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The Principles of Medical Imaging

Revised Edition

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ICP

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Published by

Imperial College Press
57 Shelton Street
Covent Garden
London WC2H 9HE

Distributed by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Cover design from Mog's Mumps, first published in 1976 by William Heinemann Ltd, and in paperback in 1982 by Penguin Books Ltd.

AN INTRODUCTION TO THE PRINCIPLES OF MEDICAL IMAGING
(Revised Edition)

ISBN 1-86094-502-3

Printed in Singapore.

Preface

We were originally motivated to write *An Introduction to the Principles of Medical Imaging* simply because one of us, CNG, could not find one text, at an appropriate level, to support an optional undergraduate course for physicists. Shortly after we started the book, we realised that both medical students in general and medical research scientists in training could also benefit from the conceptual approach that we had chosen for this book. Thus from the outset we have been keeping in mind the needs of two apparently different parishes of readers. Although we have had to take care over the different levels of assumed knowledge for the two parishes, our teaching experience has shown that they share one very important characteristic: neither group by choice uses the symbolic language of applied mathematics in their own descriptions of the physical world. Thus it is inappropriate to introduce medical imaging with too heavy a reliance on purely mathematical descriptions. Instead we have chosen to use words and pictures wherever possible.

In many ways a more conceptual, even qualitative approach to the subject is actually more appropriate since neither human biology nor medicine are exact sciences. The instrumentation and technologies used in medical imaging are certainly susceptible to exact mathematical analysis, but the individual human body is not. In health, human beings come in a wide variety of shapes, sizes and constitutions so that, when a disease process is to be diagnosed in one individual, this has to be accomplished against a background of a wide range of normality. This requires an informed qualitative judgement on the part of the clinician. When imaging forms part of an investigation, its results often provide another partial clue to the solution of a complex puzzle, rather than a single definitive answer.

The increasing use of quantitative measurement and computers in clinical medicine is gradually changing the traditional education of medical students. In addition, the use of modern imaging methods, as an aid to diagnosis, is blurring the traditional relationship between clinical and technical staff, shaped historically by the century long use of X-ray radiography. Roughly speaking the technologists, medical physicists, radiographers were, historically, just employed to maintain the X-ray sets, take the exposures ordered by the radiologist, develop the films and hand over the pictorial results on film. Traditionally the medic's job really began when she received the films and this terminated the involvement of the technologists, barring instrument malfunction. A clear and strict division of legal and ethical responsibility in medicine is of course absolutely necessary and will remain unchanged in the future. We suspect, however, that the related division in scientific understanding will not survive long in this century. Medics increasingly need a strong understanding of the technical principles, especially the limitations of the instruments that they use, a traditional preserve of the hospital technologist.

Modern imaging is gradually moving away from the production of qualitative static 'photographs' of anatomy towards the generation and use of graphs and maps of numbers, extracted from digitised images and measurements. The diagnostic process can now call upon more than one type of investigation whose results have to be combined into a unified picture of the problem. This influx of new and qualitatively different data has created a problem of how best to present the clinician with the results of combined imaging investigations. One obvious approach is to dream up ways of combining the results in terms of multi-coloured tokens. This however is simply replacing one qualitative picture with another and assumes that the clinician will not or cannot be concerned with how a particular combination of tokens has been assembled. An automated approach can only be partially successful and is rather limited in comparison with the power of the informed human intellect.

Throughout the book we emphasise the general principle at the expense of detailed specific technical detail. We do this because the principles are likely to be more enduring than any particular current practical implementation of a technology. As far as possible we have minimised the amount of mathematics used, in accord with Bragg's dictum that all good science is explicable to a school child. There is however one important general area where we have found this to be impossible. The central theme of the book is tomographic reconstruction and this relies on a mathematical result from Fourier analysis called the Central Slice Theorem. We have chosen to tackle this subject more or less head on rather than skirt around it. It enriches our discussion of image making throughout the book and enables us to treat the vast subject of MRI in more depth than would otherwise have been possible. In fact, the use of Fourier methods has become so imbedded in signal and image processing in general that we see no harm in the medical user of data analysis packages being given more insight into this underlying central mathematical idea.

To serve our two parishes, two extra ingredients had to be added to the book, one for each parish. The medics need an overview of basic atomic and nuclear physics and how mathematics has become the engine of the exact sciences. The physicist needs to know the clinical context in which technological tools are used. Our second chapter is primarily aimed at the medic, our final chapter is for the physicist. Since most readers will not proceed from here to the end of the book in a sequential fashion we have provided a route map with chapter dependencies for the skimmers and dippers. Dedicated sequential readers, skimmers and dippers alike will benefit from attempting the questions and short problems at the end of each chapter. None of the problems involve the use of any mathematics beyond school A level, some will benefit from the use of a programmable calculator or home computer.

The Organisation of the Book

Chapter 1 + Appendices A, B

Chapter 1 together with the appendices describe the principles of tomographic reconstruction using words and pictures. All the later chapters dealing with the separate technologies rely on this central chapter, since after data has been collected, all tomographic imaging schemes reconstruct their particular pictures using almost the same basic scheme. Readers with a medical background will, it is hoped, benefit from the introduction to Fourier analysis and the concept of *K* space given in Appendix A. A more rigorous derivation of the central slice theorem, intended primarily for the physicist, is provided in Appendix B. We encourage the medical reader to struggle with these appendices, since as we have already said, Fourier methods underpin a great deal of standard image and data processing.

Chapter 2

Chapter 2 is written primarily for non-scientists. It starts with a discussion of how physics and engineering construct approximate but successful mathematical models of the physical world and emphasises the underlying unity in methods and concepts employed. Imaging technologies using X-rays, γ-rays and magnetic resonance all depend on a detailed quantitative description of the atomic and nuclear structure of individual atoms and the ways in which light (photons) and energetic particles, such as electrons, can exchange energy with these objects. Sections 2.2 to 2.5 provide a qualitative background to atomic and nuclear physics. Section 2.6 is devoted to the enumeration and description of the ways in which atoms and photons interact. These sections lay the foundation for understanding X-ray contrast mechanisms used in Chapter 4 and the scattering of γ-rays, used in diagnostic nuclear medicine, described in Chapter 5. The final section on magnetic resonance is a preparation for the more detailed discussion of MRI in Chapter 6. This introductory section is intended to emphasise the fact that MRI depends ultimately on intrinsic nuclear properties (the nuclear magnetic moment) and that resonance is a generic process, very similar to the absorption and emission of visible light by atoms.

Chapter 3

Much of this chapter will be new to both parishes. It provides the standard definitions used in ionising radiation measurement and radiological protection and a brief overview of the two vast subjects of radiation biology and radiation physics. The chapter emphasises the modern view, that ionising radiation is intrinsically dangerous and harmful to biological tissue but that the risk of permanent damage can and is now kept within perfectly acceptable bounds by careful monitoring and dose control.

Chapters 4 to 6

In turn these chapters describe the principles underlying the modern imaging methods of X-ray radiography and CT (4), SPECT and PET (5) and MRI (6). All of the tomographic applications use nearly the same mathematical methods to reconstruct cross-sectional images of human anatomy which are described in Chapter 1. Each individual technology uses the physics of electromagnetic waves and particles, described in Chapter 2, to obtain the data required for image reconstruction. We have been intentionally brief as far as detailed engineering is concerned, concentrating on underlying physical principles. In each chapter we describe the contrast mechanisms, the factors affecting spatial and temporal resolution and the more general engineering constraints.

Chapter 6 on MRI is by far the largest and perhaps the most difficult chapter of the book for both parishes. The size is intentional, the difficulty is probably inevitable. NMR and MRI are so versatile in their application that, over the past fifty years, a very wide range of applications of several different manoeuvres has been developed. The chapter deals first with the basic physics of NMR, before embarking on MRI. Within its rather shorter lifetime, MRI has thrown up a wide range of different ways of combining contrast flavours, nearly all of which can be obtained from standard clinical machines.

Chapter 7

Diagnostic ultrasound imaging, the subject of Chapter 7, is not a tomographic technique and thus falls outside the general theme of the book. Our brief description of ultrasound is included for completeness, since ultrasound is second only to X-ray projection radiography in its frequency of clinical use.

Chapter 8

This chapter is intended mainly for the physicist and engineer. Our aim is to illustrate just how imaging, providing some pieces of evidence, fits into the very human activity of medical diagnosis. The final section, on neuroimaging illustrates one of many medical research areas using modern imaging and the one which just happens to be close to our own interests. The human brain is sometimes referred to as the last frontier of science. The last twenty-five years have witnessed a second revolution in medical imaging but this has been largely confined, in its tremendous success, to human anatomy. The last frontier is likely to be the scene of a third revolution in imaging, the creation of movies of human function. Thus our last section points to the future illustrating how far we have to go and the limitations of the tools that are presently in use.

Appendices

Appendix A provides a reminder of basic wave concepts such as frequency and phase and then introduces the ideas underlying Fourier analysis and its use in image and signal processing. Appendix B gives a reasonably rigorous account of the central slice theorem and filtered back projection and describes the simpler filtered modifications that are commonly used in SPECT and PET. Appendix C is devoted to an account of the simplified Bloch equations of NMR and an introduction to the idea of the rotating frame of reference, commonly used in NMR and MRI to describe the properties of the resonance signal.

Preface to the Revised Edition

After coming to the book again, after a gap of a few years, we found several glaring errors in presentation that demanded rectification. By far the worst of these was the automated index of an earlier draft, which had attached itself to the final copy. The philosophy of this revision has been to leave the basic structure untouched, remove the errors, tidy up some figures, make some changes in the sequence of sections in some chapters, particularly Chapters 2 and 6.

The biggest changes occur in Sections 2.1 and 2.2. The early parts, intended to outline classical physics to non–physicists in less than ten pages have been shed. These are replaced by a more focussed qualitative introduction to the science specifically involved in the four imaging modalities. Section 2.2 now includes a short description of the properties of molecules, in particular water, which are central to contrast mechanisms in both ultrasound and MRI. The biggest change in Chapter 6 amounts to putting our short description of MR hardware at the end of the chapter.

We have put a short table of major key points with cross-references to other chapters and the appendices at the end of each main chapter as a study aid. Finally the index of this revised edition does indeed refer to the book in your hands.

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Acknowledgements

We are indebted to colleagues who have toiled through the earlier drafts of this book, pointing out errors and making valuable suggestions. In particular we would like to thank Dr Gonzalo Alarcon for reading all of it and Dr McRobbie for politely correcting some of our more quaint misconceptions about realities of real modern medical imaging practice. CNG would also like to thank the several years of Imperial students who bore the brunt of his medical imaging teaching apprenticeship. An introduction to medical imaging would hardly be complete without the inclusion of examples of real images. For this we are grateful to Ms Judy Godber of Siemens UK, Mrs Margaret Dakin of St Thomas' Clinical PET centre, Dr Steven Williams of the Institute of Psychology and Dr Donald McRobbie of Charing Cross Hospital. The cover cartoon is reproduced from "Mog's Mumps" a delightful children's book by Helen Nicoll and Jan Pienkowski. We are grateful to them both for providing our cover illustration and the telling quotation, opening Chapter 8. Our thanks are also due to the staff of World Scientific Publishing, in particular Sook Cheng Lim for her help and tolerance of long delayed returns of the draft, Rajesh Babu for patiently guiding us through the mysteries of indexing in MS word, and Ms Linda Kwan for meticulously ensuring that layout and style of the book is consistent and accurate. Finally, we are indebted to Ms Elaine Tham for her exceptionally careful and intelligent copyediting of our manuscript.

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A Glossary of Units and Common Terms

Scale : Powers of Ten Used Throughout Science

pico (10^{-12})	p	tera (10^{12}) T
nano (10^{-9})	n	giga (10^{9}) G
micro (10^{-6})	μ	mega (10^{6}) M
milli (10^{-3})	m	kilo (10^{3}) k

SI Units

Length	metre	m
Mass	kilogram	kg
Time	second	s
Force	newton	N ($kg \cdot m \cdot s^{-2}$)
Energy	joule	J ($kg \cdot m^2 \cdot s^{-2} = N \cdot m$)
Power	watt	W ($kg \cdot m^2 \cdot s^{-3} = N \cdot m \cdot s^{-1}$)
Frequency	hertz	Hz (s^{-1})
Pressure	pascal	Pa ($kg \cdot s^{-2} = N \cdot m^{-2}$)
Electric current	ampere	A
Electric Potential	volt	V

Electric charge	coulomb	C (A · s)
Magnetic Field	Tesla	T

Fundamental Constants

velocity of light	c	2.998	10^{8} m s^{-1}
electron charge	e	1.602	10^{-19} coulomb
electron mass	m	9.1	10^{-31} kilogram
proton mass	M	1.67	10^{-27} kilogram
Planck's constant	h	6.63	10^{-34} joule s
	$h/2\pi$	1.06	10^{-34} joule s
Bohr Radius	a_o	5.29	10^{-11} m
Bohr (Atomic) magneton	μ_b	9.27	10^{-24} A m^2
Nuclear magneton	μ_n	5.05	10^{-27} A m^2
Boltzman's constant	k_B	1.38	10^{-23} joule/deg

Definitions of Some Common Terms from Physics

Velocity

The rate of change of position or the distance travelled, in a specific direction, divided by the time taken. Speed is the rate of change of position, without reference to a direction, the magnitude of the velocity. Both speed and velocity have SI units of metres per second, ms^{-1}.

Acceleration

The rate of change of velocity: the change of velocity divided by the time taken by the change. It is measured in SI units of metres per second per second, ms^{-2}.

Momentum

A quantity characterising the motion of any object. Momentum is the product of the mass and the linear velocity of a moving particle. Momentum is a vector quantity, which means that it has both magnitude and direction. The total momentum of a system made up of a collection of rigidly connected objects is the vector sum of all the individual objects' momenta. For an isolated composite system, total momentum remains unchanged over time; this is called the conservation of momentum. For example, when a cricketer hits a ball, the momentum of the bat just before it strikes the ball plus the momentum of the ball at that moment is equal to the momentum of the bat after it strikes the ball plus the momentum of the struck ball (neglecting the small effects of air resistance).

Force

Force is any action or influence that accelerates, or changes the velocity of, an object.

Newton's Three Laws of Motion

The First Law

The first law of motion states that if the vector sum of the forces acting on an object is zero, then the object will remain at rest or remain moving at constant velocity. If the force exerted on an object is zero, the object does not necessarily have zero velocity. Without any forces acting on it, an object in motion will continue to travel at a constant velocity. In our everyday world, such perpetual motion is not observed because friction, either from air resistance or contact with a surface eventually dissipates the kinetic energy of the moving object. Thus in its flight through the air, the cricket ball slows down because there is a small resistive force, arising from the impact of air molecules on the ball.

The Second Law

Newton's second law relates force and acceleration. It is possibly the most important relationship in all of physics. A force on an object will produce an acceleration or change in velocity. The law makes the acceleration proportional to the magnitude of the force and is in the same direction as the force. The constant of proportionality is the mass, m, of the object thus $F = ma$. The unit of force, 1 Newton, is defined as the force necessary to give a mass of 1 kg an acceleration of 1 ms^{-2}.

The Third Law

Newton's third law of motion states that when one object exerts a force on another object, it experiences a force in return. The force that object A exerts on object B must be of the same magnitude as the force that object B exerts on object A, but in the opposite direction.

Friction

Friction acts like a force applied in the direction opposite to an object's velocity. Dry sliding friction, where no lubrication is present, is almost independent of velocity. Friction results in a conversion of organised mechanical energy into random heat energy. Although the concept of a net frictional force is quantitatively defined in classical physics this is not so in quantum physics, where the frictional (dissipation) process involves an exchange of quanta between one system and a large reservoir of particles, sometimes referred to as a heat bath. Friction actually presents a much more difficult computational problem in quantum physics than in classical physics.

Angular Momentum

The angular momentum of a rotating object depends on its speed of rotation, its mass, and the distance of the mass from the axis. Formally the angular momentum of a particle is given by the product of its momentum mass × velocity and its distance from a centre (often a centre of rotation).

When a skater on (almost) frictionless ice spins faster and faster, angular momentum is conserved despite the increasing speed. At the start of the spin, the skater's arms are outstretched. Part of the skater's mass is therefore at a large radius. As the skater's arms are lowered, thus decreasing their distance from the axis of rotation, the rotational speed must increase in order to maintain constant angular momentum. The conservation of angular momentum, just like the conservation of linear momentum follows directly from Newton's laws. An isolated body experiencing no net torque (torque is the product of force and the distance from an axis) will maintain its angular momentum.

Energy

The quantity called energy ties together all branches of physics. In mechanics, energy must be provided to do work and work is defined as the product of force and the distance an object moves in the direction of the force. When a force, exerted on an object, does not result in any motion, no work is done. Energy and work are both measured in the same units, joules. If work is done lifting an object of mass, m, a distance h, energy has been stored in the form of gravitational potential energy given by $E = mgh$. If the object is released it will acquire a kinetic energy, given by $\frac{1}{2} mV^2$, by virtue of its acquired speed V.

Many other forms of energy exist: electrical and magnetic energy; potential energy stored in stretched springs, compressed gases, or molecular bonds, thermal energy, heat, and mass itself. In all changes from one kind of energy to another, the total energy is conserved. For instance, the work done in raising a ball a distance h, increases its gravitational potential energy by mgh. If the ball is then dropped, the gravitational potential energy is transformed into an equal amount of kinetic energy, thus, $\frac{1}{2} mV^2 = mgh$. When the ball hits the ground and has come to rest all of the organised motional energy of the ball is dissipated into random motions that we call heat. The ball and its immediate surroundings become a tiny bit hotter as a result of the impact.

Power

Power is the rate of change of energy with time. It is measured in watts, 1 watt = 1 joule/s. Domestic appliances, such as light bulbs, are rated by power that they consume 40 watt, 60 watt, 100 watt etc. A 100-watt bulb dissipates 100 joules of electrical energy (Volts × Current) each second.

Temperature

Temperature is the property of systems in contact that determines whether they are in thermal equilibrium. The concept of temperature stems from the idea of measuring relative hotness and coldness and from the observation that the addition of heat to a body leads to an increase in temperature, as long as no melting or boiling occurs. The terms temperature and heat, although interrelated, refer to different concepts, temperature being a property of a body and heat being an energy flow to or from a body by virtue of a temperature difference. When a quantity of matter is in equilibrium at a temperature T, the constituent particles are in random motion and the average energy is approximately $k_B T$ where $k_B = 1.38\ 10^{-23}$ joule/deg is called Boltzmann's constant.

Field

A field of force is a region in which a gravitational, magnetic, electrostatic, or other kind of force can be exerted on an object. These regions are imagined to be threaded by lines of force. The lines are close together where the field is strong and are proportionately wider-spaced where it is weaker. The concept of action at a distance or a field of force was first introduced by Newton in his theory of universal gravitation. It has since become a central theme in modern physics. Each of the fundamental forces, gravitation, electromagnetic and nuclear has a characteristic scale of length. Nuclear forces are appreciable only on the scale of the nuclear radius 10^{-15} m. Gravitational forces at the other extreme produce tangible effects right across the galaxy, over distances of 10^{15} m.

Electricity and Magnetism

Physical phenomena resulting from the existence and interaction of electrical charges. When a charge is stationary, it produces electrostatic forces on charged objects in regions (the electrostatic field) where it is present. When a charge is in motion (an electrical current) it produces additional magnetic forces on other moving charges or currents.

Magnetic Moment

There are no magnetic charges or monopoles to provide a source of a magnetic force field in the way that the electric charge of the electron or the proton are the source of a surrounding field of electrostatic force. Rather, it is moving charges or currents that produce all magnetic fields. It is however convenient in atomic and nuclear physics to describe the magnetic force field, surrounding an atom or nucleus, in terms of an effective fictitious magnetic charge called the magnetic moment. The units of magnetic moment are electric current × area. Internal motions of charge within tiny objects such as atoms and nuclei create a surrounding magnetic field of force with a characteristic topography called a dipole field. This field is completely specified by quoting the strength and direction of the effective magnetic moment. The dipole field is the same as that arising from a very small loop of wire carrying an electric current. If the loop encloses an area S and the current is I then the magnetic moment is $I \times S$ Am^2.

Planck's Constant

Planck, in his theory of black body radiation, came to the conclusion that light or electromagnetic waves could only be exchanged in discrete amounts, quanta. In particular according to Planck, the energy of a quantum of light is equal to the frequency of the light multiplied by a constant, $h = 6.626 \times 10^{-34}$ joule-second. Planck's idea was the first step on the road to quantum mechanics. The constant h sets a scale for the graininess of the energy exchanges between atoms.