Real Time Spatial Compound Imaging in breast ultrasound: technology and early clinical experience

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In current clinical practice, high-resolution real-time ultrasound has an established and important role in the diagnosis and management of breast disease. It is used as an adjunct to mammography and clinical breast examination[1] to evaluate lesions when findings in those examinations are indeterminate. Ultrasound imaging often allows the clinician to classify a breast mass as benign or malignant by using established descriptive parameters.[2] Sonographic features used to characterize a mass include its shape, orientation, echogenicity, heterogeneity, margin characteristics, and posterior acoustic shadowing or enhancement.

These characteristics can aid in assessing the level of suspicion of a mammographically indeterminate lesion, and therefore help determine if a biopsy is indicated. Ultrasound is also an efficient tool for guidance of fine needle aspiration and core biopsy of suspicious breast lesions.

Ultrasound, like all imaging modalities, is subject to a number of inherent artifacts that compromise image quality. For example, ultrasound images are degraded by coherent wave interference, known as "speckle", which gives a granular appearance to an otherwise homogeneous region of breast parenchyma.[3] Speckle reduces image contrast and detail resolution, and diminishes the ability to differentiate normal and malignant tissues within the breast. Speckle artifact reduces the conspicuity of small, low contrast lesions and masks the presence of calcifications, an important indicator of possible malignancy. Conventional ultrasound images also exhibit a form of acoustic noise, known as "clutter", that arises from sidelobes, grating lobes, multi-path reverberation, and other acoustical phenomena. Clutter consists of spurious echoes, which can often be visualized within a breast cyst. Clutter may lead to concern whether a cyst is truly "simple", or whether it is a complex cyst that contains purulent matter or haemorrhage.

In conventional ultrasound, the breast is insonified from a single direction, and thus all the ultrasound beams are parallel, as portrayed in Figure 1a.

This gives rise to "acoustic-shadowing" artifacts behind high-attenuation structures, and "acoustic enhancement" artifacts behind low-attenuation structures. In some cases, these artifacts provide useful diagnostic criteria. Central shadowing is frequently associated

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Figure 1: Comparison of conventional and compound acquisition with a linear-array transducer.

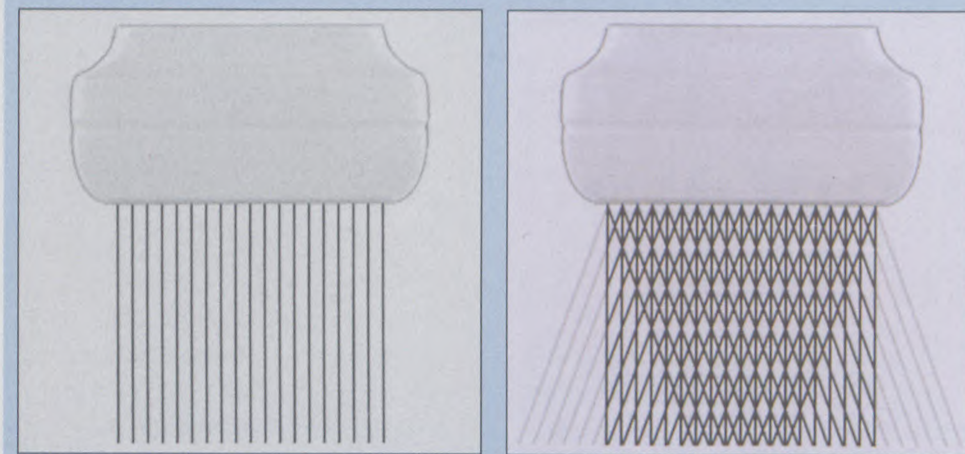

Figure 1a: Conventional acquisition: all scan lines are parallel to each other, and perpendicular to the face of the transducer.

Figure 1b: Compound acquisition: successive frames use different steering angles. The outermost regions of the compound image may not be included in the display.

with malignant solid lesions, and posterior enhancement is characteristic of simple cysts.[4] However, shadowing can also confound the diagnostic process. Strong shadows can obscure anatomy posterior to an attenuating mass. Small spurious shadows, cast by refraction from normal or benign anatomic structures, can be distracting and misleading. The sonographer must manoeuvre the transducer to view suspicious shadows from a variety of angles to verify the origin of the artifact, and exclude a small, occult malignancy.

Conventional ultrasound is also prone to reflection artifacts from specular (mirror-like) reflectors, such as those that arise from thin pseudocapsular margins, lactiferous ducts, and connective tissue within fat lobules. Because of the single "look direction", those portions of specular structures perpendicular to the ultrasound beams produce strong echoes or "glints", but tilted or "off-axis" reflectors may produce weak echoes, or no echoes at all (acoustic "drop out"). This, especially when combined with speckle artifact, produces a discontinuous appearance of structures which are, in fact, curvilinear and continuous.

Real Time Spatial Compound Imaging technology

The application of compounding principles to real-time ultrasound imaging is not new,[4,5,6] but the practical implementation of this technology has only recently been made possible by the substantial computational power of modern, all-digital ultrasound systems. Compound Imaging starts by acquiring multiple frames from different viewing angles, as shown in Figure 1b. These overlapping frames are then combined to form a real-time compound image on the display. Compound Imaging can be implemented on a conventional ultrasound system, with two modifications.

First, the beamformer electronics must be programmed to acquire ultrasound beams that are steered "off-axis" from the orthogonal beams used in conventional ultrasound. The number of frames and steering angles varies, depending on the transducer characteristics and the clinical application. In general, the more frames in the compound acquisition sequence, the better the compound image quality.

Second, the image processor must be programmed to accurately render the steered frames into the appropriate display geometry, and then combine them by frame averaging. The compound image is updated as each new frame is acquired, so there is no reduction in frame rate. However, frame averaging introduces a "persistence" effect, with the potential for image blurring if the transducer or the target move too rapidly. In general, the more frames in the acquisition sequence, the greater the improvement in image quality and the greater the potential for motion blurring. This results in a tradeoff between improving image quality and minimizing motion blurring. However, this tradeoff can be optimized differently for different clinical applications. In addition, the availability of a "survey" mode which minimizes blurring, and a "target" mode which maximizes image quality, can be used to optimize Real Time Spatial Compound Imaging for different scanning protocols.

The ability of Compound Imaging to improve image quality primarily depends upon suppressing image artifacts. In principle, scanning from different angles produces different artifact patterns. Averaging these independent frames suppresses the artifacts and reinforces real structures. The greatest improvement occurs in the central, triangular region of the image where all the component frames overlap. Less improvement occurs in the peripheral regions of the image where fewer frames overlap.

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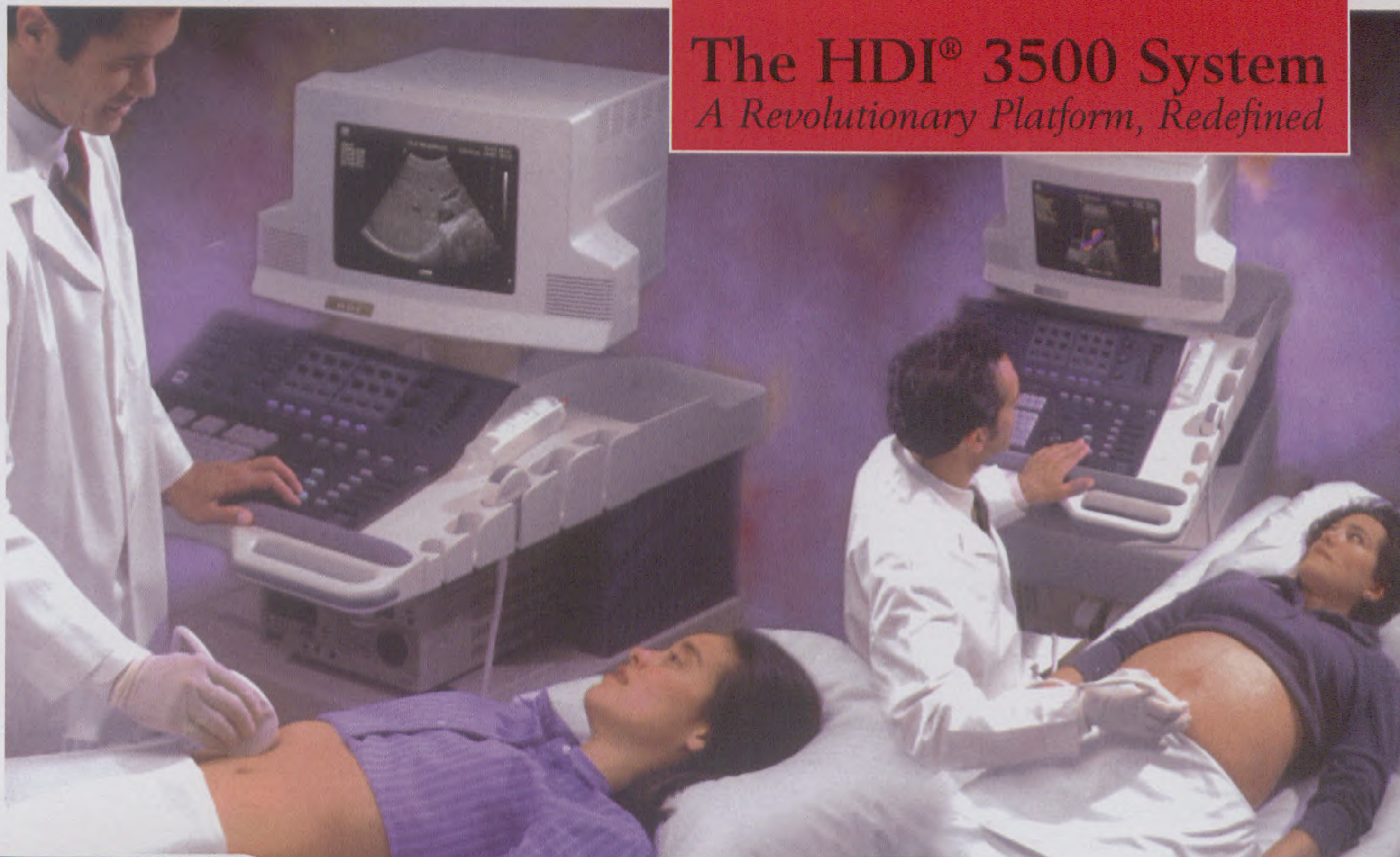

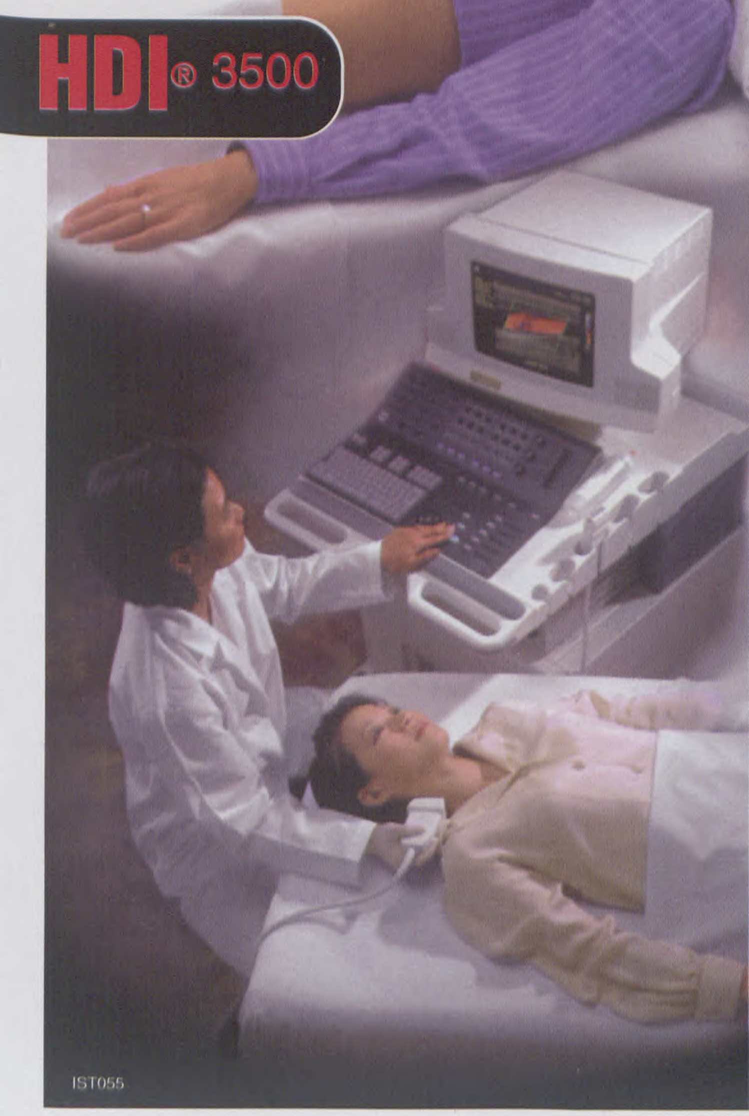

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For example, frames acquired from sufficiently different angles contain independent random speckle patterns. Frame averaging reduces the random brightness fluctuations due to speckle. The significance of speckle reduction can be appreciated in Figure 2, which shows reduced speckle and improved tissue differentiation of fat and fibroglandular tissues. The speckle signal-to-noise ratio (SNR) is an objective figure-of-merit for quantifying the amount of speckle in an ultrasound image.[7] Compound Imaging can improve the speckle SNR by as much as a factor of the square root of N, where N is the number of overlapping frames. With five frames, Compound Imaging improves the speckle SNR by more than a factor of two compared to conventional ultrasound.

Figure 2: Speckle reduction.

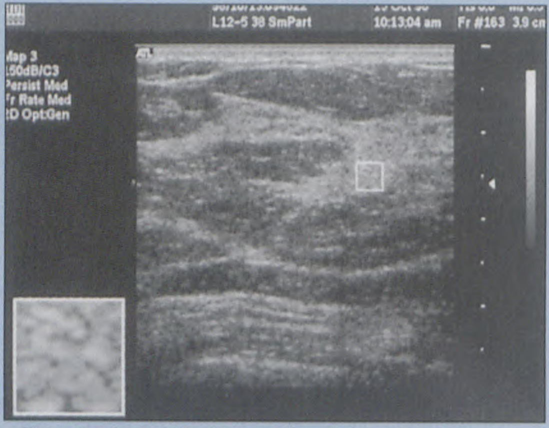

Figure 2a: Conventional image: fat and fibroglandular breast tissue both have a grandular texture (inset) with apparent lack of continuity between structures.

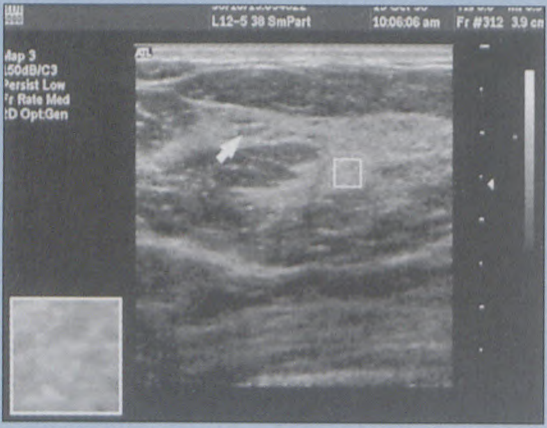

Figure 2b: Compound image: speckle suppression produces a smoother image texture (inset), and improves delineation of boundaries between structures such as the small segments of ducts (arrow) within the glandular breast tissue. Also note the improvement in the linear striations within the fat lobules.

Compound Imaging also suppresses the clutter obtained from different viewing angles. This is demonstrated in Figure 3, which shows significant clutter reduction in a simple cyst. The continuity of specular reflectors should also be improved by Compound Imaging, because a larger portion of each specular structure will be perpendicular to one of the different steering angles. This is depicted in Figure 4, which shows improved linearity and continuity of the branching ductal structures in the breast.

Figure 3: Clutter suppression.

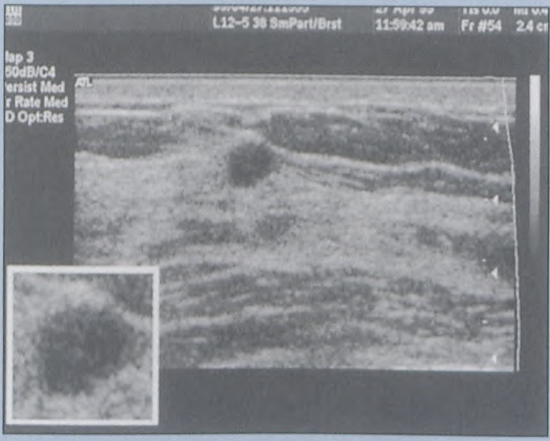

Figure 3a: Conventional image: acoustic clutter produces spurious echoes within a simple cyst (inset), which can be difficult to eliminate regardless of incident angle or adjustment of system parameters.

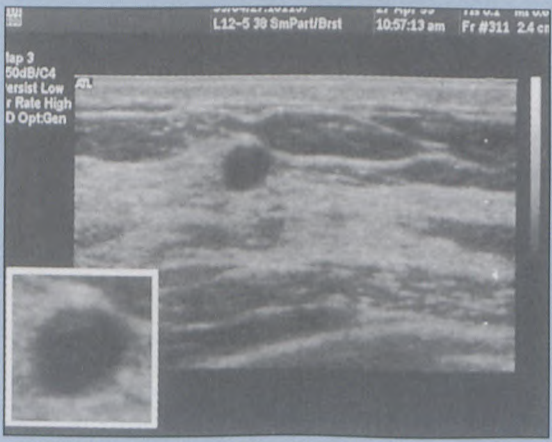

Figure 3b: Compound image: Compound Imaging results in significant clutter suppression in the cyst. Also note the good depth of field in this single focus compound image, comparable to the multi-focus conventional image.

Compound Imaging is expected to preserve central acoustic shadowing and enhancement, which are important sonographic characteristics. In a compound acquisition of a lesion with central shadowing, shadows caused by attenuation within the lesion will be cast in different directions, as shown in Figure 5. When the frames are averaged, the non-overlapping portions of the shadows will be diminished, while the overlapping shadows immediately behind the lesion are reinforced. Thus, central shadowing (and likewise enhancement) should not be eliminated, but concentrated in an elongated triangular region behind the structure that causes it. The enhancement posterior to a fibroadenoma, represented in Figure 6, demonstrates this effect.

Another source of shadowing is refraction of the ultrasound beam by normal or benign anatomic structures, such as blood vessels, cysts, pseudo-capsules around solid nodules, or Cooper's ligaments. Refractive shadows hinder the diagnostic process

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Figure 4: Continuity of linear structures.

Figure 4a: Conventional image: normal breast with branching lactiferous ducts (arrow) in glandular tissue, with adjacent fat lobule. A variety of benign and malignant tumours can arise from or within the ductal structures of the breast.

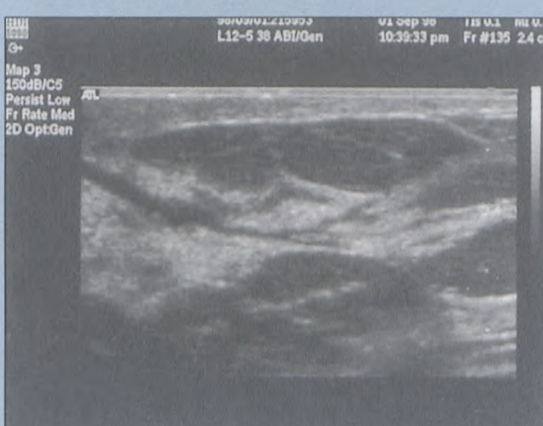

Figure 4b: Compound image: compounding improves delineation of ductal branches, which appear at numerous angular orientations. Improved continuity of linear striations within the surrounding fat lobule is also noted.

because they can mimic the central shadows from small occult malignancies. However, the aetiology of refractive shadowing is entirely different. Refractive shadows only occur when the ultrasound beam encounters a tissue interface at certain "critical" angles. Compound Imaging acquires frames from multiple angles, so a refractive shadow is not likely to be present in each frame. Therefore, frame averaging suppresses the refractive shadow. By contract, central shadows from malignancies arise from acoustic attenuation of the beam, which is independent of incident beam angle. Figure 6 demonstrates that Compound Imaging suppresses the refractive edge shadows from the pseudo-capsule of a fibroadenoma. In order to identify refractive shadowing from Cooper's ligaments with conventional real time ultrasound, clinicians routinely scan from different angles, apply pressure with the transducer, or alter patient position. If the shadow persists regardless of scanning angle, a malignancy may be present. If the shadow disappears with transducer angulation or compression, it is probably a refractive shadow associated with a Cooper's ligament. Compound Imaging should help identify the cause of shadowing quickly, without excessive manipulation of the transducer.

Early clinical experience

The preliminary clinical evaluation of Real Time Spatial Compound Imaging was conducted at First Hill Diagnostic Imaging in Seattle, Washington. The primary objective was to assess the clinical advantages and limitations of Compound Imaging compared with conventional ultrasound for targeted breast ultrasound examinations. The equipment used was an ATL HDI 5000 ultrasound system, with an L12-5 38 and an L12-5 50 high frequency linear array transducer. The system settings were optimized for imaging the breast. The prototype software in the HDI 5000 system was modified to support both conventional and compound scanning modes.

Figure 5: Central shadowing diagram.

Figure 5a: Conventional image: attenuating mass casts a stark shadow, obscuring detail posterior to the mass.

Figure 5b: Compound image: shadowing is concentrated in a triangular region behind the lesion.

Fourteen patients were examined. They were referred for advanced staging of breast cancer, for evaluation of indeterminate mammograms, for follow-up of complications of breast surgery, or for monitoring for local

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recurrence. Informed consent was obtained from each patient after the nature and intent of the procedure had been fully explained. The patients were evaluated with both Real Time Spatial Compound Imaging on the HDI 5000 and with conventional ultrasound on either the same HDI 5000 or on an HDI 3000. Patient medical history, previous mammograms or sonograms, and in some cases MR contrast breast studies, were used in conjunction with the ultrasound examinations.

Figure 6: Central enhancement and edge shadowing.

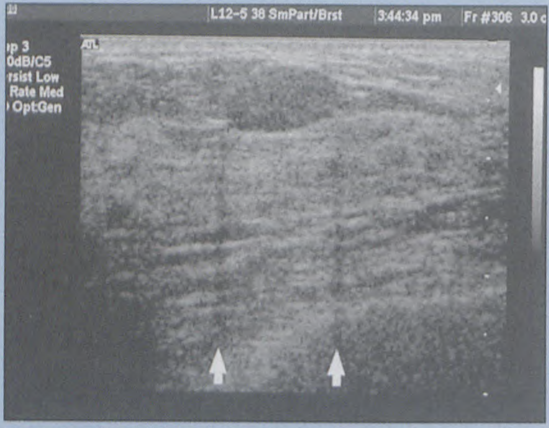

Figure 6a: Conventional image: benign fibroadenoma with refractive edge shadows (arrows) and mild posterior acoustic enhancement.

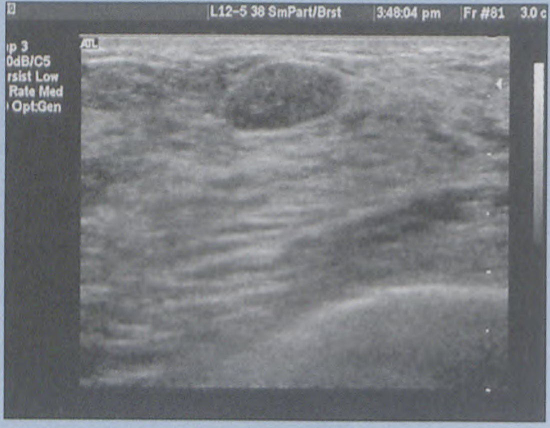

Figure 6b: Compound image: acoustic enhancement is preserved and appears somewhat triangular, as predicted in Figure 5b. Also note suppression of refractive edge shadows, improved portrayal of internal architecture, and better delineation of the fibrous capsule around the mass.

In all fourteen cases, Compound Imaging significantly reduced the appearance of speckle and improved contrast resolution. Compound images were qualitatively smoother, with no apparent loss of detail. The echo amplitude and texture of fat were strikingly differentiated from glandular tissue in the breast. Compound Imaging was also found to reduce clutter, unmasking subtle underlying diagnostic details. For example, clutter in the hypoechoic central cores of two carcinomas was suppressed by Compound Imaging, revealing small punctate calcifications. Also, in several cases, the apparent reduction of image noise and clutter extended the depth where valuable diagnostic information was visualized. This was particularly noticeable at depths greater than three centimetres.

Compound Imaging improved the continuity of specular reflectors, such as the thin, echogenic pseudo-capsule around a fibroadenoma. Although capsular margins were evaluated with conventional ultrasound, this required physical manipulation (rocking and heeling) of the transducer to view the margin from various angles, as described by Stavros *et al.*[2] The multiple steering directions employed by Compound Imaging improved the continuity of specular reflectors in real time, without significant physical manipulation of the scanhead. Lateral boundaries of masses, where conventional ultrasound is more subject to "drop out", were particularly improved by Compound Imaging. Striations within fat lobules and pectoral muscle were markedly more apparent and continuous with Compound Imaging. Depiction of the internal architecture of solid lesions was also improved.

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