Medical Physics and Physiological Measurement

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Preface

This book grew from a booklet which is used in the Sheffield Department of Medical Physics and Clinical Engineering for the training of our technical staff. The intention behind our writing has been to give practical information which will enable the reader to carry out the very wide range of physiological measurement and treatment techniques which are often grouped under the umbrella title of Medical Physics and Physiological Measurement. However, it is more fulfilling to treat a subject in depth rather than at a purely practical level and we have therefore included much of the background physics, electronics, anatomy and physiology which is necessary for the student who wishes to know why a particular procedure is carried out. The book which has resulted is large but we hope it will be useful to graduates in physics or engineering (as well as technicians) who wish to be introduced to the application of their science to medicine. It may also be interesting to many medical graduates.

There are very few hospital or academic departments which cover all the subjects about which we have written. In the United Kingdom, the Zuckermann Report of 1967 envisaged large departments of 'physical sciences applied to medicine'. However, largely because of the intractable personnel problems involved in bringing together many established departments, this report has not been widely adopted, but many people have accepted the arguments which advocate closer collaboration in scientific and training matters between departments such as Medical Physics, Nuclear Medicine, Clinical Engineering, Audiology, ECG, Respiratory Function and Neurophysiology. We are convinced that these topics have much in common and can benefit from close association. This is one of the reasons for our enthusiasm to write this book. However, the coverage is very wide so that a person with several years' experience in one of the topics should not expect to learn very much about their own topic in our book—hopefully, they should find the other topics interesting.

Much of the background introductory material is covered in the first seven chapters. The remaining chapters cover the greater part of the sections to be found in most larger departments of Medical Physics and Clinical Engineering and in associated hospital departments of Physiological Measurement. Practical experiments are given at the end of most of the chapters to help both the individual student and also their supervisor. It is our intention that a reader should follow the book in sequence, even if they omit some sections, but we accept the reality that readers will take chapters in isolation and we have therefore made extensive cross-references to associated material.

The range of topics is so wide that we could not hope to write with authority on all of them. We considered using several authors but eventually decided to capitalise on our good fortune and utilise the wide experience available to us in the Sheffield University and Area Health Authority (Teaching) Department of Medical Physics and Clinical Engineering. We are both very much in debt to our colleagues, who have supplied us with information and made helpful comments on our many drafts. Writing this book has been enjoyable to both of us and we have learnt much whilst researching the chapters outside our personal competence. Having said that, we nonetheless accept responsibility for the errors which must certainly still exist and we would encourage our readers to let us know of any they find.

Our acknowledgements must start with Professor M.M. Black, who encouraged us to put pen to paper, and Miss Cecile Clarke, who has spent too many hours typing diligently and with good humour whilst looking after a busy office. The following list is not comprehensive but contains those to whom we owe particular debts: Harry Wood, David Barber, Susan Sherriff, Carl Morgan, Ian Blair, Vincent Sellars, Islwyn Pryce, John Stevens, Walt O'Dowd, Neil Kenyon, Graham Harston, Keith Bomford, Alan Robinson, Trevor Jenkins, Chris Franks, Jacques Hermans, and Wendy Makin of our department, and also Dr John Jarratt of the Department of Neurology and Miss Judith Connell of the Department of Communication. A list of the books which we have used and from which we have profited greatly is given in the Bibliography. We also thank the Royal Hallamshire Hospital and Northern General Hospital Departments of Medical Illustration for some of the diagrams.

Finishing our acknowledgements is as easy as beginning them. We must thank our respective wives for the endless hours lost to them whilst we wrote, but the initial blame we lay at the feet of Professor Harold Miller who, during his years as Professor of Medical Physics in Sheffield until his retirement in 1975, and indeed since that time, gave both of us the enthusiasm for our subject without which our lives would be much less interesting.

Brian Brown and Rod Smallwood
Sheffield, 1981

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Chapter 1
Introduction

During the last twenty years there have been rapid and often dramatic developments in the applications of technology in medicine and health care. As diagnostic and therapeutic instrumentation becomes more sophisticated, so the demand for operator technical skill increases. This is especially true for those para-medical staff involved in medical physics, clinical engineering and physiological measurement.

Such staff are not merely 'button pushers' or 'data collectors'. They must be fully conversant with the method of operation of the equipment they use and, if possible, also have a reasonable knowledge of the clinical situations for which their equipment and procedures are employed. Furthermore, such staff may often be directly or indirectly involved in research and the further development of equipment and procedures. This latter type of work implies that these staff should have a measure of innovative skill and, more importantly, understand fully the fundamentals of their scientific work.

Useful 'technology' is usually the result of the intelligent application of 'science'. Indeed the word 'technology' is in some ways inappropriate for para-medical work and a more descriptive expression is the traditional title of 'applied science'. In the United Kingdom's National Health Service, the para-medical personnel responsible for much of this scientific work are either graduate physical scientists or appropriately trained technicians. Although this latter group form the majority, particularly for routine service work, it is only through their collaboration with graduate colleagues that optimal development of existing services can be achieved. If such collaboration is to be truly successful, then graduate and technical staff require both academic and practical training. The latter component can be subsequent to, or in parallel with, the more academic work.

The majority of scientific staff in this subject area have graduated with honours degrees in physics or electrical/electronic engineering. A small but growing number have qualified as computer scientists or mechanical engineers. This latter group is particularly important with the current development of work in 'biomedical' or 'clinical' engineering. In the future, the majority of these scientific staff, wishing to work in the National Health Service, will have to undertake a practical training period which lasts for a total of four years. The first half of this period will cover a wide range of relevant topics and, in the final two years, specialisation in two particular areas will be undertaken. This present book will be a valuable reference work for the first two years of this training period where a much wider field of practical experience is required.

Until recently, the majority of technical staff involved in this type of work within the United Kingdom have received their academic training in appropriate subjects through the Ordinary and Higher National Certificate programmes. In the future, these courses will be replaced by Technician Education Council Certificate and Diploma awards and, in time, Higher Level programmes. These new courses have been planned so as to integrate academic work with compulsory in-service practical training in the hospital environment. Once again, this present book will be a valuable if not essential general text, covering the various fields of study to which these technicians will be exposed.

In the case of both groups of staff, recourse to more specialised texts will be necessary at some stages during their training. However, a major feature of this new book is that, notwithstanding its broad coverage of the physical sciences in medicine, it still manages to treat the various topics in adequate detail, particularly if they are being studied simultaneously in the practical environment. In this respect the book will also be of value both to students and teachers of some of the 'option courses' for Medical Physics which are currently being developed, for example, by certain 'A' Level examination boards. It will also be of value to medical undergraduates taking short courses in Medical Physics or indeed, where they are offered, intercalated BSc courses in this subject.

The authors are both highly experienced members of a large department of medical physics and clinical engineering which provides a wide range of para-clinical services. Furthermore, since this department combines a university role with a routine Health Service function, they are well versed in the problems of teaching their subject both to undergraduates and technical staff.

Although there are currently one or two texts which attempt to cover some of this field of study, none does so with the specific aim of being read and used in conjunction with an in-service training programme. This is certainly the objective of this present book and is one of its most outstanding qualities. For all the above reasons I am particularly pleased to be associated with this text by way of this Introduction and believe that it will be an invaluable aid to anyone about to enter or already working in this rewarding field of study and service.

M. M. Black*

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Chapter 2
Basic Nuclear Physics and Radiation Biology

It is possible, as a medical physics technician, to use radioactive isotopes for diagnostic tests in medicine without any knowledge of basic atomic structure and what gives rise to γ (gamma) radiation. Similarly, you can use electronics without understanding solid state theory. However, if you want to understand why things work and want to be able to follow the developments which are still taking place in medical physics, then it is necessary to know some fundamental physics.

This chapter is relevant to the subsequent chapters which cover nuclear medicine and radiotherapy physics. Radiotherapy is the oldest part of medical physics and concerns the use of ionising radiations for the treatment of disease, whereas nuclear medicine, often called clinical isotopes, is the use of radioactive isotopes in the diagnosis of disease. Radioactive isotopes are used because they emit a radiation which can be detected at a distance, and therefore the position of an isotope can always be found. If the kidneys contain a radioactive material, then their position can be found by locating the radiation emitted by the radioactive material. If red blood cells have a radioactive material attached to them, then they can be followed or traced around the body because they will emit radiation.

2.1 Revision of basic concepts

2.1.1 ATOMIC STRUCTURE

All atoms consist of a nucleus of protons and neutrons, with electrons in orbit around the nucleus. The only difference between elements is in the numbers of the fundamental particles, i.e. the protons, neutrons and electrons, which the atoms contain. A piece of iron consists mainly of atoms, ^{56}Fe, each of which has a nucleus of 26 protons and 30 neutrons, giving a total of 56, which is the atomic mass number. (The conventional symbols for atoms use a superscript for the atomic mass (neutrons + protons), and a subscript for the number of protons: for instance, $^{14}_{7}N$ describes an atom of nitrogen, atomic mass number 14, with 7 protons. The subscript is often omitted.)

Protons have a positive electric charge and electrons have a negative charge but, as the number of protons is usually equal to the number of electrons, the net electric charge is zero. If an atom gains or loses an electron, so that the numbers of electric charges no longer balance, then the resulting atom is called an ion.

The lightest atom is hydrogen which has only one proton and one electron; uranium has about 238 protons and neutrons and there are other atoms which are even heavier.

There is ample evidence for the existence of smaller particles which are contained within the three we have mentioned but to explain them is not simple and, at the moment, would be of no help to somebody working in routine medical physics.

2.1.2 ISOTOPES

All the atoms of one particular element have the same number of electrons and protons, but the number of neutrons can vary. Isotopes are atoms of the same element which have different numbers of neutrons. They are referred to by their atomic mass number.

^{131}I is the isotope of iodine which is often used for treating an overactive thyroid gland, but it is not the only isotope of iodine. ^{123}I and ^{125}I are other isotopes of iodine. All the isotopes of iodine have 53 protons in the nucleus but the number of neutrons can be 70, 72, or 78 to give the three isotopes, i.e. $^{123}_{53}I$, $^{125}_{53}I$, and $^{131}_{53}I$. There are actually many other isotopes of iodine.

Stable isotopes

The neutrons and protons which form the nucleus of an atom are held together by a combination of forces such as gravitational and electrostatic forces. Some of these forces are repulsive and others attractive. The protons tend to repel each other because they all have a positive electric charge. This means that, as bigger atoms are put together, it becomes more difficult for the nucleus to be stable as one collection of particles. The only reason that the nucleus is stable is that the neutrons bind the other particles together, which is why the heavier atoms have more and more neutrons. As a general rule there are about equal numbers of neutrons and protons in a nucleus but, in heavier atoms, a greater proportion of neutrons have to be added to maintain the stability of the atom.

This question of stability is an important one as some atoms are actually unstable: these are the radioactive atoms. Stable isotopes are ones where the nucleus is well held together. ^{16}O is completely stable with 8 protons, 8 neutrons and, of course, 8 electrons.

Unstable isotopes

The nucleus of many atoms is not stable. Uranium as ^{238}U, potassium as ^{40}K, and carbon as ^{14}C can all be found naturally in the world but their nuclei are not stable. Artificial unstable isotopes can also be produced. What happens when they are unstable is that part of the atom breaks away, i.e. they emit a particle or radiation, leaving an isotope which is different from the original one.

For example, ^{238}U will emit an α (alpha) particle containing two protons and two neutrons, so leaving behind an atom of ^{234}U. This isotope is itself unstable and will decay into yet another unstable isotope and indeed become an atom of another element. The end point of this particular decay chain is lead, which is stable.

2.1.3 HALF-LIFE

We said that ^{238}U was unstable. This does not mean that the atom is so unstable that it will fall apart immediately, but merely that it has a tendency to be unstable. In a given time a certain proportion of the atoms will become unstable and disintegrate. It is a statistical process. The number of atoms which disintegrate in unit time is directly related to the number of atoms remaining. We can express this mathematically:

$$\frac{dN}{dt} = -\lambda N$$

where λ is a constant and N is the number of atoms.
We can rearrange the equation to give:

$$\frac{dN}{N} = -\lambda dt$$

which on integration gives:

$$\log_e N = -\lambda t + k$$

where k is a constant.
If $t = 0$ corresponds to $N = N_0$, then $k = \log_e N_0$ and so:

$$N = N_0 e^{-\lambda t} \tag{2.1}$$

This is the basic equation which governs the decay of unstable or radioactive isotopes. The larger the decay constant, λ, the more quickly the isotope will decay. The rate of decay is usually expressed as the half-life of the isotope, which is the time it takes for half of the original number of atoms to decay. It is quite easily shown that $T_{1/2}$ is given by $0.693/\lambda$.

Half-lives of different isotopes can range from thousands of years to fractions of a second, and are very important factors in the choice and use of isotopes in medical physics.

2.1.4 NUCLEAR RADIATIONS

There are many types of nuclear radiation which can accompany the decay of an atom. The following list covers the main types:

- X-rays
- γ-rays (gamma rays)
- electrons and β-rays (beta rays)
- neutrons
- positrons
- α-particles (alpha particles)

X- and γ-rays are the most important and also the most difficult to understand. They are difficult to understand because they are types of electromagnetic radiation, whereas the other radiations can be thought of as particles, or at least conveniently considered as such. X- and γ-rays arise as a means of getting rid of the excess energy involved when an atom decays. They carry no electric charge and simply carry away the energy equivalent to the difference in mass between the original atom and what is left after the decay. There is no fundamental difference between X-rays and γ-rays. X-rays can be produced by an electrical machine which smashes electrons into a solid target, causing the orbital electrons to become excited and subsequently emit X-rays when they return to their ground state. γ-rays are produced by the decay of a radioactive atom. Usually γ-rays have a much higher energy than X-rays. The concept of energy will be explained a little in the next section.

Beta rays, or beta particles, are fast moving electrons. Even though they travel very fast, because they have a negative charge they will interact with other electric charges when they come close to them and the result is that they soon lose their energy. A β-particle might be able to travel about one metre in air before it is exhausted but in tissue it will only travel a millimetre or so.

Neutrons are as heavy as protons but, because they have no electric charge, they can travel large distances before they are exhausted. Neutrons can be produced by a reactor and they have been used both for treatment of disease and also in neutron activation analysis. However, they are not used routinely in most medical physics departments and will not be discussed here.

Positrons. These particles have the same mass as an electron but have a positive electric charge. Their ability to travel through air and tissue is the same as a β-particle of the same energy.

Alpha particles are actually doubly ionised helium atoms with a mass of four, consisting of two neutrons and two protons. They have a positive charge corresponding to the two protons. Their relatively high mass and charge cause α-particles to be stopped easily by collisions so that the range of an α-particle in air is only a few centimetres. Even a piece of paper is sufficient to stop most α-particles.

2.1.5 ENERGY

The energy of any nuclear radiation can be related to the mass which was lost when the atom decayed and emitted the radiation. The equation relating the energy, E, to the mass loss, m, is given by Einstein's formula $E = mc^2$, where c is the velocity of light.

The units in which energy is expressed are electron volts, thousands of electron volts (keV), or millions of electron volts (MeV). The electron volt is defined as the energy which a unit charge, such as an electron, will receive when it falls through a potential of one volt.

The energy of the X-rays used in diagnostic radiology is about 100 keV and the linear accelerators used in the treatment of malignant tumours produce X-rays with energies of the order 10 MeV. Actually, X-ray energies are usually expressed in kV and not keV. The beam of X-rays do not all have the same energy and the kV refers to the accelerating potential which is applied to the X-ray generator.

The concept of energy is fundamental to the study of physics, which can almost be described as simply the study of energy. Einstein's formula

$E = mc^2$ relates mass and energy, but energy can also be related to frequency if the radiation is considered as a wave of electromagnetic energy rather than as a stream of particles. The equation $E = h\nu$ relates energy to Planck's constant, h, and the frequency of the radiation, ν. This idea of relating the frequency of radiation to its energy is important when we come to consider the biological effects of the different types of electromagnetic radiation.

2.1.6 IONISING AND NON-IONISING RADIATION

Radioactive decay is not the only way in which an atom can be changed. Another particle or radiation can collide with an atom and change its structure. A neutron can certainly do this and, in the right circumstances, can split the nucleus of an atom; this is the process of fission which is used in all current nuclear power stations. Alternatively, instead of the atomic nucleus being affected, the orbiting electrons may be removed by the interfering radiation; this process is called ionisation. It is thought to be the major cause of the biological effects which radiation can produce. A certain minimum energy is required to remove an electron from an atom. If the incident radiation does not have sufficient energy it will not be capable of causing ionisation.

The energy of the gamma rays given off when the isotope ^{60}Co (cobalt) decays is about 1.3 MeV, which is certainly sufficient to cause ionisation of an atom. If we look at the electromagnetic spectrum (Table 2.1), we can relate energy to frequency using the equation $E = h\nu$. We see that a radio wave of 300 MHz only has an energy of about 10^{-8} eV, which is not sufficient to cause ionisation. This is the basis for the classification of ionising and non-ionising radiations.

Table 2.1. The electromagnetic spectrum, showing the energy of the different frequencies of radiation.

			Frequency Hz		
3×10^{22}		3×10^{18}	3×10^{14}	3×10^{10}	3×10^{6}
Ionising	Gamma rays		Visible light	Micro waves	Radio waves	*Non-ionising*
10^{8}		10^{4}	1	10^{-4}	10^{-8}
			Energy eV		

There is not a well defined, minimum energy which is required to cause ionisation as this depends upon the particular atom to be ionised. However, we do know that ionisation in air requires about 30 eV and it is normally assumed that at least 10 eV is needed to cause ionisation. This means that radio waves, microwaves, and most of the visible spectrum do not cause ionisation, but the far ultraviolet and γ-rays are capable of causing ionisation.

2.2 Production of isotopes

2.2.1 NATURALLY OCCURRING RADIOACTIVITY

There are several radioactive isotopes which are present in the ground and in the atmosphere which contribute to what is called 'background radiation'. This background radiation is important as it is a source of interference when measurements of radioactivity are being made.

Uranium is one of the radioactive elements present in the ground and, as traces of uranium are found in most rocks, there is background radiation everywhere. There are variations between rocks, for example, granite contains a relatively high concentration of uranium so that cities such as Aberdeen, which are built upon granite, have quite a high background radiation.

^{238}U has a very long half-life, about 10^{10} years, but when it decays it produces atoms of much shorter half-life until, after about 20 stages, it becomes the stable lead isotope ^{206}Pb. One of these stages is the element radium which was the first radioactive isotope to be used for the treatment of disease. Another of the stages is radon, a gas which appears in the atmosphere as a radioactive gas. In the morning when the air is very still, radon gas coming from the ground can accumulate in quite high concentrations in the air. There are usually about 10^6 radon atoms in each cubic metre of air.

2.2.2 COSMIC RADIATION

Another contribution to the background radiation is radiation which comes from the rest of the universe. Much of this radiation is absorbed by the atmosphere or deflected by the earth's magnetic field and so never reaches the earth, but quite a significant amount does reach ground level.

The energy of cosmic radiation is very high and it can therefore penetrate large amounts of screening. Lead, which is often used to protect people from radioactive isotopes and X-rays, is totally ineffective at stopping cosmic rays which can penetrate through the earth to the bottom of mines. The average energy of cosmic rays is about 6000 MeV. Fortunately the total number of cosmic rays is relatively small but they do add a significant amount to the background radiation which affects radiation counting equipment.

2.2.3 MAN-MADE BACKGROUND RADIATION

This is the radiation which is emitted from isotopes which have escaped into the atmosphere either from atomic bombs or from the industrial uses of atomic energy. When many atomic bomb tests were being carried out, the 'fall-out' was considerable and the radioactive isotopes which were produced in the nuclear explosions could be detected over the entire surface of the earth. However, atomic bomb fall out reached a peak in the early 1960s and it is now only a very small contribution to the normal background radioactivity. The contribution from the industrial uses of nuclear energy is also very small, except in very close proximity to installations such as nuclear power stations.

2.2.4 INDUCED BACKGROUND RADIATION

Because it is so energetic, cosmic radiation can produce interesting atomic changes in the atmosphere. One of these changes results in the production of carbon-14, which is a radioactive isotope of carbon. An interesting use of this isotope is in the technique of ^{14}C dating, which is not directly relevant to medical physics but forms an educational example. ^{14}C is produced in the upper atmosphere when neutrons in cosmic radiation interact with atmospheric nitrogen.The reaction which takes place is called a neutron/proton interaction:

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$$

(Note that the total atomic mass and the total number of protons is the same on both sides of the equation.)

The ^{14}N and the neutron $^{1}_{0}n$ come together and produce ^{14}C and the proton $^{1}_{1}H$. ^{14}C is radioactive and in fact decays into ^{14}N with the production of a beta ray, so that the cosmic rays continuously make radioactive carbon from the non-radioactive nitrogen in the atmosphere.

Now, the small amounts of ^{14}C in the atmosphere are rapidly oxidised to produce radioactive carbon dioxide which circulates in the atmosphere. When plants absorb this carbon dioxide for photosynthesis the ^{14}C becomes incorporated in them. All living things therefore have a certain amount of radioactive carbon mixed in with their stable isotopes of carbon which are ^{12}C and ^{13}C.

When the plant dies, fresh ^{14}C is no longer added, and so the radioactive carbon slowly decays with the half-life of ^{14}C, which is about 5700 years. The amount of radioactive carbon, expressed as a fraction of the total carbon in the plant, will therefore be a maximum at the time the plant dies and will fall steadily as time passes. This is the basis of ^{14}C dating where the beta particles which the ^{14}C emits are counted and so related to the total amount of ^{14}C present.

Measuring the beta particles which the ^{14}C emits is not easy and more will be said about this in Chapter 10. However, it is possible to date articles by this method to an accuracy of about 50 years in 2000 years.

2.2.5 NEUTRON REACTIONS AND 'MAN-MADE' ISOTOPES

The isotopes used in medicine can only be used in small quantities and yet they must produce an easily measured amount of radiation. Their specific activity must be high. The unit of activity is either the curie or the becquerel and these will be defined and explained in the next section.

The easiest way to produce isotopes of high specific activity is to bombard a substance with neutrons and so produce nuclear reactions; the example given in the previous section, where ^{14}C was produced by cosmic neutrons interacting with nitrogen, was a nuclear reaction. The cobalt-60 used in