Teaching about the physics of medical imaging: Examples of research-based teaching materials

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Abstract

Even before the discovery of X-rays, attempts at non-invasive medical imaging required an understanding of fundamental principles of physics. Students frequently do not see these connections because they are not taught in beginning physics courses. To help students understand that physics and medical imaging are closely connected, we have developed a series of active learning units. For each unit we begin by studying how students transfer their knowledge from traditional physics classes and everyday experiences to the medical applications. Then, we build instructional materials to take advantage of the students' ability to use their existing learning and knowledge resources. Each of the learning units involves a combination of hands-on activities, which present analogies, and interactive computer simulations. Our learning units introduce students to the contemporary imaging techniques of CT scans, magnetic resonance imaging (MRI), positron emission tomography (PET), and wavefront aberrometry. In addition we are developing a unit on Alexander Graham Bell's attempt in 1881 to find a bullet in US President James Garfield. The project's website is http://web.phys.ksu.edu/mmmm/.

Keywords: Teaching physics, medical imaging, optics.

Resumen

Incluso antes del descubrimiento de los rayos X, los intentos de imagen médica no invasivas requieren una comprensión de los principios fundamentales de la física. Los estudiantes, con frecuencia, no ven estas conexiones, ya que no se enseñan en los cursos de física básicos. Para ayudar a los estudiantes a entender que la física y las imágenes médicas están estrechamente relacionados, hemos desarrollado una serie de unidades de aprendizaje activo. Por cada unidad comenzamos con el estudio de cómo los estudiantes transfieren sus conocimientos tradicionales de las clases de física y las experiencias diarias a las aplicaciones médicas. Entonces, podemos construir materiales didácticos para aprovechar la capacidad de los estudiantes en utilizar sus conocimientos y recursos existentes en el conocimiento. Cada una de las unidades de aprendizaje implica una combinación de actividades prácticas, con analogías presentes, y simulaciones interactivas en un ordenador. Nuestras unidades de aprendizaje introducen los estudiantes a las técnicas de imagen contemporánea de la tomografía computarizada, resonancia magnética (MRI), tomografía por emisión de positrones (PET), y aberrometría de frente de onda. Además, estamos desarrollando una unidad sobre el intento de Alexander Graham Bell en 1881 para encontrar una bala en el presidente de los EE. UU, James Garfield. El sitio Web del proyecto es http://web.phys.ksu.edu/mmmm/.

Palabras clave: Enseñanza de la física, medicina, óptica.

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I. INTRODUCTION

Modern Miracle Medical Machines is an educational research and development effort to teach some physics in a medical context. Because students who wish to become physicians or veterinarians complete one physics course, this context should be important and interesting to them. In this project we are focusing primarily on medical imaging. The materials are for algebra-based university level students. We are not trying to create an entire new course. We have tried to create relatively short materials that could be put into an existing course. This approach enables faculty to change part of a course which is much easier than changing all of it at once.

II. MEDICAL EDUCATION IN THE UNITED STATES

The university education for medical students in the United States is somewhat different from many other parts of the world. First, both human and veterinarian medicine is a study that students do after they have completed a Bachelor's degree. They go to the university, complete a bachelor's degree, frequently in a science but not always. Then, they attempt to be admitted to a medical college. The level of competition for admission to medical colleges is very high. Thus, these students are frequently very interested in doing well in the sense of getting high marks in their classes but not necessarily doing so well that they really learn something. The phrase frequently used for this is "pre-meds" – pre-medical students. They are very competitive for grades, and are usually very bright students. However, grades tend to be more important than learning, so that is one of the reasons we want to present physics in a way that will motivate their learning The university education for medical students in the United States is somewhat different from many other parts of the world. First, both human and veterinarian medicine is a study that students do after they have completed a Bachelor's degree. They go to the university, complete a bachelor's degree, frequently in a science but not always. Then, they attempt to be admitted to a medical college. The level of competition for admission to medical colleges is very high. Thus, these students are frequently very interested in doing well in the sense of getting high marks in their classes but not necessarily doing so well that they really learn something. The phrase frequently used for this is "pre-meds" – pre-medical students. They are very competitive for grades, and are usually very bright students. However, grades tend to be more important than learning, so that is one of the reasons we want to present physics in a way that will motivate their learning.

Typically, the physics course taken prior to their medical studies is algebra-based although in some institutions it is now calculus-based. In addition these students will complete several biology courses, two or three courses in chemistry, and a variety of other general courses at the university.

The pre-med physics course at most universities in the United States is a rather standard first introductory course in physics. Some but not all faculty have adopted some type of interactive learning. Thus, typically the course will contain some lectures, some practical work and some problem-solving sessions. Usually the course is primarily physics with perhaps a few examples from medicine. The focus is mostly on quantitative problem solving. As other apers at the conference have discussed, quantitative problem solving does not necessarily lead to understanding in physics in general.

III. OUR APPROACH TO RESEARCH AND DEVELOPMENT

Our goal is creating learning materials that are motivational for the students. Our approach is to conduct some research on students' reasoning and their mental models as they are trying to apply some physics that they have already learned to some issues in contemporary medicine. Based on the results of this research we develop some active engagement instructional materials that connect the physics to medical diagnosis and medical procedures - in our case primarily diagnosis. Then we try to integrate these materials into the course throughout the whole year.

Our approach is to focus on the physics and not the medicine. We are not trying to teach a future physician how to interpret a magnetic resonance image that they might get from a patient. We do not know how to do that, but we do understand the basic physics that is underlying the medical imaging procedure. We are hoping that we can help the students understand that physics better. We focus primarily on qualitative issues rather than quantitative issues so that we can teach some conceptual understanding. To accomplish this, we use analogies and visualizations rather frequently.

We have developed materials for the following medical applications.

- History of Medical Imaging.
- Eye diagnosis, corrections & surgery.
- Magnetic Resonance Imaging (MRI).
- Positron Emission Tomography (PET).
- X-rays & CT scans.

In this paper we will concentrate on eye diagnosis, MRI and PET.

In all of our development efforts, we do the research first, then develop a lesson, and finally use that lesson in research again. Thus, this process is similar to the approach presented by McDermott in this volume. The research first gives us a basis for developing the lesson and then we try to validate that lesson by using it with students in a variety of different situations and measuring its effectiveness. Of course, we almost always need to make some changes and go back through this cycle more than one time.

A. Our Two-Step Research Process

The research is a two-step process. We start by trying to understand what the students already know. Then, we investigate how they apply some of this information if they are challenged with applying it to an application that they do not normally see, in this case a medical application. We usually conduct this investigation with a clinical interview. This interview is partially structured in that it contains some questions that we will ask the students. However, it is not totally structured because some of the students' answers might be quite interesting and/or unexpected. In those cases we need to ask side questions to understand better the students' responses. Once we have analyzed these responses and have developed the first draft of the lesson, we conduct a teaching/learning interview. In these interviews we work with small groups of students who are learning while they are applying physics to a medical context. We analyze what they understand and how they understand it, what we need to add to make them understand the concepts better. This approach is different from interviewing to see what a student knows. Instead, we are investigating the process that the students go through as they are attempting to learn something new. We also look at how they interact with each other as they are learning because we can learn a lot about their thinking as they help each other learn.

An important aspect of the teaching-learning interview is the concept of the Zone of Proximal Development. This idea is a rather long saying that students learn best if you take them in small steps from what they already know to what you want them to know. If we make the steps too big, they will have difficulty in the learning process.

IV. AN EXAMPLE LESSON: THE FIRST ATTEMPT AT MEDICAL IMAGING

We are working on a lesson on the earliest attempt to use medical imaging but not be intrusive in the body. This situation occurred during the 19th Century. On July 2, 1881, US President James Garfield was beginning a trip by train from Washington, DC. Someone who was apparently disgruntled because he was not appointed the ambassador to somewhere shot Garfield. The President was a large man and the bullet went deep into his body. The physicians needed to know where the bullet was located relative to the vital organs before they attempted to remove the bullet. In those days the standard way to find a bullet was for the physician to put his finger in the bullet hole and feel for it. This method was unsuccessful.

Alexander Graham Bell who had just invented the telephone a few years earlier had an idea. He knew that a metallic object near an inductor changes the value of the inductance. If a listening device, such as a telephone, was connected to an audio frequency source, the change in induction would also change the audio signal. This change would be heard by the listener. Bell's recent invention, the telephone, could hear that change.

The bullet was quite small. It was made of lead which is diamagnetic and has a rather small magnetic susceptibility. Thus, finding the bullet with a simple inductor-telephone circuit would not work. However, a bridge circuit would be sensitive to very small change. Bell created several such inductance bridges to use in this situation. The inductance bridge was similar to a Wheatstone Bridge with the resistors replaced by coils of wire. One of Bell's versions is shown in Fig. 1 [4].

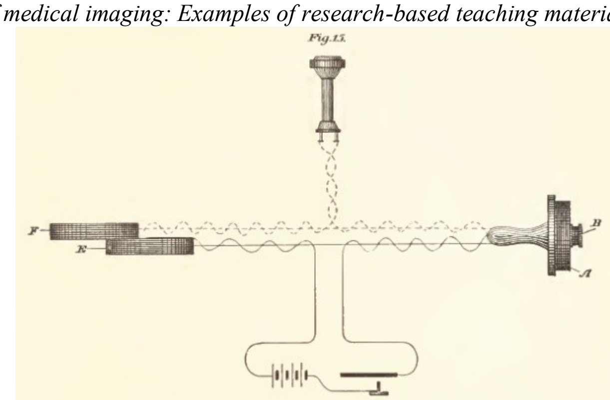

FIGURE 1. A drawing from Bell's paper showing one of the devices which he used to attempt to find the bullet in James Garfield.

Bell successfully detected bullets in sides of beef and shrapnel in Civil War veterans. But he was unable to find the location of the bullet in Garfield. Unfortunately for Bell another new invention was involved – the inner spring mattress. Garfield lay on a mattress with metal coiled springs. Bell had not yet heard of such a mattress and was unaware that his patient was lying on a uniform grid of metal that interfered with detecting a very small metal object in his body thus, this attempt did not work for some easy to understand physics reasons.

Our lesson on this topic is based on student understanding and learning of concepts related to electricity and magnetism [for example, 2-4] as well as some on learning from the history of physics [5]. It begins with hands-on activities on the basics of electricity and magnetic fields and the principle of inductance. Then we have students create and work with a Wheatstone Bridge. For this activity we use both a real bridge and a simulated bridge using the PhET DC circuit simulation [6]. The primary purpose of this part is to introduce the idea of a balanced bridge circuit with something simpler than an inductance bridge. (Our informal research has told us that Wheatstone Bridges are seldom covered in introductory physics classes.)

Next, the students build an inductance bridge. We have used coils that are part of the PASCO "Coil and Core Sets" for the coils (Part number SF-8617). However, instead of a DC current chopper and a telephone, we have introduced an apparatus that is more modern than Bell's. We have been using a computer as both an audio frequency source and an oscilloscope to detect the current change. A good and free choice for both of these functions is the Soundcard Oscilloscope [7]. The students also use an inductance bridge simulation with the PhEt AC circuit simulator.

Once students are able to detect hidden metal with their bridge, we have them attempt to find the metal when the object in which it is hidden is lying on a piece of metal. Thus, they learn and can explain why Bell's attempt does not work.

At this time the lesson has been written in draft form, but it has been tested by only one student. We hope to have it finished and ready for distribution in the fall of this year.

V. A SECOND EXAMPLE LESSON: VISION AND WAVEFRONT ABBEROMETRY

This example was primarily the work of Dyan McBride, a former graduate student. Today the diagnosis of eye defects is not the simple process of reading the traditional eye charts with different lenses and then determining which lens is better. That process is still performed but it is being replaced by more sophisticated techniques. Particularly, if Lasik surgery will occur, you want the physician to know very well what is wrong with your eye. So, wavefront aberrometry is the new process to diagnose vision defects.

A low-powered laser is directed into your eye and focused on the retina. That spot on the retina becomes, in effect, a secondary source of light and the light comes back out into a detector. In a simple model of this process if the optics of your eye are perfect the laser scan across various parts of it will produce a nice evenly spaced grid. If there is something wrong, then the result will not quite be a grid. (See Fig. 2) Through a fairly sophisticated process, actually sophisticated mathematics using Zernike polynomials, the eye doctor's computer can provide much information about what is wrong with the eye. That information can then be put back into another computer which drives the laser in Lasik surgery. Or, in those of us who do not like lasers messing with our eyes, the information can be used to drive a lens making apparatus.

FIGURE 2. The grid on the left is a simulation of the grid from an eye with no defects, while the one on the right represents significant vision defects. (Courtesy of Prof. Hartmut Wiesner, LMU, Munich).

While the detailed analysis is a fairly sophisticated process, the basic physics underlying it is somewhat straightforward. So, we have tried to build a lesson using hands-on models and computer simulations so that students can understand the underlying physics.

Several models that teach the optics of the eye are available. PASCO, for example, sells one that is based on a very old version (Fig. 3) Pasco has just added to the model an adjustable focal length lens based on a design by our group (Fig. 4). This lens includes two pieces of transparent plastic which are sealed to a small cylinder. This lens is filled with liquid. As liquid is added to it or removed from it with a syringe, the lens gets thicker and thinner. As a result the focal point of the lens changes. This process mimics what happens in our own eyes when our eyes accommodate for looking at different distances. When the eye model is filled with water, cooking oil works well in the lens. (Our adjustable focal length lens received First Prize in the 2010 AAPT Apparatus competition.)

The PASCO model is somewhat expensive but one can make something very similar to this for a very low cost by using a Styrofoam sphere and transparent plastic [8, 9]. However, this inexpensive model cannot be filled with water and thus does not model some of the eye's optics.

FIGURE 3. A functional model of the optical system of the human eye. (Image from PASCO, Part number OS-8477).

When teaching wavefront aberrometry we place a small light source at the back of the eye model and move it around. Then we can obtain for a normal lens a nice even grid similar to the one on the left side of Fig. 2. If on the other hand the students pinch the liquid filled lens, they introduce an aberration and see a grid that looks similar to the right part of Fig. 2.

FIGURE 4. The adjustable focal length lens system for use in the eye model in Fig. 3. (Image from PASCO Part number OS-8494.)

We have not asked the students to diagnose what is really wrong with the lens. Instead we are just trying to get them to understand the basic principle. We can also look at the normal, near-sighted, and far-sightedness problems by moving the retina and the source of the light.

The students do this hands-on part first. Then we introduce some of the physics concepts. To have the students understand the concepts better, together with our colleagues at Munich we developed two computer programs. One shows the ray tracing that one would use to understand simple vision and the problems introduced with nearsighted and farsighted eyes. A screen capture from this program is shown in Fig. 5. With this program the students can move the object and the retina and they can place different lenses in front of the eye.

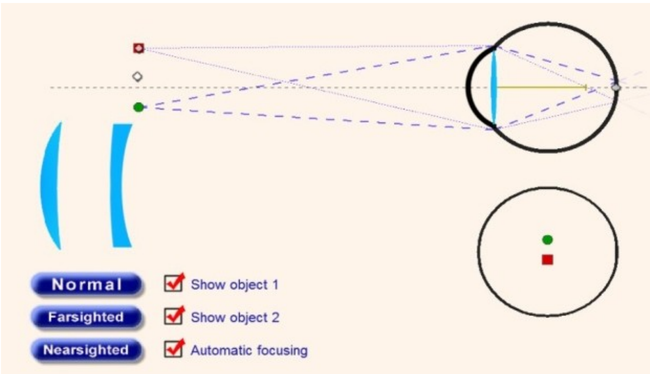

FIGURE 5. A screen capture from our optics of the eye interactive simulation.

A second program enables the students to manipulate variables in a situation similar to wavefront aberrometry. For the screen in Fig. 6, the students can put the mouse cursor at the diamond-shaped object on the eye lens and push the lens in and out in the same way that they pushed the lens in and out with the physical model. When they do that, then they see changes in the grid at the bottom of the screen. They can also still pull the retina in and out to get nearsighted and farsighted eyes. Again, they will see how the grid changes. So the first part of the lesson is a hands-on activity, then we introduce some of the basic ideas, and then they go back and explain how it is that this system works by actually watching the ray tracing with a computer program.

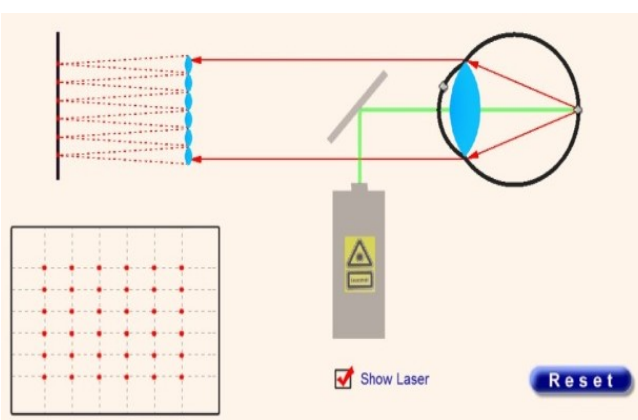

FIGURE 6. A screen capture from the interactive visualization on wavefront aberrometry.

The research on student learning [10] and the lessons are complete. We created two different versions of the lessons. One uses models of the eye that one can buy from scientific companies or build oneself; the other version uses a more standard optical bench. Both version of the lessons, software, and a low-cost way to make the adjustable focal length lens are available on our website.

VI. ANOTHER EXAMPLE: MAGNETIC RESONANCE IMAGING

Our lesson on magnetic resonance uses the same research base as the one on Bell's attempt at medical imaging. It begins with a classical experiment on magnetic resonance. Our apparatus (Fig. 7) is a triangular shaped wire which has current in it. We put a bar magnet somewhere nearby to provide a constant magnetic field and then a compass which has no damping in it near the wire. The students turn the current on and off by pushing on a momentary switch. By turning the current on and off at an appropriate frequency, they can cause the compass to resonate. When they change the location of the bar magnet, they will discover that the resonant frequency changes. Thus, in some ways this observation is very similar to the process that goes on in magnetic resonance imaging.

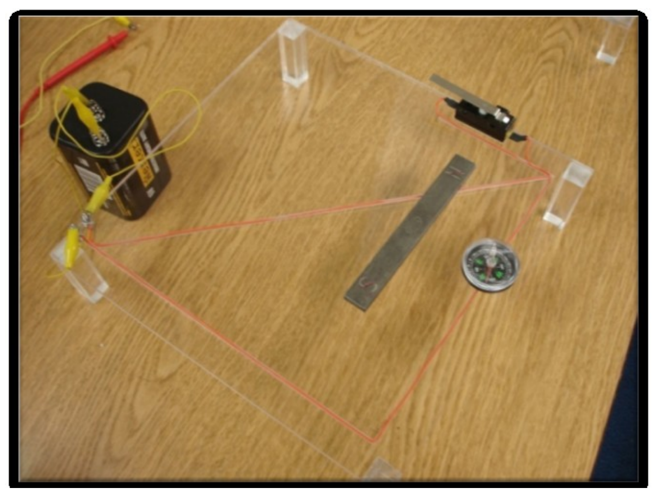

FIGURE 7. The apparatus for students to explore classical magnetic resonance of compasses.

For the version shown in Fig. 8 we have included three compasses. Depending on where the bar magnet is placed relative to those three compasses, the students will find that each of them resonates at a different frequency of the current. Again, this is very similar to how the real MRI apparatus works. (This apparatus received a prize in the 2009 AAPT Apparatus Competition.)

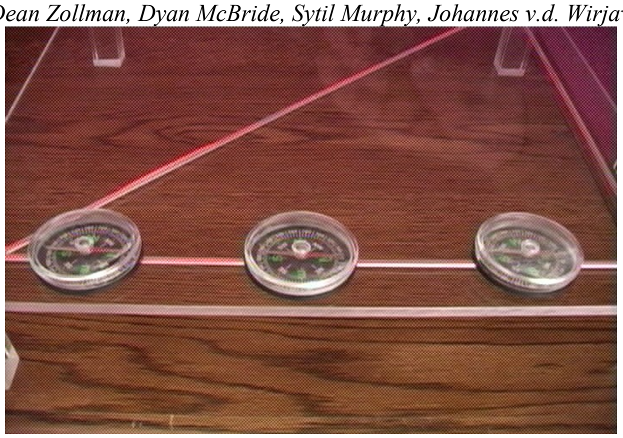

FIGURE 8. A close up of the apparatus for creating a resonance in the magnetic compasses.

The resonance experiment is the beginning of the lesson. We then introduce some of the underlying physics. This activity is followed by an activity with a PhET visualization on Magnetic Resonance Imaging. A screen capture of the visualization is shown in Fig. 9.

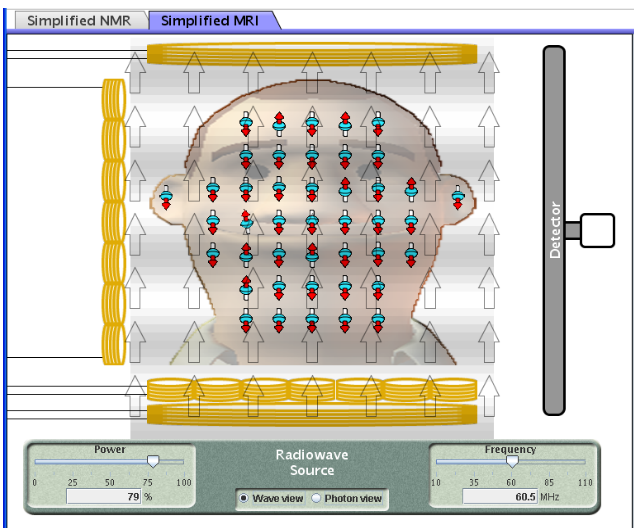

FIGURE 9. A screen capture of the MRI visualization. (Available from http://phet.colorado.edu.).

The screen shows the head of someone with a few magnets (protons) inside his head. The system basically works the same way as our classical magnetic resonance apparatus does. Coils at the top and bottom create a static magnetic field. This static magnetic field can have a gradient, so that it is greater at one end of the head than it is at the other. Additional coils provide the oscillating magnetic field. The students can see by using the variations in the power for the static magnetic field and variations in the frequency for the oscillating field when they reach a resonance. At that time many of the little magnets will flip back and forth.

To help the students understand it we help them make the connections between this visualization and the current-compass experiment. In this process we are treating the protons inside the person, as classical magnets. We have decided after several attempts at trying to do it with spin, that this semi-classical approach is much more effective. It does not get us all the way toward how magnetic resonance images are really made. It does not involve, for example, the relaxation times which are quite important when computers are collecting all the data that they need to make an MRI image. But, it is a good first step to helping people understand how basic magnetism and the basic concepts of resonance are involved in the MRI process.

If one wants to go into more detail a large amount of materials are available free online. One that is particularly useful is The Basics of MRI at Rochester Institute of Technology [11].

VII. SUMMARY

In each lesson at least part of the physics related to the medical applications is relatively. It can be easily applied to some understanding of modern medical imaging techniques. We feel that graphics, simulations, and analogies are all important. Our research and testing of the instructional materials has shown that all of them seem to be rather effective. The materials will be available on our web site.

ACKNOWLEDGEMENTS

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