RESOURCE LETTER

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This is one of a series of Resource Letters on different topics intended to guide college physicists, astronomers, and other scientists to some of the literature and other teaching aids that may help improve course content in specified fields. No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments on these materials as well as suggestions for future topics will be welcomed. Please send such communications to Professor Roger H. Stuewer, Editor, AAPT Resource Letters, School of Physics and Astronomy, 116 Church Street SE, University of Minnesota, Minneapolis, MN 55455.

Resource letter MP-1: Medical physics

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This resource letter provides a guide to the literature on the uses of physics for the diagnosis and treatment of disease. The letter E after an item indicates elementary level or material of general interest to persons becoming informed in the field. The letter I, for intermediate level, indicates material of somewhat more specialized nature; and the letter A indicates rather specialized or advanced material. An asterisk (*) indicates those articles to be included in an accompanying Reprint Book.

I. INTRODUCTION

Physicists sometimes use the terms medical physics and biophysics loosely and almost interchangeably. Within these fields, however, there is a distinction. In the United States the term medical physics has traditionally meant the physics used by radiologists to diagnose and treat disease. Originally, this was primarily the physics of x rays; as ultrasound was developed for diagnostic purposes, it also became part of medical physics. Recently the areas of interest to the medical physicist have expanded as still more diverse and sophisticated instruments are used for diagnosis and treatment. The American Association of Physicists in Medicine is the AIP-affiliated professional organization to which most medical physicists belong. Biophysics has been a very broad term, encompassing studies as diverse as molecular structure, physiology, biomedical instrumentation, radiologic physics, and mathematical biology. In recent years, the term biophysics has been used more narrowly to mean the study of molecular biology. Members of the Biophysical Society have interests primarily in this area.

This resource letter describes the use of physics to diagnose and treat disease in humans. This definition includes biomedical engineering as well as medical physics, but it ignores interesting applications of physics in physiology.

In many cases a textbook is the most appropriate way to begin learning about a topic in medical physics. The articles cited here should be considered representative examples rather than the state of the art or an exhaustive bibliography. One can explore further by reading the references in the articles cited, by scanning the journals listed here, or by using *Index Medicus* to find other articles on the same subject. The resource letter presents textbooks first, followed by a list of representative journals and a few representative articles in each area.

II. TEXTS

This section lists textbooks which are suitable references for a physics teacher; elementary physics texts containing biological examples have not been listed.

The reader unfamiliar with medical terms may find useful the following glossary, which was produced by the AAPM for science writers:

1. **Glossary of Terms Used in Medical Physics**, edited by R. J. Barish and P. F. Schewe (AIP, New York, 1984). (E)

Each year the Publication Committee of the AAPM prepares a bibliography of medical physics as a service to its members. It can be purchased for $3.00 for the AAPM, 335 East 45th St., New York, NY 10017.

A. General biophysics and medical physics

2. **Biophysical Science, 2nd ed.**, E. Ackerman, L. B. M. Ellis, and L. E. Williams (Prentice-Hall, Englewood Cliffs, 1979). This is a comprehensive general biophysics text. It covers sensory systems, nerve and muscle, ionizing and nonionizing radiation, molecular biology, thermodynamics, transport, and instrumentation. (I)
3. **Physics With Illustrative Examples from Medicine and Biology. Vol. 1. Mechanics. Vol. 2. Statistical Physics. Vol. 3. Electricity and Magnetism**, G. B. Benedeck and F. M. H. Villars (Addison-Wesley, Reading, 1974–1979). (I)
4. **Medical Physics**, J. R. Cameron and J. G. Skofronick (Wiley-Interscience, New York, 1978). This book has an excellent qualitative discussion of radiologic physics, as well as the physics of the senses and other medical instruments and procedures which use physics. (E)

5. **Medical Physics, Vol. 1: Physiological Physics, External Probes, Vol. 2: External Senses**, A. C. Damask (Adademic, New York, 1978). (I)
6. **Medical Physics, Vol. 3: Synapse, Neuron, Brain**, A. C. Damask and C. E. Swenberg (Academic, New York, 1984). (I)
7. **Intermediate Physics for Medicine and Biology**, R. K. Hobbie (Wiley, New York, 1978). (I)
8. **An Advanced Undergraduate Laboratory in Living State Physics**, J. P. Wikswo, B. Vickery, and J. H. Venable, Jr. (Vanderbilt University, Nashville, TN 1980). This laboratory manual describes experiments in bioelectric phenomena, diffusion, compartments, vision, and ultrasound. (I)
9. **Biomechanics of Human Motion**, M. Williams and H. R. Lissner (Saunders, Philadelphia, PA, 1962). This small book contains many clinical examples of resolution of forces and static equilibrium, including orthopedic traction apparatus. (E)

B. Radiological physics

1. General

Material on radiological physics is also found in Refs. 2, 4, 7, and 15.

10. **Absorption of Ionizing Radiation**, D. W. Anderson (University Park, Baltimore, MD, 1984). This is a comprehensive book on the interaction of photons, charged particles, and neutrons with matter, from the viewpoint of radiologic physics. It also discusses ionization, excitation, microscopic energy distribution, and biological radiation damage. (I)

2. Diagnostic radiology

11. **The Physical Basis of Medical Imaging**, C. M. Coulam, J. J. Erickson, F. D. Rollo, and A. E. James (Appleton-Century-Crofts, New York, 1981). (I)
12. **Christensen's Introduction to the Physics of Diagnostic Radiology, 3rd ed.**, T. S. Curry, J. E. Dowdey, and R. C. Murry (Lea & Febiger, Philadelphia, 1984). This is the third edition of a text for residents. The physics is elementary, but a physicist should find this is a good book from which to learn the medical aspects of radiology. (E)
13. **Medical Radiation Physics, 2nd ed.**, W. R. Hendee (Yearbook Medical Publishers, Chicago, 1979). (I)
14. **Medical Images and Displays: Comparisons of Nuclear Magnetic Resonance, Ultrasound, X-rays, and Other Modalities**, R. S. Mackay (Wiley-Interscience, New York, 1984). This book discusses all of the modalities currently used for medical imaging in a physical, nonmathematical way. There are many illustrations and examples. (I)

3. Radiation therapy

15. **The Physics of Radiology, 4th ed.**, H. E. Johns and J. R. Cunningham (C. C. Thomas, Springfield, 1983). This is the standard text on radiological physics, with an emphasis on therapy. It discusses the production of x rays, nuclear decay modes, accelerators, the interaction of radiation with matter, dosimetry, measurement of radiation, the physics of radiotherapy, treatment planning, and nuclear medicine. (I,A)
16. **The Physics of Radiation Therapy**, F. M. Khan (Williams & Wilkins, Baltimore, 1984). (I)
17. **Radiation therapy physics, 2nd ed.**, W. R. Hendee (Yearbook Medical Publishers, Chicago, 1981). (I)

4. Nuclear medicine

Some material on nuclear medicine is found in Refs. 2, 4, 7, and 15.

18. **Introductory Physics of Nuclear Medicine, 2nd ed.**, R. Chandra (Lea & Febiger, Philadelphia, 1982). (E)
19. **Nuclear Medicine: An Introductory Text**, P. J. Ell and E. S. Williams (Blackwell, Oxford, 1981). (E)
20. **Nuclear Medicine Physics, Instrumentation and Agents**, edited by F. D. Rollo (Mosby, St. Louis, 1977). (I,A)
21. **Physics in Nuclear Medicine**, J. A. Sorenson and M. F. Phelps (Grune & Stratton, New York, 1980). (E)
22. **Nuclear Medical Physics**, edited by L. Williams (CRC, Boca Raton, 1985). (I,A)

5. Ultrasound

23. **Biomedical Ultrasonics**, P. N. T. Wells (Academic, New York, 1977). (I)

6. Magnetic resonance imaging

24. **Magnetic Resonance in Medicine and Biology**, M. A. Foster (Pergamon, New York, 1984). This book describes many uses of nuclear magnetic resonance in biology, including magnetic resonance imaging. (I)

7. Radiation protection

25. **Introduction to Health Physics, 2nd ed.**, H. Cember (Pergamon, New York, 1982). (I)

C. Biomedical engineering

26. **Medical Physics and Physiological Measurement**, B. H. Brown and R. H. Smallwood (Blackwell, Oxford, 1981). (I)
27. **Introduction to Bioinstrumentation**, C. D. Ferris (Humana, Clifton, 1979). (I)
28. **Principles of Applied Biomedical Instrumentation, 2nd ed.**, L. A. Geddes and L. E. Baker (Wiley, New York, 1975). (I)
29. **Medicine and Clinical Engineering**, B. Jacobson and J. G. Webster (Prentice-Hall, Englewood Cliffs, 1977). This translation of a Swedish book introduces medical diagnosis and therapy to clinical engineers, medical physicists, physiotherapists, pharmacists, and administrators. The physics and engineering are elementary, but it is a good introduction to clinical terms and applications. (E)
30. **Non-invasive Physiological Measurements**, edited by P. Rolf (Academic, New York, 1983). (I)
31. **Electrical Safety in Health Care Facilities**, H. H. Roth and I. M. Kane (Academic, New York, 1975). (I)
32. **Clinical Engineering: Principles and Practices**, edited by J. G. Webster and A. M. Cook (Prentice Hall, Englewood Cliffs, 1979). As hospitals use more sophisticated equipment, clinical engineering is emerging as a separate discipline. The clinical engineer keeps the equipment calibrated, working, and safe. (I)
33. **Medical Instrumentation: Application and Design**, edited by J. G. Webster (Houghton Mifflin, Boston, 1978). (I)
34. **Biomedical Instruments, Theory and Design**, W. Welkowitz and S. Deutsch (Academic, New York, 1976). (I)

An extensive bibliography of biomedical engineering texts is found in

35. "**A biomedical engineer's library**," J. G. Webster, J. Clin. Eng. **7**, 67–72 (1982). (E)

III. JOURNALS

There are a number of journals devoted to biomedical engineering and medical physics.

Annals of Biomedical Engineering.

Annual Reviews of Biophysics and Biomedical Engineering. (Early volumes contained material on biomedical engineering. In recent years the publication has been devoted exclusively to molecular biophysics.)

Clinical Physics and Physiological Measurement.

IEEE Engineering in Medicine and Biology Magazine. (This magazine is analogous to *Physics Today* and contains tutorial articles at the elementary to intermediate level.)

IEEE Transactions on Biomedical Engineering. (I,A)

IEEE Transactions on Medical Imaging. (I,A)

Journal of Nuclear Medicine. (I,A)

Medical Physics. (I,A)

Physics in Medicine and Biology.

IV. RADIOLOGICAL PHYSICS

A. Basic matters

1. Photon interactions

Photon interactions and the relationship of dose to beam characteristics are still active areas of research. A few recent articles are cited here.

36. "**Energy imparted, energy transferred, and net energy transferred,**" F. H. Attix, Phys. Med. Biol. **28**, 1385–1390 (1983). (I)
37. "**Calculation of scattering cross sections for increased accuracy in diagnostic radiology. I. Energy broadening of Compton-scattered photons,**" G. A. Carlsson and C. A. Carlsson, Med. Phys. **9**, 868–879 (1982). (A)
38. "**Coherent scatter in diagnostic radiology,**" P. C. Johns and M. J. Yaffe, Med. Phys. **10**, 40–50 (1983). (I)

2. Image science

A great deal is known about the physics and psychophysics of images. While a good deal of this was developed for photography, it is also applied in radiology. There is also much information about the effect of photon statistics on image quality and the detectability of lesions.

39. "**Medical imaging systems,**" R. W. Redington and W. H. Berninger, Phys. Today **34**, 36–41 (1981). (E)
40. "**Medical imaging, vision and visual physics,**" in *Medical Radiography and Photography*, C. C. Jaffe (Eastman Kodak, Rochester, 1984), Vol. 60, No. 1. A monograph on some of the psychophysical aspects of detecting abnormal features in a radiologic image. (I)
41. **Radiological Imaging**, H. H. Barrett and W. Swindell (Academic, New York, 1981), 2 Vols. (I)
42. "**Transfer function analysis of radiographic imaging systems,**" C. E. Metz and K. Doi, Phys. Med. Biol. **24**, 1079–1106 (1979). (A)
43. "**A physical statistics theory for detectability of target signals in noisy images. I. Mathematical background, empirical review, and development of theory,**" P. R. Moran, Phys. Med. Biol. **9**, 401–413 (1982). (A)
44. "**Toward a unified view of radiological imaging systems. Part I: Noiseless images,**" R. F. Wagner, K. E. Weaver, E. W. Denny, and R. G. Bostrom, Med. Phys. **1**, 11–24 (1974). (I)
45. "**Toward a unified view of radiological imaging systems. Part II: Noisy images,**" R. F. Wagner, Med. Phys. **4**, 279–296 (1977). (I)
46. "**Overview of unified SNR analysis of medical imaging systems,**" R. F. Wagner and D. G. Brown, IEEE Trans. Med. Imag. **MI-1**, 210–213 (1982). (E)
47. "**Low contrast sensitivity of radiologic, CT, nuclear medicine, and ultrasound medical imaging systems,**" R. F. Wagner, IEEE Trans. Med. Imag. **MI-2**, 105–121 (1983). (I)

B. Dosimetry

48. "**Forty years of development in radiation dosimetry,**" J. W. Boag, Phys. Med. Biol. **29**, 127–130 (1984). (I)
49. **Fundamentals of Radiation Dosimetry**, edited by J. R. Greening. Hospital Physicists' Association Handbook No. 6. (Adam Hilger, Bristol, 1981). (I)
50. "**The theoretical and microdosimetric basis of thermoluminescence and application to dosimetry,**" Y. S. Horowitz, Phys. Med. Biol. **26**, 756–824 (1981). (A)
51. **Thermoluminescence Dosimetry**, A. F. McKinlay. Hospital Physicists' Association Handbook No. 5. (Adam Hilger, Bristol, 1981). (I)

C. Radiation biology

Radiobiology is concerned with the effects of radiation on viruses, cells, and organisms. Paradoxically, one area of research is concerned with understanding radiation carcinogenesis; another is concerned with improving the efficacy of radiation in cancer therapy.

52. "**Forty years of radiobiology: its impact on radiotherapy,**" J. J. Fowler, Phys. Med. Biol. **29**, 97–113 (1984). (I)
53. "**Radiation and the single cell: The physicist's contribution to radiobiology,**" E. J. Hall, Phys. Med. Biol. **21**, 347–359 (1976). (I)
54. "**Radiation carcinogenesis,**" H. I. Kohn and R. J. M. Fry, N. Engl. J. Med. **310**, 504–511 (1984). (E,I)
55. "**Radiation biology: The conceptual and practical impact on radiation therapy,**" H. D. Suit, Radiat. Res. **94**, 10–40 (1983). (I)
56. **Radiation Carcinogenesis: Epidemiology and Biological Significance**, (Progr. Cancer Therapy, Vol. 26), edited by J. D. Boice, Jr. and J. Fraumeni, Jr. (Raven, New York, 1984). (A)

D. Radiation protection

57. "**Radiation exposure in our daily lives,**" S. C. Bushong, Phys. Teacher **15**, 135–144 (1977). (E)
58. **The Biological Risks of Medical Irradiation**, edited by G. D. Fullerton, R. Waggener, D. T. Kopp *et al.*, AAPM Monogr. no. 5. (AIP, New York, 1980). (I)
59. **Health Effects of Low-level Radiation**, edited by W. R. Hendee (Appleton-Century-Crofts, East Norwalk, 1984). (I)
60. "**Forty years of development in radiation protection,**" F. W. Spiers, Phys. Med. Biol. **29**, 145–152 (1984). (I)

An interesting new development in radiation protection is the recognition that naturally occurring radon-222 and its decay products are considerably more concentrated in indoor air than in outdoor air. This effect is exacerbated for smokers, and droplets of radioactive tobacco tar lodge at the bifurcations of the bronchi.

61. "**Alpha radiation dose at bronchial bifurcations of smokers from indoor exposure to radon progeny,**" E. A. Martell, Proc. Natl. Acad. Sci. **80**, 1285–1289 (1983). (I)

E. Diagnostic radiology (roentgenology)

1. General

One can best learn about the clinical aspects of radiology from one of the textbooks listed in Sec. II. The articles listed here provide some of the history of the field.

62. "**Forty years of development in diagnostic imaging,**" M. J. Day, Phys. Med. Biol. **29**, 121–126 (1984). (I)
63. "**History of medical physics,**" J. S. Laughlin, Phys. Today **36**, 26–33 (1983). (E)
64. "**The early history of radiological physics: A fourth state of matter,**" I. A. Lerch, Med. Phys. **6**, 255–266 (1979). (I)

A description of various kinds of radiologic imaging can be found in

65. "**The physics of medical imaging,**" P. Moran, R. J. Nickles, and J. A. Zagzebski, Phys. Today **36**, 36–42 (1983). (E,I)

2. Computed tomography

Tomography is derived from the Greek *tomos*, meaning slice. Tomography has long been a standard radiographic technique, in which the film and x-ray tube are rotated about a point or line passing through an organ of interest,

thereby blurring structures which are not close to the pivot. In computed tomography, two-dimensional slices are reconstructed from a series of projections. The technique was developed simultaneously in radioastronomy, crystallography, radiology, and nuclear medicine. Two physicists shared the Nobel Prize in medicine for this development. The first two references are their Nobel lectures.

66. **"Early two-dimensional reconstruction and recent topics stemming from it,"** A. M. Cormack, Med. Phys. **7**, 277–282 (1980). (I)
67. **"Computed medical imaging,"** G. N. Hounsfield, Med. Phys. **7**, 283–290 (1980). (I)
68. **"Overview of computerized tomography with emphasis on future developments,"** R. H. T. Bates, K. L. Garden, and T. M. Peters, Proc. IEEE **71**, 356–372 (1983). (I)
69. **Image Reconstruction from Projections: The Fundamentals of Computerized Tomography**, G. T. Herman (Academic, New York, 1980). (I,A)
70. **"Design constraints in computed tomography: A theoretical view,"** D. L. Parker, J. L. Crouch, K. P. Peschmann *et al.*, Med. Phys. **9**, 531–539 (1982). (A)

It takes several seconds to record the projections for x-ray transmission tomography. The Dynamic Spatial Reconstructor has been developed at the Mayo Clinic to study the beating heart. Multiple slices are taken simultaneously in 1/60 s. A recent paper describing the machine is

71. **"High-speed three-dimensional x-ray computed tomography: The dynamic spatial reconstructor,"** R. A. Robb, E. A. Hoffman, L. J. Sinak *et al.*, Proc. IEEE **71**, 308–319 (1983). (I)

An experimental technique which may become more important in the future involves detecting the Compton-scattered photons rather than the unattenuated beam.

72. **"Compton scatter axial tomography with x-rays: SCAT–CAT,"** L. Brateman, A. M. Jacobs, and L. T. Fitzgerald, Phys. Med. Biol. **29**, 1353–1370 (1984). (I)

3. Digital radiology

Digital radiography involves making two digital images and subtracting one from the other. In temporal subtraction, pictures of blood vessels with and without contrast media are used; in energy subtraction, images from x-ray beams of different average energy are subtracted. The former technique shows the blood vessels; the latter allows one to emphasize or obliterate the image due to a particular kind of tissue.

a. Temporal subtraction

73. **Digital Radiography**, W. Brody (Raven, New York, 1984). (E,I)
74. **"Computerized fluoroscopy in real time for non-invasive visualization of the cardiovascular system,"** R. A. Kruger, C. A. Mistretta, T. L. Houk *et al.*, Radiology **130**, 49–57 (1979). (I)
75. **Digital Radiography: A Focus on Clinical Utility**, edited by R. R. Price, F. D. Rollo, W. G. Monahan, and E. A. James (Grune and Stratton, New York, 1982). (I,A)
76. **"Intravenous digital subtraction: A summary of recent developments,"** S. A. Riederer and R. A. Kruger, Radiology **147**, 633–638 (1983). (I)
77. **"The technical characteristics of matched filtering in digital subtraction angiography,"** S. J. Riederer, A. L. Hall, J. K. Maier *et al.*, Med. Phys. **10**, 209–217 (1983). (A) This paper discusses a new technique which combines several images as a bolus of contrast material passes through the field of view. The digital filter is matched to the bolus concentration.

b. Energy subtraction

78. **"Spectral considerations for absorption edge fluoroscopy,"** F. Kelcz, C. A. Mistretta, and S. J. Riederer, Med. Phys. **4**, 26–35 (1977). (I)
79. **"Digital K-edge subtration radiography,"** R. A. Kruger, C. A. Mistretta, A. B. Crummy *et al.*, Radiology **125**, 243–245 (1977). (I)

F. Radiation therapy (radiation oncology)

Radiation therapy is the greatest area of employment of medical physicists, since many patient treatments require planning by a physicist and may require the custom fabrication of absorbers. The most common beams are high energy photons or electrons; neutrons, protons and pions are also used at some centers. A recent development is the heating of tissue, hyperthermia, as an adjuvant to radiotherapy. Brachytherapy uses radioactive sources that are implanted in tissue or placed in a body cavity to deliver ionizing radiation to the tumor.

1. General

80. **"Developing aspects of radiotherapy,"** J. F. Fowler, Med. Phys. **8**, 427–434 (1981). (I)
81. **"Radiation treatment planning,"** J. S. Laughlin, F. Chu, L. Simpson, and R. C. Watson, Cancer **39**, 719–728 (1977). (I)
82. **"Forty years of development in radiotherapy,"** W. J. Meredith, Phys. Med. Biol. **29**, 115–120 (1984). (I)
83. **Radiotherapy Treatment Planning**, R. F. Mould. Hospital Physicists' Association Handbook No. 7. (Adam Hilger, Bristol, 1981). (I)
84. **"A review of time-dose effects in radiation therapy,"** R. E. Peschel and J. J. Fischer, Med. Phys. **7**, 601–608 (1980). (I)
85. **Advances in Radiation Therapy Treatment Planning**, edited by A. E. Wright and A. L. Boyer, AAPM Monogr. no. 9. (AIP, New York, 1983). (I,A)

2. X rays and electrons

86. **"Physical aspects of supervoltage x-ray therapy,"** F. Bagne, Med. Phys. **1**, 266–274 (1974). (A)
87. **"Electron linear accelerators for radiation therapy: History, principles and contemporary developments,"** C. J. Karzmark and N. C. Pering, Phys. Med. Biol. **18**, 321–354 (1973). (I)
88. **Practical Aspects of Electron Beam Treatment Planning**, C. Orton and F. Bagne, AAPM Monogr. no. 2. (AIP, New York, 1978). (I)

3. Brachytherapy

89. **Recent Advances in Brachytherapy Physics**, edited by D. R. Shearer. AAPM Monogr. no. 7. (AIP, New York, 1981). (I)

4. Neutrons

90. **"Fast neutron radiotherapy: for equal or better?"** J. J. Broerse and J. J. Batterman, Med. Phys. **8**, 751–760 (1981). (I)
91. **"Fast neutron radiotherapy,"** P. H. McGinley, Phys. Teacher **11**, 73–78 (1973). (E)

5. Protons and pions

92. **"Planning proton therapy of the eye,"** M. Goitien and T. Miller, Med. Phys. **10**, 275–283 (1983). (I)
93. **"The physics of cancer therapy with negative pions,"** C. Richman, Med. Phys. **8**, 273–291 (1981). (I)
94. **Pion and Heavy Ion Radiotherapy: Pre-clinical and Clinical Studies**, edited by L. D. Skarsgard (Elsevier Biomedical, New York, 1983). (I,A)

6. Hyperthermia

95. **"Hyperthermia for the engineer: A short biological primer,"** G. M. Hahn, IEEE Trans. Biomed. Eng. **BME-31**, 3–8 (1984). (E)

96. **Physical Aspects of Hyperthermia**, edited by G. Nussbaum. AAPM Monogr. no. 8. (AIP, New York, 1983). (I)

G. Nuclear medicine

1. General

Diagnostic nuclear medicine techniques involve measuring the distribution of radioactive substances in various organs. The spatial resolution is not as good as in radiology, but one obtains information about *function*—the uptake and disappearance of the isotope from the organ. General texts are a good place to start. The following articles give some of the history.

97. "**Early history (1936–1946) of nuclear medicine in thyroid studies at Massachusetts General Hospital,**" R. D. Evans, Med. Phys. **2**, 105–109 (1975). (E)
98. "**Forty years of development in radioisotope non-imaging techniques,**" H. Miller, Phys. Med. Biol. **29**, 157–162 (1984). (I)
99. "**Nuclear Medicine: How it began,**" W. G. Myers and H. N. Wagner, Jr., Hosp. Prac. **9**(3), 103–113 (1974). (E)
100. "**Forty years of development in radioisotope imaging,**" N. Veall, Phys. Med. Biol. **29**, 163–164 (1984). (I)
101. "**Radioimunoassay: A probe for the fine structure of biological systems,**" R. S. Yalow, Med. Phys. **5**, 247–257 (1978). (A)

The following reference describes functional imaging, especially in cardiology.

102. "**Nuclear Medicine,**" W. J. Macintyre. Four chapters in *Proceedings of the International School of Physics, "Enrico Fermi," Course LXXVI*, edited by J. R. Greening, (North-Holland, Amsterdam, 1981). (I,A)

2. Emission tomography

X-ray transmission tomography reconstructs the two-dimensional function $\mu(x,y)$ from a series of projections of $\int\mu(s)ds$. In emission tomography, the concentration of the isotope $C(x,y)$ is reconstructed form a series of projections $\int C(s)ds$. In single photon emission computed tomography (SPECT) a gamma emitter is used. In positron emission tomography (PET) a positron emitter is used, and the two annihilation photons are detected in coincidence. Because the positron emitters have very short half-lives, this requires an accelerator at the hospital. An advantage is that natural chemicals incorporating positron emitters can often be made. A recent book covering both aspects is

103. **Computed Emission Tomography**, edited by P. J. Ell and B. L. Holman (Oxford Univ., Oxford, 1982). (I,A)

a. Single photon emission tomography

104. "**Single-photon emission computed tomography,**" G. F. Knoll, Proc. IEEE **71**, 320–329 (1983). (I)
105. "**An overview of a camera-based SPECT system,**" K. M. Greer, R. L. Jaszczak, and R. E. Coleman, Med. Phys. **9**, 455–463 (1982).
106. "**A comparison of three systems for performing single-photon emission tomography,**" M. A. Flower, R. W. Rowe, S. Webb, and W. I. Keyes, Phys. Med. Biol. **26**, 671–692 (1981). (A)

b. Positron emission tomography

107. "**Positron tomography and nuclear magnetic resonance imaging,**" G. L. Brownell, T. F. Budinger, P. C. Lauterbur *et al.*, Science **215**, 619–626 (1982). (I)
108. "**Brain function and blood flow,**" N. A. Lassen, D. H. Ingvar, and E. Skinhoj, Sci. Am. **239**(4), 62–71 (1978). (E)
109. "**Positron-emission tomography,**" M. M. Ter-Pogossian, M. E. Raichle, and B. E. Sobel, Sci. Am. **243**(4), 170–181 (1980). (I)
110. "**Positron tomography and three-dimensional reconstruction technique,**" D. A. Chessler, in *Tomographic Imaging in Nuclear Medicine*, edited by G. S. Freedman (Soc. Nucl. Med., New York, 1973), pp. 176–183. (E)
111. "**Patterns of human local cerebral glucose metabolism during epileptic seizures,**" J. Engel, D. E. Kuhl, and M. E. Phelps, Science **218**, 64–66 (1982). (I)

H. Ultrasound

Ultrasound has established a firm place in medical diagnosis. Conventional ultrasound uses reflections from impedance discontinuities between structures in the body. Doppler ultrasound can detect moving structures such as the beating fetal heart or measure the velocity of red cells in flowing blood. There are several good general texts and articles.

112. "**Medical ultrasonics,**" P. N. T. Wells, IEEE Spectrum **21**(12), 44–51 (1984). (E)
113. **Doppler Ultrasound and Its Use in Clinical Measurement**, P. Atkinson and J. P. Woodcock, (Academic, New York, 1982). (I)
114. "**Ultrasound in medical diagnosis,**" G. B. Devy and P. N. T. Wells, Sci. Am. **238**(5), 98–112 (1978). (E)
115. "**State-of-the-art of single-transducer ultrasonic imaging technology,**" R. C. Eggleton, Med. Phys. **3**, 303–311 (1976). (I)
116. **Medical Physics of CT and Ultrasound: Tissue Imaging and Characterization**, edited by G. D. Fullerton and J. A. Zagzebski. AAPM Monogr. no. 6. (AIP, New York, 1980). (I)
117. IEEE Trans. Biomed. Eng. Special Issue on Medical Ultrasound. **BME-30** (8), August, 1983. (I)
118. "**State-of-the-art in two-dimensional ultrasonic transducer array technology,**" M. G. Maginess, J. D. Plummer, W. L. Beaver, and J. D. Meindl, Med. Phys. **3**, 312–318 (1976). (I)

Computed tomographic reconstructions are also done with ultrasound, although diffraction and scattering effects make the reconstruction considerably more complicated.

119. "**Computerized tomography with ultrasound,**" J. F. Greenleaf, Proc. IEEE **71**, 330–337 (1983). (I)
120. "**Ultrasonic reflectivity imaging in three dimensions: Exact inverse scattering solutions for plane, cylindrical and spherical apertures,**" S. J. Norton and M. Linzer, IEEE Trans. Biomed. Eng. **BME-28**, 202–220 (1981). (A)

I. Magnetic resonance

Nuclear magnetic resonance is currently a very active field. It is being called magnetic resonance to avoid the radioactive connotations of "nuclear."

1. Imaging

Magnetic resonance imaging provides cross sections similar to those of x-ray transmission tomography. The quantity imaged is the proton density of the tissue or the spin–spin or spin–lattice relaxation time. Because there are many ways of pulsing the magnetic moments in the tissue nuclei, the interpretation of magnetic resonance images is considerably more complicated than for other modalities.

121. "**Diagnostic NMR,**" R. W. Redington, IEEE Trans. Med. Imag. **MI-1**, 230–233 (1982). (E)
122. "**Positron tomography and nuclear magnetic resonance imaging,**" G. L. Brownell, T. F. Budinger, P. C. Lauterbur *et al.*, Science **215**, 619–626 (1982). (I)

123. "**Nuclear magnetic resonance technology for medical studies,**" T. F. Budinger and P. C. Lauterbur, Science **226**, 288–298 (1984). (A)
124. "**The physics of proton NMR,**" R. L. Dixon and K. E. Ekstrand, Med. Phys. **9**, 807–818 (1982). (I)
125. **Technology of Nuclear Magnetic Resonance**, P. D. Esser and R. E. Johnston (Soc. Nucl. Med., New York, 1984). (I)
126. "**An introduction to NMR imaging: from the Bloch equations to the imaging equation,**" W. S. Hinshaw and A. H. Lent, Proc. IEEE **71**, 338–350 (1983). (A)
127. "**Realistic expectations for the near term development of clinical NMR imaging,**" L. Kaufman and L. E. Crooks, IEEE Trans. Med. Imag. **MI-2**, 57–65 (1983). (I)
128. "**A unified description of NMR imaging, data-collection strategies, and reconstruction,**" K. F. King and Paul R. Moran, Med. Phys. **11**, 1–14 (1984). (I)
129. **NMR Imaging in Biomedicine**, P. Mansfield and P. G. Morris (Academic, New York, 1982). (I)
130. "**NMR imaging in medicine,**" I. L. Pykett, Sci. Am. **246**(15), 78–88 (1982). (I)
131. "**Principles of nuclear magnetic resonance imaging,**" I. L. Pykett, J. H. Newhouse, F. S. Buonanno *et al.*, Radiology **143**, 157–168 (1982). (I)

There are unanswered questions about the effect of strong magnetic fields and changing magnetic fields on the body, as well as the radiofrequency power involved in magnetic resonance imaging.

132. "**Power deposition in whole-body NMR imaging,**" P. A. Bottomley and W. A. Edelstein. Med. Phys. **8**, 510–512 (1981). (I)
133. "**Nuclear magnetic resonance (NMR) in-vivo studies: Known thresholds for health effects,**" T. F. Budinger, J. Comput. Assist. Tomog. **5**, 800–811 (1981). (I)

2. Blood flow

134. "**The NMR blood flowmeter—theory and history,**" J. H. Battocletti, R. E. Halbach, S. X. Salles-Cunh, and A. Sances, Jr., Med. Phys. **8**, 435–443 (1981). "The NMR blood flowmeter—design," Med. Phys. **8**, 444–451 (1981). "The NMR blood flowmeter—applications," Med. Phys. **8**, 452–458 (1981). (I,A)
135. "**Nuclear magnetic resonance blood flow measurements in the human brain,**" J. R. Singer and L. E. Crooks, Science **221**, 654–656 (1983). (I)

V. OTHER MEDICAL PHYSICS AND BIOMEDICAL ENGINEERING AREAS

A. Electrical signals from the body

There is an electrical potential difference of about 60–90 mV across the membrane of nearly every cell. As a nerve cell conducts or a muscle cell prepares to contract, it is swept by a wave of depolarization in which the membrane potential reverses sign. The resulting potential differences on the body surface give rise to the electrocardiogram, the electroencephalogram, the electromyogram, and the electroretinogram.

The electrocardiogram detects surface potential differences due to depolarization of heart muscle cells during the cardiac cycle. Thousands of papers have been written about the electrocardiogram, including quite sophisticated approaches to solving the "inverse problem," that is, determining the volume current generator distribution from the potential distribution on the body surface. The usual clinical interpretation is based on either a fairly simple model or empirical correlations with disease. An elementary discussion, which should be read in conjunction with Ref. 7, can be found in

136. "**Improved explanation of the electrocardiogram,**" R. K. Hobbie, Am. J. Phys. **52**, 704–705 (1984). (I)

A more formal discussion, which includes material about the inverse problem, is in

137. **Bioelectric Phenomena**, R. Plonsey (McGraw-Hill, New York, 1969). (A)

Current research can be found in many journals, including IEEE Trans. Biomed. Eng.

The electroencephalogram measures the much smaller potentials due to the collective effect of all the nerve cells in the brain. The interpretation of this signal is even more empirical than the electrocardiogram.

The electromyogram measures electrical activity in skeletal muscle during contraction, or motor and sensory nerve conduction. The electroretinogram measures the potential between cornea and eyelid evoked by repeated flashes of light. Signals picked up on the scalp over the visual cortex are called visual evoked responses. An auditory evoked response is picked up by scalp electrodes in response to a repetitive noise stimulus. These latter two signals are so weak that signal averaging techniques must be used.

138. **Clinical Applications of Evoked Potentials in Neurology. (Advances in Neurology, Vol. 32)**, J. Courjon, F. Maugiere, and M. Revol (Raven, New York, 1982). These articles are very clinical, but they show how the techniques are used.
139. **Electrodiagnosis of Neuromuscular Disease, 3rd ed.**, J. Goodgold and A. Eberstein (Williams & Wilkins, Baltimore, 1983). (I, but quite clinical)
140. "**The clinical use of auditory evoked potentials,**" A. R. D. Thornton, in *Proceedings of the International School of Physics "Enrico Fermi," Course LXXVI*, edited by J. R. Greening (North-Holland, Amsterdam, 1981), pp. 384–396. (I)

B. Magnetic signals from the body

It is now possible using SQUID magnetometers to detect the magnetic fields arising from the body. These can be from either electric currents as in magnetocardiography or permanent magnetic moments. Permanent magnetism comes from inhaled or ingested iron particles. The magnetic susceptibility of the liver gives a measure of the iron stores in the body.

141. "**Magnetic fields of the human body,**" D. Cohen, Phys. Today **28**, 33–43 (1975). (E)
142. "**Magnetic susceptibility measurement of human iron stores,**" G. M. Brittenham *et al.*, N. Eng. J. Med. **307**, 1671–1675 (1982). (I) This is a "clinical" paper about using a SQUID to measure iron stores in the liver.
143. "**Ferrimagnetic particles in the lung. Part 1: The magnetizing process; Part II: The relaxation process,**" D. Cohen, I. Nemoto *et al.*, IEEE Trans. Biomed. Eng. **BME-31**, 261–285 (1984). (I)
144. "**Magnetocardiography: an overview,**" D. B. Geselowitz, IEEE Trans. Biomed. Eng. **BME-26**, 497–504 (1979). (I)
145. "**Biomagnetic Instrumentation,**" G. L. Romani, S. J. Williamson, and L. Kaufman, Rev. Sci. Instrum. **53**, 1815–1845 (1982). (I)
146. "**Proceedings of the Fourth International Workshop on Biomagnetism,**" edited by G. L. Romani and S. J. Williamson, Il Nuovo Cimento **2D**(2) March–April, 1983. (I,A)
147. "**Noninvasive magnetic detection of cardiac mechanical activity: (1) Theory, (2) Experiments,**" J. P. Wikswo, Med. Phys. **7**, 297–314 (1980). (I)
148. **Biomagnetism, An Interdisciplinary Approach**, S. J. Williamson, G. L. Romani, L. Kaufman *et al.*, (Plenum, New York, 1983). (A)

C. Pacing

The cardiac pacemaker is one of the triumphs of biomedical engineering. It has provided life extension of good quality. More than 500 000 patients in the United States have permanently implanted pacemakers.

149. "**An engineering overview of cardiac pacing,**" P. P. Tarjan and A. D. Berstein, IEEE Eng. Med. Bio. Mag. **3**(2), 10–14 (1984). A number of other relevant articles appear in the same issue. (E)

150 "Control of tachyarrhythmias by electrical stimulation—Techniques and mechanisms," R. Mehra, IEEE Eng. Med. Biol. Mag. **3**(2), 29–24 (1984). (E)

151. "**Physiological stimulators: From electric fish to programmable implants,**" L. J. Seligman, IEEE Trans Biomed. Eng. **BME-29**, 270–284 (1982). (I)

A very good review article from the physician's point of view is found in

152. "**Cardiac pacing in the 1980s,**" P. L. Ludmer and N. Goldschlager, N. Engl. J. Med. **311**, 1671–1680 (1984). (I)

D. Other effects of electric and magnetic fields

Electrical stimulation is also used to enhance tissue regeneration and to control pain.

153. "**The effects of pulsed magnetic fields of the type used in the stimulation of bone fracture healing,**" A. T. Barker and M. J. Lunt, Clin. Phys. Physiol. Meas. **4**, 1–28 (1983). (I)

154. "**A review of electromagnetically enhanced soft tissue healing,**" C. B. Frank and A. Y. J. Szeto, IEEE Eng. Med. Bio. Mag. **2**(4), 27–32 (1983). (E)

155. "**Skeletal tissue electromechanics and electrical stimulation of growth and remodelling,**" A. J. Grodzinsky and L. A. Hey, IEEE Eng. Med. Bio. Mag. **2**(4) 18–22 (1983). (E)

156. "**Transcutaneous electrical nerve stimulation for pain control,**" A. Y. J. Szeto and J. K. Nyquist, IEEE Eng. Med. Bio. Mag. **2**(4), 14–18 (1984). (E)

The question of the effect of electromagnetic fields is an active area of research. A recent review of the effect of power line frequencies is found in

157. "**Power-line fields and human health,**" M. G. Morgan, H. K. Florig, I. Nair, and D. Lincoln, IEEE Spectrum **22**(2), 62–68 (1985). (I)

E. Prostheses

A wide variety of prosthetic devices are available, ranging from artificial limbs with varying degrees of sophistication to artificial sensory organs. Some limb prostheses are now being controlled by electromyographic signals picked up from the patient.

158. "**New developments in mobility and orientation aids for the blind,**" J. A. Brabyn, IEEE Trans. Biomed. Eng. **BME-29**, 285–289 (1982). (I)

159. "**Development of the Utah artificial arm,**" S. C. Jacobsen, D. F. Knutti, R. T. Johnson, and H. H. Sears, IEEE Trans. Biomed. Eng. **BME-29**, 249–269 (1982). (I)

160. "**Review of current status of cochlear prostheses,**" R. L. White, IEEE Trans. Biomed. Eng. **BME-29**, 233–238 (1982). (I)

F. Lasers and Optics

161. "**Lasers in surgery and medicine,**" A. L. McKenzie and J. A. S. Carruth, Phys. Med. Biol. **29**, 619–642 (1984). (I) This is a two-part review by a physicist and a surgeon.

162. "**Physics and ophthalmology,**" R. A. Weale, Phys. Med. Biol. **24**, 489–504 (1979). (I)

G. Phototherapy

The chief use of ultraviolet radiation has been for the treatment of psoriasis. The other widespread use of phototherapy is irradiation with blue light for the treatment of neonatal jaundice. Some experimental work is being done on phototherapy of cancer, after the tumor has been sensitized by a dye given systemically. Some of the references discuss the harmful effects of ultraviolet radiation.

163. **Ultraviolet ratiation in medicine**, B. L. Diffey. Medical physics handbook no. 11. (Adam Hilger, Bristol, 1982). (I)

164. "**Ultraviolet radiation physics and the skin,**" B. L. Diffey, Phys. Med. Biol. **25**, 405–426 (1980). (I)

165. **Biological Effects of Ultraviolet Radiation**, W. Harm (Cambridge Univ., Cambridge, 1980). (I)

166. "**Blue light and bilirubin excretion,**" A. F. McDonagh, L. A. Palma, and D. A. Lightner, Science **208**, 145–151 (1980). This article reviews phototherapy for neonatal jaundice. (I)

167. "**Dosimetry considerations in phototherapy,**" A. E. Profio and D. R. Doiron, Med. Phys. **8**, 190–196 (1981). (A)

168. "**Dye-sensitized photodynamic inactivation of cells,**" J. P. Pooler and D. P. Valenzeno, Med. Phys. **8**, 614–628 (1981). (I)

H. Dialysis

Approximately 45 000 patients in the United States are undergoing chronic dialysis for renal disease. For a discussion of some of the design problems, see

169. "**Artificial kidneys: Problems and approaches,**" C. F. Gutch, Ann. Rev. Biophys. Bioeng. **4**, 405–429 (1975). (I)

Dialysis is not without its problems; to understand the effect of dialysis on a patient, read

170. "**Iatrogenic problems in end-stage renal failure,**" H. Calland, N. Engl. J. Med. **287**, 334–336 (1972). (E)

I. Elemental analysis

171. "**An x-ray fluorescence technique to measure the mercury burden of dentists,**" P. Bloch and I. M. Shapiro, Med. Phys. **8**, 308–311 (1981). (I)

172. **X-ray Fluorescence (XRF and PIXIE) in Medicine**, edited by R. Cesareo (Acta Medica, Rome, 1982). (I)

173. "**Techniques of in vivo neutron activation analysis,**" D. R. Chettle and J. H. Fremlin, Phys. Med. Biol. **29**, 1011–1043 (1984). (I)

174. "**Techniques for trace element analysis: x-ray fluorescence, x-ray excitation with protons, and flame atomic absorption,**" R. M. Wheeler, R. B. Liebert, T. Zabel *et al.*, Med. Phys. **1**, 68–71 (1974). (I)

J. Mass spectrometry

The most common medical use of the mass spectrometer has been in conjunction with the gas chromatograph for toxicology. It has also been used for respiratory gas analysis.

175. "**Routine use of a flexible gas chromatograph mass spectrometer computer system to identify drugs and their metabolites in body fluids of overdose victims,**" C. E. Costello, H. S. Hertz, T. Sakai, and K. Bieman, Clin. Chem. **20**, 255–265 (1974). (I)

176. "**Mass spectrometer evaluation of ventillation-perfusion abnormalities in respiratory distress syndrome,**" C. E. Hunt, S. Matalon, O. D. Wangensteen, and A. S. Leonard, Ped. Res. **8**, 621–627 (1974). (I)

177. **The Medical and Biological Application of Mass Spectrometry**, edited by J. P. Payne, J. A. Bushman, and D. W. Hill (Academic, London, 1979). (I)

K. Miscellaneous

178. "**Electronics and the diabetic,**" A. M. Albisser, and W. J. Spencer, IEEE Trans. Biomed. Eng. **BME-29**, 239–248 (1982). (I)

179. "**Forty years of instrumentation for medicine,**" F. T. Farmer, Phys. Med. Biol. **29**, 139–144 (1984). (I)
180. "**Biophysical and engineering aspects of cryosurgery,**" R. D. Orpwood, Phys. Med. Biol. **26**, 555–576 (1981). (I)

VI. EFFECTIVENESS AND ECONOMICS

One must always ask whether a particular device, test, or treatment works and is less expensive than what it replaces. The effect on one patient of "high tech" treatments—dialysis and transplant for renal disease—is discussed in Ref. 170. Reference 181 below discusses the public health and social implications of a "high-tech" diagnostic technique: computerized medical imaging. References 182–184 describe the "ROC" (Receiver Operating Characteristic) technique for comparing the accuracy of different tests.

181. "**Tutorial on the health and social value of computerized medical imaging,**" H. V. Fineberg and H. E. Sherman, IEEE Trans. Biomed. Eng. **BME-28**, 50–56 (1981).
182. "**Basic principles of ROC analysis,**" C. E. Metz, Semi. Nucl. Med. **8**, 283–298 (1978) (I)
183. "**Assessment of diagnostic technologies,**" J. A. Swets, R. M. Pickett, S. F. Whitehead *et al.*, Science **205**, 753–759 (1979). (I)
184. **Evaluation of Diagnostic Systems: Methods from Signal Detection Theory**, J. A. Swets and R. M. Pickett (Academic, New York, 1982). (I)

Theoretical support for the generalized correspondence principle

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Although most people associate the correspondence principle with quantum mechanics, it has been used more generally for many years in the development of theories in essentially all branches of physics. Based upon simple assumptions which would seem to be necessary for any exact science, a more precise statement of the generalized correspondence principle is provided, with due regard to the accuracy of theories. Term correspondence is presented as a corollary to the principle. Evidently, the principle has as strong a basis as other scientific theories. Its value in theory development as well as in furthering the understanding of the history of science is discussed.

I. INTRODUCTION AND HISTORICAL OVERVIEW

Recently there has been considerable interest in the historical development of scientific theories, particularly in the revolutionary developments. Two major schools of thought have emerged among philosophers of science. One favors primarily an evolutionary description in which continuity is maintained,[1] and another, a description entailing discontinuous revolutions.[2] Although the correspondence principle has an important relationship to the transition of theories, that principle has not been adequately treated in these recent discussions. Some individuals have proposed philosophical ideas[3] which resemble the correspondence principle of physics, and these have been extensively debated; but the principle is seldom cited or discussed as a general scientific principle. That is so in large part because a generalized form of that principle has not been formally developed or extensively discussed among scientists, despite the clear history of wide-ranging applications.

The term "correspondence principle" was coined by Bohr for the procedure which he used to help induce his new theory of the atom by relating it to previous classical theories. Development of the theory and interpretation of the principle were done over the period of 1913–1923.[4] A modern statement of the principle as used by Bohr is :"In the region of very large quantum numbers, quantum predictions must reduce to equivalence with classical predictions."[5] This principle became an important tool throughout the development of quantum mechanics,[6] and in a broader form, was incorporated into the measurement theory of quantum mechanics.[7] It is because of this development that essentially all physicists are aware of the principle in its quantum mechanical form.

It would be a mistake, however, to presume that the correspondence principle is one which is primarily a part of quantum mechanics, and even less to presume, as some people do, that it was only used in the early development of the "old" quantum mechanics. Instead, it is a principle of broad application which has been used for hundreds of years.

Published statements of a more general principle appeared in two textbooks in 1960. In their book, *Elementary Modern Physics*,[8] Weidner and Sells stated the principle:

> We know in advance that any new theory in physics—whatever its character or details—must reduce to the well-established classical theory to which it corresponds when the new theory is applied to the circumstances for which the less general theory is known to hold.

In *Physics for the Inquiring Mind*,[9] Rogers stated the prin-

