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Recent technological advancements in breast ultrasound

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ABSTRACT

Ultrasound is becoming increasingly common as an imaging tool for the detection and characterization of breast tumors. This paper provides an overview of recent technological advancements, especially those that may have an impact in clinical applications in the field of breast ultrasound in the near future. These advancements include close to 100% fractional bandwidth high frequency (5–18 MHz) 2D and 3D arrays, automated breast imaging systems to minimize the operator dependence and advanced processing techniques, such as those used for detection of microcalcifications. In addition, elastography and contrast-enhanced ultrasound examinations that are expected to further enhance the clinical importance of ultrasound based breast tumor screening are briefly reviewed. These techniques have shown initial promise in clinical trials and may translate to more comprehensive clinical adoption in the future.

Contents

1. Introduction

Breast cancer is the single most commonly occurring cancer in women in the United States with over 249,000 cases, and second most common cause of cancer death in women (41,152 deaths expected in 2016) [1]. Breast cancer screening is an important step for the early diagnosis of malignancy as 5 year survival rates vary dramatically by stage of initial diagnosis (as high as 100% at stage I (see [2] for staging criteria) and roughly 25% when diagnosed at stage IV) [1]. X-ray mammography is currently the primary imaging screening tool and recommended in the United States for women 40 years and older [3], although considerable controversy currently surrounds the appropriate age to begin screening [4]. Despite its advantages mammography suffers from poor overall specificity, resulting in false-positive rates of 65–90% [5,6]. Additionally, mammography is often not adequate in the 20–50% of patients with dense breasts [5].

Ultrasound may overcome both of these limitations. Breast density does not inhibit ultrasound waves in the breast making breast ultrasound imaging a useful technique in these women [7]. Breast ultrasound has also been shown to be a useful adjunct for the characterization of masses post-mammography using an ultrasound-based Breast Imaging Reporting and Data Systems (BIRAD) scoring system. Breast ultrasound post mammography has shown to result in a down staging of roughly 20–40% of BIRADS 4A cases and of roughly 15–25% of BIRADS 3 cases, thus limiting the number of patients requiring biopsy [7]. Unnecessary biopsies are undesirable due to patient discomfort and anxiety, risk of infection, and cost of the procedure. When biopsy is still required, ultrasound is also routinely used for image guided breast mass biopsies [7].

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While ultrasound is already playing an important clinical role in breast imaging, overall specificities are still relatively low (around 66% based on a retrospective review of 761 cases using only B-mode imaging [8]). Hence, numerous techniques are currently in development to improve ultrasound's prominence in this application. This paper will serve as an overview of emerging concepts in the field, including high frequency imaging and processing approaches, automated volumetric breast ultrasound systems, breast elastography, and contrast-enhanced breast ultrasound.

2. 2D and 3D transducer technologies

High frequency, broad bandwidth transducers can produce excellent detail resolution at the relatively shallow depths (typically < 4 cm) encountered in breast imaging. Currently available commercial systems use linear arrays operating around 10–14 MHz with close to 100% bandwidth ranging from 5 to 18 MHz. With a typical (lateral) resolution close to 2λ, a 10 MHz transmit would yield resolution of approximately 300 μm. Thus, such arrays are capable of providing superior resolution at multiple depths by selecting the best possible compromise between penetration depth, which is dependent on attenuation of the pressure amplitude probing the tissue, and the wavelength dependent resolution. Examples of bandwidths in excess of 150% with center frequencies of 9–15 MHz have been reported using Polyvinylidene Fluoride (PVDF) as well as capacitive microfabricated ultrasound transducer (cMUT) probes [9–11].

A major goal in transducer development has been the construction of electronic volumetric arrays, which would allow for simultaneous beam-steering in the axial, lateral and azimuthal directions and the acquisition of full volumetric data sets (focused in all three dimensions) [10–13]. Moreover, volumetric arrays would permit true vector velocity flow imaging, since a volume data set allows flow to be interrogated at multiple angles, which could be combined to determine the true 3D flow vector. The challenge in construction of volumetric arrays has always been the large number of elements (10,000+) and, while multiplexers in the transducer handle have limited the number of wires necessary for use it will not be trivial to construct volumetric arrays operating at the higher frequencies required in breast imaging. Nonetheless, commercial volumetric phased as well as linear arrays for use in echocardiography are now available from several manufacturers [12,13]. These matrix arrays can produce real time 3D imaging (over 20 volumes per second), but they operate at frequencies too low to be suitable for breast imaging (i.e., <7 MHz; resolution of approximately 500 μm).

3. Whole breast ultrasound screening

Whole breast ultrasound screening studies to date have focused on women with elevated breast cancer risk and/or dense breast tissue [14,15]. When comparing mammography alone to screening with ultrasound and mammography the largest study to date (the ACRIN 6666 trial) involving over 2800 women found an additional 1.1 to 7.2 cancers per 1000 high-risk women; albeit with a marked increase in the number of false positives [14]. This group of investigators also compared ultrasound screening alone to conventional mammographic screening and concluded that cancer detection rates were comparable [15]. As before, false positives were more common with whole breast ultrasound screening.

However, screening examinations can be time consuming and hand held transducers are by definition limited to a 2D field of view. These exams may take up to 30 min compared to roughly 10 min for a mammogram, although with less patient discomfort and no associated radiation. As an alternative, large field of view systems capable of scanning an entire breast using very large linear arrays (14–15 cm in length) have been developed for screening purposes [16–18]. Automated 3D whole breast ultrasound systems allow the technologist to acquire high quality images (resolutions < 300 μm) in the standard mammographic views across three planes and have been shown to achieve the same diagnostic accuracy (>87%) as hand held ultrasound [16,17]. The FDA approved automated breast ultrasound in 2012 as an adjunct screening modality to mammography in asymptomatic women with dense breast tissue (breast density scores of 3–4, based on a mammography-indicated density of over 51%) for whom screening mammography findings are normal or benign. With depiction of the coronal plane, mass margins, shape, spiculations, and distortion associated with tissue retraction are visible [16–18].

4. Image acquisition and processing techniques

Two image acquisition techniques – compound imaging and tissue harmonic imaging (THI) – have become the bread and butter processing techniques of clinical breast imaging [19–23]. In spatial compound imaging several (typically 3–9) ultrasound images are acquired at different angles of insonation and averaged to produce a single image. Averaging reduces speckle and improves the delineation of lateral borders, which results in increased conspicuity of low-contrast lesions, enhanced delineation of capsular margins and ducts, and better overall image quality when using spatial compounding compared to conventional imaging [19,20,23]. Similarly, frequency compounding uses multiple filters to create images from different received frequency bands. These images are subsequently averaged to suppress speckle, increase contrast resolution and improve penetration [21]. Frequency compounding is also less susceptible to the depth-related issues that affect spatial compounding.

In THI mode, the scanner is configured to receive echoes at double the transmit (or fundamental) frequency. By optimizing the receive filters for the weak, nonlinear tissue signal components that arise once sound waves propagate some frequency dependent distance into the tissue, it is possible to reduce echoes from clutter and side lobes at the fundamental frequency, while improving contrast resolution and border delineation [22,23]. The grayscale contrast between glandular or fatty tissue and breast lesions is improved with THI compared with conventional breast ultrasound [22]. The simultaneous use of spatial compounding and THI increases overall image quality and lesion conspicuity, and is now recommended in routine clinical practice [23].

MicroPure (Toshiba America Medical Systems, Tustin, CA) is a new commercial ultrasound image processing technique that post-processes grayscale ultrasound images in order to improve the visualization of breast microcalcifications [24–26]. This software uses a filter technique, where each pixel is compared to the average brightness of the surrounding area, to detect locations where there is a characteristic change from surrounding area [24]. As the focus of MicroPure imaging is to detect microcalcifications in breast tissue, the filter kernel is optimized in the horizontal direction to detect only isolated points with higher brightness compared to the surrounding breast tissue [24–26]. An example of this technique being used to improve ultrasound visualization of microcalcifications in the breast is provided in Fig. 1. Independent investigations have established that MicroPure can detect more microcalcifications than standard ultrasound in women presenting with microcalcifications seen on mammography [24,25]. However, this method is not appropriate for a screening population as it does not possess the same level of sensitivity as mammography, and should be used in more focused applications such as for guiding a biopsy [26].