Medical Physics

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PREFACE

Instrumental or mechanical science is the noblest and above all others the most useful, seeing that by means of it all animated bodies which have movement perform all their actions.

—Leonardo da Vinci, in Sul Volo degli Uccelli (circa 1500).

MEDICAL PHYSICS is commonly regarded as a new branch of medicine. Many discoveries of fundamental physical phenomena in recent decades, combined with extraordinary developments of earlier discoveries, and successful application of numerous basic principles of physics in medical practice have fostered the notion that medical physics is a distinctive achievement of the twentieth century. That impression is not quite accurate. Although recent developments have led to a steadily increasing recognition of physics as one of the essential substructures of modern medicine, the fact is that progress in biology and medicine has always been significantly related to advances in physics. Before there could be any scientific bacteriology or pathology, there had to be a microscope to reveal the existence of micro-organisms and the structure of tissues. The science of physiology began with Harvey, who was the first to apply systematic measurements in biologic investigations and to attempt to correlate biologic phenomena with physical laws. Fundamental knowledge of blood pressure was dependent on development of suitable manometers, and many facts about the heart and circulation of the blood could not have been learned without the microscope, string galvanometer, stethoscope and roentgen rays. In short, physics has supplied instruments and methods of measurement that have led to many discoveries in physiology and medicine, and the methods of physical research have revolutionized many of the older approaches to the biologic sciences.

These facts have always been recognized to some extent. Evidence of that is furnished by such volumes as the able *Medizinische Physik*, by A. Fick of Zürich, published in 1856 by Vieweg of Braunschweig, or F. J. Brockway's *Essentials of Medical Physics*, one of the Saunders question-compends, published in 1891. The enthusiastic reception accorded by the medical profession all over the world to Röntgen's discovery of the x-rays in 1895 and the subsequent evolution of medical radiology vividly illustrate the close interrelationship between physics and medicine.

Yet the literature of medical physics as such has not kept pace with the expansion of the subject matter. Or perhaps it would be more precise to say that the literature has not been able to extricate itself from the established conventions of publication in medicine and the allied sciences, and to assert itself as a distinct entity, easily accessible to all physicians and surgeons who try to keep abreast of the advances that ultimately affect the welfare of their patients. Numerous physicists have interested themselves in the application of their researches to medicine, and many biologists, physiologists, clinicians and surgeons have studied the physical principles underlying their particular problems. The reports of such workers are scattered throughout the literature of physics and of medicine. Recently, more and more attempts have

been made to concentrate such publications in special journals and books on biophysics. Yet most of these efforts have dealt with only limited aspects of medical physics; and no attempt seems to have been made to unify all the diverse information involved in a form useful alike to practitioners of medicine and physicists.

Twenty years ago I began to collect material bearing on the specialty of radiology alone, with the plan of organizing it as an encyclopedia. Numerous difficulties frustrated that plan. When it is recalled that the dosage unit for roentgen rays, the roentgen, was not internationally adopted until 1937, the nature of some of the difficulties will be appreciated. Thus, only the gist of that earlier idea eventually emerged in the volume, *The Science of Radiology*, written by twenty-seven authorities under my editorship and published by Charles C Thomas under the auspices of the American Congress of Radiology in 1934. But some of the groundwork of that project remained as a point of departure for the present effort.

It took the vision and the courage of Mr. H. A. Simons, president of the Year Book Publishers, Inc., to see the need for a presentation of the subject matter of medical physics as a whole, and he and his associates provided the means and the enthusiasm necessary to realize the conception. Their first idea was to produce a small manual that would serve as a reference work for physicians and others dealing with medical physics. Later it was recognized that, because of the nature of the subject matter and its present status, the original proposal was inadequate. A mere assemblage of working formulas, unsupported by exposition of underlying principles, would be of limited use. It would not meet the fundamental need for a unified demonstration of the place of physics in medical practice. And it would leave untouched the requirement for a single text and reference book for teachers and students of medicine.

Out of these considerations evolved the final conception which this book attempts to embody: a combination of an *encyclopedia*, sufficiently comprehensive to serve as a reference for all those whose occupations involve any aspect of medical physics; a *textbook*, adequately detailed in exposition to serve students; and a *working instrument*, in which may be found the data necessary for actual application of the principles of physics to medicine. Readers will undoubtedly discover that this volume falls short of the attainment of that ideal. Though the work was not undertaken without some trepidation, unanticipated difficulties have been encountered during its progress. Many medical subjects naturally overlap each other, and in some instances proper classification has not been easy. Problems of straying too far afield into neighboring subjects, such as biochemistry, have arisen repeatedly. In the collection of material from many sources, as the scope of the undertaking required, it has been inevitable that, despite all efforts to eliminate them, some duplications, omissions and inconsistencies should have occurred. The approaches of various authors to their respective topics varied, of course; and it has been impossible to present all subjects with the same degree of detail. An earnest attempt has been made to compensate for some of these shortcomings by correlating the material as completely as possible in the index, which it is hoped will prove satisfactory for guiding the reader to the data in which he is particularly interested.

One of the principal inspirations sustaining the efforts of editorship has been that the subject grew to unexpected proportions during the progress of the work. A second, and indeed greater, inspiration has derived from the readiness of the authors to collabo-

rate and the excellence of their contributions. Planning of the book and discussions of its organization began in April, 1940. Invitations to contributors were issued in that year, and the first manuscripts were received early in 1941—though the last of them were not completed until October, 1943. War conditions required some alterations of the original plans, notably in regard to aviation medicine, biologic effects of high and low pressures, and some new electronic devices that may play important rôles in medicine. Among those invited to participate, enthusiasm for the program of comprehensively presenting the relation of physical principles to medical diagnosis and therapy was remarkable from the beginning. No praise would be excessive of the loyal work of the authors who, often despite serious obstacles created by the war, executed their commitments. Because of their conscientious co-operation, an astonishingly small number of the articles originally planned (on such subjects as anesthesia, fractures, physical biochemistry, physical factors in psychologic measurements, plastic surgery and speech correction) were not finally received.

The enthusiasm and generosity of the collaborating authors have been matched by similar qualities in the associate editors. Their help has been of inestimable value in the collection and organization of material and in many other phases of the work, but they cannot be held responsible for possible errors of omission or commission in their respective departments. The exigencies of publication, especially under the conditions of war, inhibited their freedom in attending to details of their parts of the book, so that final responsibility for possible shortcomings rests with the editor-in-chief.

Miss Jessie C. Tucker, assistant editor, also gave invaluable assistance throughout the process of collecting the material, organizing, editing and indexing it. Without her faithful co-operation this book could not have been brought to issue.

Mr. Edward C. Daoust, president of the Cleveland Clinic Foundation, generously put the resources of the Cleveland Clinic at our disposal. Miss Bernardine Lufkin, research secretary of the Foundation, contributed valuable services to the work. Most of the drawings for the illustrations were executed by Mr. Bernard Tautkins of the Cleveland Clinic and Mr. Charles M. Jeffries of the Victoreen Instrument Company.

The editorial and production staffs of the Year Book Publishers, Inc., were invariably helpful in connection with numerous editorial and other problems. In particular, the work of Mr. Paul Perles, production manager, Mrs. Anabel Ireland Janssen, head of the editorial department, and Miss Jean Husted, chief proofreader, deserves grateful acknowledgment. A major contribution, in the solution of mechanical problems, was made by the Mack Printing Company; and I wish to record my sincere thanks to the heads of that company, the publishers and the Cleveland Clinic Foundation for the splendid co-operation of their respective organizations.

—Otto Glasser

Cleveland, Ohio
November 20, 1943

COMMENTS, ABBREVIATIONS, SYMBOLS

Organization.—Subjects in this book are arranged in alphabetical order. The editor recognizes that this may not be an ideal method of presenting the material, but no better system suggested itself. To facilitate search for any given subject, the following suggestions are offered:

The *Table of Contents*, in alphabetical order, may be found on pages xvii–xxii, and the *Classified Tables of Contents* on pages xxiii–xlii. The *Subject Index* begins on page 1685 and the *Name Index* on page 1729.

References to literature beyond the scope of the original articles presented in this book are numbered in sequence in the articles, but arranged in alphabetical order according to authors at the end of the articles. *Bibliographies* are also arranged in alphabetical order according to authors at the end of the articles.

Cross-References to other articles appearing in this book are listed as (see Author); e.g. (see Trump) on page 28 refers to the article, Roentgen Rays: Supervoltage Generators, by John G. Trump, on page 1391.

Style.—Certain rules of style have been followed in an effort to achieve the greatest possible uniformity in material from such widely different sources.

Units and Conversion Factors.—These are furnished in the article of this title by E. C. Crittenden, on page 1596.

Abbreviations and Symbols.—A list of abbreviations is herewith presented. It is based on the American Standard Abbreviations for Scientific and Engineering Terms, approved by the American Standards Association. Essential features of the style are omission of periods following abbreviations, except when such abbreviations form a word, and omission of the comma in numerals of five digits or more, e.g., 10 000, 1 000 000, etc.

ABBREVIATIONS

A	angstrom unit
a-c	alternating current
amp	ampere
amp-hr	ampere-hour
antilog	antilogarithm
atm	atmosphere
at. no.	atomic number
at. wt.	atomic weight
avdp	avoirdupois
bar	barometer
Bé	degree Baumé
bev	billion electron volt
Btu	British thermal unit
C	degree centigrade; capacitance
c	velocity of light; cycle
ca	candle
cal	calorie (gram)
centi-	prefix meaning $^1/_{100}$
cg	centigram
cgs	centimeter-gram-second (system of units)
c-hr	candle-hour
cl	centiliter
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
const	constant
cos	cosine
cot	cotangent
CP	chemically pure
cp	candlepower
c_p	specific heat at constant pressure
cps	cycle per second
csc	cosecant
Ctu	centigrade thermal unit
cu	cubic
cu cm	cubic centimeter
cu ft	cubic foot
cu m	cubic meter
cu mm	cubic millimeter
cu μ	cubic micron
c_v	specific heat at constant volume
cyl ax	cylinder axis

D	density; diffusion constant; diopter; dioptric power
db	decibel
d-c	direct current
deci-	prefix meaning $^1/_{10}$
deg or °	degree
deka-	prefix meaning 10
dg	decigram
dl	deciliter
doz	dozen
DS	dioptric strength
E	electric tension
e	base of natural or Naperian system of logarithms; charge of electron
eH	oxidation-reduction potential
emf	electromotive force
emu	electromagnetic unit
esu	electrostatic unit
ET	effective temperature
ev	electron volt
F	degree Fahrenheit
f	farad; frequency
f-number (e.g., f-2, f2, f:2, f/2)	focal length of photographic lens divided by its diameter
fpm	feet per minute
fps	foot-pound-second (system of units)
ft	foot
ft-c	foot-candle
ft-L	foot-Lambert
ft-lb	foot-pound
Fu	Finsen unit (for ultraviolet rays)
G	gravitation constant
g	gram
g	acceleration due to gravity
g-cal	gram-calorie
gal	gallon
gpm	gallon per minute
gps	gallon per second
gr	grain
hecto-	prefix meaning 100
h	henry
h	Planck's quantum constant
hp	horsepower
hp-hr	horsepower-hour
hr	hour
hvl	half value layer
I	electric current
in.	inch
ips	inches per second
j	joule
K	degree Kelvin
kc	kilocycle
kcps	kilocycle per second
kg	kilogram
kg-cal	kilogram-calorie
kg-m	kilogram-meter
kg per cu m	kilogram per cubic meter
kgps	kilogram per second
kms	kilogram-meter-second (system of units)
kilo-	prefix meaning 1000
kl	kiloliter
km	kilometer
kv	kilovolt
kw	kilowatt
kwhr	kilowatthour
L	Lambert
l	liter; lumen
λ, lambda	wavelength
λ_{eff}	effective wavelength
λ_{min}	minimum wavelength
lb	pound
lb per cu ft	pounds per cubic foot
Le	Lenard (unit for cathode rays)
l-hr	lumen-hour
lin ft	linear foot
ln (or $\log_e$)	natural or Naperian logarithm
log	common logarithm to the base of 10
lps	liter per second
lpw	lumen per watt
M	molar; molecular weight
m	meter; mass
mM	millimolar
m^2	square meter
m^3	cubic meter
ma	milliampere
mc	millicurie
mc-hr	millicurie-hour
mega-	prefix meaning 1000000
mev	million (or mega-) electron volts
mg	milligram
mg-hr	milligram-hour
mh	millihenry
mho	unit of electric conductance
micro-	prefix meaning $^1/_{1\,000\,000}$
milli-	prefix meaning $^1/_{1000}$
min	minute
m-kg	meter-kilogram
mks	meter-kilogram-second (system of units
mL	millilambert
ml	milliliter
mm	millimeter
mm^2	square millimeter
mm^3	cubic millimeter
mμ	millimicron
mol. wt	molecular weight
mph	miles per hour

μ, mu	micron
μ^2	square micron
μ^3	cubic micron
μa	microampere
μf	microfarad
$\mu\mu$	micromicron
$\mu\mu$f	micromicrofarad
μv	microvolt
μw	microwatt
μsec	microsecond
NA	numerical aperture
ND	neutral density
n	index of refraction; neutron (unit for neutron rays)
ν, nu	frequency of radiant energy
OD	oculus dexter or right eye
OS	oculus sinister or left eye
oz	ounce
P_{cc}	periscopic concave
P_{cx}	periscopic convex
PD	interpupillary distance
pH	hydrogen ion concentration
psi	pounds per square inch
qt	quart
R	degree Réaumur; Solomon roentgen (unit for x-rays)
r	roentgen (international unit for x-rays)
r_γ	gamma roentgen (unit for radium-gamma rays)
rms	root mean square
rpm	revolutions per minute
rps	revolutions per second
S	spherical
SE	spherical equivalent
sec	secant; second
SED	skin erythema dose
sin	sine
sol.	solution
sp gr	specific gravity
sp ht	specific heat
sq	square
sq cm	square centimeter
sq ft	square foot
sq in.	square inch
sq m	square meter
sq mm	square millimeter
sq μ	square micron
SR	sedimentation rate
T	temperature on absolute scale
t	time
tan	tangent
TED	threshold erythema dose
v	volt
va	volt-ampere
w	watt
whr	watthour
X	unit for short-wave radiations
yr	year
Z	atomic number

Greek Alphabet

Greek		English	Meaning in Physics
alpha	A	A	
	α	a	angle of optical rotation; angular acceleration; coefficient of thermal expansion; degree of dissociation into ions
beta	B	B	
	β	b	coefficient of compressibility; flux density; specific heat constant
gamma	Γ	G	
	γ	g	conductivity; microgram; specific gravity; surface tension
delta	Δ	D	coefficient of diffusion; finite difference, increment; prism diopter
	δ	d	density; unit elongation; variation
epsilon	E	E	
	ϵ	e	base of natural system of logarithms; coefficient of extinction; dielectric constant; electrode potential; mean error
zeta	Z	Z	
	ζ	z	coordinates; impedance
eta	H	$\bar{E}$	
	η	$\bar{e}$	efficiency; viscosity
theta	Θ	Th	
	θ	th	angle (plane); angular phase displacement; Curie point; temperature in degrees above 0 C

Greek		English	Meaning in Physics
iota	I	I	
	ι	i	
kappa	K	K	
	κ	k	dielectric constant; electric conductivity; Stefan-Boltzman constant; magnetic susceptibility
lambda	Λ	L	electric equivalent conductivity
	λ	l	microliter; wavelength
mu	M	M	
	μ	m	coefficient of absorption; coefficient of viscosity; index of refraction; micron; electric molecular conductivity; magnetic permeability
nu	N	N	
	ν	n	frequency of radiant energy; kinematic viscosity; refractive efficiency
xi	Ξ	X	
	ξ	x	
omicron	O	O	
	ο	o	
pi	Π	P	pressure
	π	p	ratio of circumference of a circle to diameter, or 3.14149265 . . . ; osmotic pressure
rho	P	Rh	
	ρ	rh	coefficient of reflection; refractive power; specific resistance; volume density
sigma	Σ	S	summation of
	σ	s	coefficient of scattering; current density; $^1/_{1000}$ second; standard deviation; surface density; surface tension
tau	T	T	
	τ	t	time constant; temperature
upsilon	Υ	Ŭ	
	υ	ŭ	
phi	Φ	Ph	magnetic flux; radiant flux
	φ	ph	angular phase difference; potential
chi	Χ	Kh	
	χ	kh	
psi	Ψ	Ps	dielectric flux; luminous flux; phase difference
	ψ	ps	electrostatic flux
omega	Ω	$\bar{O}$	Ohm
	ω	$\bar{o}$	angular frequency; angular velocity

SYMBOLS

+	plus; add; positive; convex
−	minus; subtract; negative; concave
±	plus or minus; positive or negative
× or ·	times; multiplied by
÷ or : or /	divided by
= or : :	equals; as
≐ or ≈	approximately equals
≠ or ≉	does not equal
≡	identical, congruent, with
≢	not identical, congruent, with
>	greater than
≯	not greater than
<	less than
≮	not less than
≧	equal to or greater than
≧ or ⩾ or ≥	greater than or equal to
≦	equal to or less than
≦ or ⩽ or ≤	less than or equal to
≶	greater than, equal to or less than
:	ratio of
∝	varies as
∞	infinite
!	factorial product (4! 1 × 2 × 3 × 4)
○	combined with
$\sqrt{a}$ or $a^{1/2}$	square root of a
$\sqrt[3]{a}$ or $a^{1/3}$	cube root or third root of a
$\sqrt[n]{a}$ or $a^{1/n}$	nth root of a

a^1	the first power of a: a
a^2	a square or the second power of a: a × a
a^3	a cube or the third power of a: a × a × a
a^n	the nth power of a: a × a × a × a × . . . .
Σ	summation of
Δ	finite difference; increment; prism diopter
∇	centrad
Δx	increment of x
f(x)	function of x
dx	differential of x
$\frac{dy}{dx}$ or f′(x)	derivative of y with respect to x
y′ or ẏ	derivative of y, ordinarily with respect to time
$\frac{d^2y}{dx^2}$ or f″	second derivative of y with respect to x
y″ or ÿ	second derivative of y, ordinarily with respect to time
$\frac{\delta z}{\delta x}$	partial derivative of z with respect to x
$\int$	integral of
$\int_b^a$	integral to be taken between the value b of the variable and its value a

TABLE OF CONTENTS