Breast Ultrasound: Current Technology and Clinical Applications

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Breast Ultrasound

• First breast US image 1953 (A line mode, linear 15 MHz transducer)
• Ultrasound has been used to characterize breast masses since 1980’s.
• Recent technological advances in spatial and contrast resolution.
• Today – breast US is an indispensable adjunct to mammography in detection and characterization of breast masses
Breast Ultrasound

• Evaluation of abnormal findings on mammography
• Palpable masses not visible on mammography may be visible on ultrasound
• Ultrasound guidance for biopsy
• Identification of lesion location for surgical/treatment planning

BI-RADS classification

“Breast Imaging Reporting and Data System” diagnostic categories

BI-RADS 1: negative
  2: benign finding
  3: probably benign; short term follow-up recommended
  4: suspicious abnormality; biopsy recommended
  5: highly suggestive of malignancy
  6: known biopsy-proven malignancy
Breast Ultrasound

• Benign conditions:
  – simple cysts
  – Fibroadenomas
  – Intramammary lymph nodes

• Ultrasound indicators of malignancy:
  – Acoustic shadowing
  – Complex structure, irregular boundaries
  – Orientation perpendicular to tissue structures
  – Calcifications
  – Development of vascularity (Doppler)

Simple cysts

• Characteristic appearance on ultrasound:
  Anechoic (fluid filled), distal enhancement

• Quality control phantoms include anechoic objects
Fibroadenomas

Common, benign, often non-palpable. Made of glandular and connective breast tissue, tend to parallel tissue structure.

Malignancies

- Acoustic shadowing
- Irregular borders
- Perpendicular, crossing tissue layers
Breast Ultrasound

• Detect and characterize abnormalities within glandular or fatty tissue
• Differentiate benign from malignant conditions
• Requires high resolution imaging
• Methods to enhance contrast for a variety of tumor/tissue types.

• Ultrasound image formation
• Technological developments
  – Improvements to spatial resolution
    • Beam formation
    • Speed of sound correction
  – Improvements to contrast resolution
    • Temporal, spatial and frequency compounding
    • Harmonic imaging
  – Extended FOV imaging
  – Ultrasound elastography
How does U/S work?

Pulse repetition frequency ~ 0.5 - 20 kHz

Distance = $\frac{1}{2} \times (\text{Speed of sound}) \times (\text{Total Travel Time})$

Sound interactions in tissue

- Scattering
- Diffuse scattering
- Absorption
- Reflection, $90^\circ$
- Reflection, $\neq 90^\circ$
- Refraction
Sound propagation in tissue

• Speed
  – Depends on tissue
  – Scanners assume 1540 m/s
  – Breast tissue 1450 m/s
• Attenuation ~ 0.5 dB/cm-MHz
  – Higher frequency transducers – more attenuation
  – Trade-off between resolution and depth of penetration
• Reflection/transmission at tissue interfaces a function of acoustic impedance contrast: \( z=\rho c \) (Rayls)

Array transducers


• Small spacing between elements < \( \lambda/2 \) (minimizes grating lobes)
• Multi-frequency broad bandwidth transducers: 13-5 MHz
Transmit Focus

Selectable focal depth controlled by transmit/receive timing delays. Delays rely on speed of sound assumptions. Timing delays also used to “steer” the beam.

Dynamic Receive Focus

- Transmitted pulse
- As echoes arrive, delays adjust to focus echoes from progressively deeper structures.

Axial resolution

- Depends on pulse duration, bandwidth
- Pulse duration in μsec or cycles/F(MHz)
- Short, high frequency pulses → better axial resolution, also increased attenuation, reduced penetration
- $C = 1540 \text{ m/sec}$

$$\Lambda.R. = \frac{P.D. \times c}{2} = P.D. \times 0.75 \text{ mm}$$
Axial resolution

Horizontal spacing: 2 mm, 1 mm, 0.5 mm, 0.25 mm
Vertical Spacing: 2 mm, 1 mm, 0.5 mm, 0.25 mm

4 MHz 12 MHz

• Depends on wavelength (\(\lambda\)), aperture size (D), and focal distance (F)
• Best resolution at the focal depth
• For deeper focus, dynamic aperture must increase to maintain the same lateral resolution


Lateral (azimuthal) resolution

• Depends on wavelength (\(\lambda\)), aperture size (D), and focal distance (F)
• Best resolution at the focal depth
• For deeper focus, dynamic aperture must increase to maintain the same lateral resolution

Lateral resolution

- Dynamic aperture adjusts to activate more elements as echoes from deeper depths arrive.
- Maintains uniform lateral resolution with depth.

Elevational resolution (slice)

- 1D arrays
- Fixed focal lens in elevational direction.
- Size of aperture limited
Matrix arrays

• Elevation beam forming
• “1.5D, 1.75D” arrays
• Dynamic focus in the elevational direction to improve slice resolution


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Speed of sound correction

• Fatty tissue imaging
• Phase aberration correction
Speed of sound correction

Effect on transmit focus:
Transducer element time delays determine depth at which signal will arrive in phase. Time delays depend on sound speed assumption:
Focal Point F for \( C_0 = 1540 \text{ m/s} \)
Focal Point \( F' \) for slower velocity \( C' \)

\[ F' = \left( \frac{C_0}{C'} \right)^2 d \]
where \( d \) is the true depth

Chen & Zagzebski. Ultrasound in Med. & Biol 30(10), 2004
Speed of sound correction

Simulated B-mode images:

a) fixed transmit/receive focus, c=1540 m/s
   Dynamic receive focus:
   b) c=1540 m/s
   c) c=1450 m/s
   d) c=1630 m/s

Speed of sound difference from machine’s calibrated value results in poorer lateral resolution at most depths and inaccurate axial position (error increases with depth).

Chen & Zagzebski. Ultrasound in Med. & Biol 30(10), 2004

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Speed of sound correction

Phantom:
   c = 1540 m/s

FTI assumes
   c=1450 m/s

Mismatch between speed of sound in phantom and calibrated SOS: reduced lateral resolution

FTI Off  "Fatty Tissue Imaging" FTI (Siemens Antares)
Ultrasound Quarterly. 25(3):141-144, September 2009

\[ c = 1540 \text{ m/s} \]

Speed of sound correction
\[ c = 1450 \text{ m/s} \]

Improved resolution and border definition between dense/fatty breast tissue

\[ c = 1540 \text{ m/s} \]

Speed of sound correction
\[ c = 1450 \text{ m/s} \]

Improved lateral resolution of calcifications
Speckle reduction

- Speckle – small scale brightness patterns superimposed throughout US images. Reduces contrast resolution and obscures small structures.
- Caused by constructive/destructive interference of coherent waves. Speckle pattern changes with insonation angle and frequency.
- Approaches to reducing speckle:
  - Spatial compounding (SonoCT, SieClear)
  - Frequency compounding
  - Computer enhancement (XRES)

Compounding

Reduce speckle (improve contrast resolution)

- Temporal compounding (persistence)
  - Several frames acquired and averaged
- Spatial compounding
  - Combine images from multiple insonation angles
- Frequency compounding
  - Combine frames acquired with different frequencies
Spatial compounding

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

Fig. 1b. Compound acquisition: successive frames are different imaging angles. The convergent region of the compounded image may not be included in the display.

Greater # beams- reduces frame rate


Spatial compounding

With spatial compounding:
Improved border delineation of cysts, reduction in reverberations, changes appearance of refraction shadowing.

Spatial compounding

With spatial compounding:
Smoother image, reduced speckle

Compounding

WARNING

Because SonoCT imaging creates a compound image from multiple transmit angles, it may change the appearance of acoustic shadowing. Consider this change in appearance when evaluating the composition of a cyst or tumor.

Philips iU22 user manual
Tissue Harmonic Imaging

- Technology enabled due to development of broadband transducers
- Arises from pressure dependence of sound speed
  - Compressional wave is faster than rarefractional wave
- Transmitted fundamental frequency develops harmonics as it travels through tissue.


Harmonics

- Transmit frequency (fundamental) $f_0$
- Harmonics produced by non-linear propagation of the ultrasound wave

Tissue harmonic imaging

• Harmonic images have improved spatial and contrast resolution:
  – Harmonics formed at main lobe
    • Narrower beams
    • Lower sidelobes
  – Much acoustic noise generation at fundamental

• The fundamental and accompanying artifacts are removed –
  – Reduces artifacts
  – Reduces clutter, increasing contrast resolution
  – Improves border definition

Harmonics

• Receive higher order harmonics $2f_0, 3f_0, \ldots$

• Harmonics have a narrower main lobe and reduced side lobes: improves spatial & contrast resolution
Tissue Harmonic Imaging

CONVENTIONAL US  THI

Fibroadenoma  Hypoechoic, clearly delineated margins.

Tissue Harmonic Imaging

CONVENTIONAL US  THI

Indeterminate  Simple cyst
Invasive ductal carcinoma.
Hypoechoic mass, angular, poorly defined margins
Reduction in scatter and noise. Irregular borders, shadowing more apparent.

DCIS. Isoechoic mass, difficult to distinguish from surrounding tissue.
Hypoechoic mass, enhanced shadowing, defined margins.
Extended FOV imaging

Motion of transducer determined by correlating amount of speckle on adjacent frames.

“Panorama”, “SieScape”

Elastography

• Tissues respond elastically (Hooke’s Law) with application/release of compression, return to original size/shape.

\[
\text{Stress} = \text{Strain} \times \text{Elastic Modulus}
\]

• Stress = applied pressure (force per unit area)
• Strain = quantifiable change in object conformation
• Modulus = constant of proportionality (tissue dependent)
Elastography

Measure tissue deformation (strain). Benign lesions are more deformable than malignant lesions – appear smaller vs B-mode image. Ultrasound more sensitive measure than palpation.

Conclusions

- Breast ultrasound has evolved considerably since the first image was acquired in 1953 due to advances in hardware and software technologies.
- Improvements in spatial resolution and contrast resolution in particular, have led to increased sensitivity for detecting and characterizing breast masses.
- Emerging technologies: elastography, 3D/4D imaging, ultrasound contrast agents.
- Relative low cost, non-ionizing imaging modality provides an important adjunct to mammography (and MRI) in the detection and evaluation of breast cancer.
Selected References


