Medical diagnostic systems

(Orvosbiológiai képalkotó rendszerek)

Beamforming in ultrasound

(Nyalábalkotás az ultrahangban)

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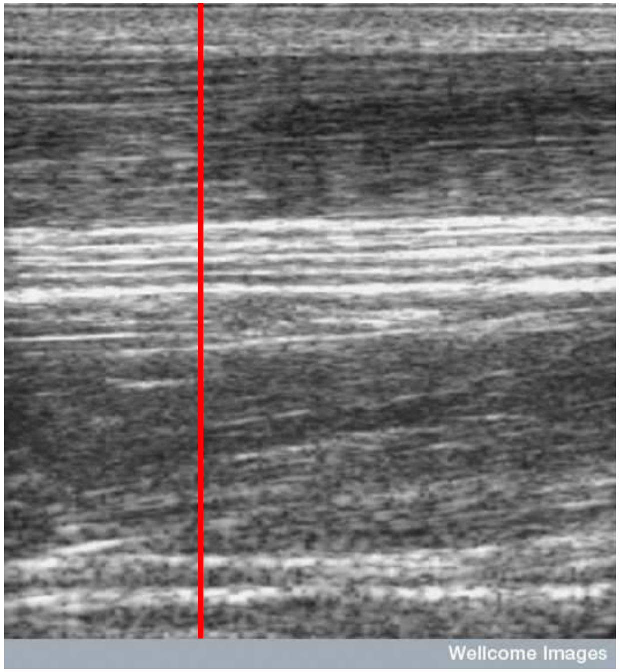
Overview of this lecture

- Array-dependent scanning methods (linear, phased, 2-D,...)
- Beamforming strategies (fixed & dynamic focus, advanced)
- Speckle reduction techniques (compounding)
- Sidelobes and sidelobe reduction techniques (apodization)

Linear array

- Typically higher frequencies
  - example: 5-10 MHz
  - high resolution (~0.2 mm)
  - short penetration depth (~10 cm)
- Subset of elements (subaperture) used to form each A-line
- Good for imaging organs with easy access (e.g. abdominal organs)
- Elevational (in-plane) focusing achieved using acoustic lens
  - typical resolution 10 mm
- Spacing between elements on the order of a wavelength (see “grating lobes” slides later on)

typically half (64/128 elements) of the entire aperture used to generate A-line



“Nerve movement in forearm during wrist extension”
http://images.wellcome.ac.uk/ B0004357
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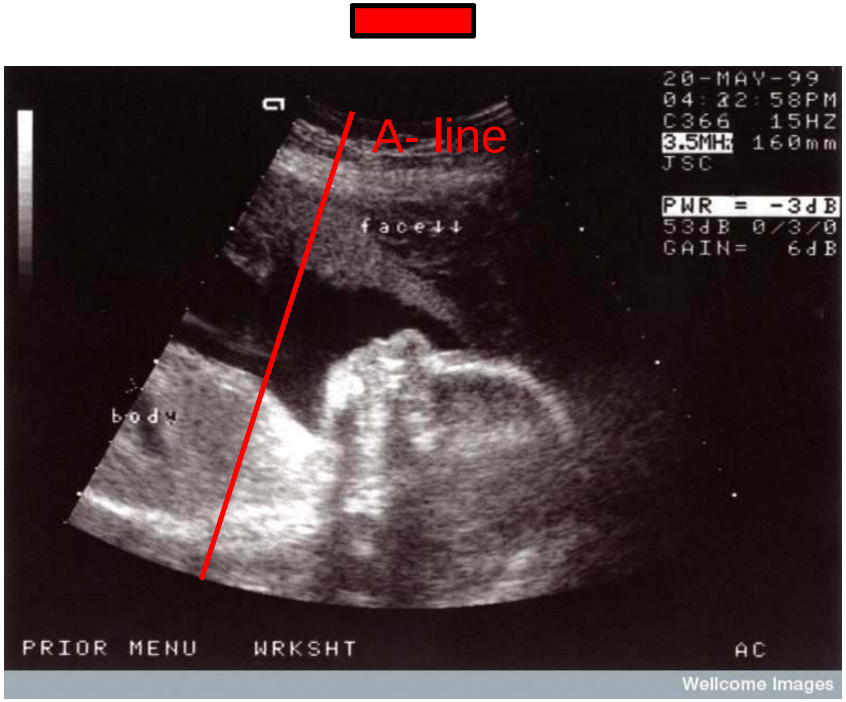
Phased array

- Typically lower frequency
  - example: 1-4 MHz
  - low resolution (~0.6 mm)
  - large penetration depth (~30 cm)
- Good for imaging deep, hard-to-access (limited acoustic window e.g. due to ribs) organs (e.g. heart)
- Elevational (in-plane) focusing achieved using acoustic lens
  - typical resolution 14 mm ?
- Spacing between elements less than half a wavelength (see “grating lobes” slides later on)

entire aperture active in generating A-line



“Ultrasound image of normal 24 week fetus”
http://images.wellcome.ac.uk N0019385

Arrays for 3-D imaging

Freehand 1D array (position feedback with e.g. optical markers)

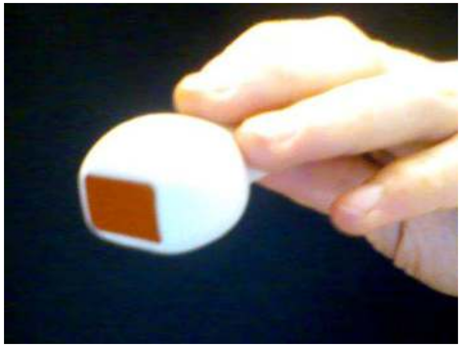
- – difficult registration (may be aided by position sensing)
- \+ simple to use

Mechanised 1D array (fixed, predictable motion e.g. inside casing)

- – inflexible
- \+ simple registration

2D array

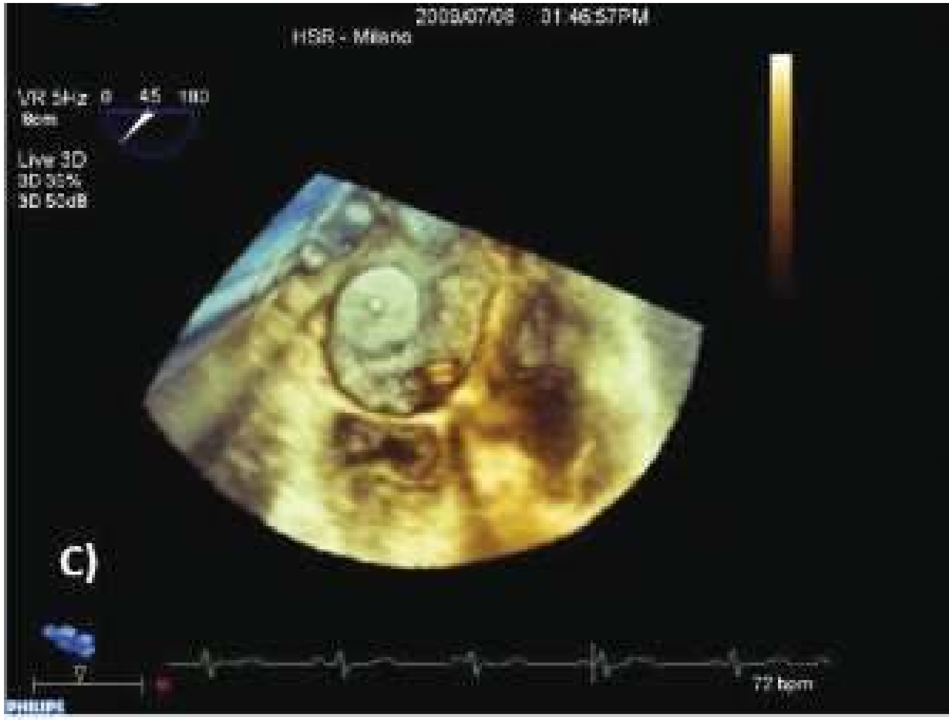
- – electronic complexity
- – element spacing
- \+ real-time 3D



x7-2 array from Philips with 50×50 elements

3-D visualisation: surface vs. volume rendering

Courtesy of Zonare Medical Systems
http://www.zonare.com/products/clinical-images/id_7/



3D US image of left atrium [Agricola *et al*. 2010]
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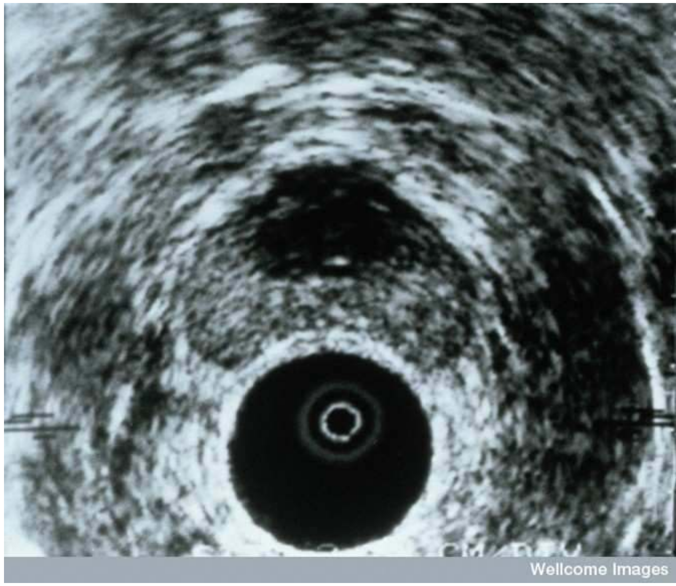
http://www.pagepress.org/journals/index.php/hi/article/viewArticle/hi.2010.e6/2133

Other types of array

- Annular (concentric rings) [Anderson 2006]
  - accurate focusing along axis to produce A-line
  - need to be moved to provide B-mode
- Element(s) inside catheter [Cobbold pp. 580-593]
  - single element moving inside catheter *OR*
    ring of elements used as phase array
  - exciting applications for imaging inside vessels, e.g. intravascular ultrasound (IVUS)



"Normal prostate"
http://images.wellcome.ac.uk/
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For now, concentrate discussion of beamforming on 1-D arrays (linear and phased)

Beamforming strategies

- Fixed delay (near-field, far-field)
- Dynamic focusing: vary receive beam with focus
- Focal zone splicing: several transmission depths
- Parallel receive beamforming (access to pre-beamformed data)
- Synthetic aperture imaging (access to pre-beamformed data)

Fixed delay beamforming

Example: two transceivers A, B; point scatterer S

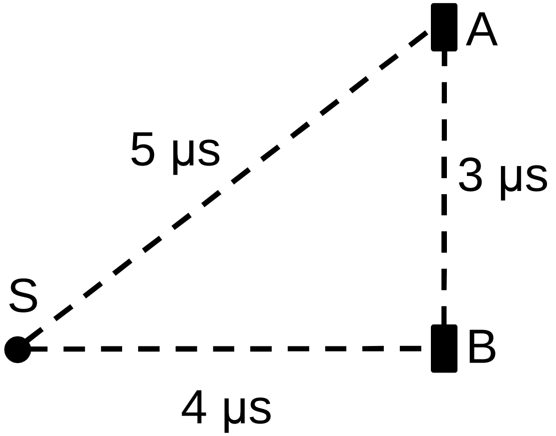
- Estimation of scatterer strength becomes minimum-variance (electrical noise, “spatial noise” from other scatterers) combination of two transmissions and two receptions (*cf.* beamforming as spatial filtering [Van Veen and Buckley 1988])
- Transmit: delay B by 1 µs

$$y_A(t) = w(t);\ \ y_B(t) = w(t\text{-}1)$$

- Signals received in phase at 5 µs
- Receive: delay A by 1 µs (relative to B); sum

$$b(t) = y_A(t\text{-}5) + y_B(t\text{-}4)$$

- *Delay-and-sum beamforming* on receive

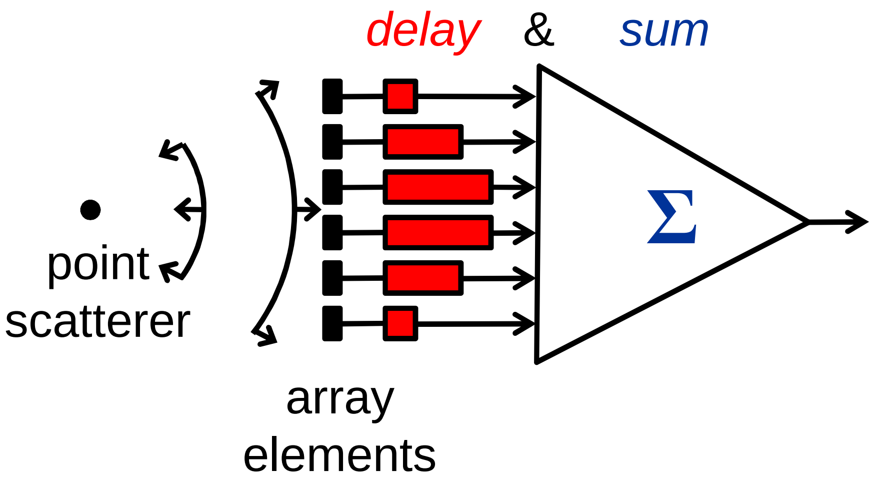


Fixed delay beamforming

- Simplest beamforming method
- Same focus for transmit and receive

  Δtransmit_delays = - Δreceive_delays
- Sharp focusing at target depth, but blurring at other depths
- Far-field limit → plane wave
- plane wave → linear variation of delays

<u>Example:</u> *D*=10 mm, *c*=1500 m/s, *f* = 1.5 MHz. Far-field from $D^2/4\lambda$ = 25 mm



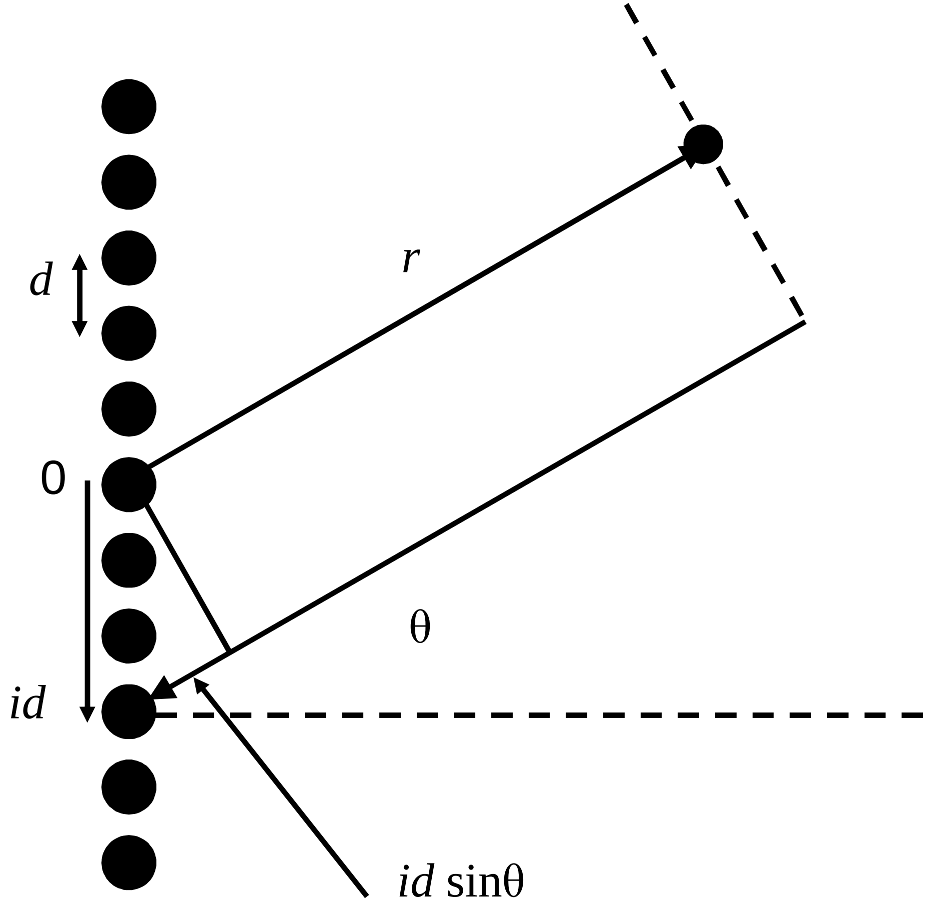
Fixed delay-and-sum beamforming on Tx, Rx. Adapted from [Burns 2005]

Medical diagnostic systems – Beamforming in ultrasound

Phased array beamforming (far-field)

- Reference time (t=0) when pulse is transmitted from central element
- Usually, number of elements is even...
- Fix relative delays, then scale time to distance accordingly
- Delay given by

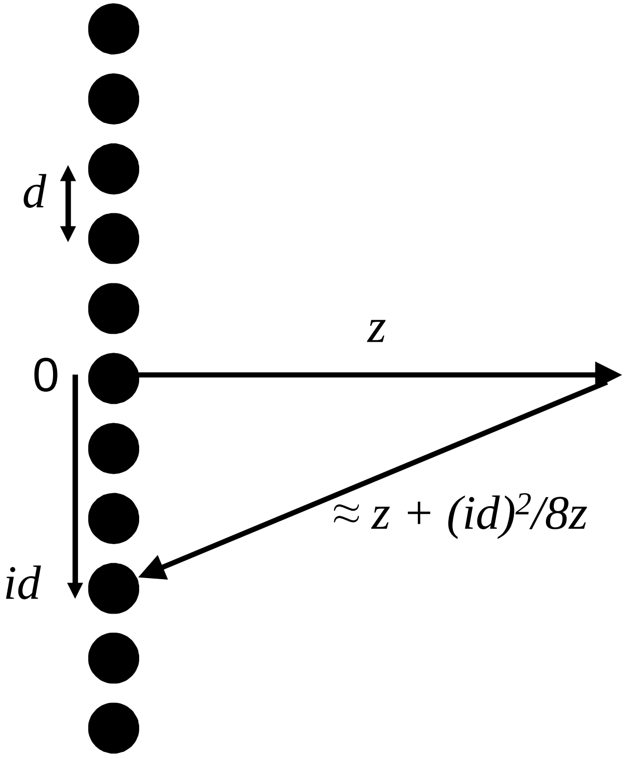
$$\tau(i,r) = 2r/c + id \sin\theta$$



Dynamic receive beamforming

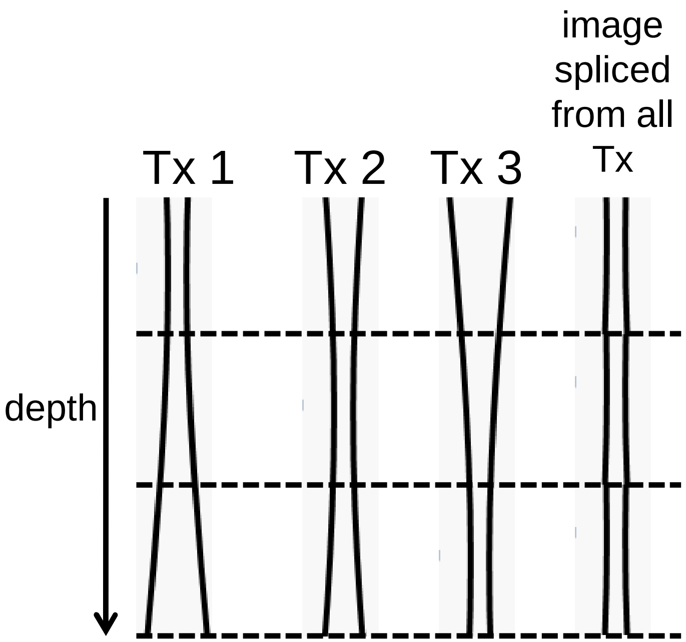
- Once electric pulse converted into acoustic pulse (transmission), no user control over pulse propagation (single beam is formed)
- Beamforming on receive, however, occurs electronically/digitally and any number of beams can be synthesised
- Observation: as echoes return, they come from deeper and deeper objects
- Idea: dynamically vary receive focus with time
- Corresponds to "stretching" (frequency modulation) of signal for out-of-centre elements
- Delay given by

$$\tau(i,r) = 2z/c + (id)2/8z$$



Focal zone splicing

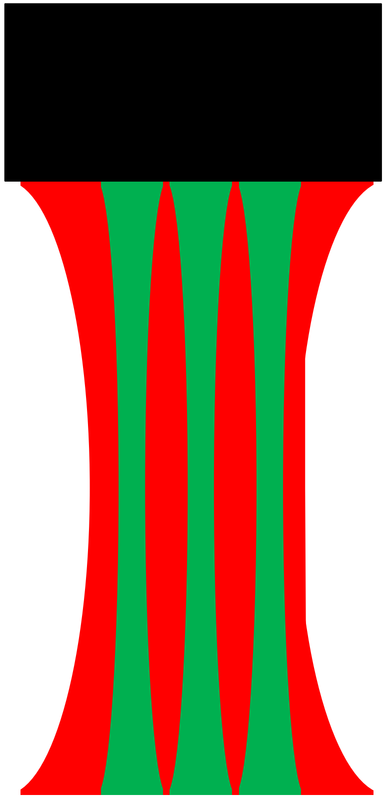
- Well-focussed transmit beam leads to good *local* sharpness
- Transmit several pulses with different foci
- Splice resulting images together
- Reduction in frame rate
- See [Szabo2004, p.309] for images



adapted from [B-K Medical 2003, p. 59]

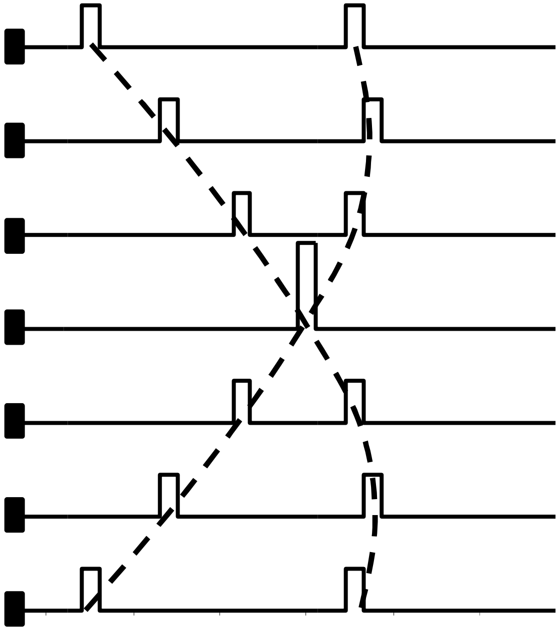
Parallel receive beamforming: zone focussing

- Frame rate depends on number of transmissions
- With parallel digitization of element signals, several receive beams can be synthesised for a single, broader, transmit beam
- Zonare Medical Systems (www.zonare.com) uses this technology



Parallel receive beamforming: multiple beam transmission

- Several transmit beams synthesised in one transmission
- Parallel acquisition allows receive focussing (and thus separation) of the beams
- Again, increase in frame rate results



simultaneous synthesis of two beams
adapted from [Cobbold 2007, p.476]

Synthetic aperture imaging [Jensen *et al.* 2007]

- Each element transmits a pulse on its own, one after the other
- Echoes recorded by all (or many elements) at once
- Assuming linearity, principle of superposition applies
- Both transmit and receive foci can be synthesised retrospectively!
- Higher image resolution
- See [Jensen *et al.* 2007] for images

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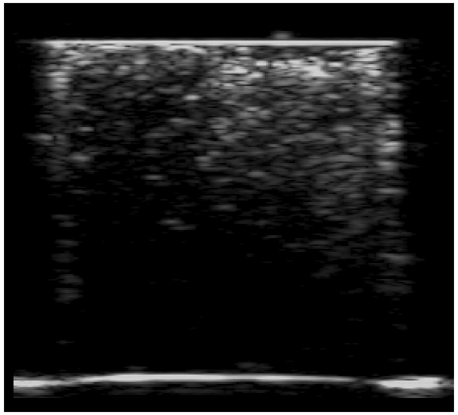
Speckle reduction techniques

- Speckle arises from interference between sub-wavelength scatterers from within one resolution cell
- Spatial averaging (blurring) reduces speckle, but also reduces spatial resolution
- Compounding
    - generate several images with different parameters
    - speckle hopefully weakly correlated
    - sum images to reduce speckle “noise”
    - averaging frames (temporal) causes blurring
    - look at two popular methods: spatial; frequency



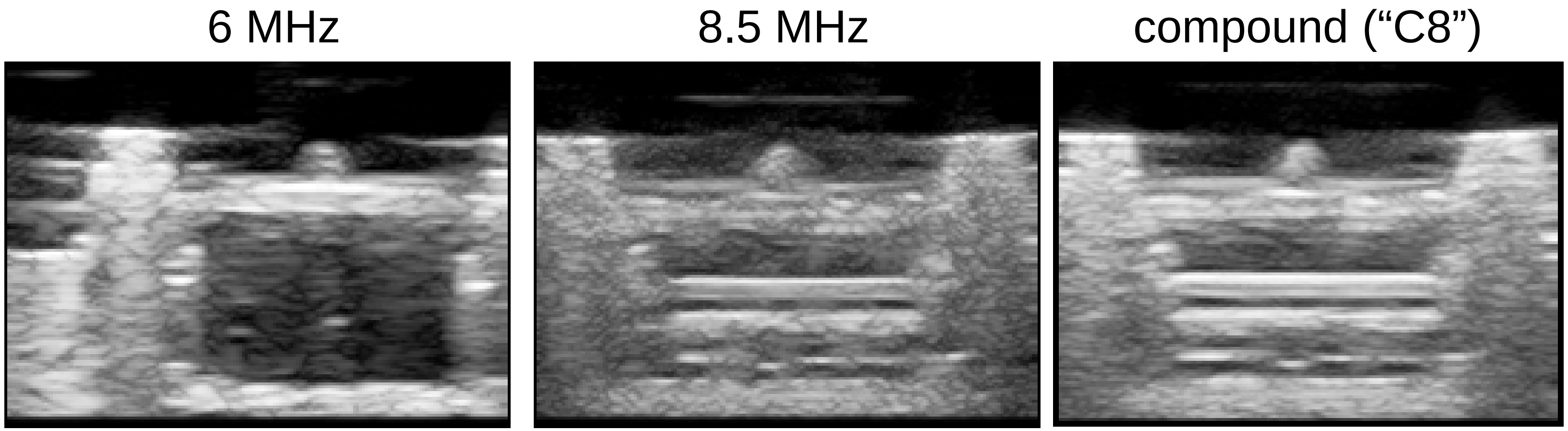
Speckle in B-mode image of agar gel. Notice that speckle has rice-like shape, elongated about the transverse direction.

Spatial/angular compounding [Cobbold 2007, p. 469]

- Subject imaged from several orientations
- Scatterers interfere with different phases when angle of insonation/reception is varied → speckle weakly correlated
- Summation of registered images from several orientations reduces speckle
- Orientations generated from consecutive transmissions:
  - array need not move
  - frames separated by less than 100 ms
  - simple registration
  - real-time compound images

Frequency compounding

- Scattering directivity changes with frequency, but not origins of scattering
- Therefore, strong correlation between images
- Modest speckle reduction



6 MHz

8.5 MHz

compound (“C8”)

Slightly different picture from other two. However, note increased speckle size

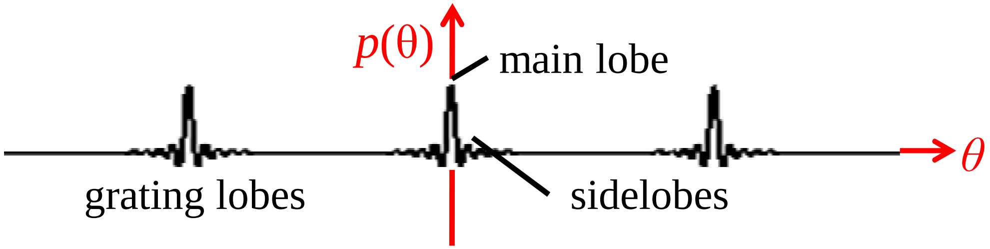
Images of tissue-mimciking agar gel wih vessel-mimicking inclusion; acquired on a z.one ultrasound system (Zonare)

Sidelobes and sidelobe reduction techniques

Sidelobes arise due to

- limited aperture
- sampled aperture (grating lobes)
- temporal quantization errors (quantization error grating lobes)

Sidelobe reduction techniques



Pressure field against angle created by transducer.
(Note that purely angular dependence implies far-field)

Grating lobes [Szabo 2004, pp. 182-185]

- Next lecture: in continuous wave mode, pressure in focal plane is 2-D Fourier transform of pressure amplitude distribution over aperture (i.e. apodization)
- More precisely, angular distribution of pressure is 2-D Fourier transform of apodozation in far-field, and focusing brings the far-field to the focal plane
- Thus (in analogy with the Fourier sampling theorem), if the discrete element spacing "samples" at $d \geq 0.5\lambda$, grating lobes ("aliasing") appear
- Grating lobes first appear at $\theta = \pm\pi$ ($d = 0.5\lambda$) and move closer to region of interest as d is further increased (new grating lobes appear every time d increased by 0.5λ)
- Are grating lobes avoided in practice?

Grating lobes [Szabo 2004, pp. 182-185]

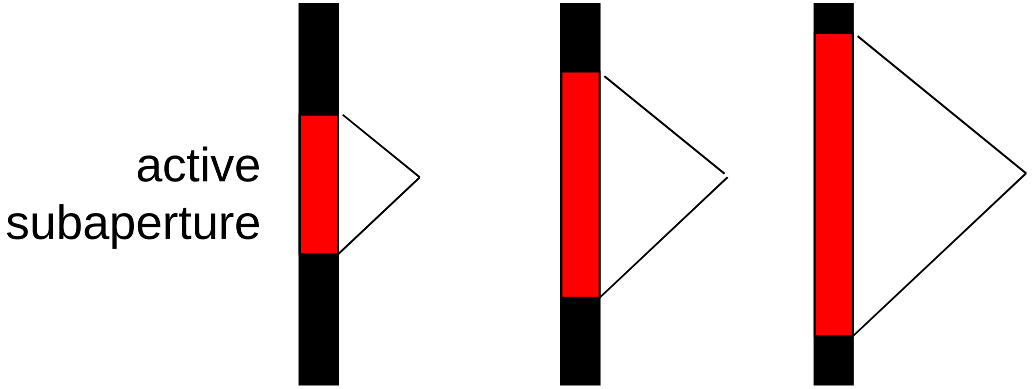
- Are grating lobes avoided in practice? Two examples:
  - L10-5 linear array: f_c = 7.5 MHz, N=128, D=38 mm → $d = 1.5\,\lambda$
  - P4-1 phased array: f_c = 2.5 MHz, N=128, D=28 mm → $d = 0.37\,\lambda$
- In linear scanning, the angle of inspection is 0, and the grating lobes are at such high angles that the interference from them is minimal (*cf.* obliquity factor reducing pressure field to 0 at $\theta=\pi$ for soft baffles such as ultrasonic transducers [Cobbold 2007, pp. 447-448])
- Therefore, the requirement for $d<0.5\lambda$ is relaxed for linear arrays
- However, in phased arrays angle of inspection varies substantially (e.g. $-\pi/4$ to $\pi/4$), so grating lobes can have an effect, and $d<0.5\lambda$ adhered to
- Grating lobes arise naturally out of CW analysis (see next lecture). Simple way to reduce grating lobes: shorten the pulse!

Apodization – beam shaping [Szabo 2004, p. 193]

- Again consider statement that pressure in focal plane is 2-D Fourier transform of apodization function (weightings used for the elements)
- Therefore, to provide a sharp beam (good imaging resolution) on transmit and receive, transducer should be as large as possible
- In the limiting case of an infinite plane or enveloping hemisphere, the beam would be an impulse
- However, in the case of a finite aperture, the beam smears
- This is in analogy with estimating the power spectrum of a signal from a limited time window
- As in power spectrum estimation, uniform apodization causes sinc beam
- Borrowing from spectral estimation techniques, different apodization (windowing) functions [Harris 1978] can be used to reduce the amplitude of sidelobes, *at the expense of increasing the main lobe width*

Dynamic receive apodization

- Increase receiving subaperture with depth
- constant f# on receive
- blurring (PSF) more uniform with depth
- easier to deconvolve blurring computationally
- easier to “deconvolve” (interpret image) by eye



Adaptive beamforming [Holm *et al.* 2009]

- Technique taken from radar and sonar (as so often with ultrasound!)
- Original aim was to cancel out jamming signal from enemy
- Vary element weights **w** (apodization) so as to reject signal from elsewhere
- This allows placing of sidelobes at regions of low energy (or low scattering) while maintaining position of main lobe (i.e. focus)
- Example: Capon beamformer – minimise beamformed signal energy while keeping |**w**|=1
- See [Holm *et al.* 2009] for illustrative images

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References

[Agricola *et al.* 2010] Real-time three dimensional transesophageal echocardiography: technical aspects and clinical applications

[Anderson 2006] A seminar on *k*-space applied to medical ultrasound. http://dukemil.bme.duke.edu/Ultrasound/k-space/index.htm

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[Holm *et al.* 2009] Capon beamforming for active ultrasound systems. http://heim.ifi.uio.no/~sverre/papers/09_MinVar-DSP-workshop.pdf

[Jensen *et al.* 2007] System architecture of an experimental synthetic aperture real-time ultrasound system. http://www.jp-embedded.com/download/press/saurus/preprint.pdf

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[Van Veen and Buckley 1988] Beamforming: A versatile approach to spatial filtering