Medical acoustical array expertise at Delft University of Technology

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Introduction

The history of medical ultrasound dates back as far as the mid 30s, first as a therapeutic tool (e.g. deep tissue heating) and a decade later as a diagnostic tool. Nowadays, a majority of all medical imaging modalities are based on ultrasound as the technique is in most cases non-invasive, harmless and relatively cheap and results in high image quality.

One way of improving the image quality is by using array technology, i.e. a large number of elements (preferably smaller than a wavelength) are positioned either in a single line (1-D array) or on a surface (2-D array). By using curved arrays or by applying a predefined time delay to the signal, either electronically or on the measured data, it is feasible to focus or steer the beam to a specific region. Next, pulse-echo or tomographic measurements are made to scan the region of interest.

In many cases, images are formed by displaying successive A-scans (the measured reflected signal is plotted in gray scale as a function of time). Measuring a sequence of A-scans along a line is called a B-scan. This results in scanning a plane that can be viewed as a 2-D image. Alternatively, M-mode images (M stands for motion) are made. In M-mode a rapid sequence of A-scans at a single position are made and displayed such that they follow each other sequently on a screen. This enables a physician to see and measure the range of a motion of e.g. an artery, as the organ boundaries that produce the reflections move relative to the probe. Finally, ultrasound can be used in Doppler mode to measure e.g. the blood flow in carotid arteries.

At the TU Delft in the section Acoustical Imaging and Sound Control we apply array technology in various medical acoustical applications. Here, it is used for its high spatial accuracy (the locations of all transducers are well defined) and to acquire large independent datasets simultaneously. In this way, it becomes feasible to predict precisely the generated acoustic wave field (e.g. for hyperthermia breast cancer treatment), to steer and focus the acoustic beam with high precision (e.g. transesophageal echocardiography (TEE)) or to apply inversion algorithms in order to both localize and characterize tumors (e.g. breast cancer detection) or plaque in arteries (intravascular ultrasound).

Echocardiography

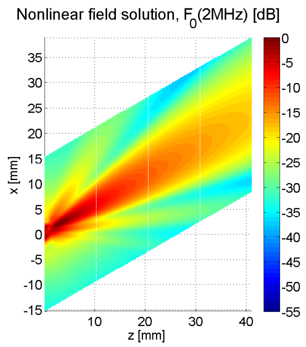
Echocardiography is used to display the hearts valves and chambers and their movements. For TEE the probe is positioned in the esophagus, on the contrary to Transthoracic Echocardiography (TTE) where the probe is positioned on the chest or abdominal wall. As a result of positioning the probe in the esophagus, TEE results in better image quality than images obtained from TTE. The main reason for this is that with TEE the probe is nearby the heart and that there are no lungs or ribs interfering with the ultrasound wave.

In order to make a full 3-D scan of the heart the acoustic beam has to be steered in several directions. This steering can be done mechanically or electronically. In the first case, a linear phased array is rotated resulting in a sequence of successive B-scans of the heart. In the second case a 2-D matrix is used. Phase delays are applied on the signals going to each element of the matrix transducer to sweep the beam through the heart and to obtain a full 3-D scan of the heart. This beam steering can be done both in transmission and reception, resulting in a large number of elements for both the transmitter and receiver.

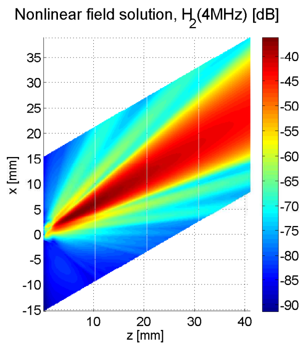
One of the drawbacks of using a matrix transducer is the formation of side lobes and grating lobes, due to the finite size of a transducer element and the discrete aperture (phased array) of the transducer. The position of these lobes is frequency dependent. Removing these lobes further improves the image quality. One method of reducing the effect of side lobes is to use different frequencies for transmission and reception by taking advantage of nonlinear acoustics [2, 3]. In nonlinear acoustics, the speed of sound of the medium changes under influence of the propagating pressure wave, resulting in the formation of higher harmonics. This is clearly visible in Figure 1. Here we have used the lossless Westervelt equation to model [4] explicitly the effect of nonlinear acoustics on a transmitted acoustic field at 2 MHz (Figure 1(a)) with high enough amplitude to generate a 4 MHz second harmonic wave field (Figure 1(b)).

Next we investigate the sensitivity of the transducer in receiving mode. This is done by computing the wave field generated by the transducer when it would transmit a 4 MHz wave field. In this case the fundamental wave field looks like Figure 1(c).

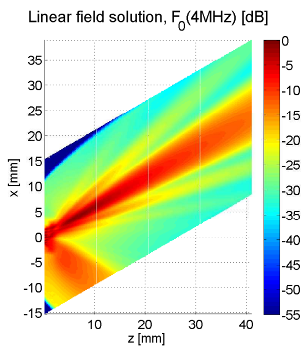
Consequently, the resulting sensitivity of the system at 4 MHz, as shown in Figure 1(d), is obtained by taking the product of the second harmonic radiation pattern with the radiation pattern of a 4 MHz transducer. Note that the side and grating lobes have disappeared. These results have been obtained with the iterative nonlinear contrast source (INCS) method [4], which is based on the



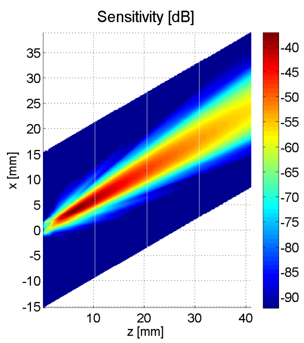
(a) $F_0(2\,MHz)$



(b) $H_2(4\,MHz)$



(c) $F_0(4\,MHz)$



(d) $H_2(4\,MHz)$
$\times\, F_0(4\,MHz)$

Figure 1: The nonlinear acoustic wave fields are computed with the INCS method. Grating and side lobes caused by a 1D linear array containing ten elements of size 0.20×3 mm^2 and a kerf of 0.11 mm are suppressed by using nonlinear acoustics. The effect of side lobes visible in (a), (b) and (c) is clearly diminished in the effective sensitivity function of the transducer (d).

Westervelt equation and is used to predict the nonlinear acoustic wave propagation.

Intravascular Ultrasound

Atherosclerosis is a disease causing hardening and narrowing of the artery due to the formation of plaque in the intima of the artery. The core of this plaque is an accumulation of soft, flaky, yellowish material with cholesterol crystals and giant cells and is referred to as atheroma. The atheroma is isolated from the lumen via a fibrous cap. Eventually, atherosclerosis might give rise to two problems. First, the atheromatous plaques may rupture and the resulting clots cause (partial) occlusion of the lumen leading to a shortage of oxygen rich blood in vital parts of the body (heart, brain, etc.). Second, the process of remodeling (the process of enlarging the artery to compensate for the narrowing of the lumen) may result in an aneurysm.

A well known method to localize stenosis is angiography, where X-ray is used to visualize the inner opening of blood filled structures. Unfortunately, these images can

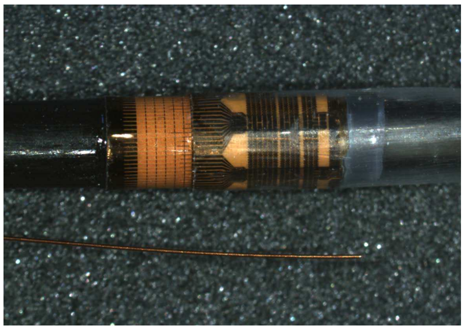


Figure 2: A photo of a commercial available IVUS catheter (Volcano) with a circular array (copper colour) containing over 60 elements. A wire with a diameter of 120 μm has been placed next to the catheter for reference.

be misleading. As the images are only a two dimensional projection of the lumen, the formation of vasa vasorum and/or remodeling might suggest that the lumen is wide open while in reality this is not the case.

To overcome the problems of angiography, research is conducted in the area of intravascular ultrasound (IVUS) to image the anatomy of arteries from inside out. The probing acoustic signal typically has a center frequency in the range of 10 to 40 MHz and is transmitted by specially designed piezoelectric transducers positioned within arteries. Several types of transducers are commercially available, varying from single element to circular arrays, see Figure 2. During a pullback of the catheter, the single-element transducer is rotated in order to obtain images of the arterial wall in the cross-sectional plane. With circular array technology, where as many as 64 transducers are used, sequences of radio frequency (RF) frames containing up to 512 RF-lines in the cross-sectional plane are obtained by using synthetic aperture focusing techniques. In this way, problems with non-uniform rotation velocities are avoided.

Current research on IVUS is to establish IVUS as a technique to detect, visualize and characterize vulnerable plaque. One detection method is based on strain computations, where Finite Element Modeling has shown that high strain values indicate the presence of soft atheroma. These strain images are obtained from the speckle present in the acoustic data. By employing cross-correlation techniques on the RF signal, shifts in the location of speckle caused by a controlled force (e.g. a small balloon positioned inside the artery) or by a physiological force (e.g. cardiac motion) are related to the compression and/or displacement of tissue. In literature, this is referred to as elastography or palpography. Note that palpography is derived from elastography and refers to the situation where only radial strain in the innermost layer of an artery is measured. This strain is measured by cross-correlating successive RF-frames measured at a 'fixed' position in the artery during the most stable (static) phase of the cardiac cycle.

To improve the characterization of the vulnerable plaque, synthetic aperture focusing (SAFT) and Kirchhoff imaging techniques are developed. With these techniques,

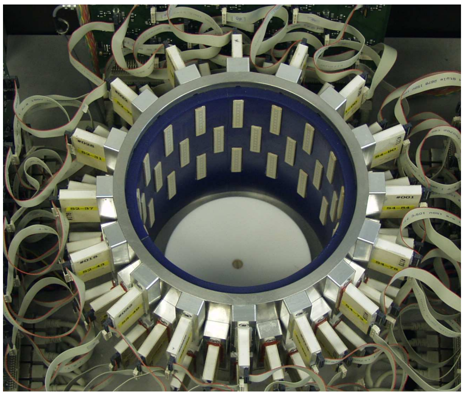


Figure 3: Ultrasound breast cancer scanner developed by Forschungszentrum Karlsruhe (courtesy of Forschungszentrum Karlsruhe).

reflection data is used to image the interfaces between the various contrasts. This method has been implemented for the angular direction [8, 9, 10] for some commercially available transducers. Despite the fact that focusing in the angular direction has become standard practice, these methods have not yet been applied in the axial direction.

The main reason for not applying in the axial direction is that there is too much catheter motion to combine successive cross-sectional measurements. In general, two types of motions are considered; *i)* in-plane motion, referring to movements in the cross-sectional plane such as rotation and translation and *ii)* out-of-plane motion, which occur in the axial direction of the artery. Preliminary results based on cross-correlation techniques suggest that the motions in the cross-sectional plane of the artery are in the order of 28^o and one millimeter. These are mainly cardiac and respiratory motions, and in minor detail caused by fluctuations in the blood flow and the pressure during the cardiac cycle. Out-of-plane motion is especially observed during the systolic phase and is minimal during the end-diastolic phase. Currently, the out-of-plane motions are neglected and only corrections for in-plane motions are made. To minimize the out-of-plane motions, ECG are used to select only those measurements which take place at the same moment in the cardiac cycle. In addition, it is assumed that these motions are based on non-curved motions in the circular domain while in reality these motions are curved. Consequently, it is expected that the results obtained with SAFT can be improved by taking both out-of-plane motions and curved in-plane motions into account.

Breast Cancer Detection

One application of medical ultrasound is breast cancer detection. In the Netherlands, one out of every nine women gets breast cancer [1]. In order to reduce the mortality rate, a nation wide screening program exists using mammography. In order to overcome the limitations of mammography it is investigated if ultrasound can form an alternative.

Currently, hand-held ultrasound scanning systems are mostly used to evaluate breast abnormalities that are found with e.g. mammography. These systems make B-scans of the breast. However, precise information about the acoustic medium parameters, essential for discriminating a benign from a malignant tumor, can not be obtained.

Obtaining these acoustic medium parameters requires the usage of acoustic wave field theory. The unknown 3-D speed of sound and attenuation profiles of the breast can be obtained by formulating integral equations, which describe the acoustic scattering problem, and successively solve them for known measured scattered wave fields using e.g. contrast source inversion techniques [5, 6]. The Forschungszentrum Karlsruhe, Germany, has built a scanner that makes the measurements required for these imaging techniques, see Figure 3. These high precision reproducible measurements can only be obtained by making use of array technology. Consequently, the system uses 384 emitting and 1536 receiving transducers positioned in the circular cylindrical surface of the scanning system. The research performed at the TU Delft aims at developing computational efficient solution schemes to solving these integral equations for large number of unknowns using the large number of independent array measurements performed by the Forschungszentrum Karlsruhe.

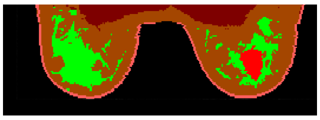
Hyperthermia Breast Cancer Treatment

Breast cancer is usually treated with surgery, radiotherapy and chemotherapy. Fever-range hyperthermia treatment (HT) enhances the effect of radiotherapy and chemotherapy. Electromagnetic (EM) radiation is commonly used, however there is an increasing interest in using ultrasound (US) due to better penetration depth and focusing capabilities. An adequate applicator for fever-range HT treatment of tumors in the entire intact breast region is not yet available. At the TU Delft in collaboration with the Hyperthermia Unit of the Erasmus MC-Daniel den Hoed Cancer Center a theoretical design and characterization of an ultrasound cylindrical phased-array applicator has been made [7].

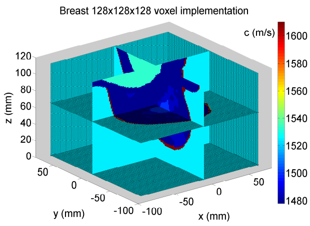
The design is based on breast models constructed from CT and MRI scans of breasts, see Figure 4. The models contain either a real tumor in the central part or an artificial tumor in the thorax site of the breast. A linear acoustic wave-field model has been used to compute total pressure fields and specific absorption rate (SAR) patterns. Design parameters such as frequency, number of transducers per ring, ring distance and number of rings have been optimized to obtain the smallest possible primary focus, while suppressing secondary foci. The SAR patterns obtained for the applicator have been converted in thermal distributions as shown in Figure 4(d), using a thermal model that is based on the Pennes Bio Heat equation.

The research resulted in a design for an ultrasound circular cylindrical phased-array containing 6×32 elements. The distance between the first and the sixth equally

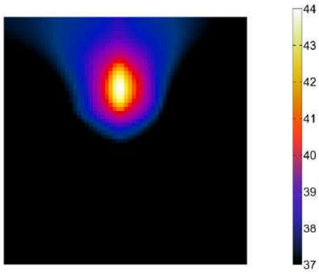
(a) MRI scan of breast



(b) Tissue segmentation showing the tumor in red



(c) 3D speed of sound profile of breast



(d) Temperature profile

(e) Circular cylindrical array

Figure 4: An MRI-based breast model (a) is segmentatized (b) and used to obtain a speed of sound profile (c). This profile, combined with an attenuation profile, is used to model temperature profiles (d) obtained during hyperthermia treatment using a circular cylindrical array (e).

spaced transducer ring equals 66 mm. Operating the transducers at a frequency of 100 kHz results in a small ellipsoid SAR focus ($5 \times 5 \times 15$ mm^3) in breasts. By changing the phase of the individual transducer elements the focus can be steered to any location. Maximum temperatures of 44^{o}C in the tumor are achieved, without affecting the surrounding healthy tissues.

Conclusion

Array technology is a strong tool to acquire in a time-efficient way reflection and tomographic data with high (both spatial and temporal) accuracy. In this way it becomes feasible to use the acoustic wave equations as a starting point for the development of algorithms for localizing and characterizing e.g. breast tumors and vulnerable plaque in arteries. In addition, array technology can be used for steering and focusing acoustic wave fields. This steering and focusing is modeled excellent for both linear and nonlinear acoustics. Consequently, it becomes feasible to design novel matrix transducers for echocardiography and circular cylindrical arrays for breast cancer treatment.

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