Rate of Temperature Decay in Human Muscle Following 3 MHz Ultrasound: The Stretching Window Revealed

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ABSTRACT: Researchers have determined that when therapeutic ultrasound vigorously heats connective tissue, it can be effective in increasing extensibility of collagen affected by scar tissue. These findings give credence to the use of continuous thermal ultrasound to heat tissue before stretching, exercise, or friction massage in an effort to decrease joint contractures and increase range of motion. Before our investigation, it was not known how long following an ultrasound treatment the tissue will remain at a vigorous heating level (>3°C). We conducted this study to determine the rate of temperature decay following 3 MHz ultrasound, in order to determine the time period of optimal stretching. Twenty subjects had a 23-gauge hypodermic needle microprobe inserted 1.2 cm deep into the medial aspect of their anesthetized triceps surae muscle. Subjects then received a 3 MHz ultrasound treatment at 1.5 W/cm^2 until the tissue temperature was increased at least 5°C. The mean baseline temperature before each treatment was 33.8 ± 1.3°C, and it peaked at 39.1 ± 1.2°C from the ultrasound. Immediately following the treatment, we recorded the rate at which the temperature dropped at 30-second intervals. We ran a stepwise nonlinear regression analysis to predict temperature decay as a function of time following ultrasound treatment. We found a significant nonlinear relationship between time and temperature decay. The average time it took for the temperature to drop each degree as expressed in minutes and seconds was: 1°C = 1:20; 2°C = 3:22; 3°C = 5:50; 4°C = 9:13; 5°C = 14:55; 5.3°C = 18:00 (baseline). We conclude that under similar circumstances where the tissue temperature is raised 5°C, stretching will be effective, on average, for 3.3 minutes following an ultrasound treatment. To increase this stretching window, we suggest that stretching be applied during and immediately after ultrasound application.

An important goal in any treatment or rehabilitation program is to attain full range of motion (ROM). There may be several limiting factors such as joint contractures, scar tissue, and adhesions that make reaching this goal difficult. Clinicians may spend considerable time working on ROM and many use modalities before ROM exercises. One modality that is often used before stretching, exercise, or friction massage in an effort to break up adhesions is ultrasound.[2,7,8,10,14,19]

Research indicates that ultrasound can be used for conditions in which scar tissue has resulted in limited ROM.[2,7,14,16] The extensibility of connective tissue can be increased when the temperature is raised to between 39°C to 47°C.[7] Gersten[7] reported that the higher the temperature reached during ultrasound exposure, the greater the resultant tissue extensibility. He attributed his results to the thermal effects of ultrasound.

In a study of patients with hip contractures, Lehmann et al[12] reported that ultrasound before exercise increased ROM to a greater extent than did infrared heat before exercise. Bierman[1] published several cases of patients suffering decreased finger ROM due to scar tissue accumulation following burns and lacerations. Several of his patients cited increased ROM following a series of ultrasound treatments. According to Bierman,[1] the application of ultrasound at intensities of 1 to 2 W/cm^2 softens scar tissue, thus allowing greater ROM during exercise.

If ultrasound before stretching is used to make scar tissue more pliable, the tissue needs to be vigorously heated.[7,14] Investigators have indicated that specific temperature increases in tissue are required to achieve beneficial effects.[7,13] Mild heating, an increase of 1°C, is used for mild inflammation and to accelerate metabolic rate in tissue. An increase of 2° to 3°C (moderate heating) decreases muscle spasm and pain, increases blood flow, and reduces chronic inflammation. However, when the goal is to increase viscoelastic properties of collagen so that tissue can be stretched, or scar tissue reduced, vigorous heating (an increase of >3°C) is warranted.[4,13]

Ultrasound can raise connective tissue temperature over 3°C.[6,14] However, before 1994, the treatment parameters with regard to time and intensity had not been firmly established, and no studies had been performed on the newer 3 MHz frequency. We recently completed research to determine the rate of tissue temperature rise during continuous ultrasound at the 3 MHz frequency at various intensities.[5] We discovered when treating an area two times the effective radiating area of the soundhead, it takes 3 to 4 minutes on average to raise muscle temperature 4°C during 3 MHz continuous ultrasound at 1.5 to 2 W/cm^2. Basically, 1 MHz ultrasound heats at only one third of this rate.[5,18] We refer to the time period of vigorous heating when tissues will undergo the greatest extensibility and elongation as the "stretching window." Knowing how long to expose tissue to a given ultrasound treatment at a given intensity is important. Equally important is knowing how long the tissue will stay at this therapeutic level. This is crucial, since the cooler the tissue becomes, the more resistant it is to stretch.[7]

To date, there have been no in vivo studies measuring rate of temperature drop or decay following ultrasound treatments. We have been left to speculate regarding how long we have after an ultrasound treatment has been administered to initiate stretches or

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friction massage. Since ultrasound has a definite role in the treatment of joint contractures and scar tissue, and since the technique of "heat and stretch" is so popular, we felt that it was imperative to perform this study.

METHODS

Eleven men and nine women (20 ± 2.1 yr) volunteered to participate in the investigation. Each participant signed a consent form after being informed about the possible risks of participation in such a project. We paid each subject a $20.00 honorarium for their participation. Approval for the study was granted by the University Human Subject's Institutional Review Board.

We used the Omnisound 3000 (Physio Technology Inc, Topeka, KS) ultrasound unit. The generator operated at a frequency of 3.0 MHz ± 10%. The transducer head was 5 cm in diameter and contained a lead zirconate titanate crystal. The beam nonuniformity ratio of the crystal was 1.8:1, which ensured superior beam uniformity for fast, effective heating with no hot spots.[4] The effective radiating area of the soundhead was 4.5 cm^2, which indicates that nearly all of the surface was transmitting the beam. The ultrasound unit was recently calibrated.

To measure temperature changes in the muscle, we used a 23-gauge thermistor needle (Phystek MT-23/5, Physitemp Instruments, Clifton, NJ) coupled to a monitor (BAT-10, Physitemp Instruments, Clifton, NJ) that gave a digital readout of temperature in°C. According to the manufacturer, the accuracy of temperature recordings of both the probe and the monitor is within 0.1°C. Therefore, if the temperature of the muscle is 40°C, the worst case error recording would read 0.2 higher or lower than 40°C, (39.8° to 40.2°C). Our coupling medium was Ultra Phonic ultrasound transmission gel (Pharmaceutical Innovations, Newark, NJ) at room temperature (25°C).

The treatment site was the triceps surae muscle of the left leg. This area was two times the size of the effective radiating area of the transducer head and within the recommended treatment size parameters. To ensure that the treatment size was equal for all subjects, we applied a 9 cm × 5 cm template to the target area (Fig 1). For this study, we measured the temperature change at 1.2 cm depth, since this is about how deep under the surface many joints and connective tissues lie. This is also an appropriate target depth for 3 MHz ultrasound.[17,18]

We followed the methods developed and reported previously.[6,20] Each subject assumed a prone position while we measured and determined the area of greatest girth on the triceps surae muscle to use as a landmark. We shaved this area, cleansed it with a Betadine scrub and then swabbed it with 70% isopropyl alcohol. A 1-cc injection of 1% lidocaine (Xylocaine) was given subcutaneously to anesthetize the area. The lidocaine did not contain epinephrine, which might inhibit normal vascular response and cloud the results. We inserted the thermistor into the injection site on the medial aspect of the triceps surae muscle belly, so that it was 1.2 cm beneath the area of application. We connected the thermistor to the monitor, and after the temperature reached its lowest point with no fluctuations for 3 minutes, we recorded this number as the baseline.

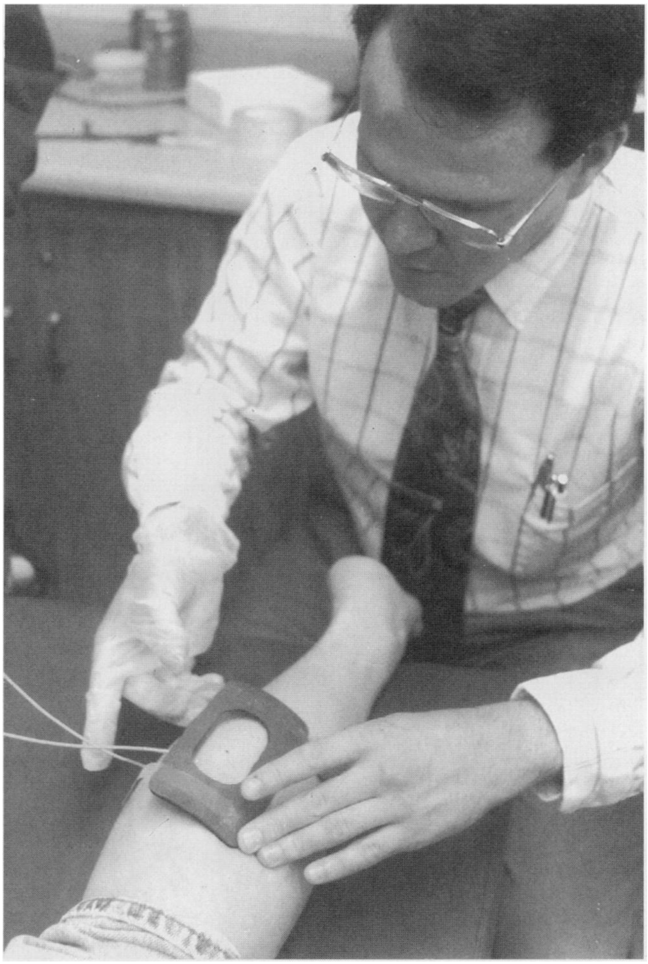

Fig 1. The examiner places a template on the skin to ensure that all treatments cover two times the effective radiating area.

The goal of the treatment was to raise the temperature at least 5°C above baseline and then to measure the rate of temperature decay. To accomplish this, we administered ultrasound at an average intensity of 1.5 W/cm^2 while moving the soundhead back and forth in the template at a speed of approximately 4 cm/sec (Fig 2). We monitored the temperature rise during the treatment and recorded when the temperature had increased 5°C. Once the treatment was completed, we recorded the rate of temperature decay to the nearest 0.1°C every 30 seconds. We recorded the temperature to the pretreatment baseline, and continued to record temperature until it stabilized. We removed the thermistor and placed it in a sterile solution of Cidex (Johnson & Johnson, Arlington, TX) after each subject had completed the temperature decay. We cleaned the injection site with 70% isopropyl alcohol, applied a bandage, and excused the subject.

RESULTS

The mean baseline temperature before each treatment was 33.8 ± 1.3°C, and it increased as a result of our ultrasound treatment to 39.1 ± 1.2°C. Thus, the temperature was raised an average of 5.3°C above the baseline in an average time of 6 minutes (3 MHz ultrasound heats at such a rapid rate that it was difficult to stop the treatment at an increase of exactly 5°C, during our 30-second recording intervals). It took 18 ± 3.5 minutes for the temperature

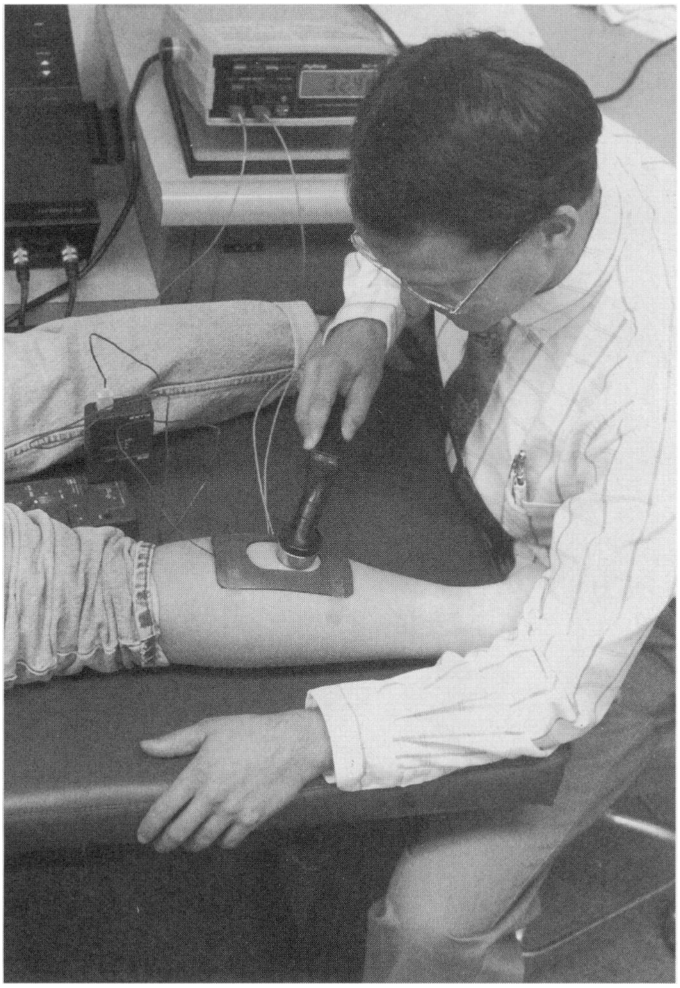

Fig 2. Application of ultrasound to a subject's triceps surae muscle.

to go from its peak to original baseline temperature. Once the temperature reached the original baseline reading, it continued to drop another 0.7 ± 0.5°C at a rate of 0.08 ± 0.05°C per minute until it stabilized. On average, the temperature posttreatment dropped 0.8 ± 0.56°C below the original baseline.

We ran a stepwise nonlinear regression analysis to predict temperature decay as a function of time following ultrasound treatments. We found a significant nonlinear relationship between time and temperature decay ($r = .99$, $r^2 = .99$, SE of estimate = .06). We obtained the following prediction equation:

$$TD = -.60321(t) + .02466(t)^2 - .000375(t)^3 - .24404$$

Where TD = temperature decay and t = time

The rate of temperature decay is displayed in Figure 3. Notice that the temperature begins to drop quite rapidly, and then slows down before reaching baseline. The average time it took for the temperature to drop each degree, as expressed in minutes and seconds is as follows: 1°C = 1:20; 2°C = 3:22; 3°C = 5:50; 4°C = 9:13; 5°C = 14:55; 5.3°C = 18:00 (baseline).

DISCUSSION

The care and treatment of contractures due to scar tissue, adhesions, tight capsules, and fibrotic muscle/tendon presents a major obstacle. The ability for connective tissue to elongate is contingent on the amount of interweaving between the meshwork of its collagen fibers.[9] Fibers with few interweavings allow a greater ROM than do fibers with many interweavings, such as scar tissue or dense connective tissue. Separation of adjacent collagen fiber attachments within the connective tissue meshwork hypothetically allows for a long-lasting elongation.[9,11,15]

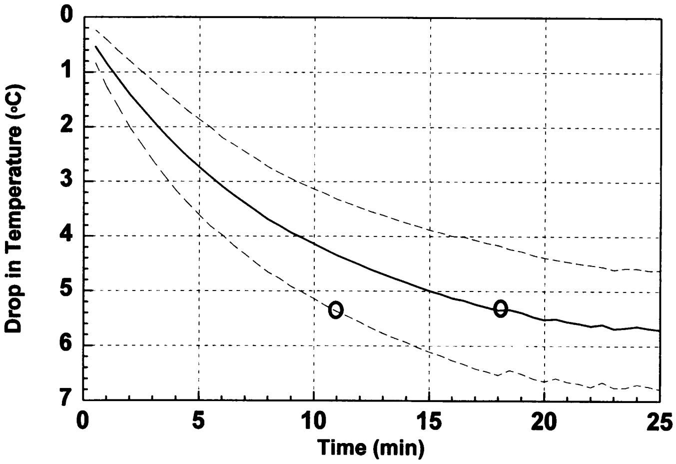

Fig 3. Rate of temperature decay following treatments with continuous 3 MHz ultrasound. Solid line = mean temperature decay. Hatched lines = 1 standard deviation above and below the mean. Oval = time to pre-ultrasound baseline.

When stressed, collagenous tissue is fairly rigid; yet, when heated, it becomes much more yielding.[7,14,21] However, the combination of heat and stretch produces a residual lengthening of connective tissue, which increases according to the force applied. The greatest lasting increase in the length of tissue has occurred when application of a stretch was continued after heating. This is due to a reorganization of tissues during the cooling process.[14] This long-lasting or plastic elongation is due to a separation of adjacent collagen fiber attachments within the connective tissue meshwork.[11,15]

The availability of methods to increase the extensibility of these tissues should make ROM and stretching exercises more effective in improving the mobility of affected joints. However, according to Lehmann,[12] further information is needed to identify the most effective method applicable. We believe our results have provided some of that information.

From this experiment, we have learned the rate of temperature decay following 3 MHz ultrasound treatments. From these data, we have determined the time frame for which heat and stretch therapy will be the most effective, and have labeled this the "stretching window."

Vigorous heating is considered a raise in the temperature >3°C above baseline temperature.[4,13] It is not feasible to put an exact time on temperature decay that will apply to all people and all situations. However, we have come up with what appears to be an accurate average time period to use with 3 MHz ultrasound.

In our study, the temperature was raised 5°C. If, for example, a clinician performed ultrasound that raised the temperature 5°C, and then applied a stretch, the critical "stretching window" would last, on average, only 3.3 minutes after the termination of the ultrasound application. If the temperature were only raised 4°C,

Ultrasound Rate of Heating Per Minute

Intensity (W/cm²)	1MHz	3MHz
.5	.04°C	.3°C
1.0	.2°C	.6°C
1.5	.3°C	.9°C
2.0	.4°C	1.4°C

the stretching window would be open less than 2 minutes. This time period can be increased by applying the stretch during the ultrasound treatment.

The Table shows the rate of heating during ultrasound treatments.[5] By using this table, one can estimate how long it takes muscle to reach a chosen temperature during 3 MHz continuous ultrasound. If, for example, the clinician applied ultrasound at 1.5 W/cm², on average, an increase of 5°C would take 5.5 minutes. However, at this intensity, an increase of 3°C would take place at 3.3 minutes into the treatment. If the clinician applied a stretch at this point and held it until the tissue temperature reached 5°C over baseline, the stretching window would have increased over 2 minutes in length. Therefore, when the tissue temperature is raised 5°C, the stretching window lasts an average of 3.3 minutes using the heat-then-stretch technique, and 5.5 minutes using the stretch-while-heating-and-cooling technique.

It is important to point out that we studied 3 MHz temperature decay, instead of the more popular 1 MHz frequency. Our reason for this is that the 3-MHz frequency is absorbed superficially and is ideal for treating structures that lie within 1 to 2 cm deep.[18] Many adhesive conditions lie <2 cm below the skin's surface. The 1-MHz frequency is used for treating areas up to 5 cm below the skin.[18] The possibility exists that temperature decay might be slower following 1 MHz ultrasound since the deeper muscle temperature is higher to begin with, and the additional tissue thickness may serve as a barrier to cooling. A further investigation could replicate our study, but measure temperature decay of 1 MHz ultrasound. This might reveal the stretching window for treating deeper conditions, such as piriformis syndrome.

Another point to consider is that our data were obtained from temperatures recorded in muscle; therefore, our stretching window may not apply to less vascular structures. Not all connective tissues are alike, and the possibility exists that their heating and cooling rates may vary. For example, it is believed that tendon, since it is a dense substance, will heat faster than muscle.[18] Because it is less vascular than muscle, the possibility exists that tendon may cool at a slower rate than muscle, but this has not yet been tested in humans. Future researchers could test the rate of temperature decay in human tendon, to see whether it differs from muscle and similar connective tissue. However, since muscle is less dense than tendon, it may yield more to heat and stretch. Therefore, we feel that if the ultrasound unit is applied to the musculotendinous junction, our stretching window has merit.

Past research has shown that ultrasound is effective in heating collagenous tissue.[2,3,7] We have uncovered a treatment window regarding stretching of superficial connective tissue structures (<2 cm deep) following ultrasound therapy. This can serve as a guideline for when optimal stretching should occur following ultrasound. This will enable clinicians to effectively increase joint ROM for adhesive capsulitis, tendinitis, and joint contractures. We feel that our research has revealed an effective technique for ultrasound use when increased extensibility of collagen tissue is desired.

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