3. Ultrasound Imaging(3)

Lectures 15, 16

Medical Imaging Systems

Jae Gwan Kim, Ph.D.

jaekim@gist.ac.kr , X 2220

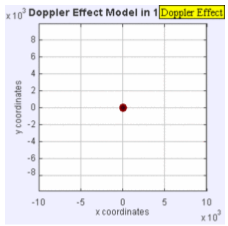
Department of **B**io**M**edical **S**cience and **E**ngineering

Gwangju **I**nstitute of **S**ciences and **T**echnology

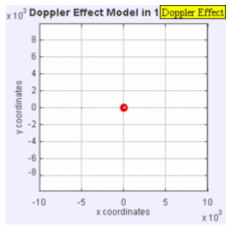
Contents

1. Doppler ultrasound for blood flow measurements
2. Ultrasound contrast agents
3. Safety guidelines in ultrasound imaging
4. Clinical applications of ultrasound
5. Artifacts in ultrasound imaging

Doppler Effect



Stationary sound source

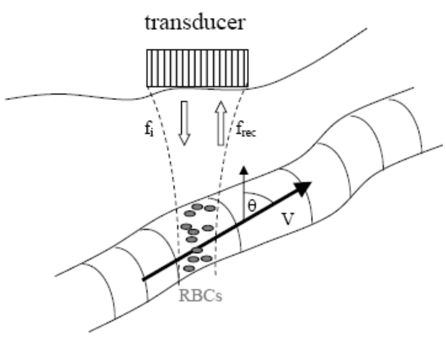


moving to the right with a speed v_s = 0.7 c (Mach 0.7)

http://en.wikipedia.org/wiki/Doppler_effect

Doppler ultrasound

- Ultrasound can measure blood velocity from the Doppler effect
- When the blood flow is toward transducer, the effective frequency (f_i^{eff}) of the incident ultrasound beam for the moving RBCs is higher than the actual frequency transmitted (f_i)
- $f_i^{eff} = \frac{c + v\ cos\theta}{\lambda} = \frac{f_i(c + v\ cos\theta)}{c}$ where $f = c/\lambda$



Doppler ultrasound

- The same process occurs during signal reception.
- Therefore, the frequency of the received ultrasound (f_{rec}) is

$$f_{rec} = \frac{f_i^{eff}(c + v\cos\theta)}{c} = \frac{f_i \ (c + v\cos\theta)^2}{c^2}$$

$$= f_i + \frac{2f_i v\cos\theta}{c} + \frac{f_i v^2 \cos^2\theta}{c^2}$$

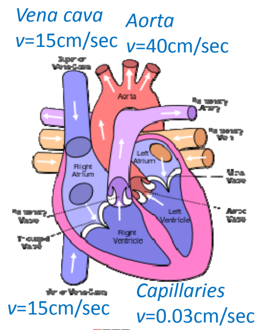
- The Doppler shift (f_D) is

$$f_D = f_i - f_{rec} = \frac{2f_i v\cos\theta}{c} + \frac{f_i v^2\cos^2\theta}{c^2} \approx \frac{2f_i v\cos\theta}{c}$$

Therefore, the blood velocity, $v = \frac{cf_D}{2f_i\cos\theta}$

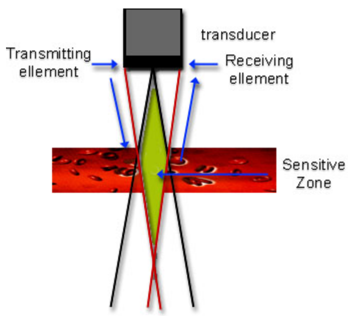
Doppler ultrasound

- Ex) f_i=5MHz, θ=45°, and v=50cm/sec
  → f_D =2.3kHz which is less than 0.05% of f_i
- Doppler measurements are typically done at high frequency (>5MHz) because the scattered signal intensity is proportional to 4th power of the frequency
- However, it decreases the depth of detection
- Accurate blood velocity can be obtained when the angle θ is known
  → simultaneous B mode scan provides this information



Continuous wave Doppler

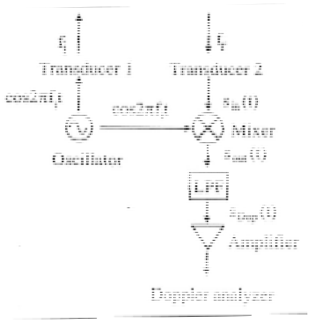
- We can use CW Doppler when you don't need to localize the Doppler signal
  → average value → simple and low cost
- In CW mode, array is split into two sections
- One section transmits a continuous US
- The other section receives the backscattered signals
- ROI is defined by the overlap of the areas defined by the transmission and reception beam-forming settings
- Quadrature detector must be used to determine the flow direction
- Advantage: CW method is neither limited to a max. depth, nor to a max. measurable velocity



http://www.centrus.com.br/DiplomaFMF/SeriesFMF/doppler/capitulos-html/chapter_01.htm

Continuous wave Doppler

- Homodyne demodulation scheme:
  $S_{in}(t) = A cos[2\pi(f_i + \Delta f)t]$
  $S_{out}(t) = A cos[2\pi(f_i + \Delta f)t]\cos(2\pi f_i t)$
  $S_{out}(t) = \frac{1}{2}A\{cos[2\pi(2f_i + \Delta f)t] + \cos(2\pi\Delta f t)\}$
- The signal is then pass through a low-pass filter with a cutoff frequency f_{co} given by $\Delta f << f_{co} << f_i$
  $$S_{Dop}(t) = \frac{1}{2}A\cos(2\pi\Delta f t)$$



- Then the signal passes through a high-pass filter (50~1000Hz) to remove high-intensity reflected signals from the relatively slow movement of vessel walls during the cardiac cycle.
- The final signal is amplified, digitized and stored.
- Fourier transform the time domain signal gives the frequency spectrum, corresponding to the range of blood velocities

Continuous wave Doppler

- Then the signal passes through a high-pass filter (50~1000Hz) to remove high-intensity reflected signals from the relatively slow movement of vessel walls during the cardiac cycle.

$$v = \frac{cf_D}{2f_i cos\theta}$$

- 50Hz → 2cm/sec
- 1000Hz → 40cm/sec

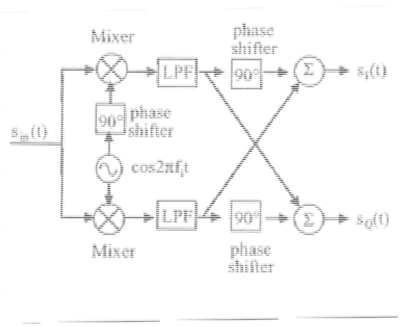
Relation between blood flow velocity and total cross-section area in human[7]

Type of blood vessels	Total cross-section area	Blood velocity in cm/s
Aorta	3–5 cm^2	40 cm/s
Capillaries	4500–6000 cm^2	0.03 cm/s[8]
Vena cavae inferior and superior	14 cm^2	15 cm/s

Continuous wave Doppler

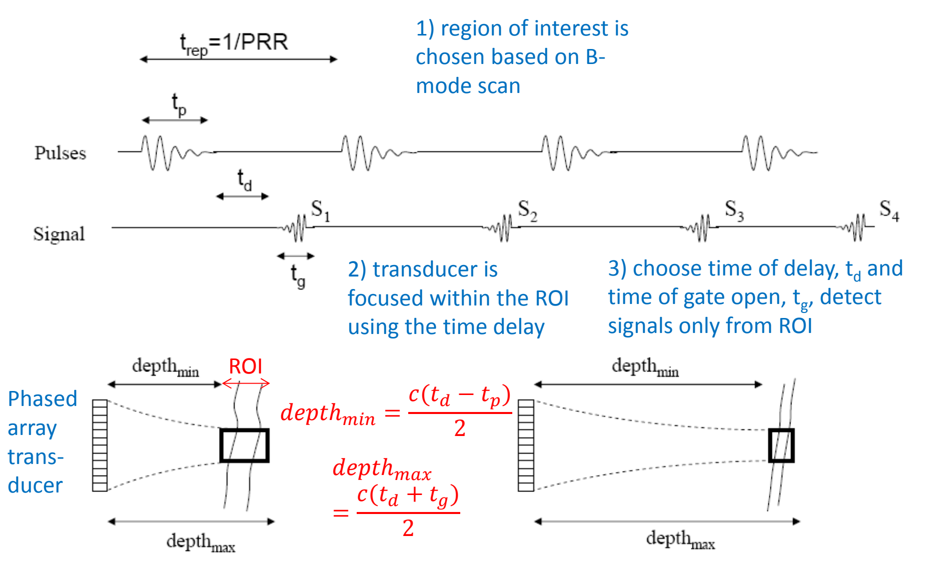
- Quadrature or Heterodyne demodulation: to overcome the problem of homodyne detector (there is a directional ambiguity in the output signal)
- Ex) when there is blood flow away from the transducer, Δf will be replaced with - Δf, which will give

$$S_{Dop}(t) = \frac{1}{2}A\cos(-2\pi\Delta f t)$$



- However, cos(t)=cos(-t) and thus we don't know the direction of the blood flow.
- Therefore, a quadrature or heterodyne detection is used.
- Positive Doppler shift: $S_I(t) = A\cos(\Delta f t)$ and $S_Q = 0$.
- Negative Doppler shift: $S_I(t) = 0$ and $S_Q = A\cos(\Delta f t)$

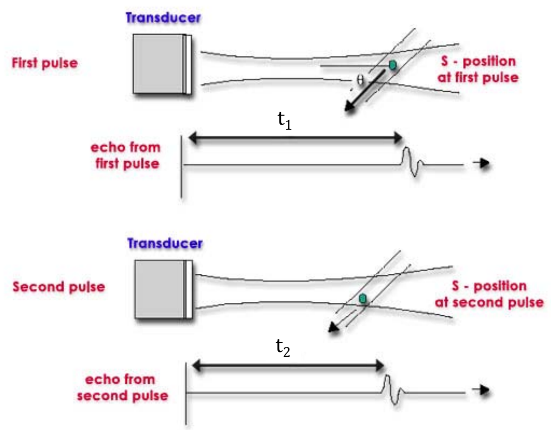
Pulsed wave Doppler measurements



$$depth_{min} = \frac{c(t_d - t_p)}{2}$$

$$depth_{max} = \frac{c(t_d + t_g)}{2}$$

Pulsed wave Doppler measurements

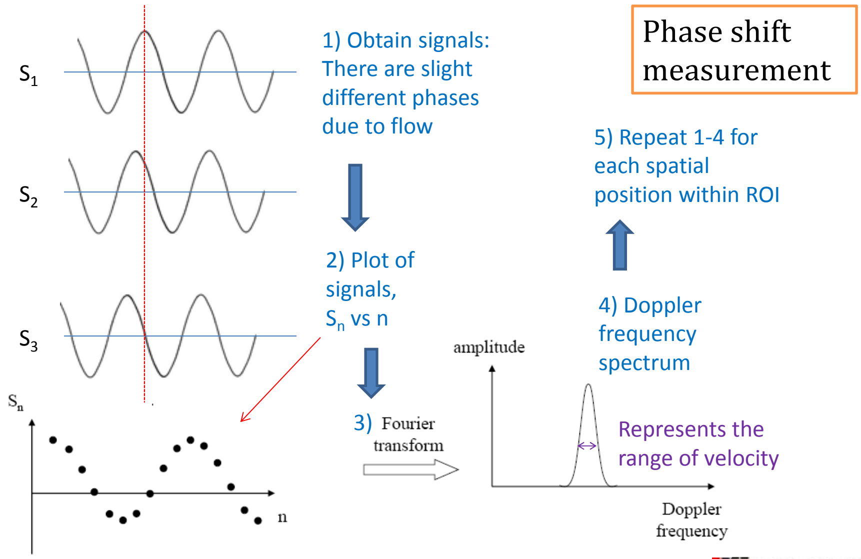


Direct time difference measurement

The diagram shows a scatterer S moving at velocity V with a beam/flow angle θ. The velocity can be calculated by the difference in transmit-to-receive time from the first pulse to the second (t_2), as the scatterer moves through the beam

http://www.centrus.com.br/DiplomaFMF/SeriesFMF/doppler/capitulos-html/chapter_01.htm

Blood velocity calculation process

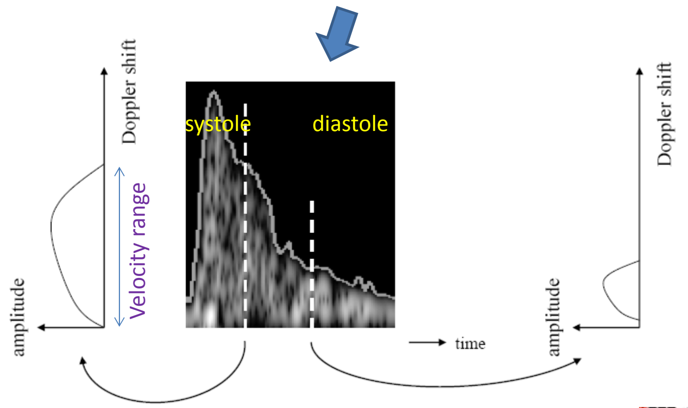


Duplex and triplex image acquisition

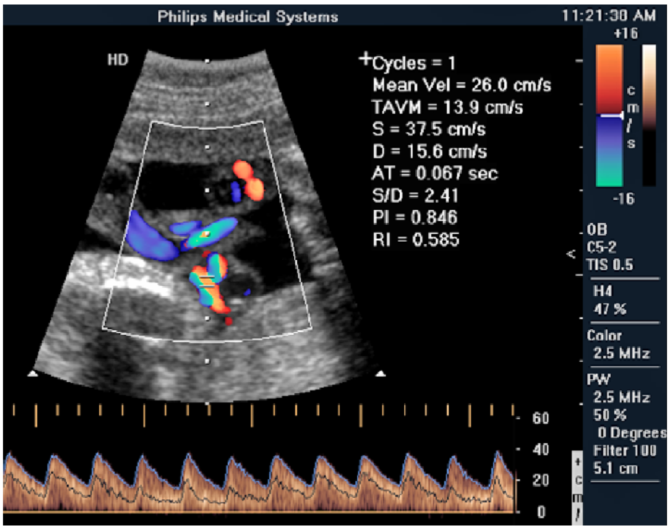
Use a long pulse since Doppler signal is very weak

Use a short pulse to have a higher resolution

- Duplex image: flow information + B-mode scan
- Triplex image: duplex + Doppler spectral display



Color flow imaging



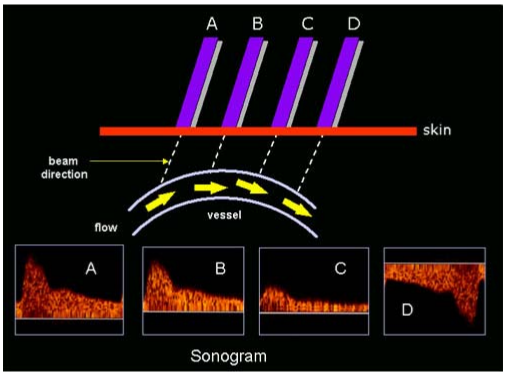
Doppler signal is dependent on

- Blood velocity: as velocity increases, so does the Doppler frequency
- Ultrasound frequency: higher ultrasound frequencies give increased Doppler frequency. However, in B-mode, lower ultrasound frequencies have better penetration

$$f_D \approx \frac{2 f_i v \cos\theta}{c}$$

- The angle of blood flow: the Doppler frequency increases as the Doppler ultrasound beam becomes more aligned to the flow direction (the angle θ between the beam and the direction of flow becomes smaller). This is of the utmost importance in the use of Doppler ultrasound.

Effect of the Doppler angle



Higher-frequency Doppler signal is obtained if the beam is aligned more to the direction of flow. In the diagram, beam **(A)** is more aligned than **(B)** and produces higher-frequency Doppler signals. The beam/flow angle at **(C)** is almost 90° and there is a very poor Doppler signal. The flow at **(D)** is away from the beam and there is a negative signal.

http://www.centrus.com.br/DiplomaFMF/SeriesFMF/doppler/capitulos-html/chapter_01.htm

광주과학기술원

Aliasing in pulse wave Doppler imaging

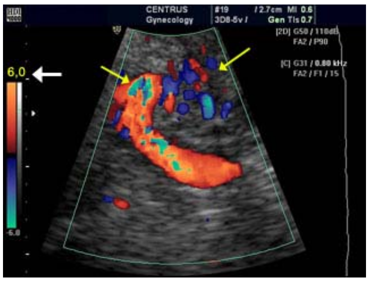
- In pulse wave Doppler imaging, the maximum velocity that can be measured is limited by the PRR value
- If the velocity exceeds the PRR, the incorrect value (even shown as opposite direction) will be displayed
  → signal aliasing occurs when the phase shift during each delay between successive pulses (1/PRR) is greater than 180°
- The max Doppler frequency shift (f_{max}) can be measured;

$$f_{max} = \frac{1}{2t_{rep}} = \frac{PRR}{2}$$

- Max velocity, $v_{max} = \frac{cf_{max}}{2f_i} = \frac{c(PRR)}{4f_i}$ ($\leftarrow v = \frac{cf_D}{2f_i cos\theta}$)
- Max depth, $d_{max} = \frac{ct_{rep}}{2} = \frac{c}{2PRR} = \frac{c^2}{8f_i v_{max}}$

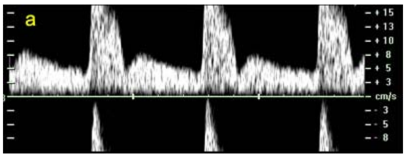
광주과학기술원

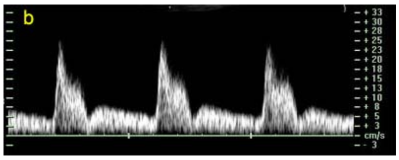
Aliasing in pulse wave Doppler imaging



Aliasing of color Doppler imaging and artifacts of color. Color image shows regions of aliased flow (yellow arrows).

Reduce color gain and increase pulse repetition frequency.





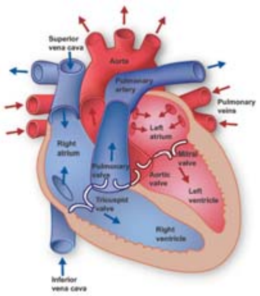
http://www.centrus.com.br/DiplomaFMF/SeriesFMF/doppler/capitulos-html/chapter_01.htm

Power Doppler

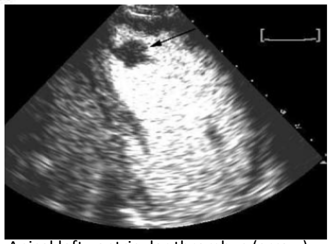
- Another potential problem happens when a vessel lies parallel to the face of phased array transducer
- In this case, one section shows flow towards and the other shows flow away from the transducer
- A vessel directly below the transducer gives a very low signal
- Power Doppler mode can help these problems
- Power Doppler integrates the area under the magnitude of the Doppler signal to give 'Doppler power'
  → both positive and negative Doppler frequencies give a positive power → signal voids are removed
- Aliasing artifacts at high flow rates are also eliminated since the integral of an aliased signal is the same as that of a non-aliased signal
- Disadvantage is the loss of directional information

Ultrasound contrast agents

- Microbubbles or microspheres
- Primarily used for echocardiography and Doppler imaging
- Ventricular opacification, assessment of left ventricular volume, systolic function, and delineation of the endocardial structures
- Enhancement of Doppler ultrasound make possible to measure blood perfusion in the heart and other organs such as the liver

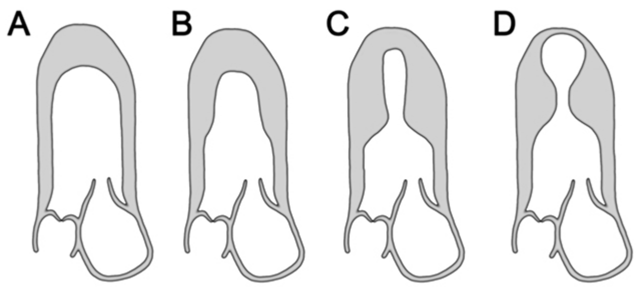


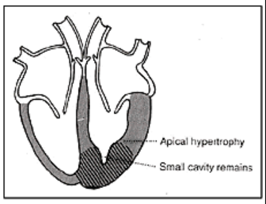
http://texasheart.org/HIC/Anatomy/anatomy2.cfm



Apical left ventricular thrombus (arrow) on two chamber apical view demarcated by contrast.

Hypertrophic Cardiomyopathy

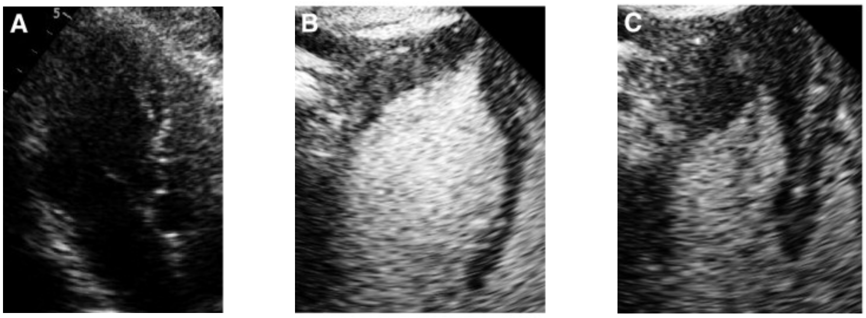




Four diagrams show different types of sub-basal HCM, variants distinct from the usual HCM that involves the proximal septum.
(A) Pure apical HCM.
(B) Apical HCM with extension to the mid-LV.
(C) Apical and mid-HCM with severe encroachment of the the LV cavity resulting in a small slit-like LV cavity in diastole, but no apical akinetic chamber.
(D) Mid-LV HCM with mid-LV obstruction and an apical akinetic chamber. Severe Symptoms in Mid- and Apical HCM. Shah et al. Echocardiography 2009.

Hypertrophic Cardiomyopathy

Apical Hypertrophic Cardiomyopathy

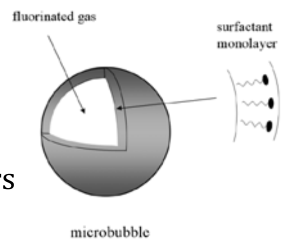


(A) An unenhanced, 3-chamber echocardiogram at rest in a 70-year-old woman referred for stress echocardiography to investigate breathlessness is of poor quality but does not suggest any significant structural disease. Following administration of a contrast agent, the characteristic spade-like left ventricular cavity contour is fully appreciated in both **(B)** diastole and **(C)** end-systole, permitting the diagnosis of apical hypertrophic cardiomyopathy to be made.

Navtej S. Chahal, MD; Roxy Senior, MD, DM,
J Am Coll Cardiol Img. 2010;3(2):188-196.

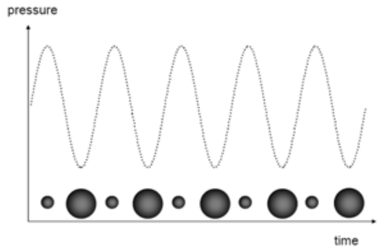
Microbubbles

- Currently, SonoVue and Optison are approved for worldwide clinical use
- SonoVue: microbubble coated with phospholipid monolayers and contains sulphur hexafluoride gas
- Optison: microbubbles which contain perfluoropropane gas within a cross-linked serum albumen microsphere
- The shells are a few tens of nm thick and diameter of 2~10μm
- Shells are needed to prevent immediate gas dissolve into blood due to high surface tension
- These are packaged as freeze-dried powders which can be rehydrated in physiological saline solution just before injection



Microbubbles

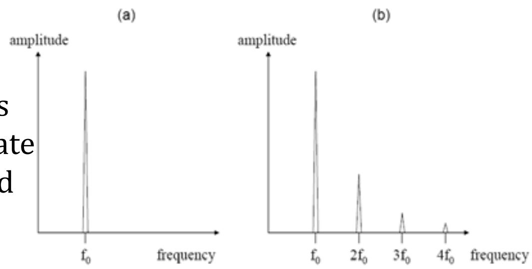
- Having a high difference of impedance from microbubbles is not a principal reason that it is so effective
- Microbubble responds to the propagating ultrasound beam by compressing (during high pressure) and expanding (during low pressure)
- It absorbs more energy during compression and re-radiate during expansion → strong echo signal
- There is a resonance condition between ultrasound frequency and the degree of expansion and compression
- This frequency is decided by the microbubble size and stiffness and thickness of coating



광주과학기술원

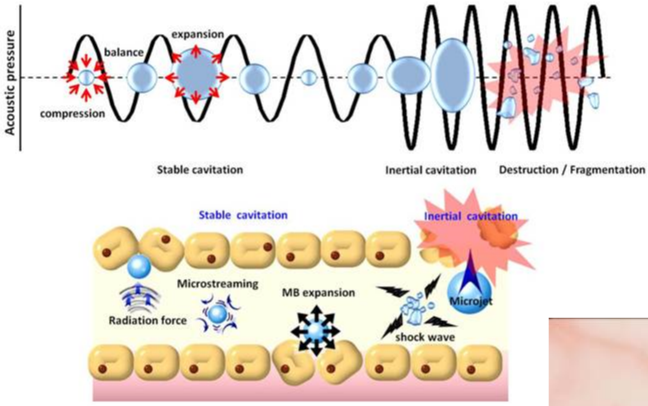
Microbubbles

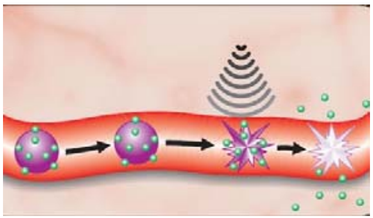
- Linear response with a low ultrasound beam intensity (a) vs nonlinear response with a high ultrasound beam intensity (b)
- Nonlinearity happens due to the US propagation speed is greater when the bubble is compressed than when it expands, also due to the possible shape change from sphere to elliptical shape
- The echo signals during this nonlinear process produce harmonic signals → signature to differentiate US signals from tissue and microbubbles



광주과학기술원

Microbubbles





As the drugs are only released at the site of the tumor, the patient's total body exposure to them would be limited, which, for certain types of cancer, could help reduce the unpleasant side effects of chemotherapy (Credit: Philips)

Obstetrics and Gynecology

- Parameters such as the fetal head and extent of the developing brain ventricles, and the condition of the spine are measured to assess the fetus health
- The below figures are 2 D B-mode scans of

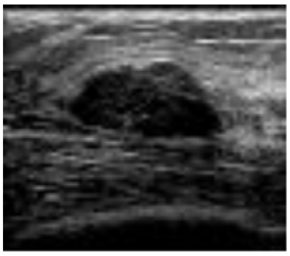
19 week fetus in the womb

Fetal brain

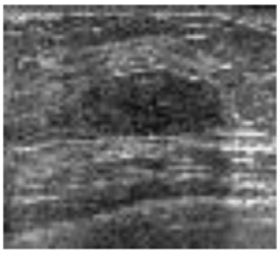
3-dimensional fetal image using 2-dimensional array and mechanical steering

Breast Imaging

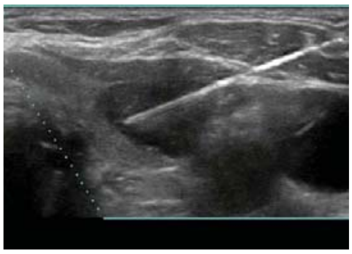
- US is used to differentiate between solid and cystic (filled with fluid) lesions.
- 9~12 MHz high frequency US is used for optimal image contrast with high resolution
- US is also used for image-guided needle biopsy



Fibroadenoma



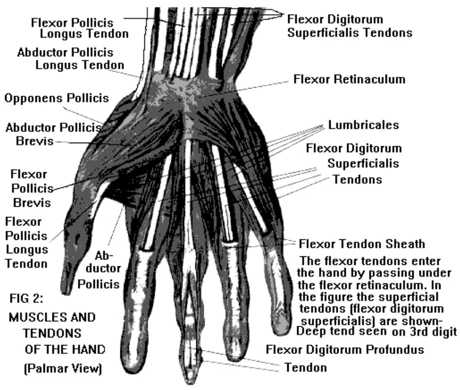
Breast mass

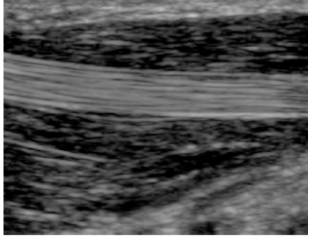


US guided Thyroid biopsy

Musculoskeletal Structure

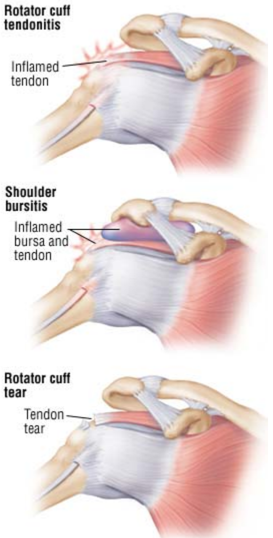
- The compound and harmonic scanning allowed to have good quality of tendon and nerve (which produces a lot of speckle)images
- Compound scan of flexor pollicis tendon in the hand





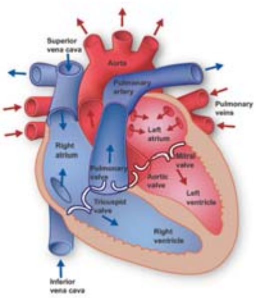
Musculoskeletal Structure

- Compound scan of a rotator cuff injury in the shoulder



Echocardiography

- Mitral regurgitation: abnormal reversal of blood flow from LV to LA due to mitral valve disruption



http://youtu.be/KmhKufTS0wQ

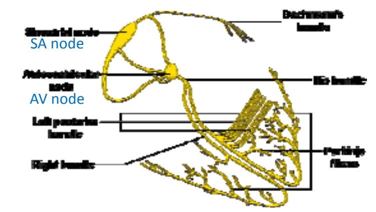
Echocardiography

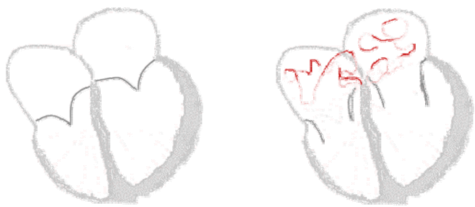
http://youtu.be/rgY7Ic_9K0M

For the introduction of cardiovascular system, check this video http://youtu.be/ctJOLgBGNIQ

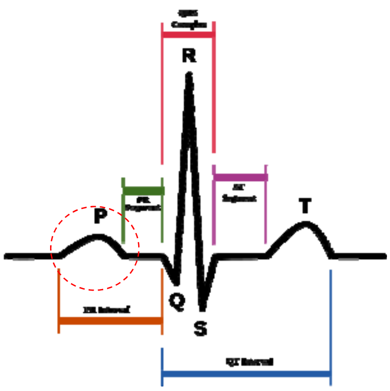
Echocardiography

- Left atrial appendage (LAA) and closure
  - Can be from atrial fibrillation (missing P signal)



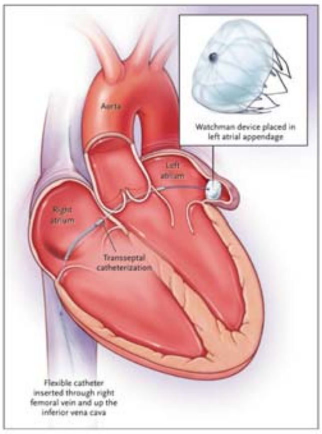


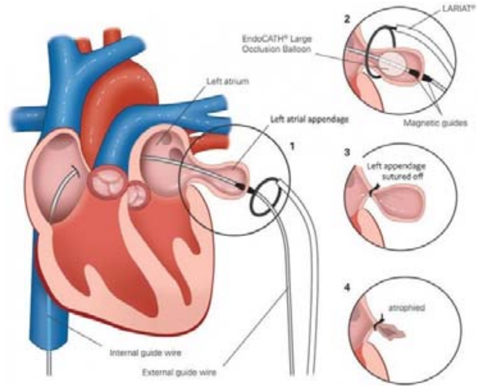
Normal sinus rhythm   Atrial fibrillation



Echocardiography

- Left atrial appendage (LAA) and closure
  - blood clots in LAA can cause stroke (5-7 times higher chance than normal)





광주과학기술원