Ionising Radiation and Mankind

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Edited by

D.V. Gopinath and N. Ramamoorthy

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FROM THE EDITORS: WHY THIS BOOK NOW?

The phenomena of radioactivity and ionizing radiations have been known since the very beginning of the 20th century. However, their wide applications in the service of mankind emerged only in the late 1940s, triggered by the developments in nuclear technology. Until then, radiation sources for applications were confined to X-Ray machines and to a limited extent, accelerators and natural radioactive materials like radium. The advent of the nuclear industry in the late 1940s and early 1950s changed the picture altogether; it provided a plethora of radiation sources widely varying in quantity, type and size and made available a variety of instrumentations with a high degree of sophistication, sensitivity, portability, etc. It also created a strong base for research and development in radiation sciences. These developments, along with some unique features of ionizing radiations such as: i) their ability to penetrate through matter and reveal its inner details, ii) their ability to deposit energy at the desired location inside the matter and bring about physical, chemical and biological changes, and iii) their unprecedented sensitivity for detection, making them one of the most powerful probes for studying nature, have led to a galloping increase in their applications in various sectors of society, be it medicine, industry, agriculture, research, etc.

Around the same time, that is the early 1950s, due to the far foresight of Dr. Homi Bhabha, atomic energy activities in India took off on a strong note. Dr. Bhabha had clearly foreseen at that stage, the immense potential of atomic energy for peaceful uses, particularly in the area of electricity generation and the application of ionizing radiation for the country. His idea was to prepare the country to fully utilize the benefits of radiation technology as it evolves and develops further. This he did and did it eminently. He scouted for experts in all of the associated fields working anywhere in the country or outside, attracted them to the Department of Atomic Energy, associated with them young and brilliant minds and built programmes around them. With this excellent start, activities related to the application of ionizing radiation and radioactivity took off very well in India and kept pace with the global development. Over the decades, enormous expertise in different aspects of radiation application has been built by the pioneers and their co-workers. Now, with the passage of time, these pioneers will be fast disappearing and many already have. We felt that their precious experience should not be lost and we should try to harness their knowledge in the form of comprehensive writings on their respective subject(s). We thought a publication having chapters on different aspects of the application of ionizing radiations, written by persons who have spent their lifetime in developing the particular area, would be a unique contribution. With this idea, we approached the concerned pioneers and their response was very heartening. All of them readily agreed to contribute to such an endeavour and extended exemplary cooperation, leading to this publication. As can be seen in the sequel, the Book encompasses developments in the application of ionizing radiation in almost all fields such as medicine, industry, agriculture, food preservation, environment, research, etc. It serves as a *State-of-the-art* document in the highly relevant area of "Ionizing radiation in the service of mankind" despite the contents of the chapters being finalised nearly two years ago. The Book deals with two other topics, radiation instrumentation and radiation safety, which are *per se* not radiation applications, but have played a very important role in the development of the applications and their acceptance by the society at large.

The applications involving ionizing radiation are contributing towards addressing many of the seventeen goals for sustainable development advocated by the United Nations (UN-SDGs). The International Atomic Energy Agency (IAEA), an inter-governmental organization under the UN, has been facilitating and fostering the peaceful uses of nuclear and radiation technologies. This has helped numerous countries to avail of professional and technological support in capacity building and adopting ionizing radiation-based technologies for myriad applications. We trust that the current Book, while emerging mostly from the experience gained in India, will be of much value to a large number of countries, academic institutions, researchers, policy makers and national/international bodies engaged in development initiatives.

We thank all the expert contributors for their fine support, cooperation and immense patience in the compilation of the book. We are grateful to Dr. R. Chidambaram and Dr. Najat Mokhtar (IAEA) for graciously providing the Forewords to the book.

D.V. Gopinath
N. Ramamoorthy

FOREWORD

Nuclear energy is an important method for producing electricity, and will become increasingly important in the future, as fossil fuel depletes in the world, and global warming caused by greenhouse gases increases. But nuclear technology is not just nuclear electricity and nuclear weapons, but impacts positively, often invisibly, almost every aspect of social and industrial activity. Nuclear technology contributes, directly or indirectly, to most of the 17 Sustainable Development Goals defined by the United Nations in 2015 - no hunger, affordable health care, and so on.

The radioactive isotopes created in nuclear reactors (or cyclotrons), and separated in radiochemistry laboratories, for medical, industrial and other applications are many. Ionising radiation from these radioisotopes finds extensive use in medical therapeutics and diagnosis, from killing of cancer cells to diagnosing thyroid problems. Another important application which is referred to in the book is the development of Computer Aided Tomography (CAT), which has revolutionized medical diagnostics, as well as industrial non-destructive testing. Radiation sterilisation of medical products has emerged as an important technique, with several advantages over other methods like autoclaving and ethylene oxide, because this is the only technique where the sterilisation is done after packaging.

Radiotracers are used to identify leakages in dams and movement of river silt. Techniques based on radiotracers and sealed radioactive sources are also vital tools in the chemical, steel, oil and petrochemical industries, for example to track degradation of linings in blast furnaces.

Radiation mutation by cosmic ionising radiation has created natural new agricultural varieties for humankind over millennia. Such mutants can also be produced by ionising radiation, with desirable properties like increased productivity, increased resistance to pests, etc. It is possible that radiation mutation may be the answer to mitigate the possible future damage caused by climate change. Food preservation using ionising radiation is another important area; for example, India is able to export mangoes by ships because of the increased shelf-life provided by this technique.

Accelerators are an important tool in frontier areas of research in physics and other disciplines; radioactive beams are a significant part of this field. In thermonuclear fusion, radioactive tritium is used. All these applications require development of advanced instrumentation. Ionising radiations have to be handled with care and, over the years, the necessary knowledge for this has been developed in the Department of Atomic Energy and other organisations around the world.

All these aspects and much more are covered extremely well, with latest information, in this excellent book edited by Dr. D. V. Gopinath and Dr. N. Ramamoorthy, who themselves have had distinguished careers in the Department of Atomic Energy. The various chapters have been written by leading experts in the respective fields. The book is very readable because each chapter starts with the scientific basis for the application, elementary applications in the beginning, followed by development of various advances and ending with the current state of the art. I am sure the book will be welcomed by young researchers and academic faculty in universities and national laboratories, as well as industry technologists and the public.

Dr. R. Chidambaram
Former Chairman, Atomic Energy Commission;
Former Principal Scientific Adviser to Government of India

FOREWORD
(FROM THE IAEA PERSPECTIVE)

I am pleased to provide a Foreword to the Book on ‘Ionising Radiation and Mankind’, which deals with several areas of applications of radioisotopes and radiation in agriculture, food preservation, radiopharmaceuticals, cancer therapy, industrial applications, among others, in eleven thematic chapters. These areas correlate directly with some of the functions and services of the International Atomic Energy Agency’s, IAEA’s, Department of Nuclear Applications (NA). Accordingly, I wish to underpin in this Foreword, the positive socio-economic impact that applications of radioisotopes and radiation in the above areas have, particularly in relation to the United Nations 2030 Agenda for Sustainable Development. As food for thought, I want to point out some of the challenges facing nuclear applications as well.

The strapline of the IAEA is ‘Atoms for Peace and Development”. The IAEA promotes the safe and peaceful uses of nuclear technology, including the use of radiation technologies and their application to achieve Sustainable Development Goals, SDGs, laid down in the United Nations’ 2030 Agenda. Sections of this treatise correlate directly with the IAEA Department of Nuclear Applications four core business areas. Radiopharmaceuticals, Industrial Applications and Radiation Instrumentation research, development and technology transfer are themes of the Division of Physical and Chemical Sciences (NAPC); Radiation Technology in Agriculture & Ionising Radiation in Food Preservation core topics in the IAEA/FAO joint Division of Food and Agriculture (NAFA); Nutrition, Application in Radiation Oncology & Nuclear Medicine central themes to the Division of Human Health (NAHU); and Radiotracer Applications in the Environment and Research part of the remit of the Division of Environmental Laboratories (NAEL).

Radiation processing technologies are based on the physical and chemical changes introduced by the interactions of ionizing radiation with matter. These have been promoted for their merit in addressing a vast range of important human needs, such as improving human health, driving industrial production and processes, sterilising products and equipment, creating and functionalising materials, preserving cultural heritages, improving food security through enhanced crop production, providing for food safety and increased shelf life in a sustainable manner, better managing scarce fresh water resources, and protecting our environment. These merits impact a number of the SDGs, including #2 End Hunger, #3 Good Health, #6 Clean Water, #8 Economic Growth, #9 Industry and Infrastructure, #11 Responsible Consumption, #13 Climate Action, #14 Life Underwater and #15 Life on Land.

In the 1990's, the estimate of total non-power nuclear technology industry sales (radioisotopes in medicine, agriculture, industry, resources development and research) was approximately US$ 270 billion per year. The economic and technical benefits of radioisotope technology (radiotracers, sealed sources and nucleonic gauges) as applied to industry and the environment are considerable, already proved and recognized by end users. A rough estimation of economic benefits from radioisotope applications in industry gives figures of around US$ 5 billion/year. Benefit to cost ratios for radiation technologies of between 100:1 and 4000:1 may be achieved. Only a few short-term investments exist which yield a return of this magnitude. While the economic impact of non-power nuclear technologies, i.e. radiation and radioisotopes, outweighs that of nuclear power generation, its societal impact is also high. Radiopharmaceuticals have demonstrated pivotal impact in the timely detection of various human diseases, such as cardiovascular disease in early stages, which has obvious health benefits but also leads to a reduction in the cost burden for both patients and governments. Therapeutic radiopharmaceuticals have successfully treated cancers such as neuroendocrine tumours and prostate, preventing unnecessary surgery and/or radiation in many cases.

In any treatise on the positive impact of nuclear medicine and radiation on patient care, the affordability of that health care becomes a prominent source of debate. One case in hand is the nuclear medicine and imaging perspective in cancer management. The last decades have seen a massive growth in the availability of radiation- and radioisotope-based diagnostic imaging technologies and techniques. Among the most exciting developments in the field has been the combining of anatomical and molecular imaging results, which has led to the development of hybrid scanners. There are two sides to the coin of these developments. On one hand, the benefits of meeting the need for more accurate diagnosis and more advanced techniques are obvious to clinicians and dominate their perspectives; on the other hand, governments and health-insurance companies are concerned by the increasing cost of health care for a growing and ageing population, and the high potential cost of imaging technologies.

Additional aspects must be considered to establish cost-effectiveness of imaging technologies. Beyond diagnosis, imaging tests in cancer have many functions in treatment. Despite the myriad of uses, policy makers often assume that new imaging technologies are only used to assess the presence or absence of disease; however, many more imaging studies are done in the course of monitoring response to treatment, evaluation of ongoing or recurrent symptoms after treatment, or for routine surveillance of patients at a high risk of relapse, than for primary staging of malignancy. The high cost of cancer treatments, and in many situations restricted access to timely treatment, demands that we select patients carefully and adapt therapies iteratively as early as possible to optimise survival and minimise morbidity. As identification and modulation of molecular targets become the key to developing, choosing, and validating molecular-targeted therapies, the role of (radiotracer-based) molecular imaging will grow in importance.

There is no doubt that delayed cancer detection, leading to patients with late-stage disease, is costing lives. Earlier diagnosis is clearly a key objective, but management of advanced cancer remains an important issue and one that consumes considerable health resources. Particularly in the setting of advanced disease, molecular imaging is important to molecular targeted therapies. When available treatments are expensive, toxic, and of inconstant efficacy, accurate characterisation of disease is crucial, particularly if it is key to treatment choice. Avoidance of futile or unnecessary therapy has not only clear advantages for patients, it also has advantages for society through direct cost savings.

Our terrestrial and marine environment provide a tremendous range of direct social-economic benefits for humans around the world. These benefits can consist of valuable but finite resources, such as food, essential nutrients, heavy metals or even groundwater, and diverse, more intangible benefits, such as natural shoreline armoring and carbon mitigation capabilities. These ecosystem-derived services are most valuable to society when the ecosystems are healthy and well-functioning.

The world’s oceans have long been perceived to contain endless bounty and capacity to absorb all human impacts. However, heightened pressures on our environment caused from rapid population increases and shifts towards coastal zones, related nutrient over-enrichment and contaminant releases have all led to the realization that the ocean's health is compromised and under threat. Indeed, today pollution, habitat alteration, and overfishing are considered primary threats to ocean health. Climate change impacts will likely only exacerbate several of these threats. While new scientific tools to study ocean health have been developed, the ability to accurately assess the wellbeing of terrestrial and marine environments remains challenging, simply due to their vastness and inherent complexities.

Nuclear science-based solutions are available to better understand and protect heathy coastal and marine ecosystems. The IAEA NAEL Radioecology Laboratory (REL) uses an integrated approach that includes both experimental and field perspectives to address the flow of contaminants through ecosystems. Ecosystem stressors most often include systemic climate-change impacts, modulated by endemic situations. Contaminants can range from inorganic (e.g., trace metals, radionuclides) to organic (e.g., hydrocarbons, marine toxins) and can be spread across a broad spectrum of marine life that can range from bacteria to mega fauna, such as sharks. Experimental approaches using radio-labelled tracers and stable isotopes to investigate physiological responses to realistic climate change-driven temperature and pH shifts are used to unravel the complexity of ecosystem reaction to stressors, including ocean acidification, harmful algal blooms, marine carbon cycling, ecotoxicology and marine plastics.

Because of their benefits, positive impacts and potential to significantly improve human welfare, the IAEA facilitates and fosters the safe and peaceful uses of nuclear and radiation technologies for all its Member States. Through coordinated research and development, it has honed these technologies and developed new ones. Through technology transfer, the IAEA has supported and enabled numerous Member States to safely adopt and apply radiation and radioisotope technologies for many applications in a sustainable manner.

With all the above facts and features in mind, we welcome this Book compiled and edited by Gopinath and Ramamoorthy, summarising the Indian experience. I am hopeful that it will benefit persons and institutions involved with the applications of ionising radiations, HR development, academics and development planning across the globe.

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CHAPTER 1

IMPACT OF IONIZING RADIATIONS ON MANKIND: AN OVERVIEW

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In the chronology of science, the phenomenon of radioactivity is a relatively new entrant; it is about 120 years old. It started with the discovery of the radioactive properties of the uranium ore pitchblende by Henry Becquerel in 1896 and the subsequent pioneering work of the Curies in isolating radioactive elements such as polonium and radium at the beginning of the last century. However, until the 1940s the subject was essentially of academic interest except for a small use of radium for medical purposes and an even smaller use in industry. It is only since the late forties, with the advent of nuclear technology, that radioactivity assumed great societal importance and concern. Whether it is exploding a nuclear device or producing electricity from nuclear energy, the generation of gigantic quantities of radioactivity is involved. Further, it is known that uncontrolled exposure to the radiations emanating from radioactive materials can have detrimental effects on living beings. Because of these reasons, some perceptions are prevailing, such as radioactivity has been brought in by nuclear technology and it is dangerous at any level. These are not true. Radioactivity is neither new nor specific to nuclear technology. It has existed all along and mankind has evolved in this ocean of radioactivity. Secondly, it has been well-established that exposure to radiations from radioactivity below certain specified limits does not result in any detrimental effects. Further, an important aspect of radioactivity and associated radiations, which has not received due importance is their positive and indispensable role in the service of mankind. Today, radioactivity and associated ionizing radiations have been rendering yeoman service to mankind in several fields of society, be it industry, medicine, agriculture, food processing, etc. To understand and appreciate this unique feature, a little background information given below could be helpful.

Radioactivity

Some naturally occurring elements, generally the very heavy ones, are unstable and disintegrate spontaneously, transmuting themselves into other elements. This phenomenon of spontaneous disintegration is known as “radioactivity”. The element that results from the disintegration of a radioactive element is called its “daughter product”. The daughter product can be a stable element or it can also be radioactive. If radioactive, it disintegrates further leading to another daughter product. In some cases, this process continues over a long chain till a stable element is reached. This results in a series of radioactive elements. In nature, three such radioactive chains exist, namely the uranium, thorium and actinium series. Most of the radioactivity that we find in nature belongs to these series; in particular, to the uranium and thorium series. Besides these, there are other naturally occurring radioactive isotopes such as potassium-40 (0.0117% natural abundance in potassium) and carbon-14. Their contribution to the overall magnitude of natural radioactivity is not significant but they gain importance as they can enter into biological systems. Apart from its natural occurrence as detailed above, radioactivity can be produced by man-made processes. When stable elements are exposed to certain elementary particles such as neutrons, the elements absorb these particles and convert themselves into radioactive species. This is known as “induced” or “artificial” radioactivity. There is one other process by which radioactive isotopes are generated. Certain elements in nature, again the very heavy ones such as uranium, on absorbing the elementary particle neutron, break up into two (occasionally three) fragments. This process is called “fission” and the fragments so generated are called “fission products”. Fission products are highly radioactive; several hundreds of them with half-lives ranging from a fraction of a second to several years are produced in the fission. In a nuclear power reactor, while it is generating power, fissions would be occurring continuously, resulting in the continuous generation and accumulation of gigantic quantities of fission products. (This is one of the major safety problems in the production of electricity by nuclear energy.) Induced radioactivity and to a lesser extent, fission products, play an important role in the application of ionizing radiations for the benefit of mankind.

Quantitatively, the unit used to specify radioactivity is the Becquerel (Bq). One Bq is 1 disintegration per second (dps). Often, an earlier unit, the curie (= 3.7 x 10^{10} Bq) is also used. Since the radioactive element is continuously disintegrating, its quantity would be continuously decreasing with time. This is termed as "radioactive decay" and the time taken for the element to decay to half its original quantity is called its "half-life ($T_{1/2}$)". Different radioactive elements have half-lives varying from microseconds or less to billions of years.

Ionizing Radiations

The most important feature of radioactive elements is that during the process of disintegration, they all emit different types of radiations called alpha, beta or gamma rays whose major features are given in Tables 1a and 1b.

Table 1a: Some important nuclear radiations and their salient features

Radiation	Constituent	Electrical Charge	Mass (amu[a])	Energy range commonly encountered[b]
α-rays	${}^{4}_{2}\mathrm{He}^{++}$	+2	4	4-8 MeV
β-rays	e^-	-1	~ 1/2000	Few KeV to 2-3 MeV
γ/X-rays[c]	Electro-magnetic radiation	0	0 rest mass	Few KeV to 6-8 MeV

[a] amu (atomic mass unit) = 1.6605 x 10^{-24} g (approximate mass of a proton).

[b] at the atomic and nuclear levels, the magnitude of energy is expressed in units of electron volts (eV). eV is the energy acquired by an electron in moving over a potential difference of one volt and it is approximately equal to 1.602 x 10^{-12} ergs. Other frequently used units are multiples of eV; keV (10^3 eV) and MeV (10^6 eV).

[c] by nature, γ and X radiations are identical; both are high energy electromagnetic radiation. The difference is in their origin; γ-rays originate from the nucleus and X-rays, in most cases, are generated outside the nucleus when electrons pass through an electric field. Another difference is that γ-rays occur at discrete energies, whereas X-rays are generally produced as a continuous spectrum.

In addition to the radiations shown in Table 1a, several other nuclear radiations/particles exist in nature, such as neutrons, protons, pions, muons, etc. Of these, the important ones from an application point of view are neutrons and protons and their characteristics are shown in Table 1b.

Table 1b: Salient features of neutrons and protons

Radiation	Constituent	Electrical Charge	Mass (amu)	Energy range commonly encountered
Neutrons	Neutral particle in the nucleus	0	~1	Fraction of an eV to several MeV
Protons	Charged particle in the nucleus	1	~1	Several MeV

Though the natures of all these radiations are quite different from one another, as can be seen from Tables 1a and 1b, a common feature of all of them is that they are all highly energetic compared to optical radiation. As a consequence, when these radiations are incident on matter they penetrate into the matter and induce "ionization" inside the matter, a process in which an electrically neutral atom/molecule is separated into an electron and a positive ion. This is the reason why they are collectively termed as "ionizing radiations". Of the above, radiations associated with electric charge (electrons, protons and alpha rays) interact directly with the orbital electrons in the atom/molecule and knock them off the atom. This is called direct ionization. In the case of **γ**/X-rays and neutrons, since they do not carry any charge, they cannot cause ionization directly; they do it in an indirect way. **γ**/X radiations interact with matter in several different ways, such as photoelectric interaction, Compton scattering and pair production, resulting in the generation of energetic electrons and these secondary electrons produce ionization like **β-**rays. Neutrons interact with the atomic nuclei in different ways leading to the production of heavy charged particles. In the case of slow neutrons, their absorption generally leads to reactions such as, (n, p), (n, α) and (n, fission), resulting in the generation of charged particles. With fast neutrons, mostly it is scattering by nuclei that generates the charged particles. A well-known case with fast neutrons is scattering by hydrogen resulting in energetic protons. These secondary particles produce ionization like **α-** and **β**-rays.

It must be mentioned here that besides radioactivity as described above, "accelerators and X-ray machines" are other important sources for high energy radiations. These machines generate high to very high energy-charged particles and in combination with suitable target materials, they can also produce high intensity, high energy X-rays. Accelerator-produced radiations play an important role in radiation applications.

Applications

The unique features of ionizing radiations which have made them extremely useful in several fields are:

i) their ability to penetrate through matter and reveal its inner details,
ii) their ability to deposit energy at the desired location (within certain limits) inside the matter and bring about physical, chemical and biological changes and
iii) their unprecedented sensitivity for detection making them one of the most powerful probes for studying nature.

A schematic of the basic mechanism, which makes radioactivity and ionizing radiations so very useful in varied fields, is given in Figure 1 and some of its important aspects are briefly described.

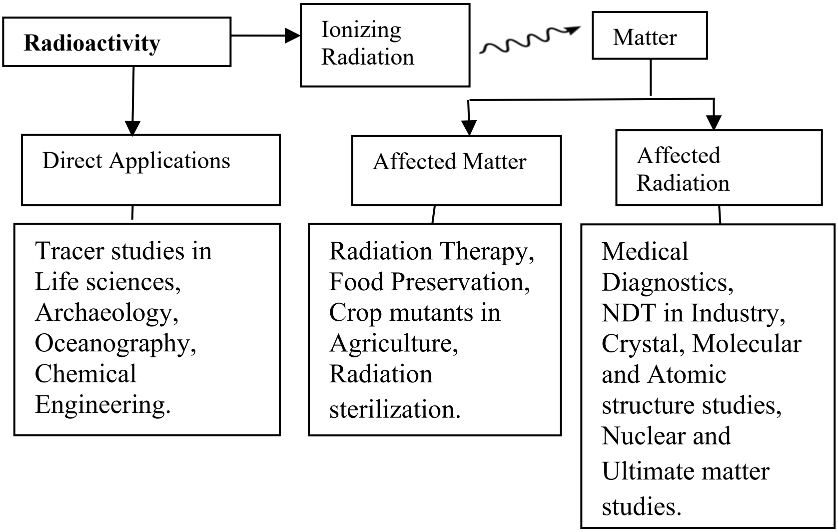

Fig. 1: Applications of radioactivity and ionizing radiations

When matter is exposed to ionizing radiation, the two interact and in the process both are affected. The affected radiation quite often carries significant information on the nature of the matter with which it has interacted and provides us with a powerful tool to understand matter at different levels, as mentioned below.

At the bulk level, ionizing radiations have become very valuable diagnostic tools in medicine and industry. As per a recent report of the WHO, 30-50% of all crucial medical decisions are dependent on X-ray diagnosis and the early detection of certain diseases depends entirely on X-ray examination. Computer aided tomography with ionizing radiation has revolutionized medical diagnostics. It has given mankind the ability to look through material, living as well as non-living, and obtain information with unprecedented accuracy and detail, in a non-invasive way.

Similarly, in industry, radiography using radiation from radioisotopes is a very widely-used technique for the non-destructive testing of welds, castings, etc. It has contributed enormously to quality improvement in industry. Today, radiography has become mandatory for quality control in several high-tech fabrication industries. Nucleonic gauges, based on the study of reflected or transmitted radiation, are being extensively used in several industries for process control and quality assurance.

Ionizing radiations are playing a very significant role in pure and applied research. At the atomic level, a large part of our understanding about the structure of molecules, particularly macromolecules, has been obtained from X-ray and neutron diffraction studies. A glorious example here is the identification of the structure of the DNA molecule, the gene material, which has revolutionized our understanding of biology. This has been entirely possible due to X-ray diffraction techniques. Neutrons have been of immense use as a tool in the study of lattice parameters of crystals, imperfections in solids, etc. In addition to neutron and X-ray diffraction methods, techniques such as X-ray fluorescence and positron annihilation have provided invaluable information on the physical and chemical nature of matter at atomic and molecular levels.

Exposing matter to neutrons results in the transmutation of elements and the production of newer isotopes, most of which are radioactive. These radioactive isotopes have extensive applications in medicine, industry, agriculture and other areas. Another common mode of interaction of radiation with matter is ionization, that is, knocking off electrons from the neutral atoms or molecules in the medium through which they are passing. The resultant electrons and positive ions eventually recombine, leading to the formation of highly active species called free radicals. Free radicals can induce a host of chemical changes in the material, with several applications in industry such as polymerization, vulcanization, etc.

If the medium happens to be a living system, the free radicals produced by the ionizing radiation interact with the bio-molecules. Such interactions can lead to several undesirable as well as desirable changes, which have been harnessed for the benefit of mankind. For instance, the interaction could be with genetic material in the cell resulting in the alteration of the genetic information of the biological entity. Or, with sufficient exposure, there could be massive cell damage leading to the death of the organism. Even these effects have found very useful applications. Radiation induced (accelerated) mutation in crops has been used to evolve newer breeds of agricultural species with improved features such as higher yield, better disease resistance and early maturity. Similarly, radiation killing has several valuable applications, the best known amongst them is the treatment of cancer. Recent reports suggest that more than sixty per cent of all cancer cases require treatment by ionizing radiation.

The extreme sensitivity of radioactive material for detection makes it eminently suitable for tracer studies. This has found applications in the medical field for metabolic studies, diagnostic imaging, monitoring diseases, blood circulation, etc. Radioactive tracers have found wide applications in industry for studying the wear and tear of machinery and for nutrition uptake studies in agriculture. Radioisotopes and stable isotopes are extensively used in the management of water resources, such as for example, ground water movement, silt movement in large water bodies and seepage from dams, leading to the development of a new discipline called isotope hydrology. A very novel application of radioactivity in archaeology is the development of carbon dating. It has been a very powerful tool for archaeologists to determine the age of ancient objects with unprecedented accuracy.

Summary

Radioactivity and associated ionizing radiations have several unique and useful characteristics and are finding an increasing number of applications in the service of mankind. At the same time, it is also true that uncontrolled and excessive exposures to ionizing radiation can result in undesirable health effects. However, this factor alone should not scare us and deter its utilization. The safety aspect of ionizing radiation is one of the most widely studied subjects. Today, there is good knowledge about the risks associated with radiation exposure at different levels and the safe practices to be adopted for keeping these risks at the lowest level. Experience shows that compared to the immense benefits gained from the use of ionizing radiations, the detriment to mankind is insignificant. What is required at present is a wide dissemination of knowledge about the ability of ionizing radiations to serve mankind and building up proper awareness about their safe usage.

CHAPTER 2

MEDICAL APPLICATIONS – PART I: RADIATION APPLICATION IN RADIATION ONCOLOGY

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1. Historical background

Cancer has been known since the time of Hippocrates when he tried to treat a woman with breast cancer, about 2500 years ago. The large veins and their geometry reminded him of a crab and he named it "karkinos" which probably means "crablike". Until the 19th century the only method known to treat cancer was through surgery. Surgery is often not successful in the treatment of cancer since it is not actually a disease and so gives no symptoms till its spread (uncontrolled tissue growth) interferes with other systems (through metastasis) causing complications and death. So, early detection is the key to the successful treatment of cancer even today, but thanks to non-surgical methods that have evolved over the years, today we can even control advanced cancers and extend the life span, without sacrificing quality of life.

Two non-surgical methods were introduced in the treatment of cancer in the early part of the 1900s, namely chemotherapy (in 1909) and radiation therapy (or radiotherapy) in the 1900s following the discovery of X-rays by Roentgen in 1895 and radium by Pierre and Marie Curie in 1898. Though I am supposed to write about the history of radiation oncology here, I cannot but help write a few paragraphs on the radiation risk which got scant attention in the early uses of radiation in medicine. This is because of two reasons: one, in the early era, the indiscriminate use of radiation caused a lot of suffering for both people and professionals in society, and two, radiation risk is also of great relevance in the radiation therapy treatment of cancer since normal tissues also get destroyed along with the cancer cells.

C. M. Dally, Edison's assistant, who made all the X-ray tubes and fluoroscopes for Edison to diagnose and treat diseases, was the first X-ray martyr. Mr. Dally tested his X-ray equipment on his own hands to ensure the tube was producing X-rays and in sufficient intensity. Eventually Dally lost both arms to malignant ulceration. He died a painful death in 1904 at the age of 39, and is now remembered as the first martyr to radiation. This led Thomas Edison to stop working on X-rays, fearing that radiation was too dangerous, but physicians continued to experiment with the device for the diagnosis of diseases in patients. By 1897, barely two years since the discovery of X-rays, about 70 cases of skin damage were reported. By 1902, hundreds of cases of x-ray injuries were documented. Surgery was often needed to repair the damage.

The frivolous use of radiation was not confined to X-rays. Radium too joined the list, as a wonder drug for general well-being and it was used in drinking water and from paste to chocolates. The case of radium dial painters is also well known. Young girls were employed to paint watch dials with self-luminous paint (containing radium) in a factory in New Jersey, around the 1920s. The women used to lick the tip of the brush into a fine point and in the process they ingested significant amounts of radium. This led to so-called "radium poisoning" causing anaemia, bone fractures, necrosis of the jaw (this came to be known as "radium jaw") and cancer. Most of them died young and others suffered long before their death. Radium (like calcium) was concentrated in bones causing leukaemia and in teeth leading to their disintegration. A Monument to the X-ray and Radium Martyrs of all Nations, erected by the German X-ray Society in the garden of the St. Georg Hospital, Hamburg, in 1936, contains 159 names of victims of overexposure. Wise men always lived in this world. The first radiation protection advice came as early as 1986 and over the years better sense prevailed and many radiation protection measures were introduced for the judicious use of radiation in medicine.

2. Principles of radiation therapy

Physicians treating cancer also realized that radiation treatment was a double-edged sword and needed to be used in such a way that it killed almost all of the cancer cells in the body but spared as many normal tissue cells as possible in the process. Ideally the aim of radiation therapy is to deliver a 100% dose to the tumour and a 0% dose to normal tissues (as shown in Fig. 1 (left)) which is impossible to achieve since the physical attenuation of radiation in the body (as shown in Fig. 1 (right)) always delivers a higher dose to proximal regions and a lesser dose to distal regions of the tumour, with all regions in the beam path receiving some dosage.

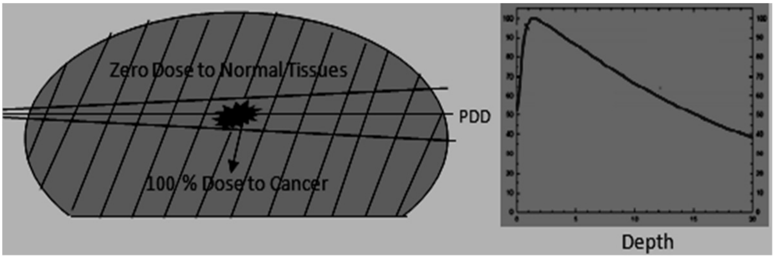

Fig. 1: Ideal and realistic dose distribution for a beam in a patient

In order to deliver a larger dose to the tumour compared to the surrounding tissue regions, the patient must be treated with multiple fields thus sharing the normal tissue dose over larger areas of the body, as shown in Fig 2. The beams are given weightages to control the dose delivered through each portal. For instance, if there is a critical organ in one of the fields, the dose delivered through this portal is reduced, in order to reduce the dose to the critical organ and the doses delivered through other portals are correspondingly increased so that the prescription dose can be delivered to the tumour.

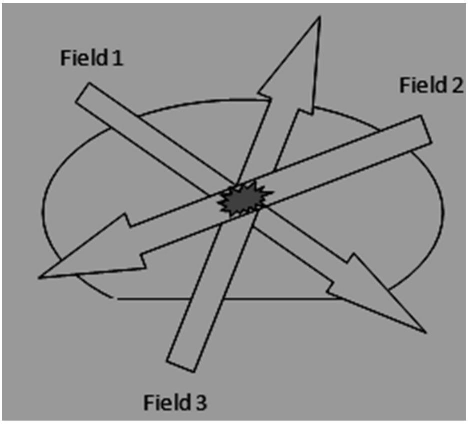

Fig. 2: Multiple fields to distribute normal tissue doses

The beam directions are chosen in such a way that there are no critical organs in the beam path, to the greatest extent possible. Although, for a given field (beam) the dose in the proximal region is larger than the tumour dose, considering all the fields, the total tumour dose is larger than the dose in the proximal regions of the beams. For instance, if the percentage depth dose (PDD) – i.e., the dose at a peak dose depth taken as 100% – at the tumour depth is 60% for each field, the three fields would deliver 3 x 60 = 180% dose at the tumour while each field delivers a maximum of 100% at its d_{max} point. d_{max} occurs at 5 mm depth for ^{60}Co, at 1.5 cm depth for a 6 MV beam, etc., for the tissue medium. The multiple fields are generated by rotating the X-ray beam around the patient and choosing the optimal directions for a given tumour site.

In spite of the therapeutic advantage of the multiple field treatment of cancer, today what limits radiation therapy treatment is not the deliverable tumour dose (any amount of dose can be delivered to the tumour), but a “safely” deliverable tumour dose. In other words, it is the normal tissue dose that can be tolerated by the patient that limits the (safely) deliverable tumour dose. If this “safely deliverable dose” is not enough to eradicate the cancer then it can only serve as a palliative dose to control the spread of cancer and the patient cannot be completely cured. So, all of the developments in radiation therapy that have occurred to this day are to spare more and more normal tissue (to reduce normal tissue complications) so that the tumour dose can be escalated to increase the tumour control probability.

3. Dose units in radiation therapy

There are several units and radiation quantities used for quantifying the radiation. One must read through the evolution of the radiation quantities to understand the subtle differences between the quantities and their relationships. It is difficult to explain them to non-specialist readers. We will just introduce one basic quantity to discuss radiotherapy application in medicine namely, the “absorbed dose”, which we generally refer to as the dose. It is just the radiation energy absorbed per unit mass of the medium. The mechanism of energy absorption is as follows.

Matter is made up of atoms and atoms are made up of neutrons and protons (commonly known as nucleons). The nucleons are bound together by nuclear forces. The electrons are bound to the nucleus through electromagnetic forces. So, to extract an electron from an atom or a nucleon from the nucleus, certain force (F) must be applied for a short