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● *Technical Note*

THERAPEUTIC ULTRASOUND IN PHYSICAL MEDICINE AND REHABILITATION: CHARACTERIZATION AND ASSESSMENT OF ITS PHYSICAL EFFECTS ON JOINT-MIMICKING PHANTOMS

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Abstract—The aim of the study described here was to quantitatively assess thermal and mechanical effects of therapeutic ultrasound (US) by sonicating a joint-mimicking phantom, made of muscle-equivalent material, using clinical US equipment. The phantom contains two bone disks simulating a deep joint (treated at 1 MHz) and a superficial joint (3 MHz). Thermal probes were inserted in fixed positions. To test the mechanical (cavitational) effects, we used a latex balloon filled with oxygen-loaded nanobubbles; the dimensions of the oxygen-loaded nanobubbles were determined before and after sonication. Significant increases in temperature (up to 17°C) with fixed field using continuous waves were detected both in front of and behind the bones, depending on the US mode (continuous wave vs. pulsed wave) and on the treatment modality (fixed vs. massage). We found no significant differences in mechanical effects. Although limited by the *in vitro* design (no blood perfusion, no metabolic compensation), the results can be used to guide operators in their choice of the best US treatment modality for a specific joint. (E-mail: caterina.guiot@unito.it) © 2014 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Ultrasonic therapy, Joint-mimicking phantom, Thermal effect, Mechanical effect, Heat, Rehabilitation, Quality control, Frequency dependence.**

INTRODUCTION

Therapeutic ultrasound has been used in physiotherapy for 50 years to treat pain and edema related to acute and chronic inflammatory diseases such as tendinitis, bursitis, synovitis and traumatic events and for the clinical management of rheumatic diseases, neuritis, vasculitis, and so on (Robertson and Baker 2001; van der Windt et al. 1999).

Most effects of ultrasound (US) depend on its ability to induce a local thermal increase, which elicits muscle tonicity, local vasodilation and toxic substance washout (Nadler et al. 2004). However, despite of the number of clinical studies already published (including meta-analyses and reviews) on the efficacy of US treatments in musculoskeletal disorders (Baker et al. 2001), details regarding equipment efficiency or even the selected nominal ultrasound parameter values (frequency, power, pulsed or continuous waves) and the selected treatment modality (fixed field or massage, duration of the treatment) are seldom reported, making it difficult to relate treatment parameters to clinical results (Johns et al. 2007; Kollmann et al. 2005).

Another issue we focus on in this article is even more important. Although US is used worldwide in physiotherapy units and in clinical practice, their real effects inside a joint are still poorly understood, making any quantitative assessment of effectiveness difficult and unreliable.

It is well known that a large part of the ultrasonic energy in biological tissues is converted into heat, and thermal measurements have been intensively performed on tissue-mimicking phantoms made of tissue-equivalent materials and properly equipped for accurate local temperature measurement (see Browne et al. 2003; Burlew et al. 1980; Shaw et al. 1999; Sun et al. 2012). Measurements performed on homogeneous phantoms (Teixeira et al. 2010) revealed that an ultrasound intensity of around 1 W/cm^2 may result in a temperature

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increase as large as 0.8°C/min, but for more realistic non-homogeneous interfaces, it may produce partial reflections and stationary waves causing hot spots (Casarotto et al. 2004).

We therefore went a step further in the simulation of a realistic joint-mimicking phantom by inserting thin disks of bovine bone simulating superficial and deep joints at different depths in a tissue-equivalent phantom, to account for their reflected/absorbed energy contribution to the overall heating.

Finally, because non-thermal effects can also be elicited by ultrasonic treatment, for example, as a result of cavitation of the air bubbles that accidentally form in the tissues (ter Haar 1987), we inserted a small liquid volume containing oxygen-loaded nanobubbles (OLNs) acting as a "cavitation" seed and investigated whether nanobubble dimensions change after sonication as a result of collapse and implosion.

METHODS

Clinical apparatus testing

The output power (OP) of the clinical apparatus (SONOPLUS434, Enraf Nonius, Rotterdam, Netherlands), equipped with two probes operating at 1 and 3 MHz and having a surface area of 5 cm^2, was investigated at INRIM (National Institute of Metrological Research) according to the European Standard for Ultrasonic–Physiotherapy systems (International Electrotechnical Commission 2013). The OP was fixed at 100% and 50% of the maximum power level and was monitored for 5 min, which is the standard treatment time.

The signal produced by a submersible load cell system (Model 31, Honeywell, Golden Valley, MN, USA), connected to an absorbing target (diameter = 150 mm) sonicated by the probe, was conditioned with a strain gauge amplifier (Sensotec Model UV-10, Honeywell), and the output DC signal was measured with a nanovoltmeter (34420 A, Agilent Technologies, Loveland, CO, USA). The duration of the tone burst ($t \leq 10$ s) used to measure the ultrasonic power, P_{out}, allows the utilization of the absorbing target up to 20 W of ultrasonic power. In these ranges of frequency and output power, the measurement accuracy of the OP provided by the device is within 4%.

The thermal and mechanical study was performed at 100% OP in both continuous wave (CW) and pulsed wave (PW) modalities, with a duty cycle of 20% at Department of Orthopaedics, Traumatology and Rehabilitation, AO Città della Salute e della Scienza, CTO Hospital, Torino, Italy.

Joint-mimicking phantom

A cartoon cylinder with removable endfaces was filled with a homemade agar-based gel, prepared using bi-distilled water (89.5% of weight), glycerin (5.5%), graphite (2%), agar (2.5%) and salicylic acid (traces). Two different phantoms were accommodated in the same cylinder, simulating at one end a "deep joint" and at the other end a "superficial joint". During the filling procedure, while the lower layers progressively hardened, two bovine bone disks measuring approximately 3 cm in diameter were carefully inserted at both ends of the phantom: a bovine bone disk 2 ± 1 mm thick at 3 ± 0.5 cm from the end of the cylinder (simulating a "deep joint") and a bovine bone disk 1 ± 0.5 mm thick inserted 1 ± 0.5 cm from the other end of the cylinder (simulating a "superficial joint"). Before solidification, six thin plastic tubes were inserted as guides for later insertion of the thermal probes. Their position can vary by about 0.5 cm.

Deep and superficial "joints" were then treated at 1 and 3 MHz, respectively.

Thermal effect testing

Thermal probes, built by connecting resistive elements (NI24 NTC Thermistor, 2.4 mm, 10 K, 1%, RS Components, Milan, Italy) to a digital signal processor (four-channel recorder/logger, Velleman, Gavere, Belgium) properly calibrated by comparison with thermometric standards and accurate to a tenth of a degree, were inserted in fixed positions both in front of and behind the "superficial joint" and "deep joint". Measurements were made before, during and after sonication lasting 5 min and performed using the most common clinical treatment modalities: electing continuous or pulsed wave on the apparatus and keeping the probe fixed or massaging the probe on the phantom surface. Such massage is performed by small circular movements where the probe (surface area = 5 cm^2) is moved on the phantom cross section (33.2 cm^2).

Temperature measurements are burdened with an overall uncertainty that includes, in addition to calibration and positioning errors, a material-dependent contribution from viscous and absorptive heating that is difficult to quantify.

Data from three independent experiments (performed on three different phantoms, containing bone disks of different thickness allowing for large data variability) were collected on a PC for offline evaluation.

Mechanical effect testing

To quantify mechanical effects, a small latex balloon filled with OLNs was positioned either proximally or distally with respect to the ultrasonic probe and by interposing a bovine bone disk as in the thermal probe. Treatments (in both continuous and pulsed regimens) were performed at 1 MHz in triplicate. OLNs comprised a dextran shell and an oxygen-storing decafluoropentane core between 400 and 800 nm (Cavalli et al. 2009a).