SIXTH EDITION • SECOND PRINTING

THE FUNDAMENTALS OF X-RAY AND RADIUM PHYSICS

JOSEPH SELMAN, M.D.

Clinical Assistant Professor of Radiology
University of Texas, Southwestern Medical School
Director, School of Radiologic Technology
Tyler Junior College
Attending Radiologist
Mother Frances Hospital
Attending Radiologist
Medical Center Hospital
Consultant in Radiology, East Texas Chest Hospital
Tyler, Texas

This is the text against which all other tomes of similar intent are measured. Now in its Sixth Edition, this classic introduction to x-ray and radium physics has again been revised and enlarged to accommodate a constantly changing field. The basic format — proven effective in many classrooms over many years — has been retained. Selected for new or amplified discussions in this edition are such topics as focal spot evaluation, modulation transfer function, new types of intensifying screens, the basic phenomena of phosphor luminescence, direct magnification in small vessel angiography, high kilovoltage radiography, and radiation protection.

CHARLES C THOMAS • PUBLISHER

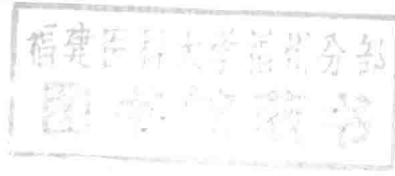
Springfield • Illinois • U.S.A.

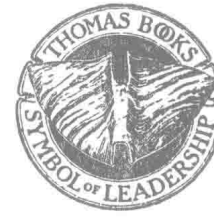
(Sixth Edition, Second Printing)

The Fundamentals of X-ray and Radium Physics

By **JOSEPH SELMAN, M.D.**

Clinical Assistant Professor of Radiology
University of Texas, Southwestern Medical School
Director, School of Radiologic Technology
Tyler Junior College
Attending Radiologist
Mother Frances Hospital
Attending Radiologist
Medical Center Hospital
Consultant in Radiology, East Texas Chest Hospital
Tyler, Texas





CHARLES C THOMAS · PUBLISHER
Springfield · Illinois · U.S.A.

Published and Distributed Throughout the World by
CHARLES C THOMAS • PUBLISHER
BANNERSTONE HOUSE
301-327 East Lawrence Avenue, Springfield, Illinois, U.S.A.

ISBN 0-398-03622-5
Library of Congress Catalog Card Number: 76-44402

First Edition—1954
6,000 copies
Second Edition—1957
11,000 copies
Third Edition—1961
16,000 copies
Fourth Edition—1965
56,500 copies
Fifth Edition—1972
30,000 copies
Sixth Edition—1977
15,000 copies
Sixth Edition, Second Printing—1978
10,000 copies

Selman, Joseph.
The fundamentals of x-ray and radium physics.
Bibliography: p.
Includes index.
1. X-rays. 2. Radium. 3. Radiography. I. Title.
QC481.S457 1977 537.5'35 76-44402
ISBN 0-398-03622-5

Printed in the United States of America
P-4

The Fundamentals of X-ray and Radium Physics

Dedicated to my wife

PREFACE TO SIXTH EDITION

AFTER A FOUR-YEAR INTERVAL, revision time has come around again. While the physical basis of radiologic technology has not undergone any revolutionary changes, certain new information is of sufficient importance to be incorporated in the curriculum. In addition, it has been felt that some well-established concepts could benefit from more detailed discussion.

Of special importance has been the development of new types of intensifying screens, both as modifications of existing phosphors, and in the form of completely novel rare earth phosphors. This subject is explored in depth. Furthermore, greater attention has geen given to the basic phenomena of luminescence of phosphors to elucidate the fundamental nature of intensifying screen behavior.

Because of growing interest in the accurate measurement of focal spot size, especially in angiography with magnification, the probems of focal spot evaluation have been presented in some detail. In connection with focal spot measurement, it was felt that a simplified description of modulation transfer function would be of interest.

Direct magnification, having escaped from the realm of "trick radiography," has become an integral part of modern small vessel angiography. Therefore, the basic principles governing this special field of radiography have been explored, and important references noted.

The advent of a practical 350-kV unit for chest radiography using a field emission tube has contributed significantly to improved image quality in this area. A section has been devoted to the practical aspects of such high kilovoltage radiography, with emphasis on depth resolution.

In the last few years the Bureau of Radiological Health has reported on its studies of population exposure to x rays in radiography. These have been of sufficient importance to contribute to the updating of the chapter on Protection in Radiology.

As in earlier editions, there has been a significant rewriting of the text in an effort to simplify even further the explanation of fundamental concepts. In some instances there has been an accompanying revision of illustrations. A number of entirely new figures have also been added.

The most recently revised definition of the roentgen, as well as the proposed new International System of Units (SI), is included to keep the technologist and student abreast of changes in terminology.

Again, the author wishes to thank the previously mentioned individuals and manufacturers who have been so cooperative in supplying pertinent material. To this list should be added 3M Company; Nuclear Associates, Inc.; and Treck Photographic, Inc.

Our artist, A. Howard Marlin, has again carried off the task of revising old figures and preparing new ones in his characteristically competent style.

Finally, the author wishes to express his gratitude to Mr. Payne Thomas and the editorial staff of Charles C Thomas, Publisher, for their encouragement, kindness, and patience during the vicissitudes of revision.

J.S.

PREFACE TO FIFTH EDITION

IN THE SEVEN YEARS since publication of the Fourth Edition, important changes have taken place in the design of x-ray equipment, although fundamental concepts have undergone relatively little revision. Accordingly, new material has been introduced covering such subjects as solid state rectifiers; newer mobile apparatus, including battery powered and capacitor-discharge units; field emission tubes; special tubes for mammography, using molybdenum targets and filters; xeroradiography; and saturable reactor for control of filament current.

Many of the illustrations have been revised or completely redrawn, and corresponding changes have been made in the descriptive legends.

Despite the many changes, the format has been kept essentially intact. However, certain areas have been expanded; for example, improvements in x-ray tube design; tomography; radiographic quality; radionuclides and nuclear medicine; irradiation therapy; and health physics.

Throughout the book, many sections have been rewritten on the basis of the author's further teaching experience, with a view toward improving the explanation of fundamental principles and the description of devices and equipment. Wherever possible, the aim has been in the direction of greater simplification. The material has been generally updated on the basis of the most reliable data available at the time of revision.

Credit is again due to the previously mentioned sources. Additionally, we would like to thank the Field Emission Corporation, the Machlett Laboratories, the Dunlee Corporation, the Xerox Corporation, and the CGR Medical Corporation for their

kindness in supplying important material relative to their products.

The author again wishes to express his gratitude to Charles C Thomas, Publisher, for providing the opportunity of preparing this new edition.

J.S.

PREFACE TO FOURTH EDITION

In order to keep abreast of new developments in the field of radiologic physics, especially those concerning the radiologic technologist and the radiology resident, a number of significant changes have been introduced into this, the Fourth Edition. Only the more important ones will be mentioned here.

Again, the format will be retained intact, all changes being made within its framework. Outdated material, such as mechanical rectification, has been deleted.

The concept of electrical field and the relationship between static electricity, electric discharge, and current electricity have been given greater emphasis. The factors in series and parallel circuits, often difficult for the student technologist, have been discussed more fully with the aid of numerical examples.

X-ray quantity and quality have been described in greater depth, and more attention given to half value layer, including a summary of the methods of measuring it. The determination of tumor exposure and absorbed dose is explained more completely and is based on the latest method of converting the data in published depth dose tables so that they become applicable to any particular therapy unit. In accordance with recent changes in terminology proposed by the International Commission on Radiation Units and Measurements (ICRU), the Capital R now designates the exposure in roentgens. The exposure rate is indicated as R/min or R/sec.

Due to lack of clarity, generally, concerning saturation current as it applies to the modern diagnostic x-ray tube, this subject is covered more fully than before.

In view of the wide use of automatic processing of x-ray films, mainly as the result of improvement in quality and reduction in cost, more space has been devoted to the principles and con-

struction of this type of equipment. In addition, the basic theory of photographic image formation is presented in greater detail for those students who seek a deeper understanding of this subject.

The chapters on radiographic quality and its control have been rearranged and largely rewritten. Radiographic grids are discussed in greater depth, the latest methods of designating grid quality presented, and newer terminology used throughout in accordance with the recommendations of the ICRU.

Under special procedures, bright fluoroscopy (image intensification) have been emphasized because of its wide acceptance by radiologists. Stereoscopic viewing of radiographs has been presented in a much more fundamental manner than before.

A completely new chapter on radioactive isotopes has been added. It is not meant to replace standard textbooks devoted exclusively to this subject, but rather to provide a well-rounded background for the medical use of radioisotopes for the general radiologic technologist. The chapter on health physics has been expanded to include the more commonly used radioisotopes.

It must be pointed out, that insofar as possible, the latest terminology is used throughout this book, conforming to the recommendations of the ICRU, and the International Union of Pure and Applied Chemistry and its twin in Physics. For example, the form "x ray" refers to the noun, whereas "x-ray" designates the adjective; thus, x rays, but x-ray physics. The form ^{131}I instead of I^{131} exemplifies the designation of radioisotopes. Attempts at international standardization of scientific terms are highly commendable in this age of automatic retrieval of information by means of computers.

The author again acknowledges with thanks the cooperation of a number of commercial suppliers in furnishing important data about their products. In addition to those mentioned in earlier editions are: Picker X-Ray Corporation; Liebel-Flarsheim Company; United States Radium Corporation; General Aniline and Film Corporation; and Smit-Roentgen Company.

Grateful recognition is due Charles C Thomas, Publisher, for interest in the preparation of the Fourth Edition, and for the excellence in publication of previous editions.

J.S.

PREFACE TO THIRD EDITION

ONLY FOUR YEARS have passed since the publication of the Second Edition, but a number of changes, some major and some minor, are considered to be of sufficient importance to warrant a fairly thorough revision. This is dictated in part by changing concepts, and in part by the author's further experience with students of widely different degrees of ability and educational background.

The format and figures have been kept essentially intact, although some figures have been revised and several new ones added. Every effort has been made to retain the simplicity of the first two editions. A decimal system of numbering the illustrations has been introduced, a practice which is gaining acceptance in scientific books.

One of the major changes in the present edition is in the chapters on the electric current, electromagnetism, and electric generators and motors. Whereas the conventional direction was emphasized previously, this has now been relegated to history, and all the directional rules have been altered to conform to the flow of electrons. This step was taken only after considerable deliberation, but was finally adopted in compliance with the vast majority of present-day physics textbooks. For the same reason, the term *condenser* has been changed to *capacitor.*

The theory of magnetism has been brought up to date, with the introduction of the concept of atomic magnets and magnetic domains. Otherwise, the same simple approach to magnetic phenomena has been retained.

There have been no radical innovations in the field of x-ray equipment generally, but certain theoretical aspects of this subject have been rewritten in an effort to improve their comprehensibility.

The sections on radiation dosage have been completely revised and expanded, although the student should be encouraged to read more advanced material on this subject, especially during his second year. The modern concept of absorbed dose and its unit, the rad, have been described in some detail. Filtration and radiation quality have received increased attention.

In the sections on radiography, special attention has been devoted to intensifying screens. Included are revised concepts of the relative importance of the effect of crystal size and active layer thickness on image sharpness; the intrinsic and extrinsic factors affecting screen speed; and comparative data on medium and high speed screens.

Because of the increasing interest in automatic processing of films, a section has been included to summarize present information in this important field.

The chapter on radiographic quality has been carefully reworked. The more accurate term *definition* has been substituted for *detail* to indicate image sharpness. The factors influencing definition have been reclassified and clarified. In the chapter on devices for improving radioactive quality, emphasis has been placed on modern collimators in preference to conventional cones, especially with regard to patient protection. The newer types of Bucky mechanisms have also been described.

In view of the recent downward revision of the maximum permissible dose, the chapter on radiation protection has been reoriented accordingly. Emphasis has also been placed on radiation monitoring methods for radiologic personnel. Furthermore, the current agitation regarding the exposure of the population to ionizing radiation has led to a more detailed treatment of the various methods that can be utilized to reduce patient dosage in radiography and fluoroscopy.

Finally, answers to the sample problems at the end of certain chapters have been included in the Appendix as an aid to the student in checking the correctness of his solutions.

As before, the author expresses his sincere appreciation to Mr. Charles C Thomas, Mr. Payne Thomas, and their competent staff for their interest in the preparation of the Third Edition.

J.S.

PREFACE TO SECOND EDITION

ALTHOUGH great advances are continuously being made in Physics, the basic concepts required for the instruction of student x-ray technicians and Radiology residents have changed very little since the publication of the First Edition. Nevertheless, new data which are considered to be of sufficient interest and importance have been incorporated in the Second Edition.

The original format has been preserved almost intact because it has proved successful in actual classroom instruction in numerous schools of x-ray technology. Simplicity is retained throughout, and abundant line diagrams are employed again to clarify the explanation of basic principles and the description of equipment.

The introductory chapter on Mathematics now includes the notation of large and small numbers as powers of 10. Terminology applied to the factors in an electric current and the heating effects of currents has been revised and simplified.

Brems radiation has received more emphasis in the discussion of x-ray production. The descriptive material relating to the interaction of radiation and matter has been enlarged to include pair production.

Fluoroscopic image intensification is introduced and described in detail, since this device and its future modifications promise to revolutionize fluoroscopy in the next few years.

More space has been allotted to the inverse square law, a simplified formula being presented for use in protection and therapy problems. Considerable revision of the chapter on radiation protection was necessitated by recent changes in the recommendations of official bodies. Emphasis is placed also on the roentgen

dosage received by patients during various diagnostic procedures. Obsolete data have been eliminated.

Finally, the Bibliography has been expanded to include additional choice references for the more venturesome student.

In addition to the acknowledgments already made in the First Edition, the author wishes to thank the Westinghouse Electric Corporation and the North American Philips Company for valuable data on image intensification.

Again, the author appreciates the interest shown by the publisher, Mr. Charles C Thomas, in making possible the Second Edition.

J.S.

PREFACE TO FIRST EDITION

It is obvious to anyone who has had experience in teaching radiologic physics to student x-ray technicians that the majority of students have had poor preparation for this course of study. Those students who may have been exposed to physics and mathematics in high school often retain so little knowledge of these subjects that they must learn anew even the simplest principles. The student x-ray technician with a background of college training in the sciences is indeed a rarity.

Many teachers devoted to the training of student x-ray technicians have long recognized the dearth of textbooks in physics designed for technicians. A desirable textbook of this type must lead the student, as painlessly as possible, from the most elementary considerations all the way to radiologic physics, a task which is by no means simple. The subject matter must be presented in great detail in order that the student may derive a more complete understanding of it. At the same time, the text must be as nonmathematical as possible and couched in language that is readily comprehensible.

On the basis of lecture notes and other data used in the instruction of student technicians over a period of years, the author has written the present book with the primary purpose of simplifying for the student x-ray technician the subject of radiologic physics in all its theoretical and practical aspects as it confronts the technician. With this aim in view, basic principles of physics and chemistry are emphasized and presented in greatest possible detail. At the same time, the simplest available terminology is employed in order to avoid a language barrier to the comprehension of these important principles. In accordance with the familiar pedagogic rule of repetition, the more significant physical prin-

ciples are repeated, presented from various standpoints, and correlated wherever possible throughout the text.

Recognizing the value of visual aids to education, the author has made free use of numerous line drawings to facilitate the study of the text. Tables have been included only to emphasize certain points rather than as a source of reference for specific data. Throughout the book, fundamental principles are stressed, and if these are grasped by the student, he is then in a better position to understand the specific data furnished by the manufacturer for the equipment or supplies in use in his radiology department.

Mathematics of the simplest type is employed only where deemed essential to the understanding of fundamental principles. A summary of elementary mathematics introduces the book so that the student's memory can be more easily refreshed. It embodies all of the mathematical principles that are to appear in later chapters, so that if the first chapter is mastered the student should encounter no difficulty with the algebra and geometry employed in subsequent chapters.

There has been included a somewhat detailed consideration of the intimate structure of matter, and some space has been devoted to the quantum theory. This may be criticized by those teachers who feel that too much emphasis is already being placed on physics in the students' overburdened curriculum. However, it is felt, in view of the great strides that have been made in atomic physics in the last few years and the growing importance of radioactive isotopes, that the student should have at least a minimum concept of atomic structure and atomic energy.

The material has been so organized that certain sections may be omitted at the instructor's discretion without seriously interfering with the continuity of the text. On the other hand, these more advanced considerations will appeal to the student technician fortunate enough to have a better-than-average scientific background.

Although it has been pointed out repeatedly that this book has been conceived primarily for the student x-ray technician, it is felt that it will also be of distinct advantage to the resident in radiology who is just entering upon his period of training and