Medical Imaging (EL582/BE620/GA4426)

Ultrasound Imaging – Lecture 2

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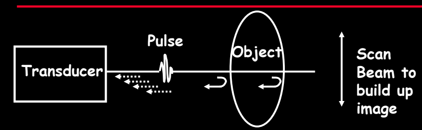
Reference

Prince and Links, Medical Imaging Signals and Systems (2nd Ed), Chap. 11

Pulse-Echo Ultrasound Imaging



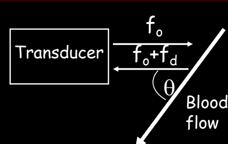
Important properties of ultrasound for imaging:

- Propagation of ultrasound in tissues (speed of sound, c)
- Reflection of ultrasound from interfaces (acoustic impedance, Z)
- Attenuation of ultrasound during propagation (α ~ 1dB/cm/MHz)

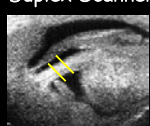
Doppler Ultrasound

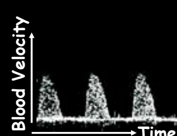
- Doppler Equation:

$$f_d = 2f_o.v.\cos\theta/c$$



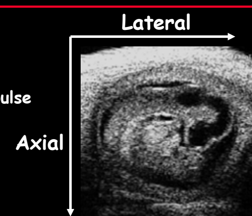
Duplex Scanner





Resolution in Ultrasound Imaging

- Axial Resolution:
  - Resolution in propagation direction
  - Determined by length of pulse propagating in tissue
  - Proportional to λ
- Lateral Resolution:
  - Resolution orthogonal to propagation direction
  - Determined by focusing properties of transducer
  - Proportional to λ

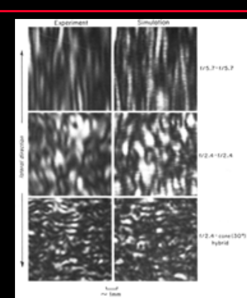


Resolution *vs* Penetration

- Resolution (axial and lateral)↑ with ↑ frequency
- Penetration↓ with ↑ frequency

Compromise between resolution and penetration

Ultrasound Images: Speckle



From: D Foster *et al*, Ultrasonic Imaging, 1983

Ultrasound Images: Speckle

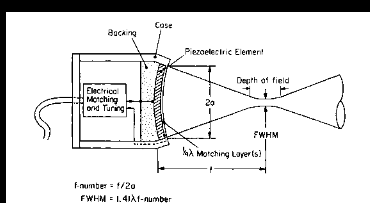
- Speckle size provides an readily available estimate of image resolution
- Speckle characteristics make image analysis (eg., segmentation) more challenging than other modalities
- Speckle reduction methods include persistence and compound imaging
- Speckle tracking can be used for flow mapping

Ultrasound Images: Speckle

- Ultrasound signal is the sum of many scattering events / reflections
- Amplitude (A) of a distribution of N vibrations with phases uniformly distributed between 0 and 2π has the probability density function:

  $\mathrm{pdf}(A) = (2A/N)\exp(-A^2/N)$ (Rayleigh, 1880)
- Mean value of this distribution (="Speckle Signal"):
  $[A] = \sqrt{(\pi[A^2]/4)}$
- "Speckle noise", the rms deviation from the mean:
  $\sqrt{([A^2]-[A])} = \sqrt{\{(1-\pi/4)[A^2]\}}$
- Inherent speckle SNR:
  $\mathrm{SNR} = \sqrt{\{(\pi/4)/(1-\pi/4)\}} = 1.91$ (!)

Single Element Transducer



From: Hunt *et al,* IEEE Trans BME, 1983

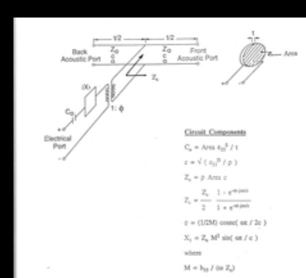
Functions of the transducer

- Used both as Transmitter And Receiver
- Transmission mode: converts an oscillating voltage into mechanical vibrations, which causes a series of pressure waves into the body
- Receiving mode: converts backscattered pressure waves into electrical signals

Piezoelectric Material

- Converts electrical voltage to mechanical vibration and vice versa
- The thickness of the crystal varies with the applied voltage
- When an AC voltage is applied across the crystal, the thickness oscillates at the same frequency of the voltage
- Examples of piezoelectric Materials:
  - Crystalline (quartz), Ceramic (PZT, lead zirconium titanate), Polymers (PVDF), Composite materials
  - PZT is one of the most efficient materials
- The crystal vibrates sinusoidally after electrical excitation has ended (resonate)
  - Resonant frequency f=c/2d (d=thickness)
  - The damping material damps the vibration after a few cycles
- When the diameter D of the surface is much larger than d, longitudinal waves are transmitted into the body

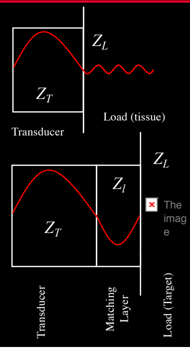
Modeling electromechanical properties of the transducer



From: Turnbull, PhD Thesis, 1991

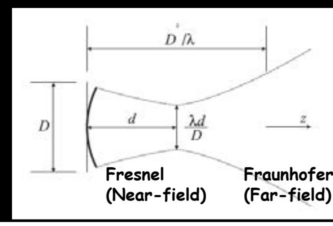
Matching Layer(s)

- To provide acoustic coupling between the crystal and patient skin and to protect surface of the crystal
- Z of PZT (Z_T) is ~15 times greater than Z of tissue (Z_L)
  - Placing crystal directly over skin would result a large amount of energy be reflected back from the boundary
    - » $R = |(Z_L - Z_T)/(Z_L + Z_T)| \sim 1$
- Matching layer
  - layer thickness = $\lambda/4$
  - $Z_I = \sqrt{(Z_T Z_L)}$
  - Maximize energy transfer into the body
- Problems: Finding material with exact Z_l value

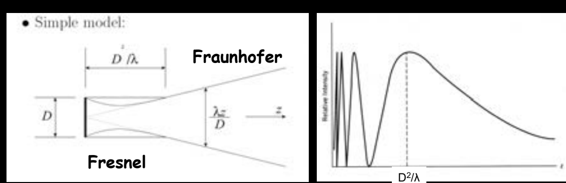


Ultrasound beam properties

- Beam focusing can be accomplished by
  - Using an element with a curved surface
  - Placing a concave lens in front of the transducer
  - Using a transducer array



Flat (Piston) Plate Transducer

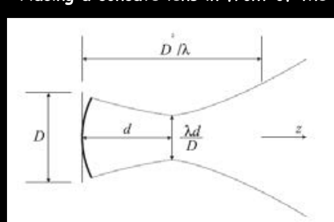


Beam Properties of a Piston Transducer

- At border of the beam width, the signal strength drops by a factor of 2, compared to the strength on the z-axis
- Beam width determines the imaging resolution (lateral resolution).
- Smaller D is good only before far field
- D=1~5 cm in practice, very poor lateral resolution
- Focused plate is used to produce narrow beam

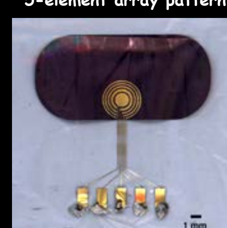
Focused Transducer

- Beam focusing can be accomplished by
  - Using a crystal with a curved surface
  - Placing a concave lens in front of the crystal

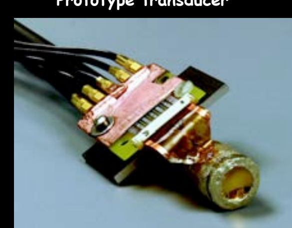


40-MHz annular array transducers for dynamic focusing

5-element array pattern

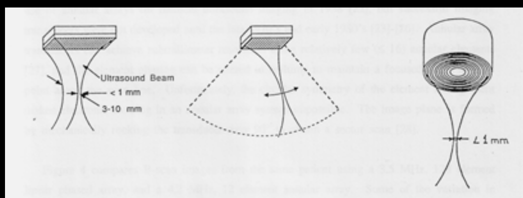


Prototype transducer



Ketterling et al, IEEE Trans UFFC 2005

Annular Array Focusing



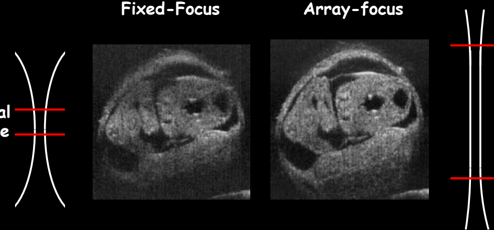
From: Turnbull, PhD Thesis, 1991

Annular array transducer improves focusing in depth

E11.5 Mouse Embryo

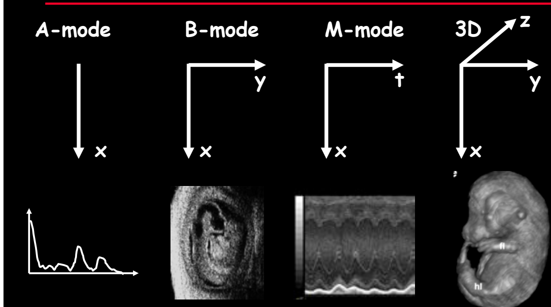
Fixed-Focus | Array-focus

Focal Zone



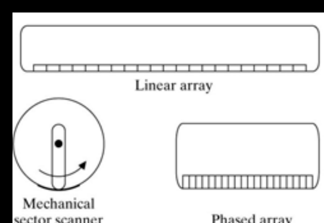
Ketterling et al, IEEE Trans UFFC 2005

Ultrasound Scan Modes



B-mode Scanner Types

- B-mode scanners use multiple transducers

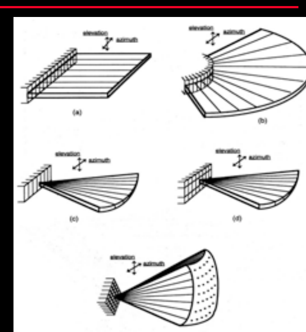


Transducer Array

- With a single element, mechanical steering of the beam is needed to produce a 2D image
- Practical systems today use an array of small piezoelectric elements
  - Allow electronic steering and focusing of the beam to optimize the lateral resolution

Array types

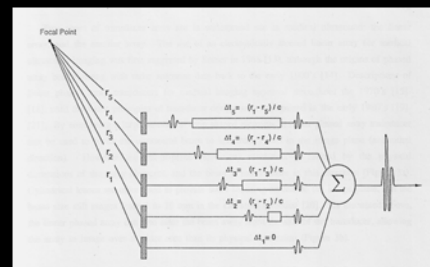
a) Linear Sequential (switched)
~1 cm × 10-15 cm, up to 512 elements
b) Curvilinear
similar to (a), wider field of view
c) Linear Phased
up to 128 elements, small footprint → cardiac imaging
d) 1.5D Array
3-9 elements in elevation allow for focusing
e) 2D Phased
Focusing, steering in both dimensions



Phased Arrays

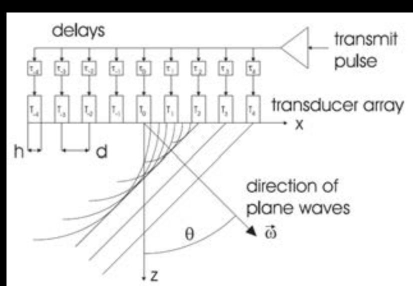
- Phased array:
  - Much smaller transducer elements than in linear array
  - Use electronic steering/focusing to vary transmit and receive beam directions

Array Focusing and Steering

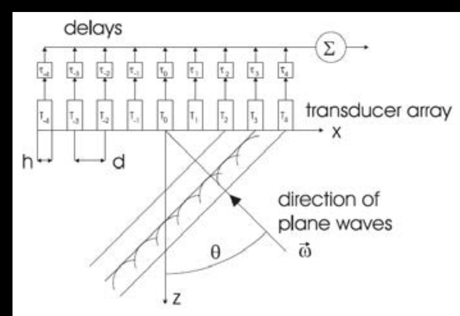


From: Turnbull, PhD Thesis, 1991

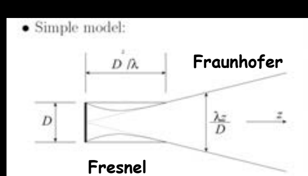
Beam Steering (Transmit)



Receive Beamforming



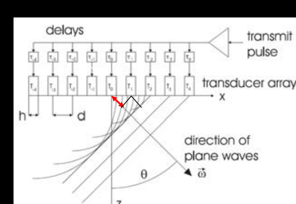
Flat (Piston) Plate Transducer



Array elements are flat pistons – operate in (Fraunhofer) farfield

Delays for Steering

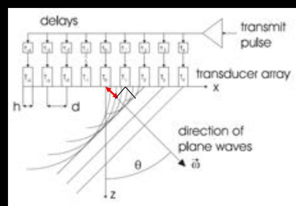
- Extra distance that T0 travels than T1:
  $\Delta d = d \sin\vartheta$
- For the wave from T1 to arrive at a point at the same time as T0, T1 should be delayed by
  $\Delta t = \Delta d/c = d \sin\vartheta/c$
- If T0 fires at t=0, Ti fires at
  $t_i = i\Delta t = id \sin\vartheta/c$



Grating lobes

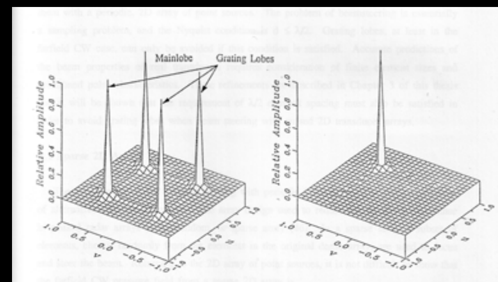
- $t_i = i\Delta t = id\ \sin\vartheta/c$
- Steering direction is $\vartheta = \vartheta_0$ (Main lobe)
- Grating lobes (unwanted) in directions:

  $\sin\vartheta_g = \sin\vartheta_0 \pm j\lambda/d, \quad j=1,2,\ldots$



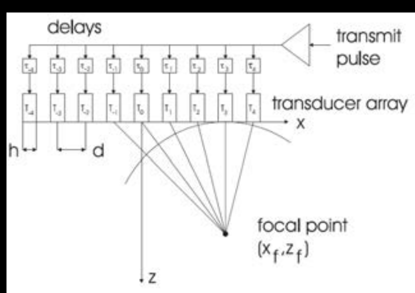
- Eg - $\vartheta_0 = 30°$, $d = \lambda$, then $\vartheta_g = -30°$
- Avoid all grating lobes by choosing $d = \lambda/2$ (!)

Grating lobes in 3D space

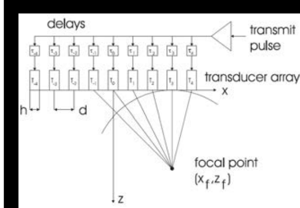


From: Turnbull, PhD Thesis, 1991

Beam Focusing (T or R)



Delays for Focusing



- Focal point at (x_f, z_f)
- T_i is at $(id, 0)$.
- Then range from T_i to focal point is:

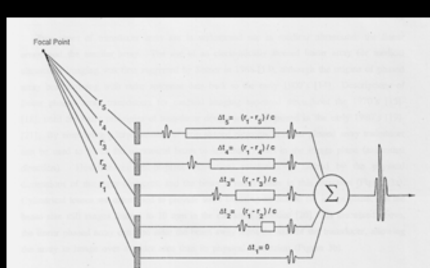
$$r_i = \sqrt{(id - x_f)^2 + z_f^2}$$

- Assume T_0 fires at $t = 0$. Then T_i fires at

$$t_i = \frac{r_0 - r_i}{c} = \frac{\sqrt{x_f^2 + z_f^2} - \sqrt{(id - x_f)^2 + z_f^2}}{c}$$

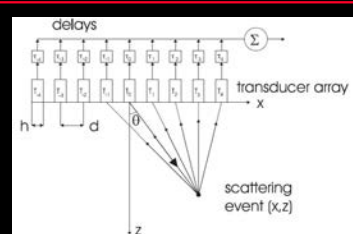
(Delays can be used to focus the beam on transmit and receive)

Array Focusing and Steering



From: Turnbull, PhD Thesis, 1991

Receive Dynamic Focusing



T0 fires in direction θ, and all Ti's receive after a certain delay, so that they are all receiving signal from the same point at a particular time

Delays for Dynamic Focusing

- First consider a stationary scatterer at (x,z)
- Time for a wave to travel from T0 to the scatterer and then to Ti is
  $t_i = \{(x^2+z^2)^{1/2} + [(id-x)^2+z^2]^{1/2}\}/c$
- Time difference between arrival time at T0 and at Ti
  $\Delta t_i = t_0 - t_i$
- Desired time delay is a function of t:

$$\tau_i(t) = t - \frac{\sqrt{(id)^2 + (ct)^2 - 2ctid\sin\theta}}{c} + \frac{Nd}{c}$$

Practicalities of dynamic focusing

- Steer and focus the transmit beam in direction θ
- Focus the receive beam dynamically along that direction
- Increment steering direction to θ + Δθ
- Repeat for the new direction / image line

Steering and Focusing: Summary

- Beam steering and focusing are achieved simply by applying time delays on transmit and receive
- The time delays are computed using simple geometrical considerations, and assuming a single speed of sound
- These assumptions may not be correct, and may lead to artifacts

Clinical Applications

- Ultrasound is considered safe; instrument is less expensive and imaging is fast
- Clinical applications
  - Obstetrics and gynecology
    - » Widely used for fetus monitoring
  - Abdominal tumor imaging
  - Breast imaging
  - Musculoskeletal structure
  - Cardiac diseases
- Contrast agents

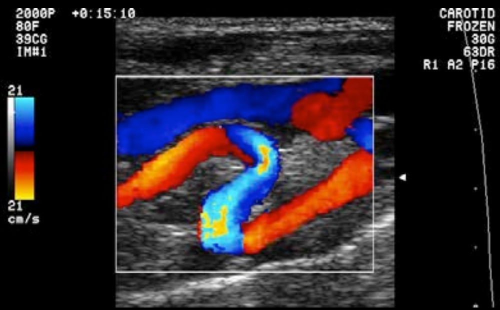
Carotid Plaque Morphology

Techniques in Noninvasive Vascular Diagnosis-3rd Ed., Rob Daigle, Summer Publishing LLC, Copyright 2009

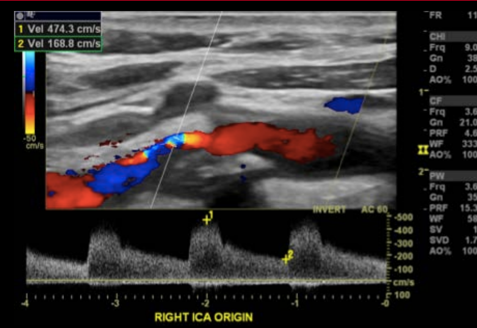
Carotid Plaque Morphology

Techniques in Noninvasive Vascular Diagnosis-3rd Ed., Rob Daigle, Summer Publishing LLC, Copyright 2009

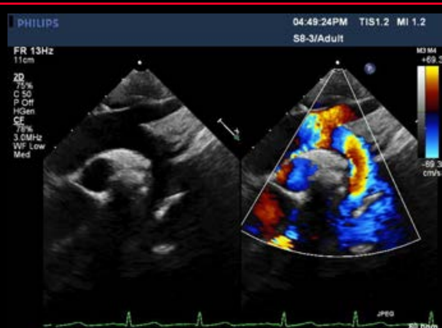
Tortuous Internal Carotid



Proximal Rt. ICA Severe Stenosis

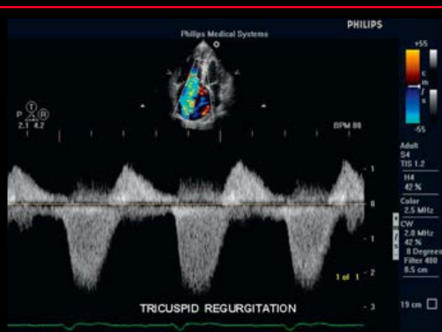


Pediatric Aortic Arch

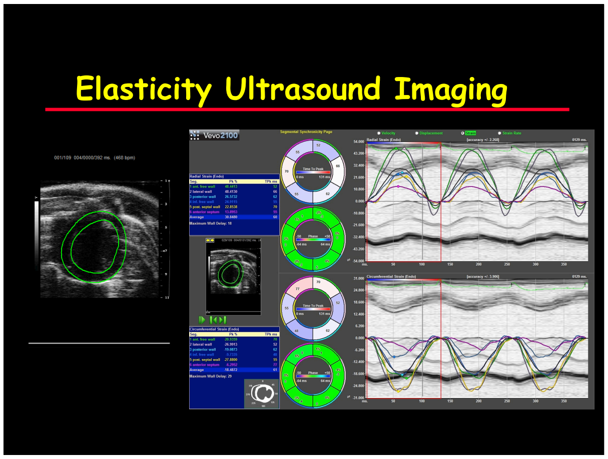


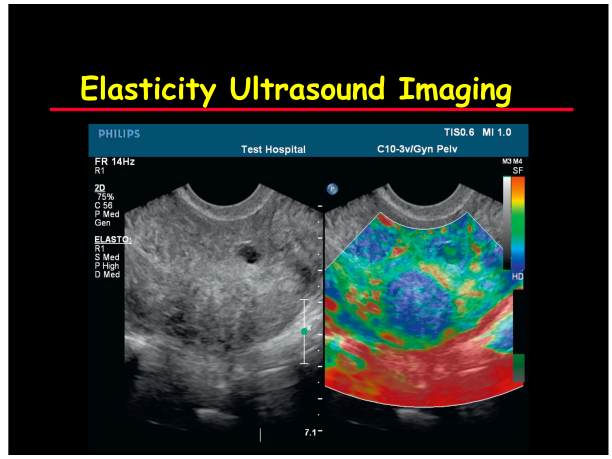
Fetal Aortic Arch

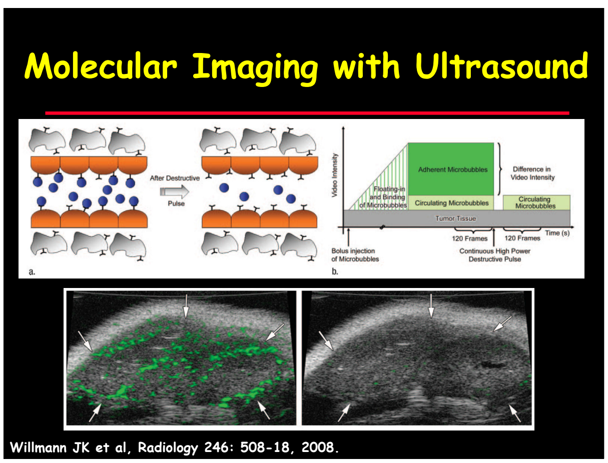
Heart Valve Assessment

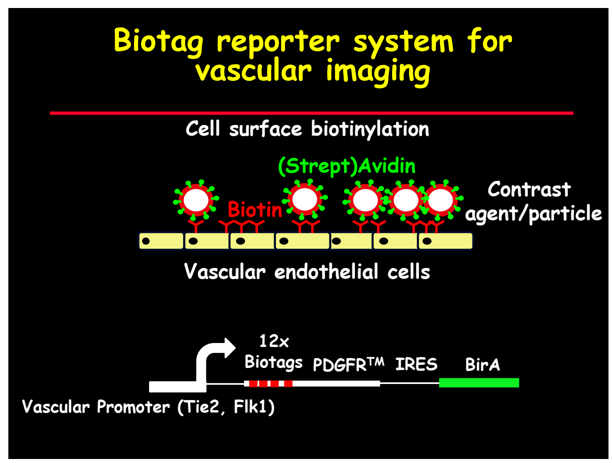


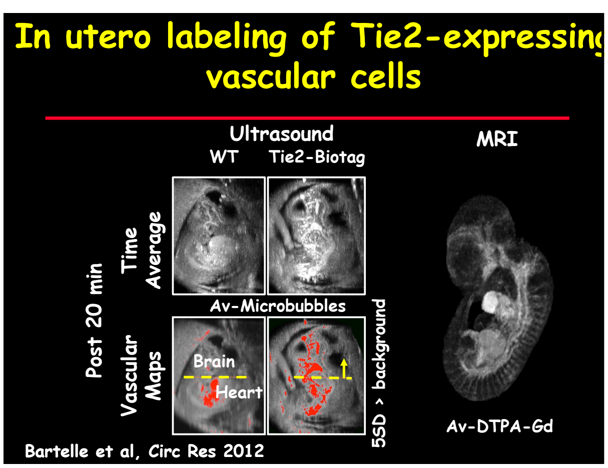
Organ Transplant Monitoring

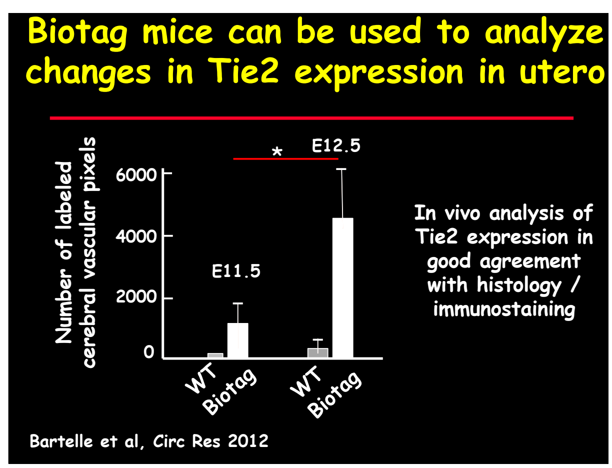

Elasticity Ultrasound Imaging


Elasticity Ultrasound Imaging
PHILIPS
TIS0.6 MI 1.0
Test Hospital
C10-3v/Gyn Pelv
FR 14Hz

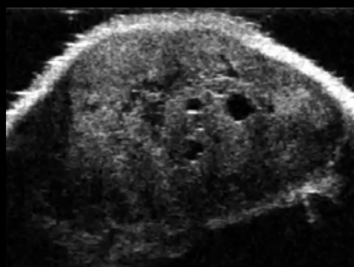

Molecular Imaging with Ultrasound
After Destructive Pulse
Adherent Microbubbles
Difference in Video Intensity
Circulating Microbubbles
Tumor Tissue
Bolus injection of Microbubbles
120 Frames
Continuous High Power Destructive Pulse
Time (s)
Video Intensity
Willmann JK et al, Radiology 246: 508-18, 2008.


Biotag reporter system for vascular imaging
Cell surface biotinylation
(Strept)Avidin
Biotin
Contrast agent/particle
Vascular endothelial cells
12x Biotags
PDGFR TM
IRES
BirA
Vascular Promoter (Tie2, Flk1)


In utero labeling of Tie2-expressing vascular cells
Ultrasound
WT
Tie2-Biotag
MRI
Post 20 min
Time Average
Av-Microbubbles
Vascular Maps
Brain
Heart
5SD > background
Av-DTPA-Gd
Bartelle et al, Circ Res 2012

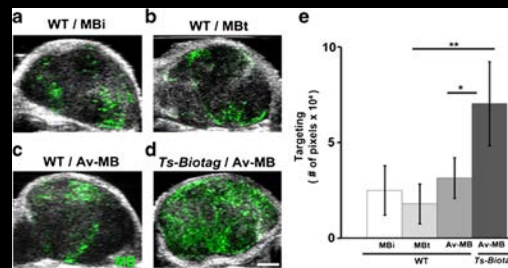

Biotag mice can be used to analyze changes in Tie2 expression in utero
Number of labeled cerebral vascular pixels
6000
4000
2000
0
E11.5
E12.5
*
WT
Biotag
WT
Biotag
In vivo analysis of Tie2 expression in good agreement with histology / immunostaining
Bartelle et al, Circ Res 2012

Contrast-enhanced ultrasound of mouse melanoma vasculature



Suero-Abreu et al, Mol Imaging Biol 2017

Analysis of Tie2 expression in mouse melanoma tumors



Suero-Abreu et al, Mol Imaging Biol 2017

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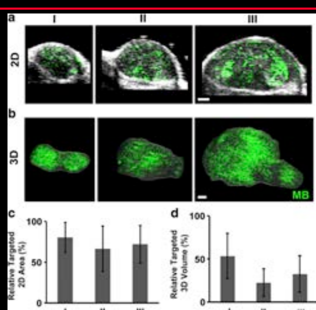

Suero-Abreu et al, Mol Imaging Biol 2016

Homework

- **Reading:**
  - Prince and Links, Medical Imaging Signals and Systems, Chapter 11
- **Problems:**
  - P11.6
  - P11.10