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Some Applications of Ultrasound in Medicine

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Abstract. Ultrasound has gained significant body of attention in the medical field in both – diagnostics and healing. It may cause thermal and non-thermal effects, which are capable of influencing the body tissues so that the healing process can be supported and the hard tissue of the stones may be destroyed. The present paper gives more insight into the physical basics of the ultrasound interaction with the soft tissue in the process of healing in the physiotherapy and the stones destruction in the shock wave lithotripsy.

Keywords: ultrasound, medicine, physical methods.

1. INTRODUCTION

Medical application of ultrasound (US) began around 1920 as a method of threating pain and eczema in physiotherapy (https://www.ultrasoundschoolsinfo.com/history/). Since then, it has found number of applications in both - diagnostics and healing. In diagnostics, there are several ultrasound modes for visualization (Hoskins et al, 2010). Among them, the most commonly used are 3D, B-mode, and Doppler.

US applications in therapy cover quite broad spectrum: pain release (Zeng et al, 2014), ultrasound-enhanced drug delivery (Kooiman et al, 2007), would (Iwanabe, 2016) and muscle damage (Filho et al, 2018) healing, nerves stimulation (Ussawawongaraya et al, 2006), and even focus US surgeries (Martínez-Fernández et al, 2018).

Present paper describes the physical basics of US in medicine, in connection with its applications in medicine.

2. INTERACTION OF US WITH BIOLOGICAL TISSUES

Ultrasound is named all material waves, having frequency higher than 20 kHz, which is above the human hearing interval of frequencies. Important parameters, dictating the possibilities of its use in medicine are US intensity, penetration depth, and the pulse shape, duration, and duty cycle (in case of pulse US).

TABLE 1 Values of the rest ultrasound intensity at different depths and tissues (Nussbaum, 1997).

Tissue	Depth, cm	Residual intensity, %	
		$\nu = 3$ MHz	$\nu = 1$ MHz
Fat	1	65	87
	2	53	76
Muscles	1	47	74
	4	17	55
Bones	1	3	30

Tissues containing collagen, such as tendons and cartilages, display strong absorption, whereas liquids absorb negligible amount of US energy (Watson, 2014; Nussbaum, 1997; Watson, 2015). As a general tendency, the absorption increases, approaching the natural frequencies of the tissues.

During the US propagation through biological tissues, another phenomenon takes also place – cavitation. All natural liquids contain small gas bubbles or some external forces (as US) can easily create such. In Fig.1, the process of US cavitation is described. After initial bubble formation, the cycles of expansion and contraction follow, because of the positive and negative excess pressure in the tissues (0 excess pressure is the tissue pressure without the US wave). At the end of each US cycle, the initial bubble size increases (stable cavitation). At certain conditions (temperature above 5000 °C and pressure of 50×10^5 Pa) a bubble implosion may be observed (unstable cavitation).

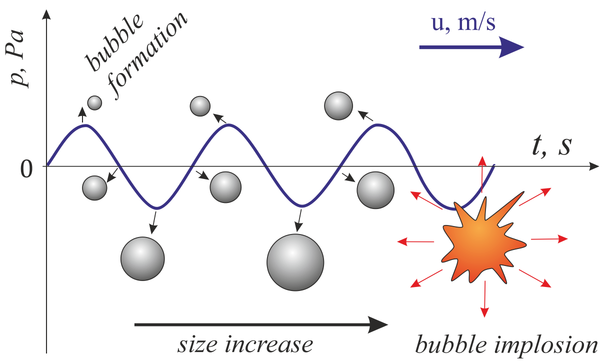

Fig. 1 Cavitation in biological liquids. Initial formation caused by excess pressure, oscillatory growth, and implosion.

Cavitation activity depends on the frequency, power, and type of US (pulse duration and pulse repetition rate), viscosity of the tissues and their temperature. The threshold intensity for unstable cavitation increases with frequency. Cavitation appears easier at pulsed US.

US waves are generated via piezoelectric transducers. They have about 20 times higher acoustic impedance, Z ($Z = p/u$, where p is the acoustic pressure and u is the speed of the US wave in the medium) than that of the biological tissues. Hence, if the transducer is in direct contact with the skin, more than 80 % of the US wave may be reflected. This requires a special care to be taken that some matching between both materials in contact is assured. Water, aqueous gels (conducting 96 % of sound), "Hydro" gels (68 %), special mineral oils, or coupling lotions become a prerequisite for successful US treatment.

3. THERAPEUTIC ULTRASOUND

Therapeutic effect of US originates from either thermal or non-thermal effects. US energy absorption causes the thermal effect, as cell vibrations and cell membranes friction increase. Both effects create heat. The US thermal effect is well pronounced. For comparison at 3 cm intramuscular depth, 10 minutes treatment, with hot packs lead to 0.8 °C temperature increase, whereas similar US treatment at 1 MHz yields about 4 °C.

Thermal ultrasound can increase collagen extensibility, nerve conduction velocities, and metabolism of edema. It can decrease joint stiffness and muscle spasms. It may lead to histamine release. Here, a continuous US is used.

Adding drugs into the contact gels enhances the US effect, where the microbubbles transport the drug to the extravascular regions (Kooiman et al, 2007). Anxiety and depression, appears to be successfully treated by multilevel approach, including US analgesic ultraphonophoresis (Chukhraev et al, 2017).

Non-thermal effects usually appear at pulsed US. They benefit acute conditions, stimulate inflammatory response, promote nerve entrapment release, and neuromas in scar tissue. At pulsed US, the mechanical effect comes into combination with cavitation.

4. SHOCK-WAVE LITHOTRIPSY

Shock-wave lithotripsy (SWL) is an extracorporeal method for kidney and ureter stones removal. The word lithotripsy comes from the Greek *"litho"* meaning stone, and *"tripsy"* meaning crushed.

SWL has revolutionized the medical practice, as it may replace the open surgery in kidney stones management. The single procedure just takes 30 minutes. It is non-invasive, leads to decrease in the complications after the treatment, reducing the healing phase drastically. One more advantage is that it does not require hospitalization of the patients.

In SWL, pulses with steep front and peak value of about 42 MPa and duration of about 1 ms, followed by a broad tail with amplitude 12 MPa and about 3 s duration are used (Fig. 2). Even though, it is called US lithotripsy, since the pulse frequency spectrum clearly indicate US region (Leighton et al, 2009) with a typical values of 20 kHz up to few MHz (Loske, 2007).

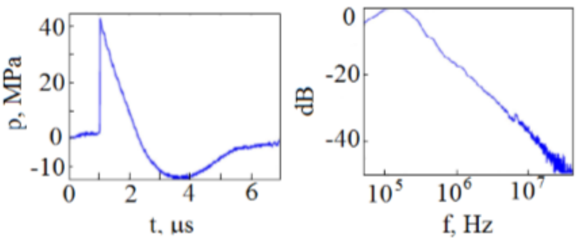

Fig. 2 SWL pulse in terms of pressure versus time dependence and intensity versus frequency dependence (after Leighton et al, 2009).

As US waves propagate in the biological tissues, their speed depends on their acoustic properties. Crossing the interface between two different tissues, causes change in the speed of US. The differences in the speed, together with the density increase during the positive half of the excess pressure period, creates some delay of the wave front, forming a steep onset of a pulse. During the negative part of the US wave (tissue elongation), long pulse tail appears. Hence, US propagation creates shocks (short pulses).

The shocks are focused onto the stone, causing its fragmentation by three different mechanisms: direct deformation, cavitation, and material fatigue.

Direct deformation is the process of weakening the stone by direct interactions with the US wave. The repetitive deformation of compression (squeezing) and elongation of the stone causes the evolution of fragmentation inside the stone. Two main processes take place: spallation and squeezing (Sapozhnikov et al, 2007).

Spallation effect appears because of US wave initial front is reflected at the distal surface of the stone, at the interface with the soft tissue. The maximum tension within the stone yields where the reflected tensile part of the wave overlaps with the negative tail of the incident wave. Therefore, the spallation failure appears at the distal part of the stone. Squeezing is supposed to appear in case the shock wave is broader but shorter than the stone. When the US travels through the tissues, its speed in the the surrounding liquids and in the stone are different. The phase difference between both US waves generate circumferential tensile stresses near proximal and distal ends of the stone, leading to fractures parallel to the US direction of propagation (Sapozhnikov et al, 2007).

Indirect fragmentation of the stones appears from the cavitation in the urine, surrounding the stone. Single bubble or their clusters generate time variable additional stress on the stone. More precisely, the stress appear directly when the bubble collapse, or by the liquid jets, created at the collapse. It may also be a result of shock waves, originating from symmetric or asymmetric bubble collapse, which have much higher-pressure peaks than the initial US shock waves. The effect of cavitation is expressed in pits and fractures in the proximal face of the stone (Sapozhnikov et al, 2007).

The last mechanism is the material's fatigue, where the applied cyclic load (US pulses) leads to a gradual weakening of the stone. In the space areas, where the stone has some defects, the pulse repetition promotes local stress increases, so that microcracks size increases and the cracks can easily propagate (Leighton et al, 2009).

The cavitation and the fatigue are very much dependent on the parameters of the US pulses (Lingeman et al, 2009). Cavitation effect becomes more significant when the pulse tail is longer and low frequencies. At short duty cycles lead to pulse overlap, which may have positive effect on cavitation but in some cases may also provoke screening effect on the propagating waves. Medical examinations show success when pulse rate of 60 pulses/minute are employed and energy from 17 mJ/pulse and stepwise increase.

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