Conclusions from a test of multi-modal ultrasound tomography research system designed for breast imaging

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Summary
Today, considering global development of digital technology, experts not only strive to perfect methods of conventional ultrasound echographic imaging of tissue structure (US), but also intensively develop other methods, focusing especially on ultrasound transmission tomography (UTT) (analogous to X-ray computed tomography - CT) and reflection tomography (URT) (based on synthetic aperture method used in radar imaging). The two techniques combined with conventional echographic imaging can be used together in a specialized hybrid ultrasonic tomograph. The device scans the examined tissue, which is submerged in water, from all the angles around it, using a circular array of elementary piezoceramic transducers that are evenly arranged on the inner side of the array. This multi-modal tomographic imaging can be successfully used for early detection and diagnosis of malignant lesions in women’s breast tissue. This study presents and analyses the results of ultrasound tomography imaging of the internal structure of biological media and their phantoms using an ultrasound computer tomography research system. The obtained results show that, after the scanning process is accelerated making it possible to perform in vivo examinations, the developed method of multi-modal ultrasonic tomographic measurements of breast tissue can successfully be used to detect and diagnose focal lesions in women's breasts.

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1. Introduction
Statistically, breast cancer is the first in morbidity in female population, being also in the first place as the cause of death. There is no doubt that the development of new methods for early diagnosis of breast cancer in order to improve the chance of successful treatment and the survival rate is a matter of great importance. Currently, ultrasound transmission and reflection tomography methods [1,2,3] which use ultrasonic waves at frequencies close to those used in conventional B-mode ultrasonic scanners are alternatives to mammography and breast ultrasound examination. The authors have developed the multi-modal ultrasound tomography (MUT) system in cooperation with DRAMIŃSKI S.A. (manufacturer of medical devices) [4,5]. The device is designed for the diagnosis of lesions in the female breast in vivo with the capability of obtaining two- and three-dimensional images of breast tissue in three different modalities using: ultrasound transmission tomography (UTT), ultrasound reflection tomography (URT) [1,2,3], real-time ultrasonography (US) and full angle spatial compound imaging (FASCI) [3,6,7]. The device is the only solution in Poland and one of a few similar solutions worldwide [4,5,8-11]. Breast examination using ultrasound tomography can complement or replace the standard mammography and breast ultrasonography, and, most importantly, contribute to correctly diagnosing and characterizing the detected lesions for cancer malignancy and risks associated with their development. These studies should lead to the reduction of invasive breast tissue biopsies. It is possible to use such examinations in screening and prevention. There are no restrictions related to the patient population due to harmlessness, the use of non-invasive ultrasonic waves and a short examination time. The only limitation may only be too flat a breast which
prevents measuring or too large one which does not fit in the ultrasonic array ring. This study presents and analyses the results of ultrasound tomography imaging of the internal structure of biological media and their phantoms using an ultrasound computer tomography research system.

2. Materials and Methods

The diagram of a multi-modal ultrasonic tomograph is shown in Figure 1.

![Figure 1. The diagram of a multi-modal ultrasonic tomograph.](image)

The main element of the device is a circular ultrasonic array consisting of 1024 piezoceramic transducers which are evenly distributed on the inner side of the ring with a diameter of about 260 mm [12]. Figure 2 shows the general construction of such an array (very similar to standard linear ultrasonic arrays) [13].

![Figure 2. General construction of the ring of 1024-element circular ultrasonic array without housing.](image)

Elementary piezoelectric transducers in the array operate on thickness vibrations at the frequency of about 2 MHz and have the shape of thin and high columns. They are arranged close to each other at small distances and supported at both longer ends in corresponding slots of flat PCB rings. The PCBs are distanced in parallel and allow leading the electrodes through the paths specially etched on their surfaces. The structure of fixing plates with transducers is filled in the rear with an appropriate load which broadens the transducer resonance bandwidth and suppresses energy which is radiated backwards. The frontal surface of transducers is coated with a thin layer (or several layers) of material that matches the acoustic impedance of piezoceramics to that of soft tissue. This layer is also protective due to the long-term operation of the transducers in an aquatic environment. A hermetically enclosed array is placed in a container of distilled water on a special rack that allows its mechanical travel with a small stroke vertically, along the overhanging breast (Fig. 3). This allows for a quick scan of the breast structure surrounded by the ring of transducers in many coronal sections.

![Figure 3. View of a circular array of ultrasonic transducers installed in the ultrasonic tomography scanner.](image)

Electronic data acquisition system enables the stimulation of vibration of individual array transducers and measurement data collection in the form of parameters of ultrasonic waves permeating through the structure of breast tissue and reflecting on its heterogeneities. Collected sets of measurements are reconstructed using a computer and visualized as images of local distributions of acoustic parameters in the structure of breast tissue examined. The electronic control system synchronized with the data acquisition system controls the measurement process, array movement, filling and emptying containers with water, water heating and temperature stabilization using valves, pumps, and water level and temperature sensors. The whole measurement process is supervised by a computer with appropriate software. Properly protected electronic systems are located under the patient’s bed which is placed directly above the measuring container on a rigid frame. The bed features a hole where the patient lying on her stomach puts the examined breast in water in the area of the array ring (Fig. 1, Fig. 3).

3. Measurement Results

Using the developed multi-modal ultrasound tomography scanner we have performed, inter alia,
cross-sectional imaging of: the chicken egg which was hard-boiled and stripped of a shell, the breast biopsy phantom CIRS Model 059 [4], and a wire sample. Such objects were chosen for measurements due to the knowledge of their structure and the ability to obtain reference section images using other methods. Figure 4 shows the image in the colors of the rainbow containing the distribution of local values of ultrasound speed in a longitudinal section of the tested chicken egg obtained after reconstruction using UTT.

Figure 4. UTT image of the distribution of local values of ultrasound speed in a longitudinal section of the tested chicken egg.

Figure 5 shows the UTT image of the distribution of local values of ultrasound attenuation in the same section of the tested egg.

Figure 5. UTT image of the distribution of local values of ultrasound attenuation in a longitudinal section of the tested chicken egg.

Figure 6 shows the image in the colors of the rainbow containing the distribution of local values of ultrasound speed in a coronal section of the tested breast phantom obtained after reconstruction using UTT.

Figure 6. UTT image of the distribution of local values of ultrasound speed in a coronal section of the tested breast phantom.

Figure 7 shows the UTT image of the distribution of local values of ultrasound attenuation in the same section of the tested breast phantom.

Figure 7. UTT image of the distribution of local values of ultrasound attenuation in a coronal section of the tested breast phantom.

Figure 8 shows the image in the colors of the rainbow containing section of the wire sample obtained after reconstruction using URT.

Figure 8. UTT image of the distribution of local values of ultrasound speed in a coronal section of the tested breast phantom.
The distribution of pixel values in the selected image lines along the x axis (image centre in the coordinate system centre), passing through the characteristic structures of the tested object sections was drawn in all tomographic images presented (Fig. 4 - 8).

4. Discussion and Conclusions

UTT image of the distribution of local values of ultrasound speed in the section of the tested chicken egg (Fig. 4) is quantitative, allowing for the differentiation between continuous and leap changes. The standard deviation of ultrasound speed measurements in distilled water around the egg (away from its edge), estimated based on a sinogram [1,2] in this case was about 0.06 m/s. One should take into account that the egg section measurement time was about 12 minutes, which caused some instability of measurement conditions: temperature changes (about 22.8 ± 0.2 °C) and the movement of liquid layers, affecting the certainty of the measurements. Moreover, no corrections were applied in this case related to the location of transducers in the ring array and the varied effectiveness and sensitivity. Standard deviation of local speed values of ultrasound in water, away from the egg edge (Fig. 4), reconstructed on the basis of such measurements, is about 1 m/s, and the average ultrasound speed in water is about 1490.5 m/s. Precise calculations show that this speed value in distilled water occurs at a temperature of 22.744 °C [14]. The egg section image clearly shows visible heterogeneous structure of the yolk ($c \approx 1495 - 1502$ m/s) and white ($c \approx 1510 - 1513$ m/s). The ultrasound speed in the boiled chicken egg structure shows some degree of variability depending on their thermal history as a result of temperature hysteresis protein networks [15]; the values obtained are in line with expectations. Egg yolk boundary is fuzzy, and a narrow area of substantially increased ultrasound speed in white and slightly decreased in water is visible at the border of the egg section (white/water). These are artefacts caused by refraction and multiple paths of the ultrasonic wave beam rays, as well as the diffraction of wave on curved boundaries of heterogeneity areas (wavelength $\lambda \approx 0.75$ mm) [14,16]. UTT image of local distribution of ultrasound attenuation in the egg section (Fig. 5) is both quantitative and qualitative, allowing for the differentiation of leap changes (most of all) and visualisation of the boundaries of heterogeneous areas. Significant errors in the reconstructed attenuation values (e.g., negative values) occur in connection with the measurement of input projection values as the maximum of the transmitted pulse, which is highly influenced by diffraction and refraction of the ultrasonic wave. Multiple paths of rays of ultrasonic wave beam due to refraction (pulse interference) cause the image to have multiplied boundaries of heterogeneous areas (e.g., ellipses in the water outside the structure of the egg section – see Fig. 5). However, the transmission image of ultrasound attenuation distribution (Fig. 5) is an excellent complement to ultrasound speed distribution (Fig. 4), as the heterogeneous structure of white and yolk in the egg is clearly visible here: the nucleus of pander, germinal disc area, yellow yolk, white yolk, outer thin white, inner thick white (compare Fig. 5 with Fig. 9).
The quantitative UTT image of the distribution of local ultrasound speed values in the tested phantom breast section (Fig. 6) allows for identifying several inclusions of different sizes, with fuzzy boundaries, which differ from the ultrasound speed in the surrounding gel by about 12 m/s. Furthermore, reduction of the ultrasound speed in phantom sectional area close to the boundary with water as the result of water penetration into its structure (Fig. 6) is visible. The standard deviation of ultrasound speed measurements in distilled water around the breast phantom (away from its edge) estimated using a sinogram [1,2] was about 0.04 m/s in this case. The measurement time for the phantom section was approximately 12 minutes, resulting in the instability of measurement conditions: temperature changes (approximately $22.8 \pm 0.2$ °C) and the movement of liquid layers, affecting the certainty of the measurements. Corrections were applied in this case related to the location of transducers in the ring array and the varied effectiveness and sensitivity using calibration measurements in distilled water at the fixed temperature. Standard deviation of local speed values of ultrasound in water, away from the phantom edge (Fig. 6) reconstructed on the basis of such measurements, is about 0.4 m/s, the average ultrasound speed in water is about 1490.6 m/s, in the phantom gel it is 1503 – 1510 m/s, and 1515 – 1522 m/s in inclusions. It should be noted that the CIRS Model 059 breast phantom is designed for exercises in biopsy with elastography, hence heterogeneities in the structure of the phantom are not visible by means of ultrasound B-mode imaging due to the lack of diversity in acoustic impedance of inclusions relative to the surrounding gel [4]. The UTT image of the distribution of local values of ultrasound attenuation in a coronal section of the tested breast phantom (Fig. 7) shows the boundaries of heterogeneity. Artefacts in UTT images of the breast phantom section caused by refraction are less evident here than in the images of the egg section due to less differentiation in ultrasound speed in phantom gel as compared to water [14,16]. In order to get a reference of the tested breast phantom section structure, the imaging was done using the CT dual-energy protocol: 80 keV and 140 keV [4,17]. CT images of the CIRS Model 059 breast phantom structure reconstructed from direct measurements using energy 80 keV or 140 keV, did not allow to recognize heterogeneous areas. However, inclusions in the phantom gel could be visualized on secondary reconstruction images obtained in dual-energy CT examination at the virtual energy level of 40 keV. The layer thickness was 0.625 mm. Heterogeneities in the CT image are poorly visible in contrast to the phantom gel, and their edges are sharp (Fig. 10). In UTT images, heterogeneities are well visible, however there are slightly more of them due to poorer vertical resolution (about 5 mm) which results in averaging of section images for a relatively thick layer and the highlighting heterogeneities in other sections (compare Fig. 6 and Fig. 7 with Fig. 10).

Figure 10. A reference CT image of the tested phantom breast section.

URT image of the wire sample section shows structures which reflect ultrasonic waves well and at a high resolution (Fig. 8), which in the case of breast examination should allow for visualization of the vasculature of a tumour. Figure 11 shows the view of the tested wire sample.

Figure 11. View of the tested wire sample.
The URT image shows the differentiation of even small changes in the diameter of individual wires of the sample (compare Fig. 8 with Fig. 11).

Images of sections of tested biological structures and phantoms obtained using a developed multi-modal ultrasonic tomograph demonstrate its extensive diagnostic capabilities. Image vertical resolution can be significantly improved using electronic or mechanical focusing. The device is now being improved in order to speed up section measurements to about 1 s, which will allow for the acquisition of tomographic measurements and reconstruction of images of about 200 coronal sections of the whole breast in a few minutes. In this way, this multi-modal tomographic imaging can be successfully used for early detection and diagnosis of malignant lesions in women’s breast tissue in vivo.

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References