IONIZING RADIATIONS

The atomic structure of matter.

For the present purpose, it is convenient to think in terms of an atomic structure comprising a relatively massive central nucleus, surrounded by one or more orbital electrons. The diameter of an atom is some $10^{-8}$ cm, whereas that of the nucleus is some $10^{-12}$ cm, i.e. some 10,000 times smaller. The simplest type of atom is that of hydrogen with one proton in its nucleus and one orbital electron. The proton is a positively charged particle of mass some 1,840 times greater than that of an electron. Normally, an atom is electrically neutral, the positive charge on the nucleus being balanced by an equal negative charge due to the orbital electrons.

In addition to protons, the nuclei of elements other than hydrogen contain neutrons. A neutron is a particle of mass approximately the same as that of a proton, but uncharged.

X-radiation.

The existence of X-radiation was discovered by Wilhelm Rontgen in 1895. It is always produced when high-speed electrons strike matter. In a modern X-ray tube, a high voltage of tens of thousands of volts is placed across a pair of electrodes mounted in a highly evacuated tube. The negative electrode or cathode, contains a heated filament which acts as a source of electrons. In a fixed anode X-ray tube the positive electrode, or anode, consists of a massive copper block in which is embedded a block of tungsten of surface area some $3 \times 1$ mm. Electrons from the cathode are accelerated under the influence of the high electric field to strike the anode, where X-radiation is emitted. In order to produce sharp shadows, a small area source of X-rays is required and the beam of electrons is focused on to this area. To prevent vaporization of the anode occurring due to heat produced, the target area of the anode is made of a high-melting-point material such as tungsten. The bulk of the anode is made from a copper block to ensure that the heat produced is conducted away. In practice, as shown in figure 1, the radiating face of the anode is cut at an angle of 19° with the plane perpendicular to its axis. X-rays emerging from this “line focus” through the exit window appear to be coming from a much shorter line. If the line focus is 3 mm long by 1 mm wide, its length will appear to be $3 \times \sin 19° = 0.98$ mm. Its width will be unaltered, and so the effective focal area is $0.98 \text{ mm} \times 1 \text{ mm}$.

From the viewpoint of the anaesthetist and surgeon, it is important to consider the precautions that are taken in the tube design to minimize stray radiation which could strike the operating team. Shielding is accomplished by fitting a lead screen around that part of the tube where the X-rays are produced, leaving only a small exit port (fig. 2). X-ray tube and lead screen are placed in a metal box which is then filled with high voltage transformer oil. The electrical supplies are brought into it by means of heavily insulated cables. Heat generated in the X-ray tube is con-
ducted through the oil to the outer metal casing and thence to the atmosphere. In order to guard against excess heating in long exposures, as in therapy, a metal bellows is placed in the oil. As the oil heats up, the bellows expand. When the safety limit is reached, the bellows trips a switch and cuts off the mains supply to the apparatus. With this arrangement there must be no gas inside the metal, oil-filled, box. This has to be evacuated before the oil is put in. As a further protection, a conical "applicator" shield is mounted over the window of the tube. This limits the spread of the X-ray beam, protecting both operator and patient. In the latest X-ray sets, a series of metal diaphragms can be placed in front of the tube exit window to define the limits of the emergent beam as required. Unwanted leakage and scattered X-radiation from the tube is of concern to the surgeon and anaesthetist. Under international regulations the leakage radiation from the tube shield is limited to 100 mrem/hour at 1 metre, when the tube is run at its maximum rated output. In practice the leakage radiation from British X-ray tubes is less than one-tenth of the permitted amount. The smaller, portable X-ray sets capable of exposures requiring up to 10 mA at 83 kV would use a fixed anode X-ray tube, whereas for currents of the order 60 mA at 95 kV, a rotating anode tube (fig. 3) is employed. The anode is spun at some 3,000 r.p.m. by means of an induction motor stator placed outside the tube. The rotating anode has a much larger effective area than a fixed anode, but all the heat dissipated must be lost by heat radiation. Below tube voltages of 100 kV, the X-ray tube itself may be used as a simple half-wave rectifier, being fed straight from the secondary winding of the high voltage transformer. At 100 kV and above, separate rectifier valves are used. Figure 4 shows a portable X-ray set using a rotating anode X-ray tube, with separate rectifier valves. It is capable of delivering 300 mA at up to 102 kV peak.

The longer exposures required during fluoroscopy present the greatest risk to the surgeon and
anaesthetist due to the presence of stray X-radiation scattered from the patient and surroundings. In general, the use of image intensifiers during fluoroscopy has not greatly reduced the X-ray tube current employed. At low tube currents, it may not be possible to see the screen well in daylight, or the electrical noise of the intensifier amplifiers may be excessive. The use of an intensifier may provide a better quality picture at higher X-ray tube currents, and this may enable the diagnosis or manoeuvre to be completed in a shorter time. Hence it may well be desirable for the surgeon and anaesthetist to wear lead-lined aprons and film badges. Lead-lined screens may also be placed around the patient to limit scattered radiation. A film badge service is available in the U.K. through the Radiological Protection Service. The film badges are designed to distinguish between various forms of radiation, and to give an estimate of the dose received. Radiation hazards of interest to anaesthetists are discussed by Webster and Merrill (1957), Keen (1960), Kyle (1962), Letard and Belleau (1962) and Little and Radford (1964). Anaesthetists are sometimes
asked to anaesthetize patients undergoing super-
voltage irradiation of tumours in conjunction with
high-pressure oxygen (Van Den Brenk, Madigan
and Kerr, 1964; Churchill-Davidson, 1964). A
good review article on linear accelerators used for
this purpose is that of Atherton (1966). A general
description of X-rays is given by Strettan (1965).

RADIOACTIVE ISOTOPES

Isotopes.
It is possible for some elements to exist in
different forms having the same atomic number
but different atomic weights. These are known as
isotopes. Some isotopes are stable, others are
radioactive. The atomic number of an atom is
equal to the number of orbital electrons in the
atom, and governs the chemical properties of the
atom. The atomic weight of an atom is simply
its weight in terms of that of an oxygen atom.
Since the chemical properties of isotopes of the
same element are identical, their separation can
difficult.

Atomic mass unit.
This is one-sixteenth that of the mass of the
$^{0}\text{He}$ atom, i.e. $1.6603 \times 10^{-24}$ g. This is the physical
unit of atomic weight and is smaller than the
chemical unit which ignores the presence of the
heavier isotopes of oxygen, and fixes the atomic
weight of oxygen as 16.000 units.

The mass number “A”.
It will be remembered that an atom consists
of a central massive nucleus, around which move
orbital electrons. The diameter of an atom is
some $10^{-8}$ cm, whereas that of a nucleus is some
$10^{-13}$ cm, i.e. some 10,000 times smaller. The
mass number is the number of (protons plus
neutrons) in the nucleus and is the nearest integer
to the atomic weight. The atomic weight of an
atom no longer has the fundamental importance
formerly attached to it, and is in a sense accidentally
determined by the mixture of isotopes in the
atom and by their abundances. In the case of
chlorine, there are two isotopes of mass 35 and
37 and having relative abundances of 3.07/1. This
leads to a mean weight of 35.460 which is almost
exactly the chemical atomic weight of 35.457.

Nuclide.
This is the name of an atom with a specific
nuclear characteristic, e.g. phosphorus of mass
number 32 and atomic number 15, and cobalt of
mass number 60 and atomic number 27.

The symbolic representation of nuclides.

<table>
<thead>
<tr>
<th>A</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>15</td>
</tr>
</tbody>
</table>

The advantage of this method is that the nuclear
characteristics are kept to one side, leaving the
righthand side free for indication of valency and
molecular state. Thus $^1\text{H}$ represents an atom of
heavy hydrogen.

Stable and unstable nuclei.
In a series of isotopes of the same element, the
ratio of neutrons to protons varies. Some of these
ratios give rise to stability, whereas other ratios
lead to instability (radioactivity). Consideration
of the stability of nuclei involves a study of the
binding energy of the nucleus. This is the dif-
fERENCE between the sum of the masses of the
protons, neutrons, and electrons associated with
the atom and the exact mass of the nuclide. These
facts are illustrated in the following table (Faires
and Parks, 1964).

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic No.</th>
<th>No. of neutrons</th>
<th>No. of protons</th>
<th>Mass No.</th>
<th>Stable/Unstable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>Stable</td>
</tr>
<tr>
<td>Heavy hydrogen</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>Stable</td>
</tr>
<tr>
<td>Tritium</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>Unstable</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>Unstable</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>Unstable</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>9</td>
<td>Unstable</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>10</td>
<td>Unstable</td>
</tr>
</tbody>
</table>

MODES OF DISINTEGRATION OF NUCLEI—ALPHA
PARTICLES, BETA PARTICLES AND GAMMA RADIATION

Beta particles.
An unstable nucleus such as carbon-14 has an
excess of energy. In order to achieve stability, it
undergoes a random rearrangement during which
energy is given out in the form of particles.
Carbon-14 has one neutron too many for stability.
The resulting nuclear rearrangement may be
represented as the change of an uncharged
neutron into a positively charged proton. The formation of the positively charged proton is balanced by the production of a beta particle which is a negatively charged electron. The maximum energy of the beta particle depends on the change in binding energy resulting in the nuclear reaction. In many cases, the nucleus still has an excess of energy after losing a beta particle. This is then dissipated in the form of gamma radiation. Gamma radiation is simply a form of electromagnetic radiation like light or X-radiation. It has a shorter wavelength than X-radiation. Gamma radiation from radioactive cobalt is widely used in radiotherapy for the treatment of tumours. Since this type of nuclear rearrangement has resulted in the formation of an extra proton, the new nuclide will have an atomic number one higher than previously. For example:

\[ ^{14}\text{C} \rightarrow ^{\text{N}}\text{+B} \]

Some substances are pure beta emitters such as tritium, carbon-14, and sulphur-35. In the majority of cases, however, both beta particles and gamma radiation are emitted.

**Alpha particles.**

The heaviest nuclides have such an excess of energy that they commonly lose larger units of energy than beta particles in the decay process. These units are known as alpha particles. They are the doubly ionized nuclei of helium atoms, having a mass of four units and a positive charge of two units. The decay of radium-226 is given by:

\[ ^{226}\text{Ra} \rightarrow ^{\text{Rn+He}} \]

**Radioactive decay and half-life.**

The decay of a radioactive element from one isotopic form to the next is governed by a simple exponential law: \( N = N_0 e^{-\lambda t} \), where \( N_0 \) is the number of atoms of the decaying substance at time \( t=0 \), \( N \) the number at time \( t \), and \( \lambda \) is a constant for the particular element concerned, known as the decay constant. \( \lambda = (1/T) \), where \( T \) is the time constant, i.e. the time taken for the activity to decay to \( 1/e \) (37%) of its initial value. In considering the life of a particular radioactive substance, it is usual to express this in terms of its half-life. This is the time taken for the activity to decay to one-half of its original value. In the case of radiotherapy sources, it is often desirable to have a long half-life so that the source does not need to be renewed at frequent intervals. Common sources here are: caesium 137, half-life 30 years, gamma energy 0.66 MeV; cobalt 60, half-life 5.26 years, gamma energy 1.17 and 1.33 MeV; radium 226, half-life 1,620 years, gamma energy 0.19–2.43 MeV. (The unit of energy is a million electron volts, MeV; this is the energy an electron would acquire in accelerating through a potential difference of one million volts.) On the other hand, for labelling drugs which have to be injected into a patient, it is desirable to work with short half-life substances. For example, iodine-131, half-life 8.04 days; sulphur-35, half-life 87.2 days; mercury-203, half-life 47 days.

**Biological half-life.**

The greatest danger when working with radioactive materials occurs when they enter the body, because once they have become deposited in a tissue, they cannot readily be removed. In the body there are two processes reducing the amount of radioactivity. These are the normal radioactive decay, and excretion. The combined effect is to shorten the natural half-life of an isotope to its effective biological half-life. Hobbs (1965) states that whilst the physical half-life of \( ^{125}\text{I} \) is 60 days, its biological half-life is 3.4 hours. Taking into account the nature and energy of the radiation emitted, and the radiosensitivity of the tissue concerned, the International Committee on Radiological Protection has laid down a maximum permissible body burden for each radio-isotope.

**Radiological protection.**

It is now widely known that the action of radioactivity on tissue can be dangerous, and the amount of radiation to which one can be exposed is carefully laid down by law. Practical problems arise when handling radio-isotopes, since radioactivity by itself is invisible, silent and odourless. Further, harmful effects arising from exposure may not be evident for many years after the exposure. In order to specify dose levels, it is first necessary to lay down units by means of which the dose can be defined.
The röntgen.

The unit of radiation dose is basically given in röntgens (r). The röntgen is defined as the quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying one electrostatic unit of electricity of either sign (0.001293 g is the mass of 1 ml of air at STP). The röntgen can be regarded as the total energy given to 1 ml of air. It is not used to measure alpha or beta particle radiation because of practical difficulties of applying it here. It is not a unit of body exposure dose, since it does not necessarily give an indication of the energy absorbed by tissue.

The rad.

One röntgen gives 83.8 ergs of energy to 1 g of air but 93 ergs to 1 g of water. Since tissue is radiologically equivalent to water, it will give 93 ergs to 1 g of tissue. The fact that one röntgen gives different amounts of energy to 1 g of air and 1 g of tissue has led to the introduction of the rad. This is the unit of absorbed dose. It is defined as that quantity of ionizing radiation which produces an energy absorption of 100 ergs per gram, and it applies to all types of radiation. In soft tissue the röntgen and the rad are approximately equal.

Relative biological effectiveness (RBE).

This is defined as:

\[
\frac{\text{Amount of } 200 \text{ keV X-rays to produce a given effect}}{\text{Amount of the radiation required to produce the same effect}}
\]

For X, gamma, and beta radiation of all energies, the RBE is taken as 1, whilst for fast neutrons, protons and naturally occurring alpha particles it has the value of 10. Thus 2 rads of alpha particles produce the same biological damage as 20 rads of X or gamma rays. Alpha particles can be stopped by a single layer of paper, and have a range in air of a few cm. In this short path, however, they give rise to intense ionization, and resulting damage in tissues. It is for this reason that alpha particle emitters constitute a real hazard if they become ingested. A 3 MeV alpha particle has a range in air of 1.6 cm and is stopped by an aluminium foil about 0.015 mm thick, whereas a 3 MeV beta particle would require about 6.5 mm of aluminium.

The röntgen-equivalent-man (rem).

The rem is the unit of adsorbed dose, and is that dose which produces the same effect as that produced by 1 rad of X-rays. Hence 1 rem of X-rays = 1 rad of beta particles = 0.1 rad of alpha particles. For any given radiation, the dose in rem is found by multiplying the dose in rad by the RBE. For example, 1 rad of alpha particles plus 2 rad of gamma radiation gives \(1 \times 10 + 2 = 12\) rem.

Maximum permissible doses.

In the United Kingdom, the maximum permissible doses are laid down by law. In Medical Schools and Research Laboratories, the “Code of Practice for the Protection of Persons Exposed to Ionizing Radiations in Research and Teaching” applies.* In hospitals the “Code of Practice for the Protection of Persons against Ionizing Radiations arising from Medical and Dental use” (H.M.S.O., 1964) applies. Users of radioactive substances are required to register with the Ministry of Housing and Local Government, and the amount of material that can be kept on the premises and the routes of disposal are carefully controlled. The storage of the material and safety precautions taken during its use are controlled by the Ministry of Labour. A competent person must be appointed as Radiological Safety Officer. In the case of “designated persons” working with radioactive materials, the maximum total dose to the whole body, blood-forming organs and gonads is given by \(D = 5(N - 18)\) rems, where \(N\) is the person’s age in years. The dose rate must not be more than 3 rems per calendar quarter. Users must also have a calibrated monitor available to check the dose rates. For quantitative work an ionization chamber type of monitor is needed, but a simple transistorized Geiger counter monitor (fig. 5) is very handy for rough checks and for locating lost isotopes or spillages. Dosimetry techniques are described by Aglintsev and associates (1965) and the principles of radiation protection by Eaves (1964).

Clinical applications of radio-isotopes.

Hobbs (1965) describes the use of iodine \(^{131}\text{I}\) and \(^{125}\text{I}\) to replace dye in the indicator dilution method for determining cardiac output. The

* Published in 1964, and available from Her Majesty’s Stationery Office.
iodine is introduced in the form of labelled serum albumin. The method offers the advantage that water may be used for the preparation of standard solutions for calibration purposes. Hobbs also discusses an adaptation of the method to enable blood volume to be measured. Regional blood flow studies can be undertaken with the use of the radioactive gas \(^{133}\)Xe (half-life 5.27 days). Dollery, Hugh-Jones and Matthews (1962) discuss the use of radioactive xenon for studies of regional lung function. When \(^{133}\)Xe is rapidly injected into a suitable arm vein, nearly all the injected dose is evolved into the alveoli on the first passage through the pulmonary circulation, giving a counting rate for each zone of the lung which is proportional to its blood supply. Bentivoglio and his colleagues (1963a) have used \(^{133}\)Xe to study regional ventilation and perfusion in pulmonary emphysema, and in bronchial asthma (1963b). Holzman and his colleagues (1964) used \(^{133}\)Xe to study the muscle blood flow in the human forearm. The blood flow in skeletal muscle was studied by Lassen, Lindbjerg and Munck (1964), using \(^{133}\)Xe. Radioactive methods of estimating hepatic blood flow are discussed by Sherlock (1964) and isotope renograms as a test of renal function by Tauxe, Mahler and Hunt (1964).

Harper, Jacobson and McDowall (1965) use krypton-85 to determine the effect of hyperbaric oxygen on the blood flow through the cerebral cortex. Veall and Vetter (1958) describe the application of many isotopes to clinical studies, including the measurement of blood volume using chromium-51, and red cell survival studies with chromium-51.

Van Dyke, Chenoweth and Van Poznak (1964) describe the use of \(^{14}C\) and \(^{35}Cl\) to label cyclopropane, methoxyfluorane, and ether in studies on the metabolism of volatile anaesthetics. The metabolism of \(^{14}C\)-labelled halothane is described by Van Dyke, Chenoweth and Larson (1965).

Daniel (1963) used \(^{35}Cl\) labelling to study the metabolism of trichloroethylene and tetrachloroethylene in the rat. Dal Santo (1964) investigated the distribution of dimethyl-d-tubocurarine by labelling it with \(^{14}C\). The fate, distribution and excretion of promazine has been studied by Walseben and Seifter (1959) with the aid of \(^{14}S\)-labelled promazine.

The little monograph by Lajth (1961) gives a clear account of the use of \(^{131}I\)-labelled serum albumin for the estimation of blood volume, and the use of \(^{51}Cr\) to estimate red cell survival time. The various correction factors that have to be brought into the calculation may reduce the accuracy of blood volume measurements to a level which may be unacceptable for research purposes, although adequate for clinical investigations. A good review of isotope applications in haematology is that of Szirmai (1965).

REFERENCES


**BOOK REVIEW**


This little book will serve as a useful introduction to high-altitude medicine and presumably the sitting of the next World Games gives it a certain topical interest. For the non-athletic anaesthetist, however, there is little of specialist relevance; the book certainly deals with adaptation to hypoxia but only in terms of long-term acclimatization. There is a chapter on anaesthesia and surgery at high altitude which lists a number of clinical impressions and makes a few rather obvious comments about the use of nitrous oxide in these circumstances. The six lines devoted to the choice of muscle relaxants are rendered valueless by the use of obscure names.

Excluding this chapter on surgery and anaesthesia, this short book might be recommended for an evening's interesting reading were it not for the fact that at $5.75 it would be an expensive evening.

D. Gordon McDowall