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Medical physics: the perfect intermediate level physics class

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Abstract

Medical physics is currently a rapidly growing field of physics. Numerous academic, clinical and industrial opportunities are open to physicists in the medical world. I report on an intermediate level physics course on medical physics taught at Carleton College. The topics covered in this course cover all areas of physics, but with examples drawn from medical applications. In addition to physics majors, this course appeals to biology, chemistry and pre-medical students who have a keen interest in physics.

1. Introduction

Physics is changing the way medicine is practised. While a doctor will still use a stethoscope, a diagnosis now often requires devices that make use of sophisticated physics and engineering. The importance of physics in medicine may be best displayed when a physicist needs to visit their doctor: we seem to be the only people who can intimidate doctors as we are the ones who actually know how their devices work. As a consequence of the technological evolution of the discipline, medical schools are admitting more and more students who major in physics or engineering.

Almost all major engineering schools will now have a department of biomedical engineering. There are numerous opportunities in academia in medical physics and biomedical engineering. Students interested in becoming an academic physicist now have a fast-growing field to aim for, a field that is providing more and more opportunities. The industrial sector in biomedical engineering is also advancing and evolving quickly. Physicists and engineers can find numerous and lucrative opportunities with companies.

With all of these opportunities it is no wonder that undergraduates are very interested in knowing more about medical physics. Partly due to student interest, and partly due to the faculty's desire to provide interesting physics classes, Carleton College offered an intermediate level course in medical physics. This was a course open to students who have completed the first year physics courses. We deliberately designed the medical physics course so that the curriculum would be advanced, thereby negating the possibility that this course alone would satisfy a pre-medical school requirement. At this level we then attracted physics majors and pre-medical students who had a genuine interest in studying more physics.

Presented in this article is a summary of the course, a very successful course. Undergraduate physics programmes should consider instituting a medical physics class. There is no end to physics examples that one can draw from; this keeps student interest very high. The present level of activity in the field of medical physics and biomedical engineering does not go unnoticed by students; they want to know more about these interesting physics topics. Finally, this course covered all of the areas of physics that we would like our students to understand, with the physics illustrated with pertinent examples.

2. Motivation

The demise of the United States' effort to build the Superconducting Super-Collider left many physicists searching for something to do. Fortunately the experimental skills required to detect the Higg's boson are very similar to those needed to make an image of a person's interior. A decade ago physicists were searching for work. Today there is an intense need for physicists in the medical world. Medical imaging techniques require sophisticated physics.

In American tertiary institutions pre-medical students must take a curriculum that consists of biology, chemistry and a year of physics. Traditionally the physics courses have been the bane of the 'pre-meds'. However, it has always been the case that there are pre-med students who liked physics, but could find no appropriate course after the first year. As physics teachers it is always our desire to spread the excitement of our field to as many students as possible. A medical physics course is a nice interdisciplinary bridge to the other natural science subjects; by providing the bridge there is a return to physics. Interdisciplinary courses are important for a number of reasons, but we especially enjoyed attracting the biology student back to physics.

A number of physics undergraduates proceed to engineering upon receipt of the degree. Biomedical engineering is now an equal to electrical, mechanical, civil and chemical engineering. At Carleton College a number of our students are searching for a humane and beneficial application of their scientific training. It would be a disservice not to provide a path for students to a career in biomedical engineering. This was another motivation for the development of a medical physics course.

Some students seek to join the workforce immediately upon graduation. With a Bachelor's degree in physics a person will try to sell themselves as *just like an engineer—but better*. This approach works especially well for students approaching industrial firms specializing in biomedical engineering. Physics majors have a background that allows them to succeed with new and difficult topics. With a background in medical physics it is a bit easier to succeed.

3. Carleton's medical physics course

Carleton College's first course in medical physics was recently presented and comments by students and the instructor indicate that it was a success. This course lasted ten weeks, with three lectures (totalling 200 min) per week. Because the students were a mix of physics and biology majors it was critical that formal lecture time did not dominate, and discussion must be encouraged. The interchange between the physics and biology students was outstanding; the physicists brought their inherent expertise of their discipline, while the biologists contributed much needed information on physiology and chemistry. Due to the varied backgrounds of the students we tried to avoid detailed mathematical derivations and examinations, and concentrated on concepts, written and oral presentation. We did have weekly assignments that required mathematical derivations of the physics, but writing assignments designed to articulate the concepts covered were also required. The importance of communication skills in science should not be underemphasized, but that is a discussion topic for another day. In lieu of examinations, research papers and oral presentations were required.

We wanted to cover all of the fundamental areas of physics, hence we started with mechanics. By examining the human hip we covered topics such as force, torque and equilibrium conditions. The students were astounded to realize the force on the hip is about 2.5 times a person's body-weight. We then examined the reduction of this force by the use of a cane or through limping. The forces on the arms and back while a person lifts something were also examined. Another interesting topic is in minimizing injury through reducing force per area on a person; a good problem to consider is a car accident, and to make calculations based on whether or not there is an airbag to distribute the force and slow the acceleration of the person. Good examples of these problems can be found in the books by Hobbie [1] and Davidovits [2].

The next area was electricity and magnetism (E&M), which is an imperative subject for a number of medical physics topics. We started with the physics of signal transmission through the body's neurons. This brought in a number of important E&M topics, including charge, current, electric fields, the electric potential and RC circuit theory as applied to signal transmission. This subject is covered well by Hobbie [1] and Hallet *et al* [4]. Neuronal signal transmission evolves nicely to the subject of cellular stimulation in the heart. The flow of the electrical excitation of the heart introduces the concept of a dipole moment. The electrocardiogram (ECG) is then introduced, and through the physics the students can understand how this important medical diagnostic tool operates. A student, who is also an emergency medical technician, brought in an ECG unit, which provided a fantastic demonstration. With the ECG the concept of an electrical field, and the importance of observing and characterizing it, brought on a whole new importance for the students. The electrical system of the heart provided much discussion, and we spent some time on devices, such as defibrillators, that are used to stabilize the heart's electrical network.

We then ventured into thermodynamics, especially Boltzmann's law. The distribution of charge across the potential difference in and out of a neuron, provided the first example. The next application served as the pathway into the world of medical imaging, namely magnetic resonance imaging (MRI). The distribution of proton spins in a large magnetic field determines the net magnetization, which is proportional to the amplitude of the nuclear magnetic resonance signal. Alignment of proton spin also introduces quantum mechanics, and a discussion of how and when one would use a quantum or classical approach to the problem (magnetization in this case). The concept of a temperature is a necessary topic under the thermodynamic heading. Through a discussion of ideal gases one can use Boltzmann's law to derive the distribution of velocities and introduce pressure.

Medical imaging is a red-hot field, and one which every student is aware of and wants to know more about. We started with ultrasound. This introduced waves, their propagation, transmission and reflection characteristics. Wave motion is sometimes not covered adequately in first year physics, so the physics of sound propagation allowed us to rectify any wave deficiencies. The students truly wanted to understand all aspects of how ultrasonic imaging works, so we also covered topics such as the pressure and intensity of a sound wave, reflection and transmission angles at medium interfaces using Snell's law, and a discussion of electrical stimulation and signal detection as applied to a piezoelectric crystal. A detailed discussion of sound wave reflection at the interface of different mediums brought forward the concept of impedance. Finally, advanced ultrasound techniques introduced the Doppler shift, and how the velocity of something (in this case blood in the heart) could be measured. A visit to an ultrasound research group at the Mayo Clinic[1] allowed the students to observe this imaging modality at first hand.

Our next imaging subject, magnetic resonance imaging, covered an amazing array of physics topics. First we discussed the intrinsic spin of a proton or an entire nucleus. This required us to talk about how angular momentum is quantized with quantum mechanics, and a bit about nuclear physics and how protons and neutrons are assembled together. E&M returned with a discussion of how a large magnetic field can be created with a solenoid, plus a discussion on superconductors. In this context we discussed electric currents, resistance, power dissipation, plus how energy can be stored in a magnetic field. Thermodynamics and

[1] See web page: www.mayo.edu.

Boltzmann's law provided the ratio of proton spins with respect to the magnetic field direction, and then we derived magnetization of some material within the field. In order to describe MRI radiofrequency (RF) coils we needed to discuss inductor–capacitor circuits, and the concept of resonance in an electrical circuit. Armed with an RF coil we could now talk about the energy required to flip the spin of a proton, plus how one could use said coil to rotate the net magnetization. Torque then returned, along with the Larmor frequency of precession. With a rotating magnetic field one then can discuss Faraday's law of induction and how the MR signal is induced as an electro-motive force in the RF coil. The relaxation of the magnetization to alignment with the magnetic field (i.e. the T_1 time) and the dephasing of the spins (i.e. the T_2 time) brought in important physics concepts pertaining to bulk materials. The creation of an image via MRI requires spatial encoding using magnetic field gradients, and since the frequency and phase of the signal corresponds to a physical location, understanding the Fourier transform is required. The class visited an MRI laboratory at the University of Minnesota (web page: www.ciamr.umn.edu), and observed all aspects of the imaging process. One could model an entire course around just the physics of MRI; MRI accounted for about 20% of our total course time.

X-rays have been used for medical imaging for over a 100 years, and with three-dimensional (3D) images from computed tomography (CT) x-rays are still the workhorse of the imaging field. The generation of x-rays provided a discussion of energy conservation in the context of converting an electrical potential into kinetic energy of electrons. Relative absorption (attenuation) of x-rays for different materials was discussed. The methods used to detect x-rays introduced experimental methods that are similar to those used in high energy physics. We covered detection with film, scintillators and solid state detectors; demonstrations were provided with NaI crystals and a germanium detector. The mathematical techniques and algorithms needed to create a 3D image were only briefly covered. The use of contrast agents (such as iodine or barium) was covered; the physical reasons for enhanced absorption with these agents (back to nuclear physics) were given, and digital subtraction angiography of the vascular system provided a great example.

Positron emission tomography (PET) was covered briefly. This allowed a presentation of how radio-isotopes are produced in cyclotrons, and how β decay can lead to positron emission. The annihilation of e^+–e^- pairs brought up a good discussion of energy and momentum conservation within the framework of high-energy physics. Once the students understood how the anti-parallel 511 keV γ-ray pair was produced we concentrated on efficient detection techniques with scintillator crystals.

The field of classical optics was covered as we discussed the human eye. Snell's law reappeared, but this time applied to light. Lenses were studied, with the first direct examples being the air–cornea interface and the crystalline lens within the eye. Near and far-sightedness presented an excellent optics problem, with focusing solutions achieved through the appropriate negative or positive lens (i.e. vision correction with spectacles). A visit to a ophthalmologist allowed the class to see how the curvature of the cornea and the focusing ability of the eye can be measured and corrected.

The physics of hearing was another topic that the students very much enjoyed. We returned to sound waves, and the intensity range of sound that can be detected by humans. The *decibel* was introduced, and we discussed the incredible dynamic range that human hearing has. The transmission of the signal from the ear drum, through the ossicle bones into the cochlea was a fantastic example of impedance matching. The process by which hair cells within the cochlea detect motion and transduce them to a neuronal signal was presented. Sound detected by one set of hair cells feeds back positively to another set of hair cells, and displays a natural application of signal amplification.

3.1. Class field trips

The class was able to visit a few institutions, which allowed first-hand observation of medical physics in action. The visit to Medtronic Corporation (web page: www.medtronic.com) gave the class a unique look into the industrial side of biomedical engineering. Medtronic is a leader in the design and production of defibrillation units for the heart. These devices displayed engineering in medicine wonderfully. The complex electrical process of the heart must be understood, and appropriate electrical impulses sent into the heart when abnormal signals are detected. The complex interplay between engineering, medicine, business and ethics must be balanced before a product can be sold. The visit to this industrial biomedical centre displayed issues that were very different from what we typically encounter on an academic campus.

At the Department of Radiology at the University of Minnesota the students experienced MRI first hand. This was a hands-on visit where the students could see (and touch) the numerous components that go into creating an MR image. A head-coil was examined, and its resonance frequency was adjusted by the students. The large magnetic field of the superconducting solenoid was best displayed through eddy current production (and the resulting viscous force due to Lenz's law) in non-magnetic conductors. A student's brain was imaged, and all could observe the sequence of (spin echo) pulses that provided the data for the image. The T_1 and T_2 times of various materials were measured from the output of the MR spectrometer.

The Department of Biomedical Engineering at the Mayo Clinic hosted our students for an afternoon. We first received a demonstration of MRI. Another group at Mayo gave us a presentation of computer methods for manipulating 3D images from multiple modalities, and using them as input for other medical needs (such as surgery assistance). The students were amazed to discover that there are vast opportunities in biomedical engineering for people with backgrounds in biology, chemistry, physics, mathematics and computer science. We concluded with a demonstration of advanced ultrasound imaging techniques, including an echocardiogram.

In order to obtain more information of the optics of the eye we arranged a visit with a local ophthalmologist (Jordan Sterrer MD). Spectacles and contact lenses are used by most of our students, so it was necessary for them to actually fully understand all the physics associated with determining the optical properties of the eye. The ophthalmologist, using students as volunteer patients, was able to demonstrate and explain the performance of devices used to measure cornea curvature and the focusing ability of the eye. We then observed a video of laser surgery of the eye, and saw how changing the curvature of the cornea can be used as a means of vision correction

3.2. Student research projects

Since this class avoided examinations, research projects served as one place where we could evaluate student performance. Written reports and oral presentations were required. This served as an equitable way to place students from differing scientific backgrounds on an equal footing; they could present a project that was tailored to their own strengths. Our department places much emphasis on the development of communication skills with our students. The students were required to produce two research reports, and an oral presentation.

We were fortunate to receive and observe some fascinating student reports that truly displayed interesting topics in medical physics. Some project titles were: Functional MRI or, How to Get PET-like Images Without Those Nasty Gamma Rays; Electron Paramagnetic Resonance; Retinal Tears and Detachments—Assessment and Repair; Bio-Robotics and Powered Prosthetics; Physics of the Ear; The Laser Involved in LASIK Surgery; Boron Neutron Capture Therapy; Backpacks and Back Pain; The Physics of Ventricular Fibrillation; Sonophoresis—Using Ultrasound to Permeabilize the Skin; Biphasic Defibrillation and the Myocardial Resynchronization Hypothesis; Physics and Fractures—The Physics of Hip Fractures, Hip Fracture Risk Assessment, and Hip Fracture Prevention.

Another short writing assignment that proved successful (as part of a weekly homework assignment) was to have the students write a one page letter to their parents. In this letter they explained the spin-echo sequence of MRI imaging. In order for the students to inform a lay-person of the operation of this sophisticated technique they were forced to fully understand it themselves. We found this writing assignment to be fun, entertaining and successful.

4. Books

There are numerable good sources and books that one may draw upon for a course like this, however we found no text that covered all of the topics we wanted. Our class primarily used *Intermediate Physics for Medicine and Biology* (3rd edn) by Hobbie [1]. This book covers a wide array of topics, and has a large number of problems to draw from. The level of the text was, at times, too advanced for undergraduates, and more suitable to graduate students in biomedical engineering. The book also lacks detailed examinations of imaging techniques, especially ultrasound.

Consequently we used a number of additional books and resources. Davidovits' book, *Physics in Biology and Medicine* [2], is at a first year physics level, and we found it to be useful when we discussed the forces on parts of the body, the electrical properties of the nervous system and the optics of vision. The book covers a number of other topics as well. Davidovits was a nice accompaniment to Hobbie's book as the students could use it for simple explanations of effects before considering the more advanced explanations.

For help with the presentation of the physics of vision and hearing we found the book by Cameron *et al* to be useful, *Physics of the Body* [3]. The level of this book was slightly higher than that of Davidivits [2]. The book also contained a wide variety of topics. For the topics of optics, hearing and electrical signals in neurons we also used *Physics for the Biological Sciences*, by Hallet *et al* [4]. This book is at a very good level for advanced undergraduates, however it is a bit out of date now on some subjects.

For medical imaging topics we very much enjoyed using *The Essential Physics of Medical Imaging*, by Bushberg *et al* [5]. This book has very good and detailed explanations of ultrasound, computed tomography and MRI. We also used Hobbie for MRI and PET. In addition, we utilized the vast amount of information found on the internet.

5. Conclusion

A medical physics course should be looked upon as a beneficial addition to the undergraduate physics curriculum. The course should be considered as an ideal addition to the intermediate level physics curriculum, as it covers almost all of the major subjects that physics undergraduates should see. Students are often bored by lack of direct applications or good examples when covering physics subjects. In our class we talked about physics within the context of medical applications. For every physical topic there was a medical application; students loved it.

The interdisciplinary nature of a course like medical physics offers other advantages. A course like this provides an opportunity for keen pre-medical students to return to physics. A number of the pre-meds are genuinely interested in physics, but lack a good opportunity or reason to take an upper-level physics course. The differing backgrounds of the physics and pre-medical students presented an additional benefit in that a fantastic environment for stimulating discussions was created. The students would share with one-another their expertise.

Finally, there can be no denying that medical physics and biomedical engineering are evolving at a breakneck pace. There are opportunities available in abundance in these fields. Students are interested in medical physics for a number of reasons. There are equally good reasons for the faculty to provide a course in medical physics. This is exciting physics and exciting science!

References

[1] Hobbie R K 1997 *Intermediate Physics for Medicine and Biology* (3rd edn) (New York: Springer)
[2] Davidovits P 2001 *Physics in Biology and Medicine* (2nd edn) (San Diego: Harcourt/Academic)
[3] Cameron J R, Skofronick J G and Grant R M 1999 *Physics of the Body* (2nd edn) (Madison: Medical Physics Publishing)
[4] Hallet F R, Stinson R H and Speight P A 1988 *Physics for the Biological Sciences—A Topical Approach to Biophysical Concepts* (Scarborough: Nelson Canada)
[5] Bushberg J T, Seibert J A, Leidholdt E M Jr and Boone J M 1994 *The Essential Physics of Medical Imaging* (Baltimore: Williams and Wilkens)