History of US Imaging

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Principal References

2. Medical Diagnostic Ultrasound: a retrospective on its 40\textsuperscript{th} anniversary, Kodak Health Sciences for the American Institute of Ultrasound in Medicine, 1988.
Presence/use of ultrasonics in animals

• Bats
  – Spallanzani demonstrated in the 1700’s a bat’s ability to navigate in the dark
• Bottle nosed Dolphin
  – 0.25-200 kHz
  – Lower frequencies for communication
  – Higher frequencies for echo location

Galton’s Whistle (~1900)

• One of the first (known) man-made ultrasound devices
• Resonance cavity, whose height is changed in known increments
• Knew precisely the frequency
• Used to determine that humans can hear frequencies up to ~18kHz

http://www.scienceandsociety.co.uk/results.asp?image=10317352
Important Early Developments

- Magnetostrictive transducers (Joule, 1840)
- Piezoelectric effect (Jacques and Pierre Curie, 1880) in quartz
- Reciprocal PZT effect (Lippman, 1981)
- Hydrophone (Langevin and Chilowsky, ~1914)
  - Sandwiched quartz array applied to underwater acoustics
- Underwater sonar (Langevin, “19-teens”; Fessenden)
  - Used in WWI
- Ocean liners equipped with sound ranging devices (~1930)

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Important Early Developments

- **Fessenden oscillator** is an electro-acoustic transducer
  - 1912, Submarine Signal Company of Boston.
  - It was the first successful sonar device
    - 540 Hz, air-backed circular plate; Morse code
    - 500 Hz, 1000 Hz and 3000 Hz devices
    - Scientific American's Gold Medal in 1929 for the fathometer, which could determine the depth of water under a ship's hull

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Bioeffects of US

• Noted by Langevin
  – (death of sea animals exposed underwater)
• Wood and Loomis work at Tuxedo Park, NY,
  – Rupture of cells
  – Death of frogs and fish
  – Pain to the hand when placed in the beam
• Early medical applications were in the area of therapeutics (treatment of gastric ulcers shown in the photo)

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Ultrasonic Flaw detectors

- Sokolov, 1930’s (through transmission)
- Firestone, 1940-42
  - Pulse-echo US
  - Two transducer operation shown here
    - Long “dead times” after transmit
    - Allows echoes from close up to be detected
  - A-mode display
    - Echo amplitude vs. time (depth)
  - Detect:
    - Dimensions
    - Cracks
    - Inhomogeneities
    - Layer thicknesses


Hyperphonography, Karl Dussik
One of the earliest attempts at imaging using ultrasound

- Exploring possibility of imaging intercranial structures
- Through transmission device

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(Patient with head immersed in a water tank; “1946”)
Hyperphonography, Karl Dussik

- Exploring possibility of imaging intercranial structures
- Through transmission device
- Optical recording or heat sensitive paper

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Hyperphonography, Karl Dussik

- Exploring possibility of imaging intercranial structures
- Through transmission device
- Optical recording
- Believed to be related to artifacts due to transmission through the skull
- A number of other attempts described to do neurological imaging

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Mid-line Machines (~1960’s, 1970’s)
(Echoencephalography; clinically accepted)

George Ludwig

- Throughout the late 1940's and early 1950's Ludwig experimented using ultrasound to
  - detect foreign bodies
  - Detect gallstones
  - Detect cancer

Electronic gear developed for radar was enabling technology for ultrasound.
(In 100 µs:
  - a sound wave travels 15.4cm in tissue
  - an em wave travels 18.6 miles in air.)
George Ludwig

- Brain, spleen, liver, kidney, 24-25°C
- Range: 1490-1610 m/s
- Average: 1540 m/s

Display technology used for ultrasound:
  - A-Mode
  - B-mode
  - B-mode imaging

In B-mode imaging, the position and orientation of the transducer (or the ultrasound beam origin and direction) is used to define the sweep direction on a display scope.
John Wild & Jack Reid

• Defined “1 D echogram”, “2-D echogram”

还想定义“1D echogram”和“2D echogram”

John Wild & Jack Reid

Howry et. al., Colorado

Used water path
Subject immersed in water within a tank
Transducer swept using a motorized system
Radar system was reconfigured for US.

Somascope, ~1952
Linear motion with sectoring
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Howry et. al., Colorado

Adapted radar rack
Lithium sulfate focused transducer (~ 2 MHz)

Somascope, ~1952
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Adapted radar rack

Lithium sulfate focused transducer (~2 MHz)

Somascope, ~1952
Linear motion with sectoring

Howry et. al., Colorado

Version 2, ~1954-1957
B-29 Gun Turret
1 focused transducer, 360 degree travel, linear sweep at each angle
(Lead weights helped the patient/subject remain submerged)
Howry et al., Colorado

Ultrasonic Tomographic Cross-Section of the Human Neck

Later generation water path scanners

Aloka water bag coupling, 1960  (UW had one ~1967)

Howry et al “Pan-Scanner” in 1957
Patient no longer had to be submerged, but was placed against a membrane window.

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Ian Donald

July, 1955, introduction to the Hughes MK4 Flaw Detector (after doing surgery on a patient whose husband was a principle of B&W ) (not Prof Donald in photo)

Carried tissue specimens to Babcock & Wilcox for measuring


Ian Donald

Fourteen week gestation showing echoes from the fetus. Patient had been thought to have had a fibroid. (Ref: Donald, I, MacVicar, J and Brown, T, “Investigation of abdominal masses by pulsed ultrasound,” Lancet 1958, 1(7032): 1188-95.)
Ian Donald

- Scanner in use from 1957 to 1964


Manual scanner of Holmes, Wright and Meyer, (Howry)

- Influenced by work of Donald et al
- Early version of a contact scanner (1964)
- Transducer moved manually
- Electronic devices tracked the motions
- Intensity modulated Storage oscilloscope

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Holmes, Wright and Meyer (Final Design)

- Influenced by work of Donald et al
- 3 rotatable arms, Sine-cosine potentiometers, wires
  - Position of transducer
  - Beam axis angle
- Storage oscilloscope

Final design
Became Physionics, 1963
Purchased by Picker, 1967

Picker Ultrasound Scanner (1971)
(Charles Kelsey, UW-Radiological Sciences)
AIUM 100 mm Test Object
useful for testing manual static scanners


Fixed arrangement of wire targets in water/alcohol having a speed of sound of 1,540 m/s

Picker B-Mode, ~1971

Long. Dorsal surface of tongue

Tongue blade, /u/

Tongue blade, rest

Tongue blade, /s/

Transverse, tongue blade

Manual scanners of the late 1960’s and early 1970’s (Picker; Rohe; Diasonics; Technicare; GE; Aloka; Siemens)

Bistable Storage Scope

Gray scale images:
- Manual (and artful) manipulation of the transducer
- Open shutter photographic recording of CRT screen


Water Path Scanners
Ultrasonics Institute, Sydney, Australia

• Kossoff, Robinson et al had been experimenting with water path scanners since the early 1960’s.
• Outstanding gray scale achieved by systematic motion of transducer, large aperture focused transducers offset from the patient

Patient on tilting gurney
Water bag brought up against, and wraps around maternal abdomen
Open shutter photographic recording

UI Bistable and gray scale in the 60’s and early 70’s

ASUM Ultrasound Bulletin 2004 August 7:3; 22-26
Water Path Scanners
Ultrasonics Institute, Sydney, Australia

- Octoson, ~1975
- 8 transducers in a water tank
- Patient coupling:
  - Gel/oil on membrane
  - Direct immersion

Gray Scale with Manual Scanners
(Analog, then Digital scan converter)

- Rather than write to a CRT, write to a storage device
  - Analog storage tube; run in “peak detection mode” so that it would not overwrite
  - Digital scan converters starting in the late 1970’s
- Output of image was to a TV monitor
  - “Venetian blind effect” during scanning
Real-time: hand-held mechanical transducers (~1973 ff)

WN McDicken, Diagnostic Ultrasonics, Principles and Use of Instruments, Wiley, 1981
Linear Array Technology (Bom)

Described in a 1971 Dutch patent

- **20 piezoelectric elements** (each 4mm x 10mm).
- Probe face was 80mm long and 10mm wide.
- 2.25 or 4.5 MHz
- frame rate of 150f/sec.
- The axial resolution was 1.25 mm at 3MHz
- Beam width at 6 cm was 1cm.
- Resulted in the 1972 “Multiscan” by
- Simple, basic design has evolved into the very sophisticated real-time scanners that are widely available today.

ADR Ultrasound Scanner (Wilcox)

- First generation ADR (1973)
  - 64 element array
  - Scanned “using stepping” element techniques (element groups).
  - Recognized as a ‘good-resolution’ abdominal linear-array scanner
- Second ADR model **the 2130** (1975)
  - application Focusing techniques.
  - sold over 5000 units worldwide.
- 3.0 MHz variable focus transducer (1980)
  - **506 piezoelectric elements**, 
  - both mechanical and phased focusing,
  - switchable focal zones.
  - More acoustic scan lines

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Phased Arrays For Cardiac Scanning

- Sommer, Netherlands, 1968 (Ultrasonics)
- Duke University work
  - 24 element phased array
- Varian Phased Array
  - V3000, ~1975
  - 32 elements
  - Mainly cardiac applications

Status of “Static,” single element transducer scanning and Real-time scanning in the early 1980’s

- Good gray scale using digital scan converters
- Image quality for abdominal scanning much better than real-time
- Often had a “real time”, hand-held probe (red) available for survey scanning
Static Scanner to Real-time only

- Originally, image quality of real-time (left) not considered as good as that of static scanners (right)
- As improvements were made, advantages of easy probe manipulation began to favor real time
  - “In the summer of 1980 we acquired another real-time machine and now there was no comparison in resolution and image quality; the new machine beat the static scanner hands down. With more than a twinge of sadness we concluded that the old [static] machine had to go.”
  
Array Beam Forming

Linear array imaging with a single focal depth
(Simulates single element transducer scan)

Array with receive beamforming”
(Modern version of Maslak “tracking lens”)

Importance of Channel Count
Allows larger aperture; improves lateral resolution

128 channels
32 channels
### Doppler and Color

- CW Doppler available in 1960's
- Pulsed Doppler late 1960's (U of Washington)
- Brandestini described multi-gated Doppler imaging method 1975; first color flow images, published in 1981
- Prior to 1985, "Duplex" Doppler, pioneered by ATL, was available on a few machines
- Aloka SSD880, 1985, introduced their color flow imager
  - Autocorrelation processor
- Quantum QAD-1 ~1986
  - Transducers had angled offsets to allow non-perpendicular incidence to vessels
- Most manufacturers followed with their own Doppler and color
- Today nearly all clinical exams include color, Doppler

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### Harmonic Imaging

- Common dolphins herd sardines with bubble nets
- Leighton et al (Southampton, UK) hypothesize dolphins may use nonlinear processing, sensitive to the nonlinear oscillations of bubbles in a sound field, to distinguish bubbles from prey.


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Tissue Harmonic Imaging (~1996)

Supposedly was being investigated for gas-bubble ultrasound contrast agents; secondary (ie, accidental) finding that it improved non-contrast studies.

Tissue Harmonic Imaging (1998)

“Noncontrast harmonic imaging significantly enhances suboptimal echocardiographic images, particularly in the regions distant from the transducer.”

Many other new techniques have been introduced in the late 1990’s and beyond

• Spatial compounding
• Frequency compounding
• Coded excitation
• Multi-D arrays to provide electronic control of slice thickness
• Hand held scanners [right]
• Elasticity imaging, ARFI
• Targeted and non-targeted US contrast agents
• Sound speed corrections (aberration corrections)
• 2-D arrays
• 3-D, 4-D imaging
• Plane wave imaging
Most common US machine processing paradigm

Focused transmit; channel data are combined in a "beamformer" 1 (or several) acoustic scan line(s) at a time.


Emerging US machine processing paradigm

Beam forming done on stored channel domain data. (Zonare)

Emerging US machine processing paradigm

Use plane wave transmit; resolution is degraded
Use several, angularly diverging plane wave transmits; resolution good at A
By adjusting phase of echo signals from the different transmits, recover resolution at B

Left, image of a phantom using focused transmit and line-by-line beam forming.
Right Image using synthetic focus of 7 angularly divergent transmit pulses, pixel processing


Conclusions

• Much of the development of ultrasound imaging was carried out by small, interdisciplinary teams of physicians, physicists, and engineers, each bringing their own interest, expertise, and vision to the task
• Ultrasound continues to evolve as new, and more cost effective methods, many driven by digital processing, are developed by these teams, by industry, and by partnerships between industry and academia.
Principal References