Ultrasound is emerging as a potential adjunct to digital mammography (DM) for breast cancer screening, and could be particularly useful for dense breasts. DM is known to have significantly lower sensitivity for dense breasts [2], but the rate of interval cancers is four to six times higher in highest density breasts (≥75% density) than in fatty breasts (<5% density) [3]. In automated breast ultrasound (ABUS), a transducer scans across the breast and acquires many shots, which constitute a 3D image. ABUS is being explored as an alternative to hand-scanning for its potential advantages such as increased efficiency [4] and consistency. In addition to raising cancer detection rates, it is also important to keep false-positive rates low, as recalls can have a high financial and psychological cost to patients [5,6]. Several studies, mostly in dense breasts, have shown increased breast cancer detection rates at similar or significantly lower false-positive rates with the addition of ABUS to DM [7,8,9]. Other studies in dense breasts show only increased cancer detection rates, but a large accompanying percent increase in the false-positive rate [10,11]. These studies and their results are summarized in tabular form in a recent review article on ABUS [12].

Digital breast tomosynthesis (DBT) is a technique where X-ray images are acquired over an angular range and reconstructed into a 3D X-ray image. DBT has been found to be more sensitive to cancer than DM in dense breasts [13]. DBT and ABUS can be registered to simplify radiologist evaluation of the two images. Since it is known that ABUS-DM registration is easier if the ABUS is performed in the mammographic geometry (as is often the case), it stands to reason that ABUS-DBT registration would also be simplified, assuming the DBT is performed in the mammographic geometry (as is often the case). ABUS in the mammographic geometry will be referred to as mammographically configured ABUS (McABUS). Registration is further eased if the McABUS and DBT are a combined system rather than separate systems requiring separate breast positioning and compression [1]. We are aware of three combined ABUS-DBT systems that have been developed and evaluated in preliminary studies, two in the mammographic geometry and one where the patient is lying down and the breast hangs into a fluid bath [1,16,17].

SECOND GENERATION COMBINED McABUS-DBT SYSTEM

The FDA-approved supine screening system, the Invenia (GE Healthcare, Sunnyvale, CA, USA), was combined with our prototype DBT unit [18,19] to make our second generation combined McABUS-DBT system. The transducer frame of the Invenia was modified and integrated into a mammography compression paddle that could be inserted into the DBT system. DBT imaging proceeds with the Invenia transducer frame swung upwards out of the X-ray path [Figure 1]. This frame swings down on top of the breast for the McABUS imaging, which is a single 10 cm long sweep with the 15.4 cm wide, 6 to 15 MHz bandwidth (center frequency 10 MHz) Invenia transducer moving from the chest wall to out past the nipple. The sweep produces a 3-D B-scan ultrasound image volume with dimensions 15 x 10 x 5 cm. The transducer and compression paddle are curved to improve contact with the breast and patient comfort.

The prototype DBT can scan in multiple different modes, but for our study with the second generation
combined system we acquired nine projections over an angular range of 24 degrees. A Simultaneous Algebraic Reconstruction (SART) algorithm [20], was used to transform the angular images into a set of slices parallel to the X-ray detector. These slices had resolution 0.1 x 0.1 mm and a spacing of 1 mm.

In a preliminary evaluation of this system [1], 13 patients had cephalocaudal (CC) and mediolateral oblique (MLO) images taken with the DBT, and a CC image taken with the McABUS. In some cases, an MLO image was also taken with the McABUS. The DBT imaging was done first, and then polysonic ultrasound lotion (Parker Laboratories, Fairfield, NJ, USA) was squeezed directly through the mesh paddle on top of the breast. Then the Invenia frame was swung down and McABUS imaging proceeded. After all cephalocaudal imaging, the breast was released and recompressed for the mediolateral oblique imaging with the DBT and possibly McABUS. The patient maintained the same orientation for the cephalocaudal and mediolateral oblique imaging, and the McABUS and DBT modalities were rotated about the patient.

DETECTION RESULTS

Out of the 13 cases, six contained a cancer, and 5/6 cancers were detected by at least one of the two modalities. The DBT found 5/6 cancers and the McABUS found 3/6 cancers. The one cancer missed by both the DBT and the McABUS was too small to see in the DBT and it is unknown whether it was out of the field of view of the McABUS or again simply too small to be seen. This 6 mm cancer was detected clinically through palpation. The McABUS also missed two other cancers because of limited depth penetration. Eight benign masses were seen on at least one of the DBT or McABUS. The DBT found 6/8 of these masses and the McABUS found 4/8. The two masses missed by the DBT were missed because of high breast density. For the masses missed by the McABUS, two of these masses were missed due to limited depth penetration and the other two were too close to the chest wall and therefore out of the field of view.

EXAMPLE CASE

A case where a cancer was visible in both the McABUS and the DBT is presented as an example of dual-modality cancer visualization [Figure 2].

-REGISTRATION ANALYSIS

The ease of McABUS to DBT registration for our second generation combined system is compared with that of a previously designed combined McABUS-DBT system [16] and a standalone dual-sided McABUS system [21]. These systems will be referred to as the first generation combined system and the standalone system, respectively. For this analysis, only cases with clearly visible masses were included. We approximate the registration as a simple translation, and find this translation from the offset between the position of the mass in the McABUS and the position of that same mass in the DBT. Once the calibration offset is accounted for in this translational offset, we are left with a real physical spatial displacement, which will be referred to as the alignment error. The absolute-value alignment errors are shown in Fig. 3, and the statistical significance of the results are given in Table 1.

DISCUSSION

From this study, two major limitations of our second generation combined system were determined which could lead to potential improvements. One is the excess width of the Invenia transducer housing, which was included for patient
The absolute-value alignment errors (in mm) along all three axes are given for first- and second-generation combined systems and the standalone system.

**Figure 3.** Absolute-value alignment errors. The means and standard deviations of the absolute-value alignment errors (in mm) along all three axes are given for first- and second-generation combined systems and the standalone system.


...comfort in the supine geometry, but in the mammographic geometry prevents the transducer from getting as close to the chest wall as would be desirable. Minimizing the thickness of the transducer body and transport frame would increase chest wall coverage. Beam-steering or tilting of the transducer towards the chest wall at the start of the sweep are also possibilities.

The second limitation is the depth penetration of the McABUS, which resulted in the McABUS missing two cancers. At a center frequency lower than 10 MHz depth penetration could be increased, at the cost of a lower spatial resolution. This could be a desirable tradeoff for screening purposes if false-negative recall rates are not significantly increased. An alternative method to increase depth penetration without sacrificing spatial resolution is dual-sided McABUS imaging [21]. There were no clear improvements that could be determined for the DBT modality.

McABUS-DBT imaging could not be carried out simultaneously in our setup because the McABUS would block the X-ray beam path. As such, the compression time for the patient was guaranteed to be greater than or equal to the sum of the McABUS and the DBT imaging times. For the first generation combined system, the compression time was about 30 minutes. In the second generation combined system, the McABUS imaging is performed much more quickly, and the compression time is cut to about 15 minutes. Minimal compression times are critical for maintaining patient comfort.

Performing DBT and ABUS in the mammographic geometry enables easy comparison with DM. Increased sensitivity to breast cancer over DM alone would be expected, particularly in dense breasts. Registered McABUS and DBT images provide complementary information on the identity of masses, which would help keep the false-positive rate low.

**References**


