

Electrotherapy Explained

Principles and Practice

FOURTH EDITION



**Val Robertson, Alex Ward,
John Low and Ann Reed**

Foreword Lynn Snyder-Mackler

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ELECTROTHERAPY EXPLAINED

Principles and Practice

Fourth Edition

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Principles and Practice

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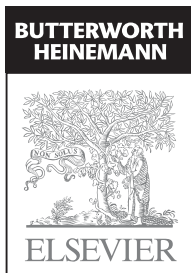
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Foreword

The fourth edition of the text, *Electrotherapy Explained* authored by Val Robertson, Alex Ward, John Low and Ann Reed is an excellent update of the classic Low and Reed book used by countless health science students and clinicians over the years and throughout the world including in the UK, Europe, Africa, India and Australasia. The title is a true reflection of the content.

The text, which has always covered both electrotherapy and physical agents, has undergone a structural and philosophical revision that incorporates the large body of scientific theory and evidence that has been published since the last edition of the book. The two new authors, Drs. Robertson and Ward are long time collaborators who have contributed substantially to the scientific literature in their studies of ultrasound, and kHz frequency alternating current. Their imprint is clearly evident in the revision.

The underlying physiology and biophysics are clearly and extensively reviewed for each intervention. Evidence for the effectiveness of the interventions is presented where available. “Evidence-based medicine (EBM) is the integration of best research evidence with clinical expertise and patient values” (Sackett et al., 2000). The authors have used the five steps of EBP in their description and analysis of the electrotherapy and physical agents interventions described in the book. For each intervention, they convert the practice problem into an answerable question, systematically retrieve the best evidence available, critically appraise the evidence for validity, clinical relevance, and applicability, describe the application of results in practice and evaluate outcomes of performance. Where evidence is lacking, they discuss reason why and inform the readers of what needs to be done in the future to validate the practices described. Finally, they have reinforced one of the historic strengths of this text in their complete and clear descriptions of the application of the modalities.

This new edition of *Electrotherapy Explained* is contemporary, complete and well written. It will be a terrific addition to the libraries of clinicians and will continue to serve as an excellent text for health science clinicians and students.

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Preface to the fourth edition

Explaining electrotherapy is every bit as needed now as it was when the first edition of this book was published in 1990. Electrotherapy still has the problems identified in the preface to the first edition as confusions with ‘traditional naming systems, jargon and didactic statements which have perhaps not always been justified by reason or research’. Didactic statements are still made for some modalities for which there is too little evidence either from first principles in biophysics or physiology or from clinical studies. Ironically at the same time other modalities languish as they are currently unpopular despite demonstrated benefits. A new book was needed to keep on explaining electrotherapy and electrophysical agents (EPAs). While the physical agents used clinically are much the same, the uses and the equipment change quite quickly. For example, batteries are technically more advanced and electronic devices, including electrotherapy equipment, are much smaller and more sophisticated than even 5 years ago. Microprocessor control allows a much wider range of selection and control of treatment parameters. At the same time, our electrotherapy knowledge base has expanded and continues to expand.

The new edition of ‘Electrotherapy Explained’ is designed to explain electrotherapy to both current and future users. The user group is widening and now includes more dentists, veterinary surgeons, physiotherapists, podiatrists, hand therapists, medical practitioners and many other clinicians who are alert to the benefits of using EPAs.

The content and the arrangement of chapters in this edition have changed and two new authors have been added. What has not changed is the focus on explaining how different modalities work and on presenting relevant clinical and biophysical and physiological evidence. In some instances the evidence might suggest that an EPA is not as effective as assumed by clinicians. In other instances it may be more effective than generally recognized or assumed. In several chapters it is made clear that there are considerable gaps between theory, clinical practice and demonstrated clinical effectiveness. We have indicated this where we are aware of gaps and the reader will hopefully recognize the thinness of research reported in some sections and draw their own conclusions.

The aim of this book is not simply to deliver judgement on the merits of different electrophysical agents. If it did, it would be dated far too quickly, given the rapid rate at which new research evidence is accumulated. Rather it seeks to evaluate electrophysical agents in terms of both:

- biophysical principles and
- clinical evidence of effectiveness.

This means that the reader is left to deliver judgement and make choices. The ‘Gold Standard’ is whether there is both a well-established biophysical basis and a body of clinical evidence demonstrating the effectiveness of a particular modality. In other words, whether there is a likelihood of effectiveness, based on established biophysical and physiological principles and whether there is documented empirical evidence.

Failing this the clinician must make a value judgement based on available evidence.

- If there is some clinical evidence but no biophysical/ physiological explanation, the modality could be given provisional acceptance.
- If there is a sound biophysical/ physiological basis for claims of clinical effectiveness, the modality might be given provisional acceptance, subject to clinical evaluation.
- If the claims of clinical effectiveness by proponents (clinicians or manufacturer sales representatives) are contradicted by biophysical/ physiological reasoning, the modality should not be accepted unless there is sound clinical evidence.

Having been subject to the above tests, a clinical modality must then be judged by other standards. Factors such as the simplicity of application and the capital investment and maintenance costs are important considerations in selecting a modality.

The new co-authors of this book, Val Robertson and Alex Ward have worked closely with John Low and Ann Reed to continue the tradition established by the first edition of ‘Electrotherapy Explained’: to present the biophysical and physiological evidence for each modality and summarize the relevant clinical evidence so that clinical decisions are well informed. A central intention of this book continues to be encouragement of understanding the underlying science. To this end the website (<http://booksite.elsevier.com/9780750688437>) accompanying the text now includes both ‘Physical Principles Explained’ by Low and Reed and ‘Biophysical Bases of Electrotherapy’ by Ward.

We dedicate this book to students of electrotherapy; past, present and future.

Val Robertson, Alex Ward, John Low and Ann Reed
July 2005

Preface to the first edition

Electrotherapy has tended to be a subject confused by traditional naming systems, jargon and didactic statements which have perhaps not always been justified by reason or research. In this book we have attempted to demystify electrotherapy for the physiotherapy student.

We have tried to give a fairly complete coverage of the field describing the most common modalities known to us to be employed by physiotherapists. Our intention is to explain how these modalities work and their effects upon the patient. We have used a different approach to some electrotherapy texts. In the initial chapter of each section we have tried to lay the foundations of the principles of modern electrotherapy, because we feel that a thorough understanding of these principles will ultimately lead to safer and more effective clinical practice. Therefore, the book builds up from the basics without, we hope, sacrificing accuracy to give a description of the types of energy available to the therapist. We have classified treatments of the same kind together so that the book is divided into sections devoted to electrical, mechanical, thermal and radiation energy.

The nature, production, effects and uses on the body tissues of each modality are explained and illustrated with what we hope is a reasonably comprehensive range of references to support the points made. With the very welcome involvement of physiotherapists in research, we hope to give undergraduates access to the vast amount of literature upon which they are encouraged to base their final clinical intervention. For postgraduates and practitioners our aim is to stimulate a vigorous search for answers.

We are well aware of the inherent dangers in explaining 'how things work' and in an attempt to communicate our ideas easily we may have been deliberately less precise than we could have been in some instances. We have tried to use the words that would convey the most meaning in the hope that a thorough understanding of even the more difficult concepts might be reached. Perhaps some of the ideas we offer will ultimately be shown to be too simple or just plain wrong, but we console ourselves that even these explanations can lead to debate and serve as a stepping stone to greater accuracy. Many treatments that have faded from use over the years are now returning in an appropriately modern guise, with new rational explanations. One such

example is the use of low-frequency electrical stimulation following the development of the pain gate theory.

Rather than producing a step-by-step guide to technique, we have aimed for a description of the principles, the modalities and practical applications of their use. We believe that if the modality is well understood there can be a wide variation in acceptable technique and treatment within the confines of safe and effective practice.

After many years of teaching electrotherapy we both felt the need to attempt such a book. For our omissions and failings we apologize. However, our sincere hope is that we will have made electrotherapy more comprehensible for some which, in turn, will raise the standards of safe and effective treatment for our patients – the aim of us all.

John Low and Ann Reed, 1990

Introduction

CHAPTER

1

Searches for ‘electrotherapy’ on the world wide web produce over a quarter of a million hits. This indicates something of the importance of electrotherapy. The number of manufacturers’ sites found suggests it might be a financially rewarding market and the breadth of topics, a multifaceted area of interest to many. Some sites focus on equipment and the types of electrotherapy used to treat pain, some on veterinary electrotherapy products, others provide references and information on different types of electrophysical agents (EPAs) and how and when they are used. Considered together, the web sites on electrotherapy represent a wide range of countries, many different types of equipment, a large range of uses of electrotherapy and a treatment approach of relevance to those treating humans and animals.

The aim of this book is to present the most commonly used EPAs along with the biophysical principles which affect how they are applied and the potential effects they can have on a living body. The different modalities will all be discussed in terms of the relevant biophysical principles as well as their clinical effects. Where available, evidence of the therapeutic effectiveness and any known dangers and contraindications will also be presented together with the principles for applying each type of energy. The content of this book is also intended to provide a basis for evaluating and assessing other, new, modalities as they come onto the market.

WHAT IS ELECTROTHERAPY?

The term ‘electrotherapy’ is relatively recent and has a range of meanings. Earlier names for clinically used electrophysical agents include ‘electrotherapeutics’ (Neiswanger, 1912) and ‘medical electricity’ (Cumberbatch, 1939). This second term was consistent with the early focus on using electric currents for patient treatment. The view of the human body as containing electrical energy, which distinguished it from dead, inanimate matter, was advocated by Galvani (1780) and subscribed to by many. This view is reflected in literature, such as in the classic novel ‘The Frankenstein Monster’ where the man-creature that Doctor Frankenstein has assembled from parts of exhumed

A later development was the use of electrostatic fields for patient treatment (Geddes, 1984). Such treatment was impressive: arcs of electric discharge between the patient and electrodes, hairs standing on end and glowing tubes emitting coloured light as the current flowed. One could argue, at least that the placebo response would be significant!

human corpses is brought to life by the electrical energy of captured lightning bolts. It is perhaps not surprising, then, that the application of electric current was believed by some to be a means of enhancing or supplementing the natural energy of the human body and which could therefore be used for the treatment of disease and injury.

Nowadays the term 'electrotherapy' generally has a broader meaning that usually includes assessment despite the word suggesting it should only include treatment or therapy. Present day uses of the term in regions such as Europe and the Antipodes mean treatment or assessment using one of a range of modalities including electrical stimulation, ultrasound, different methods of heating and cooling, shortwave diathermy and clinically used electromagnetic radiation such as infrared and light therapies including ultraviolet and laser. In other countries, such as the USA, electrotherapy is another word for assessment or treatment using electrical stimulation. The other types of electrophysical agents are then typically called 'physical agents'. Whatever the definition, the aim of this book is to provide a basis for understanding the broader range of electrophysical agents.

Here the terms 'electrotherapy' and 'electrophysical agents' (EPAs) will be used interchangeably to indicate any forms of treatment or assessment conducted using an electrophysical agent which can be applied externally to the human body. This means a range of topics will be considered from electrical stimulation to ultraviolet radiation exposure as used to produce a beneficial outcome for a human or animal patient. Some types of EPAs are also used internally such as implanted electrical stimulators like gastric or cardiac pacemakers. While these uses will be mentioned the focus is on the external applications to the skin rather than within a body cavity or part.

Summary

- Electrotherapy is widely used with human and animal clients.
- Definitions of 'electrotherapy' differ throughout the world.
- Electrotherapy includes the following for treatment or assessment:
 - electrical stimulation
 - biofeedback
 - ultrasound
 - superficial heating including infrared
 - cooling
 - shortwave diathermy
 - microwave
 - phototherapy including laser
 - ultraviolet radiation.

EXOGENOUS ENERGY AND THE SKIN

An underlying premise of all EPAs is that external or exogenous applications of energy can beneficially alter physiological processes. Those processes can be normal ones: for example where ultrasound or a type of heating is applied to promote the healing of tissue following a tear, a sprain or strain. Similarly, ice or a form of cooling is applied to limit the secondary damage that can follow the normal bleeding and production of oedema in damaged tissue. Or, the healing processes may have been delayed and the EPA is used to increase the rate to a more usual level: for example, electrical stimulation with some types of wounds. Other types of EPAs are used to supplement normal learning and relearning: biofeedback and electrical stimulation can be used this way. Many EPAs are also used to reduce pain of different types and from different sources.

The skin is a barrier to all forms of exogenously applied energy. The extent to which it is an effective barrier depends on the properties of the skin itself and on the type of EPA applied and the mode and parameters of the application. The skin is not a homogeneous structure throughout the body. In some locations it is deeper and has strong fibrous connections with the underlying tissues as over the calcaneum and gluteal muscles. In other areas it is very thin, such as over the tibia, patella or malleoli or a spinous process. In some locations it is quite extensible, such as over the dorsal surface of the hand but on the palmar surface it is relatively fixed. These types of differences in skin in different locations all have implications for users of EPAs.

The relation of skin to the underlying structures and their depth can be even more important. The thickness and depth of underlying structures affects how much energy can reach deeper structures. The penetration of different forms of heating, cooling, ultrasound and electric current for example, are all affected by depth but in different ways. Skin is also altered by many different disease processes as well as by ageing and the current nutritional and medical status of the person or animal. All of these factors can potentially alter its response to different energy forms such as heat or light or electrical stimulation and the extent to which they are transmitted through it.

The type of skin in some animals is quite different from that in humans. It is often much looser and the response to an EPA can be different. By contrast, the skin of pigs has a similar structure and the underlying soft tissues a similar distribution to that of humans. This difference can be important in laboratory studies of different modalities and their likely clinical effectiveness. The amount of hair on an area in animals and humans can also alter the transmissivity of some types of energy. In summary, many properties of skin can affect the outcomes of applying all types of exogenous energy.

CHAPTER OUTLINES

Most chapters in the present book have a similar, but not identical, layout to previous editions. Chapter 2, for example, discusses topics from a biophysical perspective. This includes nerve structure and function and the response of the body to inflammation and trauma. The focus is not on modalities and how they affect the body and when they should or should not be used. Instead, chapter 2 provides details of some of the physiological processes that can be altered or affected and, in so doing, some of the boundary conditions when using electrotherapy. These issues are discussed further in later chapters where directly relevant.

Chapter 4 differs from later chapters on electrical stimulation in that, unlike them, the focus is on laboratory research and theory and not clinical research and therapeutic effectiveness.

Chapters 3 to 6 investigate the different aspects of clinically used electrical stimulation. These chapters start with a general overview in chapter 3 of electrical stimulation and how to use it. The more complex theory underlying some of the differences between pulsed and alternating currents is the focus in chapter 4. Chapters 5 and 6 both discuss some of the major clinical uses of electrical stimulation, from treatment to assessment. The major difference between the chapters is that chapter 5 focuses on motor stimulation using electrical stimulation. This means that a large range of uses and ways of stimulating innervated and denervated muscles is explored. How applying stimulation works, suitable parameters and what is known of the clinical effectiveness is discussed. Chapter 6 uses a similar approach but the focus is on the use of electrical stimulation for sensory stimulation, particularly for pain control. Other sections in chapter 6 focus on iontophoresis and other uses of electric current. The category 'other uses' is broad and includes some well known and understood uses and some for which the physiological underpinnings are weaker.

Safety is an issue associated with the use of electrical stimulation and many other types of EPAs. Infection control and electrical safety are among the factors that can affect safety. These and other equally important topics are discussed in chapter 7 along with the concepts of risk and contraindications.

Chapter 8 investigates the many types of biofeedback available and how they are used. A large part of this chapter considers the use of electromyographic (EMG) feedback. The reason is, it is commonly used and increasingly becoming more practical and reliable. The advantages and disadvantage of using biofeedback and when it might be preferred to electrical stimulation that produces a motor response is also considered.

Ultrasound is the focus in chapter 9, both therapeutic and diagnostic. The biophysical properties of ultrasound are described and their implications discussed along with what is currently known of its therapeutic effectiveness. Some of the methodological issues in answering such questions are discussed as well as recent research suggesting new directions for users to consider when selecting this modality. The last part of this chapter has brief overviews of longwave ultrasound, sonophoresis and diagnostic ultrasound.

Chapter 10 is connected with chapters 11 and 12 as all discuss some aspects of heating or cooling. Chapter 10 outlines the uses of heating or cooling and how they affect the body. Chapter 11 develops the information on superficial heating and discusses commonly used methods; similarly in chapter 12 but the topic is cooling.

Chapter 13 is stand-alone. It describes shortwave therapy, which involves the application of high-frequency alternating electric or magnetic fields to the body.

Chapters 14 and 15 are related. Chapter 14 describes the fundamentals of electromagnetic radiation. A particular type of electromagnetic radiation, microwave, is the topic of chapter 15. This topic received relatively poor press with the introduction of microwave ovens and is now little used clinically, despite clear evidence of its depth effectiveness.

The types of EPAs based on electromagnetic radiation in the visible and near visible parts of the spectrum provide the content for chapter 16. Specifically, infrared, visible light and lasers are discussed in this chapter together with their actual or proposed modes of action and their known levels of therapeutic effectiveness.

The final chapter, chapter 17, concerns ultraviolet (UV) radiation. While UV is clinically used much less often in many countries than previously, the chapter is important. UV continues to be used and there is a risk that fewer clinicians are able to use it effectively. The other potential risk is that users are not always aware of the extent of current knowledge on the dangers and long-term risks associated with using ultraviolet radiation, from equipment in tanning salons to the larger, more powerful clinical machines.

Microwave diathermy was introduced following World War II. Radar transmitters, operating at a frequency of 2.54 GHz were found to be effective for deep heating of tissue and they were quickly adopted by clinicians. Later it was established that lower microwave frequencies are more beneficial (chapter 15).

GENERAL STRUCTURE OF MOST CHAPTERS AND COMMON ISSUES

The structure of most chapters is similar. Most focus on an EPA and present a structured development of its features and how and why it might be used clinically. The following points are used in most chapters to develop the topic.

Biophysical principles

In most chapters the first section concerns what is known of the physics of a type of energy. This is developed into the biological implications; how from first principles it might affect the living body. In most the focus is on humans but, with some provisos related to hair structure, type of skin, and tissue depth, it can equally well relate to animals which can be and are treated with the same EPAs.

The known physics, biophysics and physiology related to the modality can provide the clinician with the basis for making a considered judgement in the absence of adequate clinical evidence.

Laboratory studies using animals can provide evidence of potential clinical significance. This is particularly important when clinical studies have not been carried out or where confounding variables make the clinical findings ambiguous.

Therapeutic and clinical effectiveness

First principles suggest that without empirical evidence of effectiveness there can be little justification for using a modality. Despite this, for many of the commonly used modalities there is little evidence other than anecdotal of beneficial effects. Sometimes this is easily understood as the evidence is unlikely to be collected as the modality, such as infrared, has a limited adjunctive role. In other instances, there is a clear need for high quality research involving patients being treated with an appropriate condition that is expected to respond to a particular EPA. Irrespective of the quality and types of evidence available, the known evidence regarding the therapeutic and clinical effectiveness is discussed for each modality covered in the present book. In some instances reasons for the lack of evidence are also discussed, such as the problems in evaluating ultrasound with ongoing issues of transducer calibration and of knowing the actual dosage levels at the affected site in treated tissue.

This book is not and does not attempt to provide systematic reviews of all modalities discussed. One reason is that there is too little high quality clinical research on many topics. Also, systematic reviews cannot provide guidance in specific circumstances as is well known (Petticrew, 2003). A goal of this book is to enhance the understanding of clinicians of all types of EPAs. That requires more explanations and a broader research base than systematic reviews alone can provide. The absence of a clinical evidence base does not mean a lack of evidence (Petticrew, 2003). With EPAs the issue is what should be included as evidence. Even if appropriate clinical trials and systematic reviews exist, relevant evidence also includes laboratory studies and evidence from biophysics or other basic sciences. Where the hard science and the clinical evidence agree, a convincing evidence base exists. Where the clinical evidence is inconclusive but a sound biophysical basis exists, the modality can be given provisional approval. Where the clinical evidence is inconclusive and no sound biophysical basis exists, the modality should be given provisional disapproval, meaning that the modality should not be used but that this view could change if appropriate evidence were forthcoming.

More often than not the conclusion of a systematic review is that 'there is insufficient high-quality research to justify the use of this modality. There is an urgent need for high quality controlled clinical trials'. This offers little assistance in clinical decision making.

Principles of use

The many and varied problems that can be effectively treated by an EPA mean that their selection requires a knowledge of first principles. No book could cover all possible contingences, so this book presents the principles a user needs to consider to optimize the outcome and to minimize any existing risks. Similarly, this book could not describe or illustrate all types and brands of EPA equipment currently used clinically in all countries throughout the world. Consequently, the focus is on explaining the principles of use and the factors to consider with each EPA. This is designed to provide potential users with a flex-

ible basis for understanding and mastering specific items of equipment they may have now or obtain in the future.

The principles are considered in most chapters in a range of appropriate headings from the following listing:

Patient

Once a therapist has completed an assessment and selected a modality, they need to discuss the options with the patient. The treatment principles therefore typically include advice on explanations and warnings, positioning, instructions, examination and testing of the area to be treated. The aim is to ensure valid consent is obtained and that electrotherapy is used only how and when it is appropriate and all known risks are identified prior to treatment. In addition, any preparation of the area being treated such as cleaning the skin or testing some aspect of cutaneous sensation or blood flow is discussed when appropriate. The therapist also has an obligation to use appropriate methods of ensuring the privacy of the patient. Such ethical conduct is an essential component of professional practice.

Preparation and testing of apparatus and examination

This includes collecting and assembling the items and parts of equipment needed. When appropriate, visual checks should be made of electrodes, leads, cables, plugs, power outlets, switches, controls, dials and indicator lights. In addition, the output of some machines such as ultrasound units and stimulators should be checked, as described in the relevant chapters. The equipment must be set up so as to minimize risk and promote patient comfort during treatment and to minimize the exposure of the operator to the output of the modality being used.

Application

Depending on the modality, checking throughout an application is required to ensure safety. This is covered in the relevant chapters and advice given regarding the frequency and types of advisable checks.

Termination of treatment

On termination of treatment the area treated should be examined to identify if expected effects such as superficial vasodilation have occurred and any unexpected effects such as a burn. If appropriate, an explanation is given of what to expect after treatment, instructions regarding future treatments, and what should be done between treatments. Written instructions should also be given if, for example, the patient is taking home a stimulator.

Recording

An accurate record of all the parameters of treatment including region treated, technique, dosage and the resultant effect must be made each time. This is for assessment purposes, to meet legal requirements and sometimes to facilitate treatment audits. In addition, details of the advice and warnings given prior to treatment should be recorded.

Further details of applications are provided by many national professional bodies. These are designed to meet local conditions of practice as well as conforming with internationally agreed standards for using EPA equipment.

Contraindications and dangers

When contraindications and the different dangers or levels of risk are presented each is done so with an attempted justification. Sometimes this is easy. Some EPAs should never be used under certain circumstances. For example, an application of electrical current or shortwave or microwave diathermy through an implanted electronic device is always contraindicated. The probability of damage is sufficiently high and the outcome sufficiently disadvantageous to the patient that using these modalities is never justified. By contrast, some 'contraindications' are repeatedly advised as the possible implications of an adverse outcome are sufficiently important that use of the modality is rarely justified. A typical example of this would be the application of many different types of EPAs through the lower abdominal region of a pregnant or possibly pregnant woman because of the possible effects on a fetus. Although the risk is very small, almost any possible risk of adverse effects is sufficient to warrant contraindication.

Other so-called 'contraindications' are often based on historical misinformation that, repeated for long enough, is granted accepted status. One such example is the claim that ultrasound over an epiphysis should be a contraindication. As in the example of a pregnant woman, although the risk is very small, even improbable in a conscious child, this treatment is possibly better avoided. This is discussed in chapter 9.

An issue that also has to be considered is the use of multiple modalities either sequentially or concurrently. While not addressed in individual chapters, clinicians must be aware that this can change the level of risk of using a particular modality. If, for example, a treatment that alters sensory awareness is applied, a modality that relies on accurate sensory feedback cannot safely be used concurrently. It can be applied sequentially if sufficient time is allowed between applications, otherwise the risk is increased to an incalculable level by the addition of a second modality.

Summary of factors affecting the choice of an EPA

The choice of whether to use an EPA and which particular one is not always obvious. In some instances the known benefits of an EPA may be clearly identified and well accepted and in others it is not. Similarly, the risks of applying some EPAs are necessarily higher and must be evaluated by a clinician with appropriate training in their use and an understanding of the underlying physical principles.

Before applying an EPA the following questions should be considered:

- What outcome is intended? An intended outcome may be immediately obvious such as pain relief with heat or cooling and others, such as strengthening using electrical stimulation, may take weeks to be evident.
- Can using this EPA produce or assist in producing this outcome? Different EPAs can produce a similar outcome. For example, heat, cooling and electrical stimulation are all used for pain relief. However, the circumstances under which each is optimally effective can be quite different. The decision as to which to use and when requires an appropriately trained clinician with experience in patient evaluation as well as a thorough knowledge of EPAs.
- Is use of the selected EPA safe in the circumstances? Almost all effective treatment interventions have some attendant risks. Most types of electrotherapy have relatively low levels of risk if appropriate precautions are taken (excluding issues such as the presence of indwelling electronic devices and reduced cutaneous circulation). The risks are generally specific to the type of energy being applied and no treatment should be considered without a thorough knowledge of how each affects the body and possible consequent risks.
- What is the best treatment option in terms of patient and/or therapist time, and other costs such as initial capital and ongoing maintenance costs? This arises particularly with shortwave diathermy with its high initial capital costs and requirement for intensive supervision of treatment. Another example is the time-cost for a patient of the long-term use of electrical stimulation of denervated muscles. In this case there may be no alternative so the costs can be justified if there is the likelihood of a beneficial outcome. Where pain and discomfort are concerned, alternatives to electrotherapy, such as active exercise or mobilization using manipulation or massage, may be more effective long term for strengthening or pain reduction. However, these also raise issues of time, costs and compliance. Consequently, decisions regarding the use of any form of treatment imply the need for well-informed patients and clinicians.

Similarly with electrical stimulators: different types are all claimed to be effective for, for example, pain control, muscle strengthening, oedema reduction and muscle re-education. The important question is whether machine type A is better than machine type B for a specific clinical condition.

EPA users should confine themselves to using modalities for which they have both sufficient and current relevant theory and practical skills to be competent. Usually electrotherapy is part of an overall treatment plan which is selected and modified on the basis of repeated examination and assessment.

EVALUATING EPAS

The Cochrane Collaboration is a foundation set up to foster review and analysis of existing research into clinical interventions.

There are different sets of criteria for evaluating new and existing treatments. Even if the Cochrane Collaboration and equivalent collections of clinical research contained many meta-analyses and systematic reviews of the use of EPAs, methods for evaluating new equipment and treatment methods would still be needed. With the lack of existing methodologically rigorous studies on many topics in electrotherapy, the need is even more obvious.

The following list of five criteria includes modified versions of four of the five that Sullivan proposed and used to evaluate three different types of electrical stimulation treatments (Sullivan, 1999). They are altered here to ensure the appropriateness for all types of electrotherapy, including electrical stimulation, ultrasound and the many other forms from heating to ultraviolet radiation. The fifth was added to counter an obvious issue in evaluations of some EPAs. The criteria included are broader than those adopted by the Cochrane Collaboration but are perhaps of more practical value.

Criterion 1. The underlying theory justifying the use of an EPA must be sound and supported by appropriate biophysical, anatomical and physiological evidence.

Criterion 2. How a modality is used or applied should be based on appropriate biophysical, anatomical and physiological evidence.

Criterion 3. Evidence of potential risks should be ascertained prior to initial uses and data should subsequently be actively collected and reviewed by proponents and independent researchers.

Criterion 4. Evidence of beneficial outcomes that justify the use of EPAs may be sought from the general scientific literature and must be sought in the clinical. Clinical studies should include people who have the condition for which a benefit is claimed. The methodologies used, while ideally randomized controlled trials, will also include other studies such as quality cohort studies, series of cases, single subject experimental designs and case studies.

Criterion 5. In clinical trials patient selection should relate to the expected effects of a modality and the outcomes should be assessed using relevant outcome measures.

The role of biophysical evidence is the first important difference in this list from that of Sullivan. Evidence supporting the use of most types of EPAs comes initially from studies using the methods and knowledge base of physics. For EPAs the effect of a particular energy on biological events is also pivotal, hence the need for biophysical evidence to be considered. The aim should be to obtain a dose-response

curve or similar for each type of modality. Without this type of evidence it is difficult to identify appropriate levels of dosages for different tissues (types and pathologies). As well, other considerations such as the anatomy and physiology of the human or animal to which the modality is to be applied must also be considered.

The inclusion of the need for independent researchers in the process of identifying possible risks (side-effects) and outcomes is another difference. In the past some clinical and non-clinical trials reporting favourable outcomes have been sponsored by manufacturers or others who potentially might benefit. Unless replications of the method, conducted by independent researchers, produce similar results, beneficiary-related evidence should never be accepted as sufficient. It is necessary during the development process but not sufficient to justify the purchase or continuing use of the equipment. With the existing bias to publication of positive findings, this can be a difficult condition to meet. This same bias has another potential adverse implication: their over-representation in systematic reviews and meta-analyses (Sutton et al., 2000).

In an ideal world all EPAs would be investigated using well-designed randomized controlled trials with sufficient subjects to identify any real effects. The reality is that randomized controlled trials are not always possible with a clinical population. Obtaining sufficient homogeneous subject populations to identify an effect is a general problem, as has long been evident in the relatively limited existing clinical literature (Robertson, 1995). Using a randomized controlled trial can also limit the type of information obtained. For example, if compliance is a possible issue there is little scope for obtaining qualitative information if the trial is strictly controlled. A risk is that the literature has limited clinical relevance. If, however, a broader range of methodologies is accepted as providing valid sources of information, clinically relevant and valid material can be collected. For example, a series of cases can add considerably to our knowledge about a particular modality including the boundary conditions of use. Subsequently, researchers may investigate relevant aspects of the question using a randomized controlled trial if possible. Hopefully also replications are conducted.

The inclusion of clinical trials involving patients for whom the treatment is intended is most desirable. The results of *in vitro* research, for example, are difficult to extrapolate to clinical usage because of the problem of knowing how the *in vitro* dosage relates to dosages in clinical practice. Ultrasound at an intensity of 1 W cm^{-2} applied to cells in a dish, which might have a volume of 2 mL will produce very different effects if the same cells are part of a tissue with a volume of, for example, 200 mL. And it is not simply a case of adjusting the intensity in proportion to the tissue volume, as the distribution of energy in a particular volume will vary. Biophysical analysis can bridge the knowledge gap but demonstrated clinical effects avoid the possibility of errors in extrapolation.

Similarly, the findings of studies involving the treatment of experimentally induced pain, particularly if positive, should be replicated

A problematic example is laser therapy. Biophysical evidence indicates that any physiological effects must be superficial yet claims are made that deeper effects can be produced. A physiological basis for the depth effectiveness of laser therapy is lacking. The research findings are mixed and generally inconclusive. Identifying a biologically probable and plausible mechanism is important especially when improbable statistical relationships are identified between the use of a modality and an outcome (Cromie et al., 2002).

Replications should either be systematic, in which parts of the method are modified to extend knowledge of a topic, or direct replications which might, for example, use a larger subject population if a previous study found an effect which did not demonstrate statistical significance.

Clinical evidence of effectiveness, a demonstrated dose–response relationship and a sound biophysical and physiological explanation together provide the best rationale for using a particular modality.

This last point, independence, can be difficult as research, traditionally government funded, is increasingly being outsourced in many countries. This can affect both what is funded and what is published and hence reduce the opportunities for truly independent research.

using a patient population because conditions such as pain can be markedly altered by context (see chapter 6). While studies using university or college students may allow better control of confounding variables, because these subjects do not meet the same criteria as a relevant patient population, the clinical significance of the results are still open to question. Subsequent clinical studies are needed to explore the generalizability of a finding. Does it apply, for example, to older patients as well as to younger? Does the presence of specific co-morbidities alter the expected outcomes?

Research into EPAs must also take into account the possibility of a placebo contribution from often impressive looking equipment. In itself a positive outcome from an inert treatment is quite acceptable but this does not advance the argument for using a particular modality in the future. Clinical trials need to account for, exclude or minimize the possibility of a placebo effect as part of the process of identifying a dose–response relationship for a modality and an explanation of why it works.

The fifth criterion proposed above relates to selecting appropriate types of patients for clinical trials and using relevant outcome measures. Many modalities are used to promote healing. A relevant question concerns the extent to which the timeframe for healing can be reduced. If there are no neurological, metabolic, vascular, immunological or other such impediments there is an onus on those recommending an EPA to show how its use will expedite repair. This is particularly so when few outcome measures could identify small changes, such as a half-day benefit, in an expected 7-day process. By contrast, with pathologically slowed healing, demonstrating a change in the rate of expected healing should be considerably easier. An integral part of this is identifying a plausible mechanism by which the modality affects the outcome. For example, methods of increasing blood flow, such as sensory level electrical stimulation, might increase the rate of healing of chronic ulcers by stimulating the autonomic nervous system and increasing the local blood flow if the area has normal or near normal sensory innervation.

Evidence that by itself should generally not be viewed as sufficient is that produced by a manufacturer or salesperson. Both have a vested interest in sales and should not be expected to be able to present a balanced argument and overview of all the supporting and non-supporting literature. The effects of ‘positive only’ reporting and a lack of scrutiny of the methodology of published research can lead to clinical adoption of suspect modalities. For example, the use of lasers increased in parts of Europe during the 1990s but without a commensurate level of methodologically adequate supporting evidence from systematic reviews or individual clinical studies (Cambier and Vanderstraeten, 1997). Extending this and including Sullivan’s fifth criterion suggests that the proponents of new equipment and advocates of new uses of existing equipment should always be prepared actively to seek independent scientific and critical evaluations. To ensure independence such evaluations must not involve subsidization

or other active assistance beyond that available to any other researcher or user.

ISSUES IN OBTAINING EVIDENCE

An issue that affects the quality of evidence for some modalities concerns dosage. Evidence that equipment has been adequately calibrated is not always provided, particularly with ultrasound equipment. Even if provided, the stability of the output is uncertain in some machines. Other issues affect the reliability of related evidence. How energy is provided clinically can require very specific descriptors such as the speed of movement of an applicator (if ultrasound) and the area to which it is applied (many modalities including ultrasound, heating, cooling and electrical stimulation) or the ambient temperature to ensure replicability. This is not always achievable in a clinical trial and the results of laboratory trials, as noted above, although more easily controlled, often cannot be directly extrapolated to clinical conditions.

COMPARISONS

Comparisons of different types of treatment approaches are important. One such study compared the outcomes from using electrical stimulation or a medication to treat osteoarthritis of the knee (chapter 6). Others have investigated the role of cooling following orthopaedic surgery (chapter 12), microwave with primary dysmenorrhoea following the usual medical treatments (chapter 15), and the contributions of ultraviolet radiation and photosensitizers to changes in psoriasis (chapter 17). This type of approach permits cost-benefit analyses of treatments as the benefits can be identified and the relative cost levels evaluated.

Considerably more comparisons between different EPAs and of EPAs and other types of treatments are needed. For example, which type of deep heating is optimal and when: shortwave diathermy, microwave diathermy or MHz frequency ultrasound. Similarly, without further research it is only conjecture that a hot pack is a simpler, cheaper form of heating than 45 kHz ultrasound (chapter 9). Without such studies it is hard to establish the conditions under which a particular type of treatment is optimal and, generally, when an EPA is preferred to the other options.

THE FUTURE FOR EPAS

Two major factors will affect the future of electrotherapy: research on the topic and future technological advances. Without considerably more research that is methodologically acceptable and relevant there

is a risk that users will limit their use of EPAs. The focus on ‘evidence-based practice’ has grown considerably over the past decade. While the principles are usually now core concepts in entry-level education of clinicians, there is also an increasing recognition that the criteria used to define acceptable evidence are far too restricted. Such restricted evidence alone cannot be used to make sound clinical decisions (Guyatt et al, 2005). Similarly, systematic reviews cannot provide guidance in specific circumstances, as is well known along with the idea that the absence of answers does not mean a lack of evidence (Petticrew, 2003).

It is important that graduate clinicians continue to have sufficient depth and breadth of knowledge to be effective and discriminating users of a range of EPAs and they should also conduct clinical research. This could only improve our knowledge of which EPAs are clinically effective and under what conditions and what the risks are.

Technological advances that will be important for users of EPAs include the increasing miniaturization and concurrent sophistication of electronic hardware. Also, the development of increasingly adaptable software that can alter the output in response to a patient’s input will have a major impact. So, too, will the increasing the storage capacity of batteries and decreasing the size of electronic devices.

All in all, the future of EPAs lies in the hands of researchers, clinicians and technological developers. More research is needed to identify when using an EPA is effective, more well-informed and effective clinicians are needed, using and researching their uses of EPAs, as is increasingly better and more reliable equipment. If this is the direction for the future it bodes well for users of EPAs.

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Background biophysics and physiology

CHAPTER

2

Electrophysical agents have a long and interesting history and many uses were discovered long before the underlying biophysical and physiological processes were understood. Thus electrical stimulation was used well prior to any real understanding of the nervous or musculoskeletal systems. Historically, the discovery of many physical phenomena has led to exploration of their effects on the human body. Sometimes the results have been productive, as evidenced by the range of electrophysical agents available today. Sometimes such exploration has proved to be an electromedical cul-de-sac (for example, the discovery of magnetism and the subsequent pursuit of the possible benefits of magnets for healing).

The aim of this chapter is to provide a biophysical and physiological basis for the electrophysical agents which are commonly used clinically. This is to aid the understanding of clinically useful modalities and to explain why some treatments are likely to be useful and others unlikely to be so. It also provides a basis for evaluating the potential usefulness of new modalities as they are introduced into the market, as indicated in chapter 1. In the absence of adequate clinical evidence, a test must be carried out to investigate whether any claimed benefits are biophysically and physiologically plausible. If the clinical evidence does not yet exist but the physiological basis of the intervention is sound, the therapist can have much more confidence than if the clinical evidence is lacking or there is no sound physiological or biophysical basis. The emphasis in this chapter is on the hard science rather than clinical studies. Individual chapters provide more detail on some specific issues, where directly relevant.

An issue of central importance in electrotherapy is how electrophysical agents can affect the target tissue. One aspect of this, the skin as a barrier, was mentioned in chapter 1. The other aspect is that the human body is homeostatic, i.e. it resists any physiological change from predetermined values. Thus, for example, body temperature is controlled, as is the neural activity of the autonomic nervous system. Yet the aim of electrotherapy intervention is to change the body's activity or response to existing injury.

Homeostasis relies on physical structures (e.g. the skin) and neurological activity affecting the behaviour of tissues and organs to resist

change. The physiological response to electrophysical agents is markedly influenced by the skin. It is the barrier which separates the organism from its external environment. It resists heat flow, the flow of electric current and the transmission of electromagnetic radiation. The response to an electrophysical agent is also determined by the organs and organ systems of the body. Thus if a particular treatment modality produces tissue heating, homeostatic mechanisms respond to reduce the heating. Any understanding of the clinical effects of a particular modality must be set against a backdrop of physiological homeostatic mechanisms.

THE SKIN AS A BARRIER

The skin is the largest organ of the human body with an area, in the adult, of about 2 m². It serves a number of important roles:

- as a first line of defence against infection. Very few microorganisms can penetrate the skin and various skin glands secrete antimicrobial molecules.
- to protect against water loss. The significance of the skin's role in restricting water loss is seen in burn victims who need intravenous fluid replacement if the area of skin loss is large.
- as a key element of the body's temperature regulation mechanism. Heat gain and loss are controlled by blood flow in the skin and immediate subcutaneous tissue and also by perspiration. This is discussed further in chapter 10.
- to shield deeper tissue from electromagnetic radiation, in particular, infrared, visible and ultraviolet radiation. This is discussed further in chapters 16 and 17.
- to protect against mechanical injury of the underlying soft tissues.

Subcutaneous tissue

The tissues under the skin include the blood and lymphatic vessels, the fat, muscles, bones, nerves, and a range of organs ranging from sensory to digestive and excretory. An important feature of these for users of electrophysical agents is that their function can be affected despite the homeostatic mechanisms which invariably operate. In the following we consider cells, tissues and organs with a focus on properties which help to explain the effects of electrophysical agents.

CELLS

A particular feature of cells is that, although they are electrically neutral, the outside of the cell is positively charged while the inside is

equally negative. This is because of two factors: (i) the concentration of potassium ions, K^+ , inside the cell is high and (ii) the membrane is relatively permeable to K^+ ions. All human cells have a higher concentration of potassium ions inside. For sodium ions the situation is reversed: the concentration of Na^+ inside the cell is low and outside is much higher. A sodium/potassium pump in the cell membrane uses energy to actively move sodium ions out and potassium ions in to maintain the imbalance.

Because the membrane is quite permeable to K^+ ions but relatively impermeable to Na^+ ions or most negative ions, K^+ ions diffuse out, down their concentration gradient and the outside of the membrane becomes positively charged. K^+ ions do not take negative ions with them as most of the negative intracellular ions are too large to be able to cross the membrane. Thus a potential difference is established across the membrane. The outside is positively charged and the potential difference or voltage across the membrane is typically 70 mV or so. The inner surface of the membrane remains negative to the outer under most, but not all, circumstances.

Similar charge differences exist across the membranes surrounding the intracellular organelles, such as the endoplasmic reticulum, Golgi apparatus and nucleus. Mitochondria require hydrogen ions (H^+) to be in a higher concentration outside the inner mitochondrial membrane in order for the mitochondrion to be able to synthesize ATP. Thus cells have a net positive charge on their membranes due to K^+ ion movement, while mitochondria have a net positive charge on their membranes due to outward movement of H^+ ions. (For an extensive and valuable description of the electrical features of cells and cellular activity, see Charman (1990b,c).)

As already noted, the difference of potential across a normal cell membrane at rest, known as the resting membrane potential, has the inside of the cell negative relative to the outside. The potential varies in the cells of different tissues, being anything between -60 and -90 mV. In nerves and smooth muscle fibres it is usually about -70 mV, for skeletal muscle cells -80 mV and for glial cells -90 mV (Bray et al., 1986). This electrical potential – as it were an ‘electrical pressure’ – across the cell membrane is due to the fact that such membranes are much more permeable to K^+ than to Na^+ . The Na^+/K^+ pump ejects three ions of sodium for every two of potassium that it takes in. The result of both mechanisms is a deficiency of positive charges inside the cell compared to the outside, hence the membrane potential.

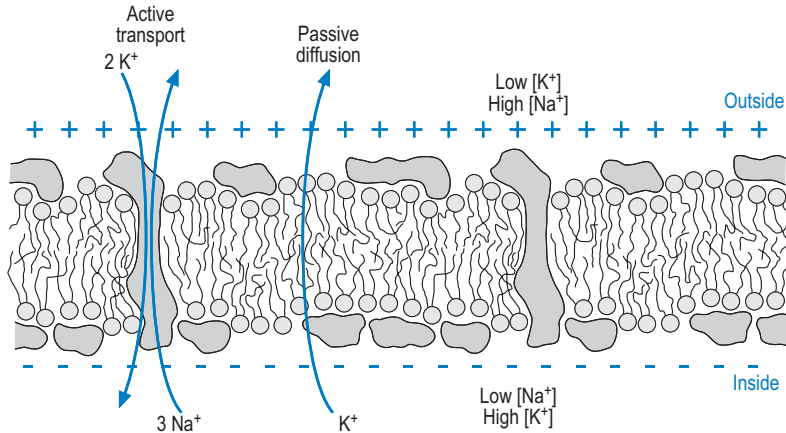
This sodium-potassium (Na^+/K^+) ‘pump’ uses active transport to move these ions against their passive gradients. Potassium ions also move out of the cell by passive diffusion.

As well as the Na^+ and K^+ pump, the concentration of Ca^{2+} inside the cell is maintained at a much lower level than outside by an important Ca^{2+} pump mechanism. In both cases adenosine triphosphate (ATP) supplies the energy needed.

The resting membrane potential of nerves

Neurons consist of a cell body and several extensions which convey the nerve impulses to and from the cell body. As with other cells, a resting membrane potential is present across the membrane of the cell body. The same membrane potential exists across the whole length of

Figure 2.1 The resting membrane potential is principally determined by passive diffusion of potassium ions and active transport of sodium and potassium ions (the sodium/potassium pump).



In many tissues the individual cells are connected by gap junctions which allow some electrical conduction between cells. This does not occur in skeletal muscle or nerve tissue (Finean et al., 1978).

the processes, the nerve fibres, which are extensions of the plasma membrane. The longest extension is usually called the axon.

As already stated, the resting membrane potential is ultimately due to active transport (the Na^+/K^+ pump) and to the difference in permeability to Na^+ and K^+ . These ideas are illustrated in Figure 2.1. The situation is like that of a ship at sea in which the lower parts are below the water level but contain air able to pass freely in and out, like K^+ . The seawater, like Na^+ , is kept out by the hull and the small amount that does leak in is easily removed by the bilge pumps, an active transport mechanism. Thus different compounds – air and seawater – are separated by the ship's hull; due to the greater density of water a pressure difference is developed across the hull. If the hull is holed, water will rush in with great force because of the pressure difference, but if the hole is then quickly blocked the small quantity of additional water is ultimately removed by the bilge pumps to restore the situation.

THE NERVE IMPULSE OR ACTION POTENTIAL

The nerve impulse is a wave of electrochemical activity which passes along the nerve fibre using energy already stored as part of the membrane potential. It is a reversal of the membrane potential from -70 to $+30$ mV which occurs very briefly – taking about 1 ms – and spreads along the fibre without decrement. It is also called an action potential.

The impulse is initiated by depolarization – an alteration of the balance of charges – of the fibre membrane due to chemical disturbance at a synapse or receptor or to some other disturbance such as an electrical pulse. Depolarization means that the potential difference across the membrane is reduced from the -70 mV of the resting membrane. However, the impulse is only triggered when the membrane is depolarized by about 10–15 mV (i.e. to about -55 mV). Once this

threshold is reached the impulse, or action potential, is generated automatically (Figure 2.2) and spreads along the nerve fibre at a rate that is characteristic of the particular fibre. If the impulse is initiated normally it will pass only in one (orthodromic) direction (distally if an efferent nerve and proximally if an afferent). If the middle of a nerve fibre is artificially stimulated two impulses will travel away from the point of stimulation, one in each direction, orthodromic and antidromic (opposite to the anatomical direction for that nerve fibre). This is shown in Figure 2.3. Whether antidromic stimulation has any physiological effect (either positive or negative) is unknown.

The effect of depolarization beyond the threshold level is to cause the membrane to become much more permeable to Na^+ by opening special channels or gates. Na^+ rushes through these channels into the fibre causing an abrupt and rapid local reversal of membrane polarity (-70 to $+30$ mV, Figure 2.4a), after which the Na^+ channels close. Depolarization also causes K^+ channels to open but the response of the K^+ channels is slower. Consequently, the rush of Na^+ into the fibre is soon stemmed and there is a loss of K^+ from the fibre. In this way the membrane repolarizes again (Figure 2.4b). Once the process is started, rapid depolarization followed by repolarization occurs automatically. A period of hyperpolarization follows (Figure 2.4c), during which time the K^+ channels are closing and the membrane takes several milliseconds to return to the normal resting state.

The voltage-gated sodium ion channels operate by an alteration of their protein configuration in response to varying local electrical potentials (Hille, 1992). Thus these Na^+ channels can be in at least three states:

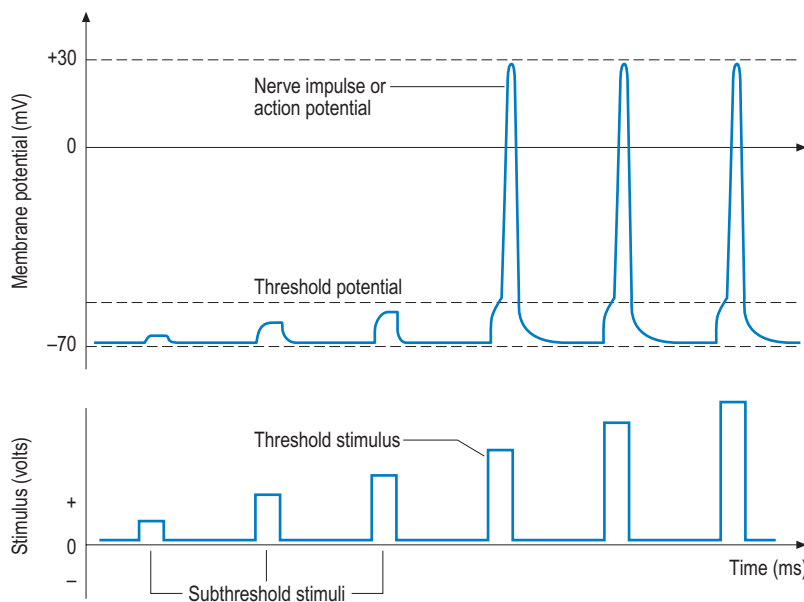


Figure 2.2 Response of a nerve fibre to electrical stimuli of increasing intensity.

Figure 2.3 Orthodromic and antidromic propagation of action potentials in response to electrical stimulation.

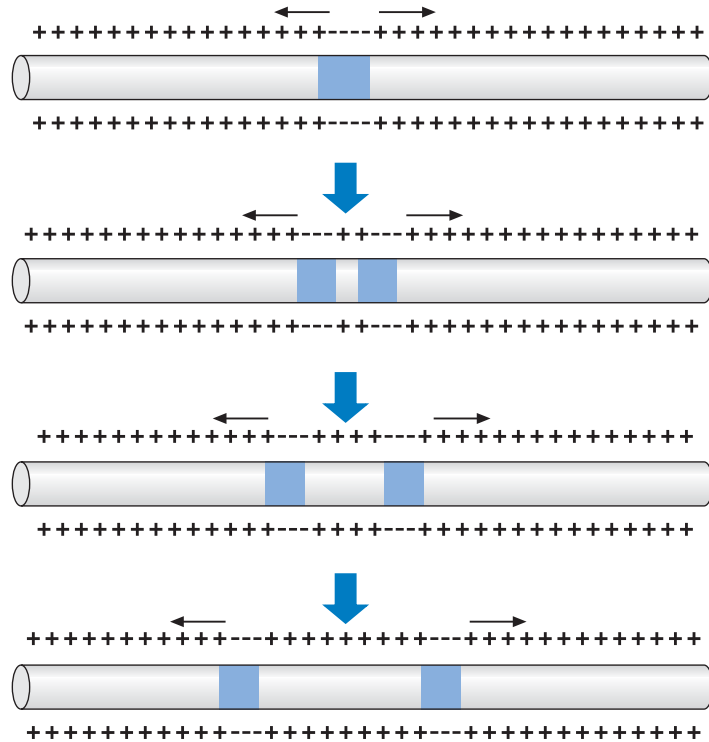
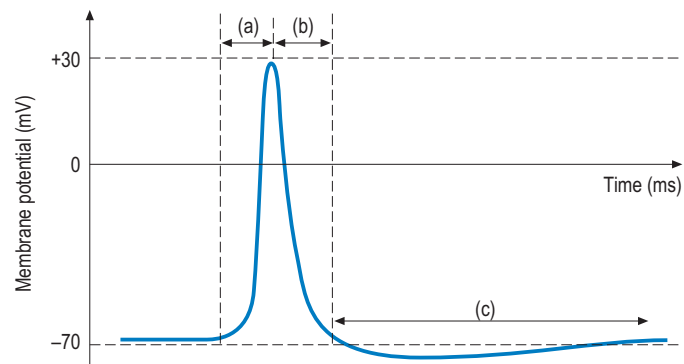


Figure 2.4 Stages of the action potential: (a) depolarization, (b) repolarization and (c) hyperpolarization.



In reality, Na^+ channels are constantly opening and closing due to random local voltage fluctuations, but this is inconsequential until a large number of channels are affected simultaneously.

- closed, but ready to open instantly
- open
- closed but unable to open instantly.

They go through these states in sequence in response to a voltage change beyond threshold, spending a very brief time open and a longer

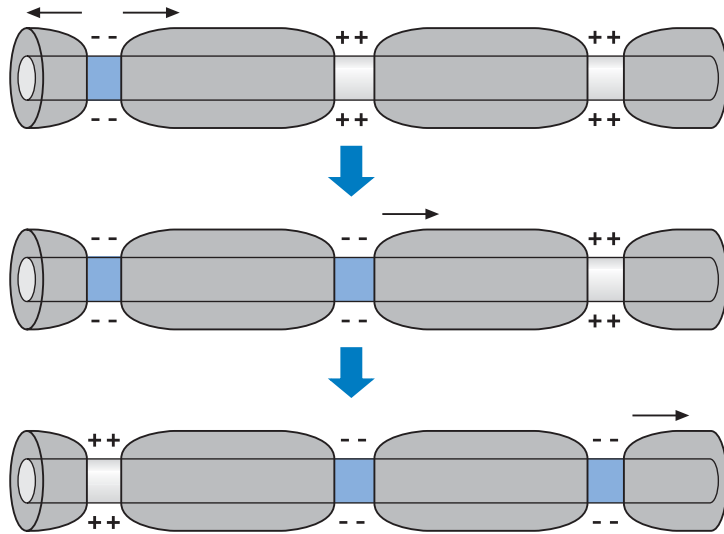
time – a millisecond or so – in a closed but inactivated state. These are absolute states for the channel which ‘flips’ almost instantaneously from one to the other: there is no half-open condition. The smooth rise and fall of the action potential, as in Figure 2.4, is due to many Na^+ channels opening and closing to cause an average voltage curve.

Although an action potential involves Na^+ ions moving into the cell and K^+ ions moving out, the change in concentration of these ions is extremely small. For example, it has been calculated that an outflow of only one hundred thousandth of the total K^+ in the cell can alter the membrane potential by 100 mV (Alberts et al., 1994). Similarly small quantities of Na^+ ions enter the cell. Ultimately the situation is restored by the Na^+/K^+ pump. Even without the activity of the pump, the impulse can occur many hundreds of times before the concentrations change enough to alter significantly the membrane potential. The ship analogy used above is appropriate; many small rushes of water could be allowed to enter the hull before the ship is in danger of sinking, even if the bilge pumps are not working.

The impulse will travel along the length of the fibre because the depolarization spreads in all directions. Since the voltage-dependent sodium gates are opened once the threshold is reached, the electrical charge spreading along the surface of the membrane causes the next area of the fibre to depolarize and so on. Once the impulse has passed, that particular part of the fibre membrane is refractory, i.e. it cannot be stimulated until it has repolarized. The first part of the action potential (Na^+ ions rushing in) is analogous to a line of dominoes set up so that when the end domino is pushed over it falls against the next which falls against the next and so on. A wave of falling dominoes thus travels along the prearranged line. Such a system has the characteristics of the initial part of the nerve impulse in that energy is stored in the upright position of the domino, like the store of energy in the membrane potential. Also the domino has to be disturbed sufficiently to bring its centre of gravity outside its base – beyond the threshold – from which point it accelerates downwards, tipping over the next domino as it goes. The falling domino has the same positive feedback properties – rapid acceleration to the limit of the system – as the reversal of membrane polarity due to the inrush of sodium ions. Of course, the nerve membrane potential is automatically reset but the domino line needs the attention of a dexterous human hand to reconstruct it.

The speed of propagation of the nerve impulse along the nerve fibre varies in different nerves. Generally, the larger the nerve fibre diameter the faster its conduction. Further, many nerve fibres are surrounded by an electrically insulating sheath, the myelin sheath, interrupted at intervals by the nodes of Ranvier which are exposed areas with no myelination and many voltage-gated ion channels. The electrical potential of the nerve impulse travels along the fibre but only triggers depolarization at the nodes of Ranvier. When one node is depolarized this triggers depolarization in the next node without the action

Figure 2.5 Saltatory conduction of the action potential in myelinated nerve fibres.



potential having to travel along the intervening myelinated region of the fibre. The change in the membrane potential when an action potential is produced at one node (about 100 mV) is large enough to trigger an action potential at the adjacent node. Thus the nerve impulse can be described as skipping from node to node (Figure 2.5) using less energy and travelling much faster. This is called saltatory conduction. Single nerve impulses can be recorded on the skin surface to investigate their conduction rates in peripheral nerve conduction studies.

The action potential will actually be spread over many nodes of Ranvier at any one time. The higher the conduction velocity the greater the length of fibre which is depolarized. At the extreme, for instance, an impulse travelling at 100 m.s^{-1} may occupy some 5 cm of axon length (Bray et al., 1986).

The transfer of information in the nervous system and the regulation of muscle contraction are 'coded' by the number and frequency of nerve impulses.

Summary

A nerve impulse is:

- an 'all-or-none' event
- triggered by a disturbance of the nerve fibre membrane electrical potential beyond threshold potential
- an electrochemical disturbance – a depolarization – which travels along the length of the nerve fibre
- identical in magnitude and velocity for any given nerve fibre
- able to travel more rapidly in a myelinated nerve fibre.

ACTIVATION OF MUSCLE FIBRES

Like nerves, muscle fibres also produce an electrical disturbance: this causes them to contract. Action potentials in motoneurons result in release of the neurotransmitter acetylcholine (ACh) at the nerve fibre ending, the neuromuscular junction. The ACh triggers depolarization of the muscle fibre membrane at the junction and a wave of depolarization spreads along the muscle fibre membrane. It is this wave of depolarization which causes the whole muscle fibre to contract. A single motor nerve innervates, i.e. synapses with, many muscle fibres and so will activate them as a group. A *motor unit* consists of a single motor nerve together with the muscle fibres it supplies, which can range from several hundred in a large muscle to only several in smaller muscles involved with precise movement and control. The central nervous system thus has control of motor units rather than individual muscle fibres. A fascinating feature of muscles is that they are extremely well designed to produce smooth, precise contractions regardless of the force required. For low force contractions, motor units with small numbers of muscle fibres are activated, and activated at a low frequency. For increased force production, motor nerves fire at higher frequencies and more motor units are activated. As the force requirements increase, motor units with larger numbers of muscle fibres are recruited. This is discussed further in chapters 4 and 5.

When many muscle fibres contract, the electrical signal produced is quite large, much larger than that of the motor nerve fibres activating them. This is simply because one motor nerve innervates many muscle fibres. The electrical activity of muscle can be measured at the body surface. Skeletal muscle activity can be detected using skin-mounted or needle electrodes and amplified, then displayed as an electromyograph or EMG. The size of the signals recorded depends on the number of active muscle fibres. There is, therefore, considerable variation in the size of the EMG signal, depending on the size of the muscle and the proportion of the muscle fibres activated.

Nerve fibre activity is much harder to detect and record because the electrical signal is so much smaller. The normal method of making non-invasive measurements is to use skin-mounted electrodes and record multiple events, e.g. the nerve response to repetitions of a single electrical stimulus, then average the measurements so as to reinforce the nerve activity signal while averaging-out the random variation in the electrical signal, which is called 'noise'.

Another example of this is the way in which information about the heart can be provided in the form of an ECG or electrocardiogram.

ELECTRICAL POTENTIALS OF OTHER CELLS AND TISSUES

Nerve and muscle cells are not unique in having a potential difference across their plasma membranes. All tissue cells have this characteristic. The difference is that nerve and muscle fibre membranes

undergo large, transient changes in the membrane potential (action potentials) as part of their normal function, while other cells do not. The membrane potential is important in all cells as it acts as a source of energy for moving molecules across the membrane. This is important because the principal role of the membrane is to be a barrier to the ingress of most molecules. Nonetheless, there are many molecules which are needed by the cell and which must be able to enter without difficulty. The membrane potential is a source of energy for the process of secondary active transport, whereby molecules which would otherwise be unable to cross the membrane are moved across at specific transport sites using the electrical energy of the membrane potential.

Tissue potentials

A transcutaneous voltage normally exists in human skin. The stratum corneum is negatively charged with respect to the dermis, with an average potential difference of 23 mV (Foulds and Barker, 1983). One study reports that relatively hairless skin surfaces, such as the hands and feet, show a greater potential difference, but always negative to the dermis in all areas and with all subjects tested. Similar skin potentials occur in animals, and experiments on guinea pigs showed that incisional wounds are associated with a decrease in the measured potential difference (Barker et al., 1982). Similar changes have been observed in human subjects.

These differences have been argued as evidence that wound healing may be partly controlled by electrical signals and hence that electrical stimulation might influence wound healing. The argument is not fully convincing, particularly given the developing explanation of the possible contribution of another factor, the stimulation of the autonomic nervous system by cutaneous stimulation. The (limited) clinical findings are discussed in chapter 6.

Electrical charges generated by connective tissues

Strain generated potentials are found in bone and other connective tissues. These are charges resulting from, and proportional to, mechanical deformation of the tissue. The mechanism is not fully understood but is widely described as a piezoelectric effect (see chapter 9) though it involves greater complexities (Charman, 1990e). Bone growth and remodelling are known to be controlled by mechanical forces causing strain generated potentials, which in turn stimulate cells (osteoblasts or osteoclasts) and cause either bone growth or absorption. Similar mechanisms are believed to apply in the control of connective tissue remodelling in which the balance of collagen fibre synthesis and breakdown is controlled by strain generated potentials along the collagen fibrils.

Electrical gradients in embryonic development

In animals and plants that have been extensively studied, embryonic development is associated with potential gradients. These are generated by cellular activity and seem to have a growth-regulating function. Experiments with some simple animals have shown that artificially reversing the electrical polarity can reverse the direction of head-to-tail development. All embryos seem to have electrical polarity which develops soon after fertilization.

Electrical gradients in limb regeneration

Most adult animals including humans are entirely unable to regenerate the complex masses of tissues involved in the regrowth of limbs. A few, however, notably the salamander, have the ability to regrow a new limb after surgical amputation. This appears to be achieved by blastoma formation near the amputation site whose undifferentiated cells develop to form the new limb tissues. Innervation seems to be an essential component. A similar amphibian, such as a frog, that has no regenerative capacity shows a very much smaller change in potential across the wound.

The importance of wound potentials in both healing and regeneration is uncertain, particularly in determining what is cause and what is effect. The importance has been shown in humans in the amputation of part of the terminal phalanx of a child's finger. Such a wound has been shown to heal and the end of the finger regenerate if kept moist (Illingworth and Barker, 1980). Several other small tissue potentials and gradients have been described, some in the nervous system but entirely separate from the impulses due to varying transmembrane potentials described above. For a review of this whole topic see Charman 1990(a–f) and 1991(a and b).

There are claims of partial regeneration in non-regenerative animals produced by the application of artificial currents in various experiments; see Charman (1990d) for a review.

THE HEALING PROCESS

Throughout this book reference is made to the effects of various therapeutic modalities on the inflammatory, healing and repair processes, and pain symptoms of healing. It seems appropriate to give an outline of these changes at this point with some discussion of the mechanisms involved.

The tissue response to damage is often described in terms of mechanical injury to the skin and subsequent infection by bacteria. The series of changes that ensue are much the same whatever the tissue involved and however the injury is caused. Thus the visible changes of an accidental cut in the skin are very similar to the less visible changes following a muscle or ligament tear. The reason is, of course, that the response to any kind of damage is similar in all vascularized

tissues; it is the response to some irritant. This could be the products of damaged cells or some introduced organism, say a bacterium, or a chemical or radiation irritant. It is usual and convenient to describe these changes as a sequence of stages which decidedly overlap and occupy varying lengths of time. Thus the process can be characterized in the four stages of initial injury, inflammation, proliferation and remodelling.

Initial injury

Consider a slip with a kitchen knife resulting in a flesh wound. The initial laceration produces little damage or cell death. Far greater damage occurs secondarily when blood clotting, essential to prevent blood loss, causes local hypoxia and secondary cell death in the vicinity (see chapter 12).

This results in damage to cells and small blood vessels. Cells die as a consequence of direct damage. This is followed by secondary cell death due to factors such as oxygen deficiency due to the damaged blood vessels, or chemicals released from other damaged cells. The extracellular structure of the tissues may also be damaged with tearing of fibres and disruption of the ground substance. If the damage is at the surface, bleeding is visible, otherwise the extravasated blood is trapped in the damaged tissue. Within a few minutes the released blood starts to clot, which serves to plug the leaking blood vessels, helps to immobilize the area and traps bacteria. Clotting is precipitated by the aggregation of platelets and the activation of a 'cascade' system of enzymes. These convert prothrombin to thrombin which causes the soluble plasma protein, fibrinogen, to become the insoluble fibrin. This complex process of blood clotting, which involves an extrinsic and intrinsic system, is an important trigger to the inflammation that follows. It causes, among many other important reactions, the production of bradykinin and initiation of the complement cascade, which is a system of interacting proteins in plasma associated with the activity of antibodies, especially in the presence of contaminants. The clots are dissolved after about 5 days by fibrinolysis.

Inflammation

This word, derived from a Latin word meaning to burn, is especially apt since, when the skin is involved, it becomes hot, red, swollen and painful (calor, rubor, tumour and dolor). These are the four cardinal signs of inflammation. To these it is appropriate to add a fifth – loss of function. Inflammation is basically the result of the microcirculation of the tissues reacting to injury.

Vascular changes

First, there is a very brief vasoconstriction of the non-injured vessels in response to irritation, followed by prolonged dilation. This dilation includes arterioles, venules and lymphatics in both active and dormant channels. The total blood flow to the region is, therefore,

increased, although the rate of flow in individual channels may be diminished. This leads to both redness and increased temperature of the skin. White blood cells – polymorphonuclear leucocytes – move to the edge of the blood stream, lining up along the endothelial vessel wall, in a process called margination. They subsequently pass through the vessel wall into the adjacent tissue fluid. The endothelial cells forming the vessel walls partially separate at their junctions, leading to increased vascular permeability. This is due to direct damage which loosens the intercellular junctions in both capillaries and venules. The endothelial cells of venules are also able to contract – pulling away from one another – when affected by chemical mediators such as histamine. This has tremendously important consequences, because it allows much more plasma protein (albumin, globulin and fibrinogen) to leave the blood vessel and enter the tissue fluid. Because of this, the osmotic pressure between the blood and tissue fluid is altered so that fluid leaves the vessels and enters the tissue spaces. This is further encouraged by the increased capillary hydrostatic pressure due to arteriole dilation. The resulting increase of fluid in the tissues is called oedema and the fluid itself is called an exudate. This, then, is the cause of the swelling associated with inflammation. It seems to be beneficial in the presence of infection since it dilutes bacterial toxins and allows the passage of immunoglobulins (antibodies circulating in plasma) and complement (a system of plasma enzymes) which will promote the destruction of bacteria. By the same mechanism that leads to coagulation of blood, fibrinogen in the exudate is converted to a fibrin network. This both limits the spread of bacteria and makes them more susceptible to phagocytosis by white blood cells, as discussed later.

Where no infection is present, the value of the laying down of fibrin is less evident, as it can lead to restriction of movement in the tissues and hence later functional impairment, which is sometimes permanent.

Activation and control

While the vasodilation and exudation are a standard universal response, the causative agents are complex and multiple. Initially, histamine, formed from the amino acid histidine, is released during many kinds of injury, much of it being from degranulated mast cells; these are wandering cells found in large numbers in connective tissue. Also at this stage, serotonin (5-hydroxytryptamine), probably from platelets, contributes together with local inactivation of adrenalin. Collectively, these allow early vasodilation to occur, which is maintained by the activation of kinins by enzymes triggered by some of the processes of blood clotting. (Kinins are a group of polypeptides, which includes bradykinin.) There are many other groups of substances which provoke features of the inflammatory reaction, particularly a group of fatty acids formed from arachidonic acid in or on the cell surface. These form a group called prostaglandins and another group called leukotrienes. Prostaglandins are affected by non-steroidal anti-inflammatory drugs and both groups by corticosteroids, which may account for the anti-inflammatory action of these drugs. Additionally, steroids may inhibit macrophage levels. Further mediators

include enzymes from the complement pathway. These are also involved in histamine release and chemotaxis, specifically the attraction of neutrophils to the area. Among many other mediators are platelet activating factor, plasmin and cytokines. The complex sequential appearance of so many different substances to promote vasodilation seems complicated, but these are systems that control not only the initiation and completion of inflammatory change but also its nature and intensity.

Pain

The pressure applied to sensory nerve endings by exudate accounts for some of the pain associated with inflammation. This becomes very obvious if expansion of the tissues is restricted, leading to higher pressure. Pain is also provoked by all the chemical mediators that cause vasodilation, notably the kinins. Histamine may only provoke itching and the prostaglandins may act by potentiating the effect of other pain-provoking substances. Other chemicals liberated by cell injury may also cause pain.

Cellular response

Almost immediately after formation of the fluid exudate, polymorphonuclear leucocytes (neutrophils) start to pass through the vessel wall by inserting pseudopodia in the gaps between cells and 'flowing' through, a process called diapedesis and a continuation of the margination noted above. A little later, these neutrophilic granulocytes are joined by monocytes which, once in the damaged area, develop into macrophages. Both types are attracted to the area by chemotaxis due to many of the mediator factors noted above. The principal function of the polymorphonuclear leucocytes is phagocytosis of pathogenic bacteria. This process of engulfing and destroying bacteria and other unwanted particles invariably leads to the death of neutrophils. If very large numbers are involved due to the extent and virulence of the invading bacteria then pus is formed, which is usually extruded from the surface. Macrophage cells are not only phagocytic and much longer lived than neutrophils, they also release chemical factors needed for the proliferative and remodelling phases. Phagocytosis appears more effective when particles and bacteria are trapped in the fibrin mesh. Lysosomes release digestive enzymes which break down dead cells and bacteria.

Influence of the nervous system

Although inflammation will proceed apparently normally in denervated tissues, the vascular responses, at least, are influenced by nerve fibre activity. At a very basic level the triple response occurs as a result of sensory and vasomotor nerve activity. At the site of the damage there is an initial red reaction which appears within a few seconds.

The contribution of the higher levels of the nervous system can be seen from the fact that hypnosis can be used both to increase and decrease the vascular inflammatory response, although it does not directly affect cellular activity.

This is caused by capillary dilation due to direct pressure. It is followed by local mild swelling – a wheal – because of the increased permeability of capillaries and venules, and a more diffuse redness – a flare – caused by arteriolar dilation. It is due to an axon reflex in which sensory nerve stimulation results in impulses being relayed antidromically via a branch (axon) of the peripheral nerve to the arterioles. Stimulation of polymodal pain receptors also leads to the release of neuropeptides from the (pain signalling) C fibres which help to trigger inflammatory responses; substance P is probably the most important of these. Adrenalin, controlled by the sympathetic nervous system, can inhibit the vasodilation of inflammation. The effects of the higher centres of the nervous system on the perception of the pain of inflammation are well known and can both inhibit and exaggerate.

Summary

Initial injury:

- damage to cells
- damage to extracellular structures
- bleeding into or outside tissues
- blood clotting.

Inflammation – ‘calor, rubor, tumour and dolor’:

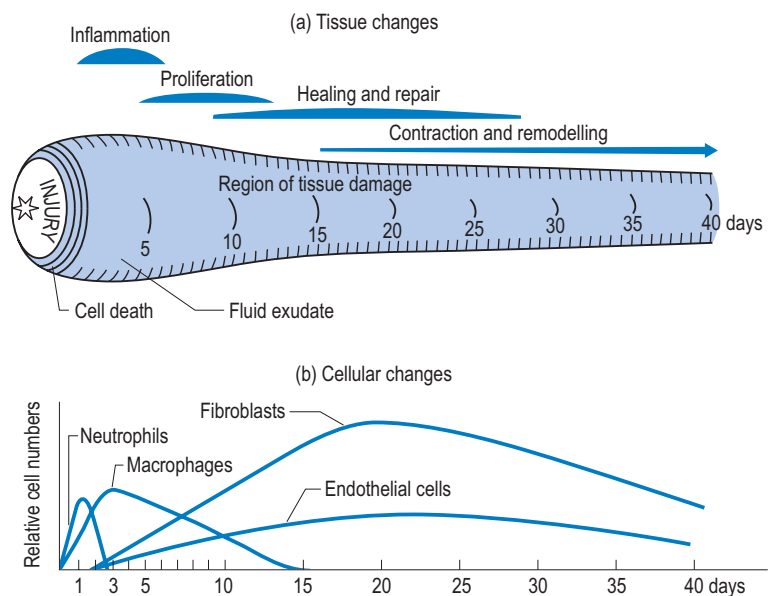
- vasodilation
- increased vessel permeability allowing plasma protein to leak into tissues which produces oedema to dilute toxins and promote destruction of bacteria
- local pain due to pressure of exudate and chemical mediators
- cellular activity
- polymorphs exhibit margination and diapedesis and phagocytosis
- macrophages appear later and are longer lasting than polymorphs. Macrophages are not only phagocytic but also release important chemical agents controlling later phases
- control of inflammation effected by complex sequential cascades of chemical activators including histamine, various kinins and prostaglandins
- leucocytes attracted by chemotaxis
- some influence from the nervous system.

Proliferation

This stage lasts about 3–4 weeks. It includes reconstructing the tissues, resurfacing if necessary and giving strength to the wound. It involves the activities of three kinds of cells: macrophages, fibroblasts and endothelial cells (to form new blood vessels, a process called angio-

genesis). Acting in concert, these form new, highly vascular, wound-filling granulation tissue. It is called granulation tissue because of its grainy appearance when sectioned. Macrophages are essential for healing to occur. Not only do they digest and remove wound debris but they also migrate into the damaged area, releasing chemotactic agents which stimulate fibroblast activity and angiogenesis. These new blood vessels appear at first as buds of endothelial cells which grow into the damaged area, branching and eventually joining adjacent buds to form capillary loops when they canalize. As blood starts to flow through them, the oxygenation of the region increases and, at the same time, fibroblasts lay down new collagen fibres to provide a supporting framework. Thus new granulation tissue proceeds, growing in from the normal tissue edges, replacing the dead or dying injured tissues. The macrophages are notably able to tolerate low oxygen levels and thus tend to lead the process. Some of the fibroblasts become myofibroblasts which are able to contract and effect wound contraction by pulling the edges together. Dehydration (drying) also plays a role with skin wounds. The processes can, in certain circumstances, lead to contracture and considerable scarring of the affected tissues. Figure 2.6(b) illustrates the changing populations of the different cells during these phases.

Figure 2.6 The time scale of inflammation and healing.



Remodelling

The repair process continues until the whole damaged area is replaced. At the same time the granulation tissue becomes more fibrous and less vascular, ultimately to become dense fibrous tissue (i.e. scar tissue). At 3 weeks the strength of the wound is only approximately 15% of that of the original tissue. The process of remodelling may continue for months, the structure of the new tissue altering slowly. The number of blood vessels reduces to that appropriate to maintain viability of the tissues. Arterioles, venules and lymphatic channels redevelop, and there is concurrent regeneration of small nerve fibres. The fibroblasts not only lay down new collagen fibres, but also the mucopolysaccharide (proteoglycan) matrix of typical connective tissue. Further, there is remodelling of the connective tissue with time. This phase can last for years, depending on the size of the connective tissue structure. At first the collagen fibres appear to be randomly oriented but subsequently they become rearranged in a way that best resists the stresses to which the tissue is normally subjected. Importantly, this last mechanism depends on appropriate stresses being applied by activity.

If the skin surface has been damaged, the epithelial cells are able to regenerate to cover the area with new skin, a process called epithelialization. A small wound can be covered in 48 hours. This forms a protective barrier which lessens the chances of infection and prevents fluid loss. However, no new hair follicles or sweat glands are formed. This is because some specialized cells are able to replicate while others are not. Most cells lose their ability to replicate when they become specialized (differentiate). Several more or less specialized cells are able to regenerate (i.e. replicate themselves to replace lost tissue) in humans; liver cells are particularly notable in this respect. The general repair of human tissue is, however, restricted by most differentiated cells not being able to replicate. A consequence is that dense fibrous tissue can replace the dead or damaged normal tissue, i.e. there is permanent scarring as a result of the injury.

The application of stress to undamaged connective tissues is essential for them to retain their integrity and mechanical strength. Unstressed connective tissue will atrophy. Repetitive loading can produce tissue hypertrophy.

Timing of the processes

The processes just described overlap to a considerable extent and the length of each phase is very variable depending on the severity of the original injury and whether injury continues over time. The initial bleeding usually lasts only a few minutes but cell death may continue over a few days. Vasodilation starts within an hour or so and continues over several days. Tissue oedema follows a similar pattern but often lasts rather longer. Phagocytosis starts within hours, reaches a peak about 3 or 4 days later, but continues over several days as the debris is cleared. The inflammatory phase lasts approximately 3–4 days. The development of granulation tissue can often be identified after a few days, merging into fibrous repair which may continue for

weeks or months. The time scales of these tissue and cellular changes are illustrated in Figure 2.6.

Summary

Proliferation, healing and repair:

- involves activity of macrophages and fibroblasts as well as angiogenesis to form granulation tissue
- also involves wound contraction.

Remodelling:

- more fibrous tissue formed and resorbed
- scar formation
- regeneration of vessels, nerves in the damaged tissue.

HEALING OF AVASCULAR TISSUES

Most tissues of the human body are vascularized. They have a good blood supply: an elaborate network of capillaries infiltrates the tissue, providing nutrients to the cells and removing waste products. Damage to vascular tissue has the characteristics described above and damage and repair follow the distinct phases described. Some connective tissues – most importantly articular cartilage and intervertebral discs – are avascular (and aneural) and the response to injury does not follow the same path. Because the tissues are avascular, blood clotting and the resulting hypoxia and secondary cell death are absent, as is the inflammatory response. An unfortunate consequence is that the third phase, repair, is also compromised. Tendon is not truly avascular but the blood supply is much lower than normal vascularized tissues and it repairs poorly and at a lower rate.

Generally speaking, the tissue cells function in, and are adapted to, an environment with restricted oxygen and nutrient supply so unless they are directly damaged, injury has little impact on their status. The downside is that because of the restricted supplies, their ability to carry out rapid and efficient repair is strictly limited.

Articular cartilage trauma and repair

Of all the avascular connective tissues, articular cartilage is least able to repair. When cartilage is lacerated superficially, i.e. when the damage does not extend to the underlying bone, very little necrosis occurs. Cell death is minimal as the cartilage cells (chondrocytes) are relatively insensitive to hypoxia and their oxygen and nutrient supply

is relatively unchanged. Inflammation is absent as the tissue is avascular and the third phase, repair, is virtually non-existent. The lacerated region remains essentially unchanged. Chondrocytes are not triggered into repair mode as there are not the stimuli that are produced in injured vascularized tissues. Nor would chondrocytes be able to kick into high gear metabolically because of their restricted nutrient supply. A consequence is that damage remains and this can lead to a downhill spiral of events whereby the cartilage progressively degenerates.

Articular cartilage consists of a framework of collagen fibres embedded in a gel consisting principally of the mucopolysaccharide aggrecan and water. Aggrecan is needed to give the cartilage its compressive stiffness. If the collagen framework is disrupted, aggrecan can escape and the region becomes softer and mechanically weak. This means that, under compressive loading, the stress in adjacent regions will be increased. If the increase in stress is high enough to damage further the collagen fibre framework a vicious circle is set-up, whereby the tissue progressively degenerates.

Although superficially lacerated cartilage does not repair, damage which does not disrupt the cartilage surface at a microscopic level can repair effectively (Buckwalter, 2002). This is presumably because the collagen fibre damage is not extensive and aggrecan has not escaped, so the repair requirements are within the means of the chondrocytes.

With a deeper injury, extending to the vasculature of the subchondral bone, significant repair will occur. The normal response of necrosis, inflammation and repair is evoked. New bone is formed and calcification does not proceed beyond the cartilage–osseous end-plate boundary. A problem is that the cartilage is repaired with a plug of dense, fibrous collagen of a different type to the original and lacking in aggrecan. It is scar tissue rather than true cartilaginous tissue. The repaired cartilage is thus much weaker than the original as the stress distribution under load is quite irregular.

An interesting aspect of articular cartilage is that, because it is completely avascular, it is isolated from the immune system. The collagen in articular cartilage (type II collagen) is different to that of collagen fibres in vascular tissues such as skin and bone (type I collagen). A consequence is that the immune system does not ‘know’ type II collagen and if it is exposed, an immune reaction follows.

The most abundant mucopolysaccharide in articular cartilage is aggrecan. Aggrecan attracts and binds water, resulting in a high internal osmotic pressure, which gives the cartilage its ability to withstand compressive loading.

In rheumatoid arthritis, exposure and sensitization of the immune system to type II collagen leads to an ongoing attack on the microscopic fibrous framework of articular cartilage.

Intervertebral disc trauma and repair

Repair of damaged intervertebral discs is a relatively slow process as there is no inflammatory response. Nonetheless, they do have a limited repair capacity due to the vascularity of the vertebral end-plates and the soft tissue surrounding the disc. This provides a (strictly limited) supply of oxygen and nutrients. If the annulus fibrosus is punctured superficially then, providing that the damage does not extend to the nucleus pulposus, the structure will repair. If the damage extends to

The development of a fibrous mass in the damaged nucleus is because the cells that are stimulated to produce aggrecan also produce collagen. When stimulated by injury, the cells produce not only type II but also type I collagen which forms the coarse fibres found in skin, tendon, ligament and scar tissue.

the nucleus, the annulus does not repair and major changes occur to the nucleus pulposus over time.

The end result is that the nucleus becomes more dense, fibrous and matted, both due to the accumulation of type I collagen and the depletion of aggrecan. Aggrecan depletion means that the nucleus pulposus also has reduced water binding and retention capability. The disc overall is thus more compressible, is intrinsically weaker (because greater compression focuses stress on the outer regions of the annulus fibrosus) and is hence more susceptible to further damage. A problem if the disc is re-injured is that it is not soft, jelly-like nuclear material which is squeezed through the damaged annulus but a tougher fibrous solid. If this impinges on and compresses nerves or the spinal cord, the effects are a good deal more severe and longer lasting than those of the original injury.

Tendon trauma and repair

Tendon is not truly avascular but the blood supply is much more restricted than in normal vascular tissues. Capillaries extend from muscle into the tendon at the musculo-tendinous junction. At the osteo-tendinous junction (the insertion) a much more limited supply is provided. The tissue surrounding the tendon is also well vascularized and so provides a source of oxygen and nutrients (Sharma and Maffulli, 2005).

A complication with tendon repair is the formation of adhesions which can restrict tendon gliding and limit the range of movement (Woo et al., 2000).

When a tendon is torn, cellular injury is confined to a limited number of tendon cells (tenocytes) damaged directly by the trauma. The cells in tendons are widely dispersed in the much more extensive extracellular matrix of collagen fibres and it is the matrix which suffers the main injury. A systemic response is provoked but it is primarily the surrounding vascular tissue which responds and becomes inflamed. Tenocytes near the site of the damage respond slowly (because they can only operate within the limits set by their nutrient supply). In the torn, inflamed region much more dramatic events occur. Granulation tissue is produced and this gradually transforms into dense connective tissue as fibroblasts lay down a new extracellular matrix of collagen fibres joining the two torn ends. The joining region is bulbous and the collagen fibres are disorganized. With time, vascularization reduces and the tissue starts to resemble tendon. Over a period of months, the scar tissue remodels so that fibres are aligned along the axis of the tendon (Lin et al., 2004).

Tendon injury can provoke swelling and inflammation of the tendon sheath and surrounding tissues and this can produce the pain. The pain and inflammation follow the usual pattern and reflect the course of injury. The symptomatic changes which occur are rather unreliable indicators of the rate or extent of repair of the tendon itself as the mechanical strength may not be regained for several months, though the injury may be asymptomatic at a much earlier stage.