Ultrasound Computed Tomography
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Ultrasound (US) is an indispensable tool of medical imaging that has sustained remarkable growth over the past several decades. It is interesting to note that despite undergoing many significant technical advancements over this period, the basic imaging paradigm of US has remained unchanged, namely image formation results from transmit-receive detection of 180 degree backscatter assuming straight-line propagation. For more that 20 years, quantitative Ultrasound Computed Tomography (USCT), which attempts to create images from both transmitted and scattered signals, has been researched by several groups with varying degrees of success. It can be shown that conventional US imaging is actually a subset of USCT and to this end a brief historical perspective on the pioneering works of many scientists will be presented, including some present at this conference.

While pulse-echo US provides a two-dimensional image of relative tissue “echogenicity,” USCT attempts to compute quantitative three-dimensional maps of tissue acoustic properties, usually sound speed, attenuation, compressibility, scatter density, etc., while accounting for refraction, reflection, multiple scattering and more. Significantly, laboratory and *in vivo* measurements have suggested that normal breast tissue, benign lesions and cancerous lesions may be identified by these inherent acoustic properties (particularly sound speed and attenuation). In general, due to limitations of both instrumentation and algorithms, the early methods used two-dimensional linearization techniques to solve what is inherently a non-linear and three dimensional problem. In order to capture a large segment of the scatter field around the object, these methods have been attempted only in the breast. From this early work it is now clear that the range of tissue properties encountered in the breast is sufficiently large that linear approximations lead to severe artifacts and inadequate spatial resolution. Recently, new methods capable of implementing advanced USCT algorithms in patients and are progressing towards clinical use. A review of these new scanner systems will be presented.

One such breast scanner, developed by Techniscan Medical Systems, Inc. (Salt Lake City, Utah), was installed at the University of California, San Diego to evaluate clinical feasibility of using USCT to analyze and detect breast masses. The system uses a multi-frequency non-linear 3D inverse-scattering algorithm. Until very recently the engineering technology and mathematical methods for full-wave inverse-scattering 3D tomography have been so complex that practical results in humans were not realized. To solve the numerically ill-conditioned problem of full-wave inversion, discrete frequency domain data is used by a 3D inverse-scattering algorithm that incorporates multiple scattering within and between the planes. The starting estimate for the 3-D algorithm is a time-of-flight reconstruction followed by a series of 2-D inverse scattering reconstructions that are concatenated together. Local minima encountered in the non-linear optimization are avoided by discrete frequency hopping from low to high (0.3-2 MHz). Despite computational complexity of the problem, the method solves an accurate approximation to the full Helmholtz equation. Recent advancements using a GPU cluster complete the full inversion within approximately 30 minutes, a remarkable accomplishment given the very large computation cost. In its current form, 3D volumes of the entire breast are reconstructed as accurate maps of sound speed, attenuation and aberration-corrected reflectivity (Figure 1).

System performance and tissue characterization are excellent. Accuracy and linearity of sound speed measurements by USCT is very high (R^2=0.988) over the range of 1400 to 1600 m/sec Fig. 2). The FWHM of the point spread function is 1.5 mm in the inverse-scatter images and approximately 0.5 mm in the reflection tomograms. Sound speed and attenuation reliably classify tissue and mass types (Figure 3) and the volumetric images provide detailed depiction of the masses (Figure 4).

Additional motivation for the continued interest in USCT is that conventional breast sonography is a notoriously difficult exam to perform. The quality and reproducibility of the results are highly dependent on the skill of the operator and the radiologist as well as the technical features of the scanner. In order to obtain the needed high resolution the field of view in sonography is very small, which greatly complicates interpretation and localization of a mass. USCT promises an essentially automated scanning system that does not depend on operator expertise. Furthermore, the images present a global view of the entire breast in 3D, facilitating comparison to prior exams including mammography and MRI, as well as aiding surgical intervention.

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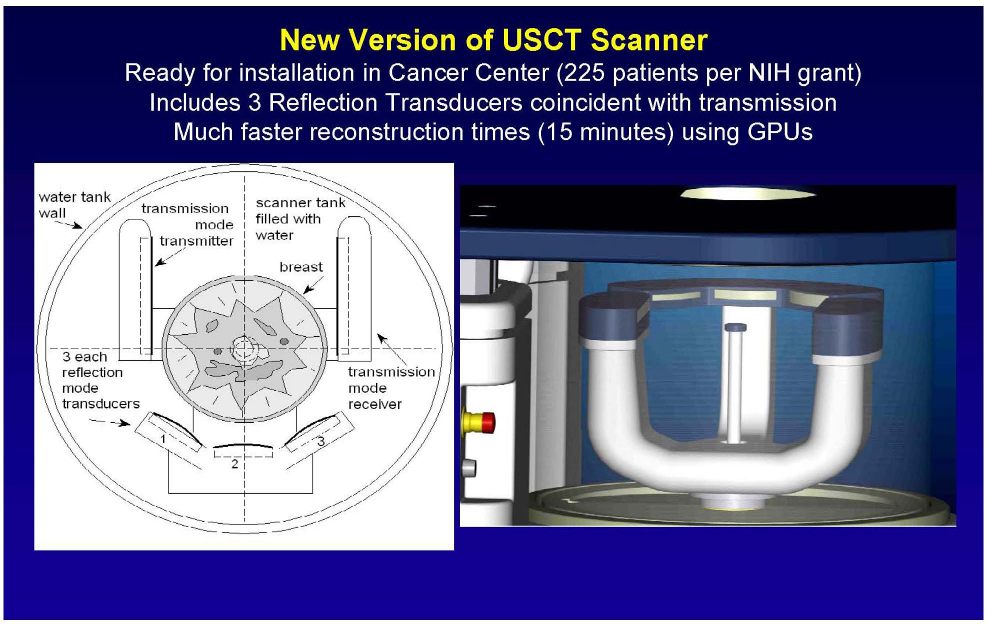

Figure 1. New scanner with transmission and reflection transducers.

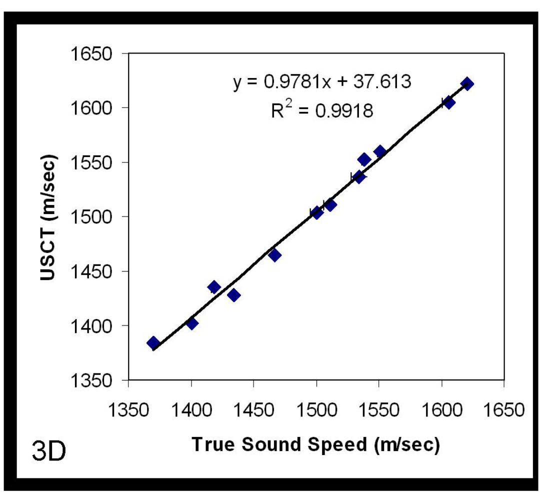

Figure 2. Measured sound speed vs. true sound speed

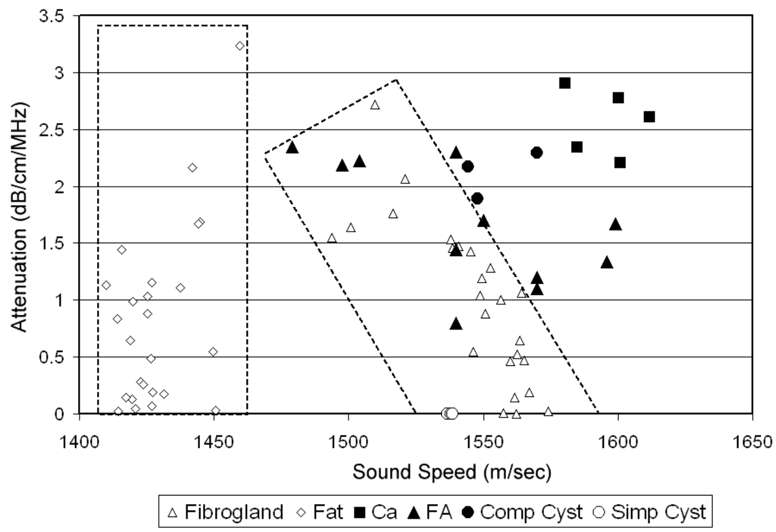

Figure 3. Sampling of acoustic properties of normal tissues and masses

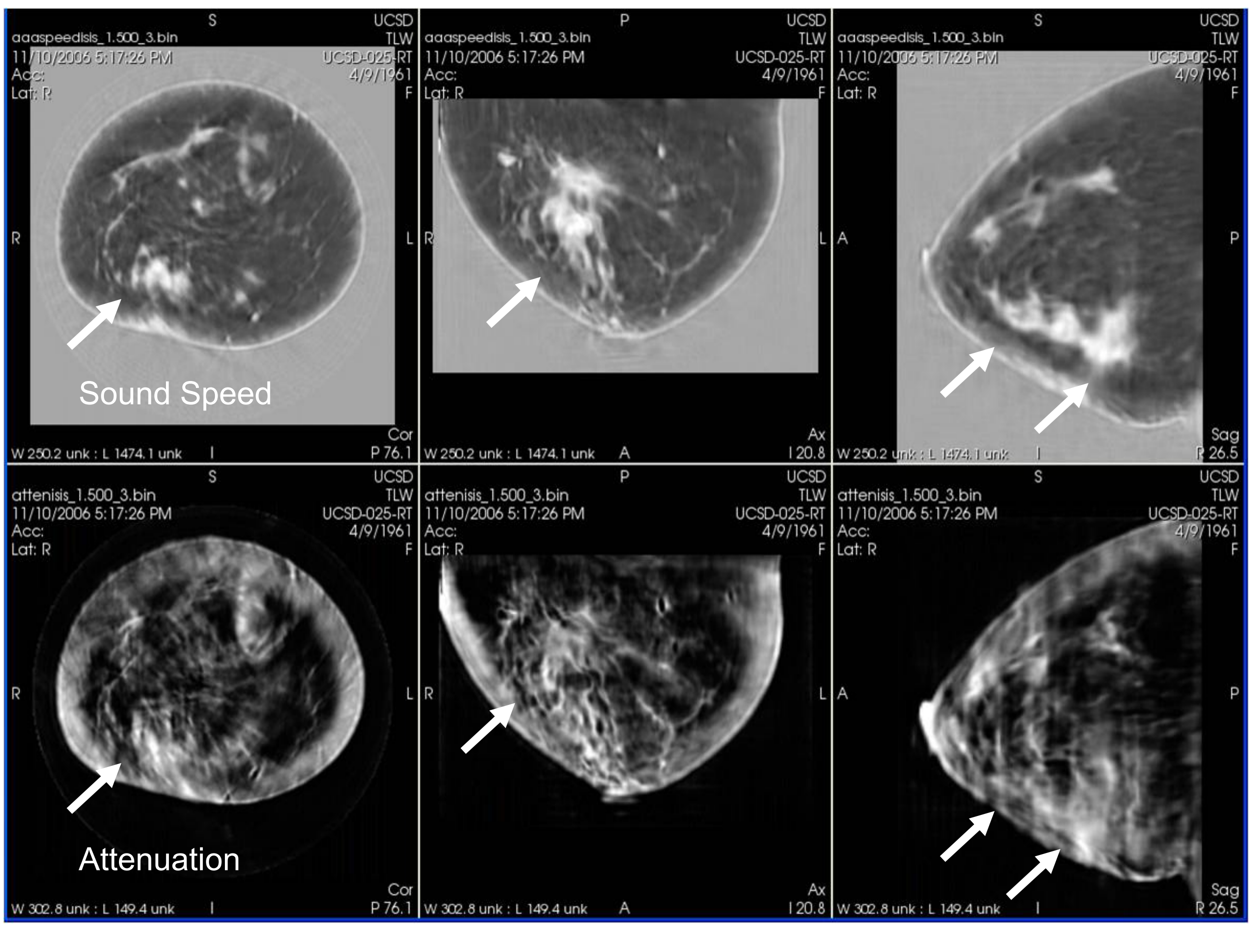

Figure 4. Invasive Tubular Carcinoma, spiculated mass with high Speed (upper row) and high Attenuation (lower row) viewed in coronal, axial and sagittal planes from left to right.