Medical Physics Resources: Budget Demos and YouTube Videos

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Here, we outline several good budget demonstrations of several of the physical principles at the heart of medical physics, and by extension, at the heart of much of modern medicine! Virtually everyone has an experience with modern medical diagnostic and treatment techniques such as an endoscopy, MRI, CT scan, or PET scan, or radiation therapy, ultrasound therapy, or even laser surgeries, be it personally, or through friends and relatives.

Any technology required to demonstrate medical physics is often associated with prohibitively high cost, putting it out of reach for high school courses. However, the fundamental concepts behind these methods are well within reach of the classroom, and can be used to cultivate an appreciation and an interest in medical physics, and by extension, physics in general. It never hurts to point out, however, that by definition literally every observation of and mechanism within the entire Universe has physics at its core, whether completely understood or a total mystery. The possibilities are endless; for a great exercise, students could pick any aspect of medicine, and dig down until hitting the physical mechanism responsible, even if it means going to the sub-atomic level.

This is by no means a comprehensive resource. In compiling this guide, the following link from Haverford College was used for reference, and contains additional demonstration possibilities not outlined here: http://www.haverford.edu/physics/demonstrations/medical_physics.htm Another great site is that of the Nobel Prize, www.nobelprize.org, which is also the source for any Nobel-related notes mentioned here. Just browsing through the Nobel Prizes awarded in Physics, Chemistry, and Physiology or Medicine is extremely educational. Throughout this summary, numerous other resources are mentioned.

To finish this introduction, we have a great motivating quote from Neil deGrasse Tyson, astrophysicist and proponent of science outreach:

“If you take a tour through a hospital, and look at every machine with an on/off switch that is brought into the service of diagnosing the human condition, that machine is based on principles of physics discovered by a physicist”

Enjoy!

Visible and near-visible light interacting with tissue

The most important principle here to be conveyed to students is that electromagnetic radiation interacts in distinguishable ways for different materials. The visible spectrum (light) of different wavelengths (and energies) can be affected in very different ways, over a relatively small difference in wavelength, depending on the length scales and energy levels present in the material they are interacting with. There are numerous outcomes depending on their energy and the material they are interacting with: dissipative absorption, reflection, scattering, fluorescence. Longer wavelength equals lower energy, i.e., red photon has less energy than blue photon. Wavelengths of visible light are 390 nm to 780 nm (violet to red).

Absorption and transmission of light in tissue: Using any strong light source, the absorption and transmission of light of human tissue can be demonstrated. Red light can be seen to pass through tissue, such as ones hand. Blue and green light, however, is quickly absorbed. This can be seen with white light as well; the light passing through a hand has a reddish hue to it. Another easy example familiar to just about everyone is trying to shut out the morning sun (or another bright light) with your eyelids, while trying to catch a few more minutes of sleep. A reddish hue to the light that makes it through is also observed. This demonstrates how red and infrared (IR) can be transmitted through the body, though it should be noted with diminished intensity due to scattering, absorption, and reflection losses.

Absorption of light by colored filters: Coloured filters can be used to demonstrate absorption and transmission is strongly dependent on the wavelength (colour) of light in question, as well as show why objects appear the colour they are. A red filter, for instance, absorbs all other wavelengths (colours) of light while allowing red to pass through, thus appearing red. A green laser, however, is observed not to pass through the red filter, demonstrating absorption. Alternately, blue filters absorb red light.

A fluid filter is another way to demonstrate this, while also examining penetration depth. Here, food dye from a grocery store is used as an absorbing pigment. For example, the intensity of a green laser shining into water with a drop of red dye can be seen to have a scattering track that diminishes in intensity, with no light transmitted at the other side of the clear vessel. Meanwhile, red light shines through the red water unimpeded. Varying the concentration of the dye in the water will vary the penetration depth. The tie to penetration depth of radiation in tissue works much in the same fashion; there is a loss in intensity with depth.

Light Scattering in tissues: Any collimated light can be shone into diluted milk to observe the effect of scattering on tissue. Milk is, among other things, largely an emulsion of fats and water. The light is scattered by the fat globules present in the water, making the milk opaque to the light.

How light interacting with tissue is used in medical physics:

Examining the light transmitted or absorbed can be incredibly instructive, since depending on the quantity and wavelengths of light absorbed, transmitted, or reflected, the contents of the tissue in question can be determined, and even imaged!

Pulse sensor (pulse oximetry): The oxygen saturation of hemoglobin strongly affects the absorption of near infrared (IR) light (780 nm – 3000 nm). A combination of an IR light emitting diode (LED) and phototransistor allows a detection of oxygen-rich blood. This is a relatively simple circuit, which is part of our electronics workshop here at Ryerson. A simple pulse sensor can be built from readily available components from any hobby electronics supply, for approximately $12. Pulse oximeter principles of operation are described at **http://www.favoriteplus.com/pulse-oximeter.php**

Optical coherence tomography: A powerful diagnostic tool that uses the light reflected by sub-surface features of tissue to provide high resolution images of tissue. In this way, it is very similar to ultrasound, depending on reception of the reflected sound. This is limited by the penetration depth discussed earlier, though as mentioned, longer wavelengths in the red and infrared aren't attenuated as much as shorter visual wavelengths and are typically used. This is typically useful to depths of a couple mm.

References:

E. Hecht, Optics 4th Edition (2002)

Interaction of X-rays with tissue

Physical Principles:

This is a fairly straightforward extension of the interaction of visible light with tissue. At shorter wavelengths on the electromagnetic spectrum, (0.01 to 1 nm), x-rays are of significantly higher energy than visible light. The penetration depth of x-rays in the body is much longer than that of visible light. Measureable quantities of x-rays, on the order of several percent of original beam intensity, can pass through. It is very instructive to point out here that the first Nobel Prize in Physics was awarded in 1901 to Wilhelm Conrad R□ntgen for the discovery of high energy electromagnetic radiation which he coined "x-rays".

X-rays are ionizing radiation, which means some care is required in their use. Unfortunately this puts them out of the reach of typical high school classrooms, with the exception of hospital or university visits. However, discussion of the physics behind it is certainly within reach.

How x-rays are used in medical physics:

Imaging: No doubt everyone has had an x-ray at some point or another, if not for a broken bone or pneumonia, then instead at the dentist. An x-ray is a photographic negative; where an x-ray strikes the film or imaging plate, the film is darkened. Bones and dense tissue absorb x-rays, and thus the image appears white

Computed Tomography (CT) scans: In order to get past the limitations of absorption of visible light in tissue and "see" deeper into the body, x-rays can be used in a similar method to optical coherence tomography. Low level x-rays are shone at different angles and from the quantity of x-rays reflected and transmitted and at what angle, an image can be reconstructed. Cormack and Hounsfield were awarded the Nobel Prize in Physiology or Medicine in 1979 for developing computed x-ray tomography.

Open CT Scanner: http://www.youtube.com/watch?v=72X_PySQj8Y

How a Linear Accelerator Works

http://www.youtube.com/watch?v=jSgnWfbEx1A

References:

E. Hecht, Optics 4th Edition (2002)
Lapp and Andrews, Nuclear Radiation Physics, 3rd Edition (1963)

Guiding light with fibre optics

Physical Principles:

Fibre optics are made possible by the condition of total internal reflection, where the angle of incidence of light on an interface between two materials is greater than the critical angle. This fantastic property means light can be transmitted without a requirement of straight-line geometry. What is required is a higher index of refraction core, with the surrounding interface less than the index of the core. For example, a typical fibre has a core index of 1.6 with a cladding of index 1.5.

Optical signal path demonstrator The guiding of light can be demonstrated with a laser and two smoked plastic rods, one straight and one curved. The beam path is made easily visible, showing total internal reflection in action. Plastic Lucite guides with green lasers also make for an easily visible beam path. Microscope slides can also be used as waveguides to demonstrate total internal reflection. This is an excellent demonstration so students can visualize what actually occurs in a fibre.

Optical fibre combined with any light source (room lighting, flashlight, LED, laser) provides an inexpensive way to illustrate the wave guiding of light. Fibre is available at very affordable rates from numerous suppliers. Thefiberopticstore.com is one such supplier, where depending on the fibre, 50' can cost as little as ~$10. A word of caution: do NOT use glass optical fibres. Plastic fibres are all that should be required for typical classroom work. Glass optical fibres require a great deal of care and experience, and come with numerous safety concerns.

Optical fiber image conduit: Careful arrangement of bundles of optical fibres, where each individual fibre occupies the same position on the exit face of the bundle as it does on the entrance face, can make what is called a coherent bundle. These arrangements, which can be either flexible or inflexible, are capable of transmitting images! There are some great ways to demonstrate this. Microscope slides, stacked on end, and placed on a sheet of paper, or picture, demonstrate the coherent bundle very effectively. Even better, microscope cover glass (thickness ~ 0.15 mm) stacked and bundled with an elastic band also show this very well.

How fibre optics are used in medical physics:

The use of fibre optics in medicine carries over from the previous description of light interacting with tissue. It enables internal use of light in medicine, which would otherwise be limited by the penetration depth of tissue discussed in the previous section. One of the most basic uses of fibre optics, image transmission, is the most common use at this point.

Endoscopes: Optical fibers are the technology at the centre of modern endoscopy! One optical fiber typically behaves as a light source, while a coherent bundle of fibres collects and carries back the image of the area in question. The image can be viewed and recorded. Endoscopes are crucial in making diagnostics and surgeries as minimally invasive as possible. They enable much smaller incisions, can be accompanied by cutting tools, and can offer far better visuals of a target organ

Therapeutic uses for optical fibres are also at the disposal of medical professionals. Channeling a high intensity laser via fibre optics, the laser can be used to kill tumour tissue with heating. This is an extremely localized and careful technique, while also being minimally invasive. Photodynamic treatment also relies on laser delivery by fibre optics. Chemicals called photosensitizers congregate on tumours. The laser is then used to locally activate the photosensitizer and kill tumour cells.

Fibres for bio-sensitization: http://www.youtube.com/watch?v=yEnycUe3mpY

References:

E. Hecht, Optics 4th Edition (2002)
http://www.cancer.gov/cancertopics/factsheet/Therapy/lasers

Radioactivity and Radiation Therapy

Radioactivity, which produces ionizing radiation of alpha, beta, and gamma varieties, can have profound impact on human health, both beneficial and detrimental. The term nuclear radiation refers to the source of this radiation: the nuclei of atoms. When carefully controlled, radioactivity is an incredible tool at the disposal of medical professionals for diagnosis and treatment of cancers, and plays a huge role in medical physics as a whole. Radioactivity is quite regulated, which can make it difficult to bring to the classroom. However, there are still many opportunities to convey it to students. There are numerous resources available for radioactivity education. Several are listed, following:

The Canadian Nuclear Society (CNS)
http://www.cns-snc.ca/cns/education-communications
Canadian Nuclear Association Teachers Resources, with lesson plans
http://curriculum.cna.ca/curriculum/db/TeacherResource-eng.asp?bc=Teacher%20Resource&pid=Teacher%20Resource

Half-life demonstration: To demonstrate radioactive decay, all that is required is any simple exercise in probability (coin flip, roll of a die, deck of cards), which is representative of the decay process of a given atom. Using a coin flip as the most basic example, an entire class standing up each individually flips a coin. Those with a heads outcome sit down, and do not participate in further flips. This is repeated, with number of remaining students, charting the decay of the number of students. For small class sizes, give each student 5 coins (or 5 dice, etc.) and have the students remove “decayed” (heads) coins from the experiment as they proceed, while tallying the entire class’ remaining coins. This demonstrates a half-life (ideally) of one measurement period. Decreasing the probability of a decay event occurring, by using 1 side of a 6-side die as the event as an example, would lead to a longer half-life.

A short discussion of counting statistics would be appropriate here, to point out the importance of choosing measurement times appropriate to the probability an event will occur over a certain time period (or with a certain number of repetitions of an experiment). To take it far beyond the coins or die, a deck of cards can make for even longer half-lives. Make drawing a black card from a freshly shuffled deck a decay event in which students sit. Compare the recording of this decay to that of an event hinged around picking a Jack out of a freshly shuffled deck. These three examples should make it very easy to relate that the reasons half-lives are longer or shorter is purely dependent on the probability of a certain event occurring.

Radiation detectors: If a Geiger-Mueller counter is available, great! This is incredibly useful. If not, there are numerous ways to come across them, including commercially available units from science education suppliers.

http://www.vernier.com/products/sensors/radiation-monitors/drm-btd/

There is a very cool homemade ionizing radiation detector, a product of the Cold War. Designed by Oak Ridge National Laboratory in the US, the Kearny Fallout Meter is made from common household materials. The dose levels are outside the scope of low activity sources that you would want to deal with, but it’s educational nonetheless.
http://www.cddc.vt.edu/host/atomic/pdf/kfm_inst.pdf

CNS has a Geiger donation program: http://www.cns-snc.ca/cns/education-communications

Alternately, the world electronics hobbyist community has come up with many affordable options, which have the added educational benefit of learning how to interface with these devices. Use your preferred search engine to see what is out there. One ready-to-go example is the Mighty Ohm Geiger Counter, http://mightyohm.com/blog/products/geiger-counter/, which is ~$100 USD.

Radiation sources: With a radiation detector in hand, numerous possibilities for experimentation are available even without commercial sources. An ionization-type smoke detector can be opened up to utilize a good alpha and beta particle source, americium-241. From CNS, a great resource discussing ionization type smoke alarms: **http://media.cns-snc.ca/pdf_doc/ecc/smoke_am241.pdf.** A very interesting list of measurably radioactive consumer products is available here: http://www.orau.org/ptp/collection/consumer%20products/consumer.htm

Experiments with shielding: With any type of radiation source, statistics and shielding can be explored. Have students experiment with different types of shielding by simply recording a count rate, and how that changes by varying distance from source, and introducing shielding such as paper, aluminium, and lead.

Uses in medical physics:

Radiation is quite a double-edged sword. As can be shown with the above demonstrations, count rate (intensity) is extremely important. We are exposed to a finite quantity of radiation every day. The key is how much and for how long. Higher levels of radiation are extremely detrimental to living tissue, ionizing molecules in the body and causing cellular damage. Radiation exposure is even a cause of cancer. In a fortunate twist, however, we can use its damaging properties to our benefit. Cancerous cells are just as vulnerable to radiation, and its therapeutic use in killing cancer, while keeping the body intact, is extremely common.

Brachytherapy uses sealed source radioisotopes implanted in the body next to the tumour. These short-range sources of radiation kill nearby tumour cells, but are sealed so as to prevent diffusion of the radioisotopes into the rest of the body.

External beam radiation therapy uses an external radiation source. X-rays fit in here as well.

See http://www.cancer.gov/cancertopics/factsheet/Therapy/radiation for a comprehensive description of the use of radiation in cancer therapies.

Gamma Knife Surgery:
http://www.youtube.com/watch?v=GXTxBd1AZYU

Intensity Modulated Radiation Therapy:
http://www.youtube.com/watch?v=_moypMx05Fw

Ultrasound

Ultrasound is another pervasive medical technique with its functioning well-understood by physics. As it is based upon transmission and reflection of sound waves, most demonstrations relating to this are a good start. Demonstrating wave motion, including reflection at fixed and open boundaries, is very useful. The reflection at interfaces is what gives imaging contrast in the body. If a sonar motion sensor is available, this can convey echo technique, relying on reflected sound waves in order to establish the position and motion of an object. Stethoscopes can demonstrate how sound travels in the body; an oscillation of the heart is a source of acoustic waves, which are transmitted through the various tissues of the body, to be received as sound waves at the surface of the skin.

Use in medical physics:

Ultrasound is extremely well known as a powerful imaging technique, as anyone who has ever seen or had an ultrasound to observe a growing fetus can attest to. However, there are also therapeutic applications. One such method is the use to ultrasound to kill tumours. Focused high intensity ultrasound can target a specific region in the body, and like a magnifying glass focusing light, can heat the region enough to damage the cells beyond repair.

Magnetic Resonance Imaging

Compass Magnetic Resonance Demonstration: A very straightforward demonstration of magnetic resonance can be accomplished with just a few bar magnets and a compass. Set up a north pole and south pole of two separate magnets on either end of the compass, so the needle aligns in the field. Bringing a third magnet near the needle causes a displacement of the needle from the aligning field. Removing the magnet prompts an oscillation. The frequency depends on the field strength, which can be lowered by moving the magnets providing the static field further away. With lower field, you see a slower oscillation of the compass needle. As the oscillation amplitude damps out, you can also observe the "relaxation time" of the needle. The resonant frequency can be explored by oscillating the third magnet manually at a frequency close to the field dependent natural frequency of the compass needle (around 1 Hz). This demonstrates how small additional fields can produce a big oscillation if they are in phase with the oscillation! This is a great quasi-two-dimensional demonstration of the principles of MRI.

This video demonstrates the use of the "compass needle" java applet: http://www.youtube.com/watch?v=1OrPCNVSA4o , basically the experiment described above. Exercises based on the demonstrated freely available software are described at http://www.drcmr.dk/MR.

Another video with an MRI tutorial:
http://www.youtube.com/watch?v=Q9-X4uV8ymk

There is an entire online course available on MRI, which requires free registration. It is fairly comprehensive: http://www.imaios.com/en/e-Courses/e-MRI/

Fluids

Non-Newtonian Fluids, defined by a non-linear relation of viscosity to shear force, are important for life sciences. For example, synovial fluid found in joints, which is essential for smooth functioning of healthy joints, and blood are just two examples of biologically important fluids. Synovial fluid (found in joints) is an example of viscoelastic thixotropic liquid in which viscosity decreases with the duration of stress. Blood is an example of shear thinning fluid in which viscosity decreases with increased stress.

There are several easy-to-use demonstrations of these properties. In terms of shear-thinning, whipped cream and ketchup are both great examples which have decreased viscosity with increased shear. On the other side, shear-thickening fluids, where there is an increased viscosity with increased shear, are a great contrast. The classic demonstration of this is corn starch and water, forming oobleck. When placed on a speaker pumping out a lot of low frequency, dancing tendrils show up, demonstrating significant increases in viscosity, as can be seen here: http://www.youtube.com/watch?v=3zoTKXXNQIU. For comparison purposes, here is a discussion on quicksand http://www.youtube.com/watch?v=a2VJqud3Ls8 (not related to medical physics, but impressive).