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MODERN MIRACLE MEDICAL MACHINES: A COURSE IN CONTEMPORARY PHYSICS FOR FUTURE PHYSICIANS*

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Many of the diagnostic devices which are used by physicians have their technological foundation in contemporary physics. To understand techniques such as magnetic resonance imaging (MRI) and positron emission tomography (PET), students require knowledge of nuclear and quantum physics. Thus, these instruments can provide motivation for future physicians to study contemporary physics. To exploit this motivation we have built on the Visual Quantum Mechanics project (http://www.phys.ksu.edu/perg/vqm/) and created a course in contemporary physics that focuses on applications to medical diagnosis. In addition to MRI and PET, the students study the basics of x-ray production and absorption, CT scans, and ultrasound. The course has been offered once to students who were in their last year of studies before entering medical school and who had completed one year of algebra-based physics. Most aspects of the course were successful for both motivating and learning

Contemporary medical diagnosis and treatment relies heavily upon recent advances in physics. Computer-assisted tomography, nuclear magnetic resonance imaging and positron-emission tomography are just three areas in which the imaging relies heavily on developments in physics during the 20th century. Likewise, treatments involving lasers for surgery and nuclear isotopes for therapy again are recent developments in medical treatment. Unfortunately, students preparing to become physicians seldom have the opportunity to study the physics underlying these techniques. To address this deficiency, we have recently undertaken the development of a course on these topics. The course, Modern Miracle Medical Machines is the result.

1. CONTEXT OF THE COURSE

In the United States the study of medicine is a post-baccalaureate effort. Prior to applying for admission to medical school, students generally complete a course of study at a university. This course of study is frequently related to the biological sciences but could be in almost any scientific related discipline. In most cases students complete a four-year baccalaureate degree prior to admission to medical college. The level of competition for students to enter medical colleges is extremely high. Thus, students who have medicine as a career goal must perform well during their undergraduate degrees.

While at the University and preparing for medical studies the students (commonly called pre-medical students or pre-meds) will be required to complete some specific science and mathematics courses. While each medical college may have a slightly different set of requirements, students are generally required to complete courses in mathematics, biology, chemistry and physics. For medical colleges near Kansas State University, the requirements include two semesters of algebra-based physics, at least two semesters of biology, general chemistry and organic chemistry.

Modern Miracle Medical Machines was created to provide additional instruction in physics beyond the required algebra-based physics course. We assumed that our students would have the basic knowledge in physics that would come from studying it for two semesters in a course that involved both laboratories and lectures. In addition, we could assume that the students had some basic knowledge of algebra, biology and chemistry. Thus, we could teach contemporary physics and its applications to medicine with the understanding that students had a basic knowledge in the background sciences.

2. APPROACH

Our overall objective was to motivate the pre-medical students to study contemporary physics. Because they are likely to be applying these topics the background knowledge should be useful in their careers. Even if it is not directly useful, such knowledge should be of general interest to future physicians. At the same time we felt that we could teach them about contemporary physics in a broader context than just the medical diagnostic applications. By using the medical applications as a motivating factor we would be able to give them a broad base of understanding about modern physics. The course was not designed to be a replacement for the required algebra-based physics course. In fact, the Medical College's Admission Test includes questions about many topics in a typical introductory physics course. Thus, if students were to take the medical machines course as a replacement for the introductory course, they could obtain a lower score on the admissions test. Thus, this course is considered an enhancement for their physics knowledge rather than a replacement.

The basic approach to the science in the course was to focus on the physics and not the medicine. The primary reason for this was that the instructor knew much more about the physics than the medicine. A secondary reason is that we were not in a position to teach students diagnostic techniques. Thus, by focusing on the underlying science we emphasized

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that we were discussing science and not training them to be able to complete diagnosis with various imaging tools.

The basic approach to the sciences involved qualitative problem solving. Most of the contemporary physics ideas were presented qualitatively and with frequent use of visualization. Students were then expected to be able to use concepts, apply them to a variety of situations, and reach conclusions through a problem-solving procedure.

In selecting materials for the course we wished to build on our efforts with Visual Quantum Mechanics and use, as much as possible, some of the visualization tools that we have already developed. After reviewing the various options we decided to focus on the following topics:

X-rays
Computer Tomography Scans
Nuclear Medicine
Positron Emission Tomography
Magnetic Resonance Imaging, and
Lasers & Surgery

The course operated with the following syllabus:

- Review of Conservation Principles
- Solids & Light from Visual Quantum Mechanics
    - Quantized Energy Levels & Atoms in Solids
- X-ray Emission and Detection
    - Energy Levels and Fluorescence
    - CT Scans
- Radioactivity
    - Nuclear Medicine
    - The Gamma Camera
    - Positron Emission Tomography
- Magnetic Resonance Imaging
- Lasers & Laser Surgery (briefly)
- Ultrasound (briefly)

The textbook [1] provided an overview of most of these topics while a much more detailed reference [2] was critical for developing teaching materials. Links to Web sites used for references and images are available at http://www.phys.ksu.edu/perg/vqm/mmmm/links_modern_miracle.htm

The major focus of the course was on medical imaging. For this paper I will concentrate on this aspect of the course.

PRELIMINARY STUDIES

The primary goal of Solids & Light from Visual Quantum Mechanics [3] is to introduce empirical evidence for quantized levels in atoms and energy bands in solids. This unit, as it was originally written, required very few prerequisites in physics. The primary prerequisite was to understand conservation of energy and the many different forms of energy. From that we built, through observation, the empirical evidence that energy in atoms is quantized and that the energies available to electrons in solids were in bands with energy gaps between these bands. This unit did not contain any medical applications and was used as a way to introduce material that would be fundamental background for the rest of the course.

X-RAYS

We chose x-rays as the first topic directly related to medical diagnosis. Essentially all students have been x-rayed at some time in their life and so they are familiar with the concept and its use in medicine. Thus, x-rays formed a nice context to begin our study of the application of 20th century physics. (Even though x-rays were discovered slightly before the 20th century.) We divided the study of x-rays into production, interaction with matter and detection. When discussing production we focused on both the acceleration of charged particles and the energy change in the inner shells of atoms. Thus, we were able to connect the production of x-rays back to the study of energy levels in atoms in the Solids & Light unit.

While studying the interaction of x-rays with matter we looked at basic scattering techniques such as Compton scattering as well as the biological damage that x-rays can cause. We discussed briefly the sensitivity of different types of cells to x-ray sand thus the reason for wanting to limit the dose. The limitation of dose led naturally to a discussion of the contemporary ways of x-ray detection and how physics could be used to help assure that the position received the maximum amount of information while the patient received the minimum dose possible. We began this study with fluorescence. The Visual Quantum Mechanics unit, Luminescence: It's Cool Light! contains an activity that studies fluorescence. This activity includes an interactive computer visualization that helps students understand how fluorescence is used in household and office lighting. Because we did not have a similar visualization which provided visualization for detection of x-rays using fluorescence, we asked the students to complete the unit on fluorescence with visible light. Once they had completed this unit, we extended the same concept to fluorescence in x-rays. This method proved to be an effective way to teach fluorescence without the need for extensive reprogramming of our visualization. The same techniques were then applied to creating visible light from x-rays that strikes film. Thus, we were able to discuss both direct observation using fluorescence and fluorescence in the use of film by relying on one of our previous visualization activities.

Electronic x-ray detectors were also discussed in the form of Vidicons, charge couple devices and photomultiplier tubes. In each of these cases the interaction of x-rays with charged particles formed the primary underlying physics.

In completing the x-rays unit we were able to show students effective use of a relatively old discovery in physics. However, we were also able to show that by applying more contemporary techniques we could lead to high quality diagnosis with lower doses and thus increase safety for the patients and the physicians.

3. COMPUTER TOMOGRAPHY

We approached computer tomography as a sophisticated way to use a large number of x-ray images. We began this unit with two explorations that are quite similar to classical scattering experiments in which you ask students to learn something about the shape of a hidden object. We provided students with an object to which absorbed all light and a laser pointer. We asked them to use the light from the pointer to learn as much as they could about the object. The experiment was then repeated with a piece of plastic which absorbed some but not all of the light. In our case we used a rather simple technique in which the students simply looked at what light was reflected, absorbed, and transmitted. In this way they could find locations by looking at different angles. They could also obtain some information about shape. Recently, Delaney and Rodriguez [4] have published a much more sophisticated version of this analogy for computer tomography.

This exploration was used as an analogy to the back projection methods of computer tomography. While static pictures can provide the basic introduction to this idea, animated films that show how the image can be built from a large number of individual images are significantly better. Even more instructive are interactive computer programs that show the effect of continually adding back projections from a variety of different angles. Perhaps the best of these interactive programs is CTSim available from the website of the Lehrstuhl fur Didaktik der Physik at the University of Munich. [5]

4. POSITRON EMISSION TOMOGRAPHY (PET)

Positron Emission Tomography involves introduction of a radioactive positron emitter into the patient's body. Once the positrons exist in human tissue, they very quickly annihilate with electrons. In most cases this annihilation leads to the emission of two gamma rays which move in opposite directions and each of which has an energy of 0.511 MeV. Looking for coincidences and counting time delays between the receipt of the two ex gamma rays at the detectors allows one to determine the location of the annihilation event. By using carefully selected positron emitters the developers of this technique are able to look rather carefully at a variety of functions in the human body, including basic brain functions.

To introduce the concept of coincidence and its value in determining the location of an event, we created a mechanical analogy. Two students worked together with low-friction carts. We used the collision carts available from Pasco that have spring-loaded plungers in one end. A large piece of cardboard hid the location of the carts from one of the students. The other student released the carts using the plunger from some location behind the cardboard. The student who could not see the release site, needed to measure the time from the release (which he or she heard) and the appearance of the cars from behind the cardboard. Using the time and the speed of travel of the cart, the student could reproduce the location of the release.

The incidence of detection of course is only one small part of the PET process. To be able to discuss the production of positrons we needed to introduce the students to beta radioactivity. Then, anti-matter and the concept of annihilation were used to explain how gamma rays were produced in this situation. For detection of the relatively high energy gamma rays we needed to talk about the photoelectric effect. Finally, we discussed artifacts in the images. This required a discussion of the scattering of photons off matter and how that could change the determination of the location of the annihilation. Thus, the positron emission tomography unit was very rich in a variety of 20th Century Physics principles.

5. MAGNETIC RESONANCE IMAGINING (MRI)

We deliberately chose MRI as the last of the imaging techniques to study. The number of different topics in physics that are needed to adequately understand the basics of MRI are rather large. The students in their previous physics course studied some of these such as magnetic fields, resonance, and basic wave properties. Others such as quantized energy levels and the basics of constructing an image from multiple signals were studies in earlier sections of this course. Thus, MRI represents a way to synthesize a large number of different physics concepts. In addition, we must introduce the basic concept of quantum mechanical spin, a topic that is difficult at any level.

Our introduction to spin once again relies on materials that we had created for the Visual Quantum Mechanics activities. In this case we had created an interactive visualization to help undergraduate physics students understand the basic principles underlying the Zeeman effect. This program enables students to watch changes in atomic energy levels as they modify the magnetic field in which an atom is placed.

With this beginning, we then introduce the concept of nuclear spin. We approached both atomic and nuclear spin primarily as a method of separating otherwise degenerate quantized energy states. This approach is somewhat different from the physics that appears in most books which are written about MRI and which are aimed at physicians. In those cases, the presentation usually involves small spinning spheres that are for some mysterious regions quantized in their energy states. We preferred to avoid answering the question "What is spinning?" Instead, we focused on how magnetic fields affect the energy of the spinning entity.

We then introduced the resonance ideas as a way of matching energies between the radio frequency magnetic fields and the energy levels in the nuclei. From that point a discussion of the energy detection of signals by looking at changes in energy from the emitted to the detected signal was rather straightforward. Because we had discussed back projection and the use of multiple signals to reconstruct an image in both the computer tomography and positron emission tomography sections of the class we could just refer to that method for creation of the full image of the inside of a body. Thus, we were able to introduce MRI with a minimum of new, complicated concepts and a heavy reliance on materials that the students had studied earlier in the course.

6. SUMMARY

We found that contemporary medical imaging techniques is a good resource for applications of modern physics. By using these techniques as the motivating factor we were able to introduce students who might otherwise not be involved in the study of modern physics to concepts that underlie much of their tools in their chosen careers. We were also able to introduce these techniques primarily at a qualitative level but with a great deal of interaction and problem-solving and logical challenges to the students. By ordering the imaging techniques so that each one introduced just a few new concepts and built on the ones that came before we were able to increase the level of complexity gradually as we developed new ideas.

At this time this course has only been taught once at Kansas State University. The students who took the course demonstrated a very high level of learning as measured by the class examinations. The end of semester evaluations by the students showed that they were extremely pleased with the course and with the type of material covered in it. While both the learning and the attitudes were very high, we must be aware that the number of students was very small and they were self-selected. As indicated in the introduction to this paper the level of competition for U.S. medical college admissions is very high. Thus, many students for whom the course would be interesting chose not to enroll because they feared that another physics course might adversely affect their grade average. Thus, the students who enrolled in the course were those who had a very high level of confidence in being able to succeed.

In spite of this limited ability to make a full assessment of the materials to date, we are confident that the first offering of this course was a good first step in creating a course for these students. With further development and modification it should be a very effective course for introducing future physicians to the underlying physics behind the tools that they will use throughout their careers.

7. ACKNOWLEDGMENTS

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