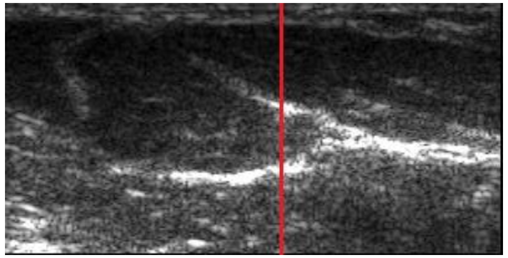
Lecture 14 – Ultrasound Imaging

This lecture will cover: *(CH4.8-4.13)*

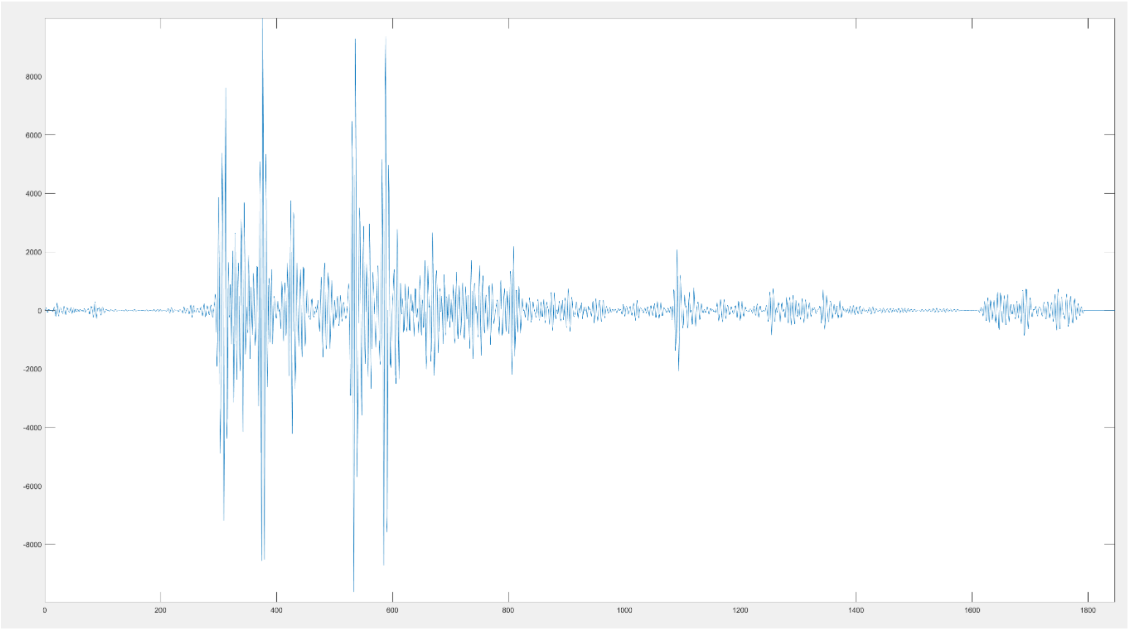
- Ultrasound signal acquisition and processing
- Clinical diagnostic scanning modes
- Imaging characteristics
- Imaging techniques
- Doppler Ultrasound
- Ultrasound contrast agent
- Harmonic and pulse inversion imaging
- Application

(*Supplementary reading: The Essential Physics of Medical Imaging CH14.5-14.9, FMI 6.5*)

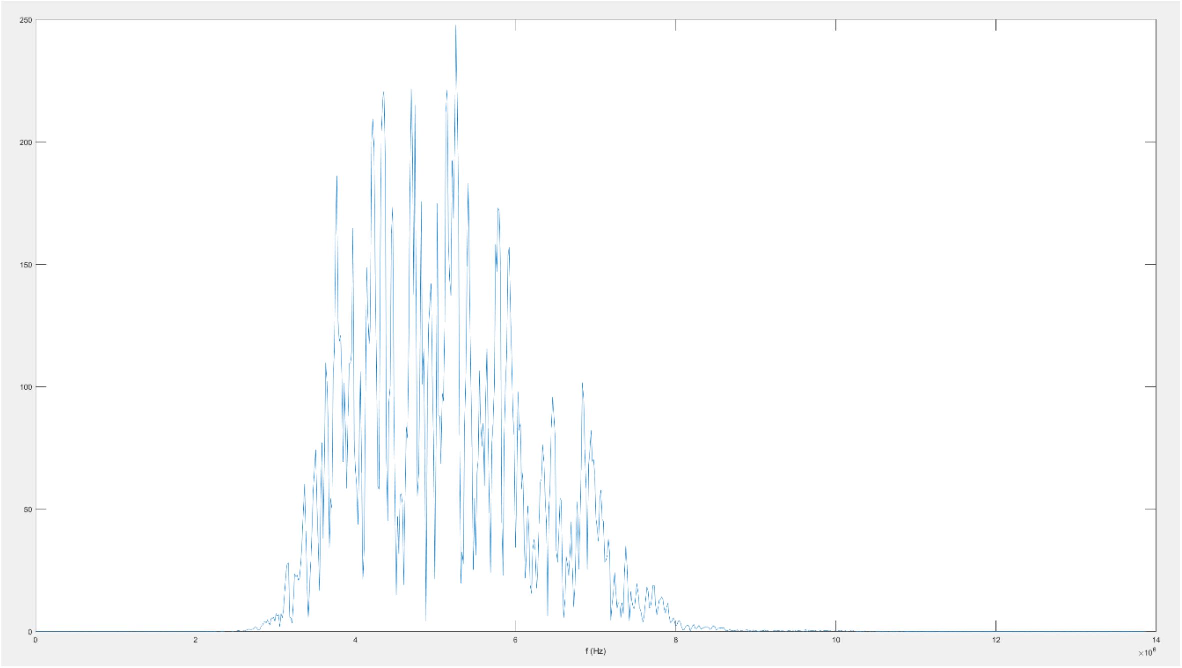
Ultrasound signal



Original time signal

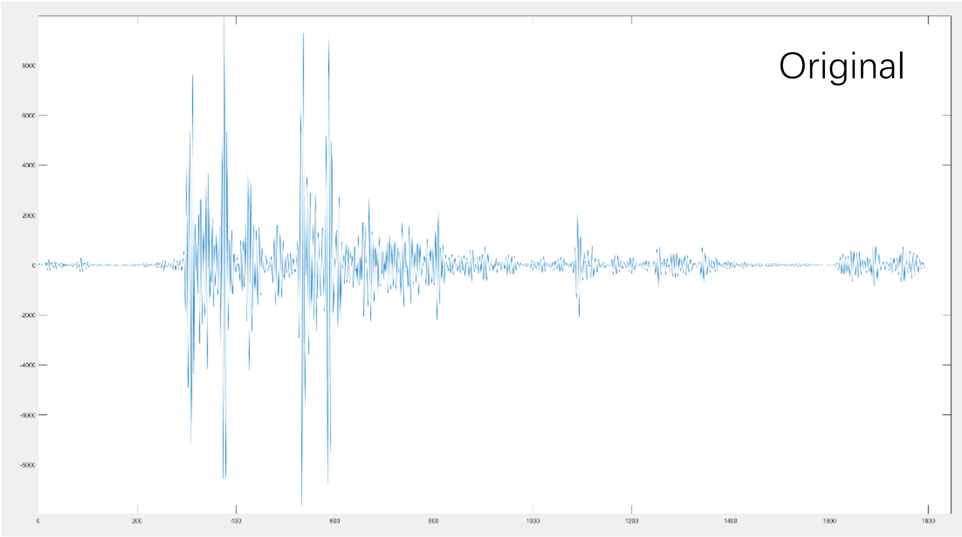


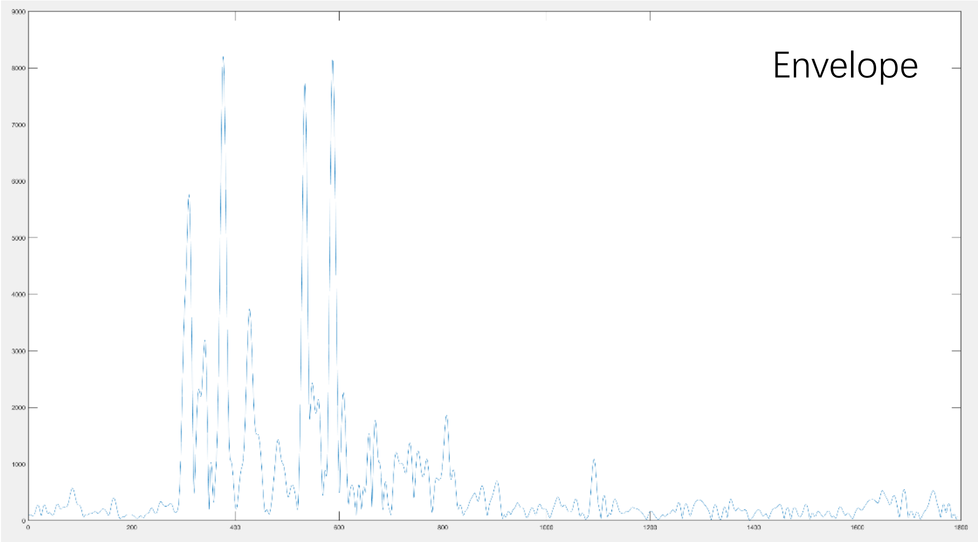
Spectrum

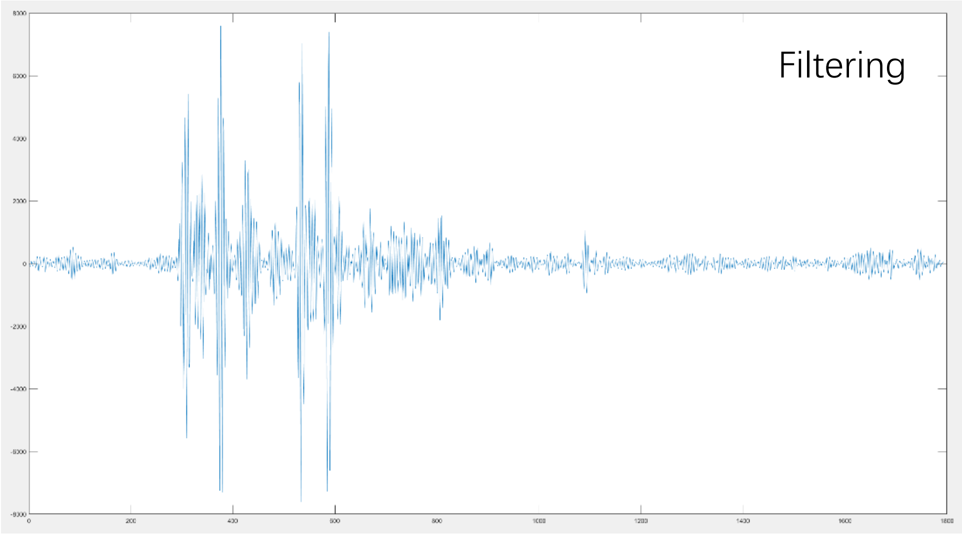


Ultrasound Signal Processing

- Filtering - noise deduction
- Envelope – peaks from interfaces
- Amplification – enhancement
- Other processing steps







Clinical diagnostic scanning modes

- **A (amplitude) mode :**

  a one-dimensional “line image” which is a plot of amplitude vs time

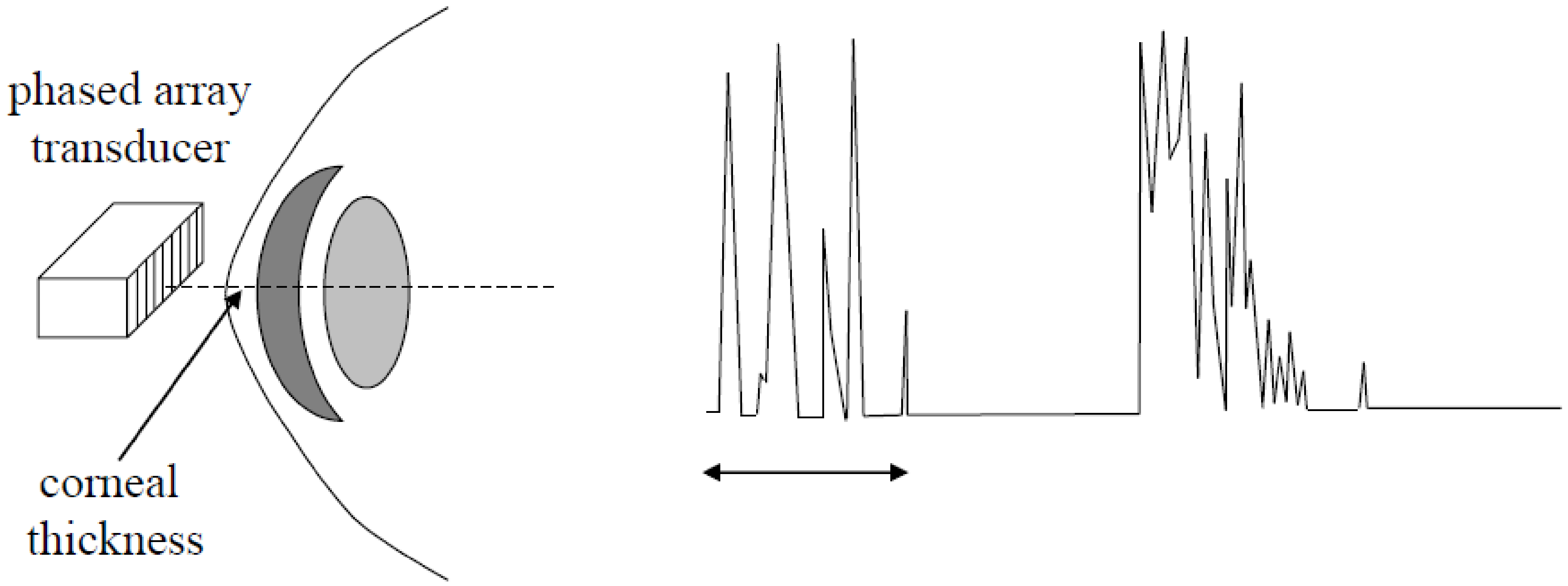


Fig. Use of A-mode ultrasound scanning to measure the corneal thickness of the eye. A single line of high frequency ultrasound is used, and the one-dimensional signal plot is shown on the right. The double headed arrow represents the thickness of the cornea..

Clinical diagnostic scanning modes

➢ **M (motion) mode:**

a continuous series of A-mode lines and display them as a function of time.

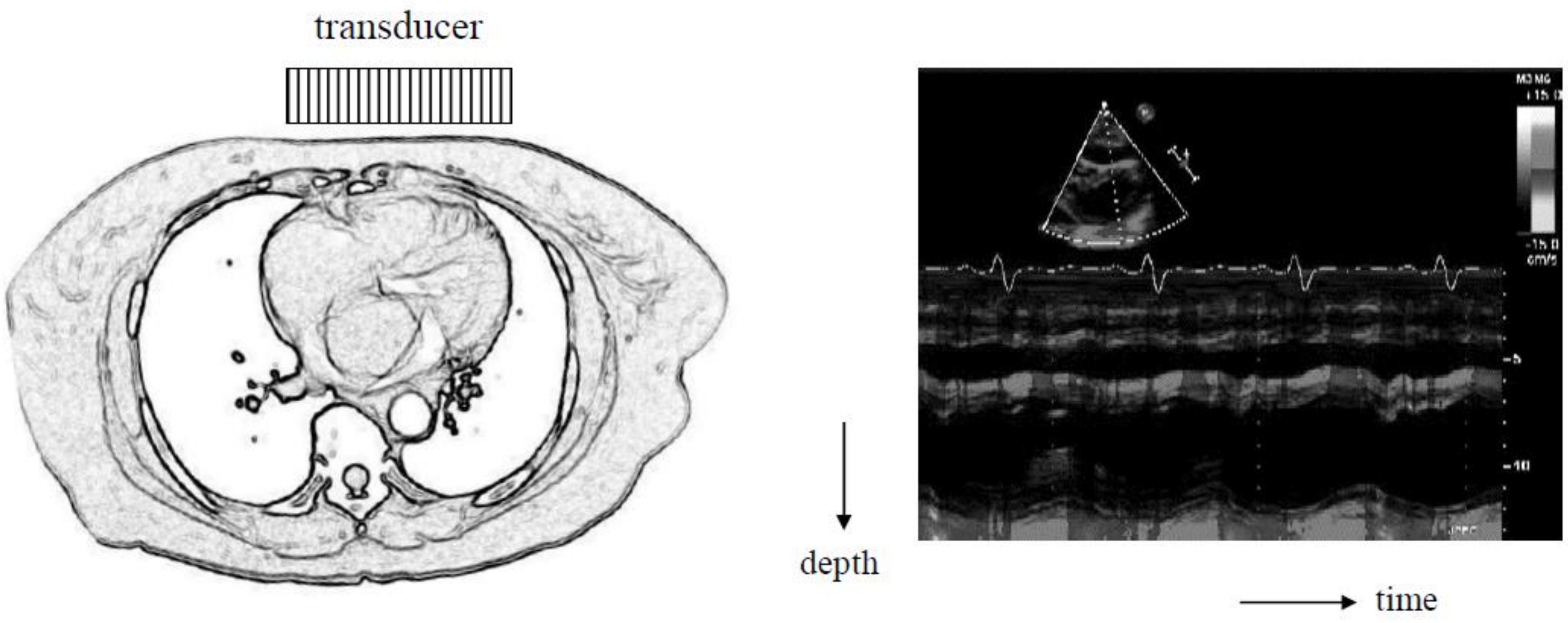


Fig. M-mode data acquisition. The transducer is placed above the heart and sends out a single line of ultrasound. An A-mode scan is recorded, and as soon as the last echo has been acquired, the A mode scan is repeated. The horizontal time-axis increments for each scan, and therefore a time-series of one-dimensional scans is built up. A straight line represents a structure that is stationary, whereas the front of the heart shows large changes in position.

Clinical diagnostic scanning modes

- **B (Brightness) mode:**
  - most commonly used in clinical diagnosis
  - a 2D image through a cross-section of tissue;
  - 3D imaging can be performed by multi-dimensional arrays

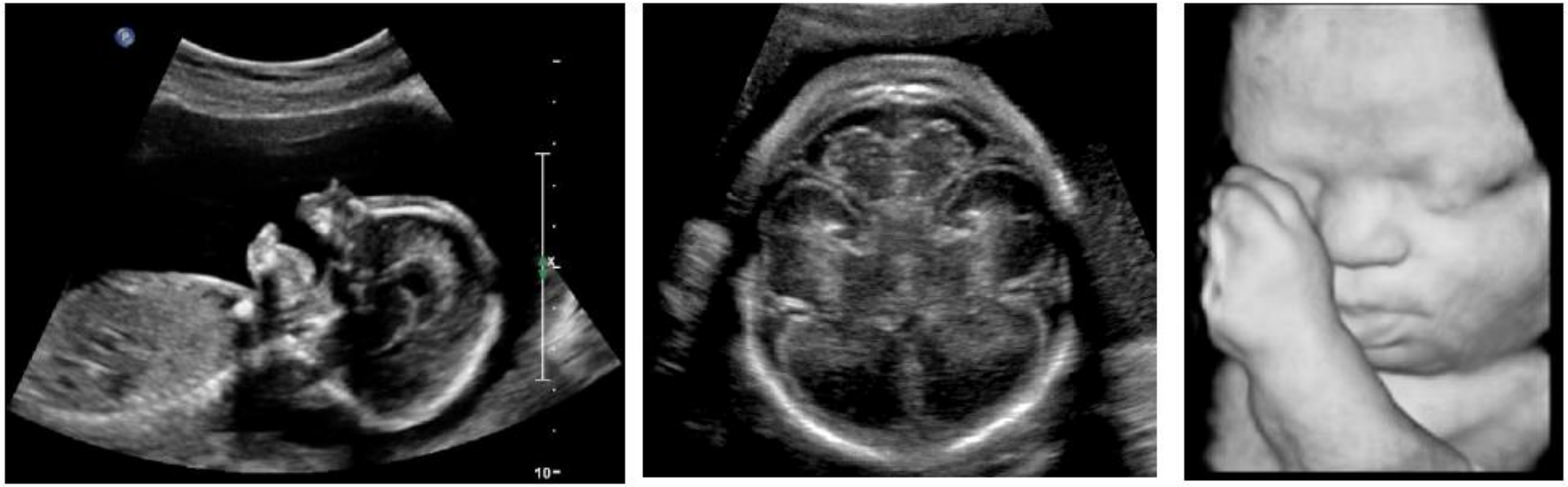


Fig. Two-dimensional B-mode scans of (left) 19 week fetus in the womb, and (centre) foetal brain. (right) Three dimensional foetal image using a two-dimensional array and mechanical steering.

Clinical diagnostic scanning modes

Compound scanning

- Acquire an ultrasound image from multiple angles and combine the images together;
- Reduce the speckles caused by scattering;
- Present the irregular curvatures without influence of structures parallel to the beam;
- Reduce other artifacts such as acoustic enhancement and shadowing;

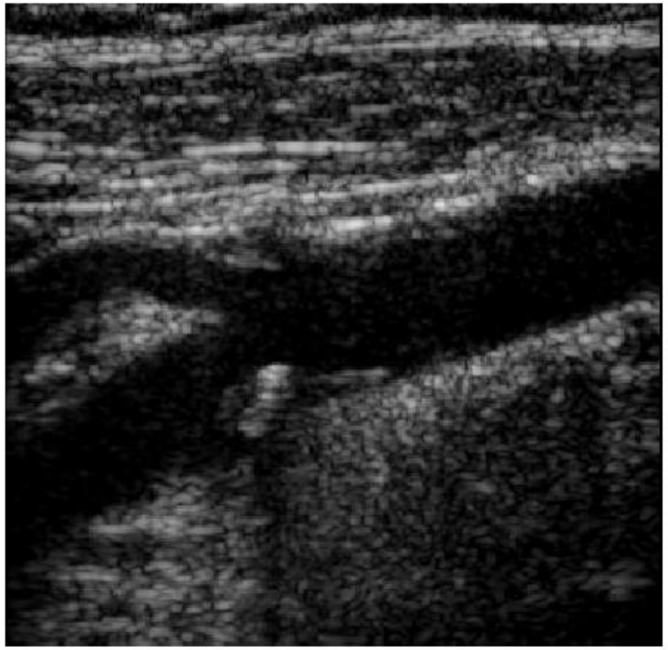


Fig. Comparison of a carotid artery bifurcation acquired using a conventional B-mode scan on the left, and a compound scan with nine different orientations on the right.

Image characteristics

- **Signal-to-noise**
  - The intensity of transmitted pulse;
  - The operating frequency of transducer: higher frequency, lower SNR;
  - The type of focusing: the higher focusing, the higher SNR at focal area, but lower SNR outside of depth-of-focus;
  - Noise sources: speckles from scattering and clutters from side lobes, grating lobes, multi-path reverberation and tissue motion;
- **Spatial resolution**
  - Lateral resolution: focusing and frequency, pitch of array transducer.
  - Axial resolution: ½ wavelength of ultrasound pulse, therefore higher damping, frequency provide better resolution
- **Contrast-to-noise:** similar to SNR

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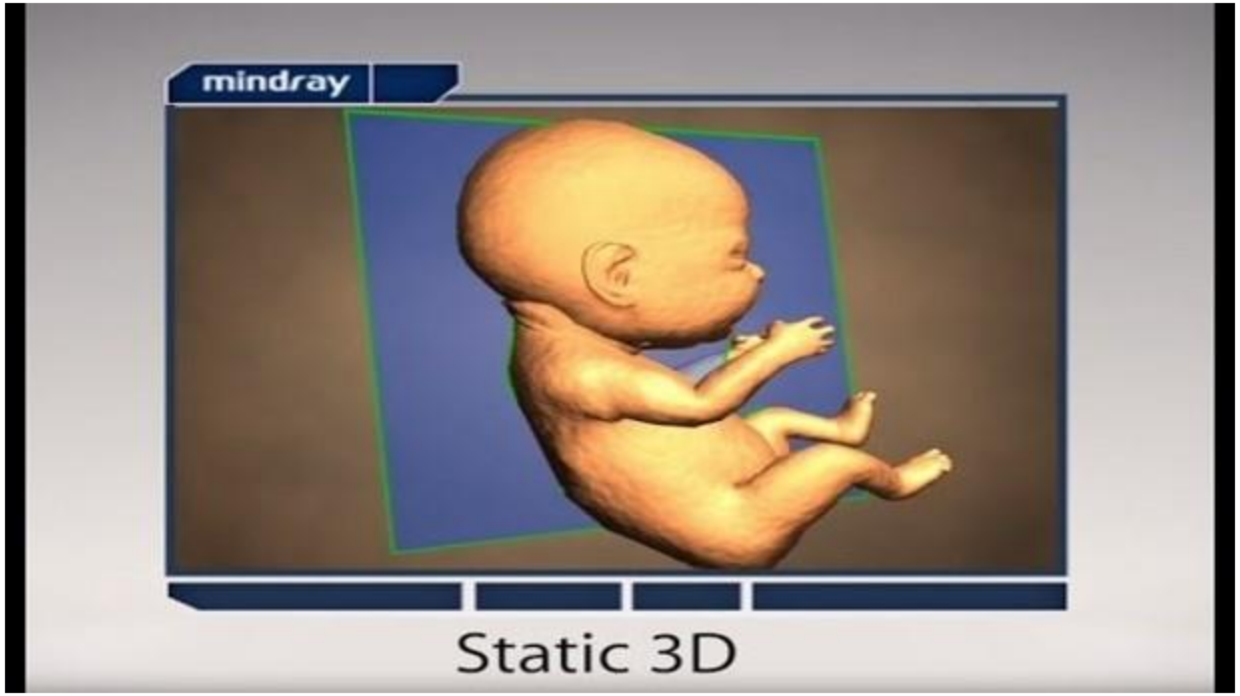
3D/4D Imaging

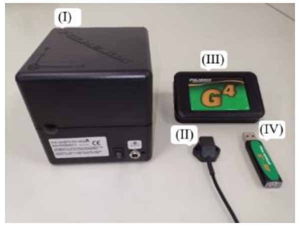
- Used in fetal, cardiac, trans-rectal and intra-vascular applications;
- Referring to the volume rendering of ultrasound data;
- Generating methods:
  - Freehand
  - Mechanically,
  - Endoprobe
  - 2D matrix array transducer



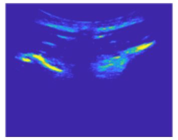
Portable 3D Ultrasound Imaging

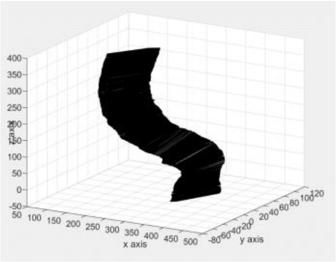
Compact 2D ultrasound scanner

Portable tracking system

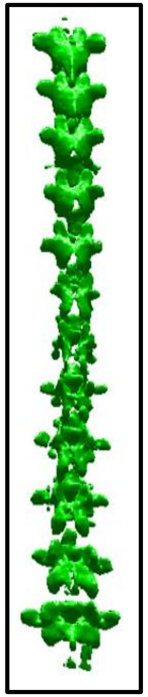


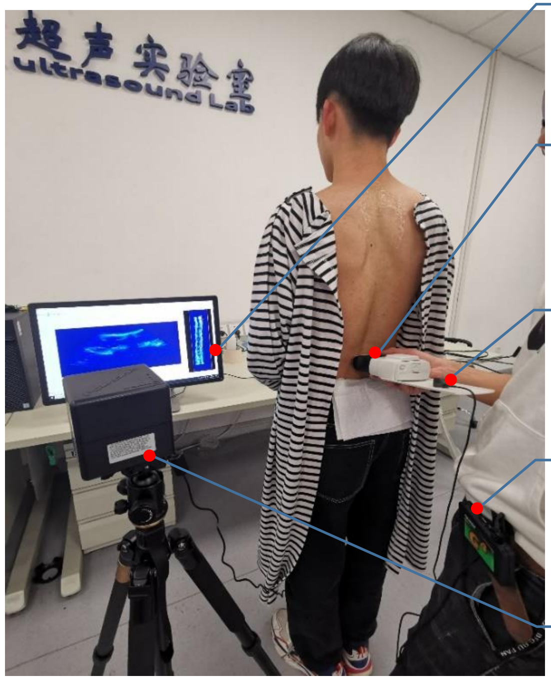
2D transverse frames





Location information





Monitor displays the reconstruction result
in real time

Scanner was used to transmit 2D frames continuously to the host computer by the WI-FI connection

(II) Sensor was installed about 10*cm* behind the scanner

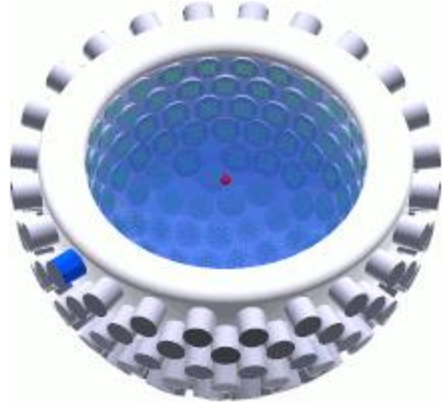
(III) Hub was used to deliver tracking data to the host computer wirelessly via a ***RF/USB*** module ***(IV)***

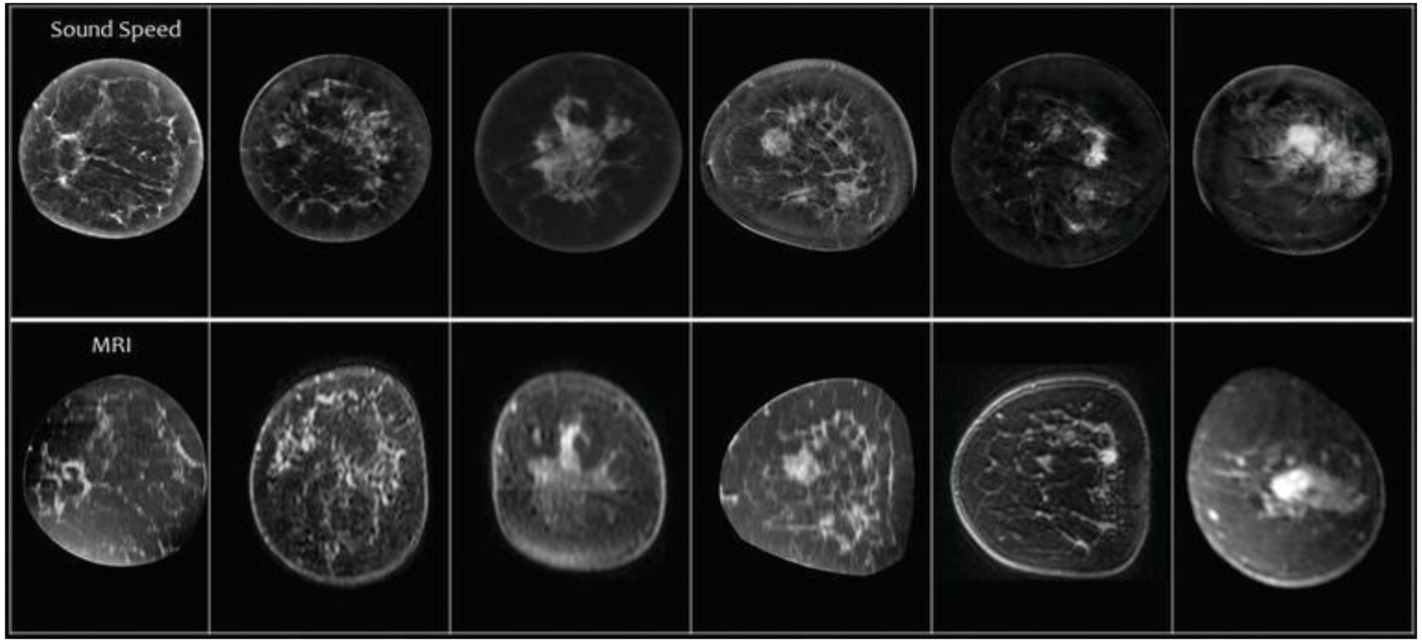
(I) Source generates the electromagnetic (EM) field to track ***sensor***

Fig. Portable 3D ultrasound imaging system

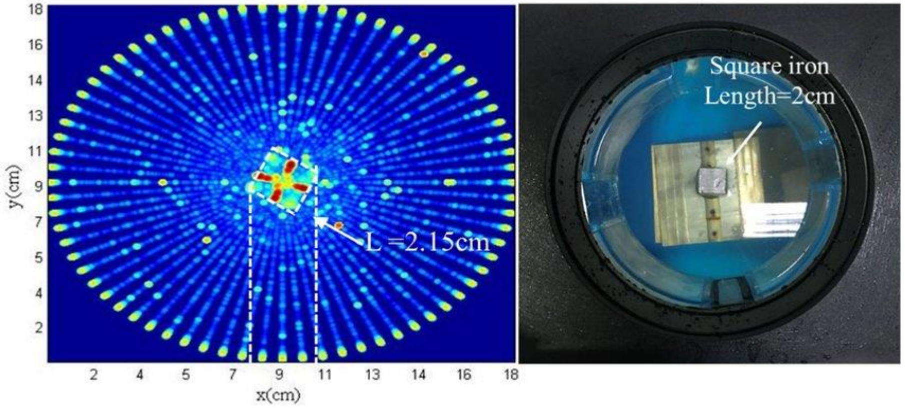
Ultrasound Tomography

- Circular scanning using the ring system;
- Currently most used for breast cancer;
- More complex algorithm based on wave equation and inverse problem;





Top: Coronal UST sound speed images for six different patients.
Bottom: Corresponding fat subtracted contrast-enhanced MR images



Endoscopic Ultrasound

Endoscopic Ultrasound (EUS, 内窥镜超声)

- a minimally invasive procedure to assessing digestive (gastrointestinal) and lung diseases;
- high-frequency ultrasound
- detailed images of the lining and walls of digestive tract and chest, nearby organs such as the pancreas and liver, and lymph nodes;
- combined with fine-needle aspiration (细针抽吸活检)

https://www.youtube.com/watch?v=DLjKze7a6Y8&list=PL08eXrSEzsLbI-mcLwho0n3vY7TfZ8tIg&index=1

Elastography

Elasticity Imaging (Elastography, 弹性成像)

- Mapping the elastic properties and stiffness of soft tissue;
- Ultrasound elastographic techniques
  - Quasistatic elastography / strain imaging;
  - Acoustic radiation force impulse imaging (ARFI)
  - Shear-wave elasticity imaging (SWEI)

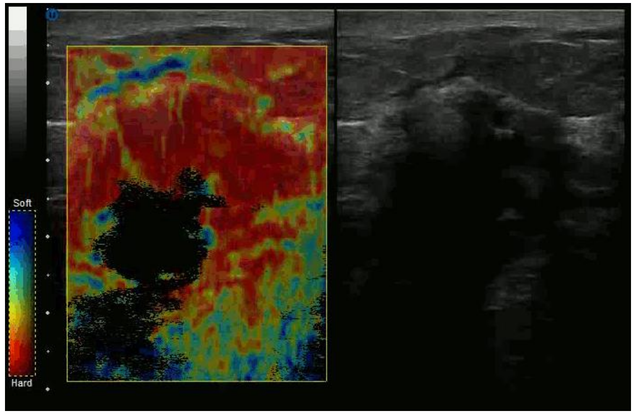


Fig. Manual compression (quasistatic) elastography of invasive ductal carcinoma, a breast cancer.

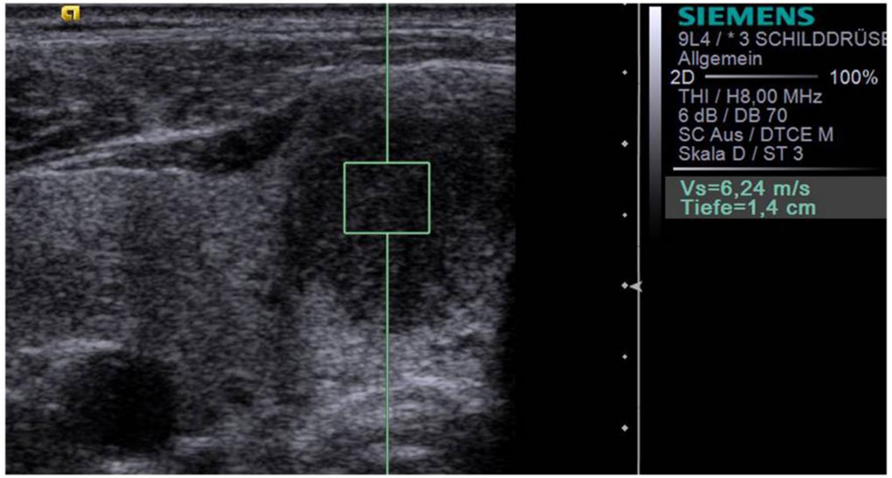


Fig. An ARFI image of a thyroid nodule in the right thyroid lobe. The shear wave speed inside the box is 6.24 m/s, which is reflective of a high stiffness. Histology revealed papillary carcinoma.

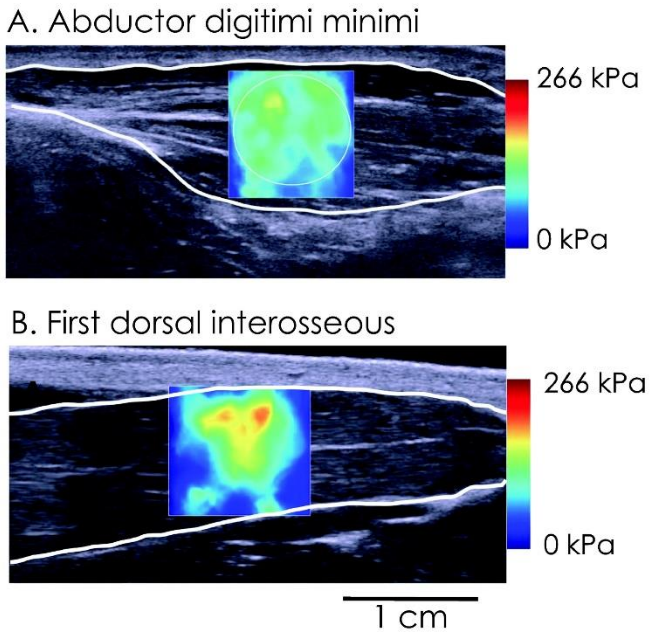
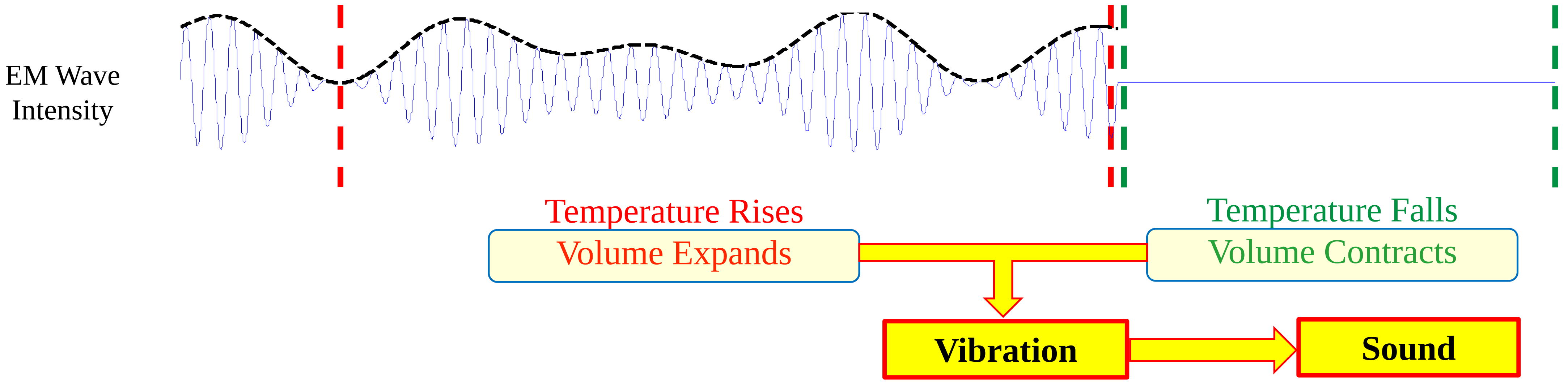


Fig. Supersonic shear imaging of the stiffness during contraction of the hand muscles abductor digiti minimi (A) and first dorsal interosseous (B). The scale is in kPa of shear modulus.

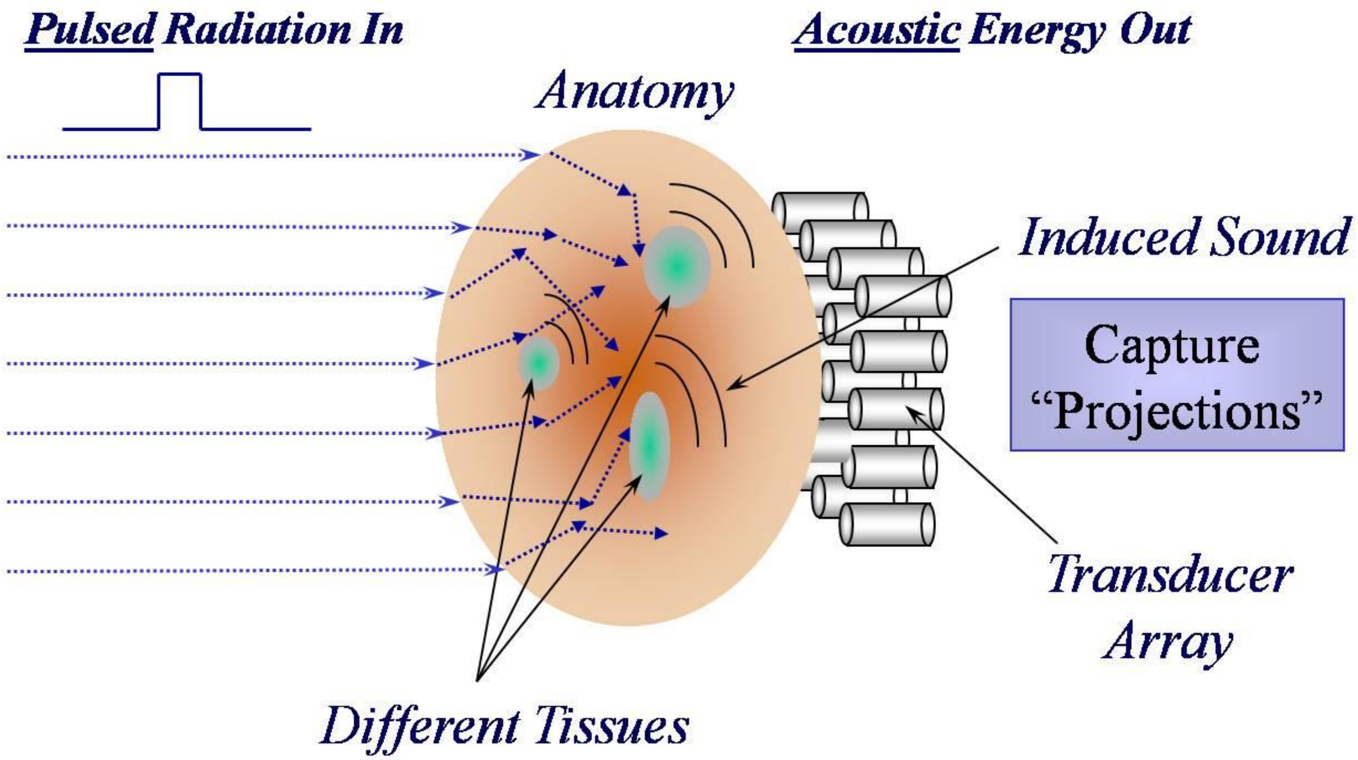
EM wave induced imaging

- Audible sound could be created by illuminating an intermittent beam of sunlight onto a rubber sheet. --- by A. G. Bell in 1880
- Hybrid imaging techniques: electromagnetic-to-acoustic energy conversion
- Radio, microwave (Thermoacoustic, TA), terahertz, optical (Photoacoustic, PA)



EM wave induced imaging

- Using microwave to image biological samples was proposed by T. Bowen in 1981, microwave-induced thermoacoustic imaging (TAI);
- Using Laser to image biological tissues from 1980s, photoacoustic imaging
- Incident electromagnetic wave intensity must be modulated or usually in the form of a pulse;
- EM energy absorption is closely associated with physiological properties of tissues.

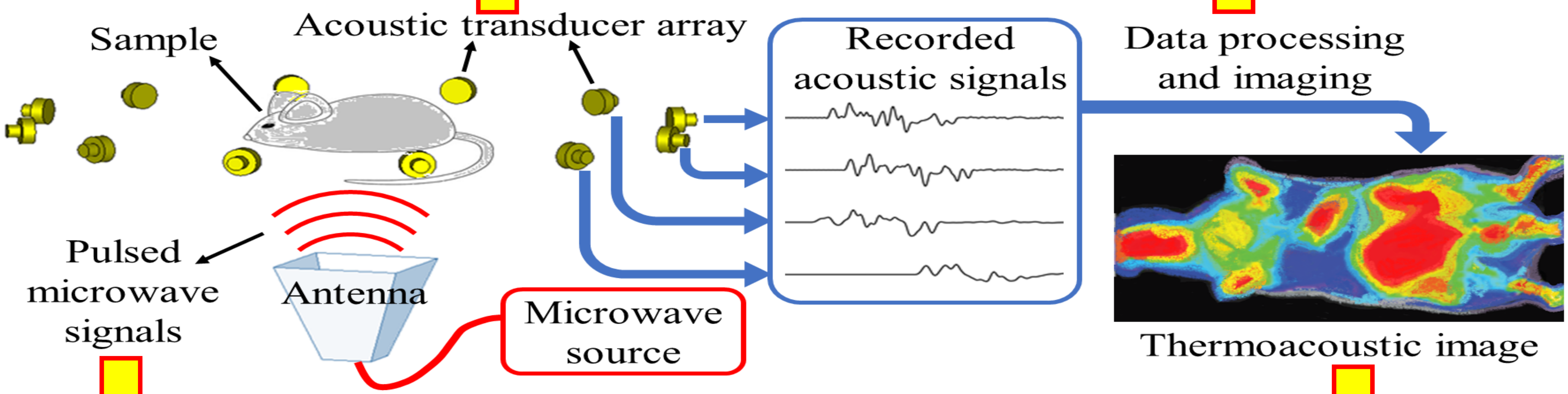


Thermoacoustic Imaging

Basic Setup

- Acoustic signal frequency: kHz – MHz

- Imaging algorithm: back-projection, delay and sum, compressive sensing



- Pulse width: ns – μs
- Frequency: below 10 GHz
- Peak power: kW

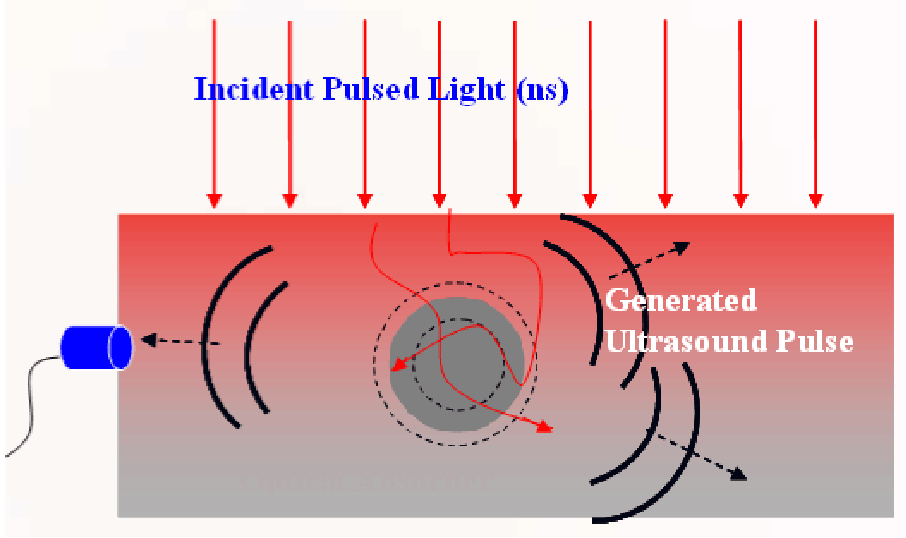
Advantages:

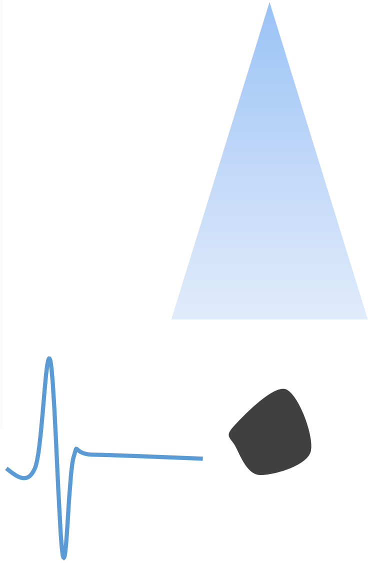
- Non-ionizing and noninvasive
- High contrast (microwave imaging)
- High resolution ~mm (ultrasound imaging)
- Low cost and compact
- Easy imaging procedure (<10% acoustic heterogeneity)

Applications:

- Breast cancer, brain cancer, prostate cancer
- Foreign body, renal calculi, explosive
- Temperature monitoring

Photoacoustic imaging





combining light and sound

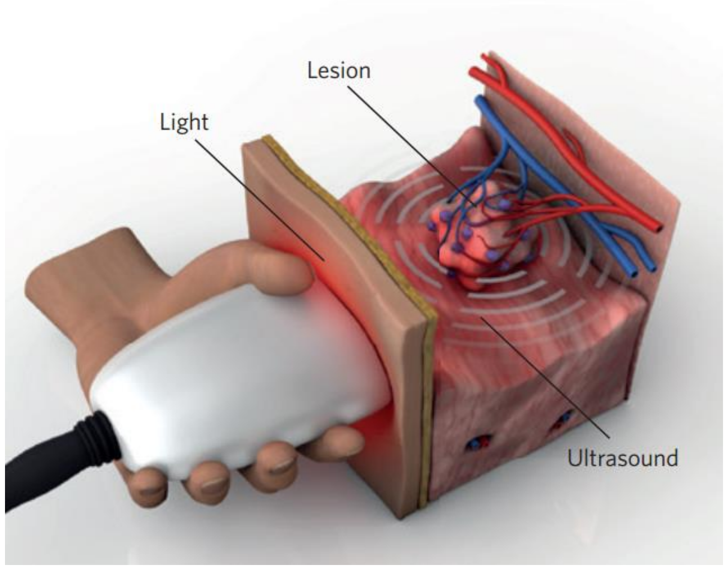
>> Pulsed light illumination

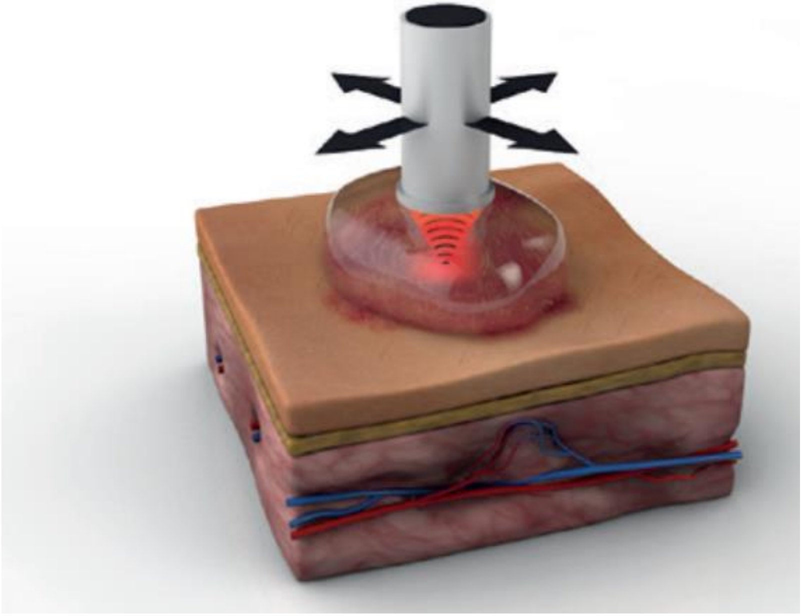
>> Transit light absorption

>> Heating

>> thermoelastic expansion

>> acoustic emission





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Doppler effect

- The change in frequency or wavelength of a wave in relation to an observer who is moving relative to the wave source:
- If the source and receiver motion are aligned

$$f' = \frac{c \pm v}{c \mp u} f$$

Where f: the frequency of source

c: velocity of wave

u: the velocity of source

v: the velocity of receiver

- If the source and receiver motion are angled

$$f' = \frac{c \pm v\cos\beta}{c \mp u\cos\theta} f$$

Where β: the angle between the receiver motion and source-receiver line

θ: the angle between the source motion and source-receiver line

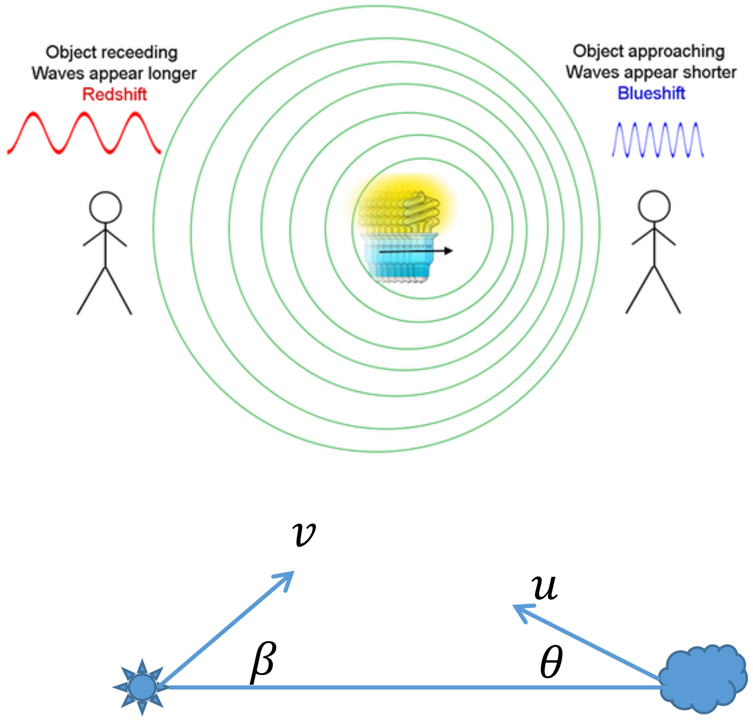


Fig. Doppler effect .

Doppler Ultrasound

- Doppler effect occurs due to scattering from red blood cells (RBC) with A diameter of 7-10 μm;
- B-mode images acquired by phased array transducers to
  - localize specified vessels or their region
  - estimate the vessel size
  - measure blood velocities converted into blood flow values;
- Blood flow velocity

$$f_{\mathrm{r}} = f_{\mathrm{i}}\left[\frac{(c + v\cos\theta)}{c}\right]^2 = f_{\mathrm{i}} + \frac{2f_{\mathrm{i}}v\cos\theta}{c} + f_{\mathrm{i}}\left[\frac{v\cos\theta}{c}\right]^2$$

$$f_{\mathrm{D}} = |f_{\mathrm{i}} - f_{\mathrm{r}}| \approx \frac{2f_{\mathrm{i}}v\cos\theta}{c} \Rightarrow v = \frac{cf_{\mathrm{D}}}{2f_{\mathrm{i}}\cos\theta}$$

Where f_{D} is the Doppler shift

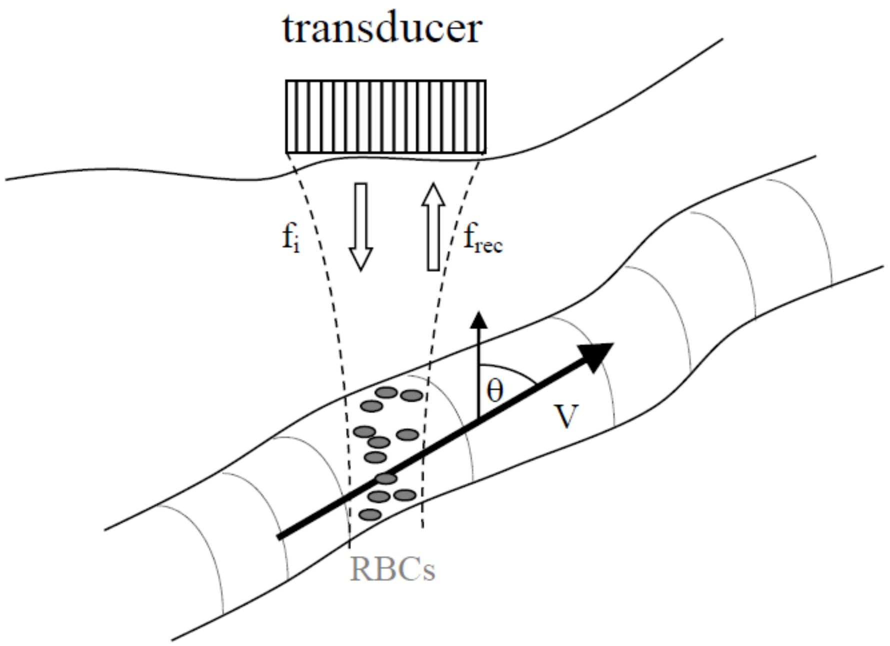


Fig. Showing the origin of the Doppler shift in ultrasound imaging of blood flow. The ultrasound beam is scattered from the RBCs in a vessel. The backscattered ultrasound beam is detected by the transducer at a slightly different frequency (f_{rec}) from that transmitted (f_i) into the body.

Pulse wave (PW) Doppler

➢ The phased array transducer used to:

- Pulse transmission and receiving
- Locate the region-of-interest (ROI)

$$\text{depth}_{\text{min}} = \frac{ct_d}{2}$$

$$\text{depth}_{\text{max}} = \frac{c(t_d + t_g)}{2}$$

Where by using a gate on receiving signals, the signals from tissue outside of the ROI are not recorded.

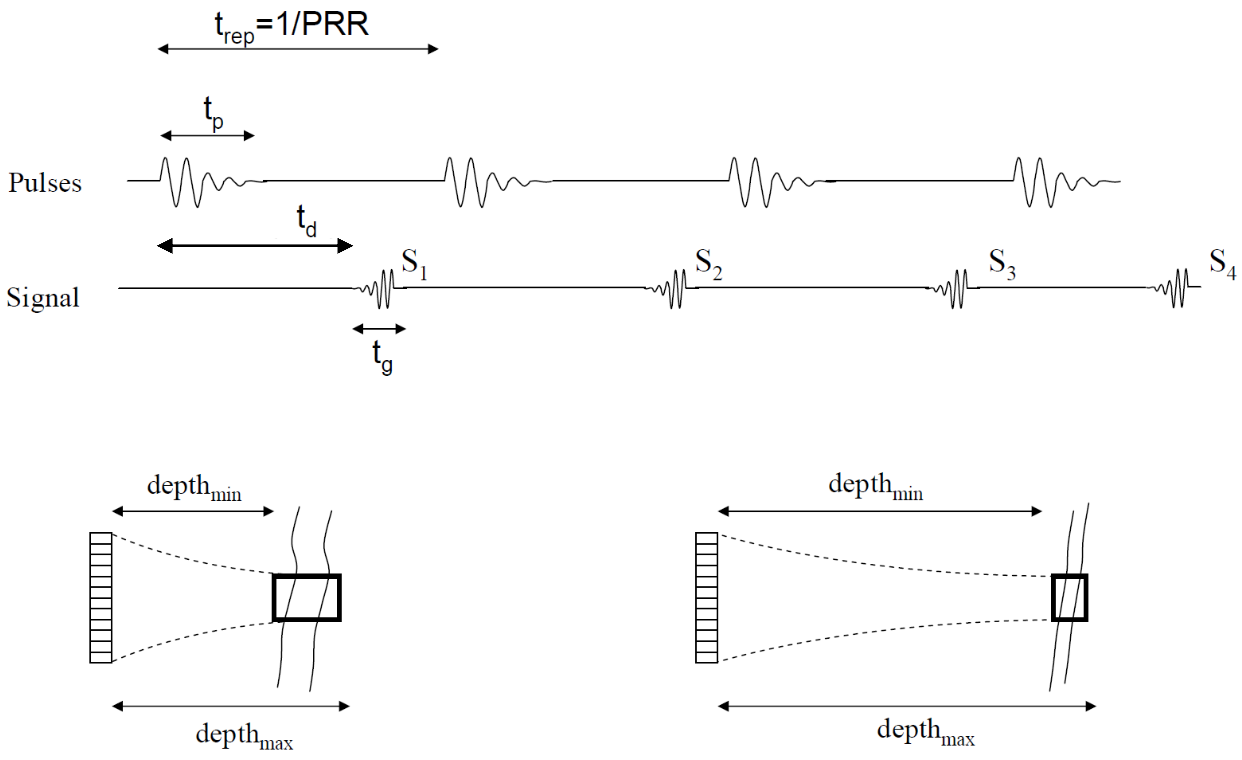


Fig. (top) General mode of operation of pulsed mode Doppler imaging. A series of signals S_1, S_2,. . . . .S_n are acquired to estimate the blood flow. (bottom) The parameters t_p, t_g and t_d are chosen to localize the received signal to the desired ROI, defined by the focal point of the phased array transducer and the minimum and maximum required depths: shown are examples of obtaining information from a vessel close to the surface (left) and deeper within the body (right).

Pulse wave (PW) Doppler

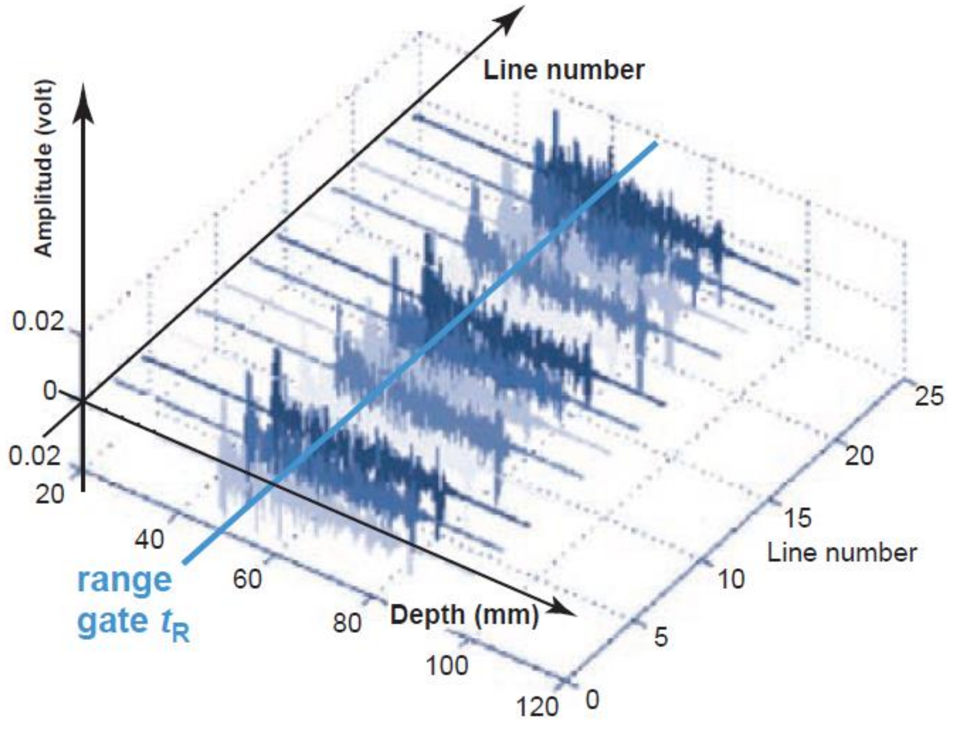


Fig. Pulsed wave Doppler uses the M-mode acquisition scheme and samples the subsequent reflected pulses at a fixed range gate t_R to calculate the Doppler frequency f_D.

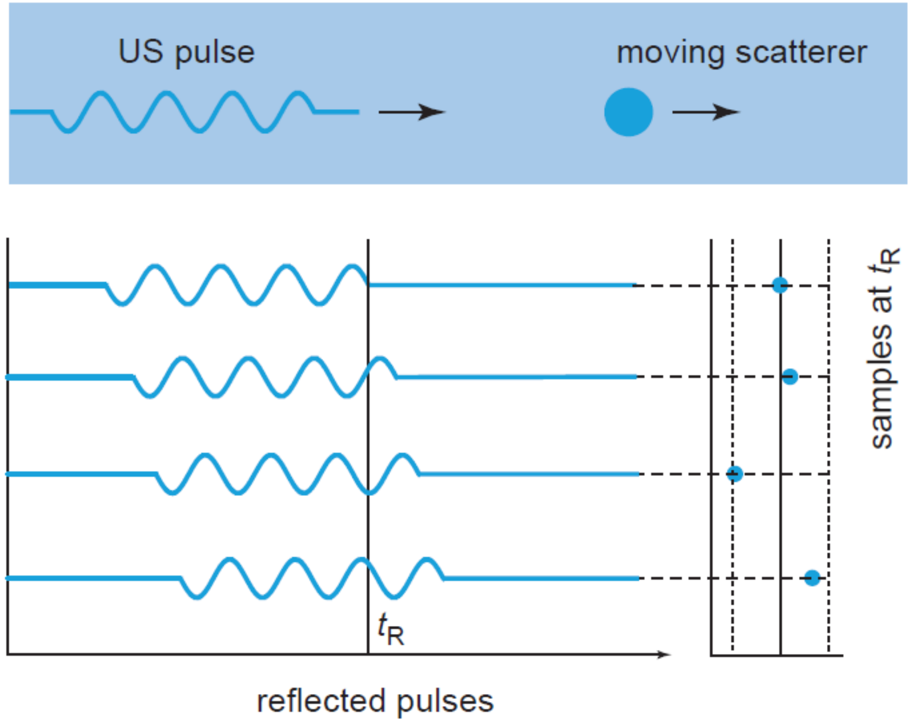


Fig. Schematic representation of the PW Doppler principle. Pulses are transmitted at a fixed pulse repetition frequency (PRF). They are reflected at a scatterer in motion. Because of this motion, the reflected pulses are dephased. Measuring each reflected pulse at the range gate t_R yields a sampled sinusoidal signal with frequency f_D.

Phase shift

- The phase shift between two subsequent received pulses:

$$\Delta\phi = 2\pi f_T \frac{2v_a T_{\mathrm{PRF}}}{c}$$

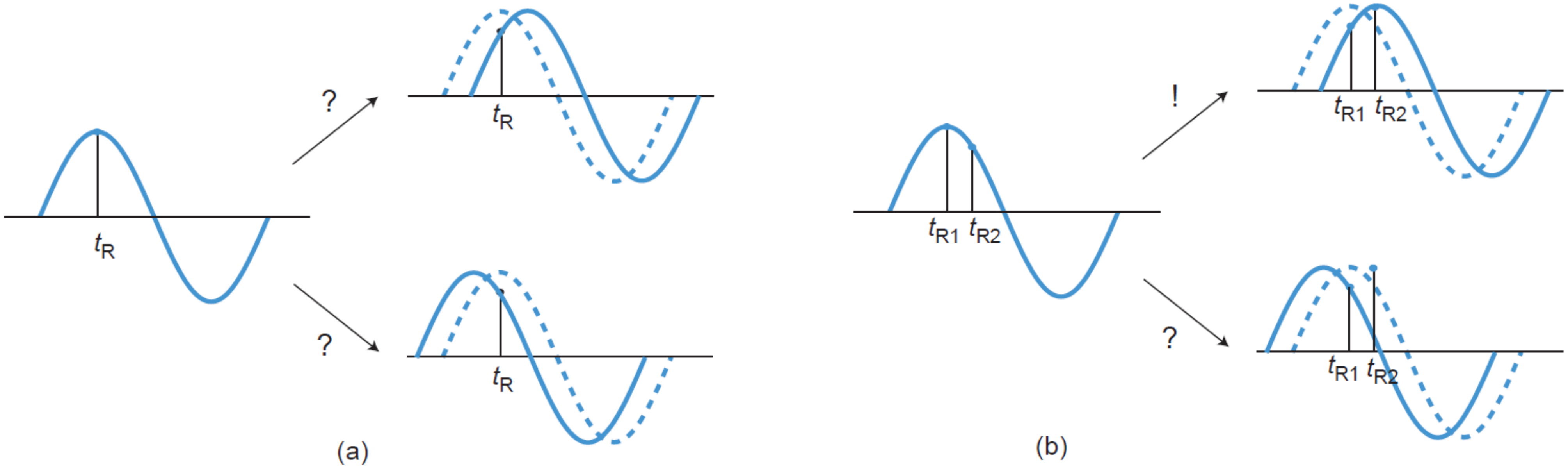


Fig. (a) If a single sample is acquired at the range gate, no directional information is obtained. (b) However, if a second sample is acquired slightly after the first one, the direction of motion is uniquely determined since a unique couple of samples within the cycle is obtained.

Spectral Doppler

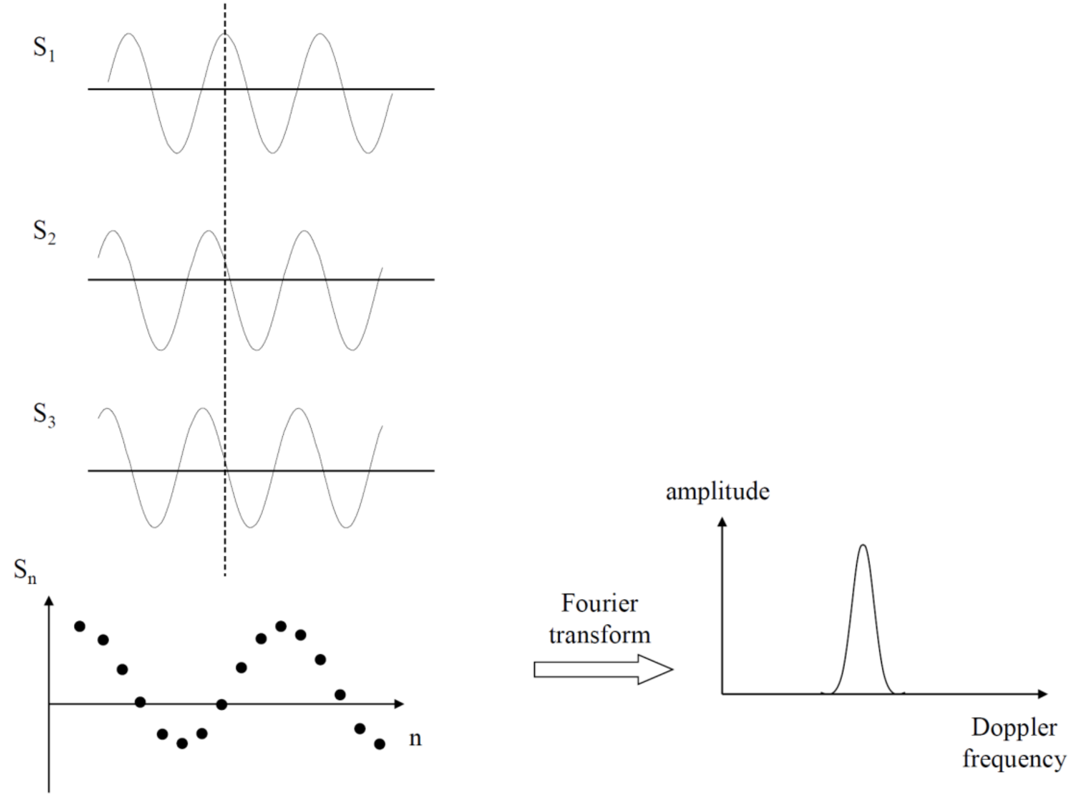


Fig. Steps in the production of a Doppler frequency distribution from one particular axial position within the ROI, determined by the particular time-point in signals S1. . .Sn that is analyzed. In this example a timepoint is chosen at the dashed line. A plot of the signals (Sn), taken at the dashed line, as a function of n is shown at the bottom left. Since the value of n is directly related to the time after the initial RF pulse is applied, a Fourier transform of the Sn vs. n plot gives the Doppler frequency spectrum shown on the right.

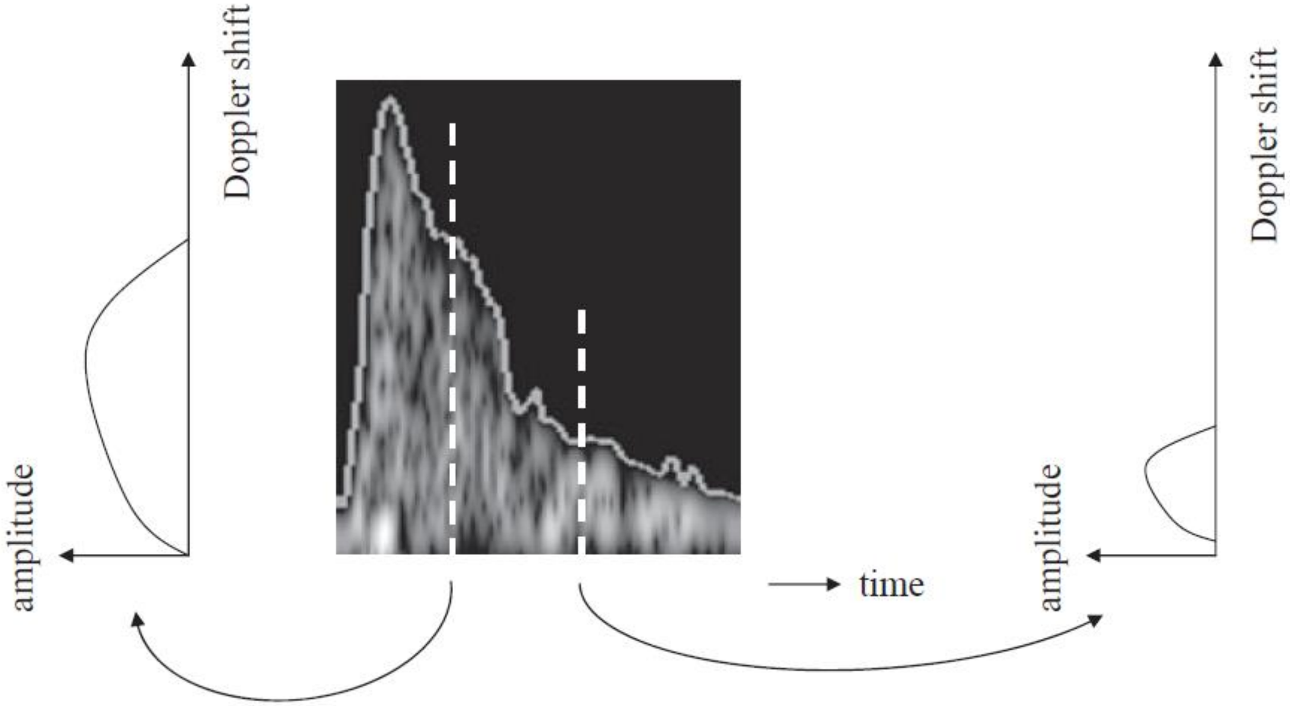
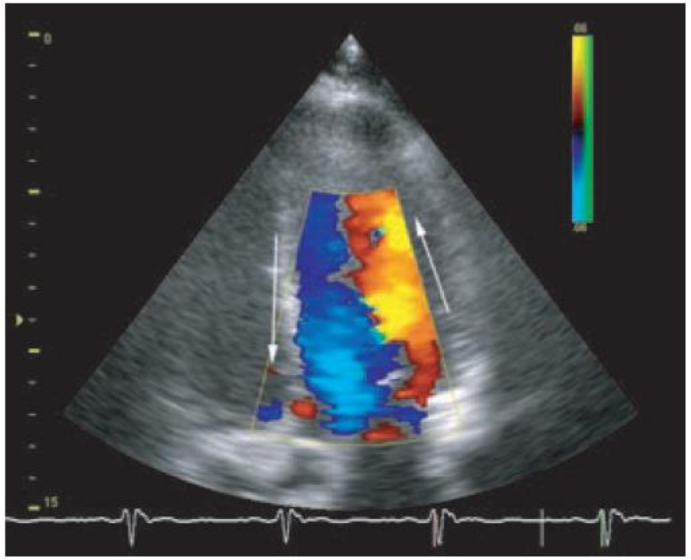


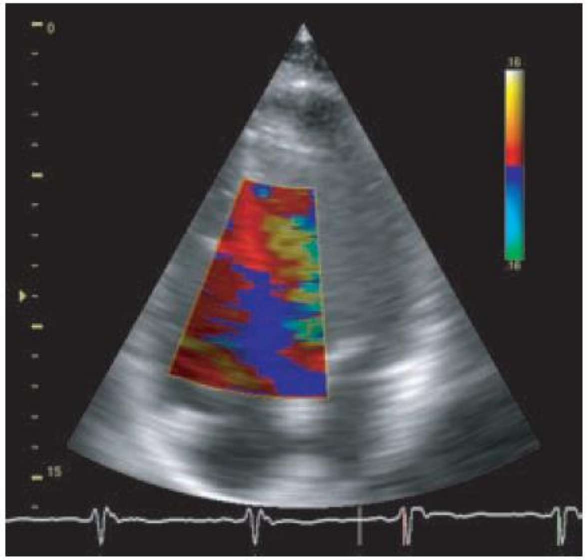
Fig. A spectral Doppler plot, with the amplitude of each frequency component of the Doppler shift being reflected in the intensity of the plot (white is the highest amplitude). The horizontal axis represents time. The left-hand plot shows high Doppler shift frequencies corresponding to high blood velocities just after the heart has reached full contraction and pumped blood into the arteries. The right-hand plot, which occurs at a later time, shows much lower Doppler shift frequencies, and coincides with the heart expanding to fill with blood ready for the next contraction.

Color Doppler

- Display flow information combined with a B-mode scan:
  - Blue/red represents flow towards/away from the transducer,
  - Intensity of color shows velocity;



(a)



(b)

Fig. (a) Using color Doppler techniques, blood flow within the ventricles can be visualized. This image shows the flow in a normal left ventricle at the beginning of diastole. Red colors represent flow toward the transducer, coming from the left atrium through the mitral valve and into the left ventricle. Blue colors show the blood within the left ventricle flowing away from the transducer toward the aorta. (b) Doppler techniques can be used to acquire the slower, regional velocities of the heart muscle itself. Local velocities in the direction of the transducer are represented in red, and velocities away from the transducer are in blue.

Aliasing

- From the Nyquist theory, the maximum Doppler frequency shift that can be measured:

$$f_{\max} = \frac{PRF}{2}$$

- The maximum blood velocity

$$v_{\max} = \frac{c f_{\max}}{2 f_i} = \frac{cPRF}{4 f_i}$$

- The maximum depth

$$d_{\max} = \frac{c}{2PRF} = \frac{c^2}{8 f_i v_{\max}}$$

- Continuous wave Doppler: no limit to depth and velocity measurement.

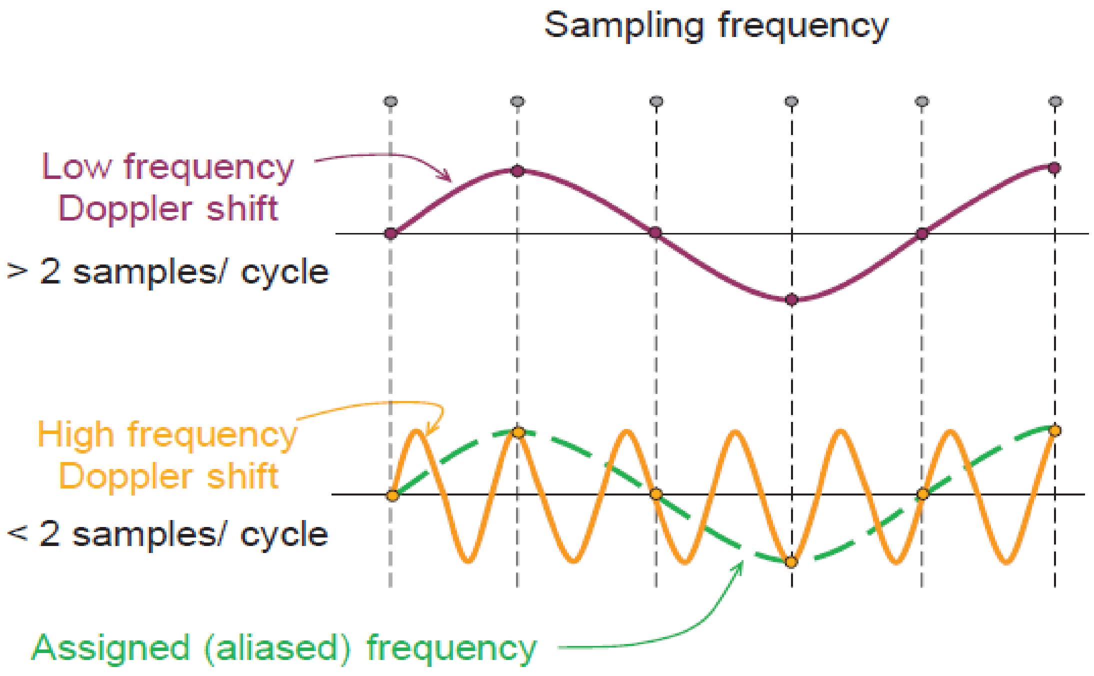


Fig. Aliasing occurs when the frequencies in the sampled signal are greater than ½ the PRF (sampling frequency). In this example, a signal of twice the frequency is analyzed as if it were the lower frequency and thus mimics (aliases) the lower frequency.

Functional Ultrasound Imaging

- To image dynamic deep brain activity;
- Directly measuring subtle cerebral blood volume (CBV) changes induced by neurovascular coupling (神经血管耦合)

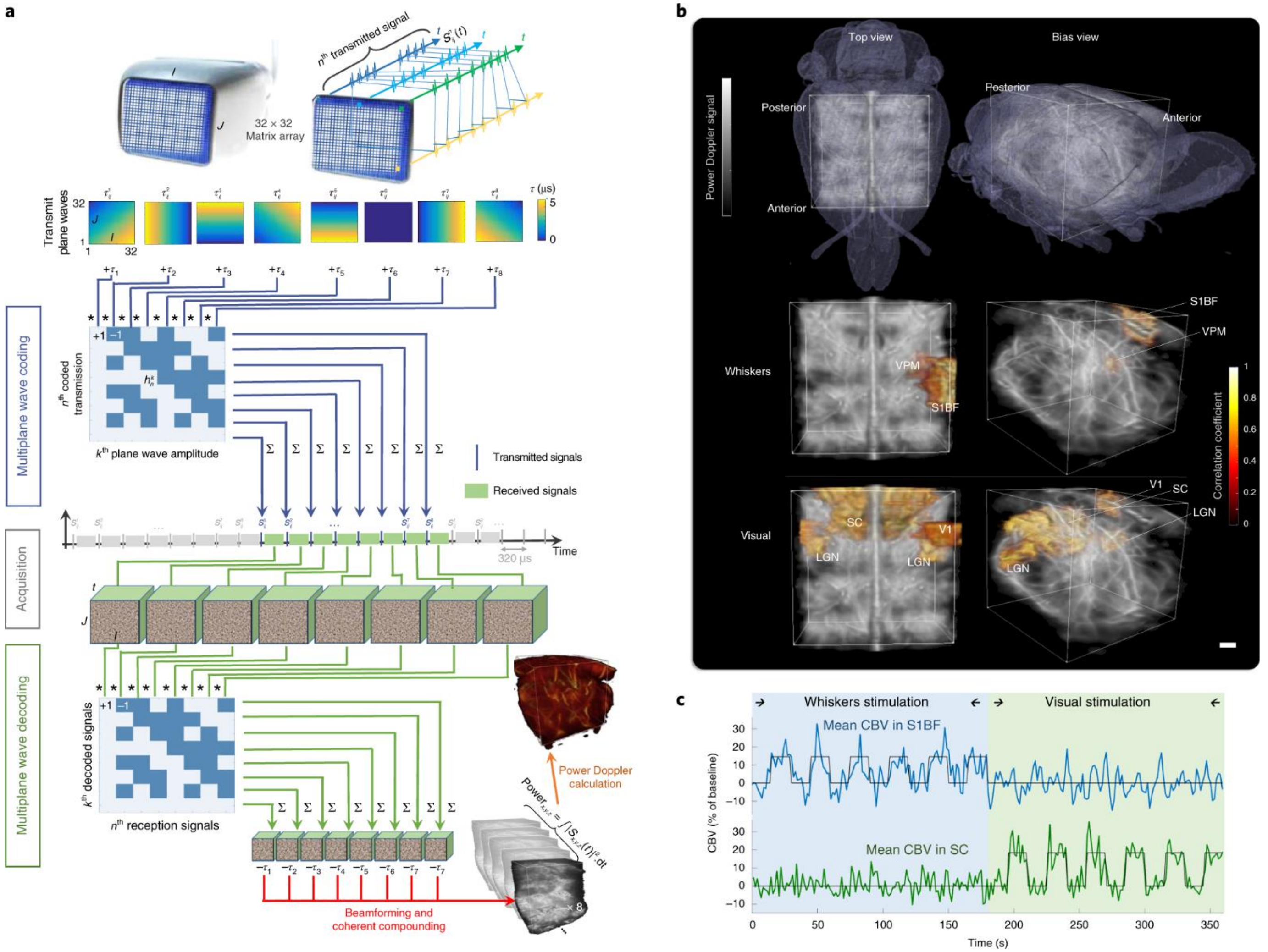


Fig. (a) a, Schematic representation of the multiplane-wave compounding method, with eight plane waves. At transmit signal no. 1, eight wavefronts tilted with eight different angles are quasi-simultaneously transmitted into the medium. Each plane wave is generated by transmitting a signal Sij(t) on all elements (i,j) of the array. In order to avoid any overlapping in the multiplane wave transmission, each kth tilted plane wave is delayed by a constant delay τk. This transmit is repeated eight times with different polarizations +1 or −1 given by the Hadamard matrix H8. These coefficients hkn are then used as weights for the summation (represented by Σ) to retrieve each plane wave individually with an amplitude N. The amplitude increase obtained by this summation of ultrasonic raw signals results in an improvement of the signal-to-noise ratio of the image. b, Example of activation maps (top views and bias views) obtained from the same rat after left whisker stimulation and visual stimulation, respectively. Gray color represents the baseline Doppler signal and activated regions are represented in 'warm' colors. Activation maps were obtained by estimating the Pearson correlation coefficient between the power Doppler signal and the stimulus pattern. Color scale is proportional to the correlation coefficient. Activated regions of interest: somatosensory barrel field (S1BF) r = 0.68, and ventral sosterior medial nucleus (VPM) r = 0.58 during whiskers stimulation and primary visual cortex (V1) r = 0.23, superior colliculus (SC) r = 0.91 and lateral geniculate nucleus (LGN) r = 0.82 during visual stimulation (Pearson correlation coefficient test). Scale bar, 1 mm. c, Normalized mean CBV signal over responding pixels in the responding areas during the two stimulation periods. From top to bottom: blue curve, mean CBV signal in S1BF; green curve, mean CBV signal in SC.

Lecture 14 – Ultrasound Imaging

This lecture will cover: *(CH4.8-4.13)*

- Ultrasound signal acquisition and processing
- Clinical diagnostic scanning modes
- Imaging characteristics
- Imaging techniques
- Doppler Ultrasound
- **Ultrasound contrast agent**
- **Harmonic and pulse inversion imaging**
- Application

(Supplementary reading: The Essential Physics of Medical Imaging CH14.5-14.9, FMI 6.5)

Ultrasound contrast agent

- Goals:
  - To enhance the signal intensity of Doppler ultrasound;
  - To measure the blood perfusion in the heart and other organs;
- Microbubbles:
  - A diameter of 2-10μm with shells of a few tens of nm thick;
  - A resonance condition which corresponds to the ultrasound frequency at which the degree of expansion and contraction of the bubble is greatest;

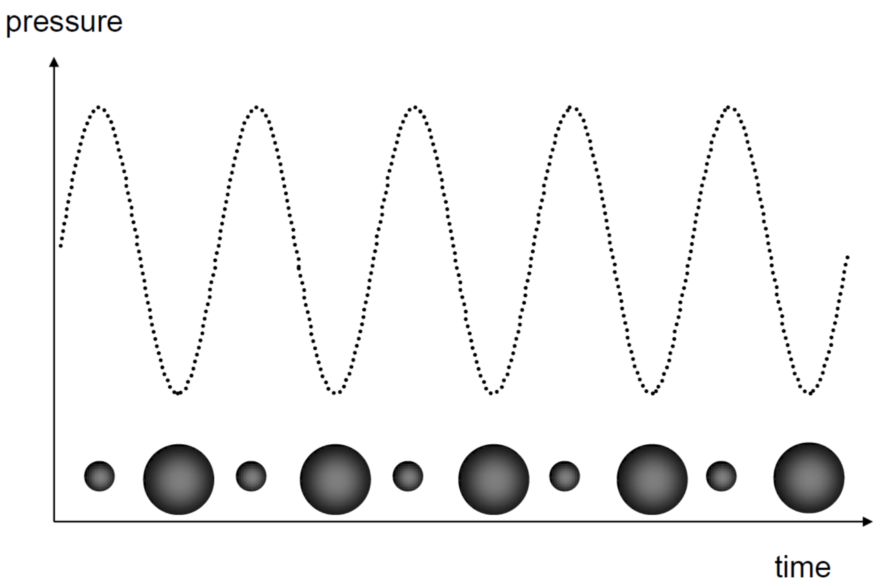


Fig. Change in the shape of a microbubble as an ultrasound pressure wave passes through the tissue in which the microbubble is located.

Harmonic and pulse inversion imaging

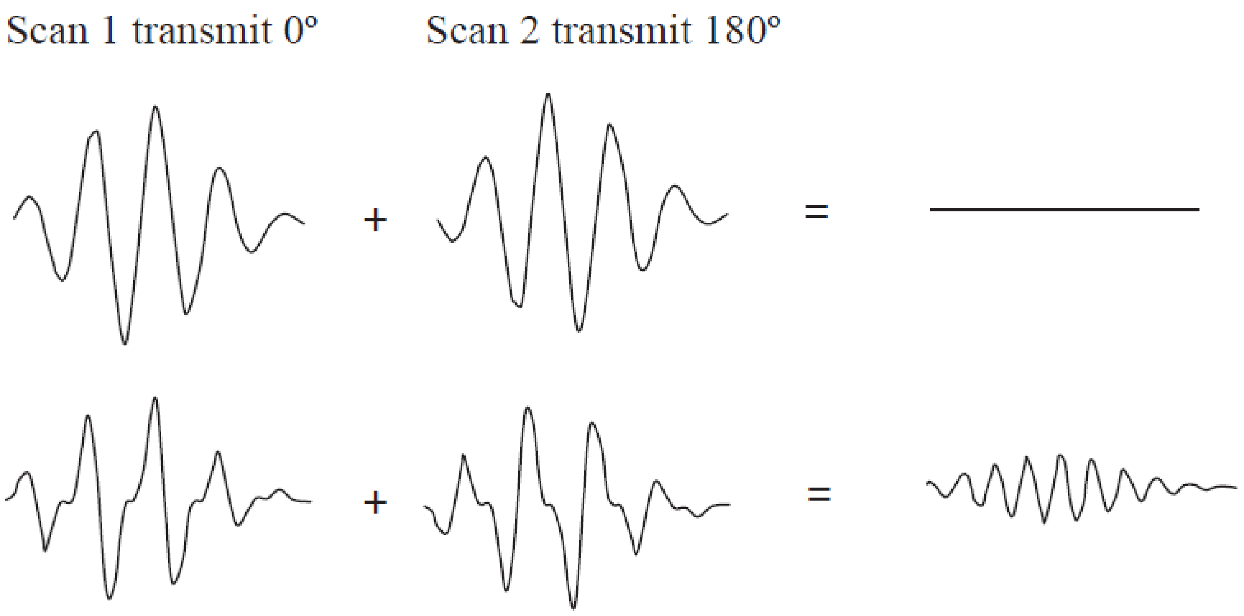


Fig. The principle of pulse inversion imaging. At the top, any signal which contains only components at f_0 is cancelled out by addition of the two scans. At the bottom, the signal contains components at both f_0 and 2 f_0 : in the summed signal, the component at $2f_0$ remains.

- Harmonic frequency
  - Amplitude peaks at $2f_0$, $3f_0$, $4f_0$ ··· for Doppler ultrasound;
  - Nonlinear phenomenon;
  - High intensity ultrasound pressure on microbubbles;
- Pulse inversion
  - Signal cancellation between two transmitted pulses with 180° phase difference;
  - Nonlinear scattering signal do not completely cancel out.

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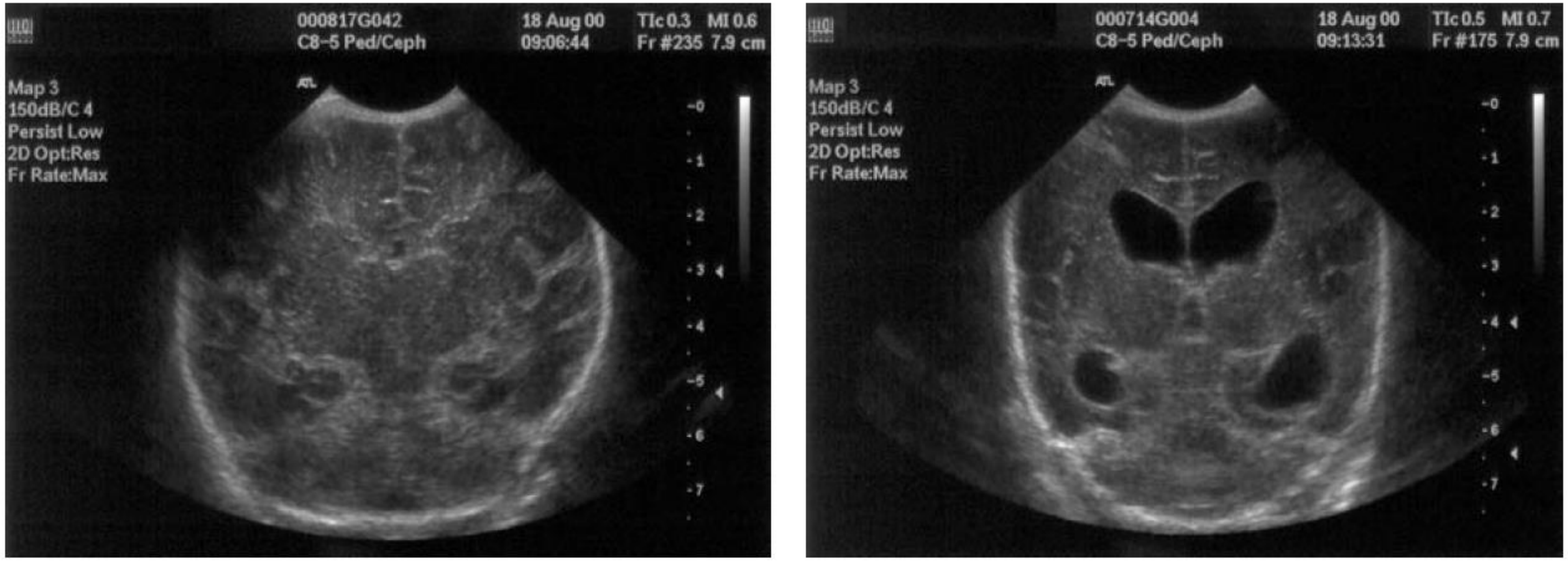
Structural Imaging

- Head



(a) (b)

Fig. (a) Normal cranial ultrasound. (b) Fluid-filled cerebral cavities on both sides as a result of an intraventricular hemorrhage.

Structural Imaging

- Neck

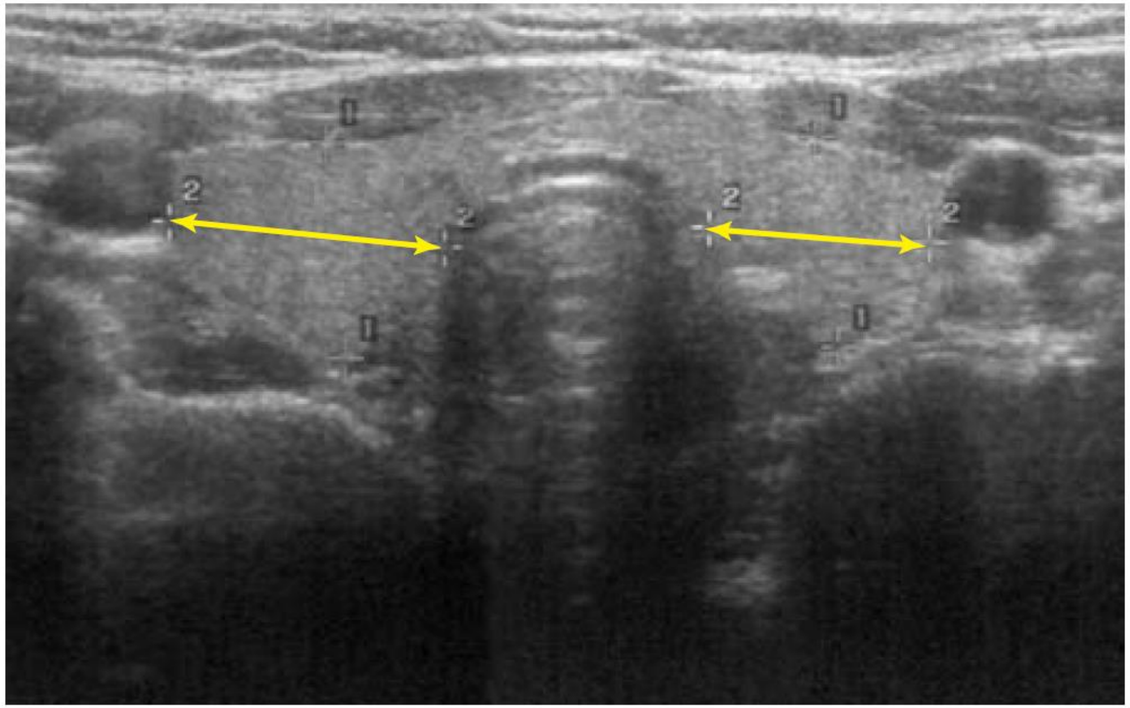


Fig. Ultrasound image of the thyroid showing a mild bilateral enlargement (arrows) suggesting an inflammatory disease or hormonal inbalance.

Structural Imaging

- Abdomen

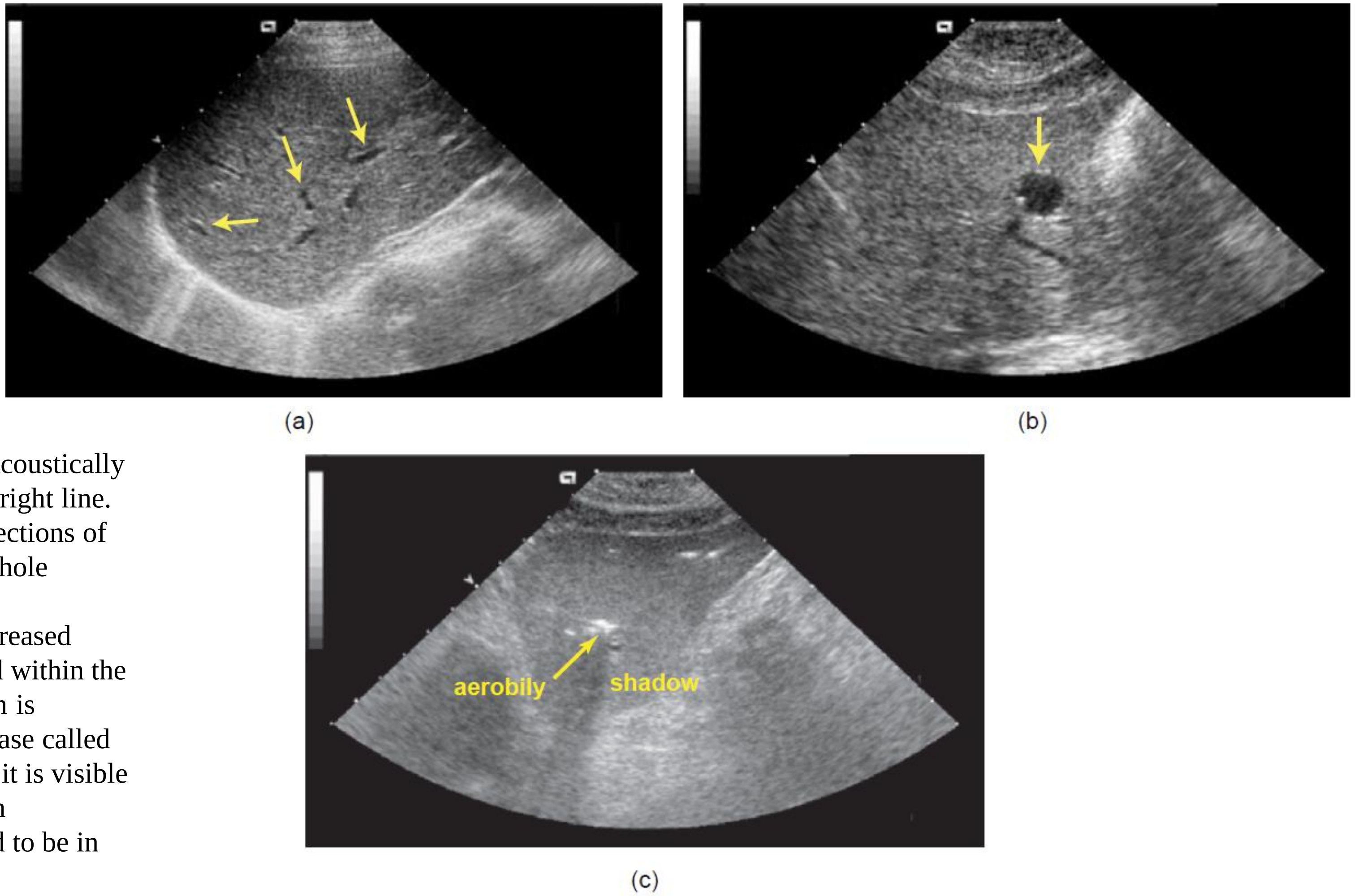
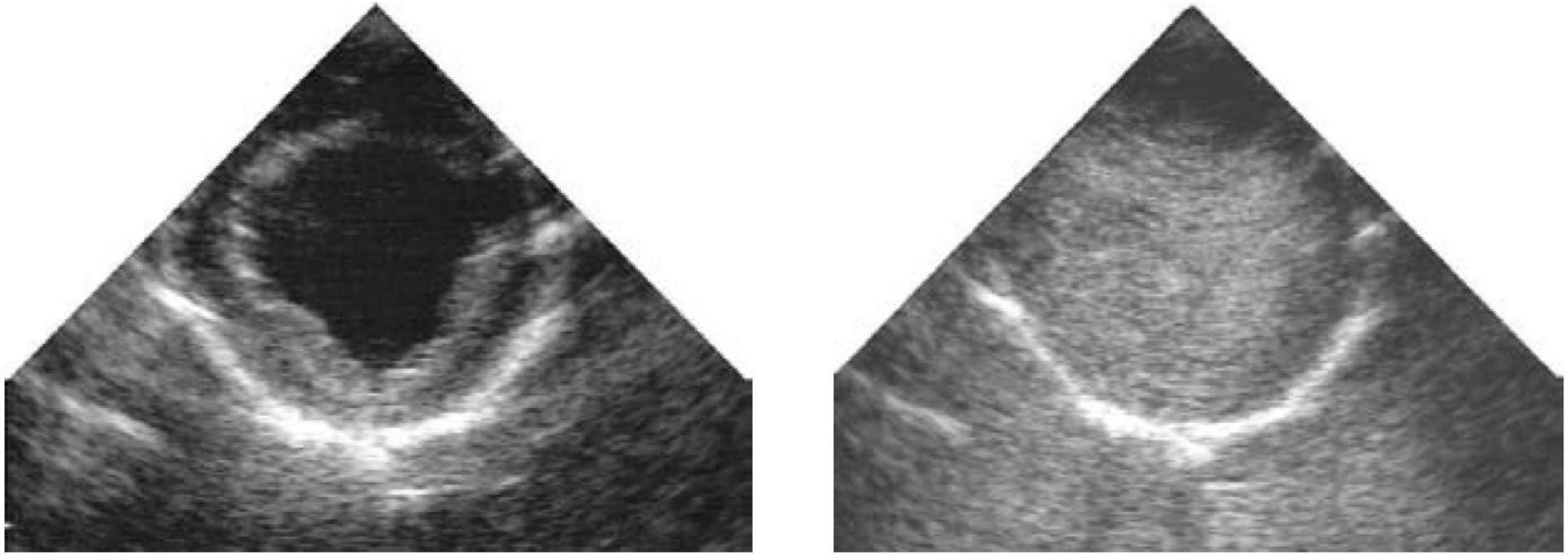


Fig. (a) B-mode image of a normal liver. The liver is an acoustically homogeneous, large organ. The boundary is visible as a bright line. The little black holes (arrows) inside the liver are cross-sections of blood vessels. (b) Liver with cyst visible as a large black hole (arrow). Note the so-called acoustic retroamplification, a hyperechoic region behind the cyst. The origin of this increased reflectivity is the reduced acoustic attenuation in the fluid within the cyst. (c) The opposite effect of acoustic retroamplification is observed when air is present in the bile ducts, as in a disease called aerobily. Because air is a perfect reflector for ultrasound, it is visible as a very bright reflection. Because of this extremely high attenuation, deeper regions cannot be imaged and are said to be in the “acoustic shadow” of the air.

Contrast echography



(a) (b)

Fig. B-mode gray scale image of the left ventricle of the heart in a short-axis view before (a) and during (b) pervenous injection of a contrast agent.