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● *Original Contribution*

PLANE-WAVE COMPOUNDING IN AUTOMATED BREAST VOLUME SCANNING: A PHANTOM-BASED STUDY

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Abstract—The goal of this study was to assess whether it is viable to implement plane-wave imaging in the Automated Breast Volume Scanner (ABVS) to speed up the acquisition process. This would allow breath-hold examinations, thus reducing breathing artifacts without loss of imaging quality. A calibration phantom was scanned in an Automated Breast Volume Scanner-mimicking setup using both dynamic receive focusing with a fixed transmit focus and unfocused plane-wave compounding. Contrast-to-noise ratio and lateral resolution were compared using two beamforming schemes, delay-and-sum and Stolt's *f–k* algorithm. Plane-wave compounding using only 11 compounding angles and Stolt's *f–k* algorithm provided image quality similar to that of focused transmission with dynamic receive focusing (contrast-to-noise ratios = 10.3 and 10.8 dB for Stolt's *f–k* migration with Hann apodization and focused transmission, respectively; full width at half-maximum = 0.38 and 0.4 mm, respectively; all at 30-mm depth with transmit focus at 30 mm) with a higher signal-to-noise ratio at all depths. Furthermore, a full 3-D volume of a breast-mimicking phantom was scanned using this optimal set of compounding angles and different speeds (10, 20 and 50 mm/s) to assess the impact of scanning time on image quality. Only minor differences in contrast-to-noise ratio were found (cyst 1: 6.0 ± 0.3 dB, cyst 2: 5.5 ± 0.2 dB, cyst 3: 5.7 ± 0.5 dB). These differences could not be correlated to the movement speeds, indicating that acquisition speed does not significantly affect image quality. Our results suggest that plane-wave imaging will enable breath-hold automated breast volume scanning examinations, eliminating breathing artifacts while otherwise preserving similar image quality. (E-mail: gijs.hendriks@radboudumc.nl)

Key Words: **Automated Breast Volume Scanner, Plane-wave imaging, Breast ultrasound, Fourier-domain beamforming, Ultrafast imaging.**

INTRODUCTION

Breast cancer is the most commonly diagnosed type of cancer and the most common cause of cancer death in women worldwide (Torre et al. 2015). To improve its therapeutic prospects, it is vital to have high-quality diagnostic methods that can detect the disease at an early stage. The current standard in breast cancer screening, mammography, has two main shortcomings: (i) it cannot differentiate well between cysts and solid masses, and (ii) its sensitivity is low for women with dense breast tissue (Kolb et al. 2002). Unfortunately, women with dense breasts tend to have a higher risk of cancer (Boyd et al. 2007). Increasingly, hand-held ultrasound (HHUS) is being used as an additional diagnostic imaging method to assess malignancy in patients whose mammogram is hard to interpret because of the presence of dense tissue. This leads to an increase in sensitivity and detection rate (Ohuchi et al. 2016). However, the main drawback of HHUS is its non-reproducibility during subsequent screening procedures, as well as its limited scanning area. Furthermore, the recall has to be done by the operator himself, and batch reading is not possible.

Previously, the Automated Breast Volume Scanner (ACUSON S2000 ABVS, Siemens Medical Solutions, Mountain View, CA, USA) was introduced. This device allows acquisition of large 3-D breast volumes in a single scan by linear movement of a wide 1-D linear array transducer over the breast at constant speed. Thus, the ABVS

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enables user-independent acquisition of US data. Clinical results of the ABVS suggest sensitivity and specificity similar to those of hand-held ultrasound (Wang et al. 2012). However, the relatively long scan times (~90 s per volume, 3–5 volumes for each breast) can be uncomfortable for the patient. Furthermore, artifacts resulting from patient breathing can decrease image quality (Fig. 1). Therefore, it would be highly desirable to improve the acquisition speed of the ABVS while maintaining comparable image quality. In this way, breathing artifacts would be reduced and patient comfort would dramatically increase.

Currently, the ABVS uses focused US imaging, which constructs the image line-by-line, requiring at least one transmission per line. This means that the acquisition time is directly proportional to the width of the transducer and the line density. Because of the extraordinary width of the ABVS transducer, which is 154 mm, and the high line density resulting from the large number of elements, the acquisition times are very long. An alternative to focused imaging is acquisition of the image using plane-wave imaging, first proposed back in 1979 (Delannoy et al. 1979a, 1979b). Hereby, the entire image is obtained by transmitting a single unfocused plane wave in the tissue. Thus, if, for example, 128 lines are acquired in focused imaging, the obtained speedup is 128×, allowing for high frame rates far beyond the heartbeat or breathing frequency. In B-mode imaging, plane-wave imaging has limited applicability because of its lower lateral resolution, lower contrast-to-noise ratio (CNR) and lower penetration depth compared with focused imaging. This is caused by the lower acoustic energy density in the tissue, which again lowers the scattering intensity and results in a lower signal-to-noise ratio (SNR) in the received signal.

An increase in signal strength and diagnostic image quality can be achieved by steering multiple plane waves at different angles, performing the beamforming for each one separately and summing the signals afterward. Hereby, the summation can be performed coherently or incoherently. Incoherent summation has already been studied for focused imaging (see, *e.g.*, Berson et al. 1981; Jespersen et al. 1998) and was reported for plane-wave imaging (Cheng and Lu 2006; Lu 1997, 1998). Because of the averaging of different frames, noise is suppressed. Higher SNR, higher CNR and artifact reduction (shadowing, clutter) are reported. A drawback is the decrease in lateral resolution, as well as a possible signal decorrelation in the images caused by tissue and/or transducer movement during acquisition. However, this effect should not be dramatic in plane-wave imaging, as this technology allows for very high frame rates, thus limiting signal decorrelation.

Coherent spatial compounding is another way of improving image quality with multiple plane-wave transmissions. The idea is to average the beamformed radio-frequency (RF) signals instead of the absolute intensity. This was first proposed by Kyong Song and Chang (2004) and was extensively studied by Montaldo et al. (2009). The authors illustrated experimentally that coherent compounding dramatically improves overall image quality (lateral resolution, CNR) while still preserving a speed advantage over a focused acquisition. Additionally, they theoretically compared plane-wave compounding and focused imaging.

In addition to the transmission scheme, beamforming also heavily affects image quality, more so in plane-wave imaging than in focused imaging, as plane-wave transmissions are unfocused and so only beamforming in receive is applied. Different plane-wave beamforming approaches have been studied, some of which were usually implemented in time domain, such as delay-and-sum (DAS) and minimum variance (MV) beamforming (Austeng et al. 2011), and some are based on the frequency-domain representation of the signal, for example, Lu's algorithm (Cheng and Lu 2006; Lu 1997, 1998) and Stolt's *f–k* migration algorithm (Garcia et al. 2013).

The aim of this study was to investigate if it is possible to replace conventional (focused) scanning in

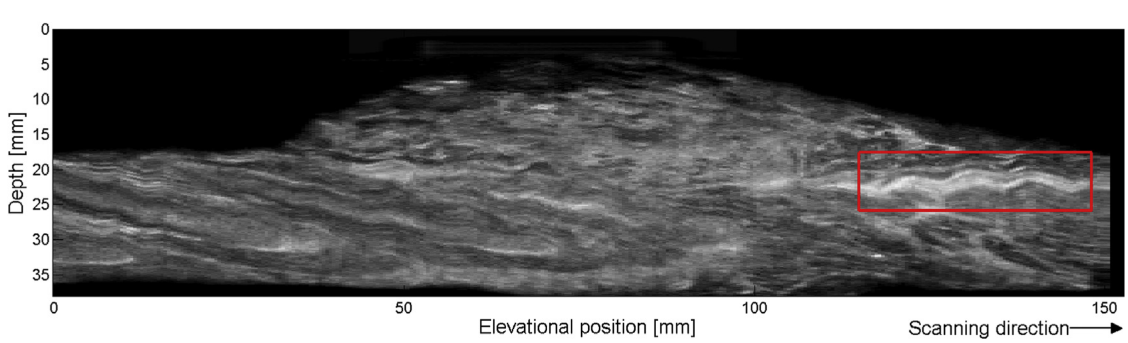

Fig. 1. Sagittal plane view of a 3-D breast volume acquired by the Automated Breast Volume Scanner. Breathing artifacts are clearly visible in the image as waves in the scanning direction (*red rectangle*).