54th Annual AAPM Meeting
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History of US Imaging

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Department of Medical Physics

Principal References

1. *Dr. Joseph Woo, "*A short History of the development of Ultrasound in Obstetrics and Gynecology" at
   http://www.ob-ultrasound.net/history1.html
2. Medical Diagnostic Ultrasound: a retrospective on its 40th anniversary, Kodak Health Sciences for the American Institute of Ultrasound in Medicine, 1988.
3. Dr. William D. O'Brien, Assessing the Risks for Modern Diagnostic Ultrasound Imaging, at http://www.brl.uiuc.edu/Projects/Bioeffects/Assessing.php

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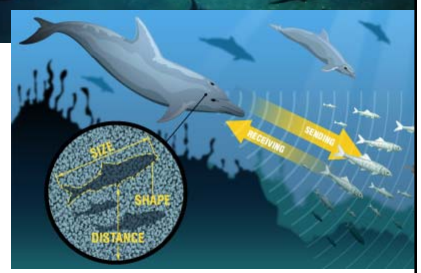
Presence/use of ultrasonics in animals

- 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

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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)

http://www.ob-ultrasound.net/history1.html

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

http://www.ob-ultrasound.net/history1.html

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http://www.ob-ultrasound.net/history1.html

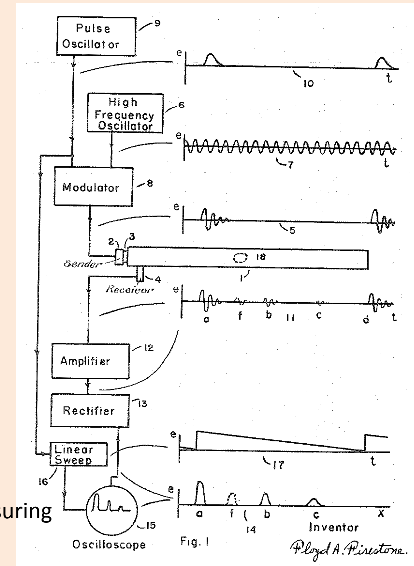
Bioeffects of US

- Noted by Langevin
  - (death of sea animals exposed underwater)
- Wood and Loomis work at Tuxedo Park, NY,
  - (R. W. Wood and A. L. Loomis: Philos. Mag. (VII) **4** (1927) 417.)
  - 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)

http://www.ob-ultrasound.net/history1.html

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
  - Later described the “reflectoscope”, a single transducer approach (F. A. Firestone: J. Acoust. Soc. Am. **17** (**1946**) 287.)

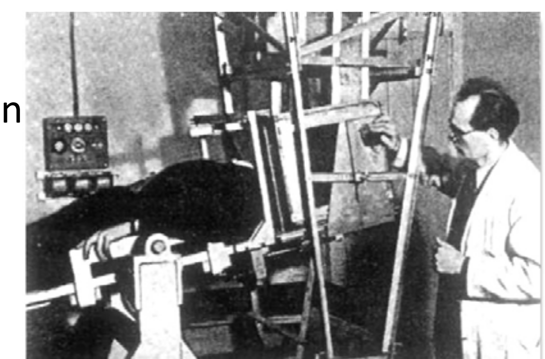


F.A. Firestone, “Flaw detection device and measuring instrument”, US Patent 2,280,226, **1942**

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

- Exploring possibility of imaging intercranial structures
- Through transmission device

http://www.ob-ultrasound.net/history1.html

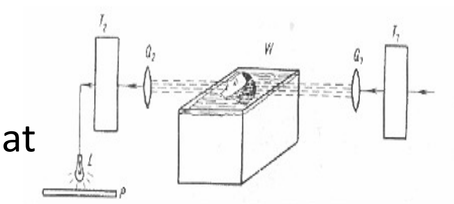


(Patient with head immersed in a water tank; ~**1946**)

Hyperphonography, Karl Dussik

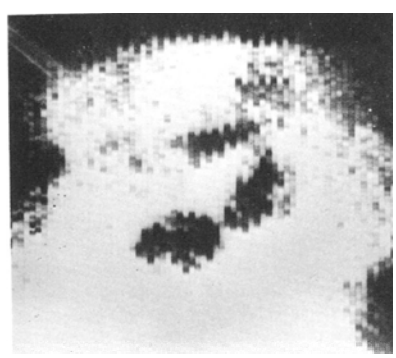
- Exploring possibility of imaging intercranial structures
- Through transmission device
- Optical recording or heat sensitive paper

http://www.ob-ultrasound.net/history1.html



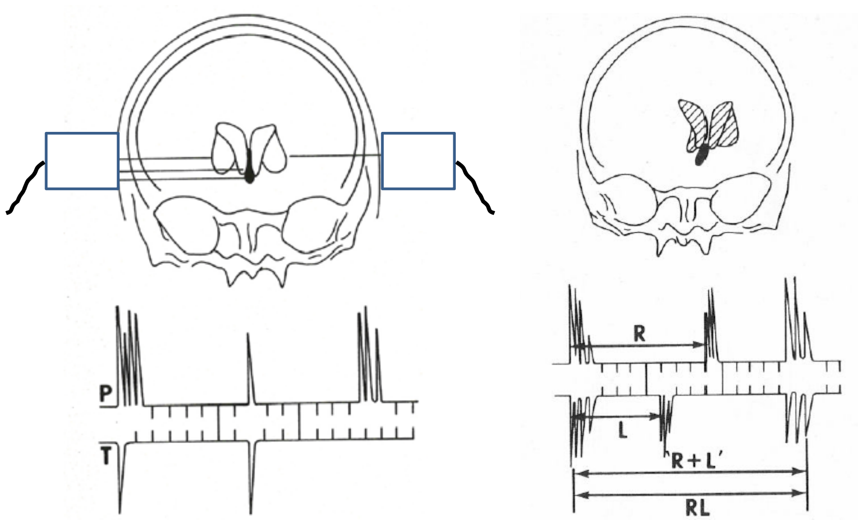
Hyperphonography, Karl Dussik

- 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



http://www.ob-ultrasound.net/history1.html

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



R. Brown, Ultrasonography: Basic Principles and Clinical Applications, Warren Green Pub, 1973.

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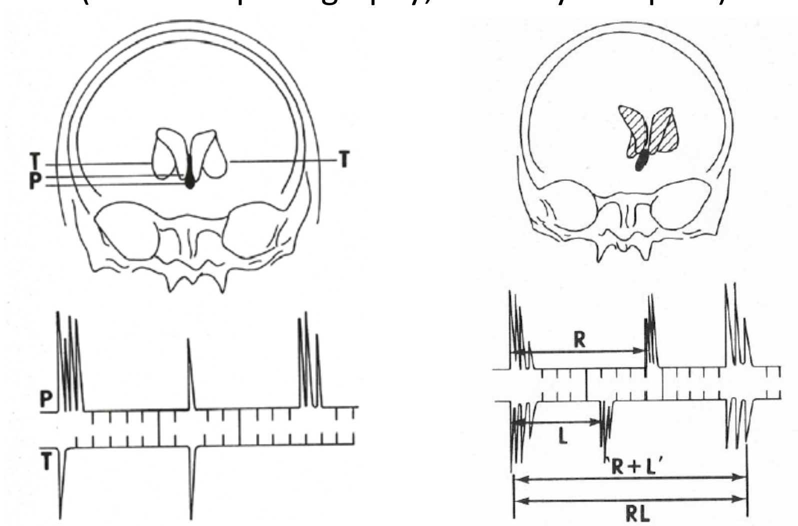


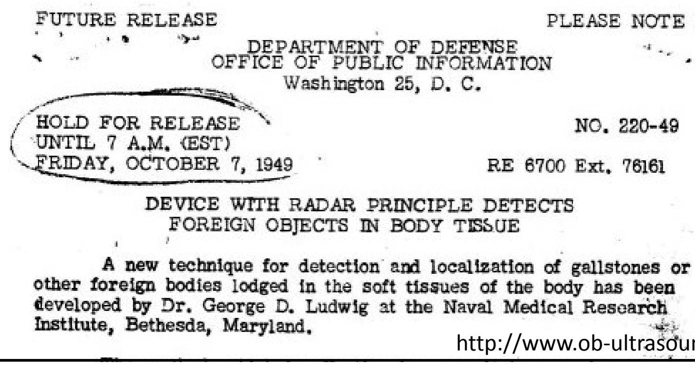
R. Brown, Ultrasonography: Basic Principles and Clinical Applications, Warren Green Pub, 1973.

George Ludwig

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

George D. Ludwig

Ludwig's A-mode apparatus in his gallstone experiments



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DEVICE WITH RADAR PRINCIPLE DETECTS
FOREIGN OBJECTS IN BODY TISSUE

A new technique for detection and localization of gallstones or other foreign bodies lodged in the soft tissues of the body has been developed by Dr. George D. Ludwig at the Naval Medical Research Institute, Bethesda, Maryland.

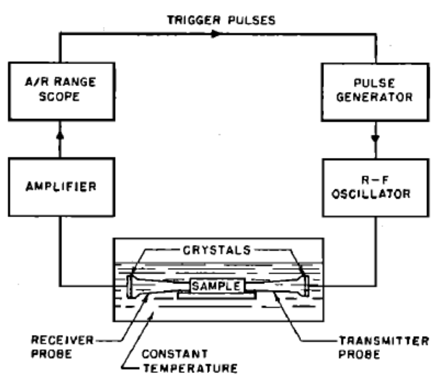
http://www.ob-ultrasound.net/history1.html

George Ludwig

- Also investigated acoustical properties of tissues
- Measured the "transmission time" vs. sample thickness
- Brain, spleen, liver, kidney, 24-25^{o}C

George D. Ludwig

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 .)

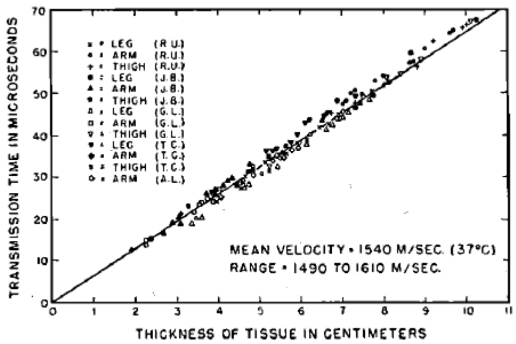


http://www.ob-ultrasound.net/history1.html

George Ludwig

- The velocity of sound through tissues and the acoustic impedance of tissues.JASA 22 (6):862, **1950**.
- Brain, spleen, liver, kidney, 24-25^{o}C
- Range: 1490-1610 m/s
- Average: 1540 m/s


George D. Ludwig

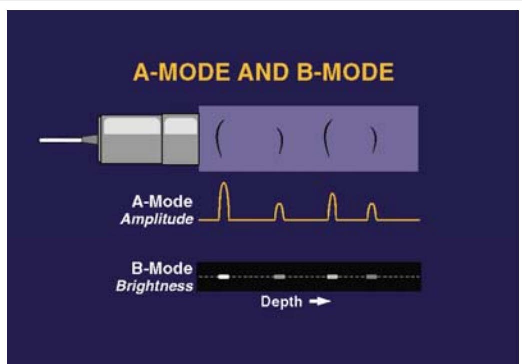


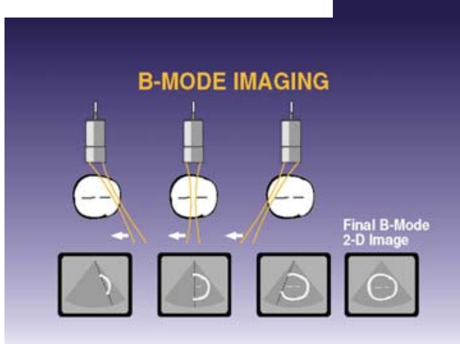
Display technology used for ultrasound:

A-Mode

B-mode

B-mode imaging



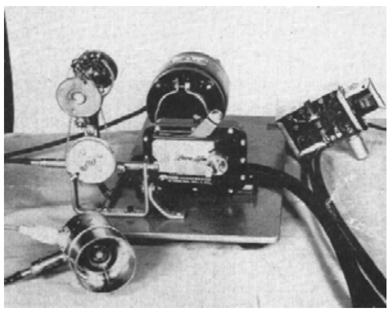


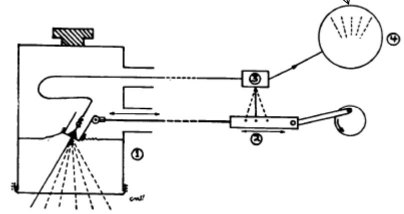
In B-mode imaging, the position and orientation of the transducer (or the ultrasound beam origin and direction) is used to define the sweep direction on a display scope.

John Wild & Jack Reid

John M Reid c.1970s

- “Application of echo-ranging techniques to the determination of structure of biological tissue,” Science 115: 226, **1952**.
- Defined “1 D echogram”, “2-D echogram”





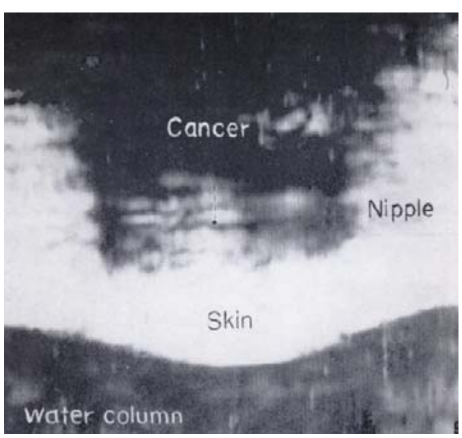
Beam Axes for linear swept, rocking transducer

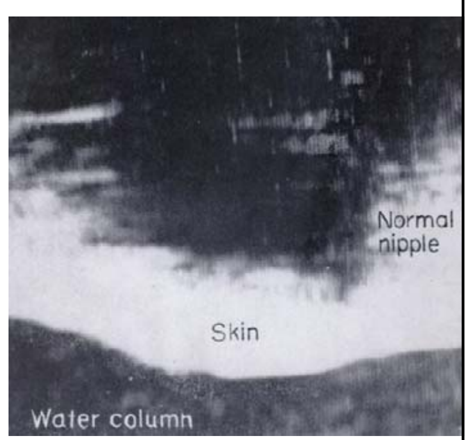
http://www.ob-ultrasound.net/history1.html

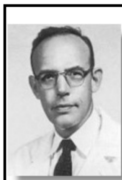
John Wild & Jack Reid

John M Reid c.1970s

- “Echographic visualization of lesions of the living, intact human breast,” Cancer Research **1954**, 14(4):277.







Joseph H Holmes
1902 - 1982

Howry et. al., Colorado

Douglass Howry c.1967

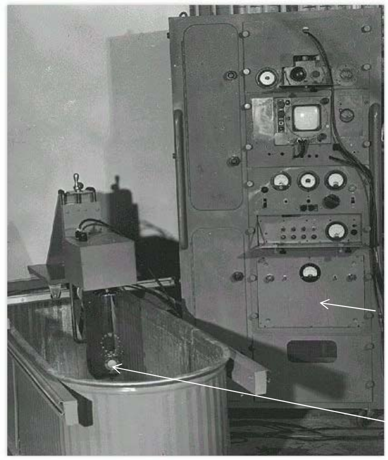
Gerald J. Posakony

Used water path

Subject immersed in water within a tank

Transducer swept using a motorized system

Radar system was reconfigured for US.

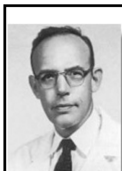


Adapted radar rack

Lithium sulfate focused transducer (~ 2 MHz)

Somascope, ~**1952**
Linear motion with sectoring

http://www.ob-ultrasound.net/history1.html



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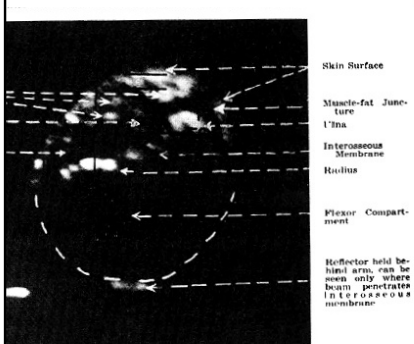

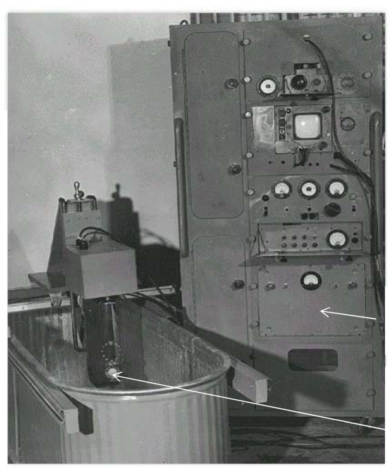

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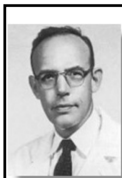

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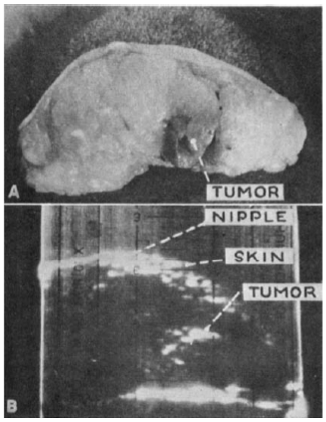

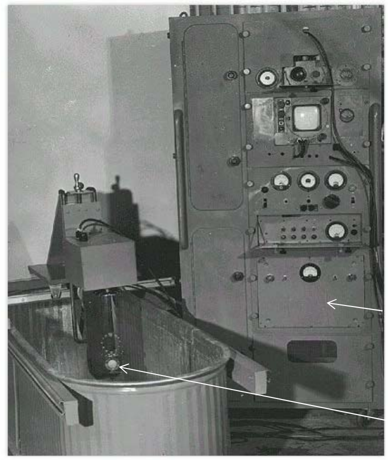

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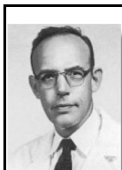

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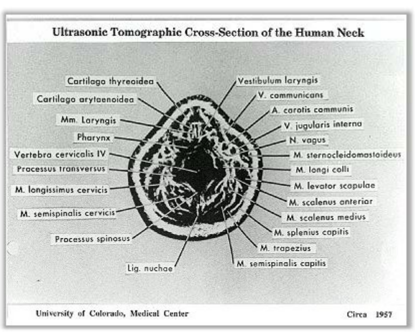
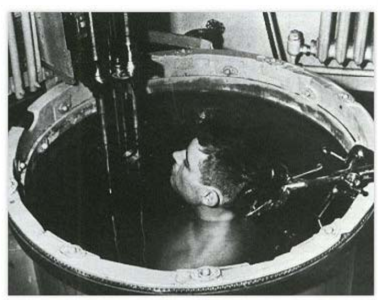
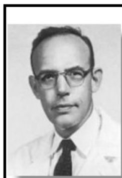




Version 2, ~**<u>1954-1957</u>**
B-29 Gun Turret
1 focused transducer, 360 degree travel, linear sweep at each angle
(Lead weights helped the patient/subject remain submerged)

Howry et. al., Colorado



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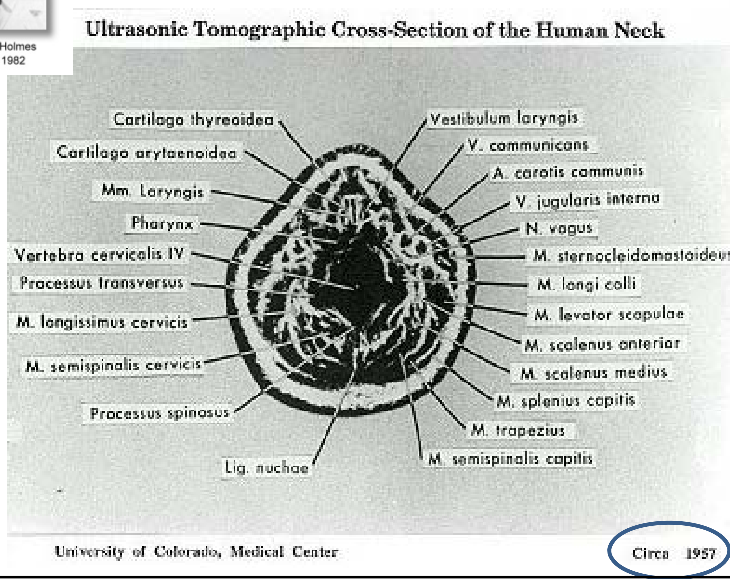


Douglass Howry c.1967

Gerald J. Posakony

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.

http://www.ob-ultrasound.net/history1.html

Ian Donald

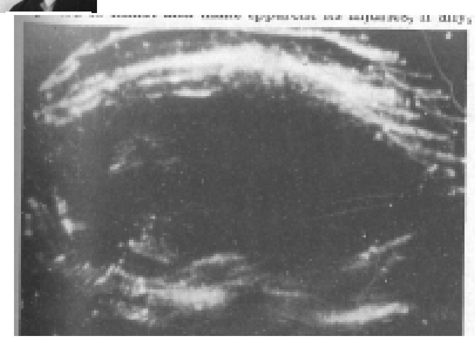
Fig. 3. Tom Brown with the first contact scanner in the development laboratory at Kelvin Hughes Ltd., Glasgow, 1957. This machine commonly is referred to as the "bed table machine," as a hospital bed table was used to support the scanning mechanism. (From BMUS Collection.)

July, **<u>1955</u>**, 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

McNay and Fleming, "Forty years of Obstretical Ultrasound 1957-1997: from A Scope to three dimensions," UMB 25: 3-56, 1999.

Ian Donald

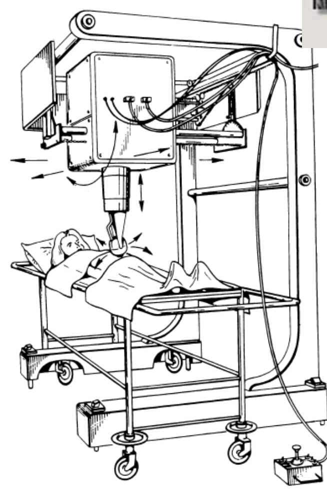


Fourteen week gestation showing echoes from the fetus. Patient had been thought to have had a fibroid. (Ref: Donald, I, MacVicar, J and Brown, T, "Investigation of abdominal masses by pulsed ultrasound," Lancet **<u>1958</u>**, 1(7032): 1188-95.)

Tom Brown

Ian Donald

- Scanner in use from **<u>1957</u>** to **<u>1964</u>**



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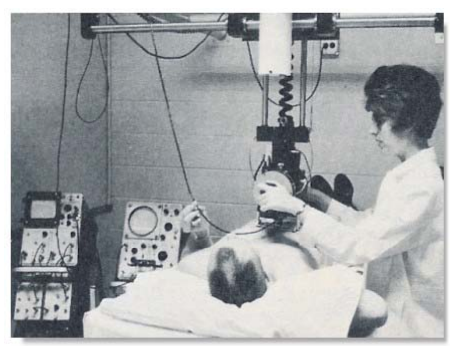
Manual scanner of Holmes, Wright and Meyer, (Howry)

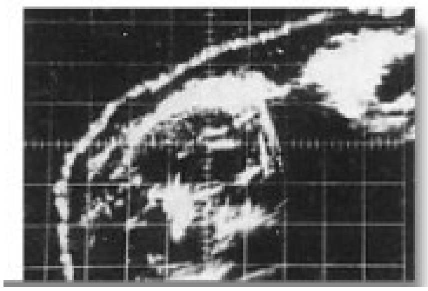
- Influenced by work of Donald et al
- Early version of a contact scanner (**<u>1964</u>**)
- Transducer moved manually
- Electronic devices tracked the motions
- Intensity modulated Storage oscilloscope

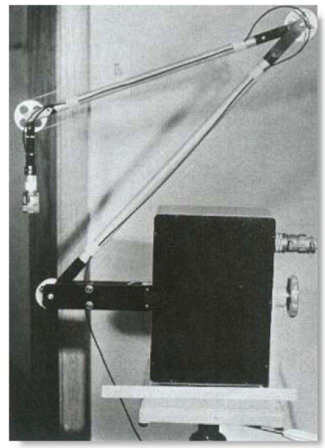


http://www.ob-ultrasound.net/history1.html

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

Carson, P., Leung, S., Hendee, W., Holmes, J., "A Sealed Test Tank for Echoscope Performance Evaluation," J. Clin. Ultrasound 1:208-212 (**1973**).

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

Minifie, Kelsey, Zagzebski, “Ultrasound scans of the dorsal surface of the tongue,” J.A.S.A. 49: 1857-1860, **1971**

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

Banjavic, Zagzebski, Wiley, Tolbert, "A projection system for effective use of ultrasound echogram information in radiation therapy," Radiology, 116(3): 731-733 (**1975**).

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

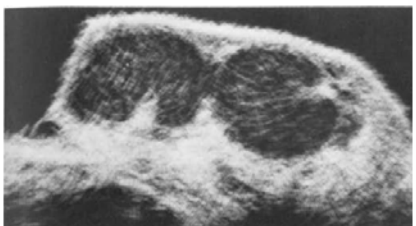
UI Bistable and gray scale in the 60's and early 70's

ASUM Ultrasound Bulletin 2004 August 7:3: 22–26

Water Path Scanners

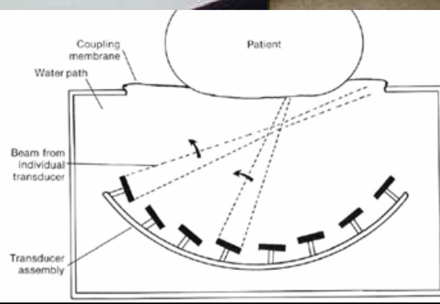
Ultrasonics Institute, Sydney, Australia

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



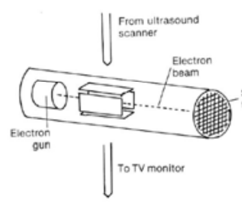
Normal testicles

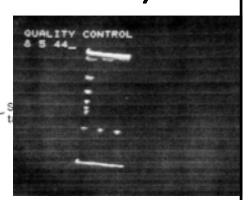
ASUM Ultrasound Bulletin 2004 August 7:3: 22–26

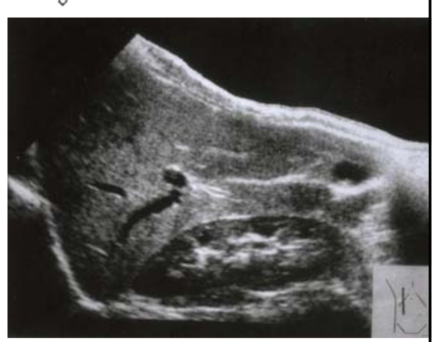


Gray Scale with Manual Scanners (Analog, then Digital scan converter)

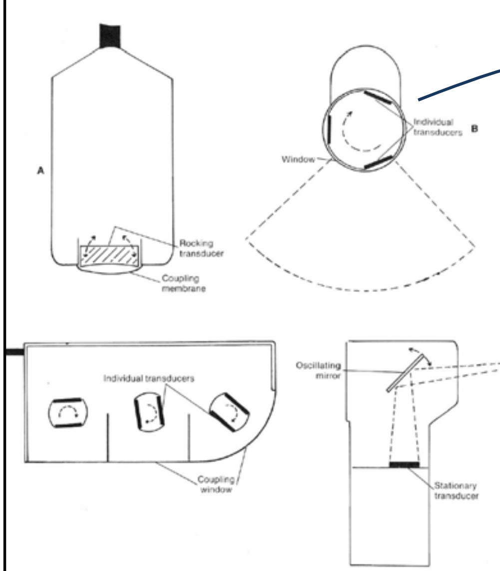
- Rather than write to a CRT, write to a storage device
  - Analog storage tube; run in “peak detection mode” so that it would not overwrite
  - Digital scan converters starting in the late 1970’s
- Output of image was to a TV monitor
  - “Venetian blind effect” during scanning

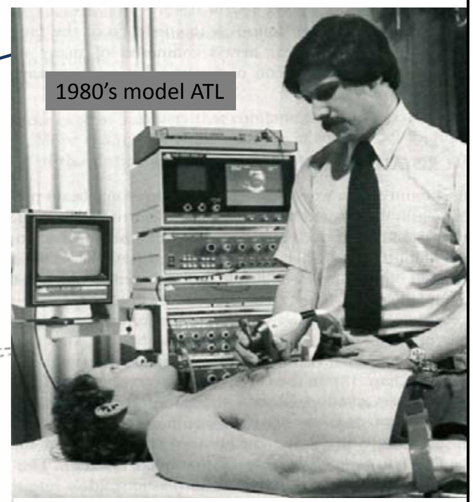






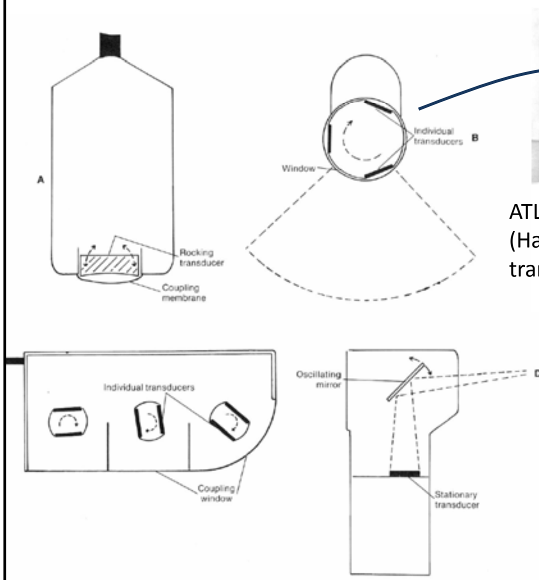
Real-time: hand-held mechanical transducers (~1973 ff)

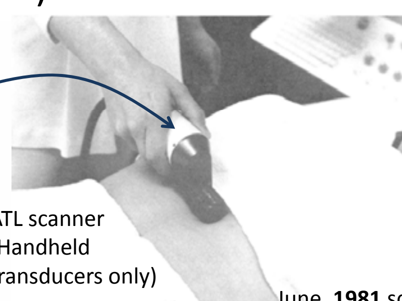




WN McDicken, Diagnostic Ultrasonics, Principles and Use of Instruments, Wiley, **1981**

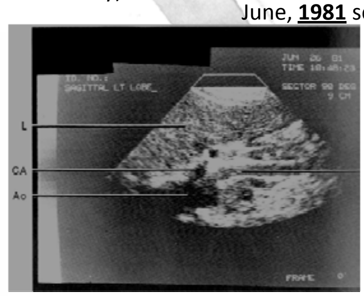
Real-time: hand-held mechanical transducers (~1973 ff)





ATL scanner (Handheld transducers only)

June, **1981** scan



Linear Array Technology (Bom)


Nicolaas Bom


Bom's prototype 2.25 MHz linear array probe

Described in a **<u>1971</u>** Dutch patent

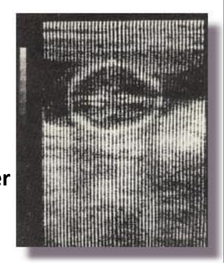
- **20 piezoelectric elements** (each 4mm x 10mm).
- Probe face was 80mm long and 10mm wide.
- 2.25 or 4.5 MHz
- frame rate of 150f/sec.
- The axial resolution was 1.25 mm at 3MHz
- Beam width at 6 cm was 1cm.
- Resulted in the 1972 "Multiscan" by
- Simple, basic design has evolved into the very sophisticated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

http://www.ob-ultrasound.net/history1.html

ADR Ultrasound Scanner (Wilcox)


Marty Wilcox c.70s


The ADR realtime scanner ****

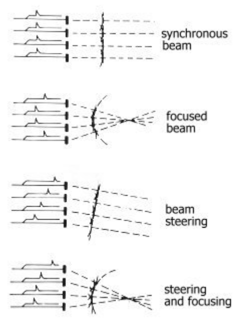


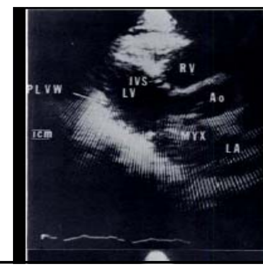
- First generation ADR (**<u>1973</u>**)
  - 64 element array
  - Scanned "using stepping" element techniques (element groups).
  - Recognized as a 'good-resolution' **abdominal linear-array scanner**
- Second ADR model **the 2130** (1975)
  - application Focusing techniques.
  - sold over 5000 units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

http://www.ob-ultrasound.net/history1.html

Phased Arrays For Cardiac Scanning

- Sommer, Netherlands, 1968 (Ultrasonics)
- Duke University work
  - 24 element phased array
  - Kisslo, vonRamm, Thurstone, "Dynamic cardiac imaging using a phased array system, Am J Med 63(1): 61-68, **1977**
- Varian Phased Array
  - V3000, ~1975
  - 32 elements
  - Mainly cardiac applications
  - Lappe, Bulkley, Weiss, "Two dimensional echocardiographic diagnosis of left atrial myxoma", CHEST, 74(1): 55-78**, 1978**



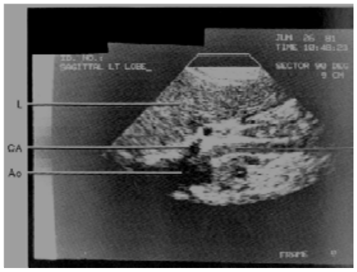


Status of "Static," single element transducer scanning and Real-time scanning in the early 1980's

- 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

The Digital Imager II from Picker, one of the newer static scanners in the early 198

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.”

Royal Bartrum, “Introduction” in ***Real-time ultrasonography***, ed. by Fred Winsberg and Peter Cooperberg, Churchill Livingstone, (**1982**).

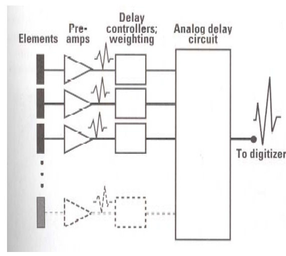
Acuson 128 ~**1983** (Maslak; Wright; Larsen, Cole)

- Linear, phased arrays
  - Later convex arrays
- 128 channels
- Analog “beam former”
  - Called a “tracking lens*”
- High channel count enabled large, aperture, good lateral resolution
- No longer a need for static scanners to get good image quality

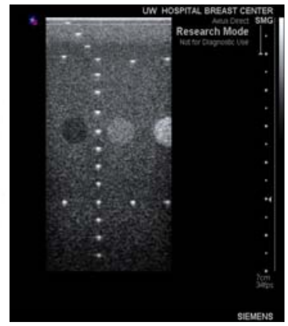
*Maslak, “Computed Sonography,” in *Ultrasound Annual 1985*, edited by R Saunders and M Hill, Raven Press, NY, **1985**

Array Beam Forming

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

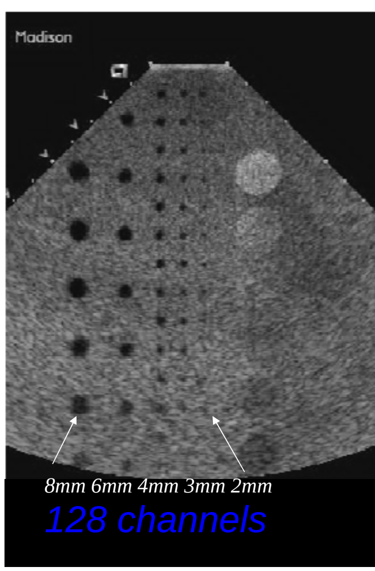


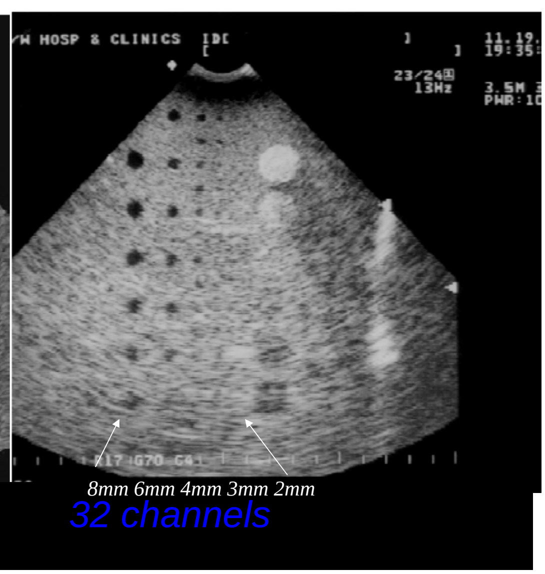
Delay and sum



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

Importance of Channel Count
Allows larger aperture; improves lateral resolution





Doppler and Color

Aloka SSD 880

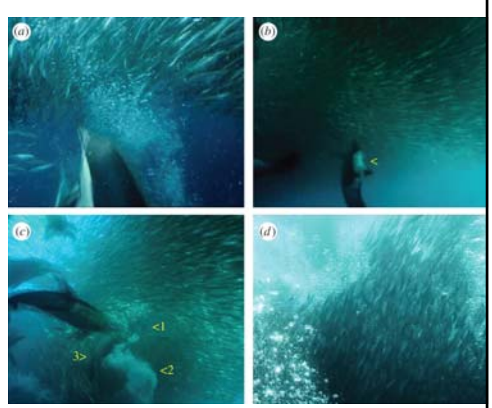
- CW Doppler available in 1960's
- Pulsed Doppler late 1960's (U of Washington)
- Brandestini described multi-gated Doppler imaging method 1975; first color flow images, published in **<u>1981</u>**
- Prior to 1985, "Duplex" Doppler, pioneered by ATL, was available on a few machines
- Aloka SSD880, 1985, 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

Quantum QAD-1

http://www.ob-ultrasound.net/history1.html

Harmonic Imaging

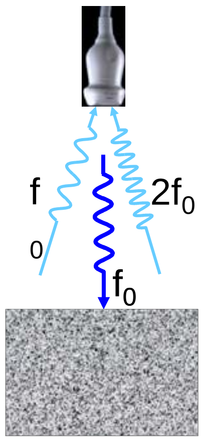
- Common dolphins herd sardines with bubble nets
- Leighton et al (Southhampton, UK) hypothesize dolphins may use nonlinear processing, sensitive to the nonlinear oscillations of bubbles in a sound field, to distinguish bubbles from prey.



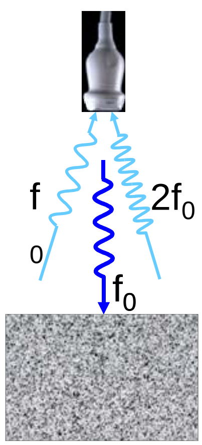
Leighton T G et al. Proc. R. Soc. A doi:10. 1098/rspa. 2012.0247

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."

Belohlavek, Tanabe, Mulvagh, Foley, Greenleaf, Seward, **Image enhancement by noncontrast harmonic echocardiography. Part II. Quantitative assessment with use of contrast-to-speckle ratio.** , Mayo Clin Proc **1998** Nov;73(11):1066-70.

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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

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- Multi-D arrays to provide electronic control of slice thickness
- Hand held scanners (1979 [right]; late 90's)
- Elasticity imaging, ARFI
- Targeted and non-targeted US contrast agents
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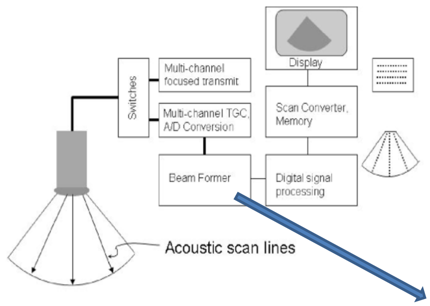
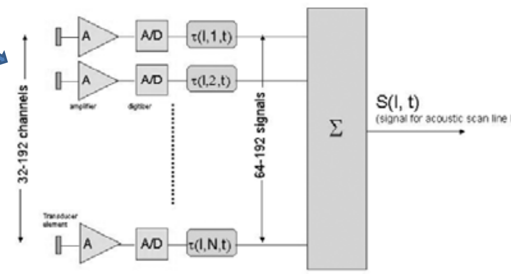
- 2-D arrays
- 3-D, 4-D imaging
- Plane wave imaging

The MiniVisor ****

Most common US machine processing paradigm

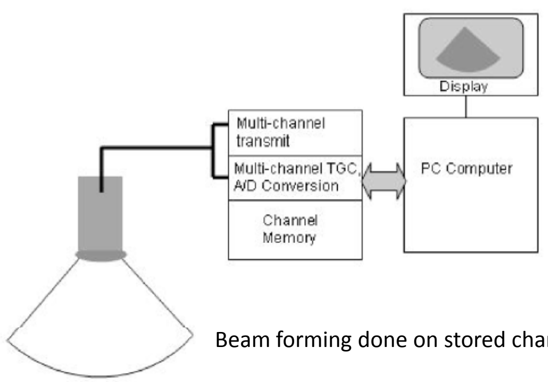




Focused transmit; channel data are combined in a "beamformer" 1 (or several) acoustic scan line(s) at a time.

J Zagzebski, "2D and 3D Data Acquisition in Ultrasound," in ***Advances in Medical Physics 2012***, edited by Anthony Wolbarst et al, Medical Physics Publishing, Madison, 2010.

Emerging US machine processing paradigm

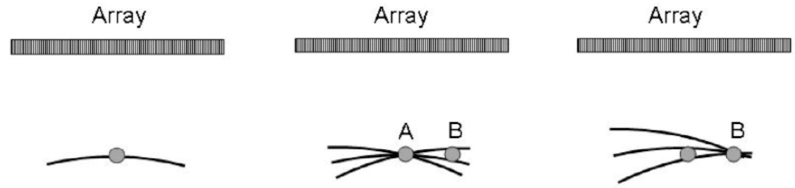


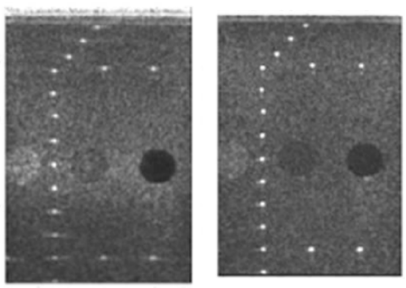
Beam forming done on stored channel domain data. (Zonare)

J Zagzebski, "2D and 3D Data Acquisition in Ultrasound," in ***Advances in Medical Physics 2012***, edited by Anthony Wolbarst et al, Medical Physics Publishing, Madison, 2010.

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

Courtesy of Ron Daigle, Verasonics

Daigle, R., L. Pflugrath, J. Flynn, K. Linkhart, and P. Kaczkowski. "High frame rate quantitative Doppler imaging over a wide field of view." Program and Abstracts. *Ultrasonics Symposium, IEEE 2009*, Rome, 2009.

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.

THE UNIVERSITY of WISCONSIN MADISON

Department of Medical Physics

Principal References

1. *Dr. Joseph Woo, "*A short History of the development of Ultrasound in Obstetrics and Gynecology" at http://www.ob-ultrasound.net/history1.html
2. Medical Diagnostic Ultrasound: a retrospective on its 40th anniversary, Kodak Health Sciences for the American Institute of Ultrasound in Medicine, 1988.
3. Dr. William D. O'Brien, Assessing the Risks for Modern Diagnostic Ultrasound Imaging, at http://www.brl.uiuc.edu/Projects/Bioeffects/Assessing.php

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