describe. The unknown object function is linearly related to the field measured using the Elliptical Fourier transform. This technique is suitable for breast inspection where the probe is either in contact with the skin or located within a near field distance when using a coupling device. The first-order Born USCT has some limitations when dealing with highly contrasted scatterers such as bones.

Results

When the problem can be reduced to the study of a fluid-like cavity buried in an elastic cylinder surrounded by water, the Compound USCT is proposed as an extension of the classical USCT, by taking into account physical phenomena such as wave refraction. The main limitation of the method is the heavy experimental-costs involved (multiple iterative experiments). We have then suggested a purely numerical non-linear inversion algorithm, and the minimization procedure between the full recorded and simulated data is solved using a conjugate-gradient method mainly developed in non-destructive testing domain, or an efficient quasi-Newton technique mainly developed in seismology (full waveform imaging method).

Discussion and Conclusion

An overview of the performances and the limitations of these tomography methods applied to breast and bone imaging problems are presented and discussed.

Scattering Computed Tomography visualizing density distributions by back-propagation

D. Kondo¹, **T.** Azuma¹

¹ The University of Tokyo dkondo@m.u-tokyo.ac.jp

Background, Motivation and Objective

Ultrasound computed tomography (UCT) has various imaging modes; sound speed profile, attenuation profile and gradient of acoustic impedance. In these imaging modes, ultrasound scattering tomography gives high resolution images highly relating to anatomical structure. In order to visualize density distribution as new efficient information in diagnoses, we use echo scattering signals and information of sound speed profile obtained by UCT.

Material and Methods

Calculation area defined in a wave-propagation simulator, K-wave, was inside of the 256-element ring array transducer with the diameter of 100 mm, and the grid size was 0.125 mm. A pulse wave was transmitted at the frequency of 2 MHz. Point scatterers, which only affected the distributions of density and not those of sound speed, were placed with distance in a heterogeneous medium modeled from a clinical MRI image. The simulation had following 2 steps: (1)A pulse wave was transmitted into the medium from an element and received at all elements. (2)Time-reversed scattering signals were calculated and transmitted into the medium.

Results

Since the sound speed distribution can't be obtained exactly in reality, the ambiguity was applied to it using the low-pass filter. In usual scattering visualizing method using synthetic aperture with sound speed correction (Fig. (a)), the distribution of sound speed and density are superimposed and these are not distinguishable. In our method, we achieved to distinguish them; density distributions were visualized in Fig. (b), and the error of sound speed distributions due to the ambiguity were visualized in Fig. (c).

Discussion and Conclusion

When we back-propagate the scattering signals from all elements, we could hardly visualize density distributions. This is because the amplitude of penetration waves are much higher than that of scattering signals. To separate the influence of the penetration and scattering waves, we visualized 2 different images using our proposal method.



Real-Time Ultrasound Transmission Tomography based on Bézier Curves

M. Perez-Liva¹, J. Udias¹, J. Camacho², E. Merčep³, J. Herraiz¹

 ¹ University Complutense of Madrid mailynpl@gmail.com
 ² Spanish National Research Council
 ³ iThera Medical GmbH

Background, Motivation and Objective

Refraction-corrected ray-tracing methods in Ultrasound Transmission Tomography (USTT) are able to reconstruct the acoustic properties of tissues with good accuracy when using medium and high frequencies (>3MHz). However, these techniques, such as the Fast Marching Method (FMM), are time-consuming. In this work, we propose a real-time reconstruction methodology that exploits the large computing capabilities of current GPUs.

Material and Methods

In the proposed method, each one of the hundreds of thousand threads that can be executed in parallel in modern GPUs, evaluates the time-of-flight (TOF) of the US pulse along smooth Bézier curves connecting emitter-receiver pairs. The evaluated curves with the shortest TOF are used for the reconstruction of both, sound speed (SS) and acoustic attenuation (AA) maps with an iterative OSEM algorithm. The method was evaluated with phantom data acquired with the USTT prototype MUBI, consisting of two coplanar rotating 3.5 MHz medical grade linear arrays, on a tissue-mimicking gelatin phantom. We then applied it to datasets acquired with a hybrid optoacoustic-ultrasound (OPUS) device (iThera Medical) using a full-ring array.

Results

The SS maps are reconstructed in less than 5 seconds/slice using 6 OSEM iterations with 5 subsets. Using the pre-calculated Bézier bent-rays from the SS reconstruction, the AA maps can be obtained in 1 second/slice. Images reconstructed with straight-rays (i.e. without refraction correction) misestimate the actual size of the structures inside the phantom acquired with the MUBI USTT prototype. In the case of the OPUS scanner working in USTT mode, the images also showed significant artifact-reduction with regard to fast reconstruction methods based on straight-rays.

Discussion and Conclusion

This method is faster than typical acquisition and processing in USTT, so it can be considered a real-time reconstruction method suited for clinical practice. The SS maps are quantitatively accurate, although AA maps have significant deviations at the edges due to wave-interference effects not considered in the bent-rays propagation model. In conclusion, the use of Bézier curves and GPUs is an effective way to perform bent-rays reconstruction of USTT data in real-time.



Figure 1. – Reconstructed images of the tissue-mimicking phantom acquired with the MUBI scanner. (Left) Reflectivity image. (Center) SS and AA maps obtained with straight rays (i.e. without refraction correction). (Right) SS and AA maps obtained with refraction correction using the proposed method based on Bézier curves.

High resolution breast ultrasound tomography with HARBUT

P. Huthwaite¹

¹ Imperial College London p.huthwaite@imperial.ac.uk

Background, Motivation and Objective

Breast ultrasound tomography can produce a map of acoustic properties through the breast, greatly increasing the potential for improved cancer diagnosis. The use of ultrasound is cheaper than MRI and safer than traditional mammography. One particular challenge seen in breast ultrasound tomography is the low resolution caused by ray behaviour commonly assumed in most reconstruction algorithms; by neglecting diffraction effects the algorithm is unable to reliably image small scale features.

Material and Methods

HARBUT (the hybrid algorithm for robust breast ultrasound tomography) has been proposed to combine ray theory with diffraction tomography to enable higher resolution reconstructions to be produced. It uses a ray-based inversion scheme to provide an approximate background image, then uses this to correct a Bornapproximation image to reconstruct the fine details. This algorithm was applied to numerically simulated data from a 3D finite difference model, as well as experimentally gathered data. In both cases the setup was an ultrasonic ring array surrounding the breast in a water bath; numerically, 750kHz ultrasound was used, while experimentally the frequency was around 1.1MHz.

Results

The results confirmed that the algorithm is robust to noise and experimental errors, while generating significantly higher resolution than ray tomography. It is also fast, taking less than a minute to reconstruct in total on a standard contemporary PC.

Discussion and Conclusion

The HARBUT algorithm has potential for significant improvements in breast ultrasound tomography. There is also potential for further improvements by accounting for 3D effects.

3D imaging of the breast using full-waveform inversion

O. Calderon Agudo¹, L. Guasch¹, P. Huthwaite¹, M. Warner¹

¹ Imperial College London oc14@ic.ac.uk

Background, Motivation and Objective

Full-waveform inversion (FWI) is an iterative algorithm that produces high-quality images from experimental data. The petroleum industry has invested large sums to make this method more efficient, robust and reliable, especially for complex and large 3D datasets. However, its application to medical imaging, especially in 3D, is still in its infancy. Our objective is to efficiently implement FWI to invert 3D ultrasound datasets and study the implications of using low-frequency transducers.

Material and Methods

We first apply our FWI algorithm to a 3D simulated dataset generated with ultrasound transducers surrounding a realistic phantom of the breast. To efficiently invert the 3D dataset, we use a highly optimised finite differences forward modelling code that solves the isotropic acoustic wave equation. The dataset is generated with only a few hundred of transducers and the inversion is successfully sped up by considering less than a third of the total number of sources per iteration. We also implement our FWI code to a 2D *in vivo* dataset acquired with a single ring of 256 ultrasound transducers and with no information other than the recorded data, the total number of transducers and their nominal position.

Results

In contrast to reflection ultrasound tomography or time-of-flight tomography, where high-frequency transducers are necessary to obtain highly resolved models, we show that using low frequency ultrasound transducers — a few hundreds of kHz— and FWI is enough to obtain high-resolution recovered models. Despite not having low frequencies present in the 2D *in vivo* dataset, we are able to image a tumour and internal structures of the breast at higher resolution than conventional travel-time tomography. The inverted models also suggest that 3D data acquisition and inversion would be necessary to separate off-plane structures for a better interpretation and a more accurate diagnosis.

Discussion and Conclusion

We conclude that the presence of low frequencies allows for a much more efficient strategy when performing FWI of ultrasound data because it eliminates the need for a priori knowledge of the target and leads to higher quality recovered images. Thus, we encourage this community to use lower frequency transducers and to acquire data in three dimensions, which would allow more efficient and robust algorithms for 3D imaging providing images at a resolution enough for direct interpretation.

A Multi-Modal Ultrasound Breast Imaging System

J. Camacho¹, J. F. Cruza¹, N. Gonzalez-Salido¹, C. Fritsch¹, M. Perez Liva², J. Herraiz², J.

 $\mathbf{U}\mathbf{das}^2$

 ¹ Spanish National Research Council (CSIC) j.camacho@csic.es
 ² Universidad Complutense de Madrid

Background, Motivation and Objective

The Multimodal Ultrasound Breast Imaging System (MUBI) is a joint development of the Spanish National Research Council (CISC) and the Complutense University of Madrid (UCM). It is intended to be a flexible platform for multi-modal ultrasound imaging research, mainly oriented to breast diagnosis. Up to now, the following imaging techniques have been implemented: Phased-Array full angle spatial compound (FASC), Acoustic Radiation Force Imaging (ARFI) and Ultrasound Computed Tomography (USCT).

Material and Methods

The first prototype is formed by two arrays that rotate into a water tank, controlled by independent stepper motors. A full parallel ultrasound system is used for excitation and signal acquisition. While only one array can be used as emitter, both of them can act as receivers, allowing pulse-echo and through-transmission operation modes. The system is able to perform emission and reception beamforming in real-time, and also gives access to the individual signals received by each array element. A standard personal computer controls the motors movement and the ultrasound equipment with Matlab scripts.

Results

An automated algorithm was developed for detecting the breast contour and correcting the beam propagation path before the scan conversion in Full Angle Spatial Compound (FASC) of phased-array sector-scan images, reducing texture speckle and improving contrast-to-noise ratio. For Acoustic Radiation Force Impulse (ARFI), a specific full angle spatial compound algorithm was developed, including depth, angle and focal length equalization of individual displacement images. Ultrasound computed tomography (USCT) was also implemented, developing fast reconstruction algorithms of speed of sound and attenuation maps. In all cases, the algorithms were evaluated with signals acquired on tissue mimicking phantoms.

Discussion and Conclusion

The MUBI platform has proven to be a flexible experimental tool for research in breast ultrasound. Several imaging modalities have been successfully implemented and tested with tissue mimicking phantoms. Current developments include a second hardware version with a complete ring of 16 arrays, reducing acquisition time by eliminating the circular movement.



Figure 1 - (a) Picture of the current MUBI prototype (b) FASC of phased-array images (c) FASC of Acoustic Radiation Force Impulse images (ARFI) (d) USCT Speed of sound reconstruction of a tissue mimicking phantom.

First steps towards the Delft Breast Ultrasound Scanning System (DBUS)

L. Heijnsdijk¹, E. Jansen¹, U. Taskin¹, H. Bok¹, E. Bergsma¹, E. Noothout¹, N. de Jong¹, K. van Dongen¹

¹ Delft University of Technology lars.heijnsdijk@gmail.com

Background, Motivation and Objective

Ultrasound is gaining interest as a modality to scan for tumors in dense breasts of young women. Tissue characterisation by full wave form inversion (FWI) has the potential to improve the accuracy of breast ultrasound. However, many of the existing systems use frequencies above 1 MHz. With these high frequencies it is difficult to apply FWI due to the computational costs involved. Consequently, we investigate the applicability of low frequencies together with FWI for breast cancer detection.

Material and Methods

Due to the absence of flexible low-frequency scanning devices suitable for FWI, we have built our own twodimensional circular scanning system. The system contains two 0.5 MHz transducers. The source is connected to an arbitrary waveform generator. The position of the source is "fixed"; only the radius to the centre of the system can be varied manually. The receiver is connected to a 400 MHz 14 bit A/D converter. To rotate the object and the receiver independently we use two rotating motors. The receiver's radius to the centre of the system can be varied manually as well.

Results

To test the system, several scans have been made and processed using SAFT. Currently, various "artefacts" present in the data, e.g. mechanical "cross"-coupling, are being investigated and eliminated. A two-dimensional scan of an agar based phantom has been made publically available on the USCT Data Exchange and Collaboration Website (http://ipeusctdb1.ipe.kit.edu/~usct/challenge/) so that the entire USCT community can take advantage of our system.

Discussion and Conclusion

A flexible two-dimensional low-frequency ultrasound scanner has been developed. The system has successfully scanned agar based phantoms. Currently, we are optimizing the system. The next step will be to use the data to test the applicability of FWI as a means for improved breast cancer detection.

Hybrid Optoacoustic and Ultrasound Imaging System with a Multi-Segment Detector Array

E. Mercep¹, X. Deán-Ben², D. Razansky³

¹ iThera Medical, GmbH

elena.mercep@ithera-medical.com

² Institute for Biological and Medical Imaging (IBMI), Helmholtz Center Munich, Neuherberg, Germany
³ Faculty of Medicine, Technical University of Munich, Germany

Background, Motivation and Objective

The high complementarity of the optoacoustic (OA) and pulse-echo ultrasound (US) modalities makes the combined usage of these imaging technologies highly advantageous. Yet, due to the different physical contrast mechanisms, the development of detection technology optimally suited for image acquisition in both modalities remains a major challenge. Here we demonstrate a multi-segment detector array whose novel design is meant to optimally support both ultrasound and optoacoustic image acquisition.

Material and Methods

For the OA signal excitation, light from the pulsed Nd:YAG-pumped OPO is guided to the specimen via a custom-made fiber bundle at 25 Hz repetition rate, with 25mJ per-pulse energy output. Switching between OA and US imaging modes is facilitated through a custom-made multiplexer (MUX) connected to the transducer array. The latter combines two detector geometries: the linear segment of 128 elements (0.25 mm pitch and 10 mm height), and two concave segments - each having 64 cylindrically-focused elements with 0.6 mm pitch, 10 mm height, and a focal distance of 38 mm. All elements have a central frequency of 7.5 MHz.

Results

Characterization of the sensitivity field of the detector by means of numerical simulation allows for quantitative assessment of the effective field of view in both imaging modes, which in OA mode along x- and y-dimensions constitutes 30x25mm2, and 30x30mm2 in the US imaging mode. Estimated OA in-plane axial and lateral resolution is within the range $90-130\mu$ m and $110-180\mu$ m, respectively. The US in-plane resolution along axial and lateral dimensions was estimated between $210-260\mu$ m and $260-340\mu$ m, respectively. The capacity of the hybrid system for real time in vivo functional imaging of blood oxygenation using multi-wavelength data acquisition is demonstrated in healthy volunteer study for anatomical regions of wrist and neck.

Discussion and Conclusion

The hybrid-array-based imaging approach can greatly facilitate clinical translation of the OA imaging technology by means of its efficient combination with a well-established US imaging modality. Imaging sessions in a healthy volunteer have proven excellent capacity of the new OPUS approach for hybrid anatomical imaging and functional angiography in humans.

Source selection for ultrasound waveform tomography: real data case from USCT Data Challenge 2017

N. Korta Martiartu¹, C. Boehm¹, V. Nicolas¹, I. Jovanovic Balic², A. Fichtner¹

¹ ETH Zurich naiara.korta@erdw.ethz.ch ² Sonoview Acoustic Sensing Technologies

Background, Motivation and Objective

Waveform inversion for Ultrasound Computed Tomography (USCT) is an emerging high-resolution imaging technique for breast cancer screening. Despite its potential, the involved computational burden is challenging. This mainly depends on the total number of wave propagation simulations solved during the inversion procedure. Thus, the computational cost can be reduced by only selecting the emitting transducers that best resolve the information about the breast tissue and avoid redundant experiments.

Material and Methods

We identify the optimal emitting transducers using Sequential Optimal Experimental Design (SOED). SOED is a powerful tool to iteratively add the most informative transducer location or remove redundant experiments, respectively. This approach simultaneously provides optimized transducer configurations and a cost-benefit curve that quantifies the information gain versus the computational cost.

We measure the quality of different configurations quantifying the expected model uncertainties postreconstruction. Using a Bayesian approach, this can be related to the properties of the posterior covariance which in general can be computed using the Hessian operator. For waveform inversion, we use the Gauss-Newton approximation of the Hessian.

Results

We use real data provided by CSIC as part of the USCT Data Challenge 2017. The dataset consists of 64768 A-Scans collected by a moving array of 16 transducers emitting with a dominant frequency of 3.5 MHz. To select the sources to be used in waveform tomography, we first apply 2D straight rays approximation mainly for two reasons:

(1) To reconstruct the initial sound speed model for waveform inversion.

(2) To gain intuition about the most relevant emitting transducers. For such high frequencies, the first Fresnel zone of the sensitivity kernels used in the Gauss-Newton approximation of the Hessian is quite narrow. Thus, similar patterns are expected when applying SOED for waveform inversion. This will be verified by the work in progress.

Discussion and Conclusion

We applied sequential optimal experimental design to optimize the transducer configuration of USCT scanning devices. With the aim of reducing the computational cost of the inverse problem, we provided a systematic framework to avoid collecting redundant information about the model and to quantify the information gain by adding more emitters. Furthermore, the method can be extended to other design parameters. In particular, it can be used in combination with source encoding strategies.



Figure 1: Time-of-flight inversion using straight rays: (a) Sound speed reconstruction using the complete observed dataset. (b) Sound speed reconstruction using 25% of the dataset. SOED method was applied to select the optimal emitting transducers. (c) Cost-benefit curve. The red line represents the number of sources with the optimal cost-benefit ratio.

Upper Bound of Accuracy for Self-Calibration of a 3D Ultrasound Tomography System without Ground Truth

W. Tan¹, T. Steiner², N. Ruiter¹

¹ Karlsruhe Institute of Technology wei.tan@kit.edu
² Pepperl+Fuchs GmbH

Background, Motivation and Objective

A Newton's method based self-calibration was presented in previous work for a 3D Ultrasound Tomography System (USCT). The method sequentially calibrates a complex USCT system with 2041 transducers based on time-of-flight (TOF) measurements. A direct evaluation of the calibration result was not possible due to unknown ground truth. In this work we present a method to estimate the upper boundary for the calibration accuracy.

Material and Methods

The overall calibration accuracy is given by the sum of residuals r of the equation systems in N calibration steps and the estimated TOF error $|\Delta b|$ weighted by the condition numbers κ_i , see Fig.: $\epsilon = |\Delta b| \cdot c \cdot \sum_i^N \kappa_i + \sum_i^N r_i$. For a nonlinear equation system κ_i was estimated in each calibration step by investigating the error propagation, describing its sensitivity to an error in the TOF detection. For a nonlinear equation system f at a point x, κ can be computed with: $\kappa = ||J(x||/(||f(x)|| \cdot ||x||))$. We computed $\kappa_{i,max}$ for N = 3 calibration steps with 500 iterations at x equal to the default state of USCT with small changes δx .

Results

The TOF error $|\Delta b|$ was estimated for 10 consecutive USCT measurements of water only. Due to identical positions of the transducers and temperature monitoring, the detected deviation is only caused by errors in the TOF detection, characteristic deviation of individual transducers and system jitter. The maximum value of $|\Delta b|$ is given by the width of the detection window centered on the expected TOF using prior knowledge. We obtained $|\Delta b|$ of 0.11 μ s at 30°C. With sum of $\sum_{i}^{N} \kappa_{i,max} = 1.64$ and sum of residuals in the order of 10⁻⁷ m the upper bound of the calibration error is 1.2 mm and the estimated upper bound of the mean error is $\epsilon = 0.14$ mm.

Discussion and Conclusion

For a given solver and measurement setup κ can be reduced by increasing the number of independent measurements, in our case by adding TOF measurements, i.e. increasing the number of included A-scans. On the other hand, $|\Delta b|$ can be reduced by excluding A-scans with low SNR. The presented method enables finding the optimal tradeoff between reduction of κ and $|\Delta b|$ for an optimal upper bound for the calibration error smaller than 1/4 of the wavelength of 0.15 mm.



Fig.: The figure shows an example of estimated calibration error for an equation system with two unkowns

System Design of a Flexible 512-Channel Platform for Ultrasound Computer Tomography

J. Song¹, Q. Zhang¹, L. Zhou¹, Y. Peng¹, Q. Zhou¹, M. Ding¹, M. Yuchi¹

¹ Huazhong University of Science and Technology, China junjiesong91@hust.edu.cn

Background, Motivation and Objective

Breast cancer has become one of the primary diseases threatening women's health. Ultrasound computer tomography (USCT) has attracted many researchers' attention for its potential in early diagnosis of breast cancer. In USCT system, transducer with large number of elements are often be adopted. Platform with large number of channels is needed, In this paper, we describes the system design of a 512-channel USCT platform.

Material and Methods

The system architecture of the platform is shown in Fig. 1. The platform consists of a front-end subsystem and a data transmission and storage subsystem. Excitation, channel selection, signal digitization and data packing is done by the front-end subsystem. Data transmission, sequencing, storage and processing is done by the data transmission and storage subsystem.

Results

Table 1 summarizes the key technical features of the designed platform that we expected. Schematic design and PCB circuit design of the boards in the front-end subsystem have been almost completed, the hardware circuit debugging will be finish in three months. The performance of the data transmission and storage subsystem have been test. The sequential write can be up to 5000MB/S, greater than the maximum theoretical data rate of the front-end subsystem.

Discussion and Conclusion

The designed platform will be helpful for the algorithm research.







Table 1. System key features.		
Item 0	FEATURES o	
Transducer @	2048 elements, ring array.	
	Diameter: 20 cm	
	Center frequency: 2.5MHz · e	
Transmitter .	512 channels +/	
	Max output voltages: 200 Vpp	
Receiver	512 channels +/	
	Sampling frequency: 12.5-50MS/S +	
	Resolution: 14 bit.	
	Total signal chain gain: 54 dB	
Data storage «	4·TB·SSD*2, sequential write (up to) 2500·MB/s each	
	24 TB RAID-10	
Raw data rata @	3.9GB/s +	
Acquisition time .	6s per slice +	

Technologies for Piezoceramic Composites used for Ultrasonic Transducers

K. Hohlfeld¹, S. Gebhardt¹, H. Neubert¹

¹ Fraunhofer IKTS Dresden kai.hohlfeld@ikts.fraunhofer.de

Background, Motivation and Objective

Piezoelectric ultrasonic transducers are widely used in many fields, such as medical ultrasonic, nondestructive testing and structural health monitoring. The limits of piezoelectric bulk ceramics in high electromechanical coupling, broad bandwidth, good acoustic impedance matching and high resolution of acoustically separated elements lead to attention on piezoelectric 1-3 composites with improved electrical, electromechanical and mechanical properties.

Material and Methods

At Fraunhofer IKTS, several cost-effective fabrication technologies are available each enabling a specific range of structure dimensions and therefore specific frequency range of ultrasonic transducers. For high frequency ultrasonic transducers which can be operated well above 15MHz the soft mold process offers the appropriate technology. Structured PZT thick films can be prepared by screen printing with thicknesses between $20\mu m$ and $150\mu m$ on planar substrates. However, the frequency is limited to about 4MHz. Polysulphone spinning has been developed and is applied for shaping green ceramic fibres of PZT. For transducer manufacturing, the sintered piezoceramic fibres are aligned and embedded into a polymer matrix, and shaped after curing.

Results

PZT Fibres with a diameter of 460 μ m fabricated by polysylphone spinning have been processed to single-fibre transducer arrays for ultrasound tomography. Array thicknesses between 0.4 and 2.1 mm have been investigated, having resonance frequencies between 3 MHz and 500 kHz accordingly. The fibres are arranged in a specific pattern and individually contacted in order to work as a single element transducer each. They exhibit superior and homogenous electromechanical properties. However, the coupling factor decreases slightly with increasing frequency due to lateral clamping.

Discussion and Conclusion

Piezocomposites based on single PZT fibers are investigated as promising cost effective alternative to dice-and-fill transducers allowing for improved 3D-USCT systems. 3D designs are feasible within the framework of fibre arrangement and CNC processing possibilities. The minimum composite thickness achievable by machining and the minimum fibre diameter limit the maximum frequency of fibre composite transducers to about 10 MHz.

Dice-and-fill single element octagon transducers for next generation 3D USCT

M. Zapf¹, B. Leyrer¹, P. Pfistner¹, C. Liberman¹, K. van Dongen², N. de Jong², H. Gemmeke¹, N. Ruiter¹

 Karlsruhe Institute of Technology michael.zapf@kit.edu
 ² Delft University of Technology

Background, Motivation and Objective

At KIT a 3D USCT system is under development. The system is optimized for SAFT imaging and has a multistatic setup of 2041 ultrasound transducers with approx. 1MHz 3dB bandwidth and 36° 3dB opening angle for 2.5MHz. The USCT groups transducers in a semi-elliposoidal aperture surrounding a ROI of $10 \times 10 \times 10 \times 10^{3}$. To increase the ROI for a next USCT generation, the opening angle of a future transducer should be increased to approx. 60° while other characteristics should be preserved or improved.

Material and Methods

The fundamental connection between a transducer's emission and reception sensitivity in the azimuth and elevation angle is its size. Finite elemente simulations showed that approx. half the side length of current generation transducer is required. A circular instead of the current rectangular aperture would result in additional homogenity. Octagon shape transducers are therefore an improvement over previously used rectangular transducers. With the established dice-and-fill technique with 2 additional sawing cuts this form can be achieved. Inspired by compressive sensing, an irregular distribution is applied covering almost the full surface area of US transducer. Further improvements are introduced regarding connectivity and bandwidth.

Results

Transducer is built up from the backing on which top-side a flexprint is providing the connectivity for the individual transducer elements. Small PZT slabs are glued on copper pads of the flexprint with low temperature curing silver glue. On a matching layer the cured structure is glued also with conductive silver-glue providing the common ground connection, defined distance and parallelity is provided by a laser cutted precise spacer ring. The completed structure is water proofed and mechanical stabilized with a hard-rubber like PU. Electrical characterization was performanced with a phase-impedance analyzer for all piezo fibres. Ultrasound characteristics were evaluated quantitatively with a hydrophone in a 3-axis water tank.

Discussion and Conclusion

First prototypes were assembled with the described process and first results ares encouraging. Yet, the process is currently not as stable and reliable as aimed for. The currently not fully automatized process lead to variations and in result to the failure of a significant portion of the transducer elements. This is currently under intensive investigation with further test prototypes to improve and stabilize the process which promises to lead an improved yield >95%.



Ultrasound Tomography for Breast Cancer Screening

N. Duric¹, P. Littrup²

¹ Delphinus Medical Technologies and Karmanos Cancer Institute nduric@delphinusmt.com

² Delphinus Medical Technologies

Background, Motivation and Objective

Both mammography and standard ultrasound (US) rely upon subjective criteria within the breast imaging reporting and data system (BI-RADS) to provide more uniform interpretation outcomes, as well as differentiation and risk stratification of associated abnormalities. We have been developing a new technique for breast imaging that is based on ultrasound tomography which quantifies tissue characteristics for development of more objective criteria.

Material and Methods

Informed consent was obtained from all patients, prospectively recruited in an IRB-approved protocol following HIPAA guidelines. Images were produced by tomographic algorithms for reflection, sound speed and attenuation. All images were reviewed by a board-certified radiologist who has more than 20 years of experience in breast imaging and US-technology development. In the first phase of the study, UST images were compared to multi-modal imaging to determine the appearance of lesions and breast parenchyma. In the second phase of the study, correlative comparisons with MR breast imaging were used to establish basic operational capabilities of the UST system including the identification and characterization of parenchymal patterns.

Results

Our study demonstrated a high degree of correlation of breast tissue structures relative to fat subtracted contrast enhanced MRI. With a scan duration of $\sim 1-3$ minutes, no significant motion artifacts were observed. Initial clinical results suggest an ability to characterize lesions using margin boundary scores in combination with sound speed and attenuation parameters.

Discussion and Conclusion

Ultrasound tomography is an operator independent method of imaging the breast. Experience with the SoftVue system indicates that rendering of parenchymal structures and lesions is similar to that of MRI while providing its own unique metrics for lesion characterization.

3D Ultrasound Tomography for Breast Cancer Diagnosis at KIT: an Overview

N. Ruiter¹, M. Zapf¹, T. Hopp¹, H. Gemmeke¹, A. Menshikov¹

¹ Karlsruhe Institute of Technology nicole.ruiter@kit.edu

Background, Motivation and Objective

3D USCT emitting and receiving spherical wave fronts overcomes the limitations of 2D systems by offering a nearly isotropic 3D point spread function, a large depth of field, less loss of out-of-plane reflections and fast 3D data acquisition. Yet 3D devices for clinical practice require a more complex hard- and software due to the huge data rate, time-consuming image reconstruction, and large number of small transducers. The here reviewed KIT 3D USCT is a 3D prototype for clinical studies.

Material and Methods

The KIT 3D USCT device is equipped with 2041 transducers on a semi elliptical aperture with 2.5 MHz center frequency and 50% bandwidth. The data acquisition is carried out by sequentially sending a frequency coded chirp with a single emitter and recording with all receivers. Rotational and translational movement of the aperture is applied. Up to 80 GB of raw data is digitized with 480 parallel channels at 12 Bit and 20 MHz sampling frequency. 3D synthetic aperture focusing technique (SAFT) is applied for reflectivity reconstruction. Sound speed and attenuation volumes are created using a straight ray based algebraic reconstruction technique. Parallel reconstruction on GPUs enables high resolution breast volumes in 16 minutes.

Results

The point spread function for reflectivity imaging could be shown to be nearly isotropic in 3D and to have very low spatial variability ($0.24 \text{ mm} \pm 0.05 \text{ mm}$). In a first pilot study ten patients with different lesions were imaged. Data acquisition could be carried out for all patients with an average imaging time of six minutes per breast. Speed of sound, attenuation and reflectivity volumes of each patient were derived from the raw data. Overlaid volumes of the modalities show qualitative and quantitative information at a glance. The results are promising as the breasts' tissue structures and cancerous lesions could be identified in the USCT images. A larger clinical study with 200 patients was started.

Discussion and Conclusion

We realized a sparse 3D USCT setup, resulting in homogeneous illumination, and nearly isotropic 3D PSF and applied it successfully in clinical studies. In the preliminary clinical results speed of sound was the most indicating modality for breast cancer. Yet, the spatial resolution of speed of sound and attenuation is currently limited by the ray based reconstruction algorithm. More complex reconstruction methods for transmission tomography leading to higher resolution are under test.



Breast Tissue Characterization with Sound Speed and Tissue Stiffness Imaging

C. Li¹, G. Sandhu¹, M. Boone¹, N. Duric¹, B. Kenneth¹, P. Littrup¹

 1 Delphinus Medical Technologies, Inc., USA cli@delphinusmt.com

Background, Motivation and Objective

In this study, we are going to assess the ability of SoftVue's waveform sound speed and through-transmission based stiffness image to render a variety of breast tissue and breast masses.

Material and Methods

Transmission ultrasound provides additional characterization by measuring tissues parameters such as sound speed, attenuation, and through-transmission based tissue stiffness information. These parameters were used to assist characterization of breast tissue and breast masses. In this study, we focused on using SoftVue's sound speed image and tissue stiffness image rendered by combining sound speed and attenuation across individual coronal slices to help detection and characterization of breast tissue and breast masses.

Results

The above metrics were applied to in vivo breast images reconstructed with the SoftVue system. A few examples are presented. First in vivo case has a well circumscribed cyst with an average sound speed of 1523 m/s. The stiffness image indicates that it is soft. Second in vivo case has a well circumscribed oval shaped fibroadenoma, which has moderate stiffness and an average sound speed of 1552 m/s. Third case is a highly spiculated IDC with an average sound speed of 1550 m/s and is stiffer than the surrounding dense breast tissue. In all three cases, fatty breast tissue has the lowest sound speed among normal breast tissue and breast masses, while breast parenchyma generally has higher sound speed than cyst.

Discussion and Conclusion

We have established detection/diagnosis metrics for waveform breast sound speed and through-transmission rendered tissue stiffness information. A few examples demonstrate that a combination of sound speed and tissue stiffness information has great potential to assist detection and characterization of different breast tissues and breast masses.

Postprocessing workflow of 3D-USCT: bridging the gap to the clinic

T. Hopp 1 , M. Zapf 1 , H. Gemmeke 1 , N. Ruiter 1

¹ Karlsruhe Institute of Technology torsten.hopp@kit.edu

Background, Motivation and Objective

As first USCT systems are approaching clinical application, it is an essential task to prepare the reconstructed images for intuitive diagnosis and conform to clinical standards. We describe our post-processing workflow consisting of automated breast segmentation, image fusion, DICOM export, our dedicated USCT DICOM viewer and the methods to transfer images to the clinic.

Material and Methods

Automated breast segmentation is carried out by an active contour approach applied to reflectivity images. The binary segmentation mask can be applied to all three modalities as they are imaged in one step. To facilitate diagnosis we apply an image fusion, which color-codes sound speed and attenuation overlaid on reflectivity images. All three modalities are fused by applying thresholds on sound speed and attenuation. All images are thereafter exported into DICOM format with additional metadata. As in the DICOM standard currently no USCT SOP class is defined we apply the CT SOP class. Finally, images are transferred to a local installation of Conquest PACS and transferred to the clinic via tele radiology connection.

Results

The segmentation was tested with 14 images resulting in an average surface distance of 2.7 mm from the manually segmented images. Modalities were fused applying empiric thresholds for sound speed (>1580 m/s to distinguish cancer from other tissue) and attenuation (0.1 dB/cm). The PACS installation was tested successfully and currently holds the data of our clinical studies. A tele radiology connection to University Medicine Mannheim was established based on the DICOM e-mail concept. The exported DICOM files were checked for consistency and tested with open source and commercial DICOM viewers as well as with our dedicated USCT DICOM viewer software, which allows convenient access and automated default display protocols.

Discussion and Conclusion

We successfully established a fully automated post-processing workflow to bring 3D-USCT closer to clinical application. We consider segmentation and image fusion as essential steps for intuitive diagnosis which is focused to the most relevant clinical information. Using medical standards like DICOM and PACS allows easy integration into clinical workflows, yet in future we propose to extend the DICOM standard by a dedicated SOP class fulfilling the metadata requirements of USCT.



Tissue Characterization With Ultrasound Tomography Machine Learning

G. Sandhu¹, P. Littrup¹, M. Sak¹, C. Li¹, N. Duric¹

 1 Delphinus Medical Technologies, Inc. gsandhu@delphinusmt.com

Background, Motivation and Objective

Ultrasound tomography (UST) generates several different imaging modalities. This includes reflection, sound speed, and attenuation images. The images visualize different types of breast diseases or tissues. Typically, a radiologist views the images to determine a diagnosis for the patient. However, a learning algorithm could be trained to predict diagnosis based on the features contained within the image. Thus, our objective is to create classifier models which map features in images to labels.

Material and Methods

An region of interest (ROI) is drawn on an image corresponding to the location of a lesion. Various features, such as mean sound speed or gray level variations, are extracted from the ROI and the region surrounding the ROI. The lesion is given a label of malignant or benign. A radiologist also gives a BI-RADs like score to the lesion. Many patients with different types of lesions can be analyzed to generate a training set of data. Various classifier models such as decision trees, neural networks, and support vector machines were then trained with the training set. After the construction of the classifier model, features can be extracted from new patients with unknown labels. The classifier model can then map the unknown features to a label.

Results

We analyzed 68 cancers, 55 fibroadenomas, and 38 cysts. Using only the radiologists' BI-RADs like score, we obtain a baseline classification accuracy of sensitivity (SEN) = 82%, specificity (SPE) = 91%, and positive predicative value (PPV) = 88%. Using only the features extracted from the images, SEN = 78%, SPE = 83%, and PPV = 77%. Combining the BI-RADs like score and features, the classification accuracy improves to SEN = 86%, SPE = 98%, and PPV = 97%.

Discussion and Conclusion

Using only the extracted features to label a lesion, the only input a radiologist has to perform is the drawing of the ROI contour. Using only this input, it is remarkable how well the classifier model is able to label regions as benign or malignant. With the addition of some radiologists' assessment of lesion malignancy, the classifier model's performance improves. Some limitations of our work include small sample size. Classification accuracy should improve with more samples.



Challenges and applications of registering 3D Ultrasound Computer Tomography with conventional breast imaging techniques

P. Cotic Smole¹, N. Ruiter¹, N. Duric², T. Hopp¹

 ¹ Karlsruhe Institute of Technology patricia.smole@kit.edu
 ² Delphinus Medical Technologies and Karmanos Cancer Institute

Background, Motivation and Objective

For evaluation of the diagnostic value of Ultrasound Computer Tomography (USCT) the imaging results have to be correlated with conventional breast imaging techniques. This is challenging due to different patient positioning in the modalities with nonlinear deformations of the breast tissue. We developed a patient-specific image registration method, which simulates different breast positions through biomechanical modelling. We give a review of its recent applications and raise open challenges.

Material and Methods

For the registration, the breast is modeled with a 4-node tetrahedron mesh extracted from a volume modality (USCT or MRI). The model can be derived either from the segmented MRI volume with assigned material stiffness parameters or from a stiffness distribution model based on the USCT sound speed images. In the case of MRI to USCT and USCT to X-ray mammography registration, the buoyancy effect respectively the compression are simulated on the model within a FEM framework. Registration is done by optimizing the most influencing parameters. After applying the deformation field to the volume modality, the co-registered volumes are rigidly aligned at their centres of mass.

Results

An average registration error below 5 and 12 mm for MRI to USCT and USCT to mammography registration, respectively, allowed us to evaluate the diagnostic performance of USCT. It was shown that regions of high sound speed corresponded well with the tumor position indicated in MRI from a contrast kinetic analysis. Moreover, the quantitative analysis of sound speed and attenuation parameters with respect to segmented mammograms revealed that sound speed gives a better distinction between breast tissues than attenuation, whereas their combined information further improved the classification. A clear distinction was observed between lesions and other breast tissue.

Discussion and Conclusion

The first evaluation of USCT's diagnostic value with the proposed registration approach already showed promising results. Further evaluations are planned with additional patient datasets and with more complex modelling, e.g. dealing with the MRI breast coil deformations and comparing the performance of stiffness distribution models derived from speed sound images to the models derived from segmented MRI. Additionally, registration to the emerging X-ray tomosynthesis modality is of high interest.

Feasibility study on USCT for brain imaging to estimate artifacts and image distortion caused by bone propagation

 $\textbf{Y. Hayashi}^1, \textbf{H. Nakamura}^1, \textbf{X. Qu}^1, \textbf{D. Kondo}^1, \textbf{K. Yuge}^1, \textbf{T. Azuma}^1, \textbf{S. Takagi}^1$

¹ The Univ. of Tokyo hayashi@fel.t.u-tokyo.ac.jp

Background, Motivation and Objective

We are trying to image inside the skull with USCT with the goal of examination of acute stroke during the emergency conveyance. For transcranial USCT, attenuation and phase distortion after the pass through the skull would degrade its imaging performance. The purpose of this study is to establish the reconstruction method for the transcranial USCT through the process of a frequency optimization and an artifact cancellation to recover the energy attenuation and the focus quality, respectively.

Material and Methods

To investigate the artifacts caused by skull and evaluate the point spread function of the transcranial USCT, we obtained the data with k-Wave simulation in which the ring-shaped area simulating the skull and the point scatter were set inside the ring-array transducer with a diameter of 10 cm, an element number of 256. The frequency of transmitted pulse was 1.6 MHz. The image was reconstructed by using a synthetic aperture imaging method [X.Qu et al, J. Med. Ultrasonics, 43, 2016] for two models as shown in Fig (a), (d). In experiments, a wire set in the ABS (acrylonitrile butadiene styrene) ring-shaped skull phantom was imaged by a 1024-ch ring array with diameter of 10 cm connecting with Verasonics system to validate simulation results.

Results

The reconstructed image is shown in Fig (b). The estimated position for the scatter positioned at (10.5 mm, 10.5 mm) was (10.7 mm, 10.7 mm) and half width was 1.89 mm. In addition, artifacts were cancelled as shown in Fig (c) by taking the mode (maximum value in the histogram) of signal values instead of taking the sum of signal values in synthetic aperture imaging method. Fig (f) shows the reconstructed image obtained for more realistic model which has cancellous bone as shown in Fig (d). In experiments, the signal from the wire with diameter of 2mm was able to be detected with ring-shaped skull phantom, however the signal intensity of the same diameter in the simulation was not enough to be imaged after reconstruction process.

Discussion and Conclusion

Fig (e) shows the echo data obtained from the model in Fig (a). Transmitted wave curve was broken unlike the case without skull, which caused artifacts. We succeeded in cancelling these artifacts by taking the mode of signal values. Future studies will focus on image reconstruction method in which refraction is taken into consideration and finding the optimum frequency of transmitted pulse. Furthermore, more realistic model of skull in geometry and acoustic properties will be investigated.



Multi-perspective ultrasound imaging of abdominal aortas

N. Petterson¹, M. van Sambeek², F. van de Vosse¹, R. Lopata¹

¹ Eindhoven University of Technology n.j.petterson@tue.nl
² Catharina Hospital Eindhoven

Background, Motivation and Objective

Ultrasound functional imaging of large vessels is challenged by regional low contrast of the wall. Moreover, displacement tracking in the lateral direction suffers from poor lateral resolution. These challenges can be tackled in superficial vasculature with beam steering and compounding. However, in deep vessels like the abdominal aorta, beam steering is not possible because the aorta will not be in the field-of-view. In this study, multi-perspective imaging of the abdominal aorta is proposed.

Material and Methods

2D RF-data were acquired with an Esaote MyLab70 equipped with a curved array transducer (fc = 3.5 MHz). The abdominal aorta of healthy volunteers was imaged between the renal arteries and the iliac bifurcation in the cross-sectional view. The probe was mounted on a custom-made arch to constrict the movement and determine the angle of the imaging plane. Recordings were made from 7 angles ranging from -20° to 20° . The aorta was manually segmented in each of the 7 acquisitions. The images were aligned to a single coordinate system, whereas the segmentation of the aorta was used to register the images in post-processing. After rotation and translation of the multiple views, a composite ultrasound image was computed by averaging of the envelope data.

Results

An example of the individual acquisitions and composite ultrasound image is found in Figure 1. Combination of multiple angles leads to great improvement of the contrast between the lumen and the wall of the abdominal aorta, especially in the lateral regions. Cincloops revealed no significant artefacts due to differences in heartbeat frequency or blood pressure (temporal misalignment). Some local spatial misalignment was found caused by aberration.

Discussion and Conclusion

The proposed method has the potential to perform high contrast imaging of deeper lying abdominal organs. Aberration correction and automatic registration are required before multi-perspective motion tracking is feasible. The separation between the aorta and the vena cava remains unclear. This could be improved by increasing the maximal insonification angle. In future research, multiple probes will be used simultaneously to enable semitomographic transmit/receive compounding.



Figure 1: Cross sectional views of a healthy abdominal aorta. A: Ultrasound acquisition setup B: All 7 acquired views C: A standard single view acquisition D: Combination of the 7 perspectives. The aorta is indicated with the white arrow.

A simple method for acoustic properties determination of cancerous tissue and its implementation into the clinical workflow

F. Wolfram¹

 1 Lung Cancer Centre SRH Waldklinikum Gera
 frank.wolfram@srh.de

Background, Motivation and Objective

During USCT examination, tissue morphology, as well as acoustic properties such as speed of sound are extracted. Data based upon malignant tissue is limited, so is its reliability as a prognostic factor indicating a malignant or benign nature. It's hard to obtain tumour tissue because of their pathological use for staging. Therefore, this work will present a simple method of acoustic properties measurement and its implementation in a clinical workflow

Material and Methods

A broadband - dual immersion technique was used to determine speed of sound and attenuation of malignant and benign Lung Cancer. Tumour were resected during surgery containing Adeno-, Squamous Carcinoma and Benign as well as metastatic tissue from breast and colon carcinoma. Measurements were performed after resection before fixation and histological staining. A clinical workflow was implemented that didn't interfere with the pathological procedures. Additionally, a literature study was performed to compare the determined properties with published data.

Results

All cancer types had higher speed of sound (1560-1670 m/s) than water. The speed of sound was higher in malignant tissue than in benign. Impedance was highest for squamous carcinoma (1.88 MRayl). Attenuation varied between 0.31 - 0.8 dB/cm/MHz and showed no significant difference between the histological subtypes. The proposed measurement technique could be implemented into the surgical - pathological workflow without disturbance of the histological management.

Discussion and Conclusion

There exists comprehensive literature for acoustic properties from parenchymal, but a limited one for cancerous tissue. Measurements revealed that malignant tissue has higher speed of sound than benign tissue and might therefore be a valuable parameter for tissue classification in USCT. More work is demanded in order to determine acoustic properties from mammary tumours of different histological subtypes.

Clinical ultrasound breast tomography using Softvue textregistered: a preliminary in vitro and in vivo assessment

J. Bamber¹, J. Fromageau², A. Messa², S. Bernard², N. Duric³, A. D'Aquino², A. Ledger², M. Schmidt², M. Schoemaker², A. Swerdlow², E. O'Flynn²

¹ Institute of Cancer Research jeff.bamber@icr.ac.uk

² Institute of Cancer Research and Royal Marsden NHS Foundation Trust, London

³ Delphinus Medical Technologies, Karmanos Cancer Institute, Wayne State University, Detroit

Background, Motivation and Objective

Softvue

textregistered (Delphinus Inc.) ultrasound tomography (UST) provides images of sound speed (SS), attenuation coefficient (AC), a combination of SS and AC called stiffness, and relative reflectivity. We have compared volume-averaged SS (VASS) with MRI volume-averaged water versus fat, to quantify breast density (O'Flynn et al., 2017). Here, clinical reproducibility is assessed, stiffness compared with MRI, and VASS compared with mammographic density. Performance is estimated using phantoms.

Material and Methods

Forty three healthy volunteers underwent breast UST and Dixon MRI. Semi-automated breast segmentation was developed for VASS. Left-right breast correlation assessed reproducibility of VASS and SS breast texture. VASS and stiffness were compared with MRI water and (in a subset of 13) mammographic density (Cumulus textregistered). To further assess UST stiffness, images of a commercial elastography phantom (CIRS, model 059) and a custom built gelatine phantom with solid inclusions were compared with shear wave elastograms (SWE) (Aixplorer

textregistered, Supersonic Imagine). To assess SS and AC, gelatine and agar phantoms containing ethanol or castor oil inclusions were scanned at various temperatures and the results compared with independent measurements.

Results

Stiffness correlated extremely well with breast composition estimated by MRI, although slightly less well than previously reported VASS with MRI. VASS correlated well with mammographic density, slightly better when the density was estimated with a craniocaudal view than a mediolateral view. Good left-right breast correlation was obtained with VASS and with SS histograms of each breast, as well as with summary first-order texture measures. In phantoms, a UST stiffness halo signature signified the presence of a mass that was stiff on SWE. SS imaging detected inclusions at least as small as 3 mm diameter. The accuracy of SS and AC, and the average inclusion/background contrast, varied with inclusion size.

Discussion and Conclusion

VASS and SS breast texture are reproducible. VASS and stiffness describe breast adipose/parenchymal composition well and hold promise as breast density estimates. Correlation with mammographic density may be influenced by variability in the latter. Mass stiffness in phantoms is displayed differently by UST and SWE, suggesting the need for a clinical comparison. Small inclusions are detectable although SS and AC vary with mass size. Similar testing is required with the latest version of Softvue textregistered

The New Generation of the KIT 3D USCT

H. Gemmeke¹, N. Ruiter¹, T. Hopp¹, M. Zapf¹, I. Peric¹, L. Berger¹, W. Tan¹, R. Blanco¹, R. Leys¹

¹ Karlsruhe Institute of Technology hartmut.gemmeke@kit.edu

Background, Motivation and Objective

The first clinical studies with our current prototype, 3D USCT II, enabled us to identify the necessary improvements for transition of the method to clinical practice. The main goals are to improve the contrast of reflection tomography, the resolution of transmission tomography, and to optimize imaged volume of the breast. Furthermore, the fabrication of the transducer arrays needs to be cost-effective and the data acquisition and readout time should be reduced.

Material and Methods

We optimized the different possible transducer distributions using simulations in respect to contrast, coverage of the region of interest (hemisphere of 20 cm diameter), and minimization of artefacts. The patient bed was evaluated by test series. The design of the aperture was adapted to image as close as possible to the chest wall and to cover also parts of the pectoralis. To reduce the costs for the transducer arrays we designed an ASIC, which can handle the readout and driving of 9 transducers up to 120 V. By this design, we can now use each transducer as emitter and receiver.

Results

Most of the parts of the new system are ready for assembly. The aperture was enlarged to 35 cm, see Fig.1, to cover a hemispherical volume of interest with a diameter of 20 cm without loss of image quality. The distribution of transducers over the aperture's surface is homogeneous and random to allow statistical sampling of the volume. The simulations promise an increase of contrast for the reflection tomography of a factor 6 and significant more homogeneous contrast for transmission tomography. The data acquisition time of $1.2 \cdot 10^6$ A-scans will be 1 to 2 minutes and the readout within 1 minute. The ASIC and new transducer design has a resonance frequency of 2.5 MHz and a bandwidth of 4 MHz.

Discussion and Conclusion

So far, all known demands of 3D ultrasound tomography are fulfilled to achieve all three modalities reflection-, speed of sound, and attenuation tomography with high image quality.



Part III Poster presentations

Comparison of two ray tracing methods for sound speed imaging

X. $Fang^1$, Y. Wu^1 , M. Yuchi¹, M. Ding¹

¹ Department of Biomedical Engineering, School of Life Science and Technology, Huazhong University of Science and Technology, Wuhan, Hubei, China

d201677469 @hust.edu.cn

Background, Motivation and Objective

Sound speed imaging in USCT is a kind of functional imaging mode which can provide valuable information for differentiating normal tissue and tumor. Sound speed imaging in USCT is a kind of functional imaging mode which can provide valuable information for differentiating normal tissue and tumor. One of the key problems of sound speed reconstruction is ray tracing. This paper compares the sensitivity and the accuracy of the finite difference method and the linear interpolation method.

Material and Methods

Vidale (1988) presented a method that could obtain the first arrival travel times by a finite-difference solution of the eikonal equation. Asakawa (1993) presented a linear interpolation method, which considers a ray path crossing segment AB on a certain cell boundary and reaching point D on the opposite side of the boundary. We use the software pzflex to simulate acoustic-wave propagation in a numerical phantom. A ring array with 72 elements is used. A numerical phantom of four circles with different sound speed value are placed inside the ring array and immersed in water. Then the above two ray tracing methods were compared by the travel times detected in the receiver location and the first-arrival time diagram.

Results

The imaging area is divided into grids firstly. The two methods are used to calculate the first-arrival times in each grid. Both the two methods can "recognize" the two bigger circles with sound speed 2600 m/s. The interpolation method can show the third circle with sound speed value 1579 m/s more accurately. Both of these two method cannot "recognize" the forth circle with sound speed value 1510 m/s. We compared the travel times in receiver position when the sound speed model is true value of the four-circle phantom with the travel times detected in received waveforms. The finite difference method's result is almost the same as the standard, however there is greater error in the interpolation method's result.

Discussion and Conclusion

This paper firstly generated USCT data using software pzflex. Then two ray tracing methods were compared by the travel times detected in the receiver location and the first-arrival time diagram. The comparison came to the conclusion that the sensitivity of the linear interpolation method is higher, while the accuracy of the finite difference method is higher. Theoretically the linear interpolation method is more accurate, the phenomenon probably results from the "expanding wavefront" scheme the finite difference method used, which implies the importance of the expanding scheme used.

Contrast resolution enhancement of Ultrasonic Computed Tomography (USCT) using a wavelet-based method - Preliminary results in bone imaging

P. Lasaygues¹, R. Guillermin¹, K. Metwally¹, S. Fernandez², L. Balasse³, P. Petit⁴, C. Baron⁵

 1 Aix Marseille Univ, CNRS, Centrale Marseille, LMA, Marseille, France

lasaygues@lma.cnrs-mrs.fr

² Aix-Marseille Univ, CERIMED, Marseille, France

³ Aix Marseille Univ, INSERM, VRCM, Marseille, France

⁴ Department of Pediatric and Prenatal Radiology, "Timone" Children-Hospital, APHM, Marseille

⁵ Aix Marseille Univ, CNRS, ISM, Marseille, France

Background, Motivation and Objective

In the case of bone imaging, current medical echography does not allow imaging under the cortical zone; no information is available on cortical depth, underlying medullary tissue or marrow. Many authors have discussed ultrasonic imaging of bones. Their main objective was to evaluate the thickness of the diaphysis in axial and transverse mode, and to estimate the velocity of the sound of a wave. Our group has been focusing on the cross-sectional radial imaging process, using USCT

Material and Methods

Although this method is known to provide a potentially valuable means of imaging objects with similar acoustical impedance, in the case of bone imaging, difficulties are bound with the higher acoustical impedance difference, which strongly alters the propagation of the ultrasonic waves, and generally induces low Contrast-to-Noise Ratio (CNR). It is necessary to change the methods used for the acquisition and for the processing of the ultrasonic signals. More in particular, in order to obtain a better quantification while extracting characterization information from the received signal, we tried several approaches: filtering, spectrum analysis and the deconvolution of the signals.

Results

Loosvelt and Lasaygues (2011) developed an alternative method based on a multi-scale decomposition procedure of the signals, enabling to process all the information available in terms of frequency and time. This method, called the "Wavelet-based Coded Excitation" (WCE) method, can be used to determine, independently, the velocity of the ultrasonic wave and the wave path across the thickness of parallelepiped plate. The aim of this new study is to investigate the feasibility of the WCE method as a mean of Contrast-to-Noise Ratio enhancement of bones imaging.

Discussion and Conclusion

In this case, the wavelet decomposition alone does not suffice to optimize the signal processing and the incident wave reaching the object, also has to match the wavelets' mathematical properties. We then propose a solution to achieve this goal, based on zone-by-zone simulated annealing algorithm. Then, we show through experimental results on geometrical mimicking human bone (without soft tissues), and on an ex vivo chicken drumstick (without skin), the usefulness of this WCE method.

Fast reflectivity imaging in 3D using SAFT

N. Ruiter¹, T. Hopp¹, H. Gemmeke¹, M. $Zapf^1$

¹ Karlsruhe Institute of Technology nicole.ruiter@kit.edu

Background, Motivation and Objective

The computational burden for 3D Synthetic Aperture Focusing Technique (SAFT) is large as for each voxel the delay for each acquired A-scan has to be calculated, e.g. $O(N^5)$ for N^3 voxels and N^2 A-scans. If the 3D distribution of speed of sound is applied to correct the delays for objects with varying speed of sound the computation time increases further. This overview paper presents the implementations for 3D SAFT developed by the KIT group and discusses their performance.

Material and Methods

A fast 3D SAFT implementation using multiple GPUs is presented. It is shown that for volumes of high resolution a speed of sound correction is necessary to overcome the defocusing by assuming constant speed of sound. Speed of sound and attenuation correction was incorporated in the GPU-based SAFT reconstruction, but leads also to a significant reduction of computational performance. An approximation to SAFT, i.e. a time of flight interpolation based GPU implementation (TOFI-SAFT), accelerates our previous GPU implementation of speed of sound corrected SAFT to allow reconstruction of speed of sound and attenuation corrected SAFT images as fast as non-corrected SAFT.

Results

TOFI-SAFT achieves a maximum performance of 104 GVA/s on a GPU server with eight GTX 590, which is a speed up of factor 3 compared to the corrected SAFT and approaches the maximum performance of 106 GVA/s of the uncorrected SAFT reconstruction. Tested on one new generation GPU, GTX Titan, TOFI-SAFT can be even faster than uncorrected SAFT: a GPU server of eight GTX Titans would result in a maximum performance of 210 GVA/s for uncorrected SAFT, 62 GVA/s for corrected SAFT and 442 GVA/s for TOFI-SAFT which is a speed up of more than factor 7. Comparing speed of sound corrected SAFT and TOFI-SAFT for clinical data resulted in only small degradation of the image quality, see figure.

Discussion and Conclusion

The GPU based 3D SAFT implementations show, especially with TOFI-SAFT on high performance GPUs, that high resolution 3D reflection tomography can be done in a clinically relevant reconstruction time in the order of minutes, even including speed of sound and attenuation correction.



Minimum-variance beamforming for ultrasound computer tomography imaging

S. $Wang^1$, M. Yuchi¹, J. Song¹, L. Zhou¹, Y. Peng¹, M. Ding¹

¹ Huazhong University of Science and Technology, Wuhan, Hubei, China d201477437@hust.edu.cn m.yuchi@hust.edu.cn

Background, Motivation and Objective

The breast cancer has become the most common type of cancer among women throughout the world. The traditional delay-and-sum (DAS) beamforming has been widely used in USCT imaging. In this paper, minimumvariance (MV) beamforming method is applied to improve the image quality for USCT. The USCT image is expected to have less noises and artifacts, and higher resolution and contrast.

Material and Methods

A 1024-element ring array with the center frequency 2.5MHz was used to scan the breast phantom 052A (CIRSINC, USA). The diameter of ring array was 200 mm, and the sampling frequency was 12.5 MHz. Phantom 052A immersed in water were put in the center of the transducer. The conventional DAS beamforming is non-adaptive and blind beamformer whose weights are predetermined. In the MV beamformer, the weights are computed to optimally minimize the output power by maintaining a unity gain in the desired direction and reducing the interference from other directions.

Results

A 1024-element ring array with the center frequency 2.5MHz was used to scan the breast phantom 052A (CIRSINC, USA). The diameter of ring array was 200 mm, and the sampling frequency was 12.5 MHz. Phantom 052A immersed in water were put in the center of the transducer. The conventional DAS beamforming is non-adaptive and blind beamformer whose weights are predetermined. In the MV beamformer, the weights are computed to optimally minimize the output power by maintaining a unity gain in the desired direction and reducing the interference from other directions.

Discussion and Conclusion

The MV beamformer have been applied to improve spatial resolution and suppress clutters in USCT. The proposed method was evaluated by experimental results. The results showed that the reconstructed images of the breast phantom by the MV beamformer enhanced the image quality compared to DAS. The main disadvantage of MV beamforming method is the excessive computational complexity. In the future, the proposed methods will be testified with in-vivo data.

Piezofibre composite transducers for next generation 3D USCT

> Karlsruhe Institute of Technology michael.zapf@kit.edu
> Fraunhofer IKTS Dresden
> Technical University Dresden

Background, Motivation and Objective

At KIT a 3D USCT is under development. The system is optimized for SAFT imaging and has a multistatic setup of 2041 transducers with approx. 1MHz 3dB bandwidth and 36° 3dB opening angle for 2.5MHz. The USCT groups transducers in a semi-elliposoidal aperture surrounding a ROI of $10 \times 10 \times 10 \times 10^{3}$. To increase the ROI for a next USCT generation, the opening angle of a future transducer design should be increased to approx. 60° while other characteristics should be preserved or even improved.

Material and Methods

The fundamental connection between an ultrasound transducer's emission and reception sensitivity in the azimuth and elevation angle space is the tranducer's aperture size. Simulations showed that approx. half the side length of current generation transducer is required. A circular instead of the current rectangular aperture would results in additional homogenicity. The established Fraunhofer IMT piezo-fibre composite technology provide circular fibres of required dimensionality. In this work a transducer design is presented which utilizes individual and reproducible dimensioned piezo fibres. The fibres were fabricated from PZT powder using the polysulfone spinning process.

Results

13 fibres were positioned by a mechanical mask and filled with a matrix of epoxy, curing to a rod of 18cm length and 2.3cm diameter. From this rod discs were sawed, defining the main resonance frequency by thickness, and then uniformly polarized. Connectivity was achieved by manual wiring via heat curing glue on top and bottom printed circuits. A transducer array (TAS) was finalized in a cylindrical housing by filling with PU backing material. TAS prototypes were assembled with a matching and backing and individual electrical connections. Electrical characterization was performanced with a phase-impedance analyzer for all piezo fibres. Ultrasound characteristics were evaluated quantitatively with a hydrophone in a 3-axis water tank.

Discussion and Conclusion

The presented assembly process fulfills the expectation of reproducible positioned transducer arrays, regarding disc thickness and fibres position and size. The relative variation of the the second resonance frequency varied among the 265 samples by a standard deviation of 2.48% only. The previously noticed effect of greatly varying single fiber piezo fibre performance could to be vastly reduced in a second batch of discs. This is under ongoing analysis and further build up prototypes.



Improved temperature measurement and modeling for 3D USCT II

M. $Zapf^1$, A. Patel¹, A. Menshikov¹, N. Ruiter¹

¹ Karlsruhe Institute of Technology michael.zapf@kit.edu

Background, Motivation and Objective

Ultrasound computer tomography for breast cancer relies on accurate SOS information, mostly disturbed by the temperature dependency of $\rm H^2O$ as medium. The current KIT USCT system (3D USCT II) incorporates many temperature sensors: two accurate calibrated and many low accuracy temp. sensors for spatially densely sampled 3D information. The accurate knowledge of the temperature is important for accurate and sharp imaging as in the USCT setup approx. 50% of the US travel distance is through water. Over an USCT measurement duration the sensors are digitized in second's interval. While many experiments are represented accurately some experiments need an enhanced and robustified approach.

Material and Methods

In a 1st step temporal oversampling reduces the ADC noise and achieve sub-bit "super resolution" by a low-order polynomial fit which also models temperature drifts. In the 2nd step, locality and symmetricity for the sensors surrounding the HQ sensors is utilized. A global compensation is created by utilizing many measurements. A final step integrates all data in a mode assuming a low rate of change over space and time, by that removing individual deviations.

For added robustness, we expand our method to include procedure variations and unknown influences now: air temp., device heat up, water temp. Therefore we installed additional sensors and created a setup which applied fast temperature changes to gain data about the temperature inertia.

Results

The accuracy and precision of the temp. data has been improved by more than an order of magnitude. This is well-beyond the original hardware-limited 1-bit resolution. We achieved a sub-bit accuracy of 0.005° C for a confidence interval of 95% as opposed to the original $\pm 1^{\circ}$ C raw accuracy. Our method automatically minimizes and substitutes outliers and faulty data using a robust model, reduces the sizeable hardware-related variation of about 0.6° C among individual sensors and runs without additional time-intensive delays on the USCT measurement process.

However, that we do on occasion see significant deviation $(\pm 1^{\circ}C)$ from expected results using our method. For this reason, we are currently working to incorporate more data.

Discussion and Conclusion

An ongoing analysis of our results revealed that we have significantly layering effects, meaning that we see significant temperature differences along the vertical axis (about 1° C). We believe this to be due to heating from the DAQs on the outside of the bowl holding the water. We are currently investigating these two phenomena further.



Visualisation of Ultrasound Computer Tomography Breast Data Set

N. Tan Jerome¹, Z. Ateyev¹, V. Lebedev¹, T. Hopp¹, M. Zapf¹, S. Chilingaryan¹, A. Kopmann¹

¹ Karlsruhe Institute of Technology nicholas.jerome@kit.edu

Background, Motivation and Objective

Visualising volume images is a key factor in diagnosing and detecting early breast cancer. However, the standard visualisation approaches still revolve around 2D images slides. Although 3D visualisation is important in diagnosing and treating breast cancer, yet the potential is not entirely realized with slices based visualisation. In this paper, we present an interactive 3D web-based visualisation tool for the breast data set which overcomes this limitation and offers new possibilities.

Material and Methods

Our approach focuses in efficient utilisation of 3D data. Thus, we based our implementation on WebGL technology which utilises the GPU parallel architecture. Our tool is a web-based platform which enables data sharing without extra tool installations. We render the data with state-of-the-art algorithms with a quality comparable to the desktop application. In particular, our tool performs the volume rendering and the multimodality fusion, i.e., normal fusion and intermixing approaches. Aside, our tool allows users to perform arbitrary view slicing, modality thresholding and multiple rendering modes. Also, an adaptive method was implemented which scales with client's hardware resources to retain an interactive response of the visualisation.

Results

To measure the effectiveness and performance of our tool, we measure the frame rates of each visualisation method on various client devices. The visualisation methods are tested on (i) a mobile phone (Xiaomi Redmi Note 3), (ii) a standard desktop (integrated graphic card HD4000), (iii) a laptop (GT750M), and (iv) a powerful workstation (Tesla C2). Among the methods, the direct volume rendering method is the fastest and most efficient: (i) 12 fps, (ii) 58 fps, (iii) 105 fps, and (iv) 218 fps; followed by the intermixing approach: (i) 5 fps, (ii) 30 fps, (iii) 40 fps, and (iv) 104 fps; and lastly the normal fusion approach: (i) 2 fps, (ii) 37 fps, (iii) 60 fps, and (iv) 110 fps. Our tool maintains 30 fps and higher on standard desktops.

Discussion and Conclusion

We presented a web-based 3D visualisation tool that adapts and scales automatically to a broad range of client and standard hardware devices. Our tool supports volume rendering, normal fusion, and intermixing methods. The web-based platform encourages collaborative research. The visual representations were promising and comparable to commercial applications. Currently, we are working on integrating our tool into the needs and infrastructure of a clinical workflow for radiologists.



Comparison of registration strategies for USCT-MRI image fusion: preliminary results

T. Hopp¹, P. Cotic Smole¹, N. Ruiter¹

¹ Karlsruhe Institute of Technology torsten.hopp@kit.edu

Background, Motivation and Objective

Comparing USCT to well-known MRI is an essential step to evaluate the clinical value of USCT. Yet the different conditions of the breast either embedded in water (USCT) or in air (MRI) prevent direct comparison of tissue structures due to non-linear deformations of the breast in 3D. Previously we presented an image registration simulating the MRI subjected to buoyancy. In this work we compare it with a new strategy by applying gravity to USCT to match the breast shape in the MRI.

Material and Methods

A biomechanical model is constructed from the segmented USCT resp. MRI volume. A gravity body load is applied (USCT) or buoyancy is simulated by inverting the gravity body load (MRI). Material parameters as well as dataset rotation and cropping are automatically optimized using simulated annealing to maximize the surface agreement. Subsequently a free-form deformation is applied to further refine the matching of the outer surfaces of USCT and MRI. The registration accuracy is evaluated based on annotated tissue structures in USCT and MRI by measuring the average mutual distance of their surface points.

Results

The registration was applied to 9 datasets from 8 patients. Both registration strategies revealed similar registration accuracies (MRI to USCT: mean = 5.6 mm, median = 5.6 mm, USCT to MRI: mean = 6.6 mm, median = 5.7 mm). Compared to a simple alignment of datasets the registration error is reduced by approx. factor 2. The parameter optimization resulted in similar average material stiffnesses for both registration strategies, confirming that the optimization is able to derive a robust patient-specific parameter setting.

Discussion and Conclusion

Image registration of USCT and MRI allows to delineate corresponding tissue structures in both modalities in the same or nearby slices. Our preliminary results indicate that both simulation strategies seem to perform equally. Yet the newly developed deformation of the USCT volume is less computationally demanding: as the breast is subjected to buoyancy and can thereby serve as the unloaded state while for the contrary strategy we have to solve an inverse problem.

Measurement of the speed of sound, attenuation and mass density of fresh breast tissue

L. Keijzer¹, M. Lagendijk², N. Stigter¹, C. van Deurzen³, K. Verhoef², W. van Lankeren⁴, L. Koppert², K. van Dongen¹

 1 Laboratory of Acoustical Wavefield Imaging, Department of Imaging Physics, Delft University of Technology, the

Netherlands l.b.h.keijzer@erasmusmc.nl

² Department of Surgical Oncology, Erasmus MC, Rotterdam, the Netherlands

³ Department of Pathology, Erasmus MC, Rotterdam, the Netherlands

 $^{\rm 4}$ Department of Radiology, Erasmus MC, Rotterdam, the Netherlands

Background, Motivation and Objective

An improved distinction between benign and malignant lesions is necessary to enhance the diagnostic value of breast ultrasonography. This requires a better quantitative characterization of tissues and hence accurate knowledge about the acoustic medium parameters. Current data on these parameters is inconsistent due to variations in applied measurement protocols. We tested a standardized protocol for measuring the speed of sound, attenuation and mass density of freshly excised breast tissues.

Material and Methods

Three patients scheduled for a mastectomy, were included in the study. Tissues of skin, nipple, intra-glandular fat, glandular tissue and breast carcinoma were analysed. Two experimental methods were developed. The first uses pulse-echo measurements to measure the speed of sound and frequency dependent attenuation; the second uses a pycnometer to measure the mass density. Two important adjustments were made to mimic in vivo conditions. First, a novel sample holder using a vacuum pump was developed. This has the advantage that the sample thickness could be obtained at each grid point separately without compressing the tissue. Second, physiological phosphate-buffered saline (PBS) solution of 37°C was used to prevent absorbing.

Results

For fresh samples of fat, skin, glandular tissue and nipple, the following values are found for the sound speed: 1456 m/s, 1559 m/s, 1564 m/s and 1574 m/s; frequency dependent attenuation: 5.7 Np/m $MHz^{-1.3}$, 4.8 Np/m $MHz^{-1.7}$, 10.5 Np/m $MHz^{-1.5}$ and 4.6 Np/m $MHz^{-2.0}$; and mass density: 869 kg/m³, 970 kg/m³, 874 kg/m³, 987 kg/m³, respectively. Significant differences are observed when comparing the results with literature, see Fig. 1.

For density, higher values are found when using larger samples, see Fig. 1. An increase is seen for samples that are measured before and after being submerged in PBS. On the contrary, similar values are found for samples that are fresh, cooled, or submerged in formalin.

Discussion and Conclusion

It is shown that protocols affect the results. To measure the parameters, it is recommended 1) to use only fresh samples and perform the measurements at 37°C, 2) to avoid sample holders that deform samples, 3) to minimize submersion time to reduce absorption effects, 4) to measure properties at each location separately and 5) to use thin and smooth samples. Results suggest that PBS is not suitable as a reference medium for measuring the density and that formalin may be an alternative.



Fig. 1 (left) Comparison of the measured values for the speed of sound in fat, skin and glandular tissue with literature values. (right) Mass density as a function of mass sample for fat, glandular tissue, nipple, skin and tumour. The overview also shows the effect of submerging the samples in PBS or formalin and of cooling the samples in a refrigerator. The dotted line connects identical samples which are measured twice; i.e. fresh and after 24 hours.

The USCT reference data base

N. Ruiter¹, M. Zapf¹, T. Hopp¹, H. Gemmeke¹, K. van Dongen², J. Camacho³, J. Udias⁴, J. Herraiz⁴, M. Perez Liva⁴, C. Fritsch³, J. Cruza³

¹ Karlsruhe Institute of Technology

nicole.ruiter@kit.edu

² Delft University of Technology

³ Spanish National Research Council

⁴ Complutense University Madrid

Background, Motivation and Objective

Ultrasound Computer Tomography (USCT) is an emerging technology mostly aimed at breast cancer imaging. Following the idea of open science a USCT reference data base (http://ipeusctdb1.ipe.kit.edu/~usct/challenge/) is established with open and easy to use data and code interfaces. The aim is to promote and facilitate the exchange of available reconstruction algorithms and raw data sets from different USCT devices throughout the growing USCT community.

Material and Methods

Currently three systems with rather different transducer aperture and ultrasound frequency range provided raw data sets for the USCT data base: KIT's 3D Ultrasound Computer Tomography system (3D USCT), Delft Breast Ultrasound Scanner (DBUS) and Multimodal Ultrasound Breast Imaging System (MUBI). All data sets are provided with data access interface software. The source code is freely available and an issue tracker is provided at a Github repository. The materials of the USCT data base are provided using a free and open license, i.e. the BSD 3-clause license for code and data, allowing for free use and publication of results.

Results

As a result of the joint initiative, a data base has been set up. In addition, a kick-off event for the USCT data base took place at the USCT data challenge at SPIE Medical Imaging 2017. The aim of this event was to bring together experts from the USCT community to identify best practices, as well as to establish specifications for interfaces and to carry out a first comparison of reconstructed images. Six posters were presented and three detailed field reports of groups applying their reconstruction methods to the provided data were submitted. The challenge hosted a two-hour panel discussion, where the panelists and the audience discussed the experiences on applying the currently available datasets and future directions.

Discussion and Conclusion

We expect the data base to enable reproducible comparison of image reconstruction algorithms and USCT systems. It should establish user friendly and easy to use interfaces, standards and data formats between the different USCT systems and their reconstruction algorithms, software and data formats. Further challenges are planned, e.g. comparing the image quality and/or computational performance obtained by different algorithms. Finally, other groups are invited to join in and participate.



3D USCT



MUBI

Object Classification and Localization with an Airborne Ultrasound Imaging System

W. Tan¹, G. Erbacher¹, T. Steiner², N. Ruiter¹

¹ Karlsruhe Institute of Technology wei.tan@kit.edu
² Pepperl+Fuchs GmbH

Background, Motivation and Objective

An airborne ultrasound imaging system (ABUS) was developed at KIT for reflection tomography. The prototype system consists of sixteen ultrasonic transducers surrounding a region of interest (ROI) of defined shape with a diameter of 50 cm. The transducers have a center frequency of 200 kHz and a bandwidth of 20 kHz. The prototype aims to demonstrate possible industrial applications for object classification and localization with airborne ultrasound.

Material and Methods

ABUS can image multiple objects from multiple angles around the ROI in a single acquisition using synthetic aperture focusing technique (SAFT). Grating-lobe reduction is achieved with a sliding median filter. Challenges for automatic object segmentation are varying intensities of depicted object edges and acoustic shadowing, which causes incomplete objects in reconstructed images. A workflow for automatic object segmentation was developed, consisting of a multi-parameter SAFT reconstruction, object segmentation with local maxima detection, feature extraction, classification with a neural network and object localization using Generalized Hough Transform (GHT).

Results

The workflow was evaluated with six 3D printed objects of different sizes and shapes. Forty measurements were performed at discrete positions for each object in the ROI. The neural network was trained using Bayesian Regularization Backpropagation and achieved an accuracy of 95.4%. The localization accuracy was evaluated with a cylinder with an asymmetrical feature. A total of 60 measurements at discrete positions and angles were made. The localization with GHT achieved a position accuracy of 5 mm with a standard deviation of 2.7 mm. The angle accuracy was 2.8° with a standard deviation of 5.4° .

Discussion and Conclusion

The evaluation results showed a classification accuracy at 95.4% and a localization accuracy of 5 mm, which is smaller than the measured full width at half maximum of the point spread function of 1.5 cm. Further improvement by adding more transducers or applying a higher bandwidth could improve detection of object features smaller than 2 cm.



Cuboid imgular Prism

Elliptic cylinde linder 3

Fig. : Confusion matrix of the trained Neural

Network for the test objects





Fig. : Example of a multiple object classification and localization with ABUS