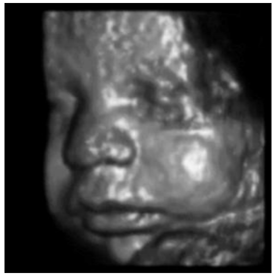
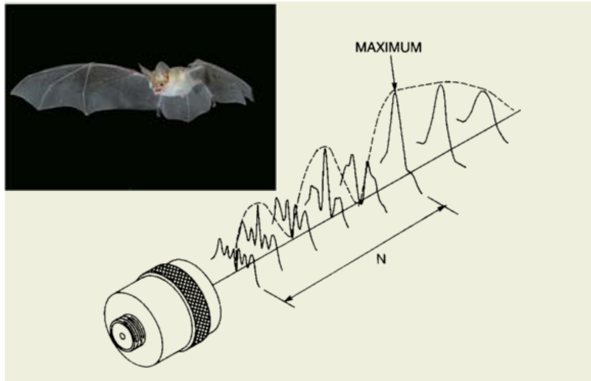
ULTRASOUND



Ultrasound
physical phenomenon
properties
basics of medical applications,



History


LEOPOLDI AUENBRUGGER

INVENTUM NOVUM
EX
PERCUSSIONE THORACIS HUMANI
UT SIGNO
ABSTRUSOS INTERNI
PECTORIS MORBOS
DETEGENDI

VINDOBONÆ,

MDCCLXI.

Dr. Leopold Auenbrugger 1761 - medical doctor

first suggests the method of **percussion** in diagnostics

History

Dr. Leopold Auenbrugger 1761 - son of an innkeeper in Graz, Austria

Percussion -------- from barrels to human body

Ultrasound – a physical phenomenon

Sound is a **Radiation, a „Wave”**

- Harmonic change of a physical parameter propagates in space
- Described by a „wave function”
- Radiation: energy propagation

Reference to remember

Electromagnetic wave:

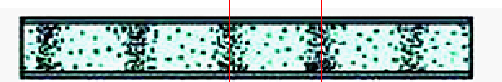
* Harmonic change of E and B field vectors propagates

* Propagation does not require a medium

***** Energy propagating : electric and magnetic

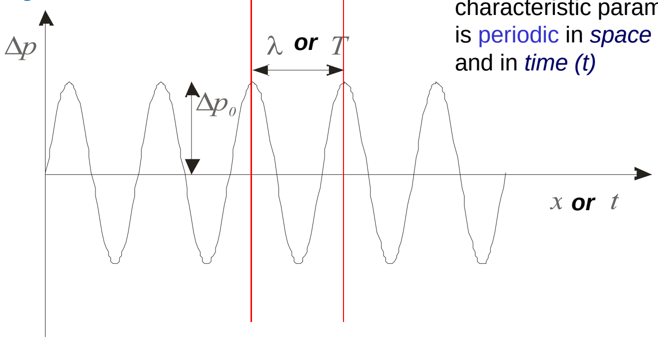
Sound is a ***mechanical*** wave: vibration of particles propagates in a medium

What is characterized by a „wave function”?



whistle

Density change of gas molecules
Deflection from equilibrium
Pressure change



The change of the characteristic parameter is periodic in *space (x)* and in *time (t)*

Sound waves are described as **pressure-waves**

Sound is a mechanical wave…..

* The energy that is propagating: ***mechanical energy***

$$Energy : \tfrac{1}{2} m v^2$$

* Propagation requires a ***medium***

Reminder…

Waves can be

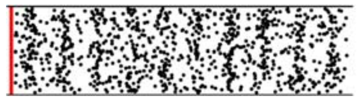
longitudinal : direction of harmonic change in the physical parameter is ***parallel*** with the direction of propagation

or

transverse: direction of harmonic change in the physical parameter is ***perpendicular*** to the direction of propagation

e.g. ***electromagnetic wave*** is a transverse wave

$$\vec{E} \perp \vec{c}$$



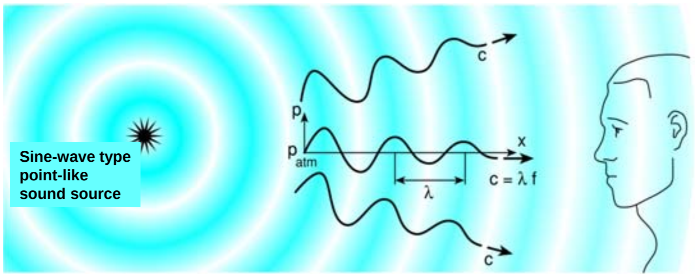
sound in liquids (tissues) and gases:
longitudinal wave

Robe or string: transverse wave

(not sound)

sound in solid materials (bones):
transverse or longitudinal wave

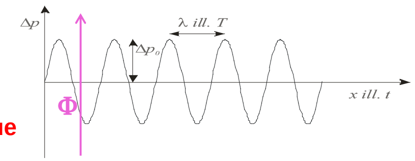
Density change in air – wave motion



Description of a sound wave in a medium

$p_t = p_{hydrostat} + \Delta p$

pressure change due to sound wave



amplitude

+phase

$$\Delta p(t,x) = \Delta p_{max} \sin\left[2\pi\left(\frac{t}{T} - \frac{x}{\lambda} + \frac{\Phi}{2\pi}\right)\right]$$

$$c \cdot T = \lambda, \quad c = f \cdot \lambda$$

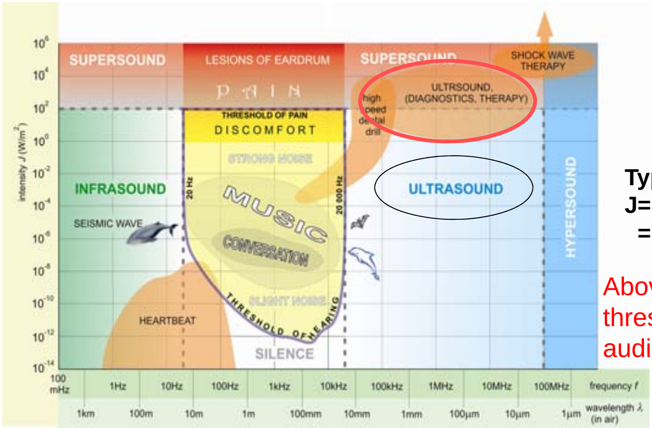
f=1/T : frequency

speed of sound wave propagation, not the speed of light!!!!

Sound - Ultrasound

f>20 kHz, ***c*** does not depend on ***f*** c_{air}= 343 m/s

therapy diagnostics



Typical value:
J= 1W/cm²
= 10⁴ W/m²

Above the pain threshold in the audible range!

Ultrasound – physical parameters

$$\Delta p(t,x) = \Delta p_{max} \sin\left[2\pi\left(\frac{t}{T} - \frac{x}{\lambda}\right)\right]$$

Intensity of US (is an important parameter in practical applications)

I or

$$J = \frac{\Delta E}{\Delta t * A}\left[\frac{W}{m^2}\right]$$

flux or energy-density
denoted now by ***J***

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flux or energy-density
denoted now by ***J***

Power - application for sound?

Ultrasound – physical parameters

$$\Delta p(t,x) = \Delta p_{max} \sin\left[2\pi\left(\frac{t}{T} - \frac{x}{\lambda}\right)\right]$$

Intensity

$$J_{el} \approx P_{el} = \frac{1}{Z_{el}} U_{eff}^{\ 2}$$

analogy

$$J = \frac{1}{Z} \Delta p_{eff}^{\ 2}$$

$$J = \frac{\Delta E}{\Delta t * A}\left[\frac{W}{m^2}\right]$$

acoustic impedance

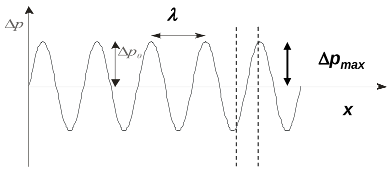
($\Delta p_{eff}^2 = \Delta p_{max}^2/2$)

$$J = \frac{1}{Z} \Delta p_{eff}^{\ 2} = \frac{1}{2Z} \Delta p_{max}^{\ 2}$$

High intensity means large Δp_{max}!

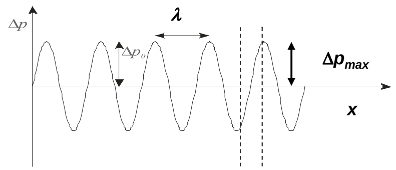
Ultrasound – physical parameters

The Intensity of Ultrasound must be limited



$\frac{\lambda}{2}$ = distance of p_{max} and p_{min}

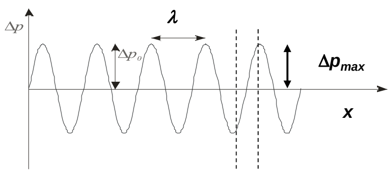
The Intensity of Ultrasound must be limited



$\frac{\lambda}{2}$ = distance of p_{max} and p_{min}

Therapy: f= 0.5 – 1 MHz → **?**

The Intensity of Ultrasound must be limited



$\frac{\lambda}{2}$ = distance of p_{max} and p_{min}

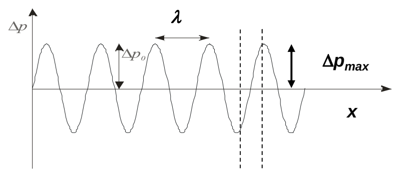
Therapy: f= 0.5 – 1 MHz

c_{muscle}=1600m/s

λ=c/f → λ= 3.2 – 1.6 mm

→ λ/2= 1.6 – 0.8 mm

The Intensity of Ultrasound must be limited



$\frac{\lambda}{2}$ = distance of p_{max} and p_{min}

Therapy: f= 0.5 – 1 MHz c_{muscle}=1600m/s

λ=c/f → λ= 3.2 – 1.6 mm → λ/2= 1.6 – 0.8 mm

- very small distance between max and min of p!
- pressure change **=2*Δp_{max}*** within a distance of **λ/2**

Therapy: f= 0.5 – 1 MHz

suggested limiting value of $J_{average}$= 1W/cm²
(in practice it may go up to 3 W/cm²)

$$J = \frac{1}{Z}\Delta p_{eff}^{\;2} = \frac{1}{2Z}\Delta p_{max}^{\;2}$$

Z_{muscle}

$2\Delta p_{max}$~ 3.2 x atmospheric !!!
within about 1 mm

danger for cavitation and chemical reactions

The Intensity of Ultrasound must be limited

Diagnostics: f= (1) 2 – 10 MHz

→ λ/2= 800 – 160 μm in soft tissue
cellular and subcellular size!

J in practice may be high : 10 W/cm²

???

The Intensity of Ultrasound must be limited

Diagnostics: f= (1) 2 – 10 MHz

→ λ/2= 800 – 160 μm in soft tissue
cellular and subcellular size!

J in practice may be high : 10 W/cm²

BUT: in most cases, ***pulse-mode*** is used

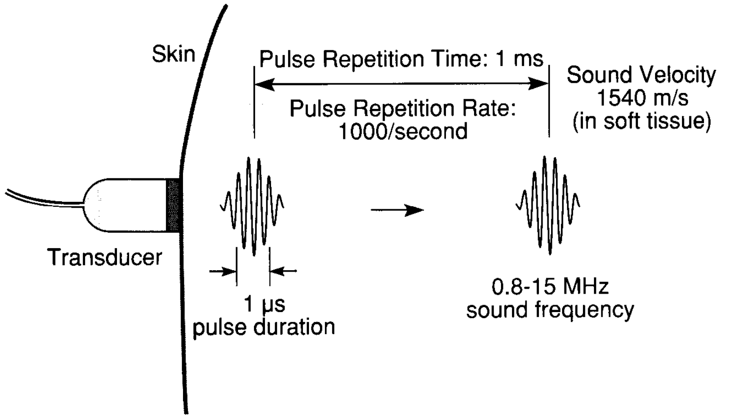
Why pulses?

Diagnostic applications are based on registering the time span between the emission and return of ultrasound pulses from a reflecting surface

↓

Pulse Echo - techniques

Features of pulsed ultrasound



J understood in the pulse with $\Delta t \sim 1\ \mu s$ and 1ms pause

average *J* ~ 10mW/cm² Low value!

Ultrasound – physical parameters - role of the medium

$$c = \frac{1}{\sqrt{\rho\kappa}}$$

Speed of propagation depends on the ***ρ density*** and ***κ compressibility*** of the medium

$$\kappa = -\frac{\frac{\Delta V}{V}}{\Delta p}$$

κ expresses the negative relative volume change (=decrease) induced by pressure change ***Δp*** (=increase)

compressibility

Role of the *medium* in the propagation….

$$J = \frac{1}{2Z}\Delta p_{max}{}^{2}$$

Z* acoustic impedance** determines how large pressure fluctuations will be generated by US flux ***J

Role of the *medium* in the propagation….

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Relation to the tissue – properties ?

Role of the *medium* in the propagation….

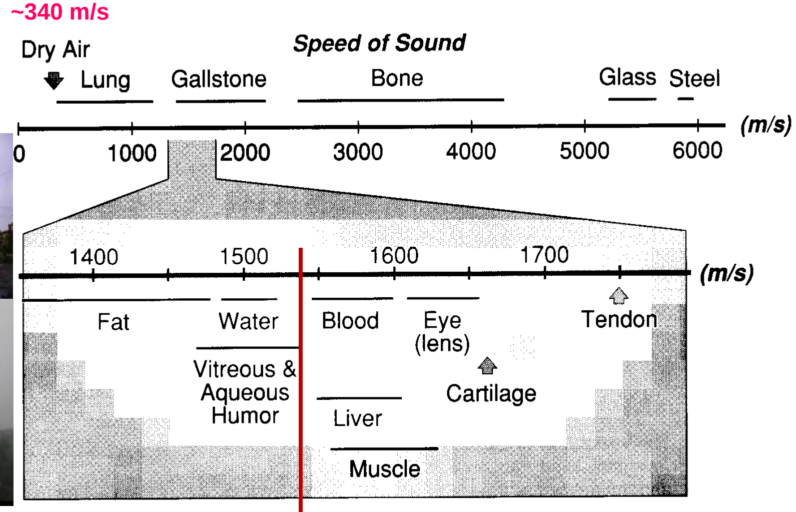
$$J = \frac{1}{2Z}\Delta p_{max}^{2}$$

Z* acoustic impedance** determines how large pressure fluctuations will be generated by US flux ***J

$$Z = c\rho = \sqrt{\frac{\rho}{\kappa}}$$

***Z* is determined by the properties of the medium**

Speed of propagation in various media



Speed in average soft tissue=1540 m/s

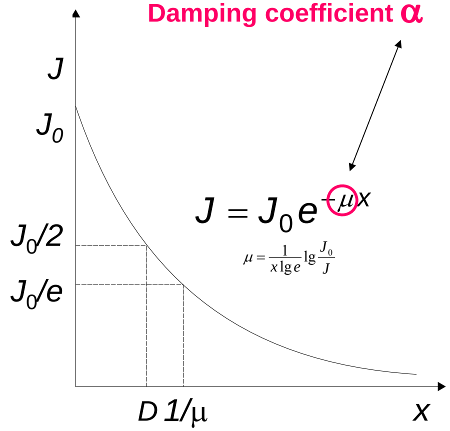
	c(m/s)	ρ(kg/m³)	Z ρ*c
air	**343**	**1.29**	**4.43*10²**
water	**1500**	**1000**	**1.5*10⁶**
muscle	**1600**	**1040**	**1.7*10⁶**
bone	**3600**	**1700**	**6.1*10⁶**
brain	**1530**	**1025**	**1.6*10⁶**

Z can be

significantly different

Another feature of tissues - Absorption of sound waves

Described by the exponential law of radiation attenuation



$$J = J_0 e^{-\mu x}$$

$$\mu = \frac{1}{x \lg e}\lg\frac{J_0}{J}$$

$$\alpha = 10 \cdot \lg\frac{J_0}{J}\ \text{dB}$$

$$\alpha = 10 \cdot \mu \cdot x \cdot \lg e\ \text{dB}$$

$$\frac{\alpha}{x} = const * \mu$$

Absorption is a disadvantage in US diagnostics!

The attenuation of sound waves** **depends on the frequency

$$\alpha = 10 \cdot \mu \cdot x \cdot \lg e \text{ dB} \quad \frac{\alpha}{x} = const_1 * \mu = 4.34 * \mu$$

$$\mu = const_2 * f$$

~ linear dependence on the frequency in the high f range

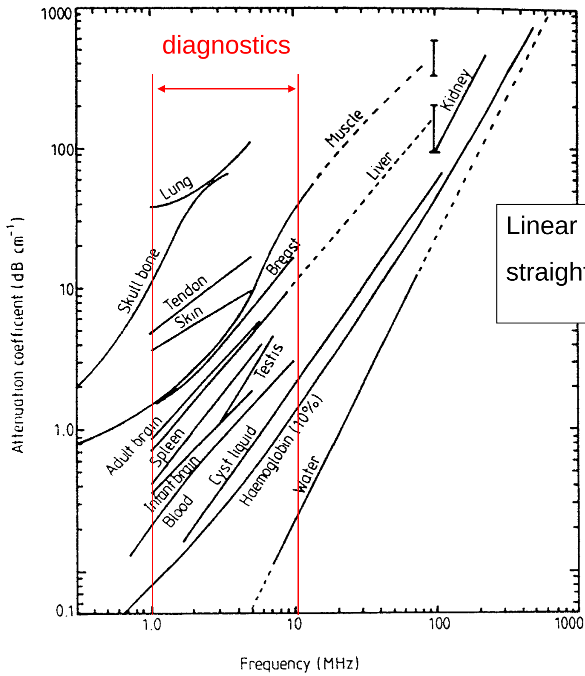
Introducing α_{spec}

$$\alpha_{spec} = \frac{\alpha}{f \cdot x}$$

Specific damping coefficient → **characterizes solely the tissue**

α_{spec} will not depend on the frequency of radiation and on the thickness of tissue

e.g. soft tissues ~1dB/(cm·MHz)



Linear dependence: straight line at 45°

$$D = \frac{0.693}{\mu}$$

	c(m/s)	ρ(kg/m³)	Z ρ*c	D(m) 10kHz	D(m) 1 MHz
air	**343**	**1.29**	**4.43*10²**	**100**	10^{-2}
water	**1500**	**1000**	$1.5*10^6$	10^5	**few**
muscle	**1600**	**1040**	$1.7*10^6$	**--**	$2*10^{-2}$
bone	**3600**	**1700**	$6.1*10^6$	**--**	$\sim 10^{-3}$
brain	**1530**	**1025**	$1.6*10^6$	**--**	10^{-2}

too high absorption

Half value thickness in function of frequency:
Radiation with higher f is absorbed more

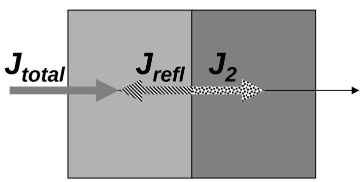
Air
Lung
Fat
Water
Water
Brain
Soft tissue
Liver
Kidney
Spleen
Muscle
Blood
Eye lens
Bone marrow
Bone-porous
Bone-solid
Al
Contact gel
Lead-Zirconate-Titanate
Quartz

anyag	ρ sűrűség [kg/m³]	κ kompresszi-bilitás [1/GPa]	c terjedési sebesség [m/s]	Z akusztikus impedancia [kg/(m²·s)]	$\alpha/(f \cdot x)$ Specific damping [dB/(cm·MHz)]
levegő	1,3	7650	331	430 = $0{,}00043 \cdot 10^6$	1,2
tüdő	400	5,92	650	$0{,}26 \cdot 10^6$	
zsír	925	0,51	1470	$1{,}42 \cdot 10^6$	0,63
víz, 20°C	998		1492	$1{,}49 \cdot 10^6$	0,0022
víz, 36°C	994		1530	$1{,}53 \cdot 10^6$	
agy	1025		1530	$1{,}56 \cdot 10^6$	0,85
lágy szövet	1060		1540	$1{,}63 \cdot 10^6$	0,3 – 1,7
máj	1060	0,38	1549–1570	$1{,}65 \cdot 10^6$	0,94
vese	1040	0,40	1560	$1{,}62 \cdot 10^6$	1,0
lép	1060		1566	$1{,}64 \cdot 10^6$	
izom	1040–1080		1568	$1{,}63 \cdot 10^6$	1,3 – 3,3
vér	1060	0,38	1570	$1{,}61 – 1{,}66 \cdot 10^6$	0,18
szemlencse			1620	$1{,}84 \cdot 10^6$	2,0
csontvelő	970		1700	$1{,}65 \cdot 10^6$	
csont, porózus	1380	0,08	3000	$2{,}2 – 2{,}9 \cdot 10^6$	
csont, tömör	1700	0,05	3600	$6{,}12 \cdot 10^6$	20,0
aluminium	2700	0,009	6400	$17{,}28 \cdot 10^6$	
csatoló gél				$6{,}5 \cdot 10^6$	
ólom-cirkonát-titanát	7650		3791	$29 \cdot 10^6$	
kvarc	2650		5736	$15{,}2 \cdot 10^6$	

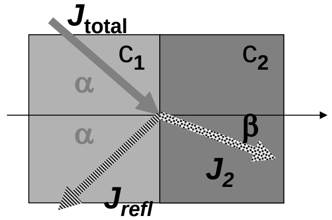
Basics of Pulse-Echo techniques

US is reflected and refracted at the boundary of media with different ρ and κ.

Incident beam is $\perp$ to the boundary



Incident beam hits the boundary at α angle



$$J_{total} = J_{refl} + J_2$$

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2}$$

Incidence at right angle to the boundary
reflection and transmission

Incidence at α angle
Snell's law is valid
US „optics" with mirrors, lenses

Pulse-echo: **US diagnostics is based on the *reflection* of radiation at internal media-boundaries**

Reflectivity R

$$R = \frac{J_{reflected}}{J_{incident}} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

Total reflection: R=1

$Z_1 << Z_2, \quad R \approx 1$

US is ***totally*** reflected at boundaries of media of very different impedances

reflection of radiation at internal media-boundaries….

$$R = \frac{J_{reflected}}{J_{incident}} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

Total reflection: R=1 $\quad Z_1 << Z_2, \quad R \approx 1$

Source ⟷ Body

AIR

Ceramics
Crystal
Solid state
material

Skin

Total reflection!

Coupling
medium
to avoid
total reflection

$$Z_{coupling} \approx \sqrt{Z_{source} * Z_{skin}}$$

(e.g. Pb-Zr-Ti source – see Table)

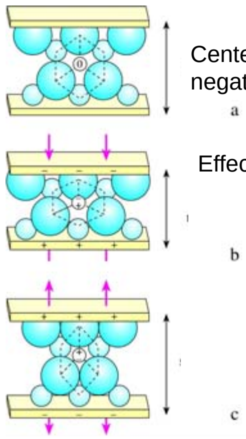
	c(m/s)	ρ(kg/m³)	Z ρ*c	D(m) 10kHz	1 MHz	R
air	**343**	**1.29**	**$4.43*10^2$**	**100**	**10^{-2}**	~1
water	**1500**	**1000**	**$1.5*10^6$**	**10^5**	**few**	
muscle	**1600**	**1040**	**$1.7*10^6$**	**--**	**$2*10^{-2}$**	~0.3
bone	**3600**	**1700**	**$6.1*10^6$**	**--**	**$\sim 10^{-3}$**	
brain	**1530**	**1025**	**$1.6*10^6$**	**--**	**10^{-2}**	

Partial reflection is good condition for diagnostics

Sources of Ultrasound radiation:

Piezoelectric crystal - ***transducer***

ELECTRIC ↔ MECHANICAL



Center of weight of positive and negative charges overlaps.

Effect of alternating compression (b) and dilatation (c)

→ Alternating charge separation

Direct piezoelectric effect
receiver

MECH → EL
Case b and c

Inverse piezoelectric effect
source

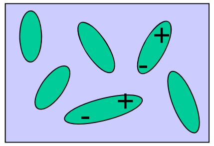
EL → MECH

The same unit can be used both as receiver and source

Examples for piezoelectric crystals:

quartz (SiO_2)
Rochelle salt ($KNaC_4H_4O_6*4H_2O$)

Ceramics based on electro/magneto-striction



Materials built up from magnetic or electric dipole elements

External field induces orientation → deformation

Comparison with piezoelectric ***transducers***:

- lower frequencies are possible
- mechanically more endurable materials

Dental applications: 20-40 kHz US transducer in direct contact with dental deposits-> disintegration ->cleaning

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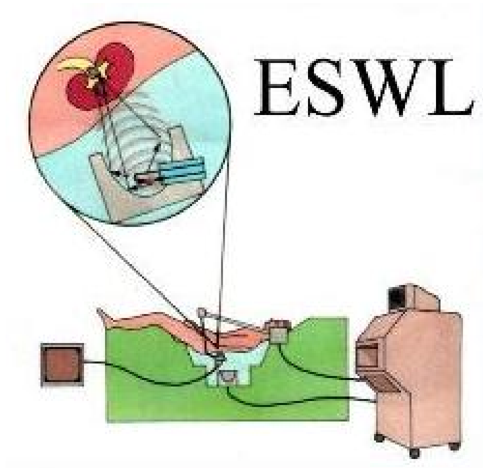
End of the first part

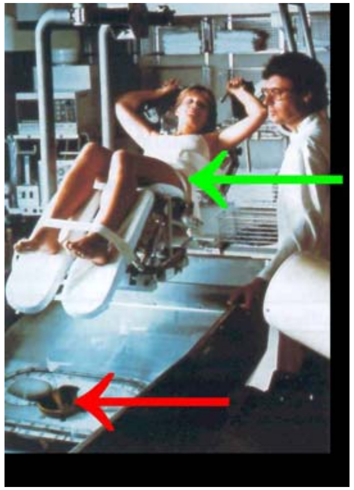
ESWL (extracorporeal schockwave lithotripsy)

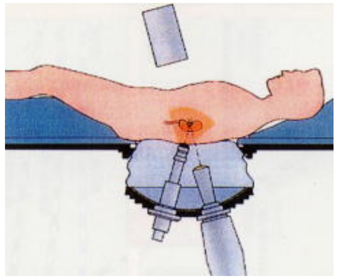
Not an Ultrasound technique!

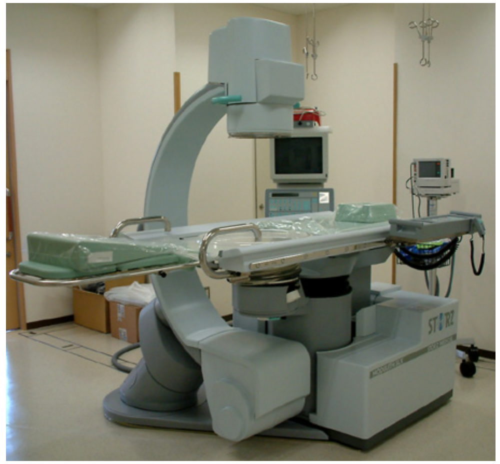
Non-invasive extermination of stones in organs (kidney, bile, etc.)

- Body is brought in contact with a conatiner filled with water
- Two electrodes of ~20 kV, immersed in water produce a spark that generates a pressure pulse in water
- Surrounding elliptical mirrors focus the pulse/shock wave to the site of the stone that becomes destroyed.
- The location of the stone is controlled by X-ray or US imaging



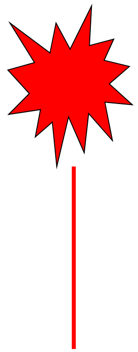






US therapy

Read in the textbook



End of Ultrasound – part I