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MEDICAL ELECTRONICS

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BY

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This book is dedicated to my Wife

PREFACE

For some time there has been a need for a short book on medical electronics, particularly on the most recent developments. A great amount of work has been done on this subject, but the papers dealing with it are widely scattered throughout the scientific and medical literature and are not readily available to the busy doctor.

This literature on the applications of electronics in medicine is no longer a stream but a river in full flood. It is very understandable that many members of the medical profession have difficulty in following the recent trends, but it is desirable that they should at least have some acquaintance with them. It is my belief that though omitting all mathematical considerations and circuit diagrams a satisfactory knowledge of the facts can still be given.

The difficulty in writing this book has not been to find illustrations but to select from among the wealth of material available that most likely to hold the reader's interest and provide him with a knowledge of the underlying principles. It is hoped that the information contained herein will also be of interest to those who are already familiar with the applications of medical electronics and that they will still find features of interest to them. The contents of the book have been selected to illustrate the wide range of the uses of electronics in medicine.

It would have been easier to write this book fifteen years ago, when our knowledge of medical electronics made a very much tidier picture, but this apparent tidiness was due to lack of knowledge. A new and rapidly expanding science is being developed and it will take us time to see our way clearly—but it is just this bewildering variety of new methods and ideas that makes medical electronics so interesting.

Medical electronics is not a circumscribed area of knowledge, but a dynamic field of inter-relationships with other branches of medicine and science. It is an "overlap zone"—and where one subject meets another is often the most productive of new advances. The basic nature of medical electronics ensures that it is involved in a great number of these overlap zones and there is hardly a branch of medicine that cannot benefit from the application of electronic techniques.

A fairly representative list of references is given at the end of each chapter so that the reader can easily find further reading and the original articles quoted.

The aim of this book is primarily to provide a bird's eye view of the uses of electronics in medicine. This review of the progress and trends is no more than a personal impression. It is the survey of one individual who, preoccupied with his own particular field of studies, gleans scattered pieces of information. But at least it may serve to show how very active is this comparatively new science.

I wish to express my thanks to Mr. H. Marriott, senior lecturer in electrical engineering at University College, London, for his advice and criticism.

Swansea G. E. DONOVAN
October, 1953

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CHAPTER 1

INTRODUCTION

ELECTRONICS has been defined as that branch of science and technology which relates to the conduction of electricity through gases and *in vacuo*. The term also embraces the action taking place in all circuits associated with electron tubes. For the purpose of this book, a more preferable definition is "that branch of science which describes the properties and control of electrons and other elementary particles which, in correlation with energy, constitute matter."

Sub-atomic entities such as electrons, protons and neutrons are generally called particles, or corpuscles, although their properties differ from those of the hypothetical small "particles" or chunks of matter that are of value in the formulation of the theories of mechanics.

Typical electronic devices are thermionic valves of all types, photo-electric cells, cathode-ray tubes and x-ray tubes—all obvious examples—and any technique which employs these devices may be classified as electronic. There are a number of devices, such as photo-voltaic cells and so on, in which the motion of free electrons is not the essential feature, but which nevertheless are usually looked upon as being electronic.

Bio-electrical quantities such as the electrical variations of the heart, muscle and brain, readily lend themselves to amplification by the thermionic valve amplifier and to demonstration in oscillographic form on the screen of the cathode-ray oscillograph. Also non-electrical quantities such as changes in pressure, intensity of light and temperature, can be converted into electrical variations, and treated in the same way.

The electron microscope permits the viewing and photographing of viri too small to be seen with the optical microscope, and the identification of bacterial structure.

Electronic devices can be used to record temperature by means of thermocouples, humidity by hygroscopically-sensitive conductors and so on. These devices can be arranged to give aural or visual indication when certain limits are exceeded or when a certain process is completed, and can be adapted to automatically controlling these limits or processes. The limits can be fixed in terms of time, speed, position, temperature, pressure, humidity, size, shape, colour and sound.

Medical men are increasingly using radio-active isotopes and devices for measuring their properties such as Geiger-Müller tubes, vacuum tube counters, and electronic apparatus of many types. It is desirable that the modern doctor should know something about high-energy accelerators such as the linear accelerator, the cyclotron, the betatron and the synchrotron. A new eight-million volt linear accelerator is being tested at Hammersmith Hospital. This machine can produce x-rays forty times as powerful as those of the conventional x-ray apparatus, and it can be used in the treatment of cancer. A 45-inch cyclotron has been installed in the same hospital for research in radio-biology, and the production of "short-lived" radio-isotopes. These short-lived radio-isotopes will be immediately available for experiments elsewhere in the building.

Servo-mechanisms also are being increasingly used in medicine; a typical example is the servo-anaesthetist. The similarities between electronic machines and certain mechanisms of the human organism are obvious. Cybernetics deals with variations of feed-back, and is the science of control and communication mechanisms in machines and animals.

A new vista has been opened up; the great variety of new advances makes medical electronics one of the most exciting branches of medicine today. In this book an attempt is made to survey the field, stimulate thought, and give a perspective which may enable us to see where we are going; the present time seems particularly opportune to do so.

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CHAPTER 2

MATTER AND ENERGY

THE ATOM is the smallest particle of an element capable of existing individually or taking part in a chemical reaction. The atom consists of a positively charged relatively heavy central core, the nucleus, around which the electrons rotate in various orbits. Almost the whole mass of the atom is comprised in the nucleus, which consists of positively charged protons and neutral neutrons. The charge of the proton is equal to, but of opposite sign to, that of the electron.

The electron is the elementary particle of negative electricity. Its mass at rest is $9 \cdot 107 \times 10^{-28}$ grammes or $\frac{1}{1848}$ that of a hydrogen atom. It has a negative electrostatic charge of $4 \cdot 803 \times 10^{-10}$ electrostatic units. It is one of the fundamental building stones of the atom.

The electrons are relatively loosely bound to the atomic nucleus. A finite number of specific energy levels is associated with each atom. Energy is needed to dislodge an electron from its atom. When the energy supplied is just sufficient to raise an electron from one energy level to another, the atom is said to be in an excited state. This state is unstable as the electron tends to return to its normal energy level. In so doing, this difference in energy appears in a new form, that of radiation.

The chemical reaction of an atom depends on its external electronic system. The electrons of the atom are influenced by physical energy, for example those in the outer orbits by heat, and in the inner orbits by high voltages, movements from one inner orbit to another resulting in energy transformations with emission of radiation such as x-rays.

The electromagnetic spectrum

The electromagnetic spectrum (Fig. 1) contains in order of increasing wavelength, cosmic rays, *gamma*-rays, x-rays, ultra-violet rays, visible light, infra-red (heat) rays, and wireless or Hertzian waves. If we exclude cosmic rays, this range then is arbitrarily bounded by the long-wavelength radio waves (about 30,000 metres) and the short-wavelength *gamma*-rays (about 10^{-13} metres). These wave motions are electromagnetic disturbances which do not require any known material medium for their propagation and travel with a speed of approximately 186,000 miles per second.

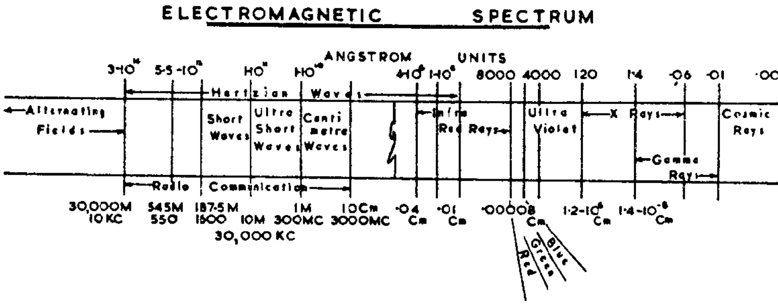

FIG. 1.—The electromagnetic spectrum contains in order of increasing wavelengths radiations extending from cosmic rays to wireless waves.

Dual nature of radiations

These radiations have a dual nature. Radiation can be assumed to be either a wave motion or a flow of energy quanta. Radiation is not emitted in a continuous fashion, but as short discrete bursts (photons). Each photon contains a definite amount of energy termed a quantum.

Wave mechanics

The modern theory of wave mechanics attempts to combine both theories into a unified whole, but does not lend itself readily to non-mathematical analysis. For our purpose, the wave mechanics theory may be considered as stating that every particle is associated with a kind of periodic wave, whose frequency and amplitude are fixed by rules which are derived in part by analogy with the propagation of waves of radiant energy, in part *ad hoc*, and in part from necessary continuity conditions. These waves are conceptions and have not a real physical existence, the term "wave" being employed as an analogy to facilitate the description of the mathematical relations employed, since in all but the easiest examples the waves would have to be conceived as existing in a "hyperspace" of very many dimensions.

Causation of the various radiations

At the long-wavelength end of the electromagnetic spectrum waves from 30,000 metres to 0·5 centimetre may be generated by radio methods. The emission of monochromatic radiation in the visible region of the spectrum depends on the physical processes due to energy changes associated with the outermost electrons in the atoms. Ultra-violet rays and x-rays are caused by similar changes of electrons deeper in the atom. *Gamma* radiation is due to energy changes in the atomic nucleus itself.

CHAPTER 3

X-RAYS

X-RAYS have many uses in medicine, in particular for diagnosis, therapy and research (Shanks and Kerley, 1951; Levitt, 1952).

The x-ray tube has a heated tungsten cathode partially surrounded by a focusing cylinder (focusing cap) for directing the electron emission toward the anode. The electrons emitted by the cathode are made to hit the anode target at a great velocity by a high potential of the order of some 10,000–1,000,000 volts. The range of voltages used in diagnostic radiology is generally from 45,000 to 100,000 volts.

The diagnostic medical x-ray tube is basically a diode thermionic valve adapted to the specific purpose of generating x-rays. A diode contains two electrodes one of which is a thermionically emitting cathode heated by an electric current, and the other is a metal plate or anode. Since x-ray tubes are diodes they can act as alternating current rectifiers, and are so used in portable instruments. This principle is not used in machines of high ratings as a heavy load may raise the temperature of the anode target to a point where appreciable electron emission may occur and cause an inverse current flow with consequent tube destruction; in such cases separate rectifiers are used. The triode x-ray tube has been introduced into diagnostic radiology and may replace the diode type for some purposes. Siemens demonstrated, at a German exhibition in 1951, an x-ray diagnostic apparatus for 150 kVp fitted with a triode type of x-ray tube.

The efficiency of the orthodox x-ray tube is normally very low; less than 0·1 per cent of the energy of the impinging electrons is translated into energy of useful x-rays.

Measurement of x-ray dosage

X-ray dosage may be measured with a gas ionization chamber, charging it to a known potential and measuring its loss of charge during irradiation. This is a convenient way (International Committee, 1937) as the dosage unit is the roentgen, which is defined in terms of the total ionization produced by the x-rays in a given mass of air under standard conditions. The roentgen is "the quantity of *x* or *gamma* radiation such that the associated corpuscular emission per 0·001293 gramme of air produces, in air, ions carrying 1 esu of quantity of electricity of either sign". An easier definition of the roentgen to remember is "the amount of *x*-radiation or *gamma*-radiation which will produce ions carrying 1 electrostatic unit of electricity of either sign in 1 millilitre of dry air", the temperature being 0° C. and 760 millimetres of mercury pressure.

Genetic effects

It is possible deliberately to produce mutations in moulds by x-rays. This has been employed in producing new strains of *Penicillium notatum*. Some strains thus produced have been better than the original strains. It is obvious that this method involves great labour in testing every new strain produced, but ultimately means cheaper and better penicillin.

X-rays can cause mutations in strains of bacteria, amoebae, insects and even mammals: and they can cause mutation of normal cells into cancer cells. The mutant cancer cell is viciously more competent than the ordinary cell: it is better able to survive in the environment in which it is born than its parent strain of normal cells.

By way of example may be quoted a selection of hybrid male mice irradiated with x-rays. The successive litters sired by these mice totalled 48,000 and 38,000 control mice were bred from non-treated fathers. The results showed that the offspring of the treated mice produced 53 new strains or mutations, while those of the untreated produced only two.

The warnings of the geneticists that mutations induced by radiations are recessive in character cannot be disregarded. There is probably no danger to the nation on this account, nor is it necessary to question the correctness of carrying out mass radiography of large numbers of people because of the possibility that these brief exposures could harm them.

X-rays and other ionizing rays act, in part at least, by virtue of the ions set free in the tissues they enter. Ionic concentrations of ionic gradients determine the degree and nature of the reactions seen or otherwise realized. The weakest link may well range from the cytoplasm to the single gene within the chromosome.

Thymonucleic acid is an important constituent in the mitosis of a cell; its synthesis is inhibited by x-rays. It has been suggested that the beneficial effect of x-rays in cancer is not limited to the direct effect of the radiation but also that the radiated cells themselves release an inhibitor of nucleic acid synthesis.

Automatic timing of x-ray exposure

The photo-electric timer is a device which automatically ends the exposure of x-rays after a time appropriate to the size of the patient. It is a means of achieving more uniform radiographs and those who have examined a series of radiographs of the same patient taken by different radiographers with the aid of a photo-electric timer appreciate its value.

The exposure timers may work on the photo-electric principle or on the ionization chamber principle.

The photo-electric principle has been employed by Morgan for automatic timing of exposure and for determining the density of radiographs (Morgan, 1942; Hodges and Morgan, 1945; Morgan and Hodges, 1945). The photo-multiplier is an important part of the Morgan-Hodges photo-timer. It is useful in mass miniature radiographic surveys of the chest and in routine radiography of the abdomen. It helps to compensate for variations in x-ray tube voltage and current. The method is not so suitable for very short exposures.

An ionization chamber with tin-coated electrodes has been used for the automatic timing of x-ray exposures. Tin is used to obtain ionization characteristics at different voltages similar to the light intensity characteristics of the fluorescent screen. The dimensions of the chamber are the same as the fluorescent screen and the thickness is 1 centimetre. The front plate of the device is cellophane coated with tin to the size and shape desired; a centre plate is made of cellophane and tin, and the