CHAPTER

Four

4

Electroacupuncture in context: the effects of electrotherapy

This chapter offers a brief guided tour to the effects of electric currents, heat and cold, non-thermal radiation, magnetic fields, vibration, sound and ultrasound, together with an afterword on our relationship with the energetic world around us. The threads drawn together here will assist understanding of how the modalities of electrotherapy can be applied in the context of acupuncture practice.

ELECTRIC CURRENTS

Electric currents have three effects: chemical, physical (or stimulatory) and thermal. These can influence the body at different levels: cellular, tissue, segmental and systemic.

Direct current (DC) stimulation

Much electrotherapy depends on stimulating nerves to elicit the '*action potentials*' described in detail in Chapter 5 of the CD-ROM resource. It is easier to activate the nerve action potential (AP) using negative rather than positive current. The negative electrode (cathode) is sometimes termed the 'active' electrode, and can provide more comfortable effective stimulation than the positive electrode (anode).

DC increases blood flow locally, with a resultant increase in temperature. It can also enhance tissue healing, for which researchers have usually adopted a protocol that involves negative stimulation initially, sometimes followed by positive currents, or even reversing polarity over several days. Pulsed DC has also been used. Cathodal high-voltage pulsed galvanic stimulation reduces acute oedema following injury, for example.

DC fields enhance bone and nerve repair if a field is applied in the same direction as the body's own electrical field. Nerves tend to grow towards the cathode. Although very low intensity DC can enhance growth and repair, stronger currents have a destructive effect. This has been utilised in treating tumours or aneurysms, in what has sometimes been called 'electropuncture,' or even 'electric moxa'.

The difference between weak and strong current effects is an example of a universal biological principle, the *Arndt–Schulz law*. This states roughly that above a certain threshold a weak stimulus enhances activity whereas a strong one inhibits it, and if strong enough can be destructive. For this reason, DC currents in electrotherapy are usually employed at relatively low intensities.

DC also has systemic effects. If it is applied in the same direction as the natural field of the body (forehead or vertex negative, occiput or leg positive), drowsiness and a sense of withdrawal may follow; there is alertness and mood elevation if current is applied in the opposite direction. Clearly, these findings could be taken into account when designing acupuncture treatments involving electrical stimulation.

Low-frequency (LF) stimulation

Most electrotherapy devices apply current transcutaneously, but electroacupuncture (EA) utilises percutaneous rather than transcutaneous stimulation ('through' rather than 'across' the skin). The effects of both transcutaneous electrical nerve stimulation (TENS) and EA occur mainly at the cellular level, leading to tissue and segmental level effects. Thermal, electrolytic and other chemical effects are minimal.

The firing threshold for a nerve fibre depends on the amount of charge in the applied pulse, that is, on both its amplitude and duration. The exact relationship between these two factors can be illustrated in the strength–duration (SD) curve (Fig. 4.1). At short pulse durations, current has to be strong for an AP to result. The longer the pulse duration, the less current is needed, until at pulse durations greater than about 0.5 ms (for motor and sensory fibres) a minimal current is reached. For nerve stimulation, longer pulse durations are therefore unnecessary. Once the threshold is reached, the fibre fires. With more stimulation, more fibres are recruited.

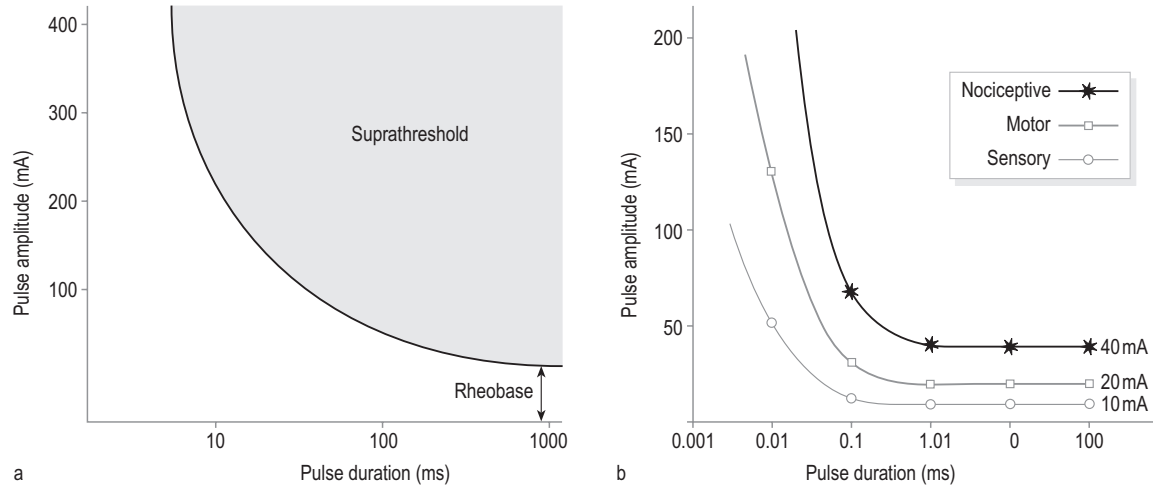

Figure 4.1 The strength–duration curve. (After Walsh 1997, Low & Read 1994.) (a) Strength–duration (SD) curve. Note minimum current (rheobase) needed to trigger an action potential at long pulse durations. (b) Strength–duration curves for sensory (Aβ) fibre, motor (α) fibre, and nociceptive (Aδ or C) fibre. Note the increased separation between the three curves at shorter pulse durations.

The curves for the different sorts of fibres are more widely separated at shorter pulse durations making it simpler to activate them selectively, with *sensory level*, *motor level*, or *noxious level* stimulation. Thus very short pulses (~10 μs) or spikes are unlikely to activate motor fibres. However, when using HF (~100 Hz) TENS, cutaneous (more superficial) C fibres may in fact reach their threshold well before the deeper muscle afferents. Furthermore, thresholds differ in different parts of the body. Thus, to avoid exciting nociceptive C fibres inadvertently, it may be important to position electrodes as close as possible to the target tissue.

Using needles may have several advantages:

- The applied waveform is less distorted by the skin.
- Less current is needed to achieve motor stimulation.
- Deeper muscle afferents can be stimulated without pain from cutaneous C fibres.

The effect of trains of pulses is cumulative, so that less charge is required to stimulate the nerve, and stimulation feels more comfortable than with more widely spaced single pulses. Even a succession of subthreshold impulses may eventually trigger a nerve impulse.

Not only are pulse duration and amplitude important, but also the rise time and shape of the pulse. A rapid rise time, as with rectangular and spike waveforms, is needed to stimulate normal nerve. For sine waves, whose rise time depends on frequency, firing threshold is lowest at around 100 Hz.

Nerve fibres exhibit a *frequency following response* (FFR), with each stimulation pulse triggering the nerve to fire. Thinner fibres, with long '*refractory periods*', cannot follow high frequencies, but only low-frequency stimulation of high amplitude and long pulse duration. Thus pain-transmitting C fibres may fatigue even at 5 Hz, and will generally not fire at more than around 10 Hz. Thicker nerves may have a FFR up to ~1 kHz (1000 Hz). At higher frequencies still, around 4 kHz, nerve and muscle fibres no longer respond to stimulation.

Frequencies above 50 Hz may produce a short term 'block' of both Aδ and C nerve fibres (for more on fibre types, see Ch. 5).

Negative currents lower the threshold to further stimulation. Even with charge-balanced biphasic waveforms, especially asymmetric ones, this can mean that the two phases may not have identical effects.

Muscle stimulation

Motor level electrical stimulation activates motor as well as sensory neurons, leading to muscle contraction. For normally innervated muscle, electrical stimulation always occurs via the motoneuron. However, in denervated muscle, where the nerve supply is interrupted, the muscle fibre itself is activated. Much greater currents and longer pulse durations are required to stimulate the latter, but rapid rise times and stronger currents are not necessary.

The FFR of normal muscle means that at low frequencies each incoming pulse produces a contraction. At around 10 Hz (the frequency of physiological tremor), this becomes a tremor. Above the *critical fusion frequency* (CFF), a smooth continuous (tetanic) contraction results. For most large muscles, tetanic stimulation is best applied between 30 and 50 Hz.

Interrupted currents, trains of pulses with relatively long intervals between them (see Fig. 3.11 on page 33), are frequently used in muscle stimulation, for muscle re-education, enhancing

blood circulation and improving joint range of motion. Brief pulses and shorter trains are more comfortable than longer ones, while ramping stimulation up and down over several seconds gives a muscle action that feels more natural than simple bursts of stimulation.

Frequencies lower than 10 Hz are experienced as tapping or pulsating; those above 400 Hz are felt as vibrating or tickling, and are less likely to be uncomfortable than those around 100 Hz when using TENS. A frequency of 50 Hz may also be better tolerated.

MUSCLE STRENGTHENING

Electrical muscle stimulation (EMS) cannot substitute for exercise in normal muscle, but can be useful if a muscle is weak or voluntary movement is restricted. Treatment has to be carried out several times a week for several weeks.

FACILITATING MUSCLE CONTROL

Motor level stimulation can encourage patients to (re)gain control over voluntary muscle.

REDUCING SPASTICITY

Stimulation can be helpful for various forms of spasticity, the effect lasting longer with more sustained treatment. The spastic muscles themselves, their antagonists, or both may be activated. If direct stimulation of spastic muscle leads to temporary aggravation, extrasegmental stimulation may decrease reflex excitability.

AFFECTING CIRCULATION AND TISSUE REPAIR

Muscle movement exerts a pumping action on the blood and lymph, enhancing oxygenation and tissue nutrition, as well as removing lactic acid and other metabolic byproducts. If used consistently, stimulation (~10 Hz) increases muscular fatigue resistance, and after about 3 months even muscle structure is permanently altered. Interrupted stimulation, as with muscle strengthening, tends to increase effectiveness.

Effects on chronic oedema are sometimes disappointing, but biphasic LF stimulation can be very helpful for tissue repair, with electrodes positioned close to the wound.

TREATING DENERVATED MUSCLE

Compression injury to a nerve results in *neurapraxia*, a conduction block that recovers relatively quickly (within days or weeks) or, if more severe, to *axonotmesis*, degeneration of the nerve beyond the injury, with subsequent slow regrowth of the nerve (1–2 mm daily). Complete severance of a nerve, *neurotmesis*, may mean the nerve never grows back to its target tissue. In neurapraxia (partial denervation), it is still possible to excite muscle via the motor nerve, but not in the case of complete denervation, when the muscle is paralysed. Without its usual electrical and neurochemical input, muscle soon atrophies, with increasing degeneration and fibrosis, a process beginning within 1–2 weeks after the initial lesion and complete (and probably irreversible) by about 3 years.

EMS can benefit muscle by maintaining nourishment to the tissue and aiding repair, thus delaying atrophy and fibrosis. It also fosters a return to normal voluntary use once reinnervation occurs. However, since vigorous movement may actually damage muscle and increase fibrosis, low-intensity LF stimulation with short pulse durations and long interruptions between contractions may be more appropriate. One key factor is that the muscle be kept under tension (i.e. using isometric contractions) during treatment. It is important to start treatment as soon as possible after the initial lesion, and to maintain it consistently, since it may take up to 2 years for normal innervation to be re-established.

A cautionary aside on surface electrodes

High current densities can lead to thermal damage and breakdown of the outer layers of skin with some electrodes, particularly if the skin is dry or if a small-diameter handheld probe (pTENS) is used.

HEAT AND COLD

Heat accelerates cellular metabolism and increases blood flow and vasodilation. It relieves pain and spasm, and increases joint and tendon mobility. Applied locally, heat encourages healing and inhibits surface infections. In combination with elevation and exercise, it is helpful for some oedema, and can also enhance visceral circulation.

Cold, locally applied, generally slows down cellular metabolism and causes an initial decrease in blood flow, followed by slowly alternating vasodilation and constriction. It can relieve pain and spasm, and may increase or decrease muscle strength. Cold may slow healing, but is used in the treatment of recent injury, chronic inflammation and oedema.

In the body, heat lowers the threshold to electrical stimulation and increases conduction, with cold having opposite effects. At frequencies higher than around 10 kHz, the energy of an applied current is absorbed and transformed into heat. Diathermy makes use of this principle. It may be longwave (~1 MHz), or shortwave (27.12 MHz).

Infrared and microwave can both be used for heating. Different wavelengths of infrared penetrate to different depths within the body. Neither penetrates as far as shortwave.

NON-THERMAL EFFECTS OF RADIATION

Microwaves (ultra high frequency, UHF)

Low-level microwave radiation, when not strong enough to cause heating, can enhance tissue repair. When modulated (pulsed) at extremely low frequencies (ELF), it has many more effects on living systems, including the heart and brain. These effects appear to occur at particular frequency or

amplitude 'windows', such as 15 Hz or 16 Hz. Microwaves pulsed at this frequency alter calcium ion outflow from nerve cells, as well as some enzyme activity.

Millimetre waves (extremely high frequency, EHF)

Millimetre waves (30–300 GHz, or 30–300 $\times$ 10^9 Hz), between microwaves and far infrared in the electromagnetic (EM) spectrum, exhibit non-thermal frequency window effects without modulation. At very low intensities, different frequencies will have different, even opposite, effects on bacterial growth, for example. These have been explained in terms of resonance, perhaps at the cell membrane level, or even of the amino acid constituents of deoxyribonucleic acid (DNA).

Athermal EHF accelerates nerve conduction and regrowth, and enhances the immune response and wound healing (particularly of peptic ulcer). Unlike microwave radiation, EHF does not appear to encourage mutation, and may indeed reduce bone marrow damage from subsequent radio- or chemotherapy.

As with acupuncture, EHF may have a *regulatory effect*, with little influence on an organism already in equilibrium. When used clinically, patients often exhibit a generalised 'sensor reaction' as soon as the most appropriate resonant EHF frequency is selected.

Low-intensity lasers and polarised light

Low-intensity laser (or light) therapy (LILT) is the therapeutic application of low-output power (< 500 mW) lasers and monochromatic 'superluminous' diodes at athermal levels. LILT obeys the Arndt–Schulz law for dosage. As with microwave and EHF, there are windows of effective wavelengths, determined in part by the absorption characteristics of different biomolecules and cell components.

Helium neon (HeNe) and some gallium aluminium arsenide (GaAlAs) lasers produce red light. Other GaAlAs and carbon dioxide (CO_2) lasers produce infrared. Different lasers and superluminous diodes are often grouped together in a multiwavelength cluster array (for treating larger areas). The light from lasers and light-emitting diodes (LEDs) may be pulsed, or continuous (CW).

Once it enters the body, laser light is scattered, so in this context lasers have little advantage over other monochromatic light sources. Red light is useful to stimulate superficial structures directly; infrared may penetrate slightly further. However, the indirect effects of LILT go much deeper. They include changes in cellular proliferation and various enzyme processes, vasodilation, enhanced vascularisation and collagen synthesis, as well as other changes central to tissue repair, especially in its early stages. LILT can also enhance immune function. Like EHF, its influence on both tissue repair and immune function comes into play only when cells are already in an abnormal (or disease) state. LILT has been used for nerve regeneration (retarding atrophy of denervated muscle), and cartilage, tendon and bone repair, as well as to enhance soft tissue healing.

More controversial than the use of LILT in tissue repair is its use for treating pain. Results in experimental studies are contradictory, and the mechanisms involved are not as well understood as those underlying LILT's role in tissue repair. However, LILT does appear to alter brain levels of various neurotransmitters, and may influence the EEG (electroencephalogram) as well. Thus there are claims that it can have contralateral, even systemic effects.

Polarised light, like LILT, can enhance immune activity, even if not monochromatic. Irradiation of only 400 cm^2 of skin (and the underlying subepidermal capillary network) can improve the circulatory and immunological characteristics of all the blood in the body, and hence of the whole body itself. Like LILT, polarised light appears to have a regulatory effect, stimulating or inhibiting to maintain homeostatic (or 'homeodynamic') balance. It also follows the Arndt–Schulz law.

LOW-INTENSITY ELECTROMAGNETIC FIELDS

Variable fields

Low-frequency pulsed electromagnetic fields (PEMF) have effects in some ways quite similar to those of high-frequency (VHF or microwave) radiation pulsed at the same low frequencies. As with all the low-intensity methods of stimulation, total energy transfer is less important than making use of certain intensity and frequency windows (15 Hz and 16 Hz again figure strongly). The Arndt–Schulz law plays its part, and initial state (at cell, tissue or whole organism level) determines the outcome of stimulation: a system in equilibrium (at rest) or fully activated does not respond, but PEMF can influence the rate of events between these two extremes, with more actively proliferating cells being most responsive.

PEMF have particular effects on some immune processes, on muscle spasm, circulation (e.g. vasodilation, atherosclerosis) and oxygenation, oedema, inflammation and arthritic states. PEMF also has marked effects on repair and regeneration, whether of nerve, tendon, ligament, bone, soft tissue, or even liver cells. As with pulsed microwave, it is likely that many of these effects are mediated by calcium ion transfer at the cell membrane. PEMF may also affect pain perception, although results are not so clear cut as in tissue repair, in part because the effects of low-intensity fields are subtle and often difficult to measure.

Waveform and frequency are important factors. Pulsed fields are more effective than sinusoidally modulated ones, and intermittent fields more effective than continuous ones. There are some interesting results on 10 Hz PEMF for ligament

and bone repair, and on 2 Hz and 15 Hz for nerve repair; 2 Hz PEMF enhanced functional recovery even after nerve transection. However, there is also evidence that frequency responses may be specific to the individual. Varying treatment parameters, rather than keeping them fixed, has been found effective in some studies.

Static fields

Static magnetic fields are produced by permanent magnets. Stronger fields penetrate the body more deeply, and in general results may be more consistent if fields stronger than about 500 G (50 mT) are used. Static fields influence cellular respiration, with dose-dependent (Arndt–Schulz) effects on blood chemistry, circulation, heart rate, thrombocytic activity, oedema, tissue healing, and even beneficial effects on tumours (in animal studies, with fields greater than about 4000 G). Static fields may also be *protective* against X-ray-induced mutagenesis, although this will depend on whether exposure to the magnetic field precedes or follows irradiation. As with DC electric fields, low-intensity static magnetic fields applied to the head will alter the EEG.

Although there are similarities between the biological effects of pulsed and static fields, in general the former seem to be stronger, and there is less convincing evidence for those of low-intensity static fields.

VIBRATION, SOUND AND ULTRASOUND

Longitudinal oscillation in the form of mechanical vibration and sound can affect the body as much as EM stimulation. Cutaneous sensitivity is greatest at around 30–40 Hz, and that of deeper tissue at 250 and 125 Hz. Vibration is sensed at between 13–18 Hz and 2.6 kHz (large-diameter sensory neurons can 'follow' the applied frequency as far as this upper limit). Motoneurons also respond to vibration, but in a different way.

Various frequencies of vibration can relieve pain, although vibration also facilitates some muscular (flexor) reflexes to pain. It has contralateral as well as local effects. Usefully, 100 Hz vibration and 100 Hz TENS appear to alleviate pain synergistically. Vibration may also enhance bone mass, and affects the EEG (predominantly at around 10–15 Hz). Not surprisingly, however, sustained high-intensity vibration can cause lasting damage.

Ultrasound therapy is very widely used, with frequencies of 0.75–3 MHz and intensities up to 1.5 W/cm^2. At such high frequencies (and power), incident energy is predominantly converted into heat. Pulsed ultrasound, on the other hand, at not more than 0.5 W/cm^2, has minimal thermal effect, and also avoids the risks of high-intensity stimulation. Levels as low as 0.1 W/cm^2 have important effects for tissue repair.

Ultrasound penetrates deeper into the body at 1 MHz than at 3 MHz, and in any case considerably further than

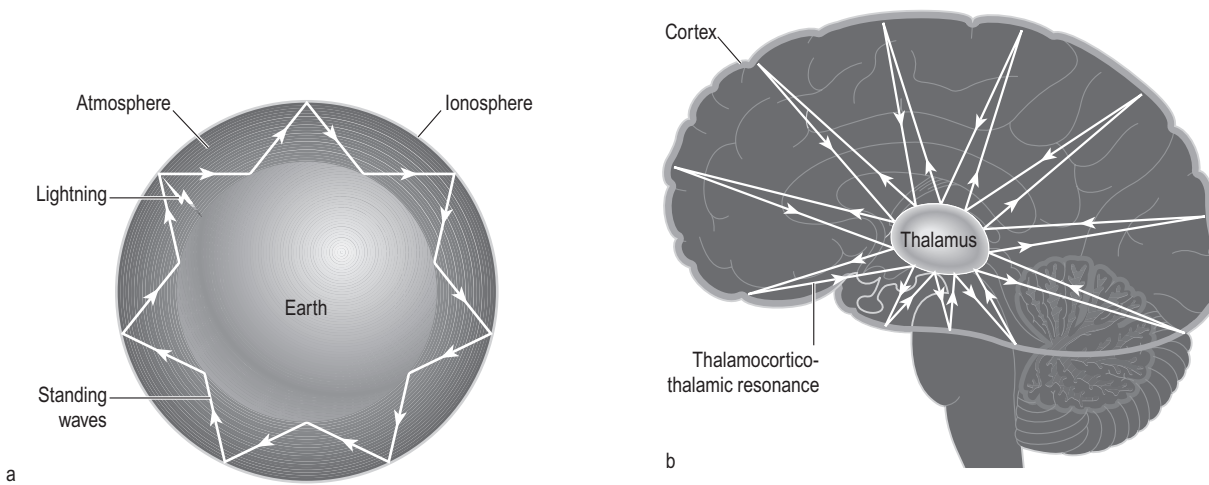

Figure 4.2 Bioresonance: the earth and the brain. (a) Resonance in the cavity between earth and ionosphere. (After Oschman 2000.) (b) Resonance in the brain, between thalamus and cortex (see also Ch. 5).

BOX 4.1

Living in the world – an afterword on bioresonance and the brain

On our planet, we have developed surrounded and interpenetrated by a pulsating web of electromagnetic fields and radiation – our very existence depends on them.

In the 'cavity' between the earth's surface and the ionosphere, lightning discharges create standing waves at *Schumann resonance* frequencies (Fig. 4.2). The fundamental Schumann frequency is about 7.8 Hz. '*Sferics*' at very low frequencies (VLF) are also generated, again pulsed at extremely low frequencies (ELF). Over distance, these become damped, leaving a signal of around 10 kHz in fine weather. In the day, ELF predominates, at night the VLF sferics. The major power density of naturally occurring ELF is thus at around 10 Hz, and that of VLF at 10 kHz.

These same frequencies are echoed within our own bodies. For example, 10 Hz is the primary EEG frequency in all animals, while 7.8 Hz is a constituent of the ECG signal. Windows of particular biological sensitivity are defined accordingly. At much higher frequencies the atmosphere is particularly transparent to 60 GHz EHF. When it comes to visible light, is it just coincidence that the predominant wavelength of the Arctic daylight is the same as that found so useful for tissue healing, about 632 nanometres?

Changes in atmospheric ELF electric fields accompany shifts in the weather, and affect how we feel. So indeed do artificial fields: 3–6 Hz electric fields, for example, may lead to uncomfortable symptoms of headache and fatigue, while reaction times may be slower at 5 Hz than at 10 Hz. EEG patterns are in fact modified in accordance with these external changes, especially in those who are more sensitive to how the weather affects them. Even very-low-intensity ELF magnetic fields have powerful effects on the brain, leading to altered states of consciousness or sensations of vibration moving through the body. Research with very weak fields that mimic those occurring naturally in the brain itself, with frequencies in the theta range, or at around 16 Hz or 40 Hz, suggests that with both magnetic fields and electric currents it is the *information content* that is presented to brain tissue that is relevant, not intensity.

In the modern world, we are surrounded by an 'electromagnetic smog' of artificial fields and radiation that affects us. Ordinary household devices have been shown to affect the EEG, for example. Furthermore, we are often affected by the distortion of the natural EM fields around us caused by the construction of the buildings in which we live, by the acres of asphalt and concrete that isolate us from the earth, and by changes in surface water distribution.

It is thus possible that the drastically altered electromagnetic environment we have helped to create may adversely affect our long-term physical and mental health. Various protective countermeasures have been proposed, examples of which include ELF incoherent 'noise' and carefully positioned magnets or absorbent ceramic materials to mitigate the biological effects of exposure to temporally coherent LF fields or microwaves. However, a clear distinction has to be drawn between long-term EM exposure and short-term electrotherapy. Even long-term treatment has not been shown to have major adverse effects, and if any are found following electrical treatment it may well be that they are less significant than those of magnetic stimulation.

LILT (quite far enough to inactivate muscular trigger points, for example). As with several of the interventions described above, ultrasound pulsed at 16 Hz may have particular effects on calcium ion transfer.

Box 4.1 describes the phenomenon of bioresonance and the brain.

SUMMARY

EM and vibratory stimulation:

- have effects at various levels (cellular, tissue, systemic)
- are gross (neurostimulatory or thermal) or subtle (involving ionic currents rather than action potentials, or athermal).

Common themes that emerge are:

- cellular membrane (Ca^{2+}) and immune effects
- the Arndt–Schulz law
- frequency windows (resonance at invariant endogenous rhythms ~10 Hz or 16 Hz, 10 kHz, or even 60 GHz)
- regulatory (homeodynamic) interactions
- the importance of the initial state of the organism treated
- possible effects on the EEG.

Additional material in the CD-ROM resource

In the electronic version of this chapter, additional material and illustrations can be found on the following topics:

- Direct current (DC) stimulation, particularly for tissue repair
- Low-frequency (LF) stimulation
- Muscle stimulation, particularly for tissue repair and denervated muscle
- Technical information on differences between constant current and constant voltage stimulators, on electrodes and the distortion of electrical signals as they travel into the body

- Heat and cold
- Infrared and microwave methods of heating
- Non-thermal effects of radiation, particularly EHF and LILT
- Pulsed EM fields and permanent magnets
- Vibration and ultrasound
- Bioresonance and the brain.

RECOMMENDED READING

In addition to the standard electrotherapy texts recommended in Chapter 3, I cannot resist mentioning one interesting nineteenth-century textbook, much of which is still relevant today:

Althaus J 1873 A Treatise on Medical Electricity, theoretical and practical, and its usage in the treatment of paralysis, neuralgia, and other diseases. Longmans, Green and Company, London (3rd edn)

Standard textbooks on TENS and LILT, full of useful information, include:

Walsh DM 1997 TENS: Clinical applications and related theory. Churchill Livingstone, Edinburgh

Baxter GD, with Diamantopoulos C, O'Kane S, Shields TD 1994 Therapeutic Lasers: Theory and practice. Churchill Livingstone, Edinburgh

There are many books on the scientific basis of electrotherapy. Some of my favourites are:

Blank M 1995 (ed) Electromagnetic Fields: Biological interactions and mechanisms. Advances in Chemistry 250. American Chemical Society, Washington, DC

Polk C, Postow E 1996 (eds) Handbook of Biological Effects of Electromagnetic Fields. CRC Press, Boca Raton, FL (2nd edn)

Reilly JP, with Antoni H, Chilbert MA, Skuggevig W, Sweeney JD 1992 Electrical Stimulation and Electropathology. Cambridge University Press, Cambridge

A useful overview of wound healing is provided by:

Vodovnik L, Karba R Treatment of chronic wounds by means of electric and electromagnetic fields. Medical and Biological Engineering and Computing. 1992 May; 30(3): 257–66

A thought-provoking collection of papers on EHF stimulation is:

Sitko SP, Andreyev EA, Binyashevski EV, Zhukovsky VD, Losimovich ED, Litvinov GS, Popovichenko NV, Talko JJ 1989 Microwave Resonance Therapy. The fundamental aspects of the application of mm range electromagnetic radiation in medicine. Provisional Collective "Otklik", Kiev

A fascinating and readable book on the role of electromagnetic signalling, and much else, in development and wound repair:

Becker RO, Selden G 1985 The Body Electric: Electromagnetism and the foundation of life. William Morrow, New York