Medical ultrasound imaging

Modern ultrasound imaging

J. Kybic[1]

Department of cybernetics, FEE CTU
http://cmp.felk.cvut.cz/~kybic
kybic@fel.cvut.cz

2008–2022

[1] Using images from J.Hozman, E.Dove, A. Stoylen

Doppler ultrasound

US contrast agents

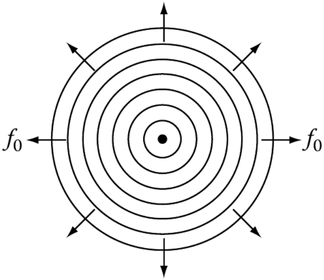
Harmonic imaging

3D US imaging

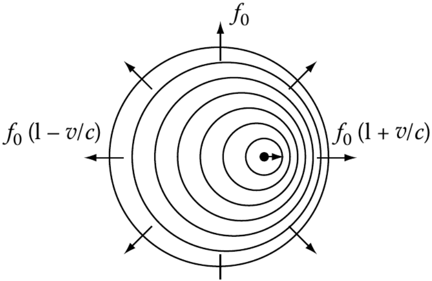
Christian Doppler

1803–1853

Doppler frequency shift

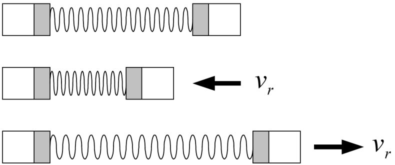


stationary



moving source

Stationary source, moving receiver

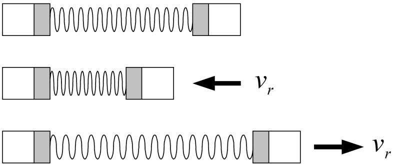


$$f_r = f_s + \frac{v_r}{\lambda_s} = f_s + \frac{v_r}{c} f_s = f_s + f_d, \quad \text{since} \quad \lambda_s = \frac{c}{f_s}$$

Doppler shift

$$f_d = \frac{v_r}{c} f_s$$

Stationary source, moving receiver



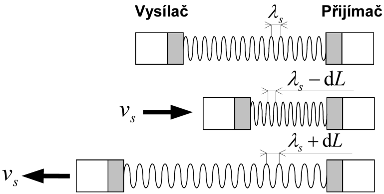
$$f_r = f_s + \frac{v_r}{\lambda_s} = f_s + \frac{v_r}{c} f_s = f_s + f_d, \quad \text{since} \quad \lambda_s = \frac{c}{f_s}$$

Doppler shift

$$f_d = \frac{v_r}{c} f_s$$

Example: For $f = 5\,\text{MHz}$, $v_r = 1\,\text{cm/s}$, $f_d = 33\,\text{Hz}$.

Stationary receiver, moving source



Wavelength change

$$\delta\lambda = v_s T_s = \frac{v_s}{f_s}$$

$$\lambda_r = \lambda_s - \delta\lambda = \frac{c}{f_s} - \frac{v_s}{f_s}$$

$$f_r = \frac{c}{\lambda_r} = \frac{c}{c - v_s} f_s$$

Stationary receiver, moving source (2)

$$f_r = \frac{c}{\lambda_r} = \frac{c}{c - v_s} f_s = \frac{1}{1 - \frac{v_s}{c}} f_s$$

Stationary receiver, moving source (2)

$$f_r = \frac{c}{\lambda_r} = \frac{c}{c - v_s} f_s = \frac{1}{1 - \frac{v_s}{c}} f_s$$

From Taylor series, for $x \ll 1$

$$\frac{1}{1-x} = 1 + x + \frac{x^2}{2} + \cdots \approx 1 + x$$

For $v \ll c$

$$f_r \approx \left(1 + \frac{v_s}{c}\right) f_s = f_s + f_d$$

Doppler shift

$$f_d = \frac{v_s}{c} f_s$$

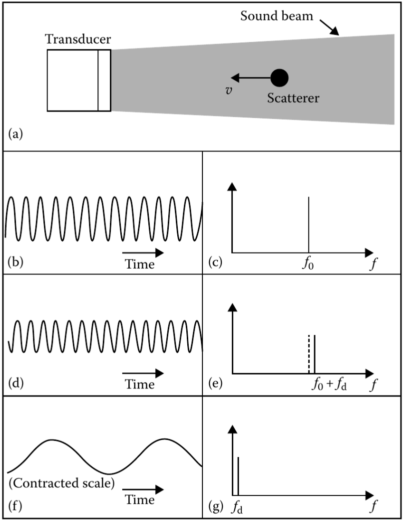
Blood flow speed measurement

- Doppler effect: Frequence changes if the source moves with respect to the receiver.
- Reflection from red blood cells
- Red blood cells
  - Moving receiver
  - Moving source
- Doppler shift

$$f_r = f_t + f_d \qquad \boxed{f_d \approx 2\frac{v}{c}f_c}$$

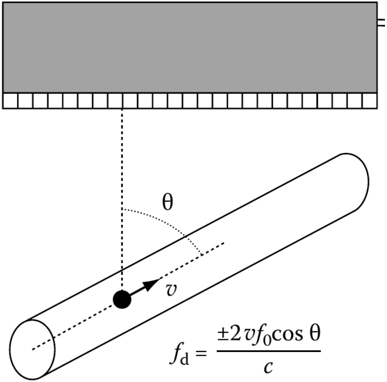
Moving scatterer

time and frequency domains



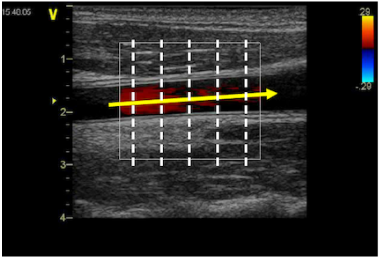
Angle dependency

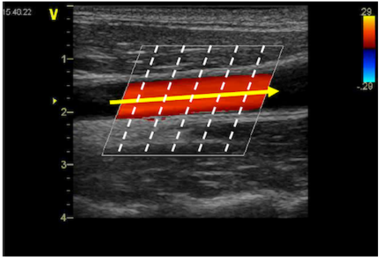
We only measure the projection along the ray: $v \cos \theta$



$f_0 = f_s$

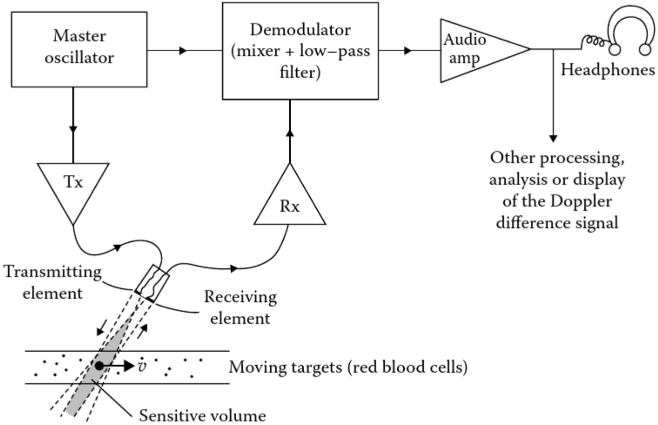
Angle dependency (2)





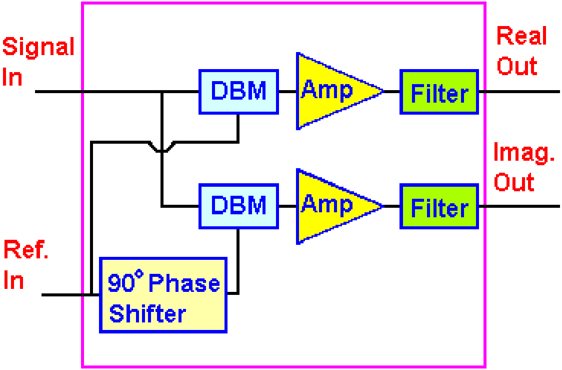
- Insonation angle $90^\circ \longrightarrow$ weak or no signal.
- Known angle $\longrightarrow$ angle correction.

Continuous wave Doppler



- separate transmitter and receiver
- can measure high velocities
- no spatial information

Quadrature detector



- *Input:* $g_a = \cos(at), \quad g_b = \cos(bt)$
- *Output:* $g = g_a g_b = \frac{1}{2}\cos((a+b)t) + \frac{1}{2}\cos((a-b)t)$
- Signal $\cos((a+b)t)$ can be filtered (low-pass filter)
- Difference frequence signal $s_r = \cos((a-b)t)$
- "Imaginary" signal s_i shifted by 90°: $\sin((a-b)t)$

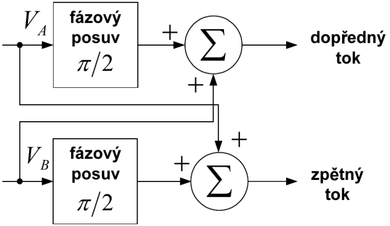
Directional demodulation

To distinguish positive/negative flow direction, $\pm f_d$.

Method 1: Phase-domain processing

- Quadrature mixer with f_s
- Phase offset $\angle s_r = \angle s_i = \pm 90°$

	$f_d > 0$	$f_d < 0$
$s_r + T_{90} s_i$	0	$2s_r$
$T_{90} s_r + s_i$	$2s_r$	0



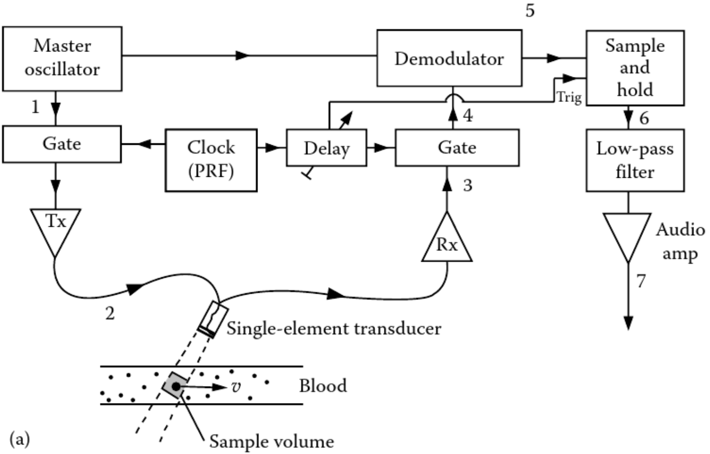
Directional demodulation

To distinguish positive/negative flow direction, $\pm f_d$.

Method 2: Frequency shift

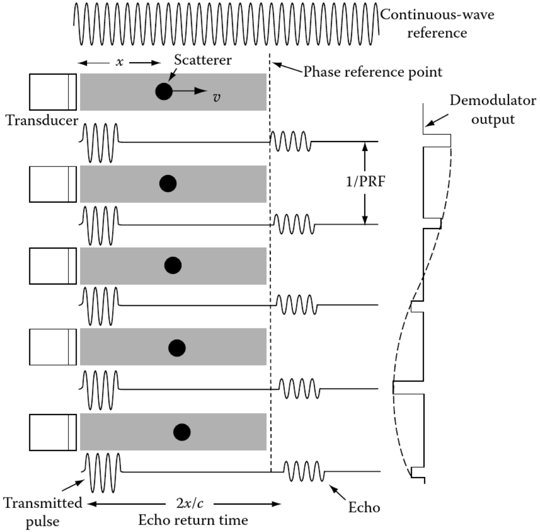
- Quadrature mixer with $f_s + f_o$
- $f_d = 0 \longrightarrow$ mixer output f_o
- $f_d = \text{freq}(s_r) - f_o$

Pulsed wave Doppler
(PW)



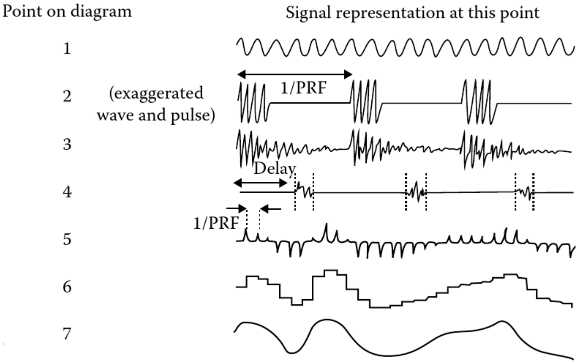
- single transducer
- repeated pulses
- spatial information
- limited velocity

Sampled Doppler shift signal



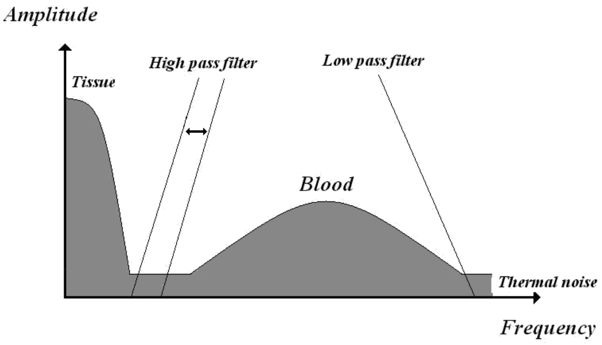
PRF = pulse repetition frequency f_p,

PW Doppler shift signals

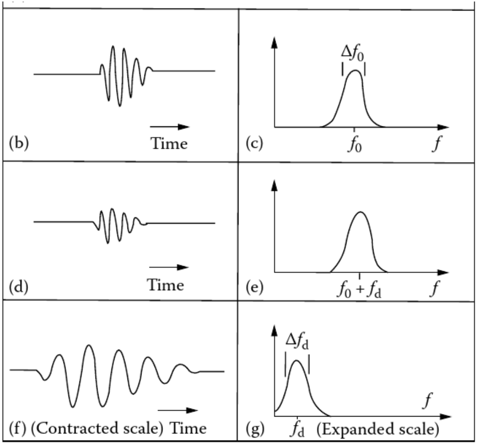


PRF:pulse repetition frequency, 2:transmitted signal, 3:received signal, 4:gated signal, 5:demodulated signal, 6:interpolated signal, 7:output

PW Doppler spectrum



Speed uncertainty

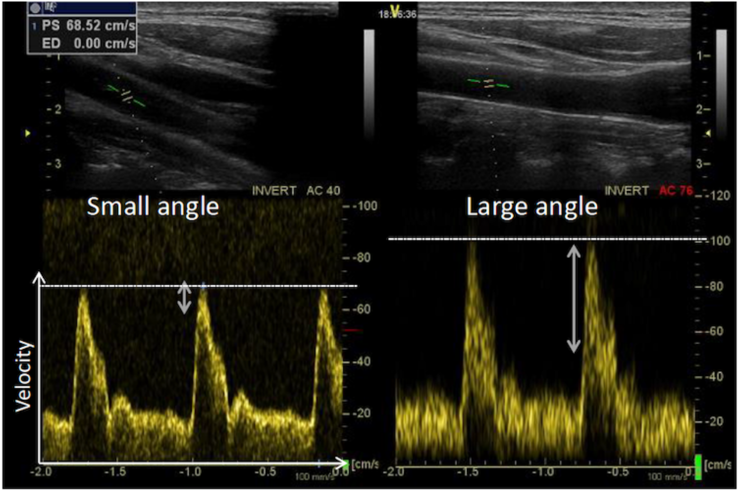


$$\Delta f_d = \frac{2v}{c\tau} = \frac{f_d}{\underbrace{f_s\tau}_{Q}}, \qquad \Delta v = \frac{v}{Q}$$

τ — pulse length, Q — quality factor, number of cycles in a pulse

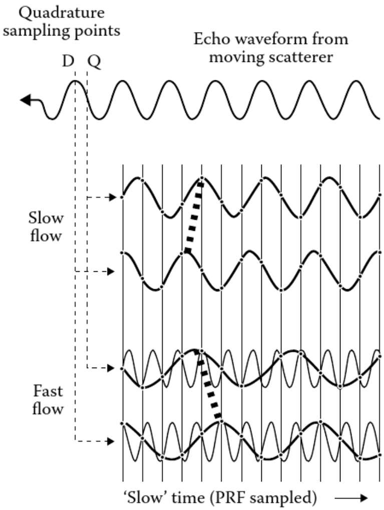
Speed uncertainty

Angle dependency



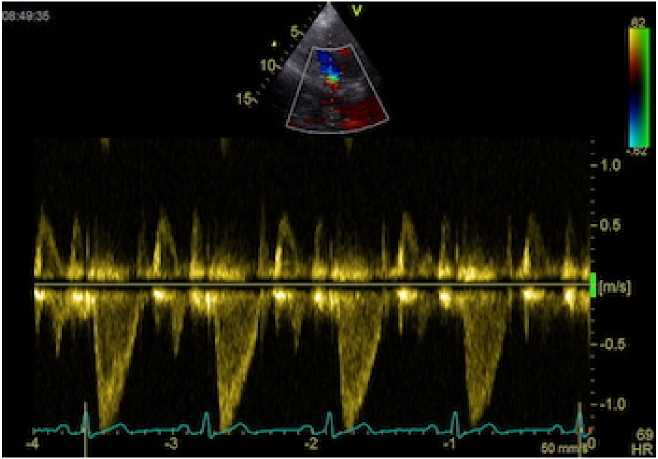
small angle $\longrightarrow$ higher number of cycles Q

Aliasing



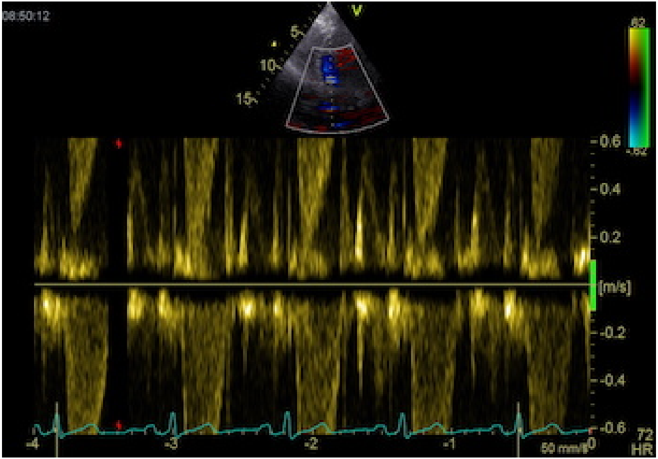
Nyquist $\longrightarrow \quad f_d < f_p/2$

Aliasing example



B-mode+Doppler+velocity spectrum — high PRF f_p

Aliasing example



B-mode+Doppler+velocity spectrum — low PRF f_p

Range-velocity tradeoff

$$f_d < f_p/2 \quad \longrightarrow \quad v_{\max} = \frac{f_p c}{4 f_s}$$

$$z_{\max} = \frac{T_p c}{2} = \frac{c}{2 f_p}$$

$$\boxed{v_{\max} z_{\max} = \frac{c^2}{8 f_s}}$$

Range-velocity tradeoff

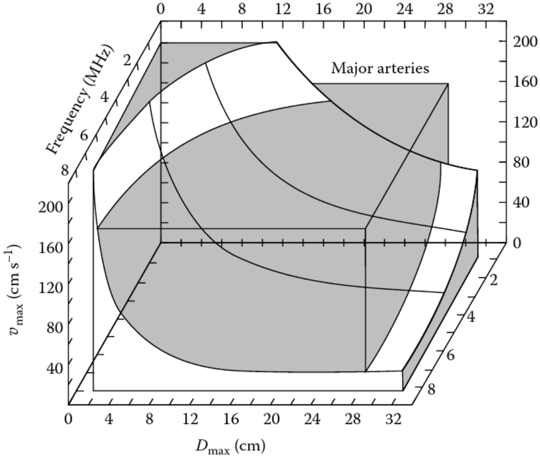
$$f_d < f_p/2 \quad \longrightarrow \quad v_{\max} = \frac{f_p c}{4 f_s}$$

$$z_{\max} = \frac{T_p c}{2} = \frac{c}{2 f_p}$$

$$\boxed{v_{\max} z_{\max} = \frac{c^2}{8 f_s}}$$

Limitation is for $(v \cos\theta)_{\max}$.

Range-velocity tradeoff



Minimum velocity

Observe at least one period of f_d

$$T_d < NT_p$$

with N transmissions per line

$$f_d > \frac{f_p}{N}$$
$$v_{\min} = \frac{f_p c}{2Nf_s}$$

Minimum velocity

Observe at least one period of f_d

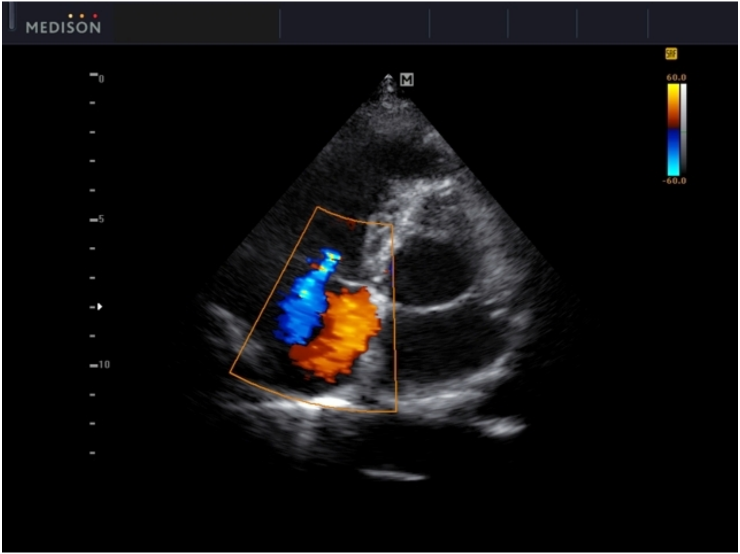
$$T_d < NT_p$$

with N transmissions per line

$$f_d > \frac{f_p}{N}$$
$$v_{\min} = \frac{f_p c}{2N f_s}$$

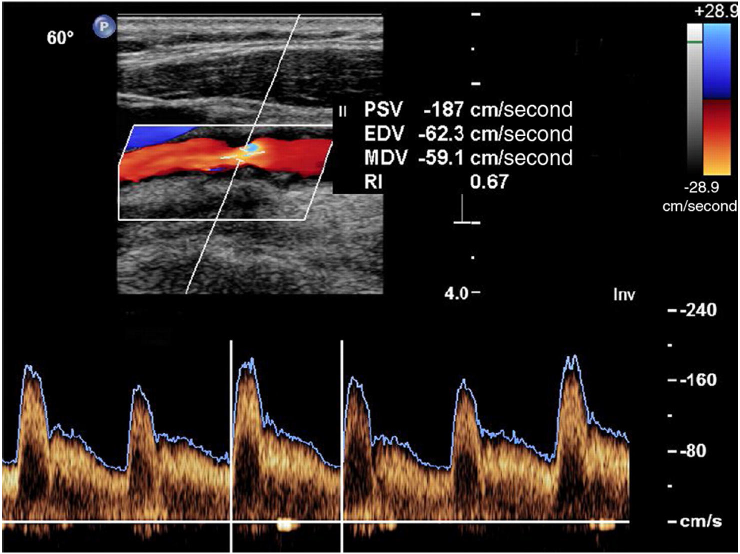
- Usually $2 \sim 3$ cycles required
- $N = 5 \sim 10$ or more
- Temporal averaging
- $\longrightarrow$ slow f_p

Doppler US — examples



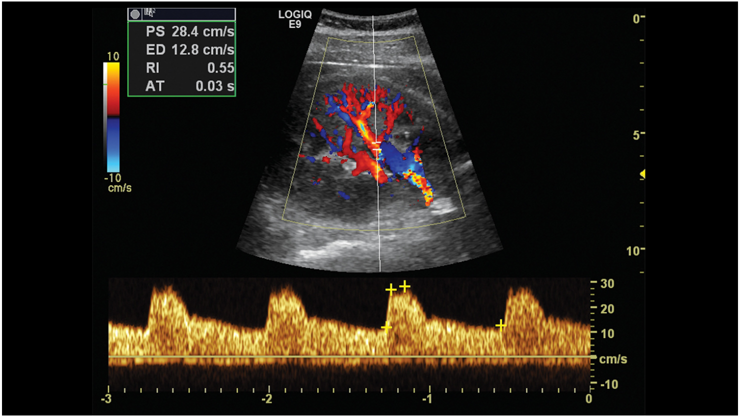
heart

Doppler US — examples



artery

Doppler US — examples



liver

Doppler ultrasound

US contrast agents

Harmonic imaging

3D US imaging

Contrast agents

- *1968, Gramiak, saline injection*
- Microbubbles ($2 \sim 5\,\mu$m)
- Asymmetric compression/expansion
- Stabilization (synthetic polymers), up to $5 - 10$ min.
- Injection
- Albunex, Optison, Echovist, Levovist. . .

Flash contrast imaging

US bubble destabilization.

normal

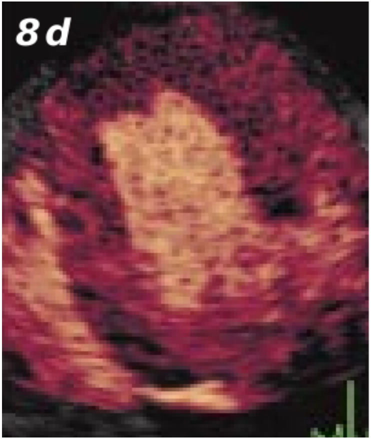
Flash contrast imaging

US bubble destabilization.

flash, bubbles broken

Flash contrast imaging

US bubble destabilization.



filling up

Myocardial perfusion evaluation.

Doppler ultrasound

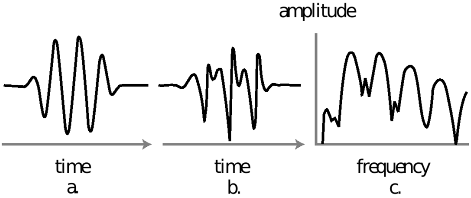
US contrast agents

Harmonic imaging

3D US imaging

Nonlinear response

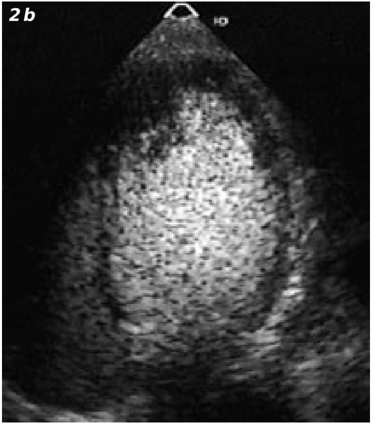
Assymetric bubble compression



Harmonic imaging

- Transmit f_0, receive $2f_0$

standard US

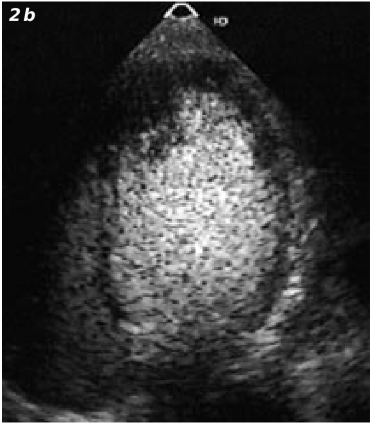


2^{nd} harmonic

Harmonic imaging

- Transmit f_0, receive $2f_0$
- Bandwith limitation

standard US

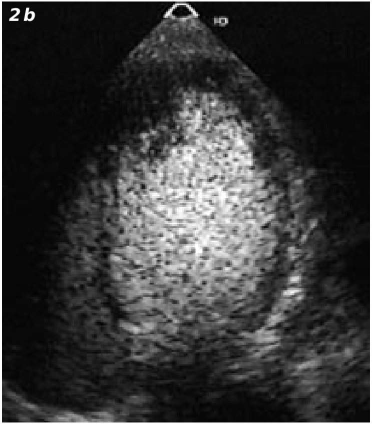


2nd harmonic

Harmonic imaging

- Transmit f_0, receive $2f_0$
- Bandwith limitation
- Bubbles not needed, tissue nonlinearity

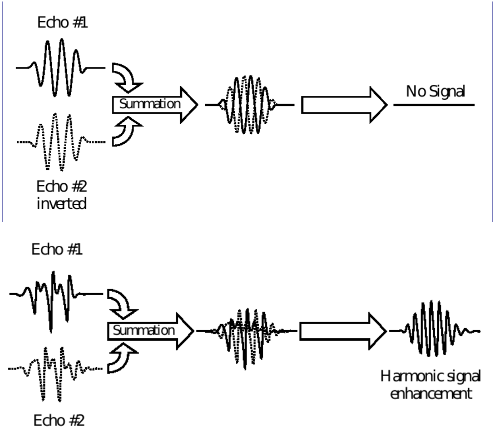
standard US



2nd harmonic

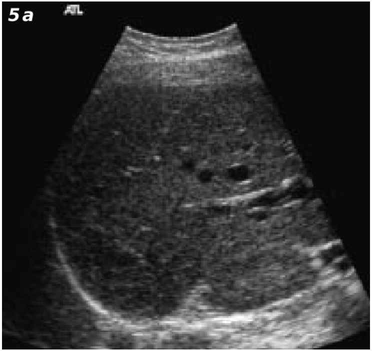
Pulse Inversion Harmonic Imaging

- Two pulses, second inverted
- Responses summed
- Filtration not needed

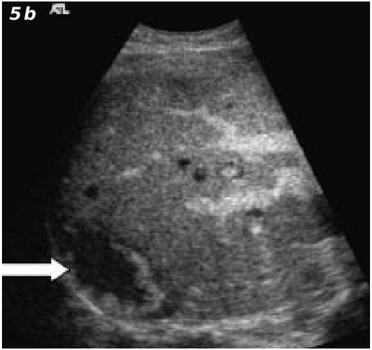


Pulse Inversion Harmonic Imaging

- Two pulses, second inverted
- Responses summed
- Filtration not needed



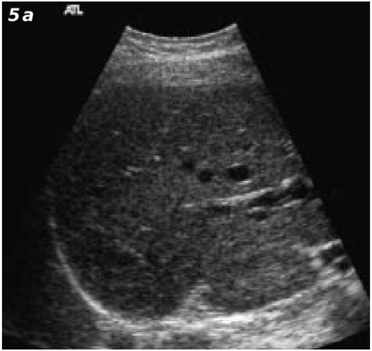
standard image (liver)



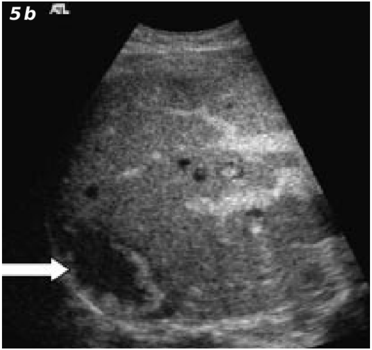
pulse inversion

Pulse Inversion Harmonic Imaging

- Two pulses, second inverted
- Responses summed
- Filtration not needed
- Several pulses (Power Pulse Inversion)



standard image (liver)



pulse inversion

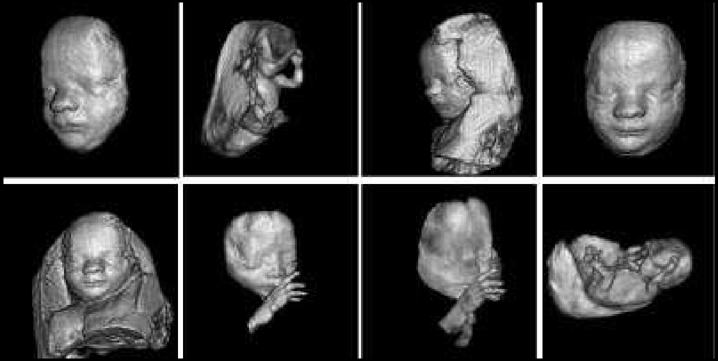
Doppler ultrasound

US contrast agents

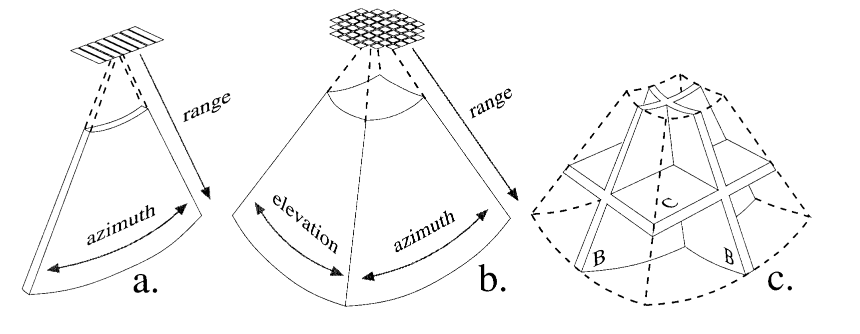
Harmonic imaging

3D US imaging

3D Reconstruction



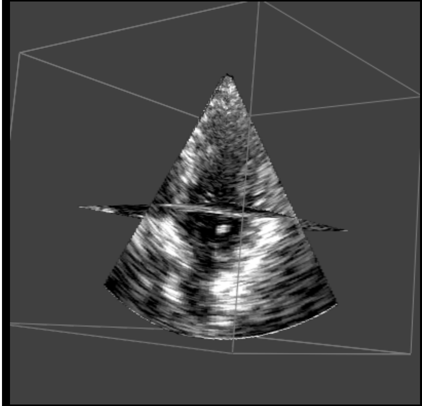
3D Ultrasound

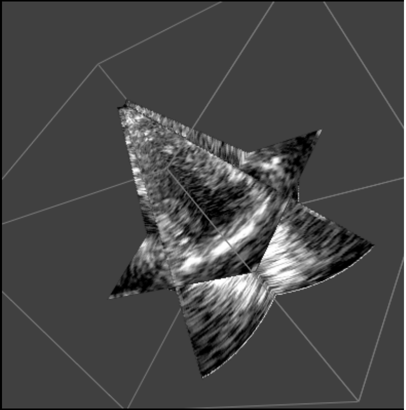


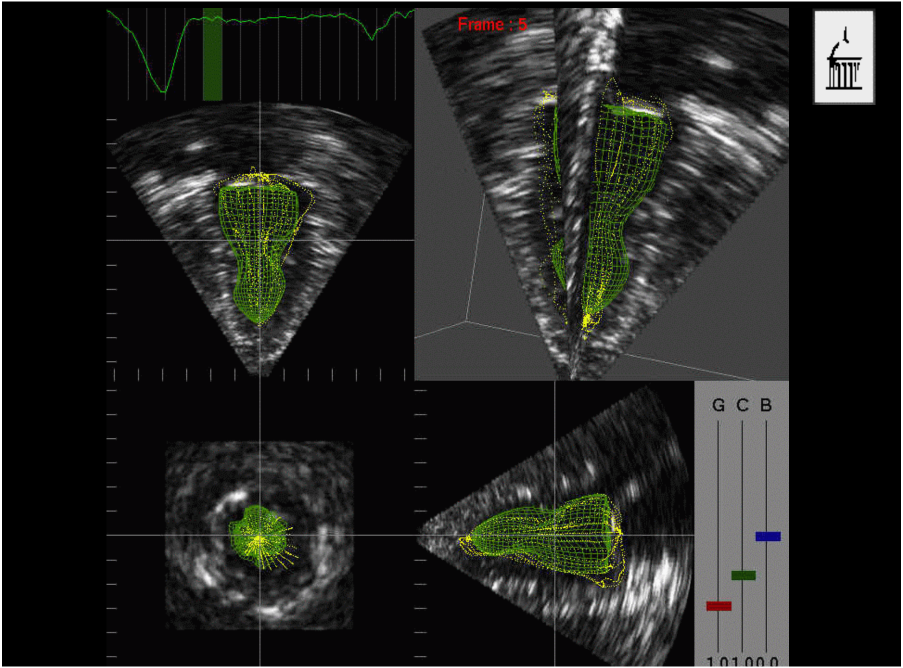
Traditional 2D

New 3D

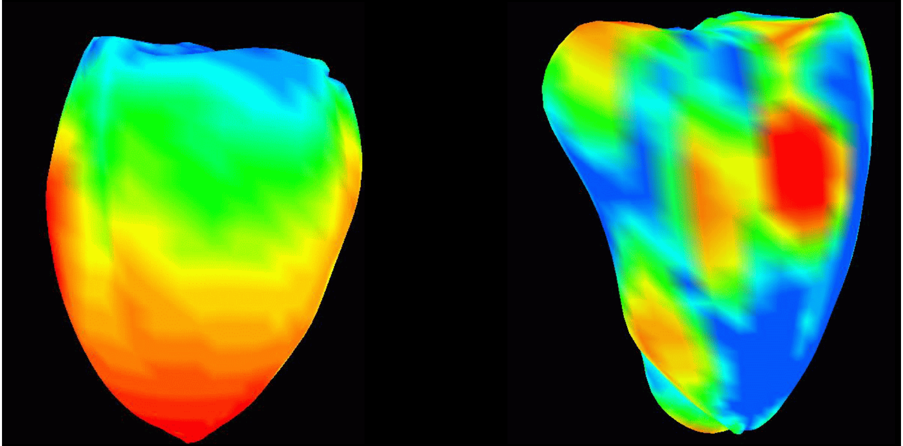
Real-time 3D Ultrasound






Frame : 5
G C B

Velocity of Contraction



Normal

Abnormal

Biological effects

- Thermal effects
  - 1.5 °C indefinitely or 6 °C for 1 min
  - highest risk in bones (transcranial imaging)
- Cavitation — growth/collapse of bubbles
  - for long pulse lengths or high pressure
  - may damage cells
  - unlikely to occur *in vivo*
- Radiation pressure — makes tissues/fluids move

Biological effects

- Thermal effects
  - 1.5 °C indefinitely or 6 °C for 1 min
  - highest risk in bones (transcranial imaging)
- Cavitation — growth/collapse of bubbles
  - for long pulse lengths or high pressure
  - may damage cells
  - unlikely to occur *in vivo*
- Radiation pressure — makes tissues/fluids move
- Clinical studies found no harmful effects

Biological effects

- Thermal effects
  - 1.5 °C indefinitely or 6 °C for 1 min
  - highest risk in bones (transcranial imaging)
- Cavitation — growth/collapse of bubbles
  - for long pulse lengths or high pressure
  - may damage cells
  - unlikely to occur *in vivo*
- Radiation pressure — makes tissues/fluids move
- Clinical studies found no harmful effects
- . . . ultrasound power output is increasing.

Conclusions

- Non-invasive, affordable and portable imaging technique
- Excellent soft tissue imaging
- Lower image quality (wrt CT or MRI) due to speckle but improving
- Low penetration depth versus resolution
- Does not pass through air or gas
- Does not pass through bones, shadows
- Modern techniques — 3D, contract agents, Doppler