1994

# Teaching medical physics to general audiences

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ABSTRACT By judiciously selecting topics and reading materials, one can teach a full semester course on medical physics appropriate for college students not majoring in the natural sciences. This interdisciplinary field offers an opportunity to teach a great deal of basic physics at the freshman level in the context of explaining modern medical technologies such as ultrasound imaging, laser surgery, and positron emission tomography. This article describes one such course which combines lectures, outside visitors, varied readings, and laboratories to convey a select subset of physical principles and quantitative problem solving skills. These resources are also valuable for enriching the standard freshman physics sequence for premedical students.

## INTRODUCTION

At a time when science and technology often dominate discussions of national policy, a large segment of our citizenry remains largely apprehensive of, and untutored in, the natural sciences. This generally accepted observation has led the government to target the science education of the general public as an important national goal. At the college level, physics courses seeking to achieve this goal have traditionally fallen into two categories: either they are a condensation of the traditional two semester freshman physics sequence, often with a review of twentieth century physics included, or they use a particular technology, such as energy consumption and production, as an organizing principle. This article describes one of a small number of courses which take an approach related to the latter: using interdisciplinary science, in this case medical physics, to attract a broad audience and to motivate students to learn a clearly defined subset of quantitative reasoning skills and introductory physics. Medical technology was selected in part because it has as much appeal for today's youth as space exploration had for an earlier generation, while providing a natural format for teaching much important and fundamental physics in detail. For this reason, these subjects are also very natural candidates for inclusion into the standard two-semester freshman physics sequence for premedical students.

The author has taught such a course for two years at Haverford College, a small liberal arts college in southeastern Pennsylvania. This course grew from exposure to two existing successful efforts along related lines. Both are out growths of the Sloan Foundation's New Liberal Arts (NLA) program. Theodore Ducas teaches a course in medical decision-making at Wellesley College using ethical issues surrounding fetal ultrasound imaging as a paradigm. His students perform physics labs in sound while studying both the science and moral aspects of the technology (Ducas et al., 1987). John Brockway teaches a related seminar course on Bioengineering and Health Technology at Davidson College, covering many of the topics discussed here (Brockway, 1989). The NLA program has also promoted the publication of reading materials useful for someone organizing such a course; these will be surveyed later in this article.

The Haverford course proceeds by examining the manifold ways modern medicine employs technology in the diagnosis and treatment of disease. In particular, students learn about the basic physics and specific implementation behind diagnostic ultrasound, laser surgery, medical fiber optic scopes, radiology, nuclear medicine, and tomographic imaging. To understand the applications, students first learn about the physics of sound and the Doppler effect (for ultrasound), light and geometrical optics (for fiber optics scopes and laser surgery), and elementary nuclear physics (for nuclear medicine). The course is taught from a combination of Scientific American articles, readings from selected texts, and an extensive set of lecture notes, which will eventually be developed into an introductory text. While the audience for this course is predominantly (over three-quarters) humanities and social science students, a sizable number of premedical students have also enrolled. The enrollments have been roughly evenly divided between male and female students. Strongly positive responses from the students in the course have shown that the attractions of the subject material encouraged many students to overcome their apprehension of learning physics, to begin to read popular science articles, and to take more advanced science courses.

The course discussed herein must be distinguished clearly from advanced undergraduate medical physics and bioengineering courses appropriate for a junior or senior either majoring in physics or planning to go on in biomedical science. Successful versions of such courses are in place at many institutions, and there exist several texts suitable in level and content (Hobbie, 1988; Bronzino, 1986). Rather, the courses taught by Ducas, Brockway, and myself address an audience of students not majoring in the natural sciences. These courses assume no background in calculus, but they do assume significant motivation to learn science and a willingness to tackle quantitative problem solving in an interdisciplinary context.

## COURSE ORGANIZATION

A perpetual problem with introductory physics courses has been the difficulty in giving students a genuine flavor of the methodology and practice of science while teaching them concepts truly within their grasp. The degree to which most students enjoy introductory biology and, perhaps to a lesser extent, chemistry derives in part from this satisfaction at being able to really understand at least some aspects of present research. Medical physics appears at first to be equally out of reach of the average student. However, many aspects of laser surgery and fiber optic scopes covered in standard laser surgery texts derive from freshman-level geometrical optics, and ultrasound imaging relies on a basic treatment of wave phenomena. Computed tomography (CT) and positron emission tomography (PET) are easier to understand than magnetic resonance imaging (MRI) and can serve as a launching point for an introduction to that technique. The basic physics being taught should be limited in scope to relatively few topics, allowing these to be explored in depth. This emphasis on intensive coverage of a limited range of physical principles using applications to place them in context is consistent with new approaches to teaching introductory physics courses emphasized in the Introductory University Physics Project (IUPP) programs (Rigden et al., 1993). This combination of delivering on what students expect (e.g., knowing exactly how laparoscopes work), while covering a few concepts in depth, also helps avoid the superficiality which can afflict science courses for general audiences.

The course was structured as a standard series of lectures, supplemented with occasional discussion sections, and a laboratory or outside visitor about every other week. Students were responsible for roughly seven problem sets, one per major topic, a short paper, two exams, and brief lab reports. The major topics covered were:

- Fiber optic scopes
  Reflection and refraction, index of refraction, Snell's law, total internal reflection, fiber optics as waveguides, image conduits made with fiber optics, focusing of collimated light with a lens.
  *Applications:* Medical fiber optic scopes: their construction, fiber size, image resolution, coherent versus incoherent bundles, use with CCD cameras, various different types of scopes and their uses, mechanical attachments.
- Laser surgery and photodynamic therapy
  Wave properties of light, frequency and wavelength, photon energy, the electromagnetic spectrum, power, absorption spectra of simple atoms and biological molecules, relation to color of tissues, examples: water, hemoglobin, melanin, visual pigments, simple atomic theory, emission spectra of atoms, electronic excitations, discreteness of photon energies emitted or absorbed; operation of lasers, spontaneous versus stimulated emission, optical resonators, temporal and spatial coherence, comparison with other light sources.
  *Applications:* Photocoagulation versus photovaporization in laser surgery, selection of laser intensity and spot size to give appropriate power density, CW versus pulsed lasers and heat transfer issues; matching laser wavelength to tissue absorption spectra.
- Ultrasound imaging and Doppler flow echocardiography Sound waves, frequency and wavelength of audible and ultrasound, speed of sound, acoustic impedance, reflection of sound waves from interfaces, measuring distances using echo ranging, the attenuation of sound waves and its dependence on distance and frequency, ultrasound transducers, focusing and diffraction of sound in tissue, construction of images using ultrasound echoes, spatial resolution issues, artifacts, the Doppler effect, Doppler flow measurements.
  *Applications:* Obstetrical ultrasound imaging, Doppler echocardiography.
- Radiography and radionuclide imaging
  X-ray energies and wavelengths, interaction of x-rays with matter, dependence of their absorption upon mass absorption coefficient and relevant values in the body, shielding of x-rays, contrast, noise, and spatial resolution issues, radiographs as projections, detectors and sources for medicine, contrast media.
- Radioactivity and the biological effects of ionizing radiation
  Nuclear structure, isotopes, radioactivity, types of decay products, half lives; source activity, exposure, absorbed dose, relative biological effect, genetic damage mechanisms, carcinogenesis, evaluation of safe levels.
- Radiation therapy
  Non-stochastic versus stochastic damage, dose-effect curves, designing therapies and characteristic values for doses, types of radiation used, methods for minimizing damage to normal tissues, interaction with chemotherapy.
- PET, CT, and MRI scanners
  Tomographic imaging versus projections, positron-electron annihilation, production of gamma rays, energy and momentum conservation, relativistic relations between mass and energy, contrast media.
  *Applications*: psychiatric uses of PET, various applications for CT scanners, comparisons of the various tomographic imaging methods.

One can easily imagine substituting other topics, such as pacemakers, electrophysiology, or prosthetic implants. However, the coverage should be quite restricted, since there is a great deal of background necessary to introduce each new subject. In particular, one must be careful to weave into the discussion the necessary general scientific concepts used throughout the course. These include an early discussion of the definition of energy, temperature, heat, electromagnetic waves, and various other fundamental physics concepts. The students will also need the sort of simple treatment of atomic physics and radiation generally offered in introductory courses. One pitfall to avoid is making too clear a clear demarcation between basic physics and applications (sound waves this week, fetal ultrasound the next.) By a careful selection of coverage and demonstrations, one can instead interweave these two threads very closely, preventing students from tuning out in a predictable way.

The lectures which have worked best at Haverford were filled with inexpensive demonstrations, either homemade (Ehrlich, 1990; Exploratorium, 1991) or available from either Pasco Scientific (Roseville, CA), Edmund Scientific (Barrington, NJ), or Central Scientific (Franklin Park, IL). The student audience for such a course will generally lack direct experience of the physical principles being discussed, so they have little intuition to draw upon in understanding how a lens works, how heat flows, etc. Thus very easy-to-understand demonstrations, some even simple enough to pass around the class, are the best. These include using a laser and air-water interface to demonstrate refraction and total internal reflection; demonstrating various fiber optic phenomena using commercially available large waveguides, fiber optic strands, image conduits and boroscopes (an inexpensive fiber optic inspection scope); teaching about wavelength and frequency, reflections from interfaces and impedance matching using mechanical wave demonstrators; using a buzzer twirled on a string to demonstrate the Doppler effect; using a liquid crystal thermal panel to show the heating due to a focused helium neon laser beam; and many others. With a more appreciable investment, one now can buy inexpensive detectors to be used with Macintosh computers along with supporting software which will allow more elaborate demonstrations (Vernier Software, Portland, OR). These include ultrasound ranging devices for measuring distances and radiation detectors which can be used to measure half lives of short-lived isotopes, among others.

The Haverford course has been enlivened by several guest lecturers, including Dr. David Rose of Bryn Mawr Hospital, who spoke about his experiences with laparoscopic surgery, Michael Cannon of Interspec Corporation, who demonstrated cardiac ultrasound imaging while discussing the medical devices industry, and John Fielding of Villanova University, a medical ethicist, who spoke about approaches to responsibly evaluating and using medical technology. The students always enjoyed these outside visitors and were especially interested in hearing a variety of perspectives. Many colleges or universities are close to medical centers or industries which can provide suitable guest lecturers or sites for field trips. In lieu of actual expert visitors, many manufacturers are willing to send promotional literature with excellent illustrations, sample devices in some cases, and videotapes demonstrating their techniques.

## READING MATERIAL

The greatest challenge in putting together such a course is locating adequate readings to accompany each topic. While some freshman physics texts do successfully cover the standard freshman physics curriculum while interleaving applications to biology and medicine, as is done in the excellent *General Physics* (Sternheim and Kane, 1991), what is desired in this type of course is a less mathematical treatment which focuses specifically on only those topics of interest. Working with the NLA program, John Brockway has published an extended syllabus for his course on Bioengineering and Health Technology, and a useful bibliography on the subject, available from the NLA program (Brockway, 1989). The NLA program has sponsored several other helpful publications, including an undergraduate text on economic and ethical issues in health technology, Medical Technology and Society (Bronzino et al., 1990) and a monograph on pacemakers, Pacing the Heart (Jeffrey, 1990). However, the main focus of these works is not on the science, though each presents brief treatments of the technologies studied. Closer to the mark are many Scientific American articles (Berns, 1991; Devey and Wells, 1978; Katzir, 1989; Gordon et al., 1975; Pyket, 1982; Ter-Pogossian et al., 1980; Upton, 1982). *General Physics* (Sternheim and Kane, 1991) includes an extensive bibliographic guide to this resource. There is at least one good article for every main subject heading, and most are simple enough to be understandable by the student audience. However, while these articles serve as excellent introductions to the material once the students have mastered the basic physics, they are inadequate as a sole resource and should be supplemented with another text.

Of course, there are many excellent advanced texts which provide the instructor with comprehensive treatments of the medical physics at a graduate level, such as (Bronzino, 1986; Hobbie, 1988; Webb, 1992; Williams and Thwaites, 1993). In addition, many medical texts on, for example, laser surgery, diagnostic ultrasound, or radiation therapy, will often include introductory chapters written on the basic physics of each technique, as is the case in Baggish (1985); Cotton and Williams (1990); Kremkau (1989); McLaughlin (1991); and Sanders and Smith Miner (1991). While these treatments are often written at an appropriate level for the course, and make excellent reserved readings with their explanation of clinical uses of the technologies and extensive illustrations, the expense of purchasing multiple medical textbooks is beyond the means of most undergraduates.

The lecture notes for the Haverford course presently cover all of the main topics listed above and are distributed to our students in a photocopied packet at cost. They are explicitly meant to be a substitute text for this type of course, with self-contained treatments of the physics and applications. Students who were already intimidated by the thought of taking a natural science course were especially emphatic about their preference for this type of reliable, central text. This need for "tightly organized text materials" designed specifically for introductory courses was noted as a major determinant of success by the IUPP (Rigden et al., 1993). The textbook which has evolved from these lecture notes and homework problems will be published by Gordon and Breach, Publishers, under the title *Inner Vision: The Physics of Medical Technology*.

## PROBLEMS FOR ASSIGNMENTS AND EXAMS

The problems supplied with the other curricular materials are meant to address the absence of textbook support for assignments. They are designed to require a combination of quantitative reasoning, interpretation of graphs, estimation, practical tradeoffs, and comparisons of related technologies. Wherever possible, the parameters are drawn from realworld situations. The math skills used are limited to algebra, some simple trigonometry, dimensional analysis, estimation, and simple graphical analysis. For example, the following problems form part of the ultrasound assignments.

Students were given the frequencies used for cardiac or abdominal ultrasound imaging, where the pulses must penetrate distances of many centimeters, and the relationship between frequency and the depth within soft tissue where the ultrasound pulse has been attenuated by a certain fraction. They were then asked to use this information along with measurements they made upon the body to find appropriate values for ultrasound examination of the eye. They were provided with anatomical drawings of the eye and asked to estimate the dimensions of various features themselves. Then, they were asked to explain which structures could be distinguished in such examinations using the limit on spatial resolution imposed by the selection of the wavelength.

In solving these problems, the students were forced to deal with the idea that, rather than there being a single correct frequency at which to perform ultrasound, the solution represented a range of correct values. Thus, by selecting higher frequencies, one can improve the spatial resolution of the image at the expense of limiting the depth inside the body to which images can be formed. In a later live cardiac ultrasound imaging demonstration, they were able to see these tradeoffs at work as the guest lecturer adjusted the frequency to suit different applications: a low frequency for imaging of the heart within the chest versus higher frequencies for imaging of the much smaller carotid artery.

In another example, students use the Fresnel formula for reflection of sound from an interface between tissues with differing acoustic impedances to compute the percentage of an ultrasound wave's intensity reflected from various interfaces between soft tissues, bone, air, and water. Students then are asked to use their calculations to explain why sonographers use a gel between the ultrasound transducer and the patient's skin (it results in impedance matching), and why ultrasound is not used to examine the brain (most of the ultrasound is reflected from the skull because of large acoustic impedance mismatches between skin and bone.) Related problems can easily be constructed for radiography or laser surgery, asking the student to explain, e.g., why lower energy x-rays can be used with mammography than for chest x-rays, or to select the combination of laser spot size and intensity which delivers the right control and type of damage for ophthalmological surgery.

Many of the problems involve reading and analyzing graphs. For example, students are asked to select the appropriate laser for surgery on a selection of tissues, an exercise which requires them to interpret absorption spectra, seeking to maximize absorption in the tissue to be operated upon while minimizing damage to nearby regions. In a similar vein, the x-ray energy for radiography or CT can be chosen to maximize or minimize the contrast due to differing tissue densities; one must understand the variation in the various tissues' mass absorption coefficients with energy to untangle this problem. Other exercises involve interpreting color Doppler flow maps in terms of the actual flow geometry. When combined with fairly standard problems on geometrical optics, light, sound waves, radiation, and other topics, these exercises, available along with the other curricular materials, present a well-rounded approach to the physics and applications.

## USING MEDICAL PHYSICS IN THE FRESHMAN PHYSICS CURRICULUM

The rapid pace of most freshman courses makes it difficult to include extensive and distinct bodies of new material. Consequently, in practice it is more effective to blend in the applications for which most of the preparation has already been supplied. For example, the treatment of light and geometrical optics from a standard course will be adequate to let students understand the operation of fiber optic scopes and most of the laser surgery topics, with the instructor deciding whether to expand upon the operation of lasers. Similarly, the ultrasound material can be included after the usual treatment of sound and waves. The information on the biological effects of radiation and therapeutic and diagnostic uses of radiation can be most gracefully included after a section on modern physics which includes rudimentary quantum mechanics, nuclear physics, and ionizing radiation. For a brief treatment of each of these topics, General Physics (Sternheim and Kane, 1991) is appropriate, especially when used alongside offprints of the Scientific American articles and the simple demonstrations described above.

## LABORATORIES

Ideally each unit of a medical physics general audience course would have an accompanying laboratory to introduce students to the basic physics behind each major topic of the course; labs on optics, lasers, sound, nuclear radiation, and simple electronic circuits would be natural candidates. Quantitative modeling and graphical analysis should be an important part of each unit, with provisions made in each case for preliminary, intuitive understanding of the data, exploring trends in measurements, and considering alternative explanations. At Haverford, we are working to put together a laboratory manual to accompany the course which will suit each lab experience to the applications studied. For example, the optics laboratories focuses on refraction, total internal reflection (for fiber optics), and focusing of collimated light, with plans for including the collection of absorption spectra of biological macromolecules. These are most effective when combined with additional lab experiences; for example, the first year's class witnessed how a laboratory Nd:YAG laser could "photovaporize" tissue at high power densities and "photocoagulate" tissue at lower values by looking at the effects of focusing the beam to different spot sizes on a tissue specimen (a thin steak). They then watched a videotape of laser surgery provided by an area surgeon. In the nuclear radiation lab, after making measurements of the half-lives of short-lived isotopes and determining the dependence of transmitted radiation with absorber thickness, students performed a survey of radiation levels across campus, carefully thinking about what statistics they needed to gather to make their results meaningful, and how to convert detector counts to meaningful units.

## CONCLUSION

The Physics of Medical Technologies project represents one of a growing number of responses to a serious concern: the scientific and technological education of college students who do not major in the natural sciences. Students respond favorably to the content and approach of this course, even though they find the subject quite challenging. The main drawback to teaching such a course is the present scarcity of appropriate texts, problems, and other resources. In addition to referring to the published materials mentioned here, interested readers may write for copies of the curricular materials developed for this purpose in the absence of a suitable textbook. Hopefully, with these resources available, starting up a similar course in a new location should be quite straightforward.

The support necessary for the development of this course was provided by the Undergraduate Biological Sciences Educational Initiative of the Howard Hughes Medical Institute and the National Science Foundation through its Course and Curriculum Development program, Grant DUE-9354422. Conversations with participants in the NLA program operated by John Truxal at the State University of New York at Stony Brook have been extremely helpful; I would especially mention Theodore Ducas and John Brockway in this context. Finally, this course has grown with much practical and philosophical help from various faculty who teach freshman physics and general audience science courses of all varieties, or work in interdisciplinary course development, including Peter Collings, Lany Gladney, Judith Owen, Lyle Roelofs, Stephanie Singer. and Jacqueline Tanaka.

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