PAN
ARCHIVES OF ACOUSTICS
Vol. **44**, No. 4, pp. 645–657 (2019)
DOI: 10.24425/aoa.2019.129723

Analysis of Using Multi-Angle Conventional Ultrasound Scanning for Efficient 3-D Object Imaging

Maciej SABINIOK, Krzysztof J. OPIELIŃSKI, Sylwia LIS

Department of Acoustics and Multimedia
Faculty of Electronics
Wroclaw University of Science and Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
e-mail: maciej.sabiniok@pwr.edu.pl, syladalis@gmail.com
*Corresponding Author e-mail: krzysztof.opielinski@pwr.edu.pl

(*received April 23, 2019; accepted September 25, 2019*)

The purpose of this work is to examine the possibility of using multi-angle conventional ultrasound B-mode scanning in efficient 3-D imaging. In the paper, the volume of an object is reconstructed from vertical projections registered at fixed angular positions of the multi-element linear ultrasonic probe rotated in relation to the object submerged in water. The possible configurations are: vertical lateral, vertical top or vertical bottom. In the vertical lateral configuration, the ultrasonic probe acquires 2-D images of object's vertical cross-sections, turning around its lateral surface. In the vertical top or bottom configuration, the ultrasonic probe acquires 2-D images of the object's vertical cross-sections, turning on the horizontal plane over the top or under the bottom surface of the object.

The method of recording 3-D volume of an object's structure and reconstruction algorithm have been designed. Studies show the method in the vertical top or bottom configuration could be successfully applied to the effective 3-D visualisation of the structure of the female breast *in vivo* as the new complement ultrasonic imaging modality in the prototype of the developed ultrasound tomography scanner.

Keywords: ultrasonic imaging; multi-angle scanning; efficient 3-D imaging; ultrasound tomography.

1. Introduction

Ultrasound tomography (UT) scanning is the novel and dynamically developed imaging technique of the *in vivo* female breast examination. The method is considered to be a near future challenge in breast cancer detection using ultrasound (Duric *et al.*, 2014; Iuanow *et al.*, 2017; Opieliński *et al.*, 2018b; Jaglan *et al.*, 2019). There is a number of benefits from using ultrasound for imaging of the biological structure of the female breast as a complement to the X-ray mammography (MMG) and magnetic resonance imaging (MRI) (Hooley *et al.*, 2013; Opieliński *et al.*, 2018a; Burgess, O'Neal, 2019). The use of ultrasound as diagnostic modalities in early detection of neoplastic lesions in breasts is especially useful and recommended for the women with a dense breast tissue where the mammography may not give satisfactory imaging results (Okello *et al.*, 2014; Freer, 2015).

One of the few advanced prototypes of the ultrasound tomography devices has been developed in Poland by the DRAMIŃSKI S.A. company in cooperation with the scientists from the Department of Acoustics and Multimedia of the Faculty of Electronics at the Wroclaw University of Science and Technology (Opieliński *et al.*, 2018a). The device employs ultrasound transmission and reflection tomography modalities (UTT, URT) for biological structure imaging and the surround mode of the conventional ultrasound echography (US). The US modality is used as complement ultrasonic imaging method to the UTT and URT modalities. This approach provides comprehensive diagnostic information about the tissue under the examination. It should be noted that additional modality of conventional ultrasound B-mode imaging of a breast in tomography scanner is very desirable by doctors as the well-known diagnosis pattern. The fusion of UTT and URT images enables automatic detection of pathological changes of the breast along with the quantitative estimation of their malignancy (Opieliński *et al.*, 2018b). However, the diagnosis of an experienced doctor with a reference to B-mode modality image is needed in cases of ambiguity (e.g. very small and dense breast). UTT and URT images are a barely researched type of visualization for the structure of breast tissue. They represent the structure differently than standard images created with the currently used diagnostic devices: ultrasound B-mode scanners, X-ray mammography scanners or magnetic resonance imaging. The clinical significance of ultrasound tomography imaging of female breast has not been well documented. No database containing ultrasound breast tomograms is available, no atlases or medical manuals describe the diagnostic approach. Only about a dozen publications present the cases of clinical *in vivo* examinations of women's breast with the use of single unique ultrasound tomography scanners. These reported cases are mainly the examinations performed in recent years by several research centers involved in developing the prototype.

Several US scanning methods can be used by means of the specially designed ultrasound tomography multi-element ring array (Opieliński, 2014; Staszewski *et al.*, 2018), which are analogous to those used in conventional ultrasound B-mode scanners: linear sequenced scanning (Fig. 1a), linear phased (steered) scanning (Fig. 1b), vector linear scanning (so-called virtual convex – Fig. 1c).

Sectoral images obtained by linear sequenced scanning (Fig. 1a) have the shape of the pie (section of the circle) and are compounded in a flat coronal section by simply adding one image to the edge of the other one.

Sectoral images obtained by linear phased scanning (Fig. 1b) or vector linear sequenced scanning (Fig. 1c) are overlapped with each other by the Full Angle Spatial Compound Imaging (FASCI) method. Overlapped regions of images are averaged by intensity in one plane (Opieliński, 2014) resulting in one 2-D coronal section layer (Fig. 2). Subsequently, the individual 2-D coronal sections of a biological structure can be assembled into a 3-D image. The linear phased scanning using ultrasound tomography ring array (Fig. 1b) and the FASCI method are currently applied in the ultrasound tomography scanner prototype developed in Poland. It involves obtaining each coronal section of an object by acquiring sectoral images from many multi-element ultrasonic subarrays (Fig. 2).

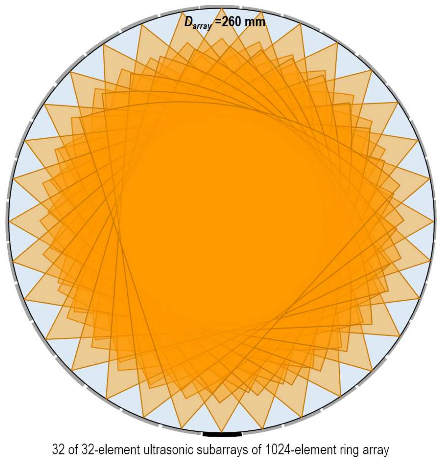

Fig. 2. Illustration of the FASCI reconstruction scheme of 2-D coronal section image using sectoral images obtained by linear phased scanning with ultrasound tomography multi-element ring array.

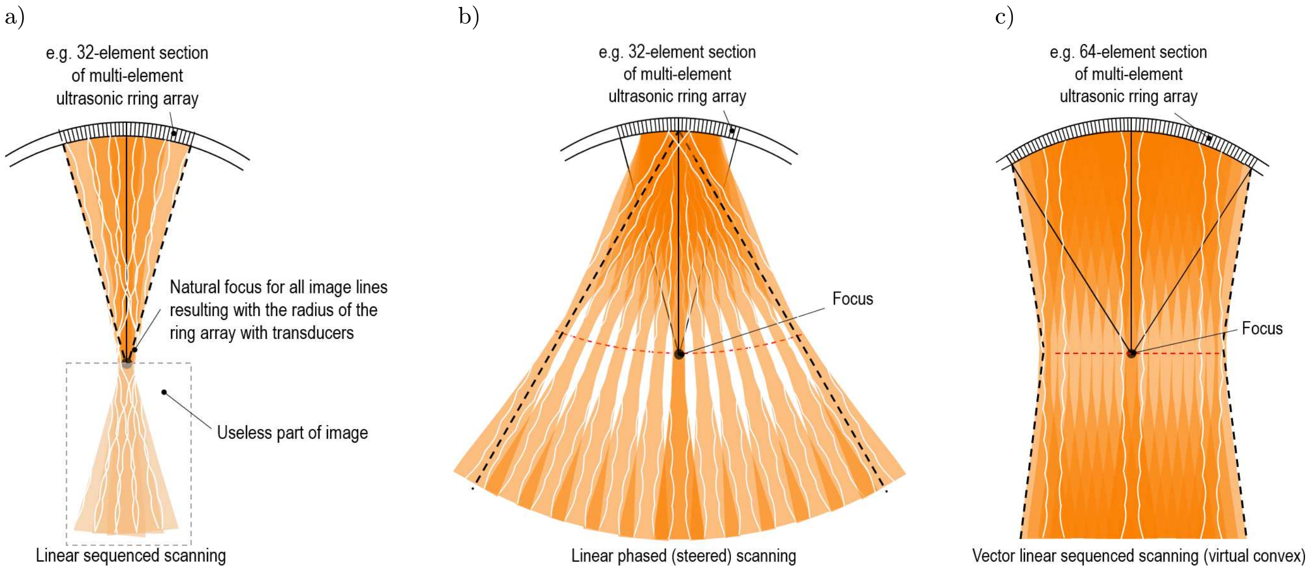

Fig. 1. US scanning methods which can be used by means of the specially designed ultrasound tomography multi-element ring array: a) linear sequenced scanning, b) linear phased (steered) scanning, c) vector linear scanning (so-called virtual convex).

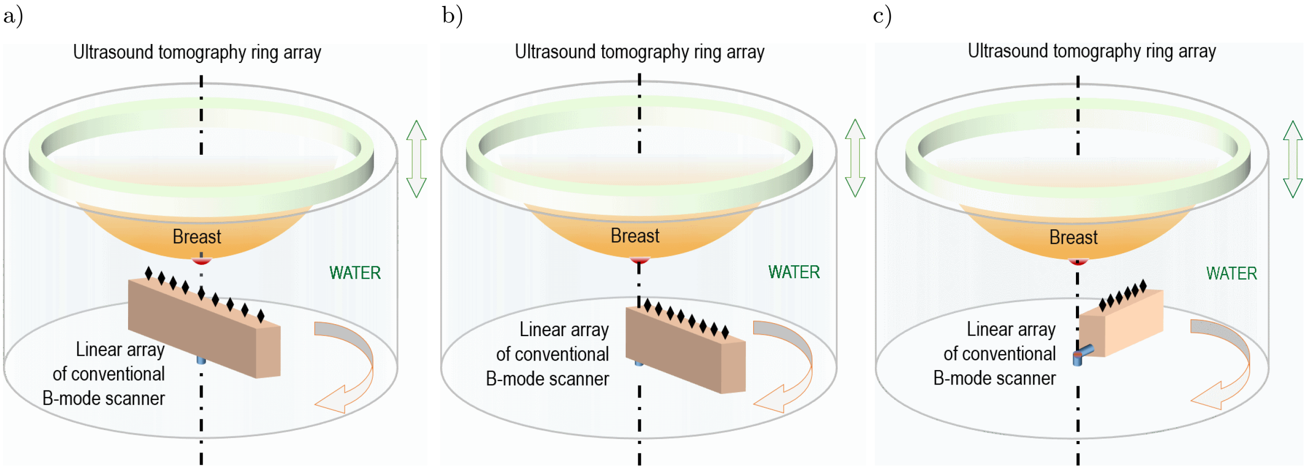

Fig. 3. Different multi-angle conventional ultrasound B-mode imaging (MACUI) methods designed as additional modality of developed prototype of ultrasound tomography scanner for *in vivo* female breast diagnosis, as an alternative to the FASCI method: a) with center of the additional linear array in the rotation axis, b) with edge of the additional linear array in the rotation axis, c) with edge of the additional linear array outside of the rotation axis.

Despite the advantages of the applied FASCI method, the physics and scanning system configuration cause a significant limitation. They reduce the benefits from the use of such US modality as the supplement to the ultrasound transmission tomography (UTT) and ultrasound reflection tomography (URT) in the examination of the female breast *in vivo*. It is discussed further in the paper. Therefore, it is desirable to develop a better method of using conventional B-mode scanning than FASCI. The preliminary study on using the Multi-Angle Conventional Ultrasound Imaging (MACUI) method as an efficient, 3-D ultrasound imaging is presented in the paper. The method is considered as a possible alternative for the FASCI method to minimise its limitation and maximise benefits of using conventional US modality in examination procedure of a female breast *in vivo*. Advantages and shortcomings of the MACUI method comparing to the FASCI method have been analysed on the basis of results for different scanning configuration of the tissue phantoms submerged in the water (Fig. 3).

In this way it is possible to simultaneously acquire of the measurements of a breast tissue *in vivo* to reconstruct four 3-D images in different ultrasonic modalities: two transmission (UTTc, UTTα) and one reflection (URT) tomography imaging (Opieliński *et al.*, 2018a) together with one conventional ultrasound B-mode imaging (US) using the MACUI method.

2. Characteristics of the FASCI method

The FASCI method used in the developed prototype has several advantages that make its use convenient in the ultrasound tomography scanner. The transducer system of the device is arranged as the ring array of 1024 individual piezoelectric transducers, which are divided into multi-element subarrays. In such a system each echography image used for the FASCI is acquired with a single subarray. This enables the use of existing ultrasound tomography ring array and the accompanying electronic control system to conduct additional B-mode ultrasound scanning. Theoretically calculated time of the measurement for a single FASCI coronal slice is around 2–3 seconds. This time can be obtained based on the minimal ultrasonic pulse repetition time required, when the diameter of the ring (260 mm), the optimal number of transducers in the subarray and the sound velocity in the breast tissue are taken into account. The analysis of calculation results of the acoustic field distribution inside the ultrasonic ring array (Staszewski *et al.*, 2018) allows us to conclude that the optimal number of transducers in a sector to obtain ultrasonic images using linear phased scanning (Fig. 1b) is $32 \leq n \leq 128$. We can obtain the shortest scanning time for $n = 32$. This provides the system with fast-enough examination to be practically useful. The low 2 MHz resonant frequency used in the transducer ring array allows long-range ultrasound imaging due to reasonably low attenuation in the breast tissue (Opieliński, Gudra, 2016).

Despite the fact that FASCI carries the advantages corresponding to the system configuration, there are also some considerable limitations of the imaging quality for medical purposes. The insufficient transducer pitch causes grating lobes in the generated acoustic field (Staszewski *et al.*, 2018). Those grating lobes are hard to suppress and limit the lateral image resolution. In addition, the geometry of the system causes backscattering and reflection inside the ultrasonic transducer ring surface. In this case, image distortion, limited contrast resolution and further quality deterioration of the resulting image can

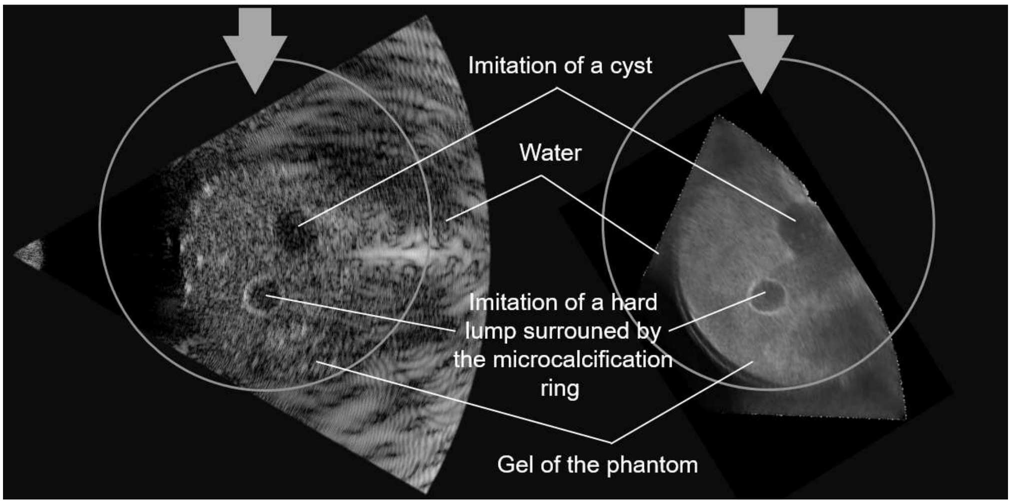

Fig. 4. Images of the same coronal section fragment of the Model B-MM – 1.2 Yezitronix breast phantom obtained by means of the 32-element subarray of the ultrasound tomography ring array (2 MHz) with linear phased mode scanning, and by means of the conventional linear array (7.5 MHz) of the SmartUs Telemed B-mode scanner with virtual convex scanning (courtesy of DRAMIŃSKI S.A. company).

be noticed in opposition to the advantage of possible long-range imaging. Moreover, the low resonant frequency of 2 MHz limits the axial and contrast resolution. The higher resonant frequency is desirable, because it gives better results for echography imaging (Fig. 4). However, it is impossible to apply in existing multi-element ring array, which is designed for UTT and URT scanning methods. Figure 4 presents the comparison between the sectoral images of the same coronal section fragment of the Model B-MM – 1.2 breast phantom (Yezitronix Group Inc. Automation & Control Industries Inc., 2017) obtained with use of the 32-element subarray of the ultrasound tomography 1024-element ring array (2 MHz) with linear phased mode scanning (Fig. 1b), and by means of the conventional linear array (7.5 MHz) of the SmartUs Telemed B-mode scanner with virtual convex scanning. Figure 5 presents the view of the Yezitronix's Model B-MM – 1.2 breast phantom. The Model B-MM – 1.2 of the multi-modal phantom is designed to image the breast internal structure using ultrasound (US), X-ray computed tomography (CT) and magnetic resonance imaging (MRI). It is intended to train fine-needle biopsy, for applications in robotics, imaging tests and demonstrations. The phantom mimics the female breast in shape, appearance, touch and acoustic properties. Multi-layer material for each tissue (fat, cysts or lesions) is independent and has its own characteristics defined by a real 3-D shape, gray level and mechanical properties. The phantom contains 2 imitations of cysts and 3 imitations of lump surrounded by a ring of microcalcifications. The base of the phantom is circular, with a diameter of 105 mm and height of 80 mm (Fig. 5).

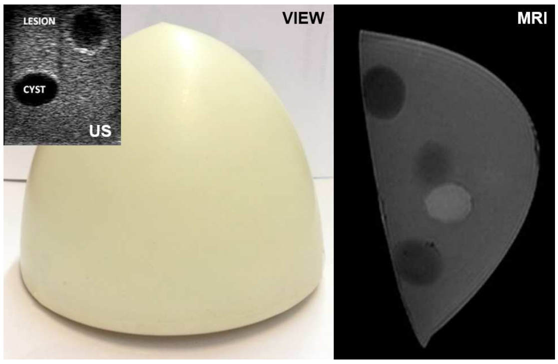

Fig. 5. Yezitronix's Model B-MM – 1.2 breast phantom: the view and exemplary cross-section images (US, MRI) provided by the manufacturer (http://www.yezitronix.com/page25.html).

Figure 6 presents the comparison between images obtained as above (Fig. 4), but after the FASCI reconstruction of 32 sectoral images acquired around the phantom (Fig. 2). It can be observed that different average ultrasound velocity in different direction generates the distortions of the object geometry after overlapping. Due to this fact, the ability to differentiate the borders of changes inside the tissue structure is reduced by the blurring effect on the edges resulting from such multi-image compounding (Fig. 2).

However, the significant improvement of the coronal 2-D image after compounding process can be noticed. This is caused by effective averaging and noise suppressing, as well as distortions reducing (cf. Fig. 4 with Fig. 6). However, it may not be sufficient in the case of imaging complex structure of a breast, because

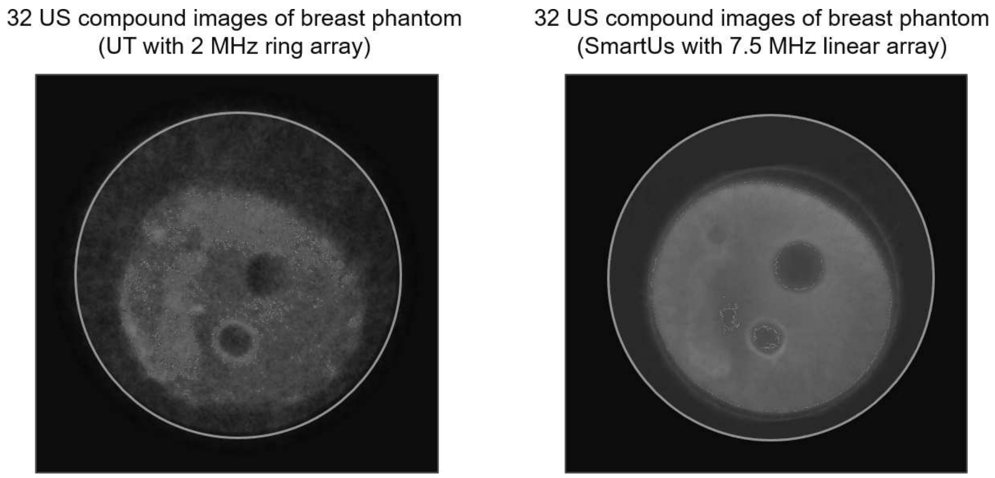

Fig. 6. The comparison between images obtained as in Fig. 4 but after the FASCI reconstruction of 32 sectoral images acquired around the phantom (courtesy of DRAMIŃSKI S.A. company).

small heterogeneities will distort and blur. Therefore, the additional complicated and time-consuming processing should be anticipated, which is required to obtain an adequately reconstructed image of the structure using the FASCI utilizing tomography ring array.

In addition to the mentioned limitation regarding the quality of the imaging process, ultrasound tomography scanning and ultrasound echo scanning cannot be carried out simultaneously due to the different ways of activating the elementary transducers of the ring array. Therefore, the scanning time of whole breast have to be doubled for each breast coronal section. The overall time of the examination is significantly extended this way. There is also the disadvantage of the direct coronal section scanning which is less informative than the transversal and sagittal sections which are reconstructed here using Multi-Planar Reconstruction (MPR) method. Reconstruction of the transversal and sagittal section based on the coronal section causes an averaging in the image and possibly missing small changes in the tissue that could be recognised if the sagittal or transversal section were measured directly.

3. Objects and the MACUI method

Three different breast tissue phantoms were used in the study: CIRS 059 USE Breast Phantom (CIRS Tissue Simulation & Phantom Technology, 2017a), CIRS 013 Mammography Breast Phantom (CIRS Tissue Simulation & Phantom Technology, 2017b) and self-made quasi-homogeneous US Agar Gel Phantom with sunken Jelly Beans (Fig. 7). The Model 059 phantom (Fig. 7a) accurately mimics the ultrasonic characteristics of tissues found in an average human breast. The size and shape of the phantom simulate that of an average patient in the supine position. The phantom contains several solid masses that appear slightly hypoechoic to the simulated breast tissue under conventional ultrasound examination. The lesions are at least two times stiffer than the background, so they can be detected on elastograms, yet are hardly visible on conventional ultrasound B-mode images because of the acoustic impedance similar to the surrounding gel. Lesions have diameters from 3 to 10 mm and are randomly distributed inside the phantom.

The Model 013 phantom (Fig. 7b) is a disposable training tool and practice medium for mammographic needle biopsy procedures. Embedded dense masses and microcalcifications vary in size and are coloured for easy visualisation. The phantom body is shaped to represent a partially compressed breast. The phantom is made from a dense proprietary gel with a physical consistency similar to human tissue, surrounded by an elastic skin-like membrane.

These 3 phantoms were chosen due to significant various acoustic properties. The CIRS 059 USE Breast Phantom characterizes with a very low ultrasound attenuation and comparable acoustic impedances between inclusions and the surrounding gel. Therefore, inclusions may be hard visible due to a very small ultrasound reflection coefficient values. The CIRS 013 Mammography Breast Phantom reveals a very high ultrasound attenuation as well as high differences in the acoustic impedance between inclusions and the surrounding gel. It can distort ultrasonic images. The self-made quasi-homogeneous US Agar Gel Phantom has a very low attenuation in the background body and a high attenuation in sunken Jelly Beans. Moreover, Jelly Beans are much harder than the agar gel caused the high value of ultrasound reflection coefficient on the agar gel/Jelly Bean border.

All phantoms were placed on the ultrasound absorbing material (Fig. 7c) and submerged in the water tank at the time of measurement. Absorbing material was used to minimise the reflection from the bottom

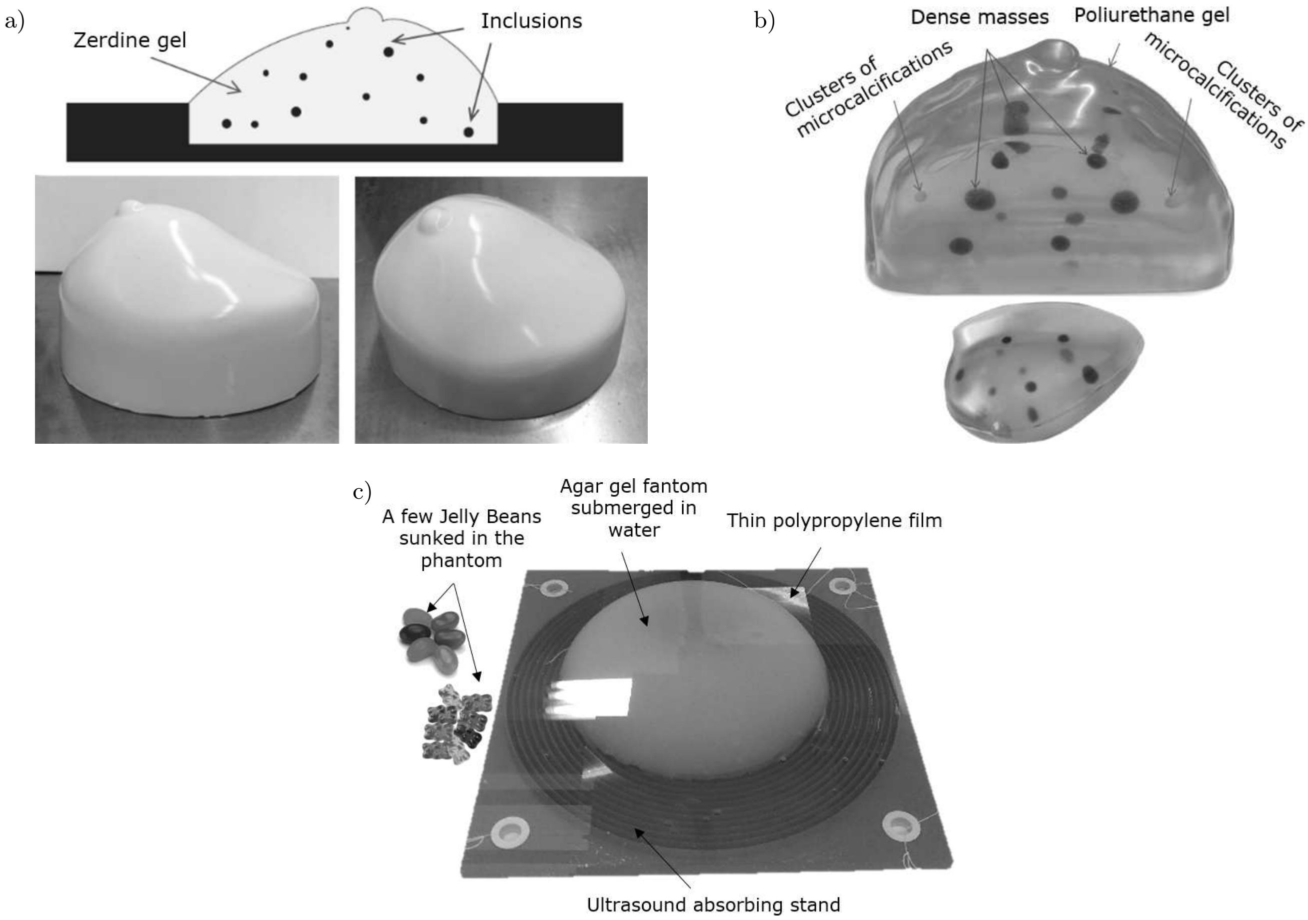

Fig. 7. Three different breast tissue phantoms used in the study: a) CIRS 059 USE Breast Phantom, b) CIRS 013 Mammography Breast Phantom, c) self-made US Agar Gel Phantom with sunken Jelly Beans.

of the tank. The SmartUs digital ultrasound diagnostic system with the transducer array probe 4 cm length was used as the B-mode imaging device. Probe resonant frequency was set to the 7.5 MHz during all measurement. The probe was mounted on the stepper motor controlled rotational head and placed above or at the side of the phantoms depending on the measurement configuration (Fig. 8).

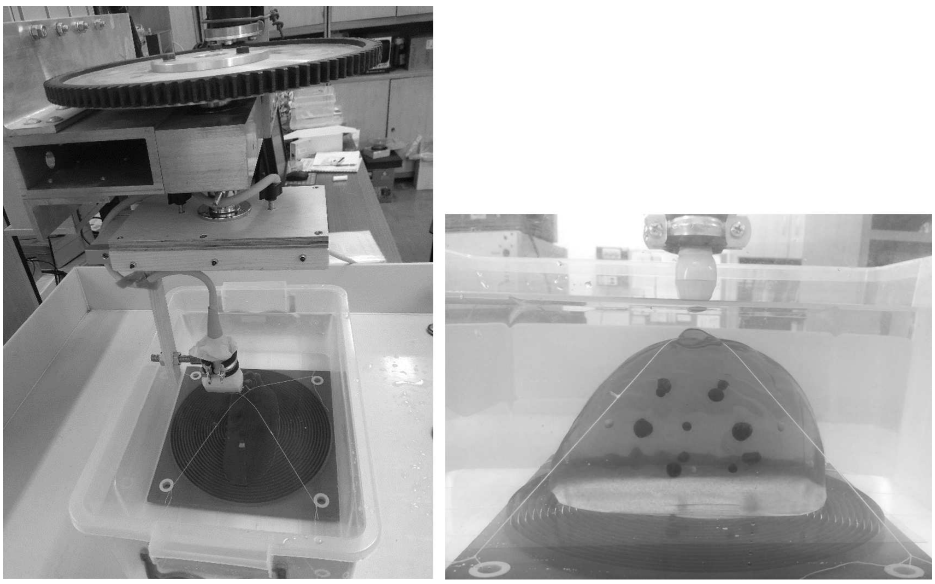

Fig. 8. Measurement system used in multi-angle conventional ultrasound imaging (MACUI).

The vertical lateral configuration and vertical top configuration were tested. In the vertical lateral configuration, the 2-D object's cross-sections are acquired by the probe turning around the object's lateral surface (Fig. 9a). Both standard rectangular view (Fig. 9b) and sectoral one (Fig. 9c) were tested. In the vertical top configuration, the 2-D object's cross-sections are acquired by the probe turning over the top of an object. The vertical top configuration fully corresponds to the vertical bottom configuration. Choice between the two depends on the measurement system arrangement. A similar method to the vertical top or bottom configuration of 3-D ultrasound imaging is used as interventional ultrasound (Fenster *et al.*, 2013). However, the vertical lateral configuration has not been yet documented to the best of the authors' knowledge.

a) b) c)

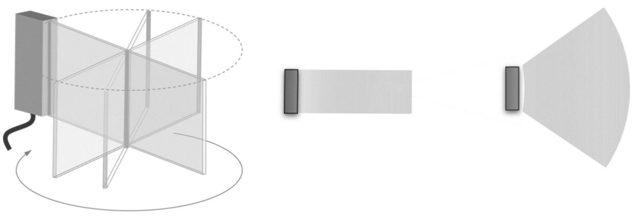

Fig. 9. The vertical lateral configuration applied in the MACUI method with different views: a) vertical lateral scanning, b) rectangular view, c) sectoral view.

Three different positions of the probe were tested for the vertical top configuration: the centre of the transducer array probe in the rotation axis (Fig. 10a), the centre of the probe moved 17 mm from the rotation axis (Fig. 10b), and the centre of the probe moved 25 mm from the rotation axis (Fig. 10c). In the last position, the edge of the entire array probe is placed outside of the rotation axis. For the configuration with the centre of the probe moved 25 mm from the rotation axis, only the sectoral view was used to cover the entire measurement area. In all MACUI configurations in the paper, the individual 2-D vertical cross-sections of the objects are acquired by the probe at fixed angular positions with the step of 2.25°. It makes 160 positions for the entire turnover. When the time needed for acquiring a single projection is assumed to be about 250 ms, then the acquisition time for the entire breast imaging (3-D volume) is less than 1 minute. This time also allows for pre-processing of the acquired vertical slices in the form of averaging and filtering for the best quality of the source images.

a) b) c)

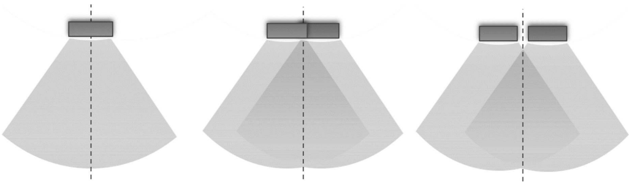

Fig. 10. Different positions of the probe for the tested vertical top configuration in the MACUI: a) centrally, b) 17 mm moved, c) 25 mm moved.

The 2-D images corresponding to the horizontal (coronal) cross-sections of the object are reconstructed by taking the image lines at the specific height and converting the angular and radial position of each pixel into Cartesian coordinates. Only the part of the images from its side to the rotational axis was taken into account in the reconstruction process. Reconstructed 2-D horizontal projections were subsequently converted into DICOM (Digital Imaging and Communications in Medicine, 2019) series. The ONIS Viewer software was used to combine the 2-D DICOM images into 3-D Volume using MPR method (multi-projection reconstruction).

4. Results and analysis

Figures 11 and 12 show the selected MACUI results of vertical lateral scanning with the rectangular and sectoral view of the imaging device accordingly. The images of CIRS 059 USE Breast Phantom and self-made US Agar Gel Phantom with sunken Jelly Beans are presented. 3-D volumes reconstructed from the sectoral images obtained using vertical lateral scanning (Fig. 12) present visible phantom shape distortion in the image. The shape distortion increases with the distance from the ultrasonic array probe and the probe's centre.

It is caused by the deviation of the ultrasound beams according to the probe centre as well as varying average ultrasound velocity through the ultrasound path. For the volumes reconstructed from acquired rectangular images (Fig. 11), generated ultrasonic beams are not as much deviated, and the object covers the greater longitudinal part of the image which results with a lower amount of shape distortion. Common for both configurations is that the phantom inclusions and heterogeneities can be clearly visible, and their borders are sharp and can be easily defined. The disadvantage in the case of the rectangular view is the limited vertical imaging distance. In both cases of rectangular and sectoral view the directly measured sagittal and transversal sections are visualised with a very good spatial resolution (threads fastening Jelly Beans in agar gel are even visible in Fig. 12b). The worse resolution is shown by the images of reconstructed coronal sections.

Figure 13 shows the selected result of vertical top scanning CIRS 059 USE breast phantom with rectangular (Fig. 13a) and sectoral view (Fig. 13b) of the imaging device and the probe placed in the rotation axis centrally, whereas Fig. 14 shows the case of imag-

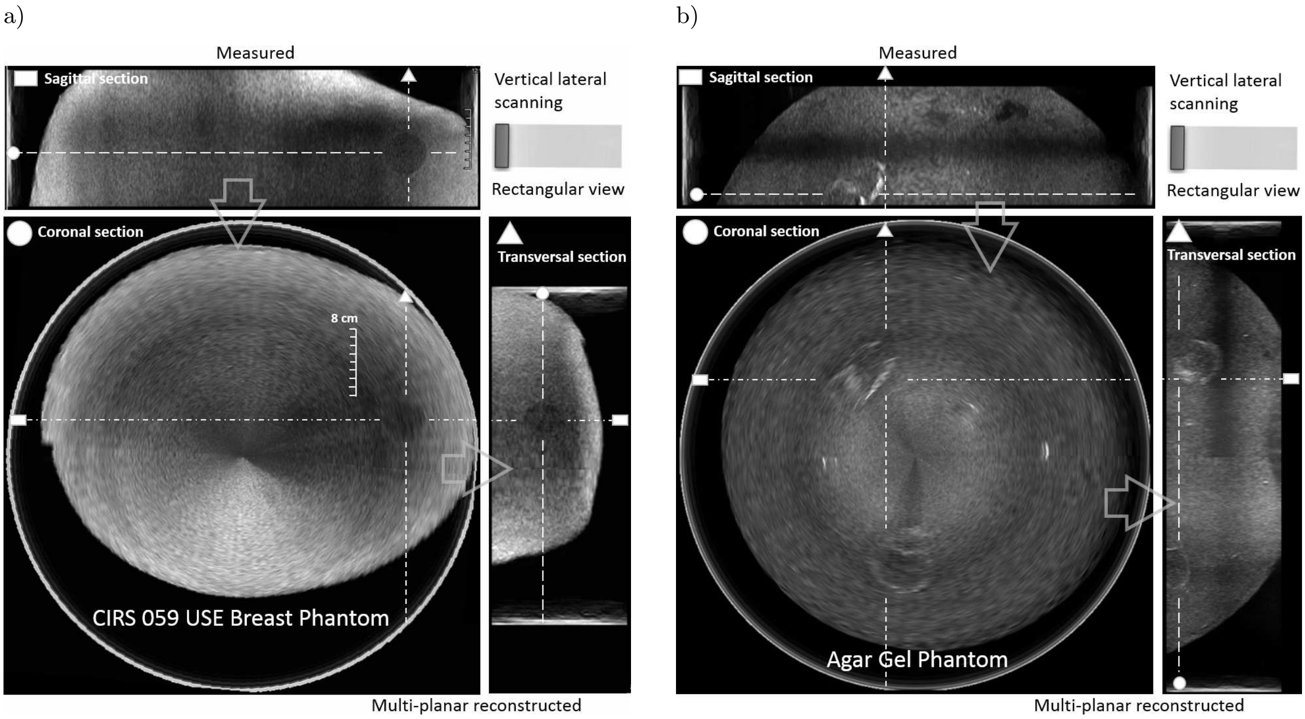

Fig. 11. Images of selected breast phantom sections acquired using vertical lateral scanning with the rectangular view: a) CIRS 059 USE Breast Phantom, b) US Agar Gel Phantom with sunken Jelly Beans.

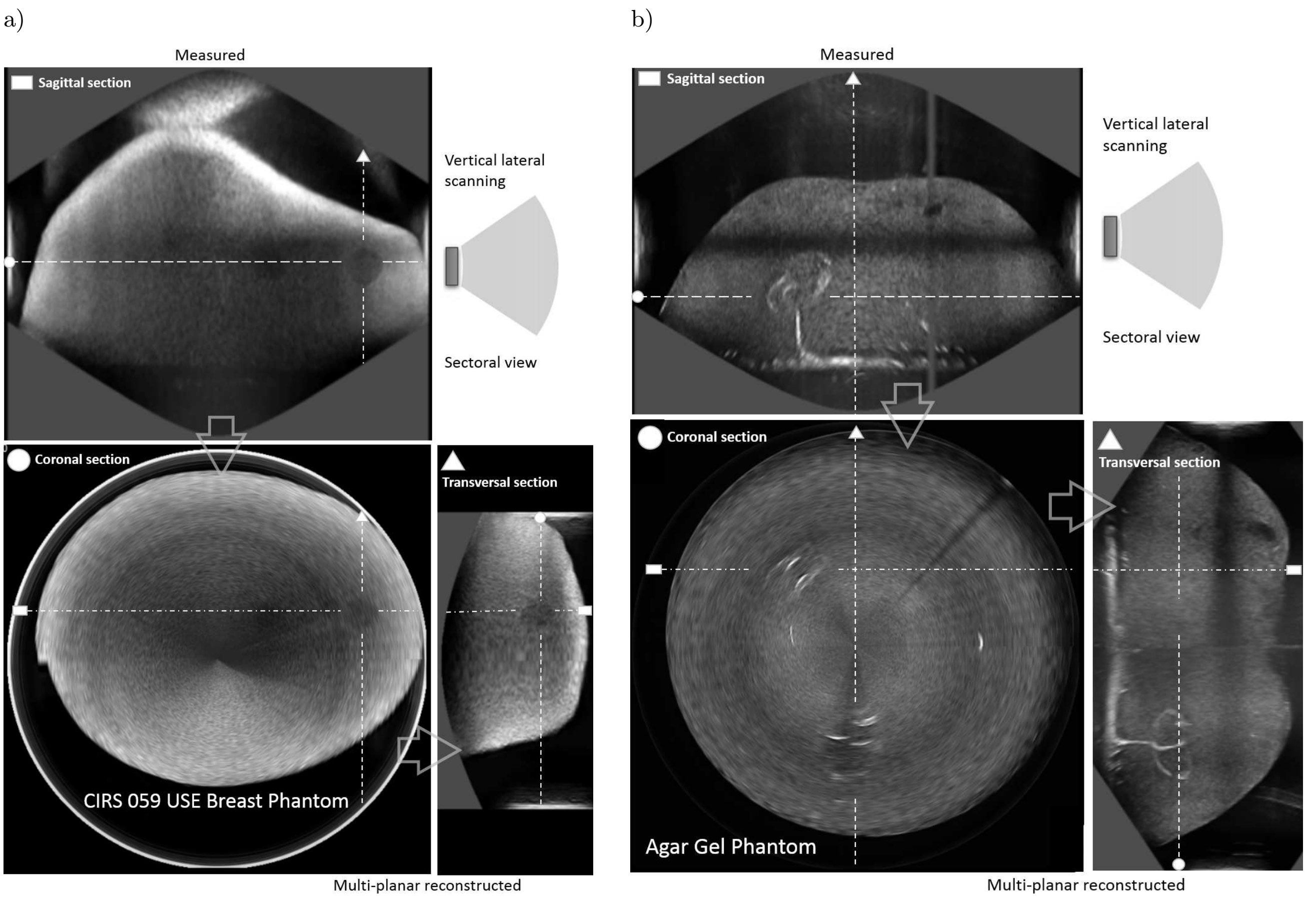

Fig. 12. Images of selected breast phantom sections acquired using vertical lateral scanning with the sectoral view: a) CIRS 059 USE Breast Phantom, b) US Agar Gel Phantom with sunken Jelly Beans.

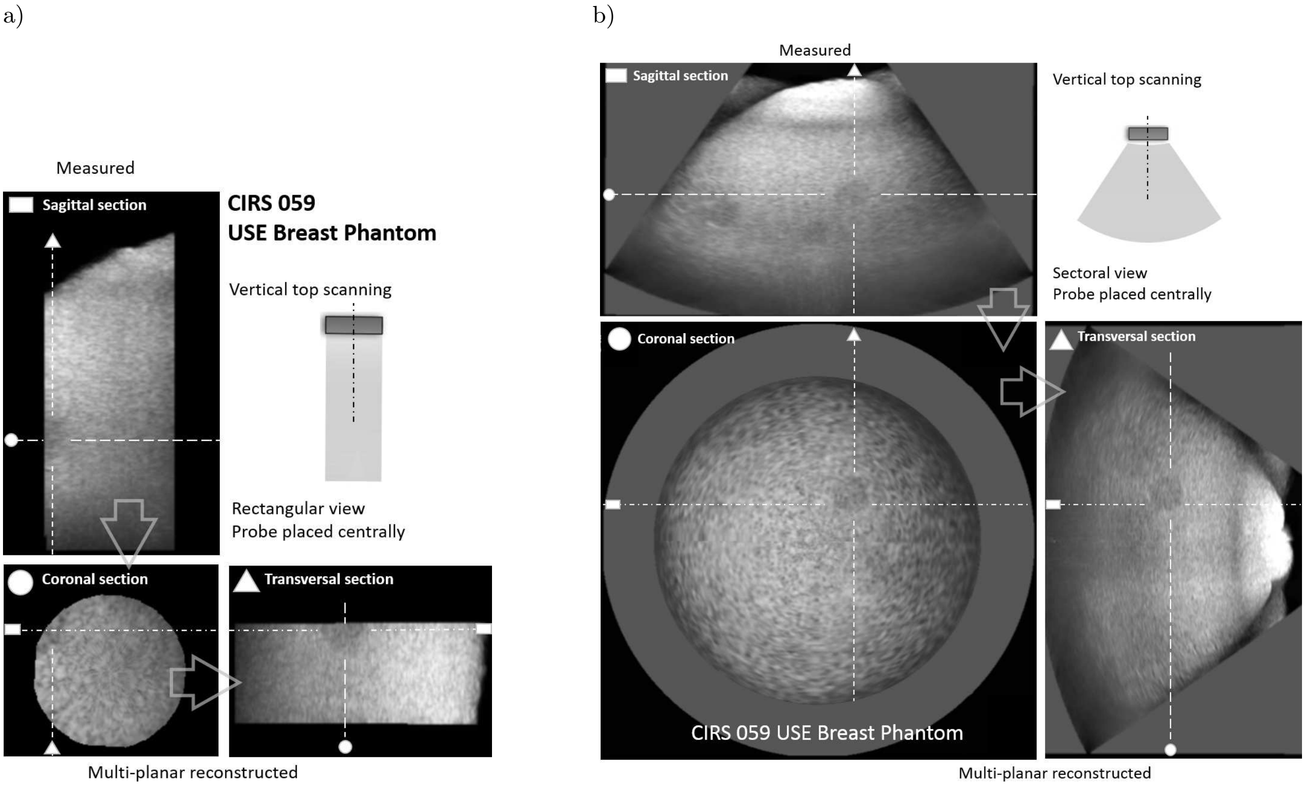

Fig. 13. Images of selected CIRS 059 USE breast phantom sections acquired using vertical top scanning with the probe placed centrally: a) rectangular view, b) sectoral view.

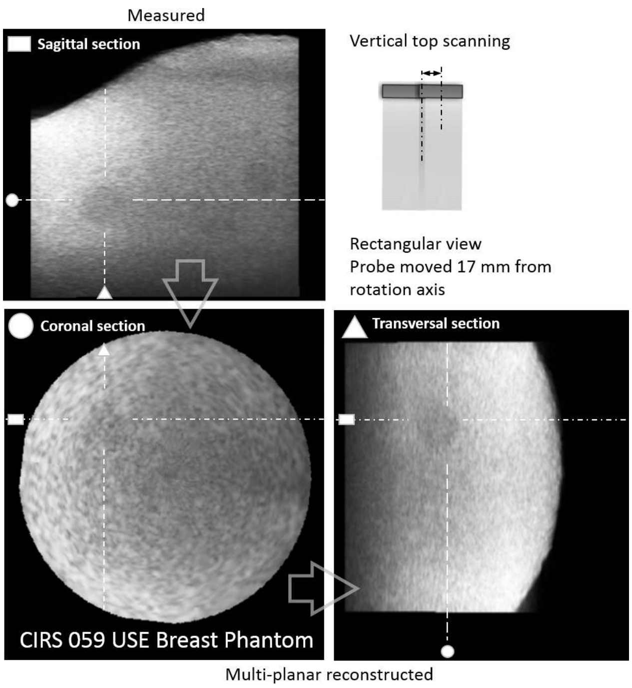

Fig. 14. Images of selected CIRS 059 USE breast phantom sections acquired using vertical top scanning with the rectangular view and the probe moved 17 mm from rotation axis.

ing the same phantom with the rectangular view and the probe centre moved 17 mm from the rotation axis. As these imaging configurations came out as not optimal for use in ultrasonic tomography device, images are presenting results for one phantom only.

All three breast phantoms' selected sections with inclusions (CIRS 059 USE Breast Phantom, CIRS 013 Mammography Breast Phantom and self-made US Agar Gel Phantom with sunken Jelly Beans) are shown in Fig. 15, which have been scanned in the vertical top configuration with the probe's centre moved 25 mm from the rotation axis. In this case, the entire transducer array probe is outside of the rotation axis. As can be seen, all probe placements in the vertical top configuration result in similar imaging quality. The phantoms' inclusions and heterogeneities are easily recognisable at the reconstructed images, and their borders are clearly defined. The main and obvious difference can be seen in the size of the imaging area.

Probe placement at the rotation axis and moved 17 mm away may not provide a large enough imaging region. This is particularly evident when the rectangular view is used. Scattering and reflection noise distortions connected with the geometry of the transducer ring array used in the FASCI method (Fig. 4) are not presented in the MACUI reconstructed volumes. The best combination of the image quality and size of the imaging area can be achieved in the case of the sectoral view when the entire transducer array probe is outside of the rotation axis (Fig. 15).

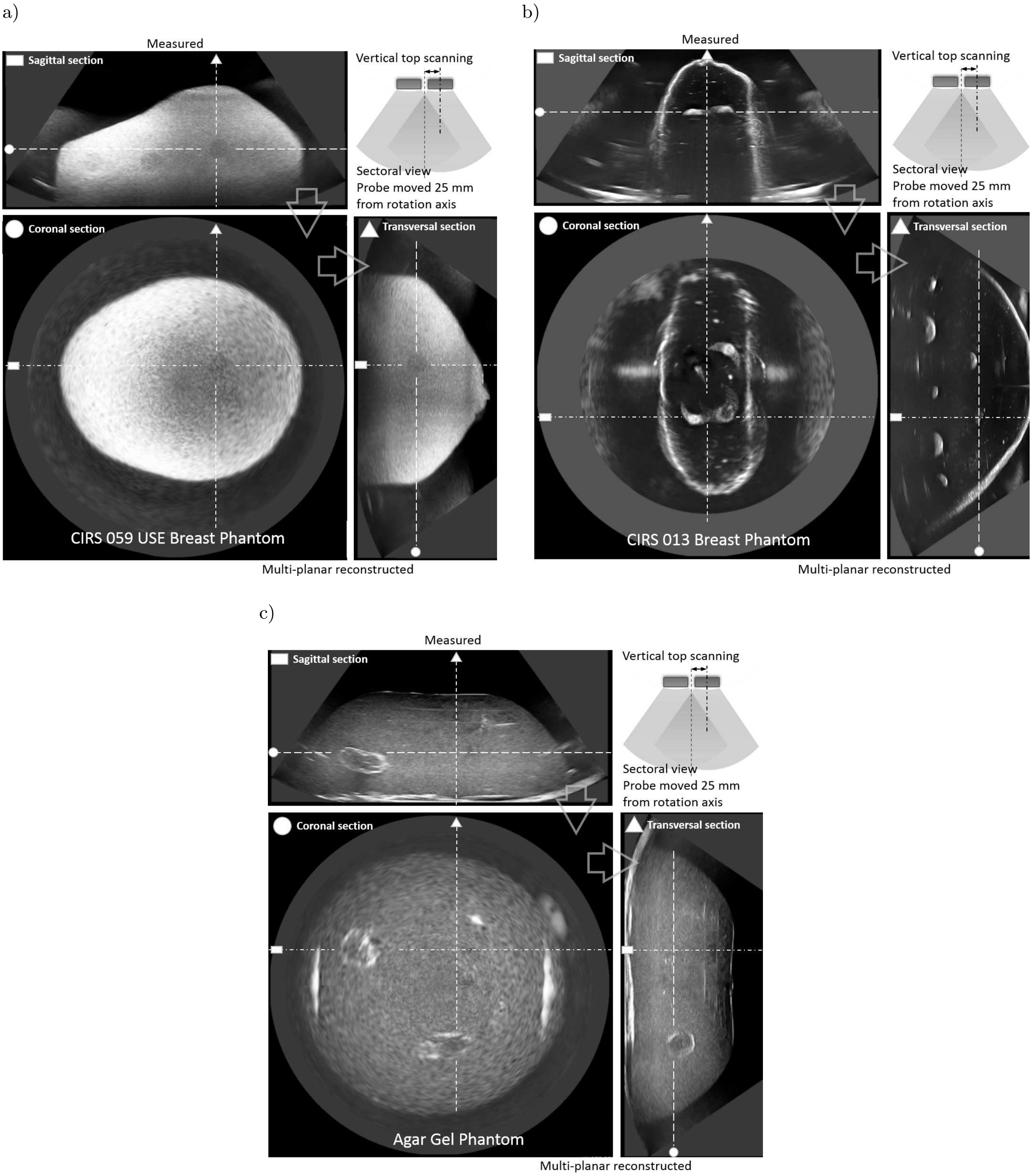

Fig. 15. Images of selected breast phantom sections acquired using vertical top scanning with the sectoral view and the probe moved 25 mm from rotation axis: a) CIRS Model 059 USE Phantom, b) CIRS 013 Mammography Phantom, c) self-made Agar Gel Phantom.

5. Conclusion and summary

The number of advantages of the MACUI 3-D method over the FASCI method has been presented in the paper. Direct acquisition of more informative transversal and sagittal sections plane (the same as in the conventional breast ultrasound imaging) makes an advantage in terms of the imaged breast tissue assessment. The efficiency of the method was proved based on acquisition time needed for gathering the information about the entire breast even with pre-processing applied. It is possible to achieve the whole breast imaging time of about one minute, which is two to three times less than for the FASCI method. The possibility of using an independent B-mode scanner electronics and probes allows for the use of the devices optimised for B-mode modality. Small pitches, higher resonant frequency and ultrasound intensities are achievable. The imaging quality is not limited by the circular geometry of the specially designed ultrasonic transducer array and resulting backscattering and reflection distortions. The 3-D image reconstruction is straightforward and with a non-complicated pre-processing can be easily implemented using MPR method commonly used in computerised tomography (CT).

The presented MACUI method can be applied as the new efficient ultrasonic modality of *in vivo* female breast tissue in the developed prototype of Hybrid Ultrasound Tomography Breast Scanner – a novel instrument designed to examine breast as a breast cancer screening method (Milewski *et al.*, 2019). The use of the vertical bottom configuration with the edge of the conventional B-mode ultrasound linear probe of the average length placed outside of the rotation axis in combination with the sectoral image acquisition seems to be optimal for ultrasound tomographic device for *in vivo* breast imaging. It can be motivated by the achievable wide imaging area that can cover entire transversal and sagittal sections even for a breast of a large size. Therefore, the configuration provides the most appropriate imaging area among these presented in the paper. Moreover, there exists another advantage regarding imaging area if vertical bottom configuration with sufficiently long range of imaging would be used in tomography device. Thus, changes close to the chest wall could be identified. Those changes can be hard to detect using ring array with the FASCI method as well as the UTT and URT modalities (ring array transducers cannot be positioned close enough to the chest due to its casing). Additionally, free space at the rotation axis leaves the space for breast holder used for the stretching of the female breast submerged in the water (Forte *et al.*, 2017) during the tomography scanning. The ultrasound tomography scanning and ultrasound echo scanning using MACUI method can be carried out simultaneously. This is enabled by the need of using an independent ultrasonic probes with independent accompanying electronic control systems. This allows for simultaneous acquiring data for both UT and US modalities. The measurements conducted according the scheme presented in Fig. 16 prove that simultaneous scanning the agar gel phantom using two independent ultrasonic setups (the transmission and the reflection one) does not affect the transmission beam (Fig. 17) and *vice versa*.

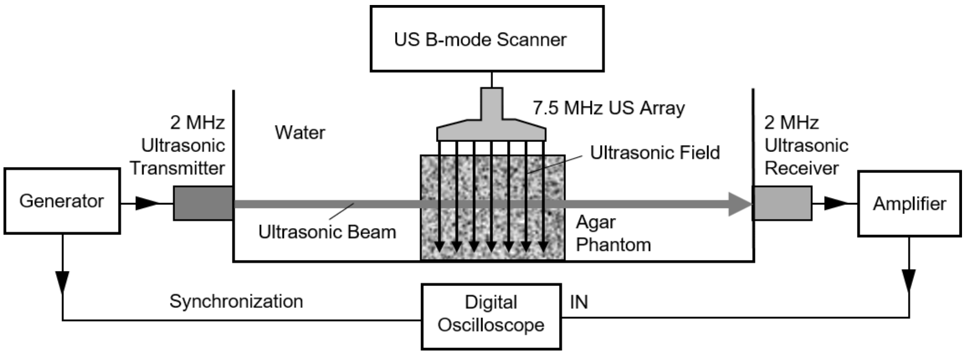

Fig. 16. The block scheme of the measurement setup to check the impact of ultrasonic fields in the ultrasound tomography scanning and the ultrasound echo scanning.

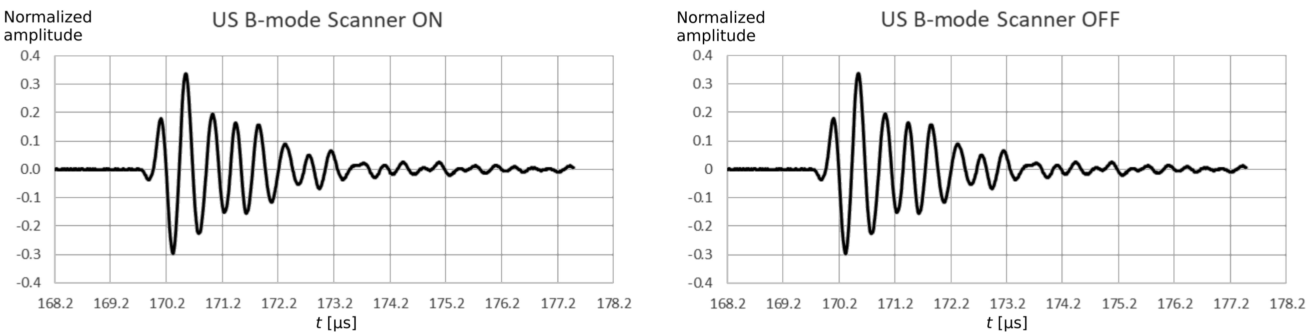

Fig. 17. The pulses transmitted through the medium as presented in Fig. 16 when the ultrasound B-mode scanner is ON and OFF.

The vertical lateral configuration of the MACUI method (Fig. 9) is hard to apply in ultrasound tomography scanner of breast *in vivo*, because the linear B-mode probe rotates around the breast's lateral surface, which limits the vertical movement of ultrasonic ring array along the breast. Moreover, images obtained in the vertical lateral configuration are of a lower quality than in the vertical top or bottom configuration, their vertical size is limited, and compounding pairs for opposite angles is difficult. However, the vertical lateral configuration of the MACUI method could be successfully applied for e.g. 3-D diagnosing injuries of limbs as well as for monitoring the fusion of limbs.

The disadvantages of the presented MACUI method according to the FASCI are the need of using an additional B-mode scanner electronics with an ultrasonic linear array and the need for mechanical rotation inside the water tank with tomography ring array. These increase the complexity and cost of the device. Furthermore, direct matching of the B-mode US sectional images to the UTT and URT images also can be associated with some difficulties.

Additionally, there are visible distortions at the centre of the image in the stated optimal configuration caused by the use of sectoral image and the object's shape distortion in this region. Further studies will cover the work on utilizing a specially designed algorithm to compound pair of opposite sectoral images acquired in MACUI method for the θ and $(\pi-\theta)$ angle to minimize those artefacts.

Finally, an exemplary comparison of FASCI and MACUI methods with the same agar gel phantom is presented in Fig. 18. Slightly distorted shapes of phantom inclusions in the image obtained with the MACUI method do not arise from disadvantages of the method. These are the result of the inaccurate surface setting of the B-mode scanner array along the rotation radius during measurements.

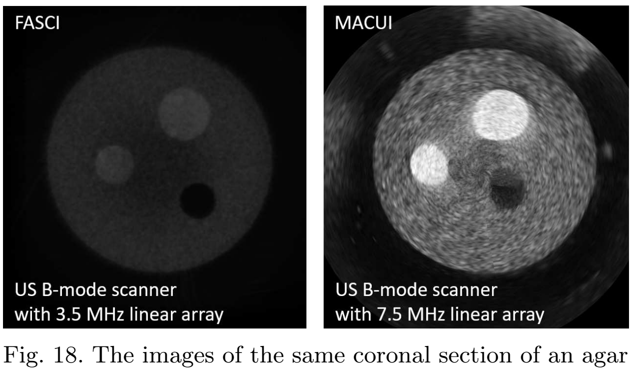

Fig. 18. The images of the same coronal section of an agar gel phantom dipped in water, obtained using FASCI and MACUI method.

References

1. Burgess M.D., O'Neal E.L. (2019), *Breast ultrasound for the evaluation of benign breast disease*, Current Radiology Reports, **7**, 3, 1–11, doi: 10.1007/s40134-019-0316-x.
2. CIRS Tissue Simulation & Phantom Technology (2017a), *Breast elastography phantom model 059*, from www.cirsinc.com/products/all/83/breast-elastography-phantom/.
3. CIRS Tissue Simulation & Phantom Technology (2017b), *Stereotactic needle biopsy training phantom model 013*, from www.cirsinc.com/products/all/44/stereotactic-needle-biopsy-training-phantom/.
4. Digital Imaging and Communications in Medicine – DICOM (2019), from www.dicomstandard.org.
5. Duric N. *et al.* (2014), *Breast imaging with SoftVue: initial clinical evaluation*, [in:] Medical Imaging: Ultrasonic Imaging and Tomography, Proceedings of SPIE, vol. 9040, Bosch J.G., Doyley M.M. [Eds], pp. 90400V-1–8, SPIE – International Society For Optics and Photonics, San Diego, doi: 10.1117/12.2043768.
6. Fenster A., Bax J., Neshat H., Kakani N., Romagnoli C. (2013), *3D ultrasound imaging in image-guided intervention*, [in:] *Advancements and breakthroughs in ultrasound imaging*, Gunarathne G.P.P. [Ed.], p. 27, IntechOpen, doi: 10.5772/55230.
7. Forte S., Dellas S., Stieltjes B., Bongartz B. (2017), *Multimodal ultrasound tomography for breast imaging: a prospective study of clinical feasibility*, European Radiology Experimental, **1**, 27, 6, doi: 10.1186/s41747-017-0029-y.
8. Freer P.E. (2015), *Mammographic breast density: impact on breast cancer risk and implications for screening*, RadioGraphics, **35**, 2, 302–315, doi: 10.1148/rg.352140106.
9. Hooley R.J., Scoutt L.M, Philpotts L.E. (2013), *Breast ultrasonography: state of the art*, Radiology, **268**, 3, 642–659, doi: 10.1148/radiol.13121606.
10. Iuanow E., Smith K., Obuchowski N.A., Bullen J., Klock J.C. (2017), *Accuracy of cyst versus solid diagnosis in the breast using Quantitative Transmission (QT) ultrasound*, Academic Radiology, **24**, 9, 1148–1153, doi: 10.1016/j.acra.2017.03.024.
11. Jaglan P., Dass R., Duhan M. (2019), *Breast cancer detection techniques: issues and challenges*, Journal of The Institution of Engineers (India): Series B, **100**, 4, 379–386, doi: 10.1007/s40031-019-00391-2.
12. Milewski T. *et al.* (2019), *Hybrid ultrasound tomography scanner – a novel instrument designed to examine breast as a breast cancer screening method*, Biomedical Journal of Scientific & Technical Research, **14**, 4, 10822–10826, doi: 10.26717.BJSTR.2019.14.002594.
13. Okello J., Kisembo H., Bugeza S., Galukande M. (2014), *Breast cancer detection using sonography in women with mammographically dense breasts*, BMC Medical Imaging, **14**, 1, article number: 41, doi: 10.1186/s12880-014-0041-0.
14. Opieliński K.J. (2014), *Full angle ultrasound spatial compound imaging*, Proceedings of 7th Forum Acusticum 2014, p. 6, Krakow, Poland.

15. Opieliński K., Gudra T. (2016), *Bioacoustic range equation*, [in:] *Hydroacoustics*, *vol. 19*, Grelowska G. [Ed.], pp. 307–318, Polish Acoustical Society, Gdansk Department Polish Academy of Sciences, The Committee on Acoustics, Gdansk, Poland, http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-136b0a14-d3f1-4b98-9c1f-81c6cc10e797/c/Opielinski_2CGudra_hydroacoustics-vol-19-pp307.pdf.

16. Opieliński K.J. *et al.* (2018a), *Multimodal ultrasound computer-assisted tomography: An approach to the recognition of breast lesions*, Computerized Medical Imaging and Graphics, **65**, 102–114, doi: 10.1016/j.compmedimag.2017.06.009.

17. Opieliński K.J., Pruchnicki P., Wiktorowicz A., Jóźwik M. (2018b), *Algorithm for the fusion of ultrasound tomography breast images allowing automatic discrimination between benign and malignant tumors in screening tests*, [in:] *Information technologies in biomedicine*, *ITIB 2018. Advances in Intelligent Systems and Computing*, Vol. 762, Pietka E., Badura P., Kawa J., Wiecławek W. [Eds], pp. 49–60, Springer, Cham, doi: 10.1007/978-3-319-91211-0_11.

18. Staszewski W., Gudra T., Opieliński K.J. (2018), *The acoustic field distribution inside the ultrasonic ring array*, Archives of Acoustics, **43**, 3, 455–463, doi: 10.24425/123917.

19. Yezitronix Group Inc. Automation & Control Industries Inc. (2017), *Multi-modality breast phantom model (Ultrasound, CT, MRI) – Model B-MM – 1.2*, www.yezitronix.com.