

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.