
Resource Letter MP-2: Medical Physics

Russell K. Hobbie
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

Bradley J. Roth
Department of Physics, Oakland University, Rochester, Michigan 43809

(Received 12 June 2009; accepted 18 August 2009)

This Resource Letter provides a guide to the literature on the uses of physics for the diagnosis and treatment of disease. It does not include molecular biophysics but does include biomedical engineering.
[DOI: 10.1119/1.3223440]

I. INTRODUCTION

Physicists sometimes use the terms medical physics and biological physics 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 to diagnose and treat disease. We have diagnostic and therapeutic radiology, diagnostic and therapeutic nuclear medicine, ultrasound (mainly diagnostic but treatments are emerging), and magnetic resonance imaging. Recently the areas of interest to the medical physicist have expanded as still more diverse and sophisticated instruments such as lasers are used for diagnosis and treatment. The American Association of Physicists in Medicine is the professional organization affiliated with the American Institute of Physics to which most medical physicists in the United States belong.

Biological physics is the study of biological phenomena using physical techniques, encompassing studies as diverse as molecular and cellular structure and function, physiology, biomedical instrumentation, the medical physics areas described in the preceding paragraph, and mathematical biology. Sometimes the terms biological physics and biophysics are used interchangeably. However, in recent years the term biophysics has been used more narrowly to mean the study of molecular and cellular biology. Members of the Biophysical Society have interests primarily in biophysics, while members of the Division of Biological Physics in the American Physical Society are concerned primarily with biological physics.

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 significant applications of physics in physiology and molecular and cellular biology.

In many cases a textbook is the most appropriate way to begin learning about a topic in medical physics. Where they are available, they open the list of references for each topic below. The journal articles cited here are 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 PubMed (www.pubmedcentral.nih.gov) to find other articles on the same subject. Another accessible source of information can be found at Scholarpedia (www.scholarpedia.org), which is similar to the better-known Wikipedia (www.wikipedia.org), except that each article is written by an expert and has a curator who must approve changes. Some Scholarpedia articles relevant to this letter are Bidomain Model, Cardiac Arrhythmias, Electroencephalogram, Functional Imaging, Functional Magnetic Resonance Imaging, Magnetic Resonance Imaging, Magnetoencephalogram, and Transcranial Magnetic Stimulation.

II. JOURNALS

A. Medical physics

British Journal of Radiology. The articles are primarily clinical. (I,A)

Health Physics the Radiation Safety Journal. Journal of the Health Physics Society. (I,A)

IEEE Transactions on Medical Imaging. (I,A)

IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control. Some of the articles are on medical ultrasonics. (I,A)

International Journal of Radiation Biology. (I,A)

Journal of Computer Assisted Tomography. This journal covers all CT modalities: Ultrasound, x-ray, SPECT, PET, and MRI. The articles are primarily clinical. (I,A)

Journal of Magnetic Resonance Imaging. This journal has both instrumentation and clinical articles. (I,A)

Journal of Nuclear Medicine. (I,A)

Journal of Ultrasound in Medicine. The articles are primarily clinical. (I,A)

Magnetic Resonance in Medicine. (I,A)

Medical Physics. This is the journal of the American Association of Physicists in Medicine. Each issue contains original papers spanning all modalities of diagnostic imaging and radiation therapy physics, as well as a "point/counterpoint" article that debates an important current issue in medical physics. These articles provide an excellent way to become familiar with current issues. A compendium of articles (through February 2008 at the time of this writing) is available at www.aapm.org/pubs/books/PointCounterpointCompendium.pdf. (I,A)

Physics in Medicine and Biology. The Institute of Physics journal covering the application of physics to medicine, physiology, and biology. Its affiliated website (medicalphysicsweb.org) provides current news about medical physics. (I,A)

Radiation Research. Devoted to radiation biology. (A)

Radiographics. Contains peer-reviewed educational articles for radiologists, trainees, physicists, and other radiologic professionals. Topics include clinical and therapeutic radiology, physics, and informatics. (I,A)

Radiology. The articles are primarily clinical. (I,A)

Ultrasonics. The articles are primarily about instrumentation and techniques. (I,A)

Ultrasound in Medicine and Biology. The articles are primarily clinical. (I,A)

Ultrasound Quarterly. The articles are primarily clinical. (I,A)

B. Biomedical engineering

Annals of Biomedical Engineering. This is the journal of the Biomedical Engineering Society. (I,A)

Annual Reviews of Biomedical Engineering. Volume 1 was published in 1999. For the topics in this Resource Letter, this journal replaces *Annual Reviews of Biophysics and Biomedical Engineering*, which in recent years has been devoted to molecular biophysics and which, after various name changes, is now called *Annual Reviews of Biophysics.* (I,A)

Critical Reviews in Biomedical Engineering. One of the CRC Critical Reviews. (I,A)

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

IEEE Transactions on Biomedical Engineering. (I,A)

IEEE Transactions on Neural Systems and Rehabilitation Engineering. (I,A)

IEEE Transactions on Information Technology in Biomedicine. (I,A)

IEEE Reviews in Biomedical Engineering. The first volume appeared in 2008. (I)

Medical and Biological Engineering and Computing. The official journal of the International Federation of Medical and Biological Engineering. (I,A)

III. RELATED RESOURCE LETTERS

A number of Resource Letters are relevant to medical and biological physics. The first five are of historical interest. They show the state of mathematical biology, biophysics, and biomedical engineering from the mid-1960s to the mid-1980s.

1. **Resource Letter PB-1 on Physics and Biology**, D. J. Baker, Jr., Am. J. Phys. **34**(2), 83–93 (1966). Provides an overview of the important problems in biophysics 40 years ago. (E,I,A)
2. **Resource Letter BE-1 on Biomedical Engineering**, C. C. Johnson, Am. J. Phys. **39**(12), 1423–1432 (1971). Discusses biological control systems, hemodynamics, biomechanics, microwave diathermy, electrocardiography, light, lasers, and ultrasound. (E,I,A)
3. **Resource Letter TPB-1: Theoretical Physics and Biology**, N. MacDonald, Am. J. Phys. **42**(9), 717–725 (1974). Provides early references to mathematical biology, ecology, scaling theory, population dynamics, feedback systems, catastrophe theory, thermodynamics, information theory, excitable membranes, and chemotaxis. (E,I,A)
4. **Resource Letter MP-1: Medical Physics**, R. K. Hobbie, Am. J. Phys. **53**(9), 822–829 (1985). This is the previous version of the present Resource Letter. Some of the references in it to pre-1985 literature are still very useful. (E,I,A)
5. **Resource Letter PPPP-1: Physical Principles of Physiological Phenomena**, B. Hoop, Am. J. Phys. **55**(3), 204–210 (1987). Identifies physical principles that are important in classical physiology, such as the circulatory system, muscle contraction and energetics, action potentials, biomagnetism, mass transport, and ion channels. (E,I,A)

The next two Resource Letters are not about Medical Physics, but they show how physics applies to biology at the cellular level. See also Ref. 15.

6. **Resource Letter PFBi-1: Physical Frontiers in Biology**, E. V. Mielczarek, Am. J. Phys. **74**(5), 375–381 (2006). Begins with a fascinating three-page essay on the role of physics in biology. (E,I,A)
7. **Resource Letter BELFEF-1: Biological Effects of Low-Frequency Electromagnetic Fields**, D. Hafemeister, Am. J. Phys. **64**(8), 974–981 (1996). Discusses the controversy about whether low-frequency (power-line) electromagnetic fields have any effect on human health. See Refs. 139–143 for articles published after 1996. (E,I,A)

The next three Resource Letters expand on material covered in this one.

8. **Resource Letter MI-1: Medical Imaging**, S. J. Riederer, Am J. Phys. **60**(8), 682–693 (1992). Describes all the medical imaging modalities with an emphasis on magnetic resonance imaging. (E,I,A)
9. **Resource Letter EIRLD-1: Effects of Ionizing Radiation at Low Doses**, R. Wilson, Am. J. Phys. **67**(5), 372–377 (1999). Points to the literature describing effects at high doses, moderate-to-high doses, and at low and very low doses. Dose-rate effects are also discussed. It concludes with three references on policy implications. (E,I,A)

10. **Resource Letter MPRT-1: Medical Physics in Radiation Therapy**, S. T. Ratliff, Am. J. Phys. **77**(9), 773–864 (2009). The extensive discussion of radiation therapy includes radiological physics (the physics of ionizing radiation), particle accelerators, dose measurement, protocols for measuring dose, radiation shielding and radiation protection, neutron, proton, and heavy-ion therapy, imaging to identify and track tumor volume and location, brachytherapy (implanted radioactive isotopes), quality assurance, treatment planning, dose calculations, intensity-modulated therapy, and image-guided therapy. It also has a list of medical physics curricula and websites. (E,I,A)

IV. GENERAL TEXTS

This section lists textbooks and articles that cover several of the areas in this Resource Letter and that are suitable references for a physics teacher. Elementary physics texts containing just a few biological examples are not listed.

11. **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 (Springer, New York, 2000). Reissue of a pioneering text from the 1970s with new editing, illustrations, and an index. A variety of applications of physics to medicine can be found throughout. (I)
12. **Physics of the Body**, 2nd ed., J. R. Cameron, J. G. Skofronick, and R. M. Grant (Medical Physics Publishing, Madison, WI, 1999). This book has an excellent qualitative discussion of radiologic physics as well as the physics of the senses and other medical instruments and procedures that use physics. (E)
13. **Intermediate Physics for Medicine and Biology**, 4th ed., R. K. Hobbie and B. J. Roth (Springer, New York, 2007). This text covers most of the topics in this Resource Letter. Weekly posts to the blog ⟨http://hobbieroth.blogspot.com⟩ may be interesting to readers of the book. (I)
14. **Introduction to Physics in Modern Medicine**, 2nd ed., S. A. Kane (Taylor & Francis, New York, 2009). This elementary text discusses fiber optics, lasers, ultrasound, x rays, nuclear medicine, radiation therapy, and magnetic resonance imaging. (E)
15. **Biological Physics**, updated edition, P. Nelson (Freeman, New York, 2007). In general, we are not listing biological physics texts in this Resource Letter, but this one is so good that we provide it as an introduction to this field. (I)

Besides textbooks, several websites exist that teachers of medical physics may find useful, including the following:

(a) www.insidestory.iop.org (an Institute of Physics website with animations related to medical physics),
(b) www.teachingmedicalphysics.org.uk (an IOP website with teaching materials about medical physics for K-12 schools), and
(c) www.physicscentral.com/discover/biology-medicine.cfm (an American Physical Society website about applications of physics to medicine and biology).

Also of interest to those thinking about adding a medical physics class to the college curriculum is the following:

16. “Medical physics: The perfect intermediate level physics class,” N. Christensen, Eur. J. Phys. **22**, 421–427 (2001). (E)

V. DIAGNOSTIC IMAGING

A. General

Diagnostic images are obtained using ultrasound, x rays, radioactive isotopes, and magnetic resonance imaging. There are two types of information a physicist may want about these modalities: First, the details of the physics behind the medical image and second, pictures of the equipment and typical diagnostic images. We give references for both. Examples are often best found in textbooks for radiologists or the allied health personnel (technologists) who actually perform the procedures.

The references in this subsection apply to all of these imaging modalities. Later subsections give references specific to each modality.

Tomography is derived from the Greek *tomos*, meaning slice. Tomography was originally a technique in which the film and x-ray tube were rotated about a point or line passing through an organ of interest, thereby blurring structures that are not close to the pivot. In computed tomography (CT), two-dimensional slices are reconstructed from a series of projections. CT is used in medical physics with x rays, radioactive isotopes, and magnetic resonance imaging. The reconstruction technique was developed simultaneously in radioastronomy, crystallography, radiology, and nuclear medicine. Two physicists shared the Nobel Prize in Physiology or Medicine for this development. The next two references are their Nobel Lectures.

17. “Early two-dimensional reconstruction and recent topics stemming from it,” A. M. Cormack, Med. Phys. **7**, 277–282 (1980). Also available at ⟨nobelprize.org/nobel_prizes/medicine/laureates/1979/cormack-lecture.html⟩. (I)
18. “Computed medical imaging,” G. N. Hounsfield, Med. Phys. **7**, 283–290 (1980). Also available at ⟨nobelprize.org/nobel_prizes/medicine/laureates/1979/hounsfield-lecture.html⟩. (I)

X-ray transmission tomography reconstructs in two dimensions the attenuation coefficient $\mu(x,y)$ from a series of projections of $\int \mu(s)ds$. In spiral or helical CT, the patient is moved through the continuously rotating x-ray apparatus along the z (long) axis, and linear interpolation is used to reconstruct the slices. It is now possible to produce three-dimensional reconstructions of organs, blood vessels, the inside of the colon, etc. and to examine them from any angle. It is estimated that in 2006 about 45 000 CT scanners were in use, most of which were whole-body spiral scanners (Ref. 53).

In emission tomography, a nuclear-medicine procedure, the concentration of a radioactive isotope $C(x,y)$ is reconstructed from a series of projections $\int C(s)ds$. In single-photon emission computed tomography (SPECT), a gammaemitting isotope is used. In positron emission tomography (PET), a positron emitter is used, and the two annihilation photons are detected in coincidence.

The following references discuss two or more imaging modalities:

19. **Foundations of Medical Imaging**, Z.-H. Cho, J. P. Jones, and M. Singh (Wiley-Interscience, New York, 1993). The description of instrumentation is somewhat dated, but Section I, Basics for Medical Imaging, provides a thorough mathematical analysis of imaging algorithms. (I)
20. **Medical Imaging Physics**, 4th ed., W. R. Hendee and E. R. Ritenour (Wiley-Liss, New York, 2002). This text describes all of the imaging methods. Chapters 16–18 discuss image science. (I)
21. **The Essential Physics of Medical Imaging**, 2nd ed., J. T. Bushberg, J. A. Seibert, E. M. Leidholdt, Jr., and J. M. Boone (Lippincott/Williams and Wilkins, Philadelphia, 2002). A widely used textbook that covers much of the same material as Ref. 20 but at a slightly higher level. (I,A)
22. **Farr's Physics for Medical Imaging**, P. Allisy-Roberts and J. Williams (Saunders/Elsevier, Edinburgh, 2008). This brief book is intended for radiologists and covers all imaging modalities. (Nuclear medicine is called gamma imaging.) (E)
23. **Radiologic Science for Technologists—Physics, Biology, and Protection**, 9th ed., S. C. Bushong (Mosby-Elsevier, St. Louis, 2008). A textbook used by radiologic technologists to learn about imaging and prepare for the American Registry of Radiologic Technologists (ARRT) exam. (E,I)
24. **Computed Tomography: Physical Principles, Clinical Applications, and Quality Control**, E. Seeram (Saunders/Elsevier, St. Louis, 2009). A very descriptive and up-to-date book on physical principles of x-ray and nuclear computed tomography. (E)
25. **Multislice CT**, 3rd ed., M. F. Reiser (Springer, Berlin, 2009). An excellent history of the development of x-ray computed tomography and the use of multislice CT. (E,I,A)
26. **Handbook of Medical Imaging. Vol. 1. Physics and Psychophysics**, edited by J. Beutel, H. L. Kundel, and R. L. Van Metter (SPIE—The International Society for Optical Engineering, Seattle, 2000). An advanced and very comprehensive handbook. (I,A)
27. **Foundations of Image Science**, H. H. Barrett and K. J. Myers (Wiley-Interscience, New York, 2004). A very mathematical book covering all aspects of image science. (A)
28. "Diagnostic imaging over the last 50 years: Research and development in medical imaging science and technology," K. Doi, Phys. Med. Biol. **51**(13), R5–R27 (2006). This review describes the advance from film to digital detectors, our understanding of image quality, image processing, and computer diagnosis. (E,I)
29. "50th Anniversary Issue," Phys. Med. Biol. **51**(13), R1–R504 (2006). This entire issue has 25 articles on the history and development of various aspects of diagnostic and therapeutic radiology. (E,I)

A number of very sophisticated image processing techniques are available to the radiologist. These include feature recognition, noise reduction, and compression techniques. Compression is important for the storage and transmission of diagnostic images. The image must be compressed in a manner that does not lose meaningful diagnostic information. The need to view, transmit, and store images from many vendors has led to the Picture Archiving and Communication System (PACS) and the standard for Digital Imaging and Communication in Medicine (DICOM). The ability to transmit and display diagnostic-quality images allows teleradiology: The radiologist can cover several clinics or hospitals from one location. All this is discussed in the next five references.

30. **Image Processing in Radiology Current Applications**, E. Neri, D. Caramella, and C. Bartolozzi (Springer, New York, 2008). Examples of image manipulation for several modalities. (I)
31. **Handbook of Medical Imaging. Vol. 2. Medical Image Processing and Analysis**, edited by M. Sonka and J. M. Fitzpatrick (SPIE—The International Society for Optical Engineering, Seattle, 2000). An advanced and very comprehensive handbook. (I,A)
32. **Handbook of Medical Imaging. Vol. 3. Display and PACS**, edited by Y. Kim and S. C. Horii (SPIE—The International Society for Optical Engineering, Seattle, 2000). An advanced and very comprehensive handbook. (I,A)
33. "Primer on computers and information technology. Part four: A nontechnical introduction to DICOM," S. C. Horii, Radiographics **17**(5), 1297–1309 (1997). (E,I)
34. "Anniversary Paper: Image processing and manipulation through the pages of *Medical Physics*," S. G. Armato, III and B. van Ginneken, Med. Phys. **35**(10), 4488–4500 (2008). (A)

Computer-aided diagnosis or computer-aided detection (CAD) of diagnostic images is becoming increasingly prevalent. Notice the word "aided." The radiologist still interprets the image but with the assistance of various computer-generated image enhancements or extracted data. The history and recent developments are described in Ref. 35.

35. "Anniversary Paper: History and status of CAD and quantitative image analysis: The role of *Medical Physics* and AAPM," M. L. Giger, H.-P. Chan, and J. Boone, Med. Phys. **35**(12), 5799–5820. (I,A)

B. Ultrasound

Ultrasound is widely used in medical diagnosis. Conventional ultrasound images show specular reflections from acoustic-impedance discontinuities between structures in the body. Doppler ultrasound detects moving structures, such as the beating fetal heart, or measures the velocity of red cells in flowing blood. The nonlinear response of tissue to high-intensity ultrasound leads to harmonic generation; these harmonics have recently been used for imaging. Ultrasound is also being used to measure the elastic properties of tissue (see, for example, Ref. 44). The use of ultrasound for therapy is described in Sec. VI.

There are several good general texts and articles. See also Refs. 13, 14, 19, 20, and 22.

36. **Diagnostic Ultrasound: Principles and Instruments**, F. W. Kremkau (Elsevier Saunders, St. Louis, 2006). This book is written for allied health personnel. The physics is elementary but complete. There are lots of

pictures of equipment and diagnostic images. (E)

37. **Essentials of Ultrasound Physics**, J. A. Zagzebski (Mosby, St. Louis, 1996). Elementary nonmathematical description of ultrasound principles and clinical applications. Explains all topics on the board exams for ultrasound practitioners. (E)
38. **Basic Doppler Physics**, H. J. Smith and J. A. Zagzebski (Medical Physics, Madison, WI, 1991). This text for allied health personnel covers some very advanced topics at an elementary level. It assumes the reader understands B-mode ultrasound. (E)

The next two books are standard clinical texts with basic physics chapters at the beginning.

39. **Diagnostic Ultrasound**, 3rd ed., C. M. Rumack, S. R. Wilson, and J. W. Charboneau (Elsevier/Mosby, St. Louis, 2005). This clinical text begins with 34 pages on physics, 20 pages on biologic effects and safety, and 20 pages on microbubble contrast agents. (E)
40. **Diagnostic Ultrasound**, J. P. McGahan and B. B. Goldberg (Informa Healthcare, New York, 2008). This is a clinical text with a short section on basic physics. (E)

The following three texts are written for graduate students in medical physics or engineering:

41. **Foundations of Biomedical Ultrasound**, R. S. C. Cobbold (Oxford U. P., New York, 2007). An advanced and mathematical book for physics and engineering students, covering physical acoustics, nonlinear propagation, transducer design, imaging instruments, Doppler, and flow measurements. (A)
42. **Diagnostic Ultrasound Imaging: Inside Out**, T. L. Szabo (Elsevier, Amsterdam, 2004). Rigorous and mathematical treatments of wave propagation in materials, transducers, clinical instrumentation, signal processing, Doppler ultrasound, and nonlinear effects. (I,A)
43. **Doppler Ultrasound: Physics, Instrumentation and Signal Processing**, 2nd ed., D. H. Evans and W. N. McDicken (Wiley, Chichester, 2000). (I,A)
44. "Anniversary Paper: Evolution of ultrasound physics and the role of medical physicists and the AAPM and its journal in that evolution," P. L. Carson and A. Fenster, Med. Phys. **36**(2), 411–428 (2008). An up-to-date review of tissue properties, imaging systems, Doppler imaging, nonlinear acoustics, breast and brain imaging, and ultrasonic therapy. (I,A)
45. "Ultrasound Imaging," P. N. T. Wells, Phys. Med. Biol. **51**(13), R83–R98 (2006). Reviews the development of ultrasound imaging and indicates possible areas of future development. (E,I)

In addition to the specular reflection from organ boundaries, there is diffuse scattering from microstructures in the organ tissue. This signal is 40–50 dB less than the specular reflection, but it can be used to characterize the tissue.

46. **Ultrasonic Scattering in Biological Tissue**, edited by K. K. Shung and G. A. Thieme (CRC, Boca Raton, 1993). (I,A)

Microbubbles are used as contrast media. This is described in Refs. 39 and 41 as well as in

47. "Ultrasound contrast microbubbles in imaging and therapy: Principles and engineering," S.-P. Qin, C. F. Caskey, and K. W. Ferrara, Phys. Med. Biol. **54**(6), R27–R57 (2009). (I,A)

C. X-ray images

Everyone is familiar with the x-ray image or radiograph made on film. A beam of x rays from a point source passes through the body and exposes a photographic plate. Structures that attenuate the x rays more appear lighter on the developed film. The x-ray dose to the patient should be the lowest that provides a satisfactory signal-to-noise ratio. To reduce the dose the film is made more sensitive to x rays by sandwiching it between fluorescent screens in a cassette. See Refs. 13, 14, 19, 20, and 21. In mammography the characteristics of the x-ray beam are optimized for soft-tissue imaging. The radiology texts listed earlier describe the apparatus in detail and have many examples of diagnostic radiographs.

Dental x-rays have their own considerations for beam energy and film properties. Many texts for the dentist and the technician are available. See, for example,

48. **Radiographic Imaging for the Dental Team**, 4th ed., D. A. Miles (Saunders/Elsevier, St. Louis, 2009). (E)

In recent years solid-state detector systems have replaced the film-screen combination. In computed radiography (CR) a storage phosphor replaces the film in the cassette. After exposure the storage phosphor is read out and digitized by scanning it with a laser and recording the light produced. Direct radiography (DR) comes in two forms. In direct conversion the x rays interact with a photoconductor that is in contact with a thin-film transistor array. In indirect conversion, the x rays strike a scintillator, and the resulting light is detected by a charge-coupled detector (CCD) array.

49. "Advances in digital radiography: Physical principles and system overview," M. Körner, C. H. Weber, S. Wirth, K-J. Pfeifer, M. F. Reiser, and M. Treitl, Radiographics **27**, 675–686 (2007). A survey of the various techniques for digital radiography, designed for residents. (E,I)
50. "Solid-state, flat-panel, digital radiography detectors and their physical imaging characteristics," A. R. Cowen, S. M. Kengyelics, and A. G. Davies, Clin. Radiol. **63**, 487–498 (2008). This review is somewhat more detailed than the previous reference. (I)
51. "The design and imaging characteristics of dynamic, solid-state, flat-panel x-ray image detectors for digital fluoroscopy and fluorography," A. R. Cowen, A. G. Davies, and M. U. Sivananthan, Clin. Radiol. **63**, 1073–1085 (2008). A companion article to the previous reference. The requirements for fluoroscopy are somewhat different. (I)

Once one has digital images, all sorts of manipulations can be done. For image manipulation, see Refs. 8, 13, 14, 19, 20, 21, 31, 34, and 35.

Most of the references in the general section above describe x-ray computed tomography. The history of x-ray CT is found in

52. "Anniversary Paper: Development of x-ray computed tomography: The role of *Medical Physics* and *AAPM* from the 1970s to present," X. Pan, J. Siewerdsen, P. J. La Riviere, and W. A. Kalender, Med. Phys. **35**(8), 3728–3739 (2008). (E,I)

53. "Review: X-ray computed tomography," W. A. Kalender, Phys. Med. Biol. **51**(13), R29–R43 (2006). A detailed history from the early work of H. A. Lorentz and J. H. Radon through spiral and cone-beam scanning. (E)

Cardiac imaging requires high spatial resolution and temporal resolution. The next two papers discuss various aspects of this technique.

54. "AAPM/RSNA Physics tutorial for residents: Physics of cardiac imaging with multiple-row detector CT," M. Mahesh and D. D. Cody, Radiographics **27**(5), 1495–1509 (2007). This tutorial description for residents is quite accessible to physicists. (I)

55. "Relationship between noise, dose and pitch in cardiac multi-detector row CT," A. N. Primak, C. H. McCollough, M. R. Bruesewitz, J. Zhang, and J. G. Fletcher, Radiographics **26**(6), 1785–1794 (2006). An interesting example of combining Poisson statistics for photon noise with the details of the x-ray tube and detector to determine the dose to the patient. (I)

56. "Experimental feasibility of multi-energy photon-counting *K*-edge imaging in pre-clinical computed tomography," J. P. Schlomka, E. Roessl, R. Dorscheid, S. Dill, G. Martens, T. Istel, C. Bäumer, C. Herrmann, R. Steadman, G. Zeitler, A. Livne, and R. Proksa, Phys. Med. Biol. **53**, 4031–4047 (2008). This paper won the 2008 Roberts Award for the best paper of the year appearing in the journal *Physics in Medicine and Biology*. They propose gathering CT images with photons of different energies and using high-atomic-number contrast agents to improve imaging. (A)

Digital techniques are now being used in mammography. See

57. "Digital mammography," E. D. Pisano and M. J. Yaffe, Radiology **234**(2), 353–362 (2005). Discusses detector physics, clinical trials, display, image processing, and advanced applications of digital mammography. (E)

D. Nuclear medicine

Diagnostic nuclear-medicine techniques involve measuring the distribution of a radioactive substance in various organs, often as a function of time. The spatial resolution is not as good as in radiology, but one obtains information about function—the uptake and disappearance of the isotope from an organ. The gamma camera or scintillation camera produces images similar to those in conventional radiography. It produces a two-dimensional picture showing "hot spots" or "cold spots," with no information about the depth of the source in the body. Computed tomography with radioactive isotopes includes SPECT and PET.

Most single-photon imaging is done with the isotope ^{99m}Tc, which has a half life of 6 h. It is produced as the decay product of ^{99}Mo. The latter's 67 h half life means it can be produced at a national facility and shipped to hospitals. The positron emitters used in PET have much shorter half lives. The one that is used almost universally is ^{18}F, with a half life of 110 min. It is made into ^{18}F deoxyglucose (^{18}FDG). Glucose is $C_6H_{12}O_6$. In the compound two-deoxyglucose (DG, $C_6H_{12}O_5$), an OH group in the glucose molecule is replaced by a hydrogen atom. Deoxyglucose enters the cell and starts down the metabolic pathway but gets trapped because the OH group is missing. Thus DG accumulates in cells with high metabolic activity. Another H can be replaced by ^{18}F to make ^{18}FDG, $C_6H_{11}FO_5$, which gets trapped at the same metabolic stage. Thus ^{18}FDG concentrates in regions of high metabolic activity, such as tumors. It was originally thought that each hospital would need its own cyclotron to produce the isotope, but it has proven feasible to have regional distribution centers that produce ^{18}F in a cyclotron by a (p,n) reaction on ^{18}O and then make and ship the ^{18}FDG.

58. **Principles of Nuclear Medicine**, 2nd ed., H. N. Wagner, Z. Szabo, and J. W. Buchanan (Saunders, Philadelphia, 1995). A classic book with an extensive discussion of physics and pharmacology—how radioactive isotopes are attached to organ-specific pharmaceuticals for diagnosis and treatment. (A)

59. **Physics in Nuclear Medicine**, 3rd ed., S. R. Cherry, J. A. Sorenson, and M. F. Phelps (Saunders, Philadelphia, 2003). This book emphasizes instrumentation. (E,I)

60. **Diagnostic Nuclear Medicine**, edited by M. P. Sandler, R. E. Coleman, J. A. Patton, F. J. Th. Wackers, and A. Gottschalk (Lippincott/Williams and Wilkins, Philadelphia, 2003). A book designed for residents containing a short description of scintillation cameras, SPECT and PET, with a great deal of material on imaging different organ systems. (E,I)

61. **Nuclear Medicine Physics: The Basics**, 6th ed., R. Chandra (Lippincott/Williams and Wilkins, Philadelphia, 2004). This book emphasizes physics and pharmacology. It does not have an extensive treatment of organ systems. (E,I)

62. **Physics and Radiobiology of Nuclear Medicine**, 3rd ed., G. B. Saha (Springer, New York, 2006). Designed for residents studying for their board exams. (E)

63. **Nuclear Medicine: The Requisites**, H. A. Ziessman, J. P. O'Malley, and J. H. Thrall (Mosby/Elsevier, Philadelphia, 2006). An up-to-date text for residents. A brief discussion of pharmaceuticals and apparatus is followed by details for different organ systems. (E,I)

64. "Review: Positron emission tomography," G. Muehllehner and J. S. Karp, Phys. Med. Biol. **51**(13), R117–R137 (2006). A detailed review of the history, detectors, and the uses of PET. (I)

65. "The uses of radiotracers in the life sciences," T. J. Ruth, Rep. Prog. Phys. **72**, Article 016701, 23 pp. (2009). A detailed discussion of radioisotopes used in medicine and other life sciences, including their production, SPECT and PET scanning, and as tracers. (E,I)

66. "Anniversary Paper: Nuclear Medicine: Fifty years and still counting," L. E. Williams, Med. Phys. **35**(7), 3020–3029 (2008). Reviews the history, present status, and possible future directions of nuclear medicine. (E,I)

See also Refs. 8, 13, 14, 20, 21, and 29.

Since the images obtained with nuclear medicine do not have the spatial resolution of x-ray images but provide information about function, one can obtain additional information by superimposing a PET image on a CT image. This is described in some of the nuclear-medicine texts and also in

67. **Nuclear Medicine and PET/CT: Technology and Techniques**, 6th ed., P. E. Christian and K. M. Waterstram-Rich (Mosby/Elsevier, St. Louis, 2007). This book is intended for technologists and residents. Half the book is devoted to the technology and techniques. It includes preparation of radiopharmaceuticals, patient care, classic gamma camera, SPECT and PET, and x-ray CT. (E,I)

E. Magnetic resonance imaging

Magnetic resonance imaging (MRI) has become one of the most versatile imaging methods in the clinician's arsenal. Nuclear magnetic resonance (NMR) depends on the precession of nuclear spins (often ^{1}H) about a strong static magnetic field. After a radio-frequency magnetic field excites the spins, they relax to their equilibrium position. The precession frequency and relaxation time constant depend sensitively on the spin's environment, which allows researchers to extract much information from NMR experiments. The addition of gradient magnetic fields allows imaging, where the spatial information is encoded in the frequency or phase of the spin precession. MRI provides high-resolution images without ionizing radiation.

In 2003, Paul C. Lauterbur and Peter Mansfield received the Nobel Prize in Physiology or Medicine for their discoveries concerning magnetic resonance imaging. The first two references are their Nobel Lectures.

68. "All science is interdisciplinary—From magnetic moments to molecules to men," P. C. Lauterbur, Nobel Lecture (2003). Available at ⟨nobelprize.org/nobel_prizes/medicine/laureates/2003/lauterbur-lecture.html⟩.

69. "Snap-shot MRI," P. Mansfield, Nobel Lecture (2003). Available at ⟨nobelprize.org/nobel_prizes/medicine/laureates/2003/mansfield-lecture.html⟩.

70. **MRI: From Picture to Proton**, 2nd ed., D. W. McRobbie, E. A. Moore, M. J. Graves, and M. R. Prince (Cambridge U. P., Cambridge, 2007). An introduction to MRI presented backward to the traditional order: Starting with clinical considerations and then working back to basic physics principles. (E, I)

71. **MRI Principles**, D. G. Mitchell and M. S. Cohen (Saunders, Philadelphia, 2004). A good introduction to MRI for radiologists. (I)

72. **Magnetic Resonance Imaging: Theory and Practice**, 2nd ed., M. T. Vlaardingerbroek and J. A. den Boer (Springer, Berlin, 2002). (I,A)

73. **Advanced Image Processing in Magnetic Resonance Imaging**, L. Landini, V. Positano, and M. F. Santarelli (CRC/Taylor & Francis, 2005). A comprehensive book. (A)

74. **Handbook of MRI Pulse Sequences**, M. A. Bernstein, K. F. King, and X.-H. J. Zhou (Elsevier Academic, Burlington, MA, 2004). 1000 pages on the physics of MRI and pulse sequences. (A)

75. **Principles of Magnetic Resonance Imaging: A Signal Processing Perspective**, Z.-P. Liang and P. C. Lauterbur (IEEE, New York, 2000). This text emphasizes signal processing more than physics, but it does analyze MRI from the point of view of its inventor, Paul Lauterbur. (A)

76. **Magnetic Resonance Imaging: Physical Principles and Sequence Design**, E. M. Haacke, R. W. Brown, M. R. Thompson, and R. Venkatesan (Wiley-Liss, New York, 1999). A widely respected textbook that covers the field in depth. (A)

Functional MRI (fMRI) has become a very important technique in magnetic resonance imaging. It detects changes in blood oxygenation to provide information on brain function as well as anatomy.

77. **Introduction to Functional Magnetic Resonance Imaging: Principles and Techniques**, R. B. Buxton (Cambridge U. P., Cambridge, 2001). (A)

78. "Brain magnetic resonance imaging with contrast dependent on blood oxygenation," S. Ogawa, T. M. Lee, A. R. Kay, and D. W. Tank, Proc. Natl. Acad. Sci. U.S.A. **87**, 9868–9872 (1990). One of the first papers about the blood oxygen level dependent (BOLD) technique for MRI contrast. (I)

79. "Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation," K. K. Kwong, J. W. Belliveau, D. A. Chesler, I. E. Goldberg, R. M. Weisskoff, B. P. Poncelet, D. N. Kennedy, B. E. Hoppel, M. S. Cohen, R. Turner, H. Cheng, T. J. Brady, and B. R. Rosen, Proc. Natl. Acad. Sci. U.S.A. **89**, 5675–5679 (1992). An early application of fMRI to human brain activity. (I)

Diffusion tensor imaging is another recent imaging method based on MRI. In anisotropic tissue, such as muscle or white matter in the brain, the technique uses magnetic-field gradients applied in different directions to determine the diffusion tensor. From this tensor one can obtain its trace, which supplies an orientation-independent measure of diffusion that is useful when imaging stroke. Alternatively, one can determine the principle axes of the tensor, which indicates the fiber direction and could be used to map fiber tracks in the brain.

80. "MR diffusion tensor spectroscopy and imaging," P. J. Basser, J. Mattiello, and D. LeBihan, Biophys. J. **66**, 259–267 (1994). A landmark paper in the development of diffusion tensor imaging. (I)

81. "Diffusion tensor imaging of cerebral white matter: A pictorial review of physics, fiber tract anatomy, and tumor imaging patterns," B. J. Jellison, A. S. Field, J. Medow, M. Lazar, M. S. Salamat, and A. L. Alexander, AJNR Am. J. Neuroradiol. **25**, 356–369 (2004). (I)

Large magnetic-field gradients are allowing magnetic resonance images with higher spatial resolution, creating the new field of MRI microscopy.

82. **Principles of Nuclear Magnetic Resonance Microscopy**, P. Callaghan (Oxford U. P., Oxford, 1994). (I)

83. "Contrast in NMR imaging and microscopy," Y. Xia, Concepts Magn. Reson. **8**, 205–225 (1996). (I)

Many other interesting applications of MRI have been developed.

84. "Magic angle effect in MRI of articular cartilage: A review," Y. Xia, Invest. Radiol. **35**, 602–621 (2000). Anisotropy of biological tissues can be measured using the magic-angle effect in MRI. When the line between two nuclei makes an angle of 55° to the main magnetic field, the interaction of the two dipoles is zero, reducing their tendency to dephase and thereby lengthening the $T2$ time constant. (I)

85. "Hyperpolarized xenon in NMR and MRI," A.-M. Oros and N. J. Shah, Phys. Med. Biol. **49**, R105–R153 (2004). MRI using hyperpolarized ^{129}Xe has several medical applications, including tracing movement of gas in the lungs. (I)

86. "Magnetic resonance imaging for ischemic heart disease," H. Sakuma, J. Magn. Reson Imaging **26**, 3–13 (2007). An overview of MRI applied to the heart, including the use of contrast agents such as gadolinium. (I)

87. "Clinical neuroimaging using arterial spin-labeled perfusion magnetic resonance imaging," R. L. Wolf and J. A. Detre, Neurotherapeutics **4**, 346–359 (2007). The method of arterial spin-labeling allows measurement of blood flow (perfusion), which is particularly valuable when imaging the brain. (I)

88. "Direct detection of neuronal activity with MRI: Fantasy, possibility, or reality?" P. A. Bandettini, N. Petridou, and J. Bodurka, Appl. Magn. Reson. **29**, 65–88 (2005). The question posed in the title of this paper has not been answered yet, but if biomagnetic fields could be used as the contrast agent in MRI, it would provide a whole new type of functional imaging. (I)

89. **Ultra High Field Magnetic Resonance Imaging**, P.-M. Robitaille and L. J. Berliner (Springer, New York, 2006). Many researchers are pushing for higher and higher magnetic-field strengths (e.g., 7 T) for use in MRI. (I,A)

90. "SQUID-detected magnetic resonance imaging in microtesla fields," J. Clarke, M. Hatridge, and M. Mössle, Annu. Rev. Biomed. Eng. **9**, 389–413 (2007). Some researchers are pushing for lower and lower magnetic-field strengths in MRI. (I)

VI. THERAPY

Radiation therapy is the greatest area of employment of medical physicists. The most common treatment beams are high energy photons; electrons or protons are also used at some centers. Brachytherapy uses radioactive sources that are implanted in tissue or placed in a body cavity to deliver ionizing radiation to the tumor. External beam therapy and brachytherapy are well covered in Resource Letter MPRT-1, Medical Physics in Radiation Therapy, Ref. 10, and in a classic text.

91. **The Physics of Radiation Therapy**, 4th ed., F. M. Khan (Lippincott/Williams and Wilkins, Philadelphia, 2009). (I)

Ultrasound is also used for therapy. At low intensities it is used for diathermy: Tissue heating by a few degrees to promote blood flow and healing. High-intensity focused ultrasound (HIFU) was first used in the 1950s to destroy deep-seated lesions by creating high temperatures at the focal region, but it did not catch on. Though there are still drawbacks, there has recently been a revival of interest that is described in Ref. 44 and the following articles. Ultrasound is also used for lithotripsy, the pulverization of kidney stones.

92. "High Intensity Focused Ultrasound: Past, present and future," G. ter Haar and C. Coussios, Int. J. Hyperthermia **23**(2), 85–87 (2007). This short review article provides a nice introduction to HIFU. It is the lead article for the March 2007 issue of *Int. J. Hyperthermia*, which is entirely devoted to HIFU. (E)

93. "A resurgence of therapeutic ultrasound—A 21st century phenomenon," G. ter Haar, Ultrasonics **48**(4), 233 (2008). This is the preface to an entire issue devoted to therapeutic ultrasound. (E)

94. "High-intensity focused ultrasound therapy: An overview for radiologists," Y.-S. Kim, H. Rhim, M. J. Choi, H. K. Lim, and D. Choi, Korean J. Radiol. **9**(4), 291–302 (2008). An extensive review article in a less accessible journal. (E,I)

VII. EFFECTS OF IONIZING RADIATION

Detailed information on the interaction of photons and charged particles is very important for designing x-ray and nuclear-medicine equipment and for understanding the dose to the patient. Cross sections, attenuation coefficients, and absorption coefficients for photons are available on the Web, as are stopping powers and ranges for electrons, positrons, and protons.

95. "Tables of x-ray mass attenuation coefficients and mass energy absorption coefficients 1 keV to 20 MeV for elements $Z=1$ to 92 and 48 additional substances of dosimetric interest," J. H. Hubbell and S. M. Seltzer, National Institute of Standards and Technology Report No. NISTIR 5632, 1996. Web version at ⟨physics.nist.gov/PhysRefData/XrayMassCoef/cover.html⟩. (I)

96. "Stopping powers for electrons and positrons," ICRU Report 37, International Commission on Radiation Units and Measurements, Bethesda, 1984. Available on the Web at ⟨physics.nist.gov/PhysRefData/Star/Text/contents.html⟩. (I)

97. "Stopping powers and ranges for protons and alpha particles," ICRU Report 49, International Commission on Radiation Units and Measurements, Bethesda, 1993. Available on the Web at ⟨physics.nist.gov/PhysRefData/Star/Text/contents.html⟩. (I)

The quantities used to describe the energy deposited in tissue or a detector are the energy transferred, the energy imparted, and the absorbed dose. The absorbed dose is measured in gray (Gy) or J kg^{-1}. The *equivalent dose* to a target organ multiplies the dose by a dimensionless weighting factor that takes into account the relative biological effectiveness of the radiation on that organ. For photons and electrons, the weighting factor is one. The *effective dose* takes into account the amount of radiation received by all organs. Both the equivalent and effective doses are measured in sievert (Sv). The details are described in Refs. 13 and 20, as well as in

98. **Introduction to Radiological Physics and Radiation Dosimetry**, F. H. Attix (Wiley-Interscience, New York, 1986). This classic text is still in print (Wiley-VCH, Weinheim, 2004). The first third describes radiation interactions; the rest discusses dosimetry. (I,A)

99. **Photon Interactions: A Simulation Study with MacDose**, R. K. Hobbie (University of Minnesota Media Resources, Minneapolis, 1991) is a 26 min QUICKTIME movie that uses simulations to demonstrate photon interactions in water. It introduces the concepts of energy transferred and energy imparted and shows the importance of multiply-scattered photons. This movie is in the public domain and is available at ⟨www.tc.umn.edu/

~hobbie/MacDose%20Movie.mov⟩ and also on YouTube (www.youtube.com). (E,I)

100. "Educational treatise: Calculation of effective dose," C. H. McCollough and B. A. Schueler, Med. Phys. **27**(5), 828–837 (2000). (I,A)

Both the immediate effects such as skin reddening (erythema) and long-term effects (such as cancer) depend on the dose. This is discussed in Refs. 9, 10, 13, 14, 20, and 59, as well as in

101. **Radiobiology for the Radiologist**, 6th ed., E. J. Hall and A. J. Giaccia (Lippincott/Williams and Wilkins, Philadelphia, 2005). Describes how ionizing radiation affects cells. (I)

A great deal has been done over the years to reduce the dose from conventional x-ray procedures.

102. "Overview of patient dosimetry in diagnostic radiology in the USA for the past 50 years," W. Huda, E. L. Nickoloff, and J. M. Boone, Med. Phys. **35**(12), 5713–5728 (2008). Describes the significant reductions in dose for conventional radiography, fluoroscopy, and mammography and the changes in dose with the advent of multislice and spiral computed tomography. (I,A)

The dose in classic x-ray procedures ranges from <0.1 to 40 mSv for non-CT exams and 1–15 mSv for a CT exam (Ref. 108). The average U.S. background radiation from naturally occurring sources is about 3 mSv. Doses for cancer therapy are typically 20–80 Sv to the tumor.

Population doses have increased significantly with the increase in the number of CT procedures. These increases in exposure are documented in

103. "Ionizing radiation exposure of the population of the United States," NCRP Report 160, National Council on Radiation Protection, Washington, 2009. (I)

104. "Health risks from exposure to low levels of ionizing radiation, "BEIR Report VII, Committee on the Biological Effects of Ionizing Radiation, National Academy Press, Washington, D.C., 2005. (I,A)

105. "Computed Tomography—An increasing source of radiation exposure," D. J. Brenner and E. J. Hall, New Engl. J. Med. **357**(22), 2277–2284 (2007). The authors argue that about 62×10^6 CT scans were done in the United States in 2007, a 20-fold increase since 1980, and that one-third of these were not necessary. Doses are 15–20 mGy per scan in adults and are two to five times larger in children. They estimate that up to 2% of all cancers in the United States might be due to radiation from CT studies. (I)

106. "The AAPM Statement on Radiation Dose from Computed Tomography, in Response to the Brenner and Hall NEJM Article Published Nov. 29, 2007," on the web at ⟨www.aapm.org/publicgeneral/CTScans.asp⟩. The AAPM agrees that unnecessary CT scans should not be done, but AAPM is concerned that people may decline scans that are warranted. (E)

The Alliance for Radiation Safety in Pediatric Imaging recently initiated the "image gently" campaign to reduce radiation exposure to children (see ⟨www.imagegently.org⟩).

The issue is not yet decided. AAPM is also concerned about some of the assumptions made in Ref. 105, such as applying data from a single radiation dose to a population that has multiple lower doses. However, some of the higher CT doses are now larger than the lowest doses encountered in the atomic-bomb survivor studies.

Considering the following model will help the reader understand the issue. The probability p of acquiring a radiation-induced cancer is assumed to be proportional to the effective dose $H: p=\alpha H$, where α is determined from higher effective doses, often in studies of the atomic-bomb survivors. This is called the linear-no-threshold (LNT) model. Since p is usually small, the number of radiation-induced cancers in a population can be predicted using the binomial distribution. The mean number of cases m in a population N is $m=\alpha NH$. The product NH is widely used in radiation protection and is called the collective dose, expressed in person-Sv. The following example, simplified from p. 15 in Ref. 104, helps put this in perspective. Among 100 people, half men and half women, about 42 will be diagnosed with cancer during their lifetime, in the absence of any excess radiation. If they had all received a *whole-body* dose of 100 mSv (100 mGy of x rays or electrons), there could be one additional cancer in the group.

Even if the LNT model is correct, mitigation efforts are sometimes misdirected. For example, there has been concern about lung cancer from radon in houses. The following study considered the lung cancer risk from radon in Quebec. In a population of 60 000, a total of 109 lung cancer deaths is predicted. Mitigation to the recommended level of $<200\ \mathrm{Bq\ m^{-3}}$ would reduce this number from 109 to 105. The same number of lives would be saved by reducing smoking by 0.04%!

107. "Indoor exposure to ^{222}Rn: A public health perspective," P. Ayotte, B. Levesque, D. Gauvin, R. G. McGregor, R. Martel, S. Gingras, W. B. Walker, and E. G. Letourneau, Health Phys. **75**(3), 297–302 (1998). (I)

A detailed reference on the effects of ionizing radiation at low doses can be found in "Resource Letter EIRLD-1: Effects of ionizing radiation at low doses" (Ref. 9).

Helical CT and multislice systems have more complicated geometries that make it necessary to define new dose parameters.

108. "The measurement, reporting, and management of radiation dose in CT," Report of AAPM Task Group 23 of the Diagnostic Imaging Council CT Committee, American Association of Physicists in Medicine, College Park, MD, 2007. This report describes in detail the multidetector CT geometries of the major manufacturers and the additional parameters required to assess dose. (I)

The discipline of health physics is concerned with the health effects of radiation and other physical stimuli (such as lasers, ultrasound, and nonionizing electromagnetic fields), as well as ways to protect the public and workers in these fields. Many of the books listed above discuss radiation protection, but texts such as these provide more details.

109. Introduction to Health Physics, 4th ed., H. Cember and T. E. Johnson (McGraw-Hill Medical, New York, 2009). (E,I)

110. An Introduction to Radiation Protection in Medicine, J. V. Trapp and T. Kron (Taylor & Francis, New York, 2008). (E,I)

VIII. OTHER MEDICAL PHYSICS AND BIOMEDICAL ENGINEERING AREAS

In the past 20 years, biomedical engineering has blossomed into a unique discipline with its own textbooks, academic departments, and even its own institute (the National Institute of Biomedical Imaging and Bioengineering) in the National Institutes of Health. The field is broad, and in this Resource Letter we focus on a few topics that highlight the application of physics to medicine.

111. Introduction to Biomedical Engineering, 2nd ed., J. Enderle, S. Blanchard, and J. D. Bronzino (Elsevier, Burlington, MA, 2005). One of the standard textbooks in biomedical engineering. (I)

112. Medical Physics and Biomedical Engineering, B. H. Brown, R. H. Smallwood, D. C. Barber, P. V. Lawford, and D. R. Hose (Institute of Physics, Bristol, Philadelphia, 1999). (I)

113. The Biomedical Engineering Handbook, 3rd ed., edited by J. D. Bronzino (CRC, Boca Raton, 2006). Comprehensive multi-author handbook in three volumes. (I,A)

114. Encyclopedia of Medical Devices and Instrumentation, 2nd ed., edited by J. G. Webster (Wiley, Hoboken, NJ, 2006). A recently updated six-volume encyclopedia (over 3500 total pages) with articles about most medical devices and instruments. (I)

A. Electrical signals from the body

Bioelectricity is a large and growing field. Several good textbooks are the following:

115. Bioelectricity: A Quantitative Approach, 3rd ed., R. Plonsey and R. C. Barr (Springer, New York, 2007). (I,A)

116. Bioelectricity and Biomagnetism, R. M. Gulrajani (Wiley, New York, 1998). (A)

117. Bioelectromagnetism, J. Malmivuo and R. Plonsey (Oxford U. P., Oxford, 1995). (A)

One important application of bioelectricity is electroencephalography (EEG), which measures the electric field of the brain.

118. Electric Fields of the Brain: The Neurophysics of EEG, 2nd ed., P. L. Nunez and R. Srinivasan (Oxford U. P., Oxford, 2005). (I)

119. "The impact of EEG/MEG signal processing and modeling in the diagnosis and management of epilepsy," F. H. Lopes da Silva, IEEE Rev. Biomed. Eng. **1**, 143–156 (2008). One of the most important applications of EEG is the study of epilepsy. (A)

Often clinically useful information can be gained by measuring the electrical conductivity of tissue.

120. Electrical Impedance Tomography: Methods, History and Applications, edited by D. S. Holder (IOP, Bristol, 2005). Overview of a growing field including recent developments such as magnetic resonance electrical impedance tomography (a combination of electrical impedance tomography and measurement of currents using MRI) and magnetic-induction tomography (a technique to image conductivity by inducing eddy currents and measuring the magnetic field they produce). (A)

121. "Electrical impedance tomography," M. Cheney, D. Isaacson D, and J. C. Newell, SIAM Review **41**, 85–101 (1999). (A)

B. Magnetic signals from the body

SQUID magnetometers can detect the magnetic fields arising from the body.

122. Biomagnetism: Interdisciplinary Research and Exploration, The Proceedings of the 16th International Conference on Biomagnetism, edited by R. Kakigi, K. Yokosawa, and S. Kuriki (Hokkaido, Sapporo, Japan, 2008). This biennial conference is the primary meeting in the field of biomagnetism. The proceedings of earlier conferences are also useful. (A)

123. "Magnetoencephalography: Theory, instrumentation, and applications to noninvasive studies of the working human brain," M. Hamalainen, R. Hari, R. J. Ilmoniemi, J. Knuutila, and O. V. Lounasmaa, Rev. Mod. Phys. **65**, 413–497 (1993). Excellent, although somewhat dated, review of magnetoencephalography (MEG). (I)

124. "Applications of magnetic nanoparticles in biomedicine," Q. A. Pankhurst, J. Connolly, S. K. Jones, and J. Dobson, J. Phys. D: Appl. Phys. **36**, R167–R181 (2003). Tiny magnets are now being used for many applications, including magnetic cell separation, drug delivery, hyperthermia, and MRI. (I)

Electromagnetic induction can be used to excite neurons in the brain, a method called transcranial magnetic stimulation.

125. Oxford Handbook of Transcranial Stimulation, E. Wassermann, C. Epstein, and U. Ziemann (Oxford U. P., Oxford, 2008). Comprehensive review with contributions from many leaders in the field. (A)

126. Transcranial Magnetic Stimulation: A Neurochronometrics of Mind, V. Walsh and A. Pascual-Leone (MIT, Cambridge, MA, 2003). Describes the use of magnetic stimulation in cognitive neuroscience. (I)

C. Pacemakers and defibrillators

The cardiac pacemaker/defibrillator is one of the triumphs of biomedical engineering.

127. Cardiac Pacemakers Step by Step: An Illustrated Guide, S. S. Barold, R. X. Stroobandt, and A. F. Sinnaeve (Wiley-Blackwell, Malden, MA, 2004). Introduction to pacemakers written "for beginners equipped with only a rudimentary knowledge of electrocardiography and no knowledge of cardiac pacing whatsoever." (E)

128. **A Practical Guide to Cardiac Pacing**, 6th ed., H. W. Moses and J. C. Mullin (Lippincott/Williams and Wilkins, Philadelphia, 2007). An often-updated guide for physicians. (A)

129. **Machines in our Hearts: The Cardiac Pacemaker, the Implantable Defibrillator, and American Health Care**, K. Jeffrey (Johns Hopkins U. P., Baltimore, 2001). Provides an excellent introduction to the history and development of this important industry. (I)

A discussion of the electrical properties of cardiac tissue, including the formation of "spiral waves" and other arrhythmias, can be found in

130. **Cardiac Electrophysiology: From Cell to Bedside**, 5th ed., edited by D. P. Zipes and J. Jalife (Saunders, Philadelphia, 2009). Standard reference for the electrical properties of the heart in general. Updated about every 5 years. (A)

131. **The Geometry of Biological Time**, 2nd ed., A. T. Winfree (Springer, New York, 2001). The late Art Winfree wrote this classic. The second edition has an expanded section on the electrical behavior of the heart from the perspective of a mathematical biologist. (A)

132. **Cardiac Bioelectric Therapy: Mechanisms and Practical Implications**, edited by I. R. Efimov, M. W. Kroll, and P. J. Tchou (Springer, Boston, 2009). This collection contains chapters by most of the leaders in the field from an experimental and theoretical rather than clinical point of view. (A)

133. "Introduction: Mapping and control of complex cardiac arrhythmias," D. J. Christini and L. Glass, Chaos **12**, 732–739 (2002). Introduces a Focus Issue of the journal Chaos dedicated to cardiac electrophysiology, which includes papers by many of the leading researchers in this field. (A)

134. "Integrative models of the heart: Achievements and Limitations," P. J. Hunter, P. Kohl, and D. Noble, Philos. Trans. R. Soc. London, Ser. A **359**, 1049–1054 (2001). The introduction to a theme issue of the Philosophical Transactions of the Royal Society about the integrated heart. It contains papers by leading researchers about cardiac electrophysiology and mechanics. (A)

D. Other effects of electric and magnetic fields

135. "Neural stimulation and recording electrodes," S. F. Cogan, Annu. Rev. Biomed. Eng. **10**, 275–309 (2008). (I)

136. "An introduction to medical imaging with coherent terahertz-frequency radiation," A. J. Fitzgerald, E. Berry, N. N. Zinovev, G. C. Walker, M. A. Smith, and J. M. Chamberlain, Phys. Med. Biol. **47**, R67–R84. (2002)

Radiofrequency ablation is particularly important in treating some heart disorders.

137. **Catheter Ablation of Cardiac Arrhythmias**, edited by S. K. S. Huang and M. A. Wood (Elsevier, Philadelphia, 2006). (A)

138. "Theoretical modeling for radiofrequency ablation: State-of-the-art and challenges for the future," E. J. Berjano, Biomed. Eng. Online Vol. 5, article number 24 (April 2006), ⟨www.biomedical-engineering-online.com/content/5/1/24⟩. (I)

There is much debate, at least in the popular press, about possible health risks of low-frequency (nonionizing) electromagnetic fields produced by power lines and cell phones.

139. "Point/Counterpoint: There is currently enough evidence and technology available to warrant taking immediate steps to reduce exposure of consumers to cell-phone-related electromagnetic radiation," V. G. Khurana, J. E. Moulder, and C. G. Orton (moderator), Med. Phys. **35**(12), 5203–5206 (2008). (E)

140. "Static and low-frequency magnetic field effects: Health risks and therapies," R. K. Adair, Rep. Prog. Phys. **63**, 415–454 (2000). (I)

141. "Power frequency electromagnetic fields and health. Where's the evidence?," A. W. Preece, J. W. Hand, R. N. Clarke, and A. Stewart, Phys. Med. Biol. **45**, R139–R154 (2000). (I)

142. "Biophysical limits on athermal effects of RF and microwave radiation," R. K. Adair, Bioelectromagnetics (N.Y.) **24**(1), 39–48 (2003). Review. (I)

143. "Modeling the interaction of electromagnetic fields (10 MHz–10 GHz) with the human body: Methods and applications," J. W. Hand, Phys. Med. Biol. **53**, R243–R286 (2008). Explains how E&M fields in the body are calculated. (A)

E. Prostheses and other medical devices

A wide variety of prosthetic devices is available, including artificial organs.

144. "Cochlear implants: System design, integration, and evaluation," F.-G. Zeng, S. Rebscher, W. Harrison, X. Sun, and H. Feng, IEEE Rev. Biomed. Eng. **1**, 115–142 (2008). Cochlear implants stimulate the auditory nerve to restore hearing. (A)

145. "Retinal prosthesis," J. D. Weiland and M. S. Humayun, Annu. Rev. Biomed. Eng. **7**, 361–401 (2005). Retinal prostheses stimulate the optic nerve to restore vision. (A)

146. "Functional electrical stimulation for neuromuscular applications," P. H. Peckham and J. S. Knutson, Phys. Med. Biol. **47**, R67–R84 (2005). Functional electrical stimulation restores muscle movement, aiding in a variety of functions including walking. (A)

147. "Deep brain stimulation," J. S. Perlmutter and J. W. Mink, Annu. Rev. Neurosci. **29**, 229–257 (2006). Deep-brain stimulation is used to treat some brain disorders, such as Parkinson's disease. (A)

148. "The medical physics of ventricular assist devices," H. G. Wood, A. L. Throckmorton, A. Untaroiu, and X. Song, Rep. Prog. Phys. **68**, 545–576 (2005). An important device to assist the heart in pumping blood. (I)

149. "Developments towards an artificial kidney," W. H. Fissell, Expert Review of Medical Devices **3**, 155–165 (2006). (I)

F. Lasers and optics

Lasers have introduced many medical applications of light, from infrared to the visible spectrum to ultraviolet.

150. **Lasers in Medicine**, edited by R. W. Waynant (CRC, Boca Raton, 2002). (I)

151. **Laser-Tissue Interactions: Fundamentals and Applications**, M. H. Niemz (Springer, Berlin, 2007). (I)

152. "Lasers in medicine," Q. Peng, A. Juzeniene, J. Chen, L. O. Svaasand, T. Warloe, K.-E. Giercksky, and J. Moan, Rep. Prog. Phys. **71**, Article 056701, 28 pages (2008). (A)

A fascinating and fast-growing new technique to image biological tissue is optical coherence tomography (OCT). It uses reflections like ultrasound but detects the reflected rays using interferometry.

153. **Optical Coherence Tomography**, M. E. Brezinski (Elsevier, Amsterdam, 2006). Overview of the physics of OCT and applications to cardiovascular medicine, musculoskeletal disease, and oncology. (I)

154. "Optical coherence tomography: Principles and applications," A. F. Fercher, W. Drexler, C. K. Hitzenberger, and T. Lasser, Rep. Prog. Phys. **66**, 239–303 (2003). (I)

With infrared light, scattering dominates over absorption. In this case, light diffuses through the tissue. Optical imaging in turbid media is difficult but not impossible.

155. "Recent advances in diffuse optical imaging," A. P. Gibson, J. C. Hebden, and S. R. Arridge, Phys. Med. Biol. **50**, R1–R43 (2005). (I)

156. "Pulse oximetry," R. C. N. McMorrow and M. G. Mythen, Current Opinion in Critical Care **12**, 269–271 (2006). The pulse oximeter measures the oxygenation of blood and is based on the diffusion of infrared light. (I)

One impetus for medical applications of light has been the development of new light sources, such as free-electron lasers and synchrotrons. In both cases, the light frequency is tunable over a wide range.

157. "Free-electron-laser-based biophysical and biomedical instrumentation," G. S. Edwards, R. H. Austin, F. E. Carroll, M. L. Copeland, M. E. Couprie, W. E. Gabella, R. F. Haglund, B. A. Hooper, M. S. Hutson, E. D. Jansen, K. M. Joos, D. P. Kiehart, I. Lindau, J. Miao, H. S. Pratisto, J. H. Shen, Y. Tokutake, A. F. G. van der Meer, and A. Xie, Rev. Sci. Instrum. **74**, 3207–3245 (2003). (I)

158. "Medical applications of synchrotron radiation," P. Suortti and W. Thomlinson, Phys. Med. Biol. **48**, R1–R35 (2003). (I)

Finally, photodynamic therapy uses light-activated drugs to treat diseases.

159. "The physics, biophysics and technology of photodynamic therapy," B. C. Wilson and M. S. Patterson, Phys. Med. Biol. **53**, R61–R109 (2008). (A)

G. Elemental analysis and mass spectrometry

Sometimes, important medical information can be obtained if you can learn what molecules or elements are present. Mass spectrometry is used in medicine to identify molecules, although the method is destructive. X-ray fluorescence allows elemental identification with high spatial resolution, often taking advantage of synchrotron x-ray sources.

160. **Medical Applications of Mass Spectrometry**, edited by K. Vekey, A. Telekes, and A. Vertes (Elsevier, Amsterdam, 2008). (A)

161. "X-ray fluorescence microprobe imaging in biology and medicine," T. Paunesku, S. Vogt, J. Maser, B. Lai, and G. Woloschak, J. Cell Biochem. **99**, 1489–1502 (2006). (A)

162. **Breath Analysis for Clinical Diagnosis and Therapeutic Monitoring**, edited by A. Amann and D. Smith (World Scientific, Hackensack, NJ, 2005). Identification of molecules in a patient's breath, using a variety of methods, can be surprisingly important for the diagnosis of some diseases. (I)

H. Miscellaneous

Finally, there is much abuse of physics that goes under the name of "alternative medicine." For a skeptical point of view by a physicist, see the following:

163. **Voodoo Science: The Road from Foolishness to Fraud**, R. L. Park (Oxford U. P., New York, 2000). (E)

164. "Alternative medicine and the laws of physics," R. L. Park, Skeptical Inquirer **21**, 24–28 (1997). (E)

ACKNOWLEDGMENTS

We thank S. R. Ratliff, J. Zagzebski, W. R. Smith, and T. M. Miller for very helpful discussions.