Microwave diathermy

G.C. Goats, PhD, MCSP
Department of Physiotherapy, The Queen's College, Glasgow, UK

Introduction

Microwave and shortwave radio frequency radiation is used clinically to heat tissue situated deep in the body and minimize the coincidental rise in skin temperature seen with other forms of therapeutic heating. Microwave radiation is defined as that with a frequency of 300 MHz–300 GHz, which lies on the electromagnetic spectrum between radio frequency and infrared radiation.

Microwave diathermy units operate at a frequency higher than that used for shortwave diathermy and this confers significant operational advantages. Microwave radiation is radiated as a beam from an antenna and absorbed by water-rich tissues 7000 times more effectively than shortwave radio frequency energy[1]. The latter must be coupled to the patient by a capacitor or an inductor[2], whilst microwave energy is radiated as a beam from an antenna. A microwave beam can be narrowed to allow small areas to be treated accurately, is highly directional, and can be aligned rapidly.

A microwave diathermy unit with antenna (*Figure 1*) is easy to use and robust, although not found as frequently in clinics as shortwave therapy units. The common indications for microwave therapy include soft tissue lesions of traumatic origin, degenerative or chronic arthropathy and some localized infections[3].

Equipment

Microwave diathermy units and domestic microwave ovens usually operate at the internationally agreed frequency of 2450 MHz (2.45 GHz). Some clinical devices, particularly in the United States, emit radiation with a frequency of 915 MHz. Although these are less common in Europe, energy at this lower frequency is absorbed more efficiently and uniformly within the tissues[4–6] and lies close to 750 MHz, the optimum frequency for therapeutic heating[7].

The power output of therapeutic microwave units can approach 250 W although the maximum in practice is limited by the design of the antenna. Small antennae and reflectors are rarely capable of radiating safely more than 25 W and protective circuitry within the generator prevents this limit being exceeded[8]. Domestic microwave ovens often deliver 600–1000 W.

Microwave energy is generated by an electronic device known as a magnetron. The magnetron was invented in 1938, but did not find civilian application until 1945 when the classified military role in airborne radar became less important. Some apparatus is designed to emit a pulsed output that causes less heating and should promote non-thermal interactions between electromagnetic energy and the tissues[9].

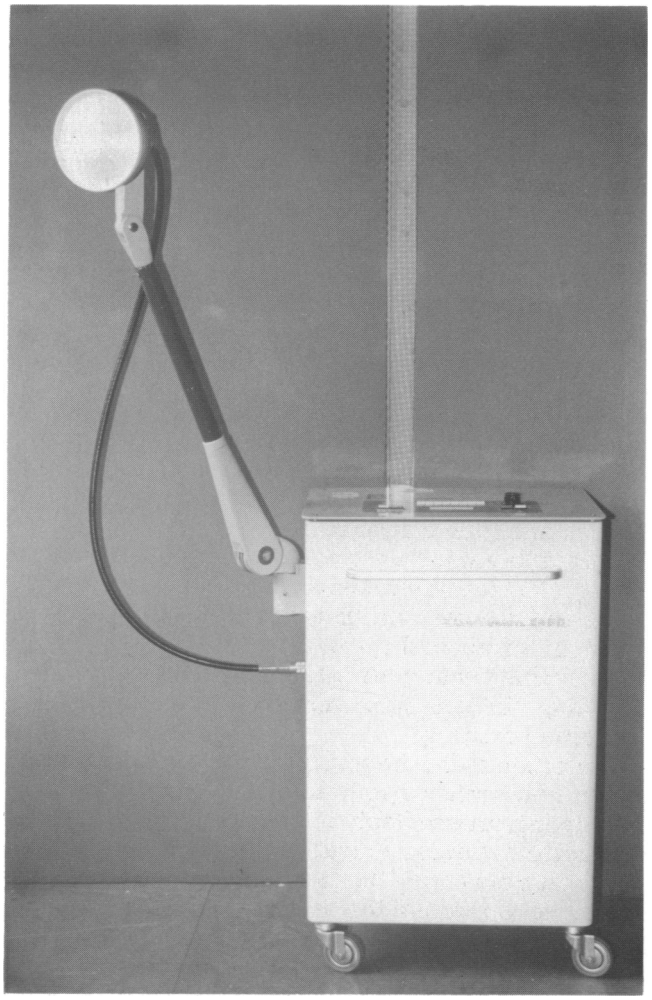

Figure 1. A microwave diathermy unit with antenna

Address for correspondence: Dr G.C. Goats, Department of Occupational Therapy and Physiotherapy, University of East Anglia, Norwich NR4 7TS

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0306-3674/90/040212–07

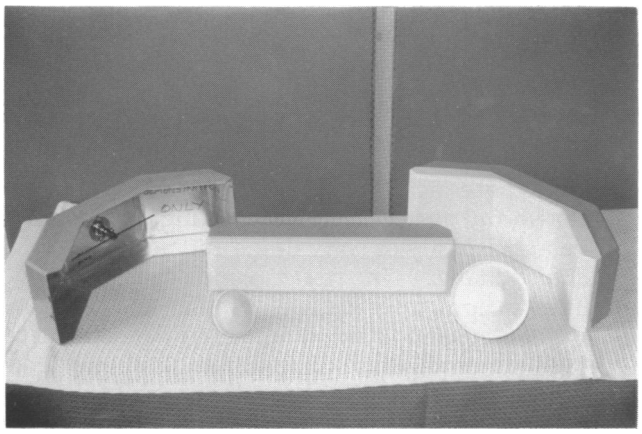

Figure 2. Non-contact microwave applicators. Note that one applicator (far left) is disassembled to reveal the antenna and reflector

The applicators consist of an antenna element backed by a reflector and enclosed within a plastic case, one face of which is transparent to microwave energy. Non-contact applicators (*Figure 2*) are common in the UK and continental Europe but not considered as safe or effective as the direct contact applicators preferred in North America[7]. Direct contact applicators release less stray radiation and produce a more uniform pattern of heating deep in the tissues[10], especially when cooled by a flow of liquid or air that limits any increase in skin temperature[11, 12]

Statutory regulations exist that detail the specifications controlling the manufacture or importation of microwave diathermy units within the UK[13].

Interactions between microwaves and tissue

Microwaves are electromagnetic radiation and as such will be reflected, refracted or transmitted at boundaries. The most serious hazard arising from reflection is the development of a standing wave in which a static field pattern is produced within the tissues due to interference between the incident and reflected beams. Excellent reflectors of microwave energy include interfaces between fat and muscle, bone and muscle, and between tissue and the metal used in orthopaedic surgery. Intense and highly undesirable heating can occur in these regions[1, 14, 15], resulting in an unpredictable and non-uniform pattern of heating[16].

Reflection at the air-skin interface occurs frequently when non-contact applicators are used, occasionally generating unacceptably intense stray radiation. The efficacy of reflection of microwaves at such interfaces is determined by the relative conductivity and dielectric constant of the tissues, whilst the pattern of reflection depends upon the geometry and size of the structures affected. Those which are large compared to the wavelength (approximately 1 mm) act as good reflectors.

Thermal mechanisms

Microwave energy is absorbed in the tissues principally by the movement within the electromagnetic field of dipolar water molecules and of ions in aqueous solution. This vibrational energy is heat. Furthermore, the dielectric nature of the tissues allows heat production by the relaxation of polar macromolecules, and closely associated water molecules, from the distortions caused by a strong electromagnetic field. Relaxation energy is also released as heat. Hence the tissue warms by the conversion of energy at one frequency to that at another[14]. The rate of energy absorption by tissue can be calculated from the conductivity and dielectric constant.

The distribution of heat within the tissues caused by the passage of microwaves depends upon the properties of propagation and absorption possessed by the irradiated tissue and is, of course, superimposed upon pre-existing temperature gradients within the body[17]. Tissues of high water content characteristically absorb microwaves strongly, and muscle[18], fluid filled organs such as the eye, joint effusions and surface water are heated preferentially[1].

The depths to which microwave energy penetrates (expressed as the distance in which the field strength has fallen to 37% of the incident value) varies according to tissue and frequency. Microwaves with a frequency of 2450 MHz penetrate 1.7 cm in muscle and skin, and 11.2 cm in fat and bone, whilst at 915 MHz these values increase to 3.04 cm and 17.7 cm respectively[8]. Experiments with dead pig tissue demonstrate that at 2450 MHz, subcutaneous tissue with a depth greater than 2 cm warms excessively and will reduce the heating of muscle, although at 900 MHz, much less energy is deposited in the superficial layers. Subcutaneous tissue 4 cm deep reduces the heating of muscle at both microwave frequencies[19]. Clinical studies have confirmed these findings, although frequency-dependent differences in temperature distribution are much reduced by the forced convection of the circulation[5] and this may explain the apparent therapeutic effectiveness of 2450 MHz radiation[20].

The final temperature distribution is affected greatly by blood flow, which can in turn be modified by microwave diathermy[20, 21]. Superficial tissues moderately heated, achieve a maximum temperature within five to ten minutes, after which local vasodilation prevents further warming[22]. Contact applicators incorporating a system of circulating coolant restrict this rise in skin temperature to acceptable levels and permit more vigorous heating of the deep tissues[23].

Non-thermal effects

Pulsed microwave diathermy operates by delivering a train of short pulses of high intensity microwave radiation. Whilst this causes the temperature of the tissues to rise momentarily, between pulses cooling occurs by the action of the forced convection of the circulation. This treatment is said to promote the true

non-thermal effects of electromagnetic irradiation, although some effects might be explained by the brief temperature rise generated with each pulse[9]. This argument also applies to the action of pulsed shortwave therapy[24]. When applied at similar mean output, no difference was found between the therapeutic effects of pulsed or continuous microwave treatment[22].

Some authors remain sceptical of a non-thermal effect of microwave radiation on biological systems[8], although evidence is accumulating to refute this view[25]. Summaries of Soviet and Eastern European studies, not readily available in the West, report many biological effects at levels of exposure less than $10\,mW.cm^{-2}$, with a significant influence seen at $150\,\mu W.cm^{-2}$ or less[26].

The animal subjects studied in this latter group would experience little heating but responded with changes in body weight and fertility; altered endocrine activity, electrolyte balance and EEG; inhibition of phagocytosis by neutrophils[27]; and an affect upon neurone membrane function[28]. Many of these observations are verified in the West and have informed the discussion setting current safe exposure guidelines. The frequency-dependent nature of these effects tends to obscure their relevance to electrotherapy practice[14].

Any non-thermal effect must be caused by an interaction between the imposed electromagnetic field and specific types, or assemblages, of receptor molecules. Weak inter- and intramolecular bonds, reversibly disrupted by the field, will allow these structures to change shape and exhibit altered biological activity[29]. Other events such as the homogeneous orientation of large molecules in the field (including the much reported, and of doubtful significance, 'pearl-chain formation'[9,30]) and induction of transmembrane potentials sufficient to alter ion flow, are highly unlikely except at very high field strengths[31]. Recent research indicates that exposure to microwaves may isomerise amino acids, an event with serious implications for protein metabolism[32].

Evidence for a direct effect of the electromagnetic field upon the shape of biologically active molecules, often referred to as the 'electroconformational coupling model', is drawn in part from work with Na^+/K^+ ATP-ases. These molecules occur within the cell membrane and appear to receive energy directly from an applied oscillating electric field. The energy appears subsequently as an enhanced rate of Na^+ and K^+ pumping across the cell membrane. This mechanism is fundamental to many cellular activities, is both frequency and field intensity dependent, and requires that the energy of the weak electric field is amplified at the cell membrane to exert an effect[33]. Clearly, if this enzyme system can be affected directly by an electromagnetic field, then so might others having many and various biological effects.

Physiological effects and therapeutic applications

Diathermy, whether achieved using shortwave radio frequency or microwave energy, exerts physical effects and elicits a spectrum of physiological responses common to both. Differences will tend to be qualitative and dependent upon the pattern of heating induced within the tissue.

The thermal effects of diathermy upon biological tissue reflect closely the more general effects of heating. These include increased plasticity of connective tissue and a potential for correcting contractures, decreased viscosity of body fluids and improved joint mobility, changes in nerve conduction velocity, modified output from muscle spindles and decrease in muscle spasm. Pain is reduced by enhanced removal of nocigenic compounds and relief of pressure of interstitial fluid together with facilitation of the 'pain gate' mechanism. Increased metabolic rate and accelerated growth, together with vasodilation in certain tissues, will assist the resolution of inflammation. These therapeutic effects are discussed at length elsewhere[1–4,35].

One should also remember that microwave diathermy is used to induce hyperthermia in the treatment of skin conditions such as psoriasis[36] and to slow the growth of malignant neoplasia. The highly directional nature of the beam facilitates accurate treatment of the latter with minimal side effects[37,38].

Vascular responses

A local rise in temperature usually produces vasodilation and an increase in blood flow. Elevated temperature appears to affect the calibre of small blood vessels by mechanisms as diverse as the reduced activity of sympathetic nerves, a direct action upon vascular smooth muscle, release of vasoactive compounds from tissue suffering thermal stress, increased concentration of metabolites and decreased oxygen tension in the tissues as a result of accelerated metabolic rate, and stimulation of a cutaneous axon reflex[1,39,40].

Studies investigating the effects of microwave diathermy have generally concentrated upon rate of blood flow in muscle. Significant increases in flow, measured indirectly using mechanical sensors, were observed after treatment at 60–80 W mean output for periods of one to 30 minutes. The rate of increase was greatest early in the treatment period[18]. Rate of blood flow in human muscle has also been estimated by monitoring the rate of washout of radioactive tracers such as Xe^{133}. Microwave irradiation of an unnamed muscle at 2.45 GHz, to the maximum tolerable temperature, was calculated to cause blood flow to rise, after a 12 minute delay, to $11.4\,ml.100\,g.min^{-1}$ compared to $2.9\,ml.100\,g.min^{-1}$ before treatment[41]. Similar experiments using the anterior musculature of the thigh in healthy subjects showed that pre-treatment flow was $2.6\,ml.100\,g.min^{-1}$, rising to approximately $32\,ml.100\,g.min^{-1}$ after irradiation at 915 MHz with coincidental skin cooling for 20 minutes at 40 W absorbed power[21]. Subsequent studies concluded that flow in heated muscle approaches $48\,ml.100\,g.min^{-1}$ once the threshold temperature of 42°C is achieved[42].

More complex vascular reflexes appear responsible

for the reduction in blood flow occuring in rested and non-heated muscle underlying heated skin[43], although exercised and heated muscle shows maximal vasodilation[44]. Cutaneous warming in one limb produces vasodilation in the contralateral extremity as well as a local response[45]. Some suggest that this phenomenon be employed to increase blood flow in vessels partially occluded by peripheral vascular disease and for which direct heating is contraindicated[46].

Joints and soft tissues

Limitation of range of movement at a joint often follows contracture of the periarticular connective tissue and shortening of other soft tissues crossing the joint line. Heat alters the viscoelastic properties of collagen and, at temperatures within the therapeutic range 41–45°C, exhibits viscous, rather than elastic behaviour. When stretched passively whilst hot, collagen remains elongated as it cools[47] and is less prone to rupture than tissue stretched without heating[48].

Microwave diathermy is reported to correct contractures of rectus femoris when combined with stretching[49], and by heating effectively structures that lie superficially, such as the interphalangeal and metacarpophalangeal joints[69], is likely to improve function in the hands. Deep structures such as the hip do not achieve therapeutically effective temperatures because microwave energy is dissipated in the thick subcutaneous tissues[50]. This reduction in force, needed to deform the soft tissues permanently, is accompanied by a decrease in the viscosity of synovial fluid and subsequent frictional stiffness[51].

Heat is often used in the treatment of the arthritides although it can activate the enzymes responsible for the destruction of articular cartilage in rheumatoid disease. This effect is most marked during mild heating between 39–41°C[52], whilst at temperatures approaching 45°C proteins are denatured and collagenase activity is diminished[53]. Experimental inhibition of the metabolic activity of animal synovial tissue by heat was achieved by microwave diathermy at 915 MHz. The microwave applicator was water-cooled and highly directional, allowing very localized irradiation. The coincidental vasodilation improved the penetration of anti-inflammatory drugs into the joint cavity[54].

Relief of pain and muscle spasm

Microwave diathermy can be used to reduce pain[1,3,34], although the narrow focus of many commercial applicators may render the treatment of diffuse lesions more difficult than with other methods of diathermy[2]. Clinical investigations of pain relief using microwave therapy are reported rarely although the mechanisms of heat-induced pain control are well understood. Vasodilation transports nocigenic compounds such as bradykinin and histamine from the tissues. Ischaemia resulting from muscle spasm is relieved[55] by the direct and predominantly inhibitory effect of heat upon those elements of the muscle spindle active in maintaining spasm[56].

Pain is also reduced by thermal activation of the 'pain gate' mechanism, in which cutaneous sensory information entering the spinal cord through the substantia gelatinosa takes precedence in transmission to the higher centres over activity in fibres conveying pain information. Thus analgesia is induced[55,57].

A descending pain control mechanism, mediated by endogenous opiate compounds, may make a lesser contribution to heat induced analgesia. This mechanism is explained fully elsewhere[55,58], but would rely for activation upon a degree of heating too vigorous and uncomfortable for routine use therapeutically.

Resolution of inflammation

Many authors consider that diathermy, judiciously applied, will assist the resolution of inflammation and promote healing[1,2,3,34,45]. The principal mechanism producing these effects is likely to be vasodilation, which facilitates the influx of material required for the healing process, efflux of metabolites and toxins, and improved drainage of the inflamed site with subsequent reduction in oedema. These effects of diathermy are described fully elsewhere[1,2,34,59] and the common indications for microwave diathermy are based largely upon experimental evidence gained using shortwave diathermy, modified with intelligent regard for the pattern of heating generated by each modality. The non-thermal effects of diathermy at various frequencies may indeed differ, although research has not advanced sufficiently in this area to allow definitive comment.

Few reports comment specifically upon the action of microwave therapy upon the resolution of inflammation. The rate of healing of radiolabelled haematomata, induced artificially in the muscles of pigs, was claimed to increase when exposed to 915 MHz microwave treatments twice daily at an output of 40 W. This caused the washout rate of radioisotope to accelerate as blood flow increased in response to a rise in tissue temperature to 42–45°C[60].

Patient safety

The contra-indications to microwave therapy include impaired cutaneous thermal sensitivity, ischaemia, local thrombosis or malignancy, metallic implants including pacemakers or other indwelling electrodes, pregnancy and recent radiotherapy. Tissues showing acute inflammation, infection or haemorrhage should not be treated, hearing aids should be switched off and, together with jewellery, removed from the field[3,34]. Structures poorly vascularized are unable to dissipate heat effectively and should not be treated. Such sites include the eyes and testes, which must be adequately screened using wire mesh goggles or shields respectively when treatment of adjacent tissues is planned. The ovaries lie too deep for microwave diathermy to cause undesirable heating but, in the absence of detailed knowledge of the

effects of such radiation, prudence directs that these organs are not irradiated[1].

The patient should be positioned to allow full relaxation in an environment in which adjacent metal fittings do not contribute to the formation of standing waves or stray radiation from incident or transmitted beams. The patient must understand the warning of the risk of burning which should be included with an explanation of the procedure. The skin must be exposed, dry and free from liniments or creams[61,62].

Occupational safety

The adverse effects of exposure to microwaves, such as cataract formation, appear to result primarily from altered thermal gradients within the body, and the case for a carcinogenic or teratogenic effect remains not proven[63–65].

The Medical Research Council considers that continuous exposure to microwave radiation at an intensity not exceeding $10\,mW.cm^{-2}$ is safe[61]. This recommendation is based upon previous studies made in the clinical environment by the UK National Radiological Protection Board and is derived from the Specific Absorption Rate (SAR) of microwave energy by the body. Therapists adhering to the simple safety guidelines set out below are unlikely to receive a dose of microwave radiation exceeding this limit[66], which is low when compared to the intensity of $100–200\,mW.cm^{-2}$ used therapeutically.

The guidelines informing the safe use of therapeutic microwave diathermy apparatus include the following. The operator should not remain within 1 m of the front or sides of an active applicator, or within 0.25 m behind, and should avoid accidental reflection of the beam from adjacent metal surfaces[13]. On the basis of field strength measurements, other authors recommend retreat to a distance of 1–2 m from apparatus operating in continuous mode and avoiding any exposure within a radius of 0.5 m[67]. Wire mesh goggles, which must be provided for the patient, rarely need to be used by the operator[13]. These guidelines are broadly similar to those governing the use of microwave diathermy in many other countries, although Australian reports, described comprehensively elsewhere[62], recommend that the minimum safe distance is 2 m from an active antenna. Non-contact applicators must be positioned carefully to achieve the same low level of stray radiation emitted by the direct contact applicators available in North America[68].

Conclusion

Microwave diathermy units, although less common in clinics than those operating at shortwave radio frequency, have an important role in physiotherapy and sports medicine. Microwave energy can be directed accurately and used to treat localized lesions vigorously without greatly affecting adjacent tissues. An appropriate choice of applicator and operating frequency allows deep tissue rich in water to be heated preferentially, although with non-contact devices the warming of subcutaneous fat often limits power output. The contra-indications and safety procedures attending the use of this equipment requires that it is operated only by trained personnel.

The indications and therapeutic effects are similar to those for shortwave RF diathermy, although modified to take account of the different pattern of heating produced in the tissue. These differences are a function of the frequency-dependent nature of propagation and absorption behaviour within the tissue. Non-thermal effects have not been elucidated clearly but may contribute to the total therapeutic effect.

The principal physiological effects of microwave induced heating upon tissues that preferentially absorb this energy, such as muscle and fluid filled cavities including joints, are vasodilation, altered mechanical properties of connective tissue, increased metabolic rate and an effect upon nerve function. Therapeutically these changes accelerate the resolution of inflammation, decrease pain and restore normal function to contracted fibrous tissue.

Microwave therapy can contribute usefully to the management of many pathologies seen in sports medicine, and when used intelligently performs a function not readily replaced by other treatments.

References

1 Lehmann, J.F. and DeLateur, B.J. Therapeutic Heat. In *Therapeutic Heat and Cold* Chapter 10, 404–562, (Ed) Lehmann, J.F. 3rd Edition, Williams and Wilkins, Baltimore, 1982

2 Goats, G.C. Continuous short-wave radiofrequency diathermy *British Journal of Sports Medicine* 1989, **23** (2), 123–127

3 Wadsworth, H. and Chanmugam, A.P.P. *Electrophysical Agents in Physiotherapy: Therapeutic and Diagnostic Use* 2nd Edition, Science Press, Marrickville, NSW, 1983

4 Lehman, J.F., Guy, A.W., Johnston, V.C., Brunner, G.D., Bell, J.W. Comparison of relative heating patterns produced in tissues by exposure to microwave energy at frequencies of 2450 and 900 megacycles. *Ach Phys Med Rehabil* 1962, **43**, 69–76

5 Lehmann, J.F., Johnston, V.C., McMillan, J.A., Silverman, D.R., Brunner, G.D. and Rathbun, L.A. Comparison of deep heating by microwaves at frequencies of 2,456 and 900 Megacycles *Arch Phys Med Rehabil* 1965, **46**, 307–314

6 Schwan, H.P. Alternating current spectroscopy of biological substances *Proceedings Of The IRE* 1959, **47**, 1841–1855

7 Lehmann, J.F., Guy, A.W., Warren, C.G., DeLateur, B.J. and Stonebridge, J.B. Evaluation of a microwave contact applicator *Arch Phys Med Rehabil* 1970, **51**, 143–147

8 Moseley, H. *Non-Ionising Radiation: Microwaves, Ultraviolet and Laser Radiation* Medical Physics Handbook No. 18. Adam Hilger, Bristol, 1988

9 Wildervanck, A. Pulsed microwave diathermy *Biomed Tech* 1978, **23** (7–8), 158–165

10 Kantor, G., Witters, D.M. and Greiser, J.W. The performance of a new direct contact applicator for microwave diathermy *IEEE Transactions On Microwave Theory And Techniques MTT-26* 1978, **(8)**, 563–568

11 Guy, A.W., Lehmann, J.F., Stonebridge, J.B. and Sorensen, C.C. Development of a 915 MHz direct contact applicator for therapeutic heating of tissues *IEEE Transactions On Microwave Theory And Techniques MTT-26* 1978, **(8)**, 550–555

12 Lehmann, J.F., Guy, A.W., Stonebridge, J.B. and DeLateur, B.J. Evaluation of a therapeutic direct contact 915 MHz microwave applicator for effective deep tissue heating in humans *IEEE Transactions On Microwave Theory and Techniques MTT-26* 1978, **(8)**, 556–563

13 Anonymous. 77/80 Microwave diathermy is safe in normal use *Health Equipment Information No 88*: 16–17 (Ed) Crisp, C.W. Department of Health and Social Security, London, 1980

14 Grant, E.H. Biological effects of microwaves and radiowaves *Proceedings Of The IEEE* 1981, **128 A** (9), 602–606
15 Johnson, C.C. and Guy, A.W. Non-ionising electromagnetic wave effects in biological materials and systems *Proceedings Of The IEEE* 1972, **60**, 692–718
16 Guy, A.W. Biophysics of high frequency currents and electromagnetic radiation *Therapeutic Heat and Cold* Chapter 6, 199–277 (Ed) Lehmann, J.F. 3rd Edition, Williams and Wilkins, Baltimore, 1982
17 Richardson, A.W. Effect of microwave induced heating on the blood flow through peripheral skeletal muscles *Am J Phys Med* 1954, **33**, 103–107
18 Gersten, J.W., Wakim, K.G., Herrick, J.F. and Krusen, F.H. The effect of microwave diathermy on the peripheral circulation and on tissue temperature in man *Archives Of Physical Medicine* 1949, **30**, 7–25
19 Lehmann, J.F., Guy, A.W., Johnston, V.C., Brunner, G.D. and Bell, J.W. Comparison of relative heating patterns produced in tissues by exposure to microwave at frequencies of 2,450 and 900 Metacycles *Arch Phys Med Rehabil* 1962, **43**, 69–79
20 Lehmann, J.F., Brunner, G.D., McMillan, J.A., Silverman, D.R. and Johnston, V.C. Modification of heating patterns produced by microwaves at the frequencies of 2456 and 900 Mc by physiologic factors in the human *Arch Phys Med Rehabil* 1964, **45**, 555–563
21 Sekins, K.M., Dundore, D., Emery, A.F., Lehmann, J.F., McGrath, P.W. and Nelp, W.B. Muscle blood flow changes in response to 915 MHz diathermy with surface cooling as measured by Xe133 clearance *Arch Phys Med Rehabil* 1980, **61**, 105–113
22 Conradi, E. and Pages, I.H. Effects of continuous and pulsed microwave irradiation on distribution of heat in the gluteal region of minipigs. A comparative study *Scand J Rehabil Med* 1989, **21**, 59–62
23 DeLateur, B.J., Lehmann, J.F., Stonebridge, J.B., Warren, C.G. and Guy, A.W. Muscle heating in human subjects with 915 MHz microwave contact applicator *Arch Phys Med Rehabil* 1970, **51**, 147–151
24 Goats, G.C. Pulsed electromagnetic (short-wave) energy therapy *Br J Sports Med* 1989, **23** (4), 213–216
25 Michaelson, S.M. Health implications of exposure to radiogrequency/microwave energies *Br J Ind Med* 1982, **39**, 105–119
26 McRee, D. Soviet and Eastern European research on biological effects of microwave radiation *Proceedings Of The IEEE* 1980, **68** (1), 84–91
27 Michaelson, S.M. Microwave biological effects: an overview *Proceedings Of The IEEE* 1980, **68** (1), 40–49
28 Blackman, C.F., Benane, S.G., Elder, J.A., House, D.E., Lampe, J.A. and Faulk, J.M. Induction of calcium-ion efflux from brain tissue by radiofraquency radiation: Effect of sample number and modulation frequency on the power-density window *Bioelectromagnetics* 1980, **1**, 35–43
29 Cleary, S.F. Uncertainties in the evaluation of the biological effects of microwave and radiofrequency radiation *Health Phys* 1973, **25**, 387–404
30 Schwan, H.P. Biophysics of diathermy. In *Therapeutic Heat and Cold* Chapter 3, 63–125, (Ed) Licht, S., 2nd Edition, Waverley Press, Baltimore, 1965
31 Schwan, H.P. and Foster, K.R. RF-Field interactions with biological systems: electric properties and biophysical mechanisms *Proceedings Of The IEEE* 1980, **68** (1), 104–113
32 Lubec, G., Wolf, C. and Bartosch, B. Aminoacid isomerisation and microwave exposure *Lancet* 1989, **2** (8676), 1392–1393
33 Tsong, Yow Tian. Deciphering the language of cells *TIBS* 1989, **14**, 89–92
34 Kloth, L. Shortwave and microwave diathermy. In *Thermal Agents In Rehabilitation* Chapter 8, 177–216, (Eds) Michlovitz, S.L., Wolf, S.L. F.A. Davis Company, Philadelphia, 1986
35 Lightwood, R. The remedial electromagnetic field *J Biomed Eng* 1989, **11**, 429–436
36 Keddy-Grant, J., Garnis-Jones, S., Adam, J., Danjoux, C., Gerig, L., Ginsburg, A., Mitchel, R. and Raaphorst, P. Complications of microwave hyperthermia treatment of psoriasis *J Am Acad Dermatol* 1990, **22** (4), 651–653
37 Hand, J.W. Microwave heating patterns in simple tissue models *Phys Med Biol* 1977, **22** (5), 981–987
38 Oleson, J.R. and Gerner, E.W. Hyperthermia in the treatment of malignancies. In *Therapeutic Heat and Cold* Chapter 12, 603–635, (Ed) Lehmann, J.F. 3rd Edition. Williams and Wilkins, Baltimore, 1982
39 Crockford, G.W., Hellon, R.F. and Parkhouse, J. Thermal vasomotor responses in human skin mediated by local mechanisms *J Physiol* 1962, **161**, 10–20
40 Hales, J.R.S. and Iriki, M. Differential thermal influences on skin blood flow through capillaries and arteriovenous anastamoses, and on sympathetic activity *Bibl Anat* 1977, **16** (2), 189–191
41 Wyper, D.J. and McNiven, D.R. The effect of microwave therapy upon muscle blood flow in man *Br J Sports Med* 1976, **10**, 19–21
42 Sekins, K.M., Lehmann, J.F., Esselman, P., Dundore, D., Emery, A.F. and DeLateur, B.J. Local muscle blood flow and temperature responses to 915 MHz diathermy as simultaneously measured and numerically predicted *Arch Phys Med Rehabil* 1984, **65**, 1–7
43 Guy, A.W., Lehmann, J.F. and Stonebridge, J.B. Therapeutic applications of electromagnetic power *Proceedings Of The IEEE* 1974, **62**, 55–75
44 Lehmann, J.F., Stonebridge, J.B. and Guy, A.W. A comparison of patterns of stray radiation from therapeutic microwave applicators measured near tissue substitute models and human subjects *Radio Science* 1979, **14**, 271–283
45 Fischer, E. and Solomon, S. Physiological responses to heat and cold. In *Therapeutic Heat and Cold*, Chapter 4 126–169 (Ed) Licht, S., 2nd Edition, Waverley Press, Baltimore, 1965
46 Erdman, W.J. Peripheral blood flow measurements during application of pulsed high frequency currents *American Journal of Orthopaedics* 1960, **2**, 196–197
47 Lehmann, J.F., Masock, A.J., Warren, C.G. and Koblanski, J.N. Effect of therapeutic temperatures on tendon extensibility *Arch Phys Med Rehabil* 1970, **51**, 481–487
48 Warren, C.G., Lehmann, J.F. and Koblanski, J.N. Elongation of rat tail tendon: effect of load and temperature *Arch Phys Med Rehabil* 1971, **52**, 465–475
49 DeLateur, B.J., Stonebridge, J.B. and Lehmann, J.F. Fibrous muscular contractures: treatment with a new direct contact microwave applicator operating at 915 MHz *Arch Phys Med Rehabil* 1978, **59**, 488–490
50 Lehmann, J.F., McMillan, J.A., Brunner, G.D. and Blumberg, J.B. Comparative study of the efficiency of short-wave, microwave and ultrasonic diathermy in heating the hip joint *Arch Phys Med Rehabil* 1959, **40**, 510–512
51 Wright, V. and Johns, R.J. Physical factors concerned with the stiffness of normal and diseased joints *Bulletin of the Johns Hopkins Hospital* 1960, **106**, 215–231
52 Castor, C.W. and Yaron, M. Connective tissue activation. VIII: The effects of temperature studied *in vitro Arch Phys Med Rehabil* 1976, **57**, 5–9
53 Harris, E. Jr. and McCroskery, P.A. The influence of temperature and fibril stability on degradation of cartilage collagen in rheumatoid synovial collagenase *N Engl J Med* 1974, **290**, 1–6
54 Fadilah, R., Pinkas, J. and Weinberger, A. Heating rabbit joint by microwave applicator *Arch Phys Med Rehabil* 1987, **68**, 710–712
55 Newton, R.A. Contemporary views on pain and the role played by thermal agents in managing pain symptoms. In *Thermal Agents in Rehabilitation* Chapter 2, 19–48 (Eds) Miclovitz, S.L., Wolf, S.L. F.A. Davis Company, Philadelphia, 1986
56 Mense, S. Effects of temperature on trhe discharges of muscle spindles and tendon organs *Pflugers Arch* 1978, **374**, 159–166
57 Melzak R., Wall, P.D. Pain mechanisms: a new theory. *Science* 1965, **150**, 971–979
58 Watson, J. Pain mechanisms: a review. 2. Endogenous pain mechanisms *Australian Journal of Physiotherapy* 1982, **28** (2), 38–45
59 Dyson, M. Mechanisms involved in therapeutic ultrasound *Physiotherapy* 1987, **73** (3), 116–120
60 Lehmann, J.F., Dundore, D.E., Esselman, P.C. and Nelp. W.B. Microwave diathermy: effects on experimental muscle haematoma resolution *Arch Phys Med Rehabil* 1983, **64**, 127–129
61 Anonymous. Microwave diathermy. Safety in normal use. *Physiotherapy* 1981, **67** (4), 108–109
62 Delpizzo, V. and Joyner, K.H. On the safe use of microwave and shortwave diathermy units *The Australian Journal Of Physiotherapy* 1987, **33** (3), 152–162

63 Brent, R.L. The effect of embryonic and fetal exposure to X-Ray, microwaves, and ultrasound: counselling the pregnant and nonpregnant patient about these risks *Semin Oncol* 1989, **16** (5), 347–368
64 Michaelson, S.M. Bioeffects of high frequency currents and electromagnetic radiation. In *Therapeutic Heat and Cold* Chapter 7, 278–352, (Ed) Lehmann, J.F. 3rd Edition, Williams and Wilkins, Baltimore, 1982
65 Roberts, N.J. and Michaelson, S.M. Microwaves and neoplasia in mice: analysis of a reported risk *Health Physics* 1983, **44** (4), 430–433
66 Moseley, H. and Davison, M. Exposure of physiotherapists to microwave radiation during microwave diathermy treatment *Clin Phys Physiol Meas* 1981, **2** (3), 217–221
67 Martin, C.J., McCallum, H.M. and Heaton, B. An evaluation of radiofrequency exposure from therapeutic diathermy equipment in the light of current recommendations *Clin Phys Physiol Meas* 1990, **11** (1), 53–63
68 Lehmann, J.F., Stonebridge, J.B., Wallace, J.E., Warren, C.G. and Guy, A.W. Microwave therapy: stray radiation, safety and effectiveness *Arch Phys Med Rehabil* 1979, **60**, 578–584
69 Rae, J.W., Martin, G.M., Treanor, W.J. and Krusen, F.H. Clinical experience with microwave diathermy. *Proceedings of Staff Meetings of the Mayo Clinic* 1950, **24**, 441
70 Anonymous. Specification for microwave therapy equipment. *British Standards Medical Equipment. Part 2: Particular Requirements for Safety*. IEC 601-2-6. BS 5724. Section 2.6. London: British Standards Institution, 1984