Joan McMeeken

Tissue temperature and blood flow: a research based overview of electrophysical modalities

Tissue healing requires an adequate blood and oxygen supply. Physiotherapy heating modalities have traditionally been used to improve blood flow and more recently, electrical stimulation, magnetic fields and laser have been promoted for that purpose.

Electrophysical modalities have been investigated for their influence on tissue temperature and blood flow. Ultrasound, hot packs and microwave irradiation increase tissue temperature with microwave providing the most clinically significant increase in blood flow.

Ultrasound, laser, magnetic fields and comfortable sensory electrical stimulation do not produce significant changes in blood flow, whereas electrical stimulation which produces a motor response is effective. The most efficient and cost-effective physiotherapeutic method of increasing blood flow is by exercise.

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The primary requirement for tissue healing is adequate blood flow with the rate and quality of tissue repair being directly proportional to the blood and oxygen supply (Niinikoski 1980). It has been said that temperatures exceeding 42 degrees C are necessary to achieve increased blood flow (de Lateur et al 1970, Hovind and Nielsen 1974, Lehmann et al 1969). Physiotherapy modalities which heat tissues, although not necessarily to 40 degrees C, such as hot packs, wax baths, microwave, shortwave and ultrasound are routinely used in the resolution phase of injuries, and in the management of chronic conditions. Electrical stimulation, magnetic fields and laser are also thought to cause blood flow changes, although such changes have not been convincingly demonstrated, nor have the possible contributing mechanisms been fully investigated (Lehmann and de Lateur 1990).

The mechanical parameters affecting blood flow are expressed in Poiseulle's Law where:

$$\text{Blood flow} = \frac{\text{Pressure gradient x vessel radius}^4}{\text{Vessel length x viscosity}}$$

which shows that blood flow is primarily dependent on peripheral resistance; and peripheral resistance, on vessel diameter. Local chemical and physical changes are the main determinants of tone in the smooth muscle of the smaller vessels in skeletal muscle, whilst sympathetic adrenergic vasoconstrictor innervation is responsible for vasomotor tone. Suggested causes of blood flow change include direct heating of the vessel wall (Abramson 1965), metabolic by-products and reflex effects due to neural stimulation.

Methods

The immediate effects of the energy produced by physiotherapeutic electrophysical modalities readily available in Australia have been investigated for their influence on tissue temperature and blood flow in:

- isolated vessels of rats
- the hindlimb of anaesthetised dogs and
- the upper limb of healthy conscious humans.

Studies by the author and co-researchers of the hindlimb in α-chloralose anaesthetised dogs (McMeeken and Bell 1984, 1987a, 1987b, 1990a and 1990b) involved intravascular heating and the application of hot packs, ultrasound,

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laser, microwave, magnetic fields and electrical stimulation. Homeostatic reflexes are maintained in these preparations. The hair on the hindlimbs of the dogs was removed for the experiments. The dog was chosen as an experimental animal as the hindlimb approaches the size and tissue composition of the human forearm. The human forearm and hand has been used extensively in blood flow studies, for example Kawai et al (1984), and was accessible and manageable for measurement of temperature and blood flow in response to microwaves, magnetic fields, electrical stimulation and active exercise. In undertaking the studies, meticulous attention was paid to equipment calibration and the careful application of the modalities.

Further details of the *in vitro* experimental methods are contained in McMeeken and Bell (1984); of the dog studies, in McMeeken and Bell (1987a, 1987b, 1990a and 1990b); and of the human forearm experiments, in McMeeken and Bell (1990c) and McMeeken (1992).

Results

Effects from heating blood and blood vessels in isolated preparations and in the dog hindlimb

A temperature increase from 35 to 40 degrees C increased the resting wall tension of rat aorta (Figure 1) and mesenteric artery. There was no further change at 45 degrees C. Temperature change increased the sensitivity and responsiveness of the aorta to noradrenaline (McMeeken and Bell 1984) probably due to an increase in α_1-adrenoceptor sensitivity, as there was no increase in sensitivity from clonidine, an α_2-adrenoceptor agonist.

In the anaesthetised dogs, rapid heating of the blood to the hindlimb to 43.7 ± 0.4 degrees C demonstrated the effect of heating the intraluminal surface of the vessel without heating the surrounding tissue. Conversely, heating the tissue with a hot pack whilst controlling blood temperature

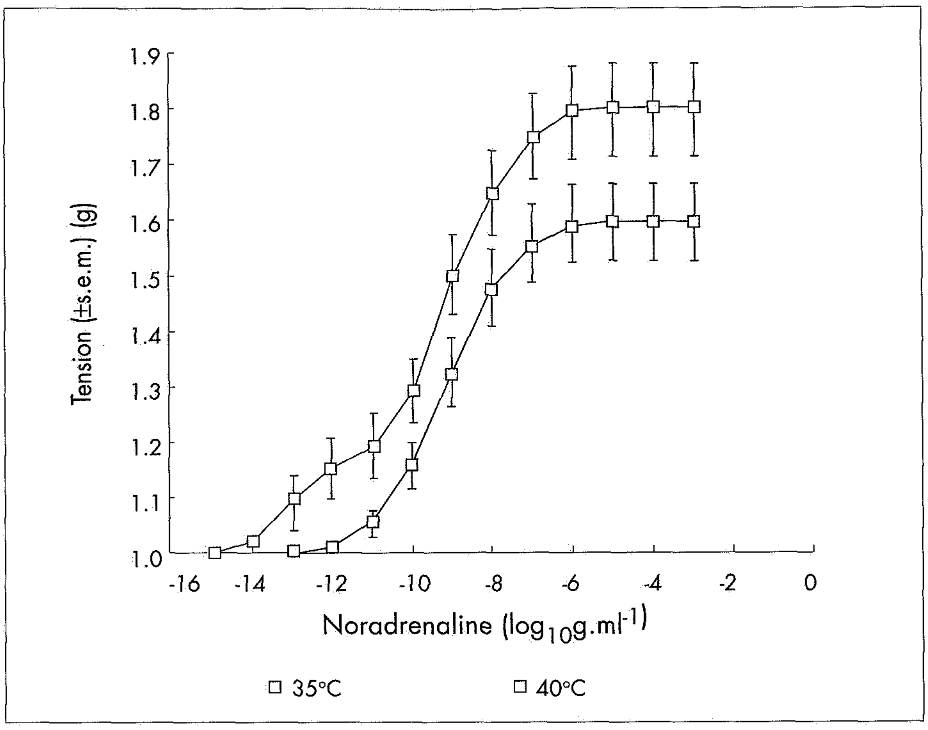

Figure 1.
Dose-response curves in the rat aortic strip to increasing concentrations of noradrenaline at 35°C and 40°C. (n = 23)

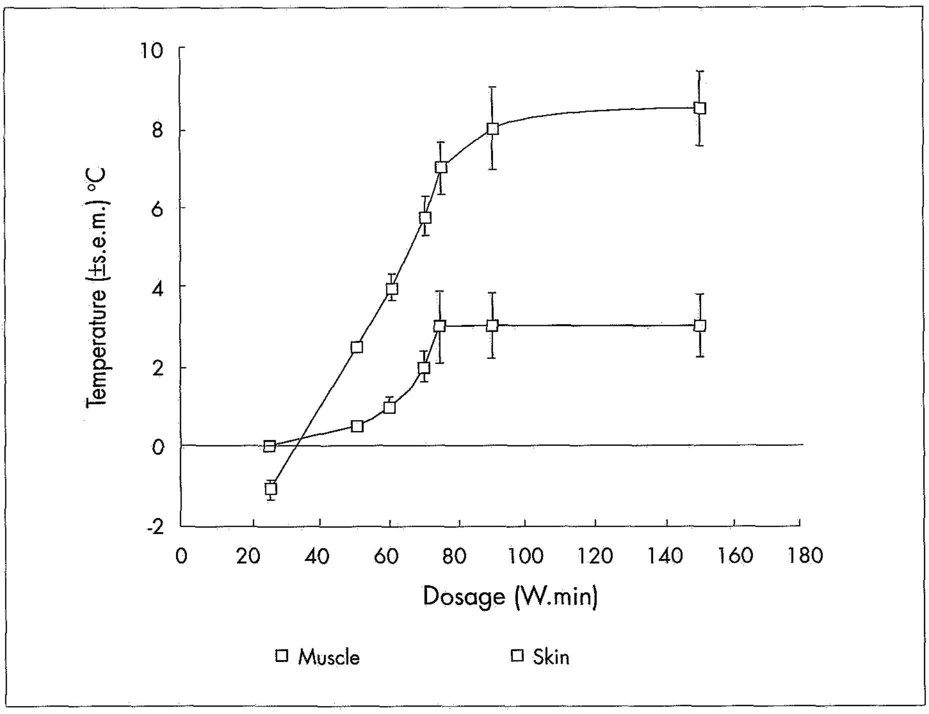

Figure 2.
Change in skin and muscle temperatures in response to ultrasound at various dosages. (n = 6)

Table 1.
Increase in muscle, blood and paw skin temperature (°C) and change in femoral blood flow ($ml.min^{-1}.kg^{-1}$) after blood heating, tissue heating (hot pack) and combined blood and tissue heating, before and after sympathetic blockade.

	Sympathetics	Isolated blood heating	Isolated tissue heating	Combined blood and tissueheating
Muscle temperature	Before blockade	0.2 ± 0.2	5.0 ± 0.8[b]	3.3 ± 1.2[b]
	After blockade	0.4 ± 0.3	5.7 ± 0.5[b]	7.0 ± 1.1[b]
Aortic blood temperature	Before blockade	4.5 ± 0.3[b]	0.04 ± 0.1	5.6 ± 0.3[b]
	After blockade	5.4 ± 0.4[b]	0.5 ± 0.3	5.8 ± 0.4[b]
Paw skin temperature	Before blockade	2.5 ± 0.3[b]	0.1 ± 0.2	5.1 ± 1.0[a]
	After blockade	1.2 ± 0.5[a]	0.5 ± 0.7	2.1 ± 0.7[a]
Femoral blood flow changes	Before blockade	-2.1 ± 0.7[a]	+1.9 ± 0.4[a]	+0.1 ± 0.3
	After blockade	-1.9 ± 0.4[a]	+1.0 ± 0.3[a]	+0.4 ± 0.7

Two-tailed paired *t*-test comparing control and end-heating values: [a] $p < 0.05$, [b] $p < 0.01$

permitted investigation of effects due to tissue heating. The combined effects of blood and tissue heating and the influence of sympathetic blockade were also examined. The significant temperature and cardiovascular changes are shown in Table 1.

In contrast with the widely held view that heating of blood vessel walls causes vasodilatation, these studies indicated that local heating of blood vessel walls affected smooth muscle by increasing both resting wall tension and the response to noradrenaline (McMeeken and Bell 1984). Responsiveness to noradrenaline at different temperatures has been shown to vary between species and from one location to another in an animal, probably reflecting the vessel's role in temperature regulation (Vanhoutte 1980). Temperature changes within the range normally experienced therefore appear to exert direct effects on smooth muscle and modify the response to noradrenaline (Millard and Reite 1975, Wade and Beilin 1970). Intravascular heating of the arterial supply to the dog hindlimb produced a large fall in blood flow which was not the result of reflex effects, since it persisted after sympathetic blockade.

The dog studies indicated that the same effects on smooth muscle that occur in isolated preparations also occur *in vivo*. Such vasoconstriction may explain the observation of Snell (1954) who found that seven of 21 subjects did not demonstrate vasodilatation in the skin vessels of the hand following intravenous infusion of saline at temperatures between 40 and 46 degrees C. Differentiation of blood flow to the dog leg and paw indicated that the vasoconstrictive effect of intraluminal heating was confined to the paw. This suggests thermoregulation of skin vessels, and possibly of arteriovenous shunts, which are localised mainly to the skin of the toes (Bell 1985).

Effects from tissue heating in the dog hindlimb

Hot pack

Hot pack heating over the area of the dog gastrocnemius muscle increased skin and muscle temperature by 12 and 4.7 degrees C respectively, and increased femoral blood flow. These responses persisted after sympathetic blockage. Feucht et al (1949) obtained similar results following application of hot packs to the dog hindlimb. Tissue heating would be expected to increase local metabolism and local blood flow. The calculation of Q_{10} values [$Q_{10} = \frac{10\log k_2/(k_1)}{t_2-t_1}$] is used to demonstrate the extent to which increased tissue temperature increases the metabolic rate of tissues. Feucht's data indicated Q_{10}s of 1.5 - 1.8, while the author's data gave a Q_{10} of 1.6. Temperature dependent metabolic processes have a Q_{10} value of about 2 (Giese 1973). The increased blood flow seen in response to tissue heating was therefore not directly attributable to increased metabolic rate, although it was likely to be a contributing factor.

Ultrasound

Metronex P300 ultrasound (Bonner Medical, Victoria) with a frequency of 1MHz, a $5cm^2$ surface area of sound head, and 15W maximum output was applied to a $25cm^2$ area of the dog hindlimb using an in-contact longitudinal stroking technique, Aquasonic (Parker Laboratories, New Jersey) gel coupling, and dosages from 25–160W.min. Although there was a temperature change (Figure 2) indicating evaporative cooling of the water-based gel at low ultrasound doses, and an increase in temperature above 50W.min, there was no change

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in femoral blood flow.

Other workers have produced similar tissue temperature changes following ultrasound application (Imig et al 1954, Paaske et al 1973, Paul and Imig 1955) and Wells (1977) suggested that this agent may increase the local circulation. Imig et al (1954) and Paul and Imig (1955), using 3.0–3.5W.cm^{-2} and a water-cooled ultrasound head, demonstrated an increase in blood flow in the dog gastrocnemius from 35 ± 1.0 to 51 ± 4.6 ml. min^{-1}, with average muscle temperature of 42 degrees C. They also found a 47 per cent increase in blood flow in the human forearm when ultrasound at 3–3.5 W.cm^{-2} with a water-cooled sound head was applied.

However, neither Paaske et al (1973) nor Wyper and McNiven (1976) showed any significant changes in skin or muscle blood flow in their experiments in the human thigh. Although ultrasound increases the temperature of the skin at doses above 50 W.min, and increases the muscle temperature at 2cm below the skin surface at 60 W.min, the results of the author's study confirmed those of Paaske et al (1973) and Wyper and McNiven (1976) that 1MHz ultrasound is not a reliable modality for achieving an increase in blood flow.

Laser

Preliminary studies were undertaken with two low powered diode therapeutic lasers, one from LTU-904 Laserex (Operations) Pty Ltd of Unley, South Australia, and the other an Omega Biotherapy 3ML soft tissue laser from Omega Universal Technologies Ltd of London. The lasers, with wavelengths of 820 and 904nm respectively, were applied for up to 10 minutes using a range of doses from 0.5 to 50mW. Both an in-contact point stimulation, and grid application over 9cm^2 stimulating each cm^2 as a single point showed no changes in continuously monitored temperature or blood flow. As there was no measurable change and the calibration of output of the lasers could not be verified, further sacrifice of animals was not considered to be justifiable. Therefore no further investigations were undertaken.

Table 2.
Heart rate (beats.min^{-1}), mean blood pressure (mm Hg), femoral flow (ml.min^{-1}.kg^{-1}), and conductance (ml.min^{-1}.kg^{-1}.mm Hg^{-1}) before, at cessation of 10 min microwave irradiation, and between 1–5 min after irradiation when blood pressure had returned to normal and flow was maximally elevated. (n=11)

	Before microwave	after 10min microwave	1-5min after cessation of microwave
Heart rate	86 ± 14	138 ± 14^b	94 ± 12^c
Mean blood pressure	110 ± 5	145 ± 9.0^b	112 ± 5^c
Total femoral flow	12.9 ± 2.8	18.6 ± 3.5^a	19.3 ± 3.3^a
Leg flow	9.5 ± 2.6	12.3 ± 2.7^a	15.6 ± 2.9^c
Paw flow	3.4 ± 0.8	6.3 ± 2.0	3.8 ± 0.9
Total conductance	0.12 ± 0.02	0.14 ± 0.02^a	0.17 ± 0.03^{ac}
Leg conductance	0.09 ± 0.02	0.09 ± 0.02	0.14 ± 0.02^c
Paw conductance	0.03 ± 0.01	0.04 ± 0.01^a	0.03 ± 0.01

Two-tailed paired *t*-test; significantly different to before microwave (0min): $^a p < 0.05$, $^b p < 0.01$. Significantly different to after microwave (10min): $^c p < 0.01$.

Shortwave

Investigation of the effects of 27.12MHz shortwave diathermy proved to be impossible. Despite the use of a variety of screening methods, including the construction and use of a Faraday cage, electromagnetic interference with the measuring devices made it impossible to accurately measure temperature or blood flow.

Microwave

Factors affected by a temperature increase due to microwave irradiation were investigated using a 2450 MHz Radarmed microwave generator by Bosch of Germany to apply therapeutic doses (40W, 10min, emitter–skin spacing 3cm) to the surface overlying the lateral aspect of the dog gastrocnemius muscle. Potential neurohumeral responses were determined by sympathetic ganglion blockade with hexamethonium, α- and β-adrenoceptor blockade with phentolamine and propranolol respectively, intravenous adrenalin infusion, adrenal vein occlusion, blood sampling of catecholamines, section of the tibial and deep and superficial fibular nerves and xylocaine block of paw afferent and efferent nerves. Histamine, bradykinin and prostaglandin contributions were also investigated.

Microwave exposure produced an even rise in tissue temperature of 6.5 degrees C in skin and 5.6 degrees C in muscle and affected cardiovascular parameters in a characteristic manner. Blood pressure, heart rate and femoral blood flow increased after a latency of 3–8 minutes and these effects plateaued over a further 2–7 minutes. At cessation of irradiation, heart rate and blood pressure rapidly returned to resting levels but total femoral blood flow took 20 minutes to return to resting levels. In 40 per cent of trials, blood flow continued to increase for up to 5 minutes after cessation of the microwave. In order to account for the increased flow attributable to increased

Table 3.
Temperatures and blood flow at rest, after brief active forearm exercise and after microwave irradiation of the forearm (n = 21).

	Rest	Forearm exercise	Forearm microwave
Forearm temperature (°C)	30.3 ± 0.2	30.3 ± 0.2	40.3 ± 0.5[a]
Finger temperature (°C)	27.7 ± 0.8	27.6 ± 0.8	29.0 ± 1.0
Forearm blood flow (ml.100 g^{-1}.min^{-1})	6.0 ± 0.6	16.3 ± 1.8[a]	44.9 ± 9.8[ab]
Finger blood flow (ml.100 g^{-1}.min^{-1})	7.9 ± 2.6	16.8 ± 5.8	9.9 ± 2.7

ANOVA: [a] significant difference between exercise or microwave and resting values ($p < 0.05$); [b] significant difference between females and males ($p < 0.01$).

blood pressure, flow was recalculated as conductance, ie

$$\text{conductance} = \frac{\text{blood flow}}{\text{mean blood pressure.}}$$

Table 2 displays results from one series of experiments.

In the study, a 5.6 degree C rise in muscle temperature, in conjunction with a 50 per cent increase in blood flow, was comparable to results obtained by Kemp et al (1948) who reported that microwave irradiation produced a 4.4 degree C rise in muscle temperature and increased blood flow by 48 per cent. The temperature rises in skin (6.5 degrees C) and muscle (5.6 degrees C) were equivalent. This might have been due to the preferential absorption of microwaves in tissues of high dielectric constant and conductivity such as muscle (Ho 1976, Ward 1986).

The femoral flow increase had two components. The first occurred in response to the temperature increase, which reflexly activated the adrenal medulla releasing catecholamines by a mean increase of 390 pg.ml^{-1}. This produced a parallel increased blood pressure and produced an 18 per cent increase in conductance. The second component, also due to the increase in tissue temperature, produced a sustained increase in flow to the leg such that after cessation of microwave, 94 per cent of the increase in leg flow reflected muscle flow. The second component of the response continued after irradiation ceased and blood pressure returned to normal. A Q_{10} value of 2.4 at the time conductance was maximal supports a progressive increase in muscle metabolic rate. This was consistent with all of the post-microwave increase in conductance being due to metabolic vasodilatation. Although this simple model adequately explained the responses seen, other local factors such as vasodilator release may contribute to both phases. However, investigations using a variety of pharmacological antagonists failed to produce evidence supporting the involvement of prostaglandins, kinins or histamine.

Clinical preference for a particular heating modality depends on the pathology and the types of tissues being treated, and the characteristics of the type of heating and its penetration depth. Comparison of the effects from hot packs and microwave applied to the hindlimb of anaesthetised dogs indicated that:

- hot packs require twice the skin temperature increase for a comparable rise in tissue temperature at 2cm depth,
- for a comparable deep tissue temperature, microwave irradiation produced nearly twice the hyperaemic effect and
- blood flow was sustained longer after cessation of microwave irradiation.

This work has been reinforced by Lehmann and de Lateur's (1990) recommendation to use microwave irradiation rather than hot packs to heat muscle tissue, particularly where a sustained increase in blood flow is desirable.

Studies of the human forearm have indicated that locally applied microwave irradiation produces substantial increases in forearm and hand blood flow, and that this effect persists after cessation of irradiation (McMeeken and Bell 1990c).

Increased blood flow in the human thigh in response to microwave has been reported (de Lateur et al 1970, McNiven and Wyper 1976, Sekins et al 1980). The author and co-researchers compared the effects on skin temperature, blood pressure, heart rate and blood flow following microwave separately to the forearm and to the hand with the effects from brief active exercise (15 squeezes of a hand dynamometer at 50 per cent of maximum voluntary contraction) in 11 females (34.8 ± 4.1 years) and 10 males (35.9 ± 3.5 years) (McMeeken and Bell 1990c). The effects following microwave to the forearm and brief active forearm exercise are shown in Table 3. Microwave to the hand increased finger skin temperature by 13 degrees C and finger flow by 203 per cent but had no significant effects on forearm temperature or blood flow.

In exposure to forearm and hand, maximum blood flow occurred within 15min of onset and was sustained for at least 20min after irradiation ceased. Forearm blood flow was the same at rest for males and females but female increases were significantly greater after microwave (male peak muscle flow of 21.5 ± 5.2 ml.100 g^{-1}.min^{-1} and female of 66.2 ± 15.5 ml.100 g^{-1}.min^{-1}). The three-fold increase seen in female subjects may reflect a greater reliance

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on vasomotor responses than on evaporative cooling (McArdle et al 1986).

Microwave irradiation is a useful means of increasing tissue temperature and blood flow in human subjects. However, such blood flow responses are much greater than those observed in anaesthetised dogs (approximately 600 per cent compared with 50 per cent). Furthermore, in contrast to the situation in the dog, irradiation using similar dosages in human subjects produced no detectable changes in blood pressure or heart rate.

Despite advice that tissue temperatures greater than 42 degrees C are required to increase blood flow (de Lateur et al 1970, Hovind and Nielsen 1974, Lehmann et al 1969) this was not the finding in these studies. Highly significant increases in blood flow in association with skin temperatures were observed at the end of microwave irradiation of about 40 degrees C.

Microwave to the forearm increased local forearm blood flow six to seven times. This increase was greater than that previously reported following similar elevation of skin temperature using water immersion of the arm (Barcroft and Edholm 1943, Kawai et al 1984). Deep tissue absorption of microwave energy (Lehmann and de Lateur 1990, Ward 1986) also resulted in greater overall warming of the arm.

Microwave to the hand increased skin temperature (from 27 to 40 degrees C) and finger blood flow (by 500 per cent). These results were similar to that obtained by Roddie and Shepherd (1956) following warming of the hand from 32 to 44 degrees C. Studies investigating the effects of microwave heating of tissue in human subjects have produced conflicting results when muscle blood flow has been measured. McNiven and Wyper (1976) irradiated the thigh and showed that muscle blood flow, as measured by Xe^{133} clearance, increased 400 per cent from a resting value of 2.9 ml.100 $g^{-1}.min^{-1}$ to 11.4 ml.100 $g^{-1}.min^{-1}$. Conversely, Xe^{133} clearance rates after irradiating the human thigh indicated that skin blood flow was elevated 20–30 times above resting level without change in muscle flow (Hovind and Nielsen (1974). The calculated resting muscle blood flow levels in the present study of 5.8 ± 0.8 ml. 100 $g^{-1}.min^{-1}$, were comparable with those of about 2.7 ml.100 $g^{-1}.min^{-1}$ reported by Edholm et al (1956) using iontophoretic suppression of skin blood flow and those of McNiven and Wyper (1976) of 2.9 ml.100 $g^{-1}.min^{-1}$.

Table 4.
Electrophysical modalities and dosage regimes of experiments applied to dog hindlimb (n = 34)

Apparatus	Dosage
Electrical stimulation[a]	1ms, 5Hz, 5–25V, 30s
Electrical stimulation[b]	20μs, 50Hz, 1s on and 0.5s off, 150–200V
Hot pack	Pack immersed 7min in boiling water, wrapped in 1cm damp towelling
Microwave	40W, 3cm spacing, 10min
Ultrasound	5–15W, 25cm² treatment area, continuous, 5–10min
Magnetic fields	5–50Hz, 0.2–10mT, 30min
Laser	0.5–50mW, up to 10min, single point/grid

[a] Grass polygraph (Grass polygraph model 79D [Grass Instruments Co. Quincy, Mass. USA])
[b] High voltage galvanic stimulator (Microdyne 11 Intellect model 500 [Chattanooga USA])

The resultant calculated muscle blood flows were based on the assumption that changes in finger blood flow after hand irradiation are likely to be at least as great as changes in forearm skin blood flow after forearm irradiation. The resulting derived values of muscle blood flow were comparable with those obtained by McNiven and Wyper (1976), 74.5 ± 18.6 ml. 100 $g^{-1}.min^{-1}$ for females and 21.6 ± 5.8 ml. 100 $g^{-1}.min^{-1}$ for males. Water-cooled applicators have been proposed by Lehmann and de Lateur (1990) as the most efficient means of increasing deep tissue blood flow. However the peak values of about 25 ml.100 $g^{-1}.min^{-1}$ obtained in their work are no greater than those evoked in this study using an uncooled applicator.

It has been postulated that the most likely mechanism involved in the increased blood flow resulting from microwave heating is an increase in metabolic rate as a result of tissue temperature elevation (Lehmann and de Lateur 1990). The Q_{10} value was 6.5 following microwave to the forearm and 3.9 following finger irradiation. These values support a local increase in metabolic rate as the predominant cause of the increase in blood flow. This mechanism is also supported by a study using brachial plexus blockade which has shown that the increase in forearm blood flow as a result of changing skin temperature from 25–40 degrees C is independent of neural activity (Crockford et al 1962).

Magnetic fields

It has been considered that some benefits of magnetic fields are secondary to changes in blood flow (Lau 1987, Warnke 1983). Lau claimed a 200–400 per cent increase in forearm and hand blood flow and Warnke stated that large blood vessels and

Table 5.
Summary of temperature and blood flow changes produced by electrophysical modalities in anaesthetised dogs.

Apparatus	Skin Temp. change (°C)	Muscle Temp. change (°C)	% change in blood flow
Electrical stimulation	< 0.2	< 0.3	68.5± 24.1[b]
Hot packs	12.0 ± 0.6[b]	4.7 ± 0.3[b]	32.0± 8.0[a]
Microwave	6.7 ± 0.4[b]	5.8 ± 0.5[b]	43.7± 20.7[b]
Ultrasound	1.1–10.0	0.0–3.0	< 5.0
Magnetic fields	0.1–5.7	-1.2–2.5	-4.7–9.3
Laser	0.0	0.0	< 5.0

Paired Student *t*-test: [a] $p < 0.05$; [b] $p < 0.01$.

capillaries dilate following exposure to magnetic fields. The author and co-researchers further investigated these effects.

Magnetic field devices for physiotherapy are available with frequencies to 100 Hz and output to 10 mT (1mT = 10 Gauss). The effects of different combinations of low and high frequency and intensity magnetic fields were examined at doses recommended for clinical practice using the anaesthetised dog model (McMeeken and Bell 1987a). There were no changes in cardiovascular parameters. One machine, a Magnetopulse International operating at maximum frequency and intensity, raised skin temperature by 5.7 degrees C and muscle temperature by 2.5 degrees C. This device was further investigated in 20 normal human subjects, 11 females (34.7 ± 4.4 years) and nine males (38.1 ± 4.0 years). The effects on blood pressure, heart rate, skin temperature and blood flow in the forearm and hand were determined and compared with brief exercise of the forearm and hand, electrical stimulation of the nerve supply to the forearm extensor muscles and no intervention (McMeeken 1992). Magnetic fields of 50 Hz, 9.9 mT for 15 minutes, were centred over the left forearm and hand by means of a Universal 105 half-cylinder applicator.

Magnetic fields did not change blood pressure, heart rate or forearm blood flow, finger blood flow or finger skin temperature. Forearm skin temperature increased by 0.5 degrees C. When the magnetic field generator was operated without relating the half-cylinder applicator to a subject, that is operated in mid air, the temperature of the applicator increased by 3.7 degrees C, and the temperature of a probe positioned 2cm from the surface of the applicator increased 0.5 degrees C. This may account for Warnke's (1983) suggestion, based on thermographic evidence, that magnetic fields elevate blood flow. A temperature increase due to infrared radiation from the applicator may therefore be observed with some magnetic field devices operating at high frequencies and high intensities.

Reported physiological changes following magnetic fields include stimulated cell respiration in muscle and kidney tissue cells (Fardon et al 1966), decreased paw volume in carrageenan-induced oedema and adjuvant-induced arthritis in the rat hind paw (Mizushima et al 1975) and angiogenesis in the rat (Dyson 1984). Although these changes could conceivably influence blood flow, no effects on blood flow were revealed by the author's studies. On the assumption that magnetic fields stimulate local circulation and inhibit tissue inflammation, Leaper et al (1985) showed no effect of 40mT magnetic fields on wound size, collagen content and tensile strength in rats. Railton and Newman (1983) performed a double blind trial on 22 normal human subjects and detected no changes in transcutaneous oxygen tension and skin temperature.

Effects from electrical stimulation in the dog hindlimb

In all the studies referred to in this paper, electrical stimulation was used and viewed as a reliable means for achieving muscle contraction and, accordingly, a reliable means of producing increased muscle blood flow. Whilst heating has been the traditional physiotherapy means of improving blood flow, direct comparisons of the effects from electrical stimulation with the effects from lasers, magnetic fields and the various heating modalities, in both the dogs (Table 4) and human subjects, have cast considerable doubt on the appropriateness of such a tradition.

The chosen parameters of electrical stimulation produced a maximum increase in blood flow, a minimum effect on mean blood pressure and no post-exercise hyperaemia. The high voltage galvanic machine produced the same responses as the Grass polygraph stimulator. Combining electrical stimulation with hot pack heating did not enhance the increase in blood flow. Electrical stimulation of nerve fibres when motor response was blocked did not change temperature or blood flow. Comparative details of the modalities are shown in Table 5.

Blood flow changes in the dogs following electrical stimulation were unaffected by sympathetic blockage, hence such changes were locally induced. Differentiation of flow indicated that electrical stimulation selectively increased the proportion of blood to the muscle from 70 to 85 per cent of the total limb flow.

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Effects from electrical stimulation in the human forearm

Brief exercise consisting of 15 submaximal squeezes of a spring-loaded hand dynamometer was compared to a control period and electrical stimulation. Transcutaneous electrical activation of the forearm extensor muscles was achieved with a bipolar technique – 20μs twin exponential pulses, 70μs interpulse intervals, 50Hz, 1sec on and 0.5sec off, 150–200V, for 15 contractions. The control period was followed by brief exercise, a recovery period, magnetic field application, a recovery period and electrical stimulation.

Exercise and stimulation increased forearm and finger blood flow but did not change blood pressure, heart rate, forearm or finger skin temperature. The effects of exercise and electrical stimulation on forearm and finger blood flows are summarised in Figure 3.

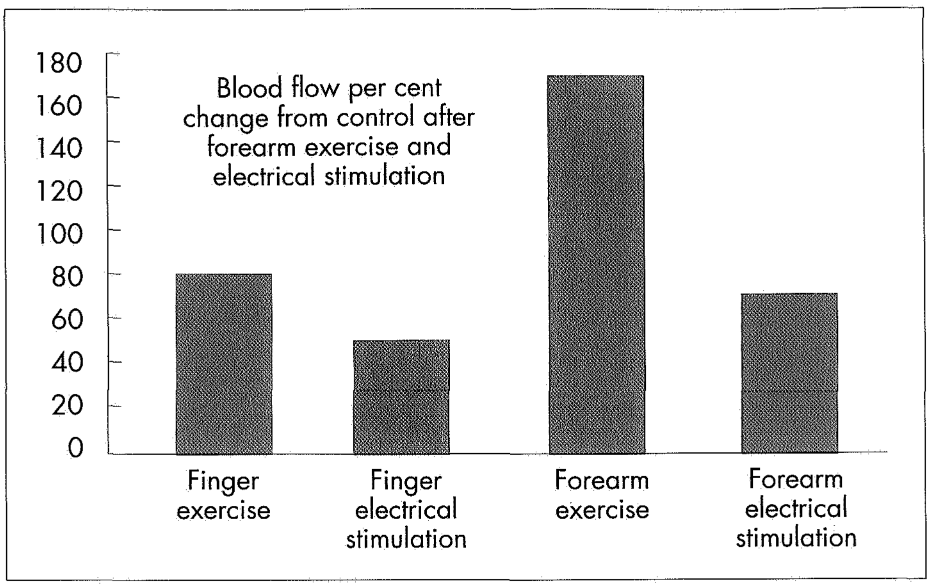

Figure 3.
Change in finger and forearm blood flow in response to brief exercise (15 submaximal squeezes of a spring-loaded hand dynamometer) and electrical stimulation (electrical activation of forearm extensor muscles for 15 contractions). (n = 20)

Exercise produces a preferential increase in muscle blood flow (Gaskell 1877), up to 35 times resting levels (Wesche 1986). This hyperaemia is induced by factors such as reduced PO_2, increased K^+, lactic acid, CO_2 and osmolarity with smaller contributions from adenosine, acetylcholine, and ATP (Shepherd 1983). The effects of exercise, such as increased perfusion and tissue temperature, may be reproduced by electrophysical modalities. Electrical stimulation of motor nerves is one means of achieving an increase in blood flow where active exercise is not possible (McMeeken and Bell 1987b) and where a significant increase in tissue temperature may be undesirable such as in the presence of joint effusion or tissue oedema.

Recommendations and future directions

Ultrasound, hot packs and microwaves are modalities with the capacity to significantly increase tissue temperature. For an equivalent increase in muscle temperature, hot packs require a substantially greater and potentially unsafe increase in skin temperature compared with microwave irradiation. The application of microwave radiation is technically simple, and has been confirmed as an effective and efficient modality when heating is required for superficial muscle or joints.

A significant clinical change in blood flow is unlikely to occur with therapeutic doses of ultrasound, laser, magnetic fields and comfortable sensory electrical stimulation. Hot packs, microwave and brief electrical stimulation have the capacity to increase blood flow. Microwave appears to be particularly useful for superficial muscle with a more vigorous response expected in women. Further data, however, must be obtained in order to clarify fully the therapeutic potential of increased blood flow. Thus the *minimum* increase in blood flow required for clinical benefit, the length of time that an increase in blood flow must be sustained to be clinically useful and how frequently this stimulus should be delivered for optimum results, remain uncertain. As well, firm guidelines should be established to determine in which clinical situations the elevated deep tissue metabolic rate induced by modalities like microwave may be deleterious rather than beneficial.

Despite the capacity of these electrophysical modalities, the most efficient and cost-effective method of increasing blood flow is by exercise. Given that a few seconds of exercise are sufficient to increase muscle blood flow to the forearm by 180 per cent and hand blood flow by 85 per cent, active exercise is the modality of choice to increase blood flow. If the individual is unable to exercise, and provided there are no specific contraindications, electrical stimulation should be the first choice to increase blood flow for tissue repair.

Acknowledgment

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