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The Evolving Role of Ultrasound in Therapy

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ABSTRACT

This study highlights the role of ultrasound in therapy and to be a step toward of further development. When an ultrasound wave moves through a tissue it will raise the temperature of that tissue. This effect is beneficial in the treatment of some acute and chronic diseases. A special device used in this study. the device is designed to provide ultrasound waves with frequencies of 1 MHz and 3 MHz which are used in therapy. The frequency of ultrasound is inversely proportional to the depth of the tissues which have to be treated, 1 MHz frequency was used to treat deep body structures reaching 5 cm depth, while 3 MHz used to treat superficial structures. The increase in tissue temperature was measured when: First, by fixing the time and gradually increasing intensity and it is noticed that there is an increase in tissue temperature 0.16-3.04 °C for 1 MHz, and 0.3-3 °C for 3 MHz. Secondly, by fixing the intensity and gradually increasing time, also it is shown that there is an increase in tissue temperature of 0.3-3 °C for 1 MHz and 0.24-2.4 °C for 3 MHz. This rise in tissue temperature is due to the absorption of ultrasound energy in tissues and this effect is used in therapy. So, in a limited time larger number of patients can be treated by reducing the period of treatment with increased intensity of the ultrasound.

KEYWORDS: Ultrasound; Therapy; Tissue; Frequency; Intensity; Temperature.

INTRODUCTION

The human ear can perceive frequencies from (20-20000 Hz), more than this range called ultrasound. They are mechanical waves and they need a medium for transmission [1]. Many physical and chemical effects occur during the passage of ultrasound waves through the body resulting in physiological effects. The extent of the physiological effects depends on the frequency of the ultrasound waves. In medicine the ultrasound waves can be used in different methods depending on the frequency:

- Low-frequency ultrasound: This is used in diagnosis for imaging of the internal structures. Therapeutic ultrasound can be used for soft tissue treatment.
- High-frequency ultrasound: This is destructive ultrasound used for irradiation of tissues as in Lithotripsy (break up a stone in the kidney) [2].

BASIC PHYSICS OF ULTRASOUND

Generation of Ultrasound

Ultrasound waves can be produced by a reverse piezoelectric effect. Many piezoelectric materials can be used for this purpose [3], commonest material is lead zirconate titanate (PZT).

If a voltage is applied to a crystal in one direction, the crystal will contract and when the voltage is reversed It will expand, this succession of compression and rarefaction will result in the production of ultrasound waves.

General properties and equations of sound

The total energy is carried by the wave as kinetic and potential energy. Kinetic energy is expressed as the velocities at which the vibrating particles move, and potential energy arises as a result of the pressure differences between the compression and rarefaction regions, that is:

$$E_t = \frac{1}{2}\, m\, v^2 + \frac{1}{2} K x^2 \qquad (1)$$

Where E_t is the Kinetic energy, m is the mass of vibrating particles, v is the velocity of particles, x is the displacement and K is the proportionality constant (stiffness).

The intensity (I) of the acoustic wave is the energy passing through 1 m^2/sec , and can be expressed as:

$$I = \frac{1}{2}\, z\, (Aw)^2 \qquad (2)$$

where Z is the specific acoustic impedance $=\rho v$, where ρ is the density of the medium, A is the amplitude and w is the angular frequency.

Table 1. Typical values ρ , v, and z , for substances at clinical ultrasound frequencies [2].

	ρ (kg/m^2)	v (m/sec)	z (kg/m^2.sec)
Air	1.29	3.31 x 10^2	430
Fat	0.92 x 10^3	14.5 x 10^2	1.33 x 10^6
Water	1.00 x 10^3	14.8 x 10^2	1.48 x 10^6
Brain	1.02 x 10^3	15.3 x 10^2	1.56 x 10^6
Muscle	1.04 x 10^3	15.8 x 10^2	1.64 x 10^6
bone	1.9 x 10^3	40.4 x 10^2	7.68 x 10^6

The velocity of ultrasound waves varies according to the medium that transmits. The intensity can also be given by:

$$I = \frac{P^2}{2\,Z} \qquad (3)$$

where p is the maximum change in pressure. The typical intensity which is used in physical therapy is generally about (1-10 w/cm^2) for the frequency 1- MHz, by using equation (1) we find the amplitude (A) for (10 w/cm^2) in tissue which is about (10^{-6} cm), the maximum pressure (P) by equation (2) is about (5) atmospheres. The change from maximum to minimum pressure occurs in a distance of one-half the wavelength for 1- MHz wave in tissue, $\lambda/2$=0.7 mm thus there is a substantial pressure change over distance.

Absorption and Attenuation of Ultrasound

The kinetic and potential energy of the waves always changing in their magnitude because the particles that carry the waves changing in movement and displacement during the oscillation. There is some energy loss due to frictional effects that occur during the passage of the sound wave through tissue. The tissue will absorb the energy and result in a reduction of the amplitude of the sound wave; at depth (x), the amplitude (A) in the medium is related to the initial amplitude (A_0) at (x=0) by the exponential equation:

$$A = A_o\, e^{-\alpha x} \qquad (4)$$

Where α is the absorption coefficient of the medium.

The intensity is proportional to the square of the amplitude and its dependence with depth (x) in the absorber; then the intensity is:

$$I = I_O e^{-2\alpha x} \qquad (5)$$

where I_o: is the incident intensity at (x=0) [2].

As shown in equations (4) and (5), we can express the absorption as the loss of amplitude in each cycle, also the loss of energy during one cycle can be expressed as logarithmic Decrement (δ) is

$$\delta = \alpha\, \lambda \qquad (6)$$

where λ is the length of the wave .

The study of attenuation will provide information about absorption and scattering processes that occur in the medium. In case that attenuation is uniform in the acoustic field, this can be recognizable by the absorption coefficient. However, the scattering occurs due to the heterogeneity in the medium [4].

Biophysiological Effects of Ultrasound in Therapy

Passage of ultrasound waves through the body results in physical effects, which are primarily an increase in temperature and pressure changes. Effects of ultrasound can be classified into thermal and nonthermal effects

Thermal effects: occur due to the absorption and attenuation of the ultrasound wave when it travels through the tissue. When a tissue absorbs the ultrasound waves, here the vibrational energy will be converted to heat. Attenuation means the reduction of the amplitude occurring during a wave's travel through the tissue as a function of distance.

Thermal effects of ultrasound include increased tissue temperature, increase extensibility of collagen, increase blood flow, increase enzymatic activity, decrease muscle guarding, increase conduction velocity in the nerve, and increase pain threshold.

Nonthermal effects: These result from cavitation, micro streaming, and acoustic streaming.

Cavitation effect occurs due to soft tissue vibration leading to the formation of microscopic bubbles and these will transmit the vibration to stimulate

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the cell membrane which enhances the cell repair effect which is induced by the inflammatory response. Other nonthermal effects are mechanical, like degradation of the mast cells resulting in the release of histamine, increase in phagocytic activity and macrophage activity, also there is an increase in the synthesis of protein and contraction of wound.

Clinical Uses of Ultrasound Therapy

Control of muscle guarding and pain, increase tissue extensibility, healing of wounds and debridement of wounds, fracture repair, enhanced healing of tendons and ligaments, resorption of calcium deposits, hematomas, and transmission of drugs (phonophoresis) [5,6].

MATERIALS AND METHODS

In this work, two kinds of patients (regarding the superficial and deep therapy) are selected and twenty cases with different diseases have been treated by ultrasound and followed for two months. The measurements that belong to two patients out of the twenty are put, one of them suffered from hamstring muscles partial rupture (deep structure), and the other got knee capsulitis (Superficial structure). We relied on the following foundations;

Effective radiating area (ERA)

This is the area of the transducer over which the energy radiates, it indicates the size of the crystal that is present in the transducer [7], as shown In Figure 1.

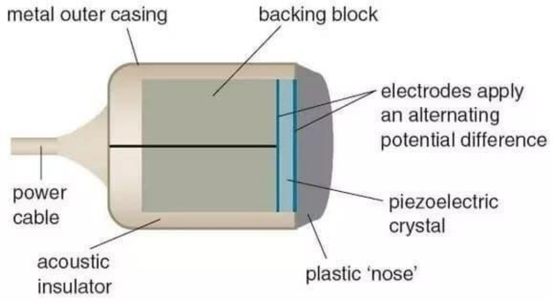

Figure 1. Ultrasound transducer.

Conduction media

Many conduction media can be used, these are water, gel, and gel pad. Water is used for structures with an irregular surfaces like feet and hands. The gel provides a more heating effect than water and gel pad. Coldwater is used for non-thermal effects and sub-acute treatment [5]. Warm water is used for chronic injuries. Ultrasound conduction is more by thinner gel layer than thick layer [8]. Here the work done by using the gel as a thin layer of conductive medium for the treatment of patients because the gel is convenient and more conductive.

Frequency

This is measured in Hertz, which is the number of compression and rarefaction cycles per unit of time for the crystal that's found within the transducer. Frequency is inversely related to the
depth of tissue penetration, so less penetration of ultrasound with 3-MHz frequency than 1- MHz, also, heat is three times faster to achieve with 3-MHz than 1- MHz but not go deep as with 1- MHz. It is 2.5 cm depth with 3- MHz (superficial heating) and 5cm depth with 1- MHz (deep heating) [9]. 1-MHz frequency of ultrasound is the treatment of choice for deep tissue pathologies as inflammation, pain, swelling, and tissue extensibility, 3- MHz frequency for the treatment of superficial pathologies [10,11]. Our work is done by using a device named ENRAF NONIUS made by vergsdweg 127 Rotterdan; Netherlonet, as in Figure 2 (a, b) which provides therapeutic ultrasound with Frequencies 1- MHz and 3- MHz. Also, Mesilife DT-8806 device used for the measurement of tissue temperature as in Figure 3.

Intensity

This is used according to the equations which are put by Draper *et al*. [12]:

FOR 1- MHz frequency the formula is:

$$0.2 \times intensity\left(\frac{w}{cm^2}\right) \times treatment(min.) = temperature\ increases(oC) \quad (7)$$

For 3- MHz frequency the formula is:

$$0.6 \times intensity\left(\frac{w}{cm^2}\right) \times treatment(min.) = temperature\ increases(oC) \quad (8)$$

In our measurements, these equations are used to obtain the increase in tissue temperature, and by measuring basic and final tissue temperature using the device shown in Figure 3.

a

b

Figure 2. a) Hands-free ultrasound device, b) Manual ultrasound device.

Figure 3. Temperature measuring device.

RESULTS

Ultrasound therapy is easy to apply, it can be used for many types of diseases, like muscle spasms, temporomandibular disorders, cervical myofascial pain syndrome, etc.

Two types of ultrasound devices are used in this study, one in which the transducer should be moved manually over the area to be treated.

Moving the transducer at different angles on the target area is very important to avoid overheating and preventing pain.

Another is a hands-free device, its transducer can be put on the target area and it will achieve the work without using hands because it possesses four chambers within the transducer producing ultrasound, so it will have similar action like the manual.

There is another modality of treatment called phonophoresis by which the ultrasound can be applied for administration of drugs through the skin to the deep tissues. Ten patients with chronic backache have been treated with topical diclofenac gel (anti-inflammatory). For five of them, ultrasound with the drug have been applied and the results of treatment were better than those treated with the drug only.

Then by using the ultrasound producing device:

First: For 1-MHz frequency ultrasound (for deep heating) the work done:

a. At a constant time (8 min.) and gradually increasing intensity, and according to the equation which is put by Draper *et al.* [12] equation (7). An increase in temperature is obtained as in Table 2 and Figure 4.
b. At constant intensity (1.5 w/cm^2) and gradually increasing time, and according to the equation (7) An increase in temperature is obtained as in Table 3 and Figure 5.

Second: For 3- MHz frequency ultrasound (for superficial heating). Here the work done:

a. Constant time at (5 min.) and gradually increasing intensity, and by using the equation (8), an increase in temperature is obtained as in Table 4, Figure 6.
b. Constant intensity at (0.4 w/cm^2) and gradually increasing time and by using the equation (8), an increase in temperature is obtained as in Table 5, Figure 7.

In tables 2, 3, 4, and 5, the increases in temperature that are obtained after the usage of the ultrasound in the treatment are included, but in figures 4, 5, 6, and 7, the temperature increases plus the basic temperature of the treated area was included. The basic temperature of the hamstring muscle for the patient was (36 °C), and the basic temperature of the knee joint for the other patient was (36.5°C).

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Table 2. For 1 MHz Frequency at a constant time (8 min.).

Intensity (w/cm^2)	Increase in Temperature (°C)
0.1	0.16
0.3	0.48
0.5	0.8
0.7	1.12
0.9	1.44
1.1	1.76
1.3	2.08
1.5	2.40
1.7	2.72
1.9	3.04

Table 3. For 1 MHz Frequency at constant intensity (1.5 w/cm^2)

Time (min.)	Increase in Temperature (ºC)
1	0.3
2	0.6
3	0.9
4	1.2
5	1.5
6	1.8
7	2.1
8	2.4
9	2.7
10	3

Table 4. For 3 MHz Frequency at a constant time (5 min.).

Intensity (w/cm^2)	Increase in Temperature (°C)
0.1	0.3
0.2	0.6
0.3	0.9
0.4	1.2
0.5	1.5
0.6	1.8
0.7	2.1
0.8	2.4
0.9	2.7
1	3

Table 5. For 3 MHz Frequency at a constant intensity (0.4 w/cm^2)

Time (min.)	Increase in Temperature (ºC)
1	0.24
2	0.48
3	0.72
4	0.96
5	1.2
6	1.44
7	1.68
8	1.92
9	2.16
10	2.4

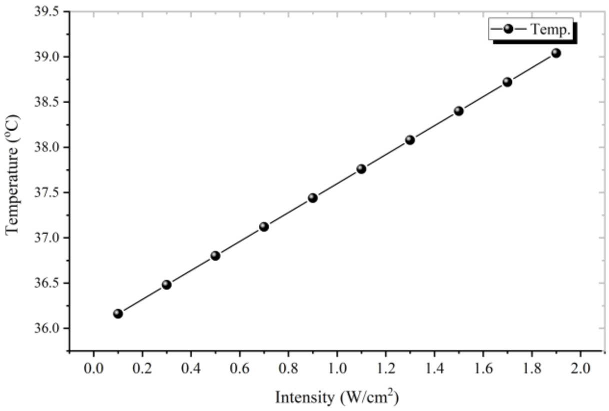

Figure 4. For 1 MHz frequency at a constant time (8 min.).

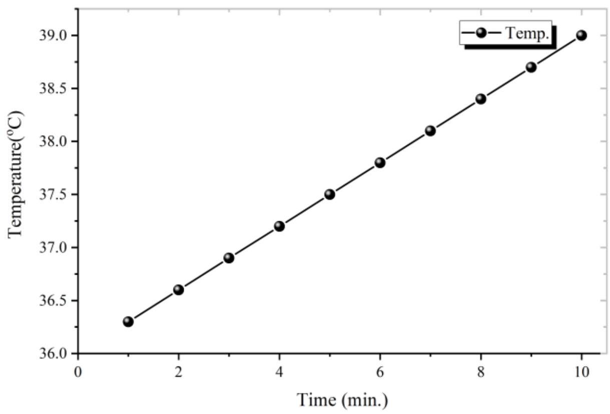

Figure 5. For 1 MHz frequency at a constant intensity (1.5 w/cm^2)

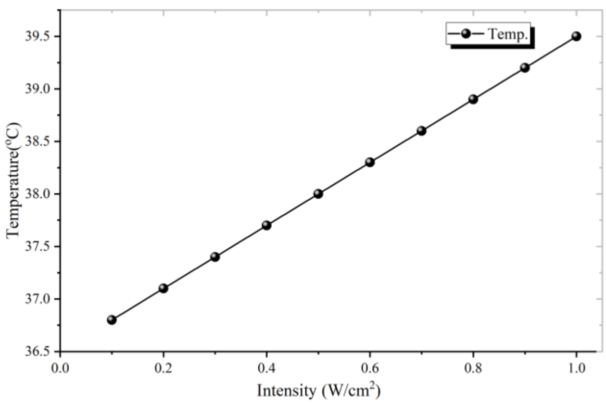

Figure 6. For 3 MHz frequency at a constant time (5 min.).

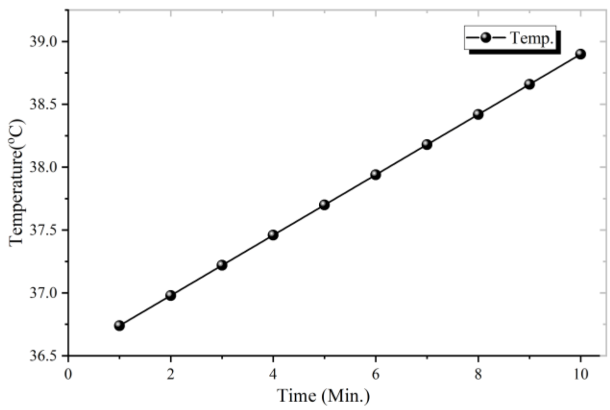

Figure 6. For 1 MHz frequency at a constant intensity (0.4 w/cm^2)

DISCUSSION

It is noticed from figures 4, 5, 6, and 7 that there is a linear increase in temperature when the intensity or the time is increased. This is explained as the increase in compression and rarefaction that occur during the passage of the ultrasound waves through the medium, this will result in increased internal friction between the medium layers. So, there is a work that must be done to overcome it, and thus work dissipated gradually in the form of thermal energy lost at the surrounding medium and it will be absorbed by the tissue.

Then when an ultrasound wave passes through the tissue of the body it will result in physiological effects, which are primarily an increase in temperature, this is a useful effect and as a result, it is used in therapy.

Also, by decreasing the intensity of ultrasound wave, more time is needed to obtain the desired increase in temperature. While we can reach the same increase in temperature by decreasing the time with increasing intensity.

From Table 2 for 1-MHz frequency at constant time (8) minutes and at intensity of (1.5) $\frac{w}{cm^2}$, it is apparent that the increase in temperature is (2.4) ℃ and it is the same as in Table 3. For 1-MHz frequency at constant intensity (1.5) $\frac{w}{cm^2}$ and at time (8) minutes, the same increase in temperature is obtained as above. These results indicate that the same target temperature can be reached and there is no difference when the intensity changes with fixed time and vice versa. Also, from Table 4 and 5 the same principles apply for 3-MHz frequency. The intensity and the period of treatment arranged according to the patient condition.

CONCLUSIONS

Ultrasound is a beneficial physical modality widely used for therapy in human. It is noninvasive, a traumatic and may be used repeatedly [13]. The conclusions obtained from this study are:

1- The physiotherapist must know the condition to be treated and the target tissue involved
2- The physiotherapist also must have information about the limitations of the U.S. unit.
3- The selected treatment parameters must be consistent with goal(s) such as: frequency duration of treatment and intensity.
4- By using different intensities and periods of treatment, time can be saved and treating a larger number of patients in a limited time

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