Simulations of acoustic wave propagation in the breast with tumors using a modified VICTRE phantom

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***Abstract*— Understanding the relationship between acoustic properties of breast lesions and resulting ultrasound images may contribute to an earlier and more accurate diagnosis of the most common cancer in women. In addition to *in vitro* studies, *in silico* tumor models can provide a lot of crucial information due to the possibility of precise determination of the influence of changes in tissue structure on the resulting ultrasound echoes. The purpose was to develop the numerical phantom of the breast with the tumor for a reliable simulation of ultrasound images. In modeling the tissue structures of the breast, the VICTRE phantom, developed by the FDA for the simulation of X-ray mammography, was used. The numerical ultrasound model of breast cancer allows the simulation of ultrasound signals and images. It could be used to interpret, validate and develop new ultrasound methods for cancer diagnosis.**

Keywords— breast tumor, numerical phantom, ultrasound imaging

I. Introduction

Breast cancer is the most common malignant tumor in women, accounting for about 24.5% of all tumors [1]. Every year, more than 2,000,000 new cases are diagnosed worldwide [1]. In 2020, breast cancer was the leading cause of female death worldwide, causing more than 680,000 female deaths [1].

An early and accurate diagnosis of breast cancer allows for effective therapy. One of the primary methods of imaging diagnosis of breast lesions is ultrasonography, which is a safe, inexpensive and easily accessible test. Based on the obtained image, a BIRADS category is assigned, which determines the method of treatment [2]. To support effective image assessment, methods using quantitative ultrasound [3], [4] or machine learning [5] are being developed.

Classification algorithms can be evaluated using numerical simulations. It requires a reliable numerical phantom of the breast and tumor. To date, two numerical phantoms of the breast have been created for ultrasound imaging simulations [6], [7]. Both models were created based on magnetic resonance imaging data, from which the tissue structures of the breast (glandular-fibrous tissue and tumor) were segmented [6], [7]. In the study [7], randomly distributed structures such as Cooper's ligaments, milk ducts and intraglandular fat were also added to the phantom. The developed models were used in ultrasound simulations with the use of Field II software [8].

As part of the VICTRE (Virtual Imaging Clinical Trials for Regulatory Evaluation) project, the U.S. Food and Drug Administration (FDA) has developed a numerical phantom of the breast consisting of seven tissue structures: adipose tissue, glandular tissue, skin, milk ducts, Cooper's ligaments, muscle and blood vessels [9]. This phantom was created for simulations of X-ray mammography, so far it has also been used in simulations of X-ray tomography [10], photoacoustic tomography [11] and digital breast tomosynthesis [12]. Until now, it has not been used to simulate ultrasound imaging.

The aim of the work was to develop the numerical phantom of the breast with the tumor for a reliable simulation of ultrasound images. The development of a 3D *in silico* model of normal tissue together with a breast tumor will enable simulations of different microscopic and macroscopic structures. The obtained images and radio frequency (RF) signals will allow to explain the relationship of ultrasound image features with the acoustic properties of tissues, thus improving the efficiency of tumor classification.

II. Methods

A numerical model of the breast consisting of normal tissue (using the VICTRE phantom) and cancerous tissue was created. The VICTRE phantom was adapted to ultrasound simulations. Geometric transformations were performed in order to obtain the geometrical characteristics of the patient's supine position and to apply the ultrasound probe in the radial/anti-radial position.

The numerical tumor phantom takes into account various features of benign and malignant lesions (shape, orientation, margin - distinct, spiculated) according to the BI-RADS atlas [2]. Using the created phantom, ultrasound simulations were carried out using k-Wave software [13].

The phantom voxel size was 0.054mm, which allowed for transmitting a maximum frequency of 12MHz. The transducer's parameters are similar to the technical specifications of ultrasonic systems used in clinical practice (Ultrasonix Sonix Touch, L14-5/38). The number of elements was set to 128, element pitch to 0.3mm, focus depth to 20mm and the transducer was excited by two cycles signal of frequency equal to 5MHz.

The method of adding the tumor to the phantom was consistent with the system used by doctors to report the

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location of the tumor in the breast, i.e. by quadrant, distances from the nipple and the skin layer. The acoustic properties of normal breast tissues as well as benign and malignant tumors used in the simulations were adopted on the basis of data collected in over 30 scientific studies.

III. Results And Discussion

The results are presented for three breast densities, i.e. for breasts with fatty, heterogenous and dense structure. The ratio of fat to glandular tissue was equal to 0.4, 0.7 and 0.9 for fatty, heterogenous and dense breast, respectively. Tumors were placed in the upper outer quadrant at a distance of 2cm from the nipple and at a distance of 1.5cm from the subcutaneous fascia, this position corresponds to the most common location of tumors. An example of a velocity map of the phantom cross-section in the plane of the ultrasound transducer is shown in Fig. 1.

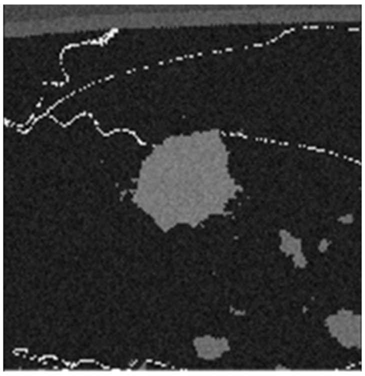

Fig. 1. An example cross-section through a fatty breast phantom shown as a velocity map.

A tissue-specific sound velocity, density and attenuation coefficient values were assigned to each of the phantom's grid voxels. The acoustic properties used in the simulations are shown in Table 1.

The simulated images for cancer in the fatty, heterogenous and dense breast and the corresponding similar real B-mode images are shown in Fig. 2. B-mode tumors images were chosen from public databases [14],[15].

For the tumor located in the adipose tissue of the breast (Fig. 2a), a hyperechoic halo is noticeable around cancer. A similar phenomenon can also be observed in images acquired with ultrasound equipment (Fig. 2d). In simulated images, in a heterogeneous (Fig. 2b) and dense breast (Fig. 2c), it is difficult to detect cancer with properties similar to glandular tissue. This corresponds to the situation in real B-mode images (Fig. 2e and Fig. 2f).

TABLE I. ACOUSTIC PROPERTIES OF NORMAL BREAST TISSUE AND DUCTAL CARCINOMA USED IN NUMERICAL SIMULATIONS

Tissue	**Properties**		
	Speed of sound [m/s]	***Density [kg/m³]***	***Attenuation coefficient [dB/cm/Mhzʸ]***
Skin	1537 [16]	1100 [16]	0.37 [17]
Fat	1440 [16]	940 [18]	0.6 [19]
Grandular	1560 [20]	1050 [21]	0.9 [20]
Duct	1545 [16],[22]	1030 [22]	0.5 [22]
Blood vessels	1570 [23]	1050 [24]	0.14 [19]
Cooper's ligaments	1750 [25]	1170 [24]	3.7 [26]
Muscle	1585 [23]	1050 [18]	0.57 [19]
Tumor	1580 [16]	1070 [27]	1.0 [19]

IV. Conclusions

Initial simulations of the ultrasound images of the breast together with the added tumor reflect the acoustic effects observed in the images obtained with the ultrasound scanner. Therefore, the modified VICTRE phantom can be used e.g. to deepen the knowledge about the properties of breast tissues and how they interact with the ultrasound wave. The presented work requires further research in order to verify the model and quantify the quality of the simulation, e.g. using real phantoms and parameters describing the statistics of the scattered signal.

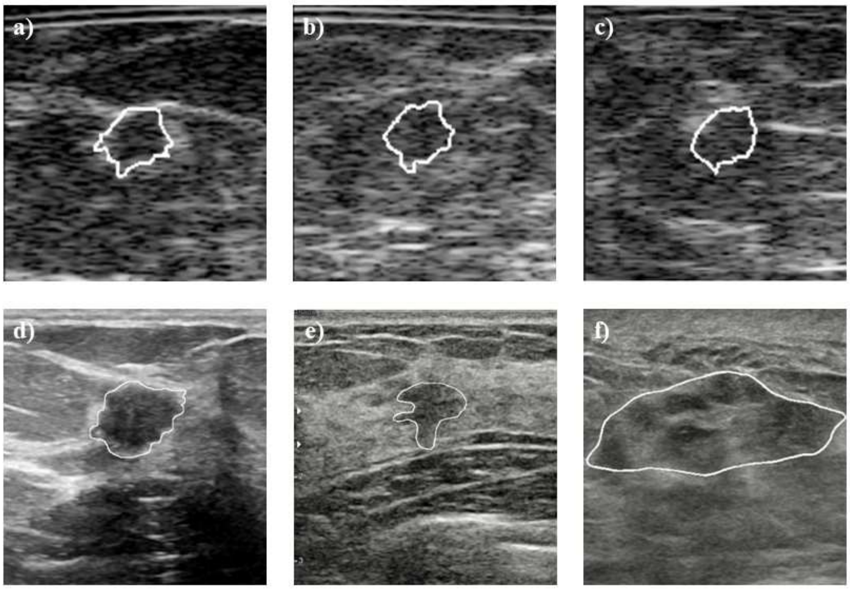

Fig. 2. Simulated (a-c) and real B-mode (d-f) images of tumors in fatty (a,d), heterogenous (b,e) and dense (c,f) breasts.

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