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A New Look at Old Principles of Ultrasound Application

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A NEW LOOK AT OLD PRINCIPLES OF ULTRASOUND APPLICATION

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This Independent Study Report, submitted by Jeffrey S. Haney in partial fulfillment of the requirements for the Degree of Master of Physical Therapy from the University of North Dakota, has been read by the Chairperson of Physical Therapy under whom the work has been performed and is hereby approved.

(Chairperson, Physical Therapy)

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CHAPTER 1. INTRODUCTION

Therapeutic ultrasound is one of the more common Physical Therapy modalities utilized in the treatment of musculo-skeletal disorders. Ultrasound is generally regarded as an effective treatment for the selective heating of deep, soft tissue structures. In fact, ultrasound appears to be rapidly becoming the modality of choice among Physical Therapists and other health care professionals because of it's relative ease of application, it's efficiency, and few contra-indications for treatment.

Therapeutic ultrasound is by no means a new treatment concept. Pohlman and associates(1) first utilized ultrasound for the treatment of sciatica in 1938. Many of the early treatment applications and experimentation of ultrasound occurred in Europe, with ultrasound first used in the United States in the 1950's.(2) Since then, there have been numerous studies and research regarding the biomechanical principles of ultrasonic application as well as the effectiveness of ultrasonic treatment.(3,4)

Current treatment concepts and application principles can be traced to earlier studies, and many application techniques have not changed significantly over the years. However, there appears to be recent literature which challenges some of the long-held treatment principles and application techniques of therapeutic ultrasound, especially within the areas of effective coupling media and phonophoresis, which is the application of ultrasound with the use of a topical pharmaceutical agent. In addition, there also appears to be controversy regarding certain contra-indications to ultrasound, such as the use of ultrasound over the growth centers of bone.(5,6) Therefore, this paper will review ultrasound application principles regarding the efficacy of ultrasound transmission by various coupling media, phonophoresis, and contra-indications of ultrasound treatment.

CHAPTER 2. APPLICATION PRINCIPLES AND COUPLING AGENTS

Ultrasound is defined as a form of acoustic vibration that is inaudible to the human ear (greater than 17,000 Hz).(7) In clinical generators, ultrasound is produced by the reverse piezoelectric effect where a high frequency alternating electric current (60 Hz) is applied to a crystal surface, generally made of quartz or other synthetic material. The alternating occilations produced by the crystal's response to the current produces ultrasonic waves. For therapeutic purposes, ultrasound is generally utilized at .8, 1 and 3 megacycles (MHz or one million cycles per second).(7) The velocity of sound is directly proportional to the wavelength and the frequency ($v = fw$), conversely as the frequency increases, the wavelength decreases. The velocity of sound in water at ambient room temperature is reported to be 1500 m/sec.(7) Therefore, if the frequency of ultrasound is 1 MHz, the wavelength would be approximately .15 cm. At 3 MHz, the wavelength would be approximately .05 cm. The depth of ultrasound penetration is reported to be indirectly proportional to the frequency, with 1 MHz frequencies having a depth of penetration of approximately 5 cm and 3 MHz frequencies penetrating approximately 1 cm.(8)

In human tissues, the propagation of ultrasound is dependent on two factors: absorption and reflection of the ultrasound energy.(7) Bone is reported to absorb 10 times more ultrasound than muscle tissue.(7) Bone also absorbs significantly more ultrasound energy than subcutaneous fat.(7) Bone is also reported to reflect a significantly greater degree of ultrasound energy as compared to soft tissue.(7) Therefore, the greatest degree of conversion of ultrasound energy into heat is reported to occur at the bone interfaces.(7)

Two styles of ultrasound application have been suggested: a stationary method(8), where the soundhead is held in one position over the area to be treated, and a stroking technique, where the soundhead is moved in slow, circular or longitudinal movements. The stationary technique is no longer recommended because it may produce a rapid, localized rise of tissue temperature ("hot spot") which may be excessive.(7) Secondly, Dyson(9) has reported that this technique of application may also produce standing waves which have been shown to damage the endothelium of blood vessels, leading to clot formation.

Because of the unique transmission properties of therapeutic ultrasound, a coupling medium is essential to efficiently transmit the energy. Because ultrasound energy does not travel well through air, a coupling medium is required to eliminate air spaces between the transducer head and the tissue to be treated. The coupling medium also serves as a lubricant during contact application. Several various coupling media have been used for ultrasound transmission including water, mineral oil and ultrasonic gels.

One of the first to investigate the effectiveness of ultrasound transmission through various coupling media were Reid and Cummings(10) in 1973. They reported that ultrasonic gel transmitted ultrasound most effectively, followed by glycerin, degassed water, and mineral oil. A further investigation performed by Reid and Cummings(11) in 1977 reported similar findings with ultrasonic gel transmitting 72% of the ultrasound energy. Glycerol was reported as an acceptable substitute. Water and liquid paraffin (mineral oil) were next in decreasing order of efficiency. Although mineral oil was noted to be a commonly used transmitting agent, it was found to transmit only 19% of the ultrasound energy.(11)

Warren et al(12) reported in 1976 that there was not a significant difference in wave transmission by the commonly used coupling agents, except for hydrocortisone ointments which had lower transmission properties. This investigation also suggested that the pressure variations between the transducer and the contact surface actually produced greater differences in transmissivity than the coupling agents themselves.(12) Griffin(13) also investigated the transmission capabilities of coupling agents in 1979 and compared water, glycerin and mineral oil and simulated an immersion type technique. The results of this investigation suggested that the wave transmission in water was significantly better than other nonaqueous liquids.

More recently, in 1986, Balmaseda et al(14) compared the transmissivity of different coupling media by comparing two specific criteria: the absorption of ultrasound by the coupling medium itself (which resulted in power attenuation), and the impedance match between the coupling medium and the sound head (which effects the percentage of power reflected back to the ultrasound source). They reported that mineral oil and water displayed similar transmission properties with a large degree of attenuation and poor acoustic impedance match with the transducer head. Ultrasonic gel and silicon offered a smaller degree of attenuation and better impedance match, although the silicon was not as efficient as the water, mineral oil or ultrasonic gel.

The immersion technique of ultrasound, in which treatment is given with both the transducer and limb submerged in water, has been proposed as a more effective treatment technique when treating bony prominences or joints with limited soft tissue covering.(15) However, both old and newer studies have suggested that the immersion technique may not be as effective as the contact method. Early investigation by Vaughn(16) in 1973, comparing the direct versus the immersion method in the treatment of plantar warts, suggested that although both methods were effective in the treatment of plantar warts, 83% of the lesions treated with the direct method were destroyed, while only 51% were destroyed with the immersion technique. A more recent investigation by Forrest and Rosen(17) in 1989 quantified the results of the immersion technique versus the contact technique utilizing a pig's extremity. The results suggested that the immersion technique heated deep tissue structures to the therapeutic range (104 - 113.9 F) while the immersion technique failed to heat to the therapeutic range.

In the clinical setting, ultrasound is often applied in conjunction with other superficial heating modalities such as hot packs or infrared. Because of this, questions have been raised regarding the effectiveness of ultrasound when performed before or following superficial heating. Lehmannn et al(18) attempted to determine whether pre-heating a skin surface with a hot pack would change the temperature distribution of ultrasound. They reported that as a result of hot pack application, the highest temperature rise was measured in the skin surface and a slight elevation was noted in the subcutaneous tissue.(18) As soon as ultrasound was applied, the highest temperature measured was at the bone-muscle interface, and the skin temperature dropped significantly and then displayed a gradual increase. Therefore, it was suggested that preheating the skin surface prior to ultrasound treatment would not adversely affect the deep heating properties of ultrasound. Miller et al(19) reported in 1979 that ultrasound performed following the application of hot packs provided a greater elevation in muscle temperature at a depth of 5 centimeters, than ultrasound given alone, or ultrasound given prior to hot pack application. At a depth of 1 centimeter however, there was no significant difference between mean temperature changes when comparing the three treatment techniques.

CHAPTER 3. PHONOPHORESIS

Phonophoresis, or the use of therapeutic ultrasound to deliver certain pharmaceutical agents transdermally, has been suggested as an effective technique in the treatment of various musculo-skeletal conditions such as tendinitis, bursitis or epichondylitis.(20,21) One of the first to examine this application technique are reported to be Fellinger and Schmid(22) in 1954. They reported that ultrasound could carry hydrocortisone across an avascular membrane in the treatment of polyarthritis.(22) Newman et al(23) reported in 1958 that hydrocortisone delivered by injection and phonophoresis was superior to hydrocortisone injection alone. Mune(24) reported similar findings in 1963 that suggested there were beneficial results when ultrasound treatment was given following injection.

Griffin and associates(25,26,27) performed a series of experiments in the 1960's that investigated phonophoresis. In 1963, Griffin et al(25,26) reported that ultrasound enhanced the penetration of hydrocortisone into swine's muscle and nerve tissue. Although these studies did suggest an increased penetration of hydrocortisone with ultrasound, they also reported increased tissue damage which was attributed to the high intensities utilized (1 watt per centimeter square and 3 watts per centimeter square). It was also suggested that the use of a stationary ultrasound application for a duration of 5 minutes may also have contributed to tissue damage. Because of these harmful effects, this treatment technique is not recommended for use on humans.

Additional investigation by Griffin and Touchstone(27) in 1968 suggested that lower ultrasound intensities (.1 watt per centimeter square and .3 watts per centimeter square) also enhanced the penetration of hydrocortisone. However, these treatment applications are also not recommended for humans because of the extremely long durations utilized (51 minutes). Further investigation by Griffin and Touchstone(28) in 1972 of cortisol phonophoresis into swine tissue suggested that both higher and lower frequencies of ultrasound enhanced cortisol penetration to a greater degree than the standard clinical frequency of 1 MHz.

Griffin et al(29) also investigated the effectiveness of ultrasound driven hydrocortisone applied at therapeutic dosages to 102 ambulatory arthritic patients. The results suggested a greater percentage of improvement of the phonophoresis patient as compared to patients treated with ultrasound alone.

Levy et al(30) reported that ultrasound could temporarily and reversibly alter the permeability of skin for both hydrophilic and lipophilic drugs. Davik et al(31) reported in 1988 that tritiated cortisol penetration was enhanced with the use of ultrasound at normal therapeutic dosages (870 KHz at an intensity of .5 watts per centimeter square for 8 minutes) when applied to the joint regions of dogs. Both 5% and 10% cortisol were used in this investigation with the results displaying a marginally significant difference between concentrations.

An earlier investigation by Klienkort and Wood(32) in 1975, reported that 10% hydrocortisone was more effective than 1% hydrocortisone during phonophoresis of various inflammatory musculo-skeletal disorders.

Although hydrocortisone appears to be one of the more commonly investigated phonophoretic products, there have also been a number of experiments that have studied the effectiveness of phonophoresis with anesthetic agents. As early as 1964, Novak(33) reported that ultrasound could enhance the transmission of Lidocaine through intact skin. In 1966, Cameroy(34) reported that ultrasound could enhance the use of Carbocaine as a local anesthetic. More recently, Moll(35) reported in 1977 that Lidocaine and Decadron applied with ultrasound appeared to be an effective means of local anesthesia. McElnay et al(36) reported anesthetic results of the percutaneous absorption of Lignocaine applied with ultrasound treatment.

Michlovitz(37) and others have reported the depth of penetration of phonophoresed substances can be up to 5 or 6 centimeters when utilizing therapeutic ultrasound parameters. Griffin(38) indicates that a depth of penetration of up to 10 centimeters can be achieved while utilizing lower ultrasound frequencies. Therefore, phonophoresis would appear to offer a more effective treatment alternative to other forms of transdermal drug delivery, such as iontophoresis, if one is primarily concerned with the depth of drug penetration, as most references will report a 1 centimeter penetration of iontophoretic applications.

Although general treatment parameters have been reported for the application of phonophoresis,(38) there appears to be a significant degree of variation of application methods in the clinical setting. Edwards(39) identifies four methods of phonphoretic application of hydrocortisone utilized in clinical settings. The centrifuged method is reported as a pharmacy mixed hydrocortisone cream and ultrasonic gel which is then applied to the area to be treated. The "smear" method involves the application of hydrocortisone cream to the skin followed by the application of ultrasonic gel with both substances then "smeared" together and used as the coupling agent for ultrasound treatment.

The third method described by Edwards(39) is that of the "pure" method in which pure hydrocortisone cream is applied to the skin and used as the coupling agent itself. The final method is reported to be the "invisible" method in which a small amount of hydrocortisone cream is rubbed on the skin over the area to be treated. This is followed by the application of ultrasound by standard treatment applications with ultrasonic gel utilized as the coupling agent. It is not currently clear which method of application is most common, although Edwards(39) reports that the smear method is a "popular" treatment style. Quanitative comparison of these various techniques has not been reported.

Recent investigations have challenged the actual effectiveness of ultrasound transmission through commonly used phonophoresis media.(40,41) In 1985, Benson and McElnay(40) reported a significant variation in the coupling coefficients of the various media that exist. The majority of media commonly utilized for phonophoresis were reported to be poor transmitters of ultrasound. Cameron and Monroe(41) reported similar findings in 1992. They also reported that 1% and 10% hydrocortisone were extremely poor transmitters of ultrasound energy but were found to be the most commonly used agents for phonophoresis according to a limited survey prior to their study.

Whether phonophoresis is commonly utilized in most clinical settings is not clearly known. However, Cameron and Monroe's(41) limited survey prior to their investigation suggested that the majority of clinical practises(77%) reported using phonophoresis. Additionally, Pottenger and Karalfa's(42) survey in 1989 tended to reinforce the fact that the vast majority of clinics utilize phonophoresis on a regular basis.

CHAPTER 4. CONTRA-INDICATIONS

Although therapeutic ultrasound is generally regarded as a fairly safe and effective treatment technique, there are certain conditions and precautions that should be observed when using ultrasound. Most references will generally identify several similar ultrasound contra-indications.(5,6,43) First, therapeutic ultrasound should not be used over or near the presence of a cardiac pacemaker because of possible malfunction due to the absorption of ultrasonic energy.(6,43) However, Griffin and Karselis(6) report that ultrasound can be used in body areas other than the thoracic region in a patient with a cardiac pacemaker because of the localized beaming properties of ultrasound.

Also, therapeutic ultrasound should not be used over or near a known or suspected malignancy.(6,43) It is felt that because of the increase heating ability of ultrasound, local blood suppy near the malignancy could tend to increase the growth of the tumor. Ultrasound is also contra-indicated over a pregnant uterus(5,6,43) because of the possility of heating the fetus, and also to avoid cavitation, which can occur in any type of fluid medium in the presence of ultrasonic energy. Lehmann(5) also reports that ultrasound should be applied with caution in the area of the spinal cord that has been treated by laminectomy because of the possible spinal cord heating or cerebrospinal fluid cavitation. However, the facet joints adjacent to this area could still be treated with ultrasound because of the excellent beaming properties of ultrasound energy.(5) Finally, as for any type of heating modality, ultrasound should not be used over areas of decreased circulation because of possible tissue damage from the body's inability to disperse the heat produced by ultrasound.(6,43)

The use of ultrasound over growing bone has been more controversial than some of the other contra-indications of ultrasound treatment. Griffin and Karselis(6) report that ultrasound should not be used on a regular basis over or near growth centers of actively growing bone as absorption of ultrasound energy in these areas may disrupt normal growth. However, Lehmann(5) states that at therapeutic dosages and without exceeding the pain threshold, growth disturbances have not been observed. Michlovitz(43) reports that epiphyseal areas in children should be exposed only minimally to ultrasound. Additionally, in a review of current ultrasound application concepts by Gann(44) in 1991, ultrasound was not recommended for use over growing epiphyses.

Early studies performed in the 1950's did suggest that ultrasound had a detrimental effect on bone growth. In 1953, Deforest et al(45) investigated the effects of ultrasound over the tibial epiphyseal region of dogs and rabbits. The dosages used for this investigation were from 5 watts for 5 minutes to 10 watts for 10 minutes. Treatment durations were from one to twenty-one treatments. A moving technique was utilized with water as the coupling medium. The results of this investigation indicated some form of damage in nearly all of the animals tested, with the severity of injury varying from rarefaction to slipping of the epiphyseal line and even fractures. Detrimental changes were seen when a minimal dosage of 5 watts for 5 minutes was given for one session.

In 1954, Bender et al(46) reported the effect of ultrasound on dog's femurs 6 centimeters above the knee joint. Dosages used were from 5 to 20 watts for 2 to 5 minutes. One to twenty-five treatments were given with a stationary technique, utilizing mineral oil as the coupling medium. The temperature elevation was monitored within the cortex and bone marrow, with temperature rise varying from 6.32 C in the bone marrow and 12.28 C in the cortex at lower dosages and up to 49.15 C at moderate dosages. The results suggested that no significant histologic changes were observed in the cortices at all dosages. However, the bone marrow demonstrated hemorrhage at lower dosages and osteogenesis and fibrosis at higher dosages.

Ardan et al(47) performed similar investigations in 1954 and reported similar, but less extensive findings. Fairly high dosages were used (15 and 20 watts) for 5 minutes but these were only applied during a series of 3 exposures within 5 minutes of each other. It was acknowledged that although the wattage use for this experiment was within the limits for human therapy, use of the stationary technique concentrated ultrasound energy in one spot and therefore, the technique used in this study was not advised for clinical use. Ardan et al(48) performed additional experimentation in 1957 that attempted to stimulate bone repair with use of relatively high intensities, and a massaging application with mineral oil used as the coupling agent. They reported that stimulation of bone healing was not seen, but that defects, including medullary fibrosis and necrosis of bone, were noted. Vaughen and Bender(49) reported no significant detrimental findings in 1959 with the use of ultrasound at therapeutic dosages and utilizing clinically comparable techniques over the tibial epiphyseal regions of rabbits. Dosages were at 1 watt per square centimeter for 5 minutes, 5 days a week, for up to 18 weeks. No significant detrimental findings were reported at these dosages.

Limited information regarding the use of ultrasound over growing bone was reported in the literature following these early experiments in the 1950's. However, in 1982, Dyson and Brookes(50) reported that ultrasound actually accelerated and modified bone repair in fibular fractures of rats. Pulsed ultrasound was utilized at .5 watts per centimeter square for 5 minutes during four consecutive days for several weeks of treatment. Both 1.5 and 3.0 MHz frequencies were used in this study.

CHAPTER 4. DISCUSSION

Therapeutic ultrasound has been proven to be an effective technique for the selective, deep heating of soft tissue structures. It has also been shown to be beneficial for it's non-thermal effects. Ultrasonic gel has been shown to be the most effective coupling agent for ultrasound transmission and is the recommended agent of choice.(10,11) Although mineral oil had previously been a commonly used ultrasound coupling agent, it has been shown to transmit ultrasonic energy poorly(11) and is not recommended for use as a coupling agent. The submersion technique of ultrasound application can be used as an alternative technique when treating areas of the human anatomy that have bony prominences.(15)

The use of a stationary application technique is not recommended in the clinical setting because of probable adverse effects.(9) The use of heat prior to, or following ultrasound application, is not quite as clear. Early reports by Lehmann et al(51) suggested that the temperature of the coupling medium may affect the temperature distribution of ultrasound. Mineral oil at 21 degrees C. was found to cause the highest temperature rise close to the bone. However, when ultrasound was applied with mineral oil at 24 degrees C., far higher temperatures were attained in the superficial tissues than in areas close to the bone. Degassed water was also used in this study with no differences noted in the temperature distribution at either 21 degrees C. or 24 degrees C. The authors concluded that the difference between the two media may be explained by the fact that water has a higher thermal conductivity and greater specific heat. However, studies performed several years after this investigation have indicated that mineral oil is a poor transmitter of ultrasound(10) which may also help explain some of the earlier temperature distribution differences between water and mineral oil. In addition, more recent experiments by Lehmann et al(18) indicated that pre-heating a skin surface did not adversely affect the deep heating properties of ultrasound.

Gann(44), in her review of current ultrasound concepts, indicates that because ultrasound heats tissue through the conversion of mechanical vibration, and not by conduction or convection, increasing superficial tissue temperature will not alter the thermal effects of ultrasound on deeper tissue. Gann(44) also indicates that pre-heating a coupling agent prior to ultrasound would have similar consequences. A warm coupling agent would heat the superficial tissues by conduction but would not alter the deep heating ability of ultrasound. Therefore, it would appear that pre-heating ultrasound coupling agents, or utilizing superficial heating modalities prior to ultrasound treatment, does not adversely affect the efficacy of ultrasound treatment.

Phonophoresis appears to be a commonly used treatment technique,(41,42) and studies have demonstrated that certain pharmaceutical products can be applied effectively.(40,41) However, there is reported to be significant variation regarding the actual technique used for phonophoresis in the clinical setting.(39) The "invisible" method of application is suggested by Edwards(39) as the preferred choice when performing phonophoresis. When using this method, a very small amount of solution is required, limiting the cost of treatment. Also, the phonophoresed substance is applied only to the involved area, whereas other methods of application ("smear method") may expose uninvolved areas. Additionally, Edwards(39) suggests that the depth of penetration may be enhanced by first rubbing the phonophoresed substance into the skin. Unfortunately, research comparing the various clinical methods of phonophoresis application does not currently exist. Therefore, effective research to standardize treatment application techniques is required to quantify the efficacy of phonophoresis treatment.

Although phonophoresis appears to be a commonly used Physical Therapy treatment, the exact mechanism of drug penetration by ultrasound in not currently understood. In their review of drug delivery by phonophoresis, Tyle and Agrawala(22) suggest that enhanced drug penetration is thought to result from thermal, mechanical, and chemical alterations of biological tissue. Ultrasound is well known for its ability to cause deep, thermal effects in living tissue and these thermal changes have been suggested as a primary mediator of trans-dermal drug delivery.(22) Levy et al(30) suggest that hyperthermia may facilitate drug penetration by increasing cell diffusivity, increasing the solubility of drugs, and increasing vasodilation and blood flow. However, Tyle and Agrawala(22) report that controlled experiments are lacking that demonstrate whether heat alone can increase drug penetration.

Additionally, Davick et al(31) reported that the rate-limiting barrier to the dermal absorption of topically applied drugs is the stratum corneum, which is the outermost layer of the epidermis. Because ultrasound produces deep thermal effects via conversion and not convection or conduction, minimal increases of surface skin temperatures occur during normal application.(30) Because of this, Levy(30) suggests that thermal changes of the skin are not likely to cause dramatic changes in skin permeability when using phonophoresis.(30) Therefore, non-thermal effects of ultrasound appear to have a significant role in drug penetration by phonophoresis. Recent studies performed by Dyson(52) would support these findings.

One non-thermal factor that may enhance drug penetration by ultrasound is cavitation, which is the formation and pulsation of gaseous or vapour-filled bubbles in fluids.(9) Tyle and Agrawala(22) suggest that cavitation may cause mechanical stress, temperature elevation or enhanced chemical reactivity, which may facilitate drug transport. Another non-thermal factor that may enhance drug penetration by ultrasound is acoustic streaming, which is defined by Dyson(9) as a steady circulation of fluid induced by radiation forces. Dyson(9) reports that acoustic streaming may produce high viscous stresses which can change cell membrane permeability. Levy et al(30) have also suggested that ultrasound can reversibly enhance the permeability of synthetic membranes. Further research is required to establish the exact mechanisms of drug penetration by phonphoresis.

Finally, contra-indications of ultrasound treatment appear to be consistent in most references except for the use of ultrasound over growing bone.(5,6) Early studies, which utilized high dosages and stationary application techniques, did demonstrate detrimental effects to growing bone.(45,46,47,48) However, when therapeutic dosages and techniques are used, reports have indicated that ultrasound did not cause detrimental effects to growing bone.(49) Also, recent studies have indicated that pulsed ultrasound also does not appear to negatively affect growing bone.(50) Further research is required to conclusively document whether ultrasound, or what type of ultrasound (continuous or pulsed), is safe in the presence of growing bone. Until that time, ultrasound should be used with caution over these areas with low intensities and short durations of treatment.(5)

Conclusion

Therapeutic ultrasound has been shown to be an effective modality for the treatment of numerous musculo-skeletal disorders. The efficacy of ultrasound treatment is dependent upon the use of safe and effective application techniques. Further research to quantify the efficacy of various ultrasound application principles is required to standardize clinical application techniques.

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