THERAPEUTIC ULTRASOUND: TEMPERATURE INCREASE AT DIFFERENT DEPTHS BY DIFFERENT MODES IN A HUMAN CADAVER

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A specific increase in temperature is necessary to achieve a temperature-mediated therapeutic impact by ultrasound in rehabilitation. In order to obtain a physical basis for a definite temperature rise at a certain depths in the human body a human cadaver study in situ was conducted. A set of 16 experiments was carried out with an ultrasound frequency of 1 and 3 MHz. For each frequency the pulsed and continuous mode of energy delivery were compared at a variable intensity of 0.5, 1.0, 1.5 and 2.0 W/cm^2. The ultrasonic energy was delivered in direct contact to the cadaver at the posterior crural compartment of the leg in a static manner. Temperature was monitored with a 1-minute interval during an insonation of 10 minutes. Results revealed that theoretical physical predictions concerning tissue heating by therapeutic ultrasound could not always be consolidated and that thermal therapeutic effects for deeper conditions are not obvious to be achieved by ultrasonic therapy.

Key words: ultrasound, thermal effect, physiotherapy, rehabilitation, therapeutic use.

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INTRODUCTION

Therapeutic ultrasound (US) is a common mode of treatment in rehabilitation and physiotherapy. Surveys in the United Kingdom (1) and Scandinavian countries (2) ascertained that in more than 50% of the treatment protocols in private practice US was used. In 1987 in Canada more than 4 million US treatments were administered (3).

US refers to mechanical vibrations like sound waves but with a frequency beyond the range of the human hearing. Typical frequencies used in rehabilitation range from 0.8 to 3 MHz. The absorption of such waves by the human body results in molecular oscillatory movements. This energy transfer is converted into heat proportional to the intensity of the US. If this heat is not dissipated by physiological means, a localized increase in temperature will occur and thermal therapeutic effects may arise. If the dissipation of heat equals the generation of it, any effect is said to be non-thermal. It is believed that such effect could be achieved by low intensities or a pulsed output of ultrasonic energy.

The thermal effects are best known by research and thought to be more controllable than the non-thermal effects, as they can in fact be measured in a rather easy way. Lehmann and colleagues investigated this matter extensively (4–7). Although these experiments did not reveal practical guidelines for present rehabilitation protocols and ultrasound equipment, it was not until the early 1990s that new and more appropriate clinical research was carried out (3, 8–10).

From former investigations it is known that specific rises in temperature are needed to obtain a beneficial influence on human tissue. According to Castel (11) and Lehmann (12) each increase of tissue temperature by 1°C will result in a 13% increase of the metabolic rate. A moderate heating of 2–3°C should reduce muscle spasms, pain, chronic inflammation and promote blood flow (8, 11, 13–15), although randomized trials do not support the clinical relevance of such estimated heating (16). A strong heating (+4°C) decreases the viscoelastic properties of collagenous tissue (8, 11). According to Forrest & Rosen (17) therapeutic thermal effects of US can only be expected when tissue temperature exceeds 40°C.

To obtain such temperatures in deeper tissue layers a rehabilitation specialist or physiotherapist has a variety of technical US parameters at his or her disposal like intensity, US frequency, mode of energy transfer, a static or dynamic treatment protocol and the option of the treatment duration. Therefore in this human cadaver experiment it was attempted to screen a variety of these parameters at several depths. This preliminary study without the coverage of cooling down by the circulation can offer a basis for future in vivo research in human tissue.

MATERIALS AND METHODS

Sixteen experiments were performed on the same cadaver that was selected based on the small amount of fat in the lower extremity. As this cadaver was balsamed (procedure of 6 weeks) and thereafter kept in a cold-storage room, the time between preparation of the cadaver and the investigation was of no importance to cause structural changes in the cadaver that might flaw the experiment. The balsaming implies that the 15 litres of balsam fluid is added. So a cadaver of 65 kg with a water content of 70% will increase in fluid content with approximately 33%. This new fluid relative content of the cadaver is kept constant during storage and thus the following experiment. In the left calf the greatest perimeter was marked as the place for introduction of thermistor probes. Three such probes (AK 28M, Comark, Dimeq NV, Belgium) were used

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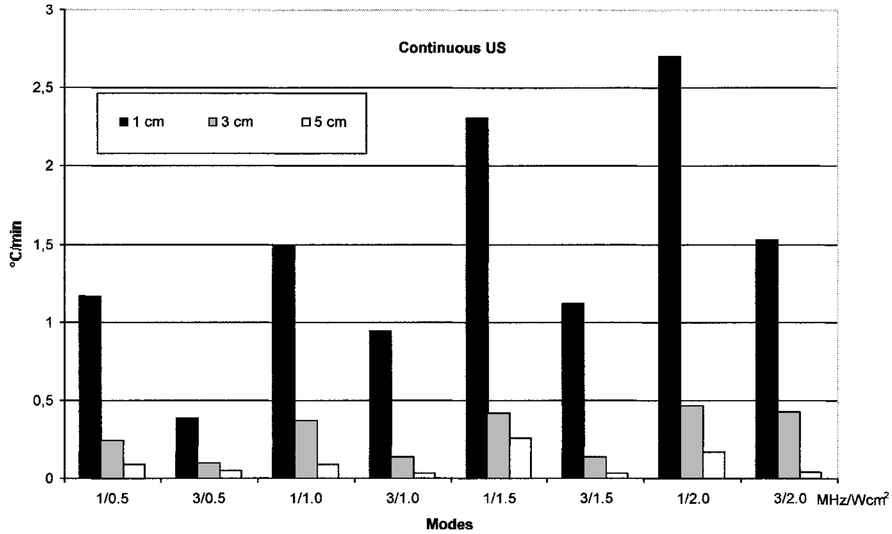

Fig. 1. Mean increase in temperature (°C) per minute for continuous ultrasound (US) at different depths.

to measure the temperature in the medial part of the calf muscles. These probes were introduced passing through a constructed probe-guide with an interdistance of 2 cm and were connected to a digital electronic thermometer (C 9001 Thermometer-Comark) which measured the temperature with a precision of 0.1°C. The probes were introduced perpendicular to the emitted sound bundle of the US applicator through the guide instrument at 1, 3 and 5 cm distance of the transducer. The probes were placed by the guide in a way that the thermocouples ended at the level of the axis of the sonic beam. To ascertain that eventual heating of the thermocouples would not flaw the results, the experiment was repeated on two occasions in which the presence of the thermocouples was compared with an intermittent placement of these couples just to register the temperature. On both trials differences were monitored of less than 0.1°C. So temperature changes independent from the presence of the plastic coated couples can be taken for granted. The US device that was used was a Pulson 330 (Gymna nv, Bilzen, Belgium) with two transducers, 1 and 3 MHz US frequency with both an effective radiating area (ERA) of 5 cm. The respective treatment head was fixed in a tripod with clamp in that the surface of the applicator could be placed perpendicular to the medial part of the calf with the cadaver in a prone position. This placement ensured that the sound waves only travelled through skin, subcutaneous fat and muscle tissue. As skin and fat were so thin and bone interfaces were avoided by sending the US from the side through the calf, the three thermocouples at 1, 3 and 5 cm of the transducer were all measuring in muscular tissue. To ensure reproducibility the contact area of the transducer was marked on the calf. A coupling medium (Contact-gel, Gymna nv, Bilzen, Belgium) was applied to the skin and the transducer. The US device and thermometer were calibrated before each experiment.

A total of 16 experiments was carried out, 8 with the use of 1 MHz and 8 with 3 MHz. Four assays with a continuous mode were conducted for both frequencies and four in a pulsed mode (duty cycle, 2 ms on–8ms off) with an intensity of 0.5, 1.0, 1.5 and 2.0 W/cm^2. In each assay the left calf muscles were insonated for 10 min, in a stationary treatment mode. Temperature was monitored each minute during insonation.

To avoid any variability in temperature changes in the muscle only one experiment took place per day. Meanwhile the cadaver was kept in a cold-storage room with a temperature of 3–5°C. The experiments were carried out in ambulant air with a mean temperature of 13.7°C. After monitoring the starting temperature at the three depths (1, 3 and 5 cm), the insonation started and changes in temperature were registered. The temperature data were expressed as changes to the starting temperature in the tissue at the respective depths.

RESULTS

The mean temperature rise per minute in a continuous and pulsed mode at the three depths with the two frequencies and specific intensities is presented in Figs 1 and 2.

As expected Fig. 1 shows clearly that a continuous mode of insonation delivered a greater and faster rise in temperature than a pulsed energy delivery for the same intensity at the same depth. The smaller the frequency the greater the increase in temperature. If the frequency and intensity remained the same, the heating decreased in function of depth. For 1 MHz at 1 W/cm^2 such an equation equalled 1.49°C per minute at 1 cm, 0.37°C at 3 cm and 0.09°C at 5 cm depth or approximately 173%, 43% and 10.5%, respectively of the theoretical value mentioned by ter Haar (18) of 0.86°C per minute.

For 1 MHz at 1 cm in a continuous mode these temperatures were high to extremely high due to the stationary application technique and the absence of the cooling effect of the blood circulation. Nevertheless these data can give us an idea of the ratio in temperature increase considering the respective parameters used for the specific depths. It was nevertheless remarkable that under these circumstances with an increasing depth the rise in temperature was decreasing very quickly and resulted in precarious perspectives for the used parameters in certain indications at deeper locations. To reach a temperature increase of 3°C in order to reduce pain and chronic inflammation at a depth of 3 and 5 cm, seemed to be a goal that hardly could be met by US. In the pulsed mode the changes in temperature at greater depths were negligible and therefore probably of no therapeutic usefulness as was expected from fundamental physics.

DISCUSSION

This investigation, confined to the human cadaver, was different

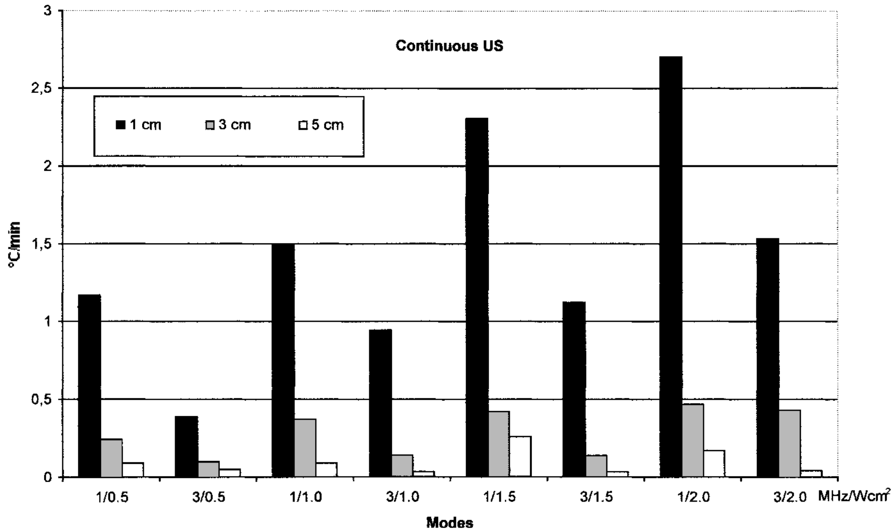

Fig. 2. Mean increase in temperature (°C) per minute for pulsed ultrasound at different depths.

from other published research material. Although previous experiments were carried out in order to obtain insight in the temperature changes induced by therapeutic US, there was no comparative analysis possible as they were all conducted under different conditions (3, 8–10). On one hand human experiments in vivo were carried out that were nevertheless lacking a thorough screening of the various parameters and therefore practical evidence (3, 6, 8, 9), on the other hand the extrapolation of animal in vivo and phantom studies to human subjects posed several problems (7, 10). As a start an experiment on a human cadaver was conducted here in order to restrain some basic features of the thermal effects of US. In order to extrapolate the yielded values this experiment had a major disadvantage, in that it lacked the thermoregulation effect of the blood circulation. Nevertheless, this ascertainment could also be interpreted as an advantage, in that no interindividual differences in circulation could contaminate the results. According to Draper et al. (9) such differences mounted up to a spectacular range of variation in temperature rise (a least the double of the arithmetic mean) in human subjects in vivo. Moreover Lehmann et al. (5) could not find any statistically significant difference between temperature increases in vitro and in vivo in pig tissue. Nevertheless the extrapolation issue of our results should be handled with care as they are mere indices for the physical behaviour of US in order to induce temperature changes. A difference with clinical use of US in this project was also the stationary application technique.

In conclusion this study confirmed all general theoretical assumptions based on general physics. The mean rise in temperature per minute is as expected greater and faster in a continuous mode than a pulsed one and this for each US frequency, intensity and depth. The lower the frequency, the faster and greater the heating regardless the depth. At the same frequency and intensity the temperature decreases with the depth of measurement. Nevertheless there seem to be some fundamental differences between the results of this assay and former reports. According to the mathematical equation described by ter Haar (18), for 1 MHz at an intensity of 1.0 W/cm^2 one could expect a rise of temperature in the order of 0.8°C/minute in the absence of a cooling mechanism such as blood flow. It was never mentioned at what depth one should expect such rise. In this experiment a mean temperature rise of 1.49, 0.37 and 0.09°C was measured at respective depths for 1.0 W/cm^2 in a continuous mode. Ter Haar (18) also stated that for an intensity of 0.25 W/cm^2, at a frequency of 1 MHz with the static transducer over a poorly vascularized region, a rise of temperature of about 1°C might be expected after an insonation of 5 minutes. The author probably divided the mean increase of 0.8°C by a quarter of 1 W/cm^2 (0.25 W/cm^2) and than multiplied this result by five minutes to equal 1°C. If the same reasoning is applied to our own experimental data, a range of increase between 0.0225°C at 5 cm, over 0.0925°C at 3 cm and 0.3725°C at 1 cm would appear. This equals a treatment duration of 44 minutes at 5 cm, 11 minutes at 3 cm and 2.7 minutes or 160 seconds at 1 cm to reach up to the proposed increase of 1°C. Ter Haar (18) described also that the absorption coefficient varies linearly with frequency, resulting in the fact that an absorption coefficient at 3 MHz is 3 times higher than at 1 MHz. In our experiment we cannot support such theoretical statement as no constant relation between frequencies could be found. The variable ratio, ranging from 1.5 to 3, seems to depend on intensity and depth. These differences between the experimental results and the mathematical predictions point out that, although several physical variables are taken into account, the propagation of sound waves in human tissue is not always as predictable as it seems. Reflection, refraction and scattering on the several tissue layers and molecules do not make equational assumptions an easy task. Otherwise Hoogland (19) stated that the half-value depth (the depth at which 50% of the original energy remains) of penetration of US in muscle tissue, perpendicular to the muscle fibers, is 9 mm for 1 MHz and 3 mm for 3 MHz. For the depth of penetration at which still 10% of the energy remains, he figured out that for the same tissue this would be 30 mm and 10 mm respectively. If the increase in temperature is a measure for the remaining level of energy, than our results confirm these mathematical predictions quite well. Therapeutic statements and clinical advise based on mathematical predictions are interesting, but not always proper guidelines. Our results, although not applicable for extrapolation to in vivo circumstances, emphasize the need for further and deeper investigation in some of the most common accepted issues in physiotherapy in general and therapeutic US in particular.

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