

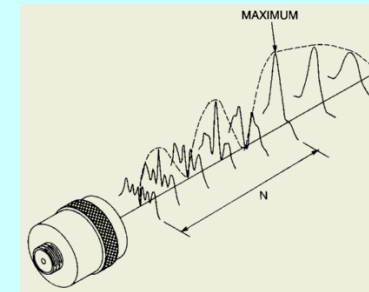
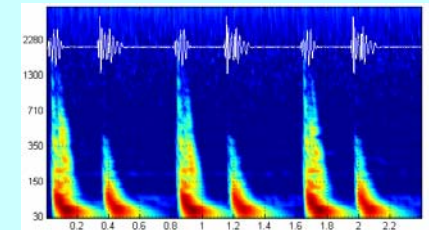
## Medical application of US

*Therapy* – due to absorption of US

*Diagnostics* – due to reflection of US

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## Physics of ultrasonography



## Reflection of US

material	$\rho$ [kg/m <sup>3</sup> ]	$\kappa$ [1/GPa]	$c$ [m/s]	$Z$ [kg/(m <sup>2</sup> ·s)]
Air	1,3	7650	331	0,00043·10 <sup>6</sup>
Lung	400	5,92	650	0,26·10 <sup>6</sup>
Fat	925	0,51	1470	1,42·10 <sup>6</sup>
Soft tissue	1060	0,40	1540	1,63·10 <sup>6</sup>
Eye lens	1140	0,34	1620	1,84·10 <sup>6</sup>
Dense merrow	970	0,36	1700	1,65·10 <sup>6</sup>
Bones (porous)	1380	0,08	3000	2,2 – 2,9·10 <sup>6</sup>
Bones (solid)	1700	0,05	3600	6,12·10 <sup>6</sup>

If  $R \approx 1$  → Total reflection

interface	R
muscle/blood	0,0009
fat/liver	0,006
fat/muscle	0,01
bone/muscle	0,41
bone/fat	0,48
soft tissue/air	0,99

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## Reflection of US

material	$c$ (m/s)	$\rho$ (kg/m <sup>3</sup> )	$Z$ (kg/m <sup>2</sup> ·s)
pulp	1570	1000	1,6 · 10 <sup>6</sup>
dentin	3800	2000	7,6 · 10 <sup>6</sup>
enamel	6250	3000	18,8 · 10 <sup>6</sup>
Al	6300	2700	17 · 10 <sup>6</sup>
borosilicate	5300	3570	18,9 · 10 <sup>6</sup>
amalgam	4350	7750	33,7 · 10 <sup>6</sup>

interface	R
enamel/dentin	0,18
dentin/pulp	0,43
amalgam/dentin	0,40

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## Reflection of US

Optimal coupling:

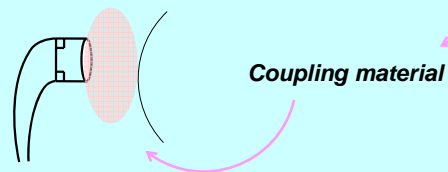
$$Z_{\text{coup}} = \sqrt{Z_1 \cdot Z_2}$$

$$Z_{\text{gele}} \sim 6,5 \cdot 10^6 \text{ kg/(m}^2\text{s)}$$

interface	R
muscle/blood	0,0009
fat/liver	0,006
fat/muscle	0,01
bone/muscle	0,41
bone/fat	0,48
soft tissue/air	0,99

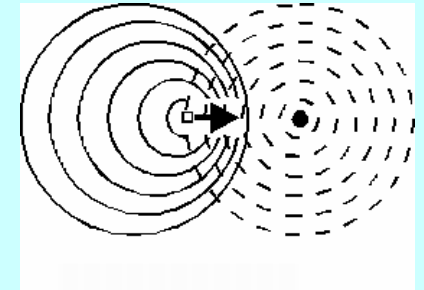
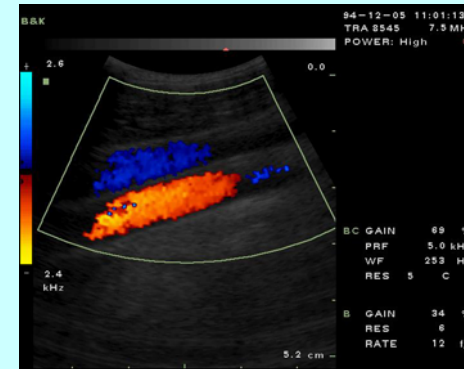


If  $R \approx 1$  → Total reflection



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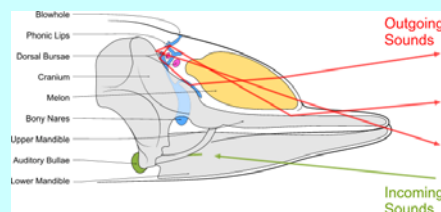
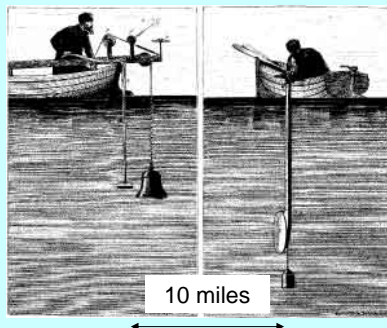
## US imaging. Modes of sonography. Doppler-echo.



## Echo principle

1794 - Spallanzani:  
bat's navigation

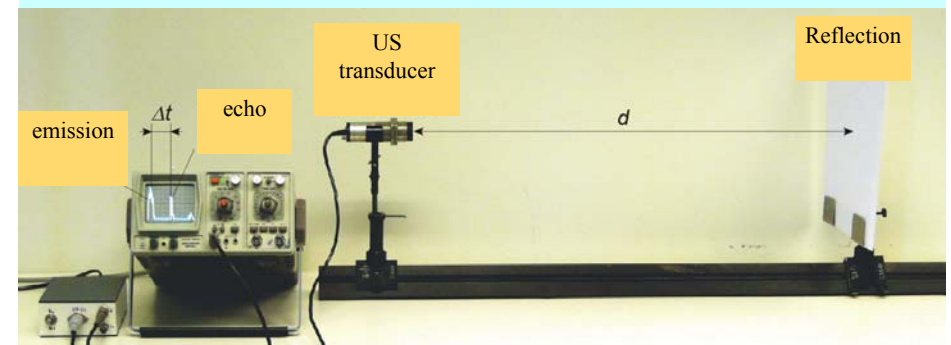
1822 - Colladen measured  
the speed of sound in water



bottlenose dolphin

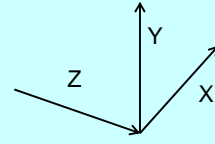
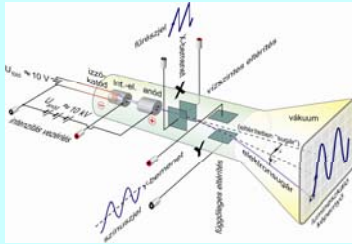
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## Echo principle



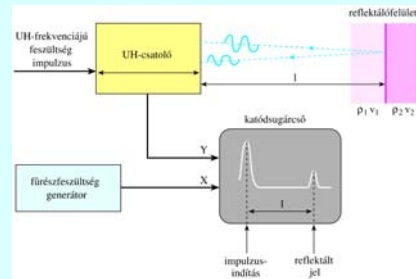
$$c\Delta t = d + d = 2d$$

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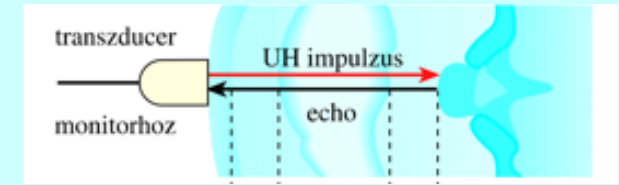
### Deflection / controlling

	A-image
X	Time ( $\rightarrow$ axial distance)
Y	Amplitude ( $\rightarrow I_{refl}$ )
Z	(Brightness)

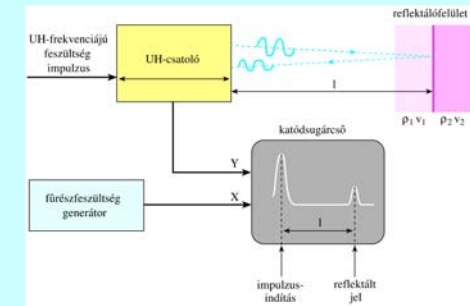


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## A-image - Amplitude



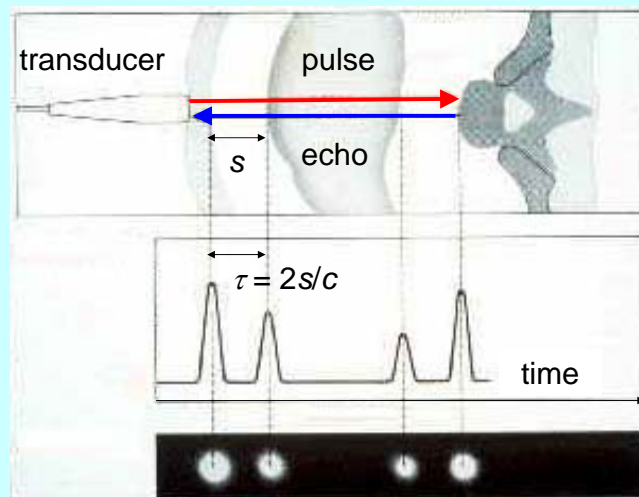
One-dimensional only



$$c\Delta t = d + d = 2d$$

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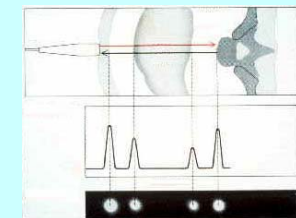
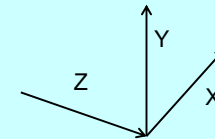
## B-image - Brightness



A-mode  
(Amplitude)  
only 1-dimensional

B-mode  
(Brightness)  
only 1-dimensional

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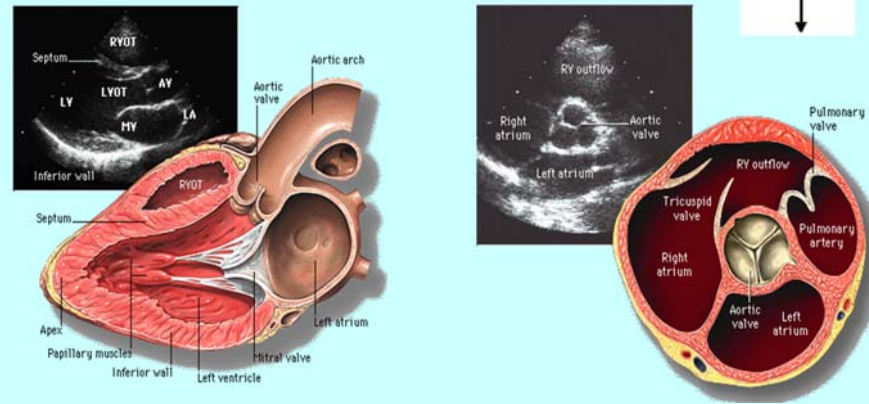


### Deflection / controlling

	A-mode	1-dimensional B-mode
X	Time ( $\rightarrow$ axial distance)	Time ( $\rightarrow$ axial distance)
Y	Amplitude ( $\rightarrow I_{refl}$ )	-
Z	(Brightness)	Brightness ( $\rightarrow I_{refl}$ )

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## 2-dimensional B-mode



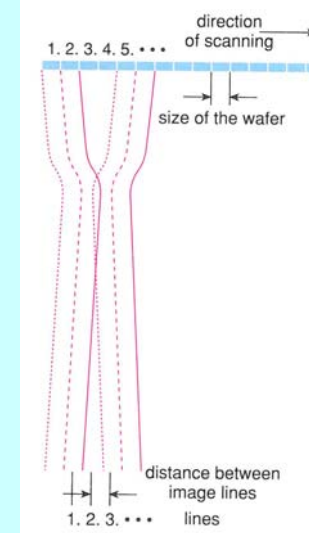
moving  
transducer



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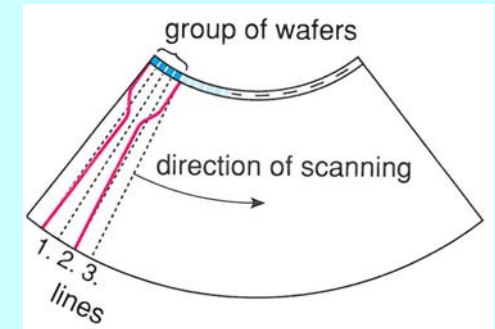
## Scanning

multi unit linear array

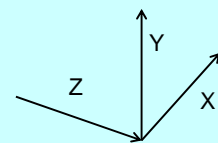


cf. Textbook Fig. VII. 36-37

multi unit curved array



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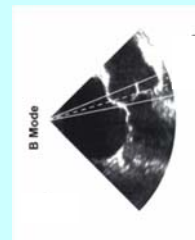
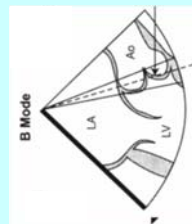
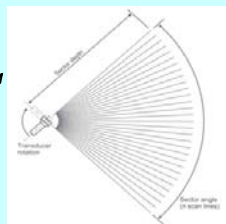


Deflection /  
controlling

X

Y

Z



2-dimensional B-mode

Time ( $\rightarrow$  axial  
distance)

Lateral distance

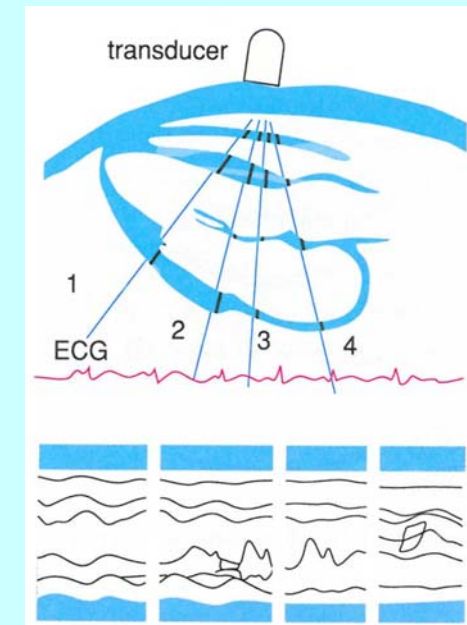
Brightness ( $\rightarrow I_{ref}$ )

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## TM-mode

ECG signal  
for reference

(vertical)  
time-dependent  
1-dimensional  
B-mode



time

(T)M-mode  
Time-  
Motion

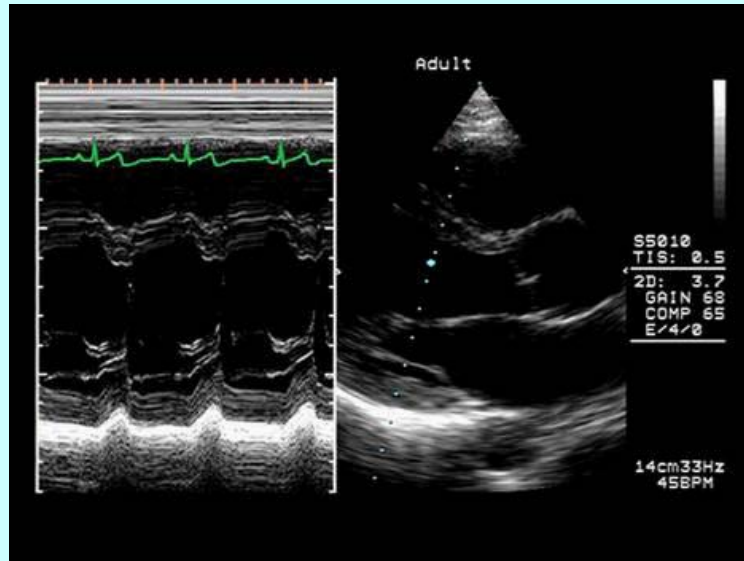
Textbook Fig. VIII.34

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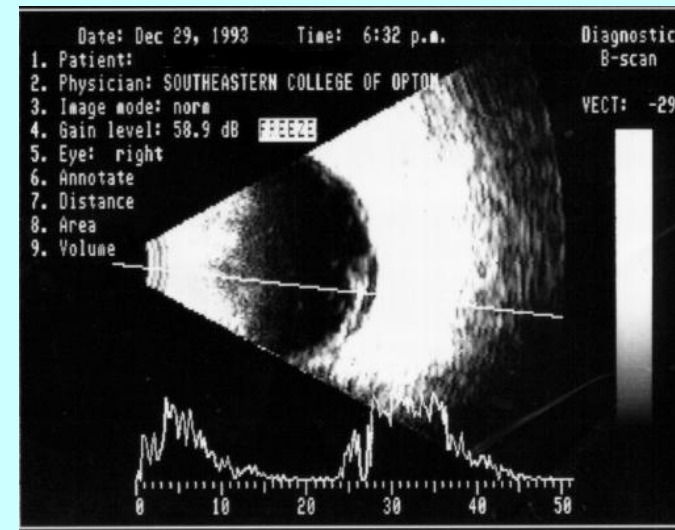
TM-mode

B-mode



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## 2-dimensional B-mode and A-mode (used in ophthalmology)



real speed of propagation for the accurate determination of distances:

cornea: 1641 m/s

aqueous humour: 1532 m/s

crystalline lens: 1641 m/s

vitreous body: 1532 m/s

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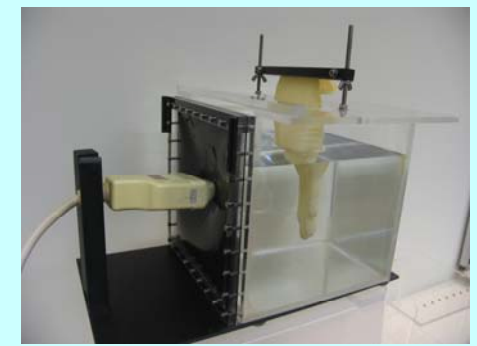
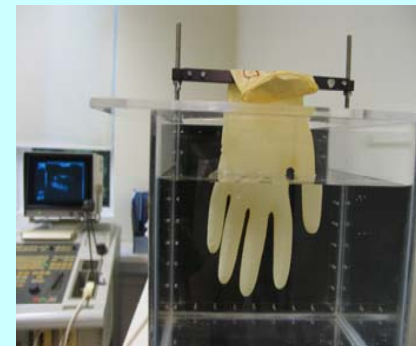
## The object and the image



The object

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## The object and the image



Imaging

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## The object and the image



Cross-section



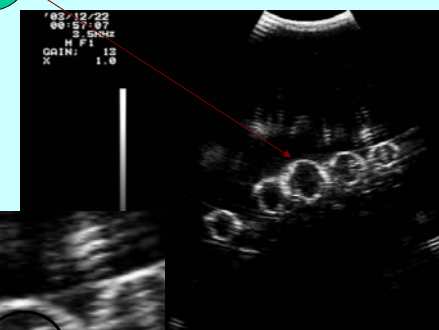
The image

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## The object and the image



Cross-section



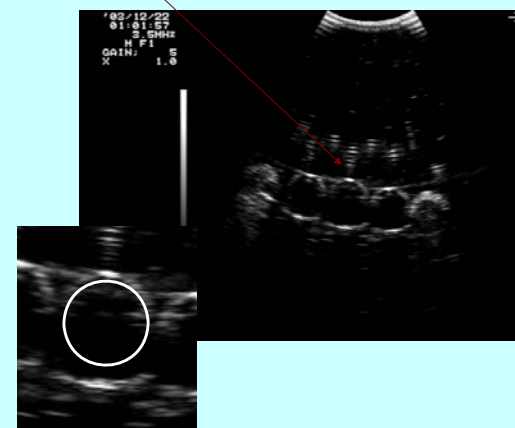
The image

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## The object and the image



Cross-section



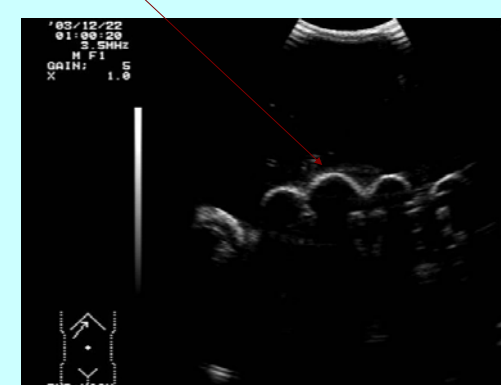
The image

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## The object and the image



Cross-section



The image

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## Resolving limit, resolution

**Resolving limit** is the distance between two object details which can be just resolved as distinct objects (the smaller the better).

**Resolution (resolving power):** the reciprocal of the resolving limit (the greater the better)

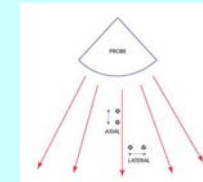
**Lateral resolving limit** - is the minimum separation of two interfaces aligned along a direction perpendicular to the ultrasound beam.

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## Resolving limit, resolution

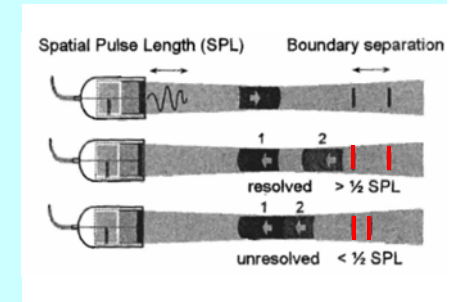
**Axial resolving limit** - is the minimum separation of two interfaces aligned along the ultrasound beam.

Achieving good axial resolution requires that the returning echoes be distinct without overlap



The minimal required separation distance between two boundaries is  $\frac{1}{2}$  SPL (about  $\frac{1}{2} \lambda$ ) to avoid overlap of returning echoes

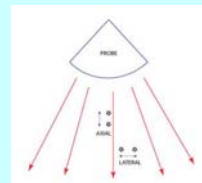
SPL inversely proportional to  $f$



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## Resolving limit, resolution

**Lateral resolving limit** - is the minimum separation of two interfaces aligned along a direction perpendicular to the ultrasound beam determined by beam width, beam density and axial position of the object.



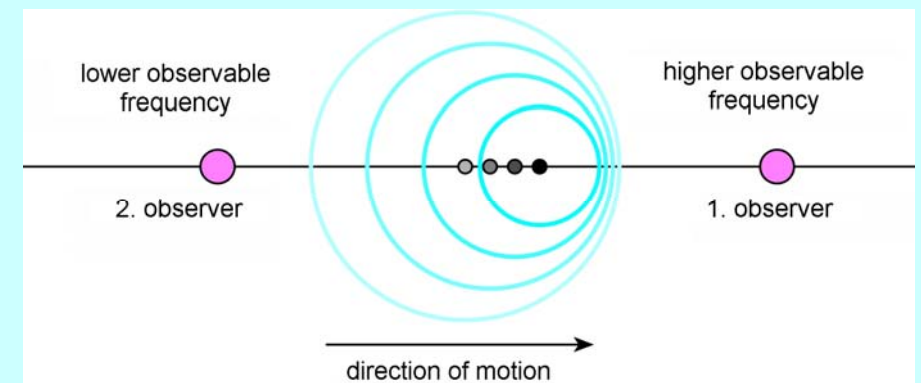
### Typical values

frequency (MHz):	2	15
wavelength (mm):	0.78	0.1
penetration (cm):	12	1.6
lateral limit (mm):	3.0	0.4
axial limit (mm):	0.8	0.15

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## Doppler phenomenon

„The pitch of a train whistle seems to get higher as it approaches, then seems to lower as the train whistle moves away.” (C. Doppler, 1842)



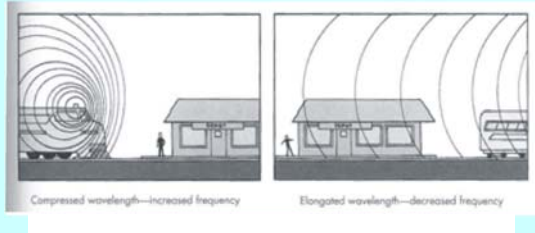
Teetxbok Fig. VIII.39

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## Doppler phenomenon

„The pitch of a train whistle seems to get higher as it approaches, then seems to lower as the train whistle moves away.” (C. Doppler, 1842)

### Moving source

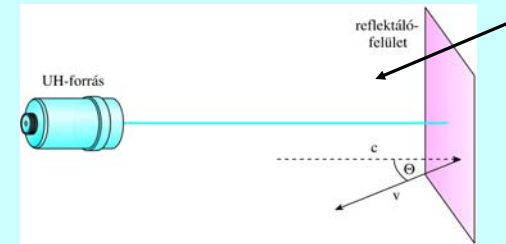


$$f' = f \cdot \left(1 \pm \frac{v}{c}\right)$$

$f$ : initial frequency  
 $f'$ : altered frequency  
 $v$ : speed of source  
 $c$ : speed of US

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### Moving reflecting object (surface),



$$f' = f_0 \cdot \left(1 \pm \frac{2v}{c}\right)$$

Doppler-shift

$$f_D = f' - f_0$$

Doppler shift is proportional to the speed of reflecting surface

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$f'$ : **observed frequency**,  $f$ : original frequency

- (a) standing source and moving observer ( $v_O$ )  
 +: observer approaches the source  
 -: observer moves away from the source

$$f' = f \left(1 \pm \frac{v_O}{c}\right)$$

- (b) moving source and standing observer  
 (if  $v_S \ll c$ , then „same” as (a))

$$f' = \frac{f}{1 \mp \frac{v_S}{c}}$$

- (c) moving source and moving observer

$$f' = f \frac{1 \pm \frac{v_O}{c}}{1 \mp \frac{v_S}{c}}$$

- (d) moving reflecting object (surface),  
 (if  $v_R \ll c$ )

$$f' = f \left(1 \pm \frac{2v_R}{c}\right)$$

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**Doppler frequency** = frequency change = frequency shift

if  $v_i, v_R \ll c$  (i= S or O)

rearranging equation (a)

**moving source or observer:**

$$\Delta f = f_D = \pm \frac{v_i}{c} f$$

rearranging equation (d)

**moving reflecting object or surface:**

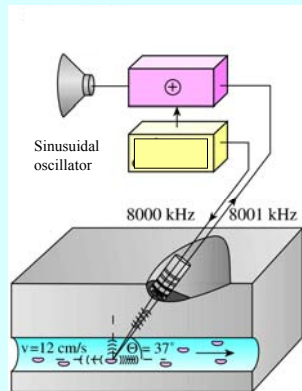
$$\Delta f = f_D = \pm 2 \frac{v_R}{c} f$$

if  $v$  and  $c$  are not parallel, then  $v \cos \theta$  should be used instead of  $v$  (remark: if  $\theta = 90^\circ$ ,  $f_D = 0$ )

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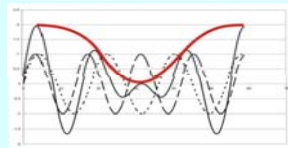
## 1-dimensional Doppler apparatus for measuring average flow velocity.



Tkv. VIII.41. ábra

CW: continuous wave  
source and detector are separated

Red blood cells as sound scatterers.



difference signal 1 kHz

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An artery of 9 mm inner diameter is examined by Doppler ultrasound method. The frequency of the ultrasound is 8 MHz. The average frequency audible for the examiner is 1200 Hz. Calculate the average velocity of blood in the artery. The velocity of the ultrasound in the body is 1500 m/s and we suppose that it propagates parallel to the axis of the blood vessel.

$$f' = f \left( 1 \pm \frac{2v_R}{c} \right)$$

$$|f_D| = 2 \frac{v_R \cos \theta}{c} f$$

$$\frac{|f_D| * c}{2f \cos \Theta} = v_R$$

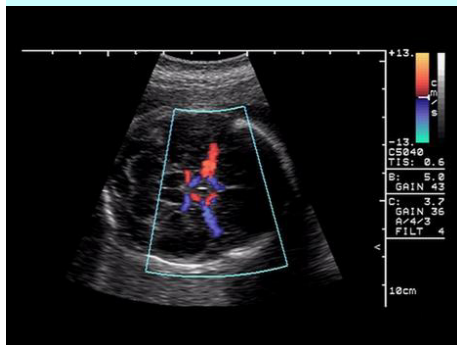
$$\frac{1200 * 1500}{2 * 8 * 10^6} = v$$

$$v = 11,25 \text{ m/s}$$

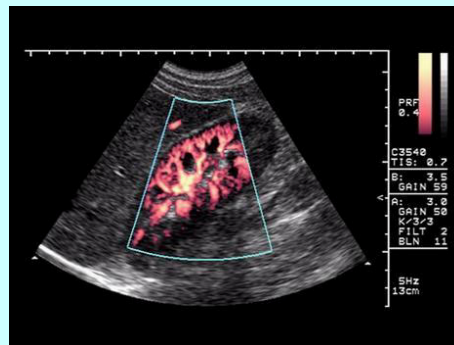
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## Colour coding

towards the transducer: warm colours  
away from the transducer: cold colours

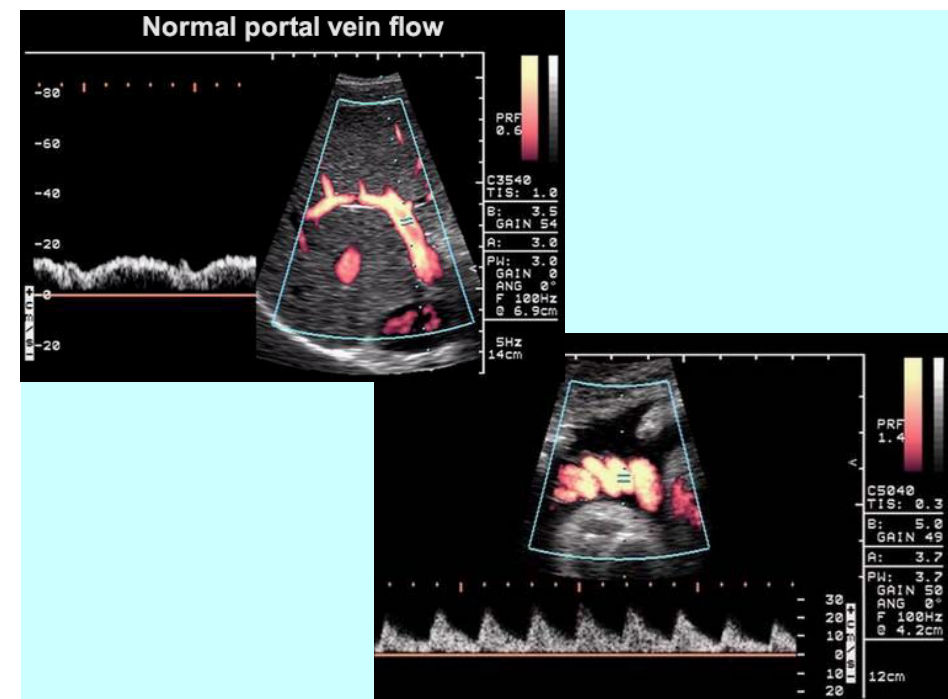


BART: Blue Away Red Towards



power Doppler

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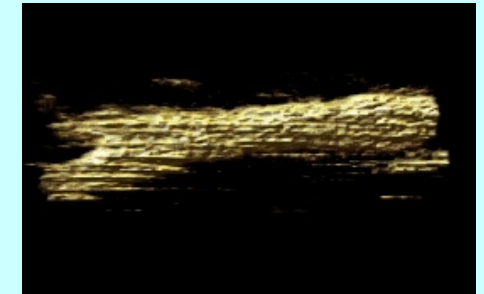
## Reconstruction of the face of a fetus



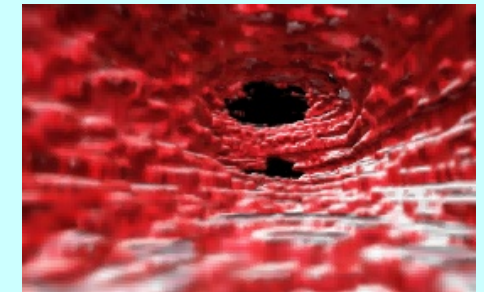
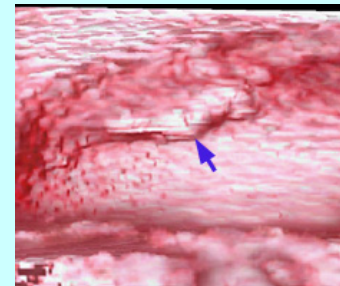
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## 3D reconstruction

carotis



bladder

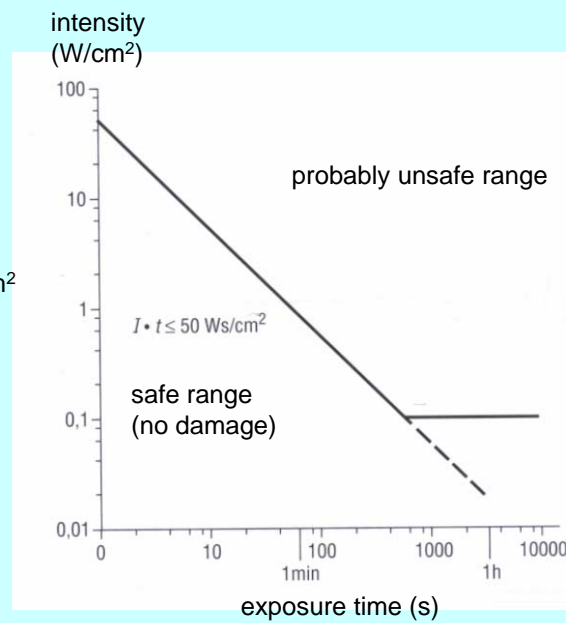


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## Safety

in the diagnostics:  
 $10 \text{ mW/cm}^2 = 100 \text{ W/m}^2$   
 cf. pain threshold:  $10 \text{ W/m}^2$

in the therapy:  $1 \text{ W/cm}^2$



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## Question of the week

What does Doppler-shift mean?

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Related chapters

*Damjanovich, Fidy, Szöllősi: Orvosi Biofizika*

II. 2.4.

VIII. 4.2.