Physical Foundations of Radiology

FOURTH EDITION

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PHYSICAL FOUNDATIONS OF RADIOLOGY

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PREFACE TO THE FOURTH EDITION

The First Edition of *Physical Foundations of Radiology,* written in 1944 by Otto Glasser, Edith Quimby, J. L. Weatherwax, and L. S. Taylor, was one of the first comprehensive, yet elementary, guides to radiation physics written specifically for the radiologist. As such, it and the two subsequent editions have been a standard textbook for radiology residents and others involved in the medical applications of ionizing radiation.

Since the appearance of the Third Edition in 1961, Otto Glasser has died (in 1964), and Edith Quimby, having retired in 1960, did not wish to assume the task of a complete revision. Thus I was asked to edit a new edition—an opportunity I welcomed, having taught radiologic physics for nearly 20 years, much of the time using *Physical Foundations of Radiology*. Dr. Quimby kindly agreed to revise some of her chapters (Chapters 12 through 15), and Dr. Morgan revised Chapter 7, which he had contributed to the Third Edition.

Recent changes in the physical aspects of radiology, particularly the advent of supervoltage radiotherapy and advances in nuclear medicine, required a new approach to the teaching of both the fundamental and the practical aspects of radiation physics. Thus Chapters 2, 3, 4, 8, 10, and 11 have been newly written for this edition, and Chapter 16 has been revised extensively. Chapter 1, 5, and 9 contain much of the material written by Glasser in the Third Edition, with revisions and additions.

Despite these major revisions, the basic objectives and character of the book remain the same. As before, it is intended as a compact and elementary guide to radiation physics, primarily for the radiologist and other nonphysicists interested in radiology. It is not intended to be an exhaustive treatment. Physical principles are considered only insofar as they are required for an understanding of medical radiology.

I am grateful to many friends and colleagues who have supplied suggestions for this edition, particularly James Kereiakes and Herbert Jackson. I also thank Dr. Quimby for careful critique of my chapters. As in previous editions, many authors and publishers have allowed reproduction of their material; these courtesies are deeply appreciated.

Many new illustrations have been prepared for this edition. Some of these were skillfully executed by Zena Lupjan, while others are by the author. Secretarial assistance was provided by a number of people, including Mrs. Gloria Sampson, Mrs. Mary Freeman, and Mrs. Gerda Osborn, and particularly my wife. Very careful editing of the entire manuscript was performed by Miss Jo Hinkel of the publisher's staff.

I wish to express here grateful acknowledgement and sincere appreciation to all who have helped in the completion of this Fourth Edition.

New York City

Paul N. Goodwin

PREFACE TO THE FIRST EDITION

Radiology combines the aspects of an art, in which each patient must be considered as an individual problem, with various characteristics which must be taken into account, and of a *science* in which much definite information is available. Clinical medicine alone can offer training in the first; radiologic physics contributes largely to the second.

In the early days of the science, the radiologist had to be his own physicist, frequently his own technician as well. Gas tubes, static machines, and induction coils meant apparatus so unstable that little or no standardization was possible. However, with the development of the hot cathode tube and the interrupterless transformer, these difficulties were swept aside. Immediately came demands for greater precision and accuracy in the use of x-ray apparatus and in the recording of physical factors employed in various procedures. Almost at the same time, the need for closer correlation in the uses of x rays and radium became apparent. Pioneering in such efforts were those radiologists who had been actively collaborating in physical developments. They were quickly joined by a few physicists who were concerned with practical applications of radiations, and for twenty-five years the two groups have worked in close and harmonious co-operation.

Within the last decade the demand by students of radiology for serious instruction in radiation physics has become steadily more urgent. Classes have been established in many medical schools, while in other places, groups of radiologists have organized for study. For several years, in the "refresher courses" offered at annual meetings of the national radiological organizations, those in physics have usually been filled to capacity. The American Board of Radiology, recognizing the importance of a knowledge of physical principles in radiology, has given the subject a place in the examination for its diploma.

As is natural with a constantly growing subject, each teacher has developed his own methods, working out courses of study, lecture out-lines, demonstrations, and so on, as seemed most appropriate for particular groups of students. For some time the present authors, coming together at national radiologic and physical meetings, have discussed the desirability of pooling their experiences and producing a book which should fit the needs of groups they worked with. These groups, in general, fall into two categories: physicians preparing to enter the field of radiology, and those already in the specialty and desirous of review or of further information. The authors have all been engaged in teaching fundamentals to the first group and in presenting shorter courses and special lectures for the second.

Accordingly the collaboration was undertaken. It was decided that the book should be elementary and nonmathematical. Those using it for teaching in medical schools may desire to supplement it with material from more advanced texts and from the periodical literature. To aid in this, both general bibliographies and special references are given. Throughout the book, the place of radiologic physics as a part of the whole subject of modern physics has been kept in mind, and the fundamental aspects stressed. To this end a considerable amount of descriptive material on nuclear physics has been included; it is realized that any chapter on this subject may be out of date before it is published, but it is hoped that a background will be formed for keeping up with current developments. The chapters on x-ray diagnosis and on biologic effects of radiation are also planned to be stimulating rather than complete. The chapter on therapy records is the direct result of many requests for assistance on this subject. To facilitate the use of the charts there proposed or similar ones, extensive tables of dosage data for both x rays and radium are presented.

Chapters were prepared by the four authors as indicated in the table of contents, and then editorially welded together and indexed by Glasser and Quimby, with the aid of Jessie C. Tucker. All illustrations were prepared by C. M. Jeffries and B. Tautkins, under Glasser's supervision.

Acknowledgement is gratefully made to the several physicists and radiologists who have permitted reproduction of their published material, and in particular to Mr. Carl B. Braestrup for his generous permission to use his unpublished data on low voltage depth doses.

Otto Glasser
Edith H. Quimby
Lauriston S. Taylor
James L. Weatherwax

PHYSICAL FOUNDATIONS OF RADIOLOGY

CONTENTS

1 Milestones in Radiology

THE DISCOVERY OF X RAYS

In November, 1895, Wilhelm Conrad Roentgen, Professor of Physics at the University of Wurzburg in Germany, was conducting experiments on cathode rays, using a Crookes-Hittorf tube. This type of tube, which was widely used by physicists at that time, consisted of a glass tube, almost completely evacuated, with two electrodes placed inside the tube, several centimeters apart. A high potential of several thousand volts was maintained between the electrodes and cathode rays (actually, electrons) passed from the negative electrode (cathode) to the anode or continued on until they struck the glass wall of the tube.

On November 8, 1895, Roentgen observed a bright fluorescence from a paper screen covered with barium plastinocyanide crystals, placed some distance from a Crookes-Hittorf tube. Immediately he recognized a clue to a new form of radiation far more penetrating than cathode rays. He pursued this clue feverishly during the next few weeks, in an amazing number of experiments carefully designed to investigate the properties of these rays, which he subsequently called "x rays."

The use of a photographic plate instead of a fluorescent screen was one of Roentgen's early and most important steps in experimenting with the new radiation. One dramatic result was a picture of the bones of his wife's hand. By means of fluorescent screens and photographic plates, Roentgen made many observations which were reported in his three classic communications in December, 1895, March, 1896, and May, 1897.

In these first three papers, Roentgen showed that x rays had the following properties:

1. They caused fluorescence in certain substances.
2. They darkened photographic plates.
3. Their behavior differed fundamentally from that of cathode rays.
4. They were propagated in straight lines.
5. They were not deviated by the influence of electric or magnetic fields.
6. They could penetrate many materials.
7. They became "harder" after penetrating several absorbers.
8. They produced different types of scattered and secondary radiations.
9. They caused the air through which they passed to become electrically conductive.

The possibility of using x-ray pictures in medical and surgical diagnosis was recognized at once and exploited immediately. Within the first year almost a thousand papers and many books on x rays were published. As early as February, 1896, an editorial in the *Journal of the American Medical Association* ventured the opinion that possibly the new rays might have therapeutic applicability. Unfortunately, the first physiologic effects of x rays were surprising, and marked the beginning of a distressing chapter of suffering by many of the roentgen pioneers.

THE DISCOVERY OF RADIOACTIVITY

One of the most important consequences of the discovery of x rays was the work leading to the discovery of radioactivity. A few weeks after Roentgen's discovery, Henri Becquerel began to investigate the possibility, suggested by Henri Poincaré, that rays similar to those emitted by a fluorescent x-ray tube might be produced by known fluorescent or phosphorescent substances. Fortunately, Becquerel began his experiment with uranium compounds, which were known to be highly fluorescent after exposure to the sun's rays. He noted that photographic plates were darkened by such uranium salts, even if they had not been first exposed to sunlight. He concluded that the radiation that darkened the plate came from the substance itself and, more important, that it was able to penetrate matter. The rays were emitted spontaneously and continuously from all uranium compounds whether or not they were fluorescent. Radiation, he found, was a specific property of the uranium atoms and presented a new and entirely unexpected property of matter. Becquerel presented the first important results of these investigations to the Paris Academy of Sciences, late in 1896.

THE DISCOVERY OF RADIUM

After Becquerel had discovered the radioactive properties of certain substances, Marie and Pierre Curie began studies to determine whether other elements had similar properties. Madame Curie continued Becquerel's experiments at the Municipal School in Paris. She tested many elements and compounds for radioactivity and soon found that thorium compounds had similar properties. Madame Curie examined many minerals in which these elements were present and discovered that certain uranium and thorium ores, notably pitchblende from the Austrian mine of Joachimsthal, showed a higher radioactivity than could be accounted for by its content either of uranium or of thorium. This abnormal phenomenon was strange and surprising. She concluded that these ores contained small quantities of some other substance much more radioactive than either uranium or thorium, and that this substance could not be one of the known chemical elements, since she had examined all of them. To test this hypothesis by experiment became so fascinating that Pierre Curie joined his wife in the search for the mysterious substance. Together they first studied the composition of pitchblende by many chemical procedures—pulverization, precipitation, and fractional crystalization—and then carefully examined the radioactivity of each separated portion of the ore by studying its ionizing effects. Large quantities of pitchblende, had to be treated to obtain traces of radioactive materials. Progressing tediously step-by-step, they finally found a strongly radioactive substance that was associated with the bismuth extract of the uranium. They announced their discovery of the substance in July, 1898, and in honor of her native Poland, Marie Curie called it polonium. Connected with the barium extract of the ore they found another substance even more strongly radioactive which emitted two million times as much radiation as uranium. This substance they called radium, and announced its discovery in December, 1898. Pierre Curie devoted most of his time to a study of the physical properties of the newly discovered elements while Marie Curie worked on their chemical purification.

Roentgen and the Curies did not profit materially from their important discoveries. They did not take out patents on methods of producing x rays or utilizing radiations from radioactive substances and they published their complete working experiments in detail so that everyone interested could make proper use of their discoveries. The work of Roentgen and the Curies opened up new fields in medicine and the natural sciences, and the excitement of both the scientific and lay worlds over their discoveries has rarely been exceeded in the history of science. A shower of honors was bestowed upon these scientists. Roentgen was given the first Nobel Prize in Physics in 1901, and in 1903 the same prize was given to the Curies. In 1911, Marie Curie received the Nobel Prize in Chemistry, and became the only scientist ever to receive two Nobel prizes. Twenty-four years later the Curie's daughter Irene, together with her husband Frederic Joliot, was honored with the Nobel Prize in Chemistry, truly a remarkable recognition of the accomplishments of a great scientific family.

SOME MILESTONES IN RADIOLOGY

There have been many brilliant achievements by many scientists in the more than seven decades since Roentgen's discovery. The following list gives some of these discoveries and events which most directly affected the development of radiology. These and many other events are described in the Bibliography at the end of the chapter.

1895 (November) W. C. Roentgen discovered x rays with a Hittorf-Crookes vacuum tube.

1896 (March) M. I. Pupin discovered the intensifying screen method.

Roentgen, A. A. Campbell-Swinton, O. B. Shallenberger, H. Jackson, and others constructed the first metal target x-ray tubes.

J. Trowbridge built the first oil-immersed x-ray tube.

(April) L. Fomm, E. Mach, and E. Thomson developed the use of stereoscopic methods in roentgenography.

W. Konig and W. J. Morton made the first dental radiographs.

(May) The first roentgen-ray journal, *Archives of Clinical Skiagraphy*, was published in Great Britain.

(July) J. M. Bleyer, A. Battelli, and J. McIntyre were the first to use a *photofluoroscope*.

(November) J. Perrin measured, by means of an air condenser, the loss of electric charge caused by the ionization produced by x rays.

A. H. Becquerel presented to the Paris Academy of Sciences the results of his discovery of radioactive radiations emitted by uranium compounds.

1897 J. J. Thomson studied the deflection of cathode rays by a magnet and came to the conclusion that cathode rays are made up of discrete particles of negative electricity, considerably smaller than atoms. He postulated that atoms are composed partly of these small particles, which he called *electrons*.

E. Rutherford examined the radiations from uranium after Becquerel's discovery of radioactivity and found two types, which he called *alpha* and *beta* rays. Later he found that alpha particles are nuclei of helium and that beta particles are electrons.

1898 M. and P. Curie announced the discovery of *polonium* in July, and *radium* in December.

P. Villard discovered *gamma* rays and found them to be the same type of ray as the x ray.

1900 (March) The Roentgen Society of the United States was founded in St. Louis, Missouri.

1901 M. Planck proposed the *quantum theory*, according to which radiant energy is emitted or absorbed in discontinuous steps or quanta.

W. C. Roentgen was awarded the first Nobel Prize in Physics, "for his discovery of x rays."