Ultrasonic Imaging Systems: From Principles to Implementation
Broad Outline of Course

• Ultrasound Scanners – Overview
• Beamformation - basics, implementation
• Analysis of beamformation
• Instrumentation
• Miniaturization
• Summary
The Healthcare Challenges …

**Healthcare costs**
- Enormous spend - $1.8T in US
- Admin costs = $300B
- Shrinking population of doctors
- System cannot handle excess capacity
- Chronic care = 70% of cost

**Clinical efficacy**
- 50% of heart failure = death (265k/yr*)
- $32B US* healthcare spend on strokes
- Adverse drug events = 770K US deaths or injuries / year**
- 9 people / 100 unintended infection

**Huge markets!**
- Traditional Diagnostic Imaging
- Broader Diagnostics Opportunity
- Pharma
- Global Healthcare Spend

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*American Heart Association, 2004
General Information about Ultrasound Scanners
Ultrasound Scanners

- Most often prescribed modality
  - Instrument sales: $4B
  - Rapid migration to smaller systems
Variety of Clinical Applications

> Portable
> Low-Cost
> Safe
> Real-Time

Ultrasound undergoing migration from Radiology/Cardiology to other specialists.
Some History

- Before the mid-70s
  - Single element scanners
- 1975 - 1980
  - Array based systems
    - Linear/curvilinear arrays
    - Linear phased arrays
  - Analog beamformation
    - Lumped constant delay lines
  - Typically 32 channels
- Mid 1980s
  - High channel count systems
  - High = 128
- Early 90s
  - Digital beamformation
- 1995 - ?
  - Mechanical and electronic 3D/4D
- 2000 - ?
  - Heavy Miniaturization
- 2003 - ?
  - Software beamformation

http://www.ob-ultrasound.net/articulated-arm.html
Overall Imager Block Diagram

- Transmit beamformation
  - relatively simple delay generation
  - ASICs, downcounters
  - generation of transmit codes

- Receive Beamformation
  - Data input:
    - sampled at 20 - 60 MHz
    - 8 - 14 bits
  - Most important roles:
    - Delay generation for:
      - Beam steering
      - Dynamic focusing
    - Dynamic apodization
  - Channel Count Definition
    - Many definitions, often marketing driven
    - I like definitions based on no. of ADCs
Image Data Acquisition

- Transmit beamformer generates pulser signals
- Transducer array converts electrical signals to pressure waves and vice versa.
- Pressure waves propagate through tissue – part of energy is reflected back to array.
- Receive beamformer takes received echoes and focuses energy.
- Image is formed from the beamformed signal and spatial data.
Beam Manipulations by the Beamformer
Focusing & Steering Delays

- Basic focusing type beamformation
- Symmetrical delays about phase center.

- Beam steering w. linear phased arrays.
- Asymmetrical delays, long delay lines
Image Data Acquisition

Multiple transmit focal zones

Transmit vector

Image formation using transmits along vectors and focal zones
Image Data Acquisition

Image formation using transmits along vectors and focal zones
Types of Arrays

Linear array beamformation:
- Generation of focusing delays
- Beam steering by element selection

Curvilinear array beamformation:
- Generation of focusing delays
- Beam steering by element selection

Linear phased array beamformation:
- Generation of focusing delays
- Beam steering by phasing
Array Geometries

Schematic of a linear phased array
Definition of azimuth, elevation
Scanning angle shown, $\theta$, in negative scan direction.
Similar definitions for a curved array
Some Basic Geometry

Delay determination:
- simple path length difference
- reference point: phase center
- apply Law of Cosines
- approximate for ASIC implementation

In some cases, split delay into 2 parts:
- beam steering
- dynamic focusing

\[ \tau = \frac{r - r_x}{c} \]

\[ \tau = \frac{1}{c} \left[ \sqrt{x^2 - 2rx \sin(\theta)} + r^2 - r \right] \]

\[ \tau = \tau_s + \tau_f \]

NOTE: On receive, dynamic focusing is used – \( r \) is a function of time.
Far field beam steering

For beam steering:
- easier to split the delays
- far field calculation particularly easy
- often implemented as a fixed delay

\[ \tau_s = \frac{x \sin(\theta)}{c} \]
Linear Scan - Transmit Beamforming
Coded Excitation and Transmit
Resolution / Penetration Dilemma

Transmit Energy Determines Penetration

Pulse Amplitude

FDA’s Mechanical Index Guideline

\[ MI = \frac{p_r^3}{\sqrt{f}} \]

Pulse Length

Longer pulse gains penetration but sacrifices resolution
Coded Excitation

Body

Transmitted Pulse Train

Received Pulse Train

• Sensitivity Increase

Encoder

1 1 1 0 1 0 1 1

Decoder

1 1 0 1 0 1 1 1

Coded Excitation improves sensitivity without resolution tradeoff
Coded Excitation - Experiment

Improve penetration by 3 cm with same resolution to -50 dB
Compounding

Compounding:
- suppress speckle to improve contrast

Spatial compounding:
- combine images from multiple angles

Frequency compounding
- combine images from different frequencies
Image Processing

Speckle Reduction

Speckle Reduction

Clarity
The basic algorithm behind speckle reduction

Smoothing and edge enhancement is performed at different scales and the outputs are combined to enhance contrast between both small details and larger regions.

Every pixel is filtered adaptively based on the content of surrounding pixels to prevent smoothing across boundaries and to enhance only true boundaries.
Beamshapes, Focusing, and all that
Anatomy of an ultrasound beam

Near field or Fresnel zone
Far field or Fraunhofer zone
Near-to-far field transition, $L$

$$L = \frac{D^2}{4\lambda}$$
Anatomy of an ultrasound beam

Spatial resolution, beamwidth

Depth of field (DOF)

F-number

\[ f \# = \frac{F}{D} \]

\[ bw = \frac{\lambda F}{D} = \lambda (f \#) \]

Closer focal locations have narrower beamwidths, shorter depths of field.
Narrow-band Far Field Analysis
Narrowband far-field analysis

• Totally unrealistic model
• Amazingly useful results
• will be used to introduce key points
Narrowband far-field analysis for a linear array

Think of an array as:
- infinite array of point sources
- confined by a \( \text{rect} \)-function

Apply spatial Fourier relation

Beam pattern is an infinite train of sinc-functions.

This model can be readily extended to 2 dimensions

\[
p(x) = \text{rect}\{L\} \cdot \sum_{n=-\infty}^{\infty} \delta(x - nd)
\]

\[
f(u) = F\{p(x)\}
= F\{\text{rect}[L]\} \ast F\left\{\sum_{n=-\infty}^{\infty} \delta(x - nd)\right\}
\]

\[
f(u) = \sum_{m=-\infty}^{\infty} \text{sinc}\left[\left(\frac{\pi L}{\lambda}\right)(u - m \frac{\lambda}{d})\right]
\]
Narrowband far-field analysis for a linear array

Illustration:
- 32 element array
- 3 MHz
- pitch \( d = 0.4 \) mm
  \[ = 0.51 \text{ mm} \]
- \( L = N d = 13 \) mm

NOTE: plot wrt to \( u \)!
Center beam is our main lobe.

Beamwidth:
- \( \lambda / L \) u-units

Side lobes critical for contrast resolution
Narrowband far-field analysis

Adjacent beams:
- grating lobes

Separation:
- $\frac{\lambda}{d}$ u-units

Beam steering:
- apply $\tau_s$ phase tilt

Danger!
- Grating lobes move w. main

Visible region:
- $\pm 0.707$ u-units or $\pm 45$ degrees

\[ \tau_s = \frac{x \sin(\theta)}{c} \]

Grating lobes avoidance increases cost
Grating Lobes

Main concern w. phased arrays
  **But** can show up in low f-# designs!

How to avoid:
  design for horizon-to-horizon safety
  safe pitch:
     \[ d \leq \frac{\lambda}{2} \]

Other points:
  wideband case
  sparse arrays

\[ d \leq \frac{\lambda}{2} \]
Side lobe suppression: Apodization

Implementation
- apply a weighting function on array elements
  - Multipliers
  - Pulser power supply weighting
- Complex control on receive

Main role
- Suppress side lobes
- Maintain image uniformity
- Supply walking aperture
Side lobe suppression w. apodization

Same array:
- 32 element array
- 3 MHz
- pitch \( d = 0.4 \) mm
- \( \lambda = 0.51 \) mm
- \( L = N d = 13 \) mm
With & w/o Hanning weighting.
Sidelobes way down.
No effect on grating lobes.

Tradeoff: wider main beam
Summary of Beam Processing

Beam shape is improved by several processing steps:
- Transmit apodization
- Multiple transmit focal locations
- Dynamic focusing
- Dynamic receive apodization
- Post-beamsum processing

Upper frame: fixed transmit focus
Lower frame: the above steps.
Harmonic Imaging
Harmonic Imaging

Perhaps the most important innovation of the last ten years.
Now default mode in most cardiac scanners
Discovery due to two major sources:
harmonic imaging for contrast agents
transducer bandwidth increases
Arises from pressure dependence of sound speed
compressional wave is faster than rarefactive
Need to understand via simulations.

Wojcik et al., IEEE95

Fig. 1. Acoustic waveform in the geometrical focus.

Nonlinear Propagation

During propagation, harmonics are formed.

Rate of generation of 2nd harmonic proportional to $p^2$.

This is equivalent to having an extra beamformer to narrow the beam shape.

Beamformer requirements:
 added transmit flexibility increased filtering capacity
Why are harmonic images so good?

Several reasons:
  harmonics formed at main lobe
    – narrower beams
    – lower sidelobes
  much acoustic noise
generation at fundamental
    – refraction from fat layers
    – reverberations near fat/muscle layers
Optimization of beamformers may be necessary.
Harmonic Imaging

Below are two images from Siemens’ web site. Clearly the cardiac structures are far clearer and blood pool areas have reduced noise.
Indeterminate vs simple cyst

Courtesy of Dr. T. Stavros
Axillary lymph nodes more hypoechoic
Contrast Agent Harmonic Imaging

Ultrasound contrast agents
Gas filled microbubbles
Strong harmonic response
  – Capitalized w. scanners
  – Transmit at f0, receive at 2f0.
Main clinical goal: perfusion
  – Myocardial perfusion & viability
  – Presence of tumors
Tissue harmonics confuse the issue
Trend toward low frequency (1.5 MHz) operation
Beamformation & Harmonics

Tissue Harmonics

Goal: best tissue images

Methods:
- Maximize harmonic energy
- Higher f-numbers to allow harmonic energy to accumulate
- Consider non-spherical focusing

Contrast Harmonics

Goal: Show distribution of contrast agents

Methods:
- Minimize propagation harmonic energy
- Transmit harmonic energy that cancels propagation related harmonics.
- Alternative phasing schemes

Two cases with diametrically opposed goals
Aberration Correction
State-of-the-Art in Ultrasound Imaging

Focusing = Geometry, or...

People are just bags of water

It’s a Crude Approximation
Real World Imaging

Fat and Muscle Layers Degrade the Image

Time-delay Errors from the Abdominal Wall are 10-50 Times Larger than beamformer delay quanta.

Digital Beamformer Accuracy is Wasted
Aberration Correction

• All beamformers today use an assumption of constant speed of sound.
• This assumption is not valid.
• In soft tissues, we have these speeds:
  fat       1440 m/s
  liver     1510
  kidney    1560
  muscle    1570 (skeletal), very anisotropic
  tumors    1620
• This variation limits further spatial & contrast resolution improvements.
Beamforming With Aberration

- Point-like scatterer
- Spherical wavefronts
- Aberrating Layer
- Transducer
- Geometric beamforming delays
- Channel data poorly aligned
Adaptive Imager

GE LOGIQ 700 MR Ultrasound Imager

Multirow Transducer

Interface Boards

Processor Board

Channel Data Beamsum Data 1.2 GB/s

Time delay Corrections 0.1 MB/s

Mercury Multiprocessor Computer

96 PowerPC Processors
In-Vivo Time Delay Correction

Pancreas and Superior Mesenteric Artery

SMA 4.4 dB darker, pancreas 1.4 dB brighter
Aberration Correction

- Perhaps the major beamformer related limitation today.
- Several groups throughout the world are addressing this issue.
- A feasible solution will have a major impact on clinical applications of ultrasound.
Channel Count Issues
With new systems, what will happen to Channel Count?

First 128 channel system introduced in 1983.
   Huge majority of high-end systems are still at 128 channels.
Does it make sense to go higher?
   What’s the cost/benefit trade-off?
   Will the performance improve proportionately to the cost?
What are some of the reasons for increasing it?
   Elevation focusing
   Real-time 3D/4D
   Aberration correction
Rationale for Elevation Beamformation

Limited performance available with 1D designs
- Poor beamformation away from elevation focus.
  - Fixed focus hurts performance
- Limits on size of elevation aperture due to fixed focus.
  - Depth of focus inversely related to aperture size.

Slice thickness improvement throughout image
- Expanding aperture, dynamic focusing in elevation

Greater acoustic power control.
- $l_{spta}$ location becomes more controllable.
Transducer Array Taxonomy

Array Element in Elevation

1D 1.25D 1.5D 1.75D 2D

Aperture

Fixed Discrete Dynamic Dynamic Dynamic

Focus

Static Static Dynamic, Symmetric Dynamic, No Symmetry Dynamic, Steerable Constraint
Single- vs. Multi-Row Arrays

Phantom with 2 mm Spherical Cysts
Channel Count Requirements

Channel counts for elevation focused systems. Let $N =$ azimuthal channel count desired, e.g. 128.

1.25D no increase over $N$.
1.5D assume 5 rows (3 independent), therefore $3N$ channels required
1.75D with 5 rows, $5N$ channels required
2D Arrays with 3,000 elements available, what about the cable?

But, for ergonomic scanning, limit to no. of cables is $256 – 512$. 
3D/4D Challenges
Mechanical 3D/4D Imaging

Attached clip with a mechanically scanned array.

8 – 16 vol/sec possible.

No compromise on 2D image quality.
Real-time 3D Beamformation
Fully connected 50 by 50 array
A Solution

Migrate beamformer components to handle.
With multi-row probes, muxing is in the handle.
Patent by Larson from 1993
    group 2D array elements into subarrays
    combine echoes from subarrays and send summed signals
cable count reduced w. reasonable spatial sampling.
Look for more system changes along these lines

Remaining Major challenge: Volume Rate
Migration of Beamformer to Probe handle.

- Connects a group of transducer elements to each system channel
- Low-power analog beamformer: Phase rotation or Delay lines
- Small delays only: static steering of small sub-aperture
- Dynamic focusing & full-aperture delays by system beamformer
2D Interconnect Strategies

Flex circuit between elements and backing:
- Complex, expensive multilayer flex
  + Transducer process similar to 1D arrays

Connections through backing:
- One flex per array row
  + Simple, inexpensive flex circuits
- More parts, more complex transducer process

Also need common electrical connection to front of elements

B. Savord & R. Solomon, Philips
2003 IEEE Ultrasonics Symposium
Patents by M. Greenstein & D. Miller
Real-time 3D/4D Imaging

RT3D promises to be yet another exciting stage for ultrasound.
Much work is on-going on defining clinical apps for this mode.
Many technical challenges remain

Multi-line acquisition
- Transmit broad beam
- Receive multiple (e.g. 16, 32, 64) beams simultaneously
Miniaturationization
Miniatuization of Scanners

Beyond the miniaturization for real-time 3D/4D:

Nearly fully-featured handheld systems are available.

Design issues:

- Level of compromise in performance required
  - Channel count reduction
  - Coarser sampling
  - Folded architectures
- Clinical utility realized
  - Portability is good but is the diagnosis?
How Miniaturization is Happening …

Typical scanner design
- Most functions processing rather than data acquisition oriented.
- Such functions can be performed by general purpose devices.
- Only purely ultrasound devices are transducers, pulsers, and TGC amps.

This is an interesting contrast with other modalities.

Migration of Functionality to Software

- Conversion to software
  - PC-based back end
    - Scan conversion
    - Doppler processing
    - Image processing
    - Networking
  - DSP-based signal processing
- Advances due to PC industry
  - Moore’s Law
- Wearable PCs
Digital Integrated Circuit Miniaturization

- Digital integrated circuit (IC) development (yellow blocks)
  - Continuous improvements in density of application specific ICs (ASICs)
  - Major impact: beamformer channels per chip
- Advances due to competition in semiconductor industry.
  - Moore’s Law once again
- Some migration to probe handle.
**Analog Integrated Circuitry (ICs)**

- Analog IC development
  - Slower size reduction than for digital ICs
  - These blocks include the most sensitive areas of a scanner
- Effort driven largely by ultrasound industry.
  - Moore’s Law less important.
- Migration of functionality to probe handle incl. analog beamformation.
What can we do with such small scanners?

**Possible applications:**

- Scanners with specialized roles
  - Example: dedicated vascular imager, carotid IMT, PWV
- Patient monitoring
  - Continuous blood pressure
  - Fetal Heart rate w. automated A/V-plane tracking.
  - Cerebral blood flow in early neonates

**Possible Patient Monitoring Areas**

- Continuous Blood Pressure
- Fetal Monitoring
- Neonatal Monitoring

[Images of monitoring devices and related technologies are shown.]