International Journal of Innovation in Science and Mathematics Education, 31(4), 40-48, 2023

Medical Physics Topics as an Anchor for Physics Learning

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Keywords: medical physics, radiation, careers, medical imaging

Abstract:

Students taking introductory courses in physics at the secondary and university levels may benefit from the inclusion of medical physics topics. Medical physics is a growing field related to biophysics that includes radiation therapy physics, medical imaging physics, nuclear medicine, and health physics. Both standard physics classes for physics and engineering students, as well as physics courses for students interested in the life sciences, may take advantage of the applied and immediately applicable nature of medical physics topics. Integrating medical physics as examples of physics topics stimulates learning as relevant and connected to students' prior knowledge and interests, develops problem solving skills, engages students with concepts involving ethical and social implications of science and technology, and introduces students to a potential career opportunity. Examples of medical physics topics are discussed. Physics educators are encouraged to consider integrating some examples from medical physics into their curricula to spur student engagement and to acquaint students with one example of a rewarding career opportunity in applied physics.

What is medical physics?

Medical physics is a diverse and dynamic field in which principles in physics and engineering are used to answer questions in medicine. The field is related to biophysics, and it encompasses the topics radiation therapy and radiation oncology; medical imaging, including diagnostic and interventional radiology; nuclear medicine; and health and regulatory physics, including radiation protection. Medical physicists are key players in the development and implementation of new algorithms, technologies, protocols, and techniques. They often work in hospitals, clinics, universities, industry, and in government settings. A major component of the medical physicist's role is to ensure the safe and effective use of radiation and medical technology, and to ensure that patients, radiation workers, medical staff, and members of the general public have minimal risk from procedures and treatments by keeping exposure to radiation as low as reasonably achievable.

Scientists in medical physics often hold graduate degrees after focused studying and research on specific subtopics within medical physics, but topics in medical physics may be explored in more general introductory physics courses at the university and secondary school levels. Individual lesson plans, units, or even full survey courses covering medical physics topics may be taught to introduce students to the field. What types of topics could this encompass?

In radiation therapy physics, medical physicists are involved in the treatment of patients using high-energy radiation targeted at cancer cells, or in the development of technology to do so.

Radiation therapy is often accomplished through external beam radiation, in which linear accelerators or other radiation-producing machines are used to direct beams of radiation at a patient’s target volume, or through brachytherapy, in which a radioactive source is placed in or near a target volume. In both cases, the goal is to treat the tumour with a high dose of radiation, while sparing healthy tissue in the surrounding region (Gibbons & Khan, 2020). Medical physicists focused on therapy physics consult with radiation therapy physicians, known as radiation oncologists, to design effective radiation therapy plans.

In medical imaging physics, medical physicists enable the reliable imaging of patient anatomy, often to identify disease. Physicists focused on medical imaging partner with radiologists, with the goal of high-quality image studies that are delivered safely. In the clinical setting, these physicists are involved in calibrating and testing imaging equipment, as well as assessing any radiation dose to the patient. They may specialise in a specific imaging modality, including fluoroscopy, mammography, computed tomography (CT), magnetic resonance imaging (MRI), or ultrasound, and they may be instrumental in developing new imaging protocols and algorithms (Bushberg et al., 2021).

Nuclear medicine overlaps with both therapy and imaging, in that it uses radioactive material administered to patients for both imaging and therapy purposes. Nuclear medicine physicists work with nuclear medicine physicians to administer radiopharmaceuticals, or drugs that contain radioactive material, to patients. This may be for the purposes of imaging, such as with a positron emission tomography (PET) scan or single-photon emission computed tomography (SPECT) scan, or for treatment, such as using iodine-131 for thyroid treatments (Cherry et al., 2012). Physicists in nuclear medicine are involved in the design, operation, and ongoing assessment of the equipment used in these procedures; they optimise the exam image quality; and they monitor and handle the required radioactive materials.

Lastly, medical physicists working in health physics focus on protecting both people and the environment from radiation hazards. They are involved in writing, interpreting, implementing, and enforcing regulations and guidelines involving the safe use of radiation and radioactive materials, and they also help in the execution of the response in the case of a radiation emergency (Bevelacqua, 2008). Some physicists specializing in health physics act as the Radiation Safety Officer (RSO) of medical facilities, an important role in the implementation of a radiation protection program.

The aim of this paper is to describe motivation for incorporating topics in radiation therapy physics, medical imaging physics, nuclear medicine, and health physics into the physics classroom, and give examples of content that could be used at the secondary education and introductory university levels. Using actual clinical data in the classroom can help connect students to real-world questions and problems without the expense, safety and privacy concerns, logistical difficulties, or time obligations involved in traveling to an industry site or a clinical radiation oncology, nuclear medicine, or radiology department.

Why use medical physics in the physics classroom?

Previous work has shown that curricula that students perceive as applicable to the “real world” or connected to content from other coursework is considered by students as engaging and interesting (Geller, Turpen, & Crouch, 2018). Unfortunately, many undergraduate students enter the introductory physics classroom with the impression that the study of physics is a collection of facts and abstract formulas, disconnected from their experience (Milner-Bolotin, Antimirova, Noack, & Petrov, 2011). Without connection to actual situations and experiences, students may become disengaged and disinterested. Cancer can be a complex topic, but many students will come to the classroom with some personal exposure to a cancer diagnosis, possibly through family, friends, or knowledge of a public figure's experience with cancer. For these students, it may be straightforward to establish the relevance of studying physics when it is presented in the context of a disease that is applicable to themselves personally or to people they know. Further, previous work has shown that university physics students struggle to identify career opportunities outside of "researcher" or "teacher" (Nielsen & Holmegaard, 2016). Including applied physics topics in the physics classroom may help to motivate students to consider possible career opportunities.

Pre-medical, pre-health, and pre-nursing students may be required to take courses in physics as a criterion for graduation and to prepare for entrance exams. Surveyed undergraduate pre-medical students indicated that during a semester of a traditional introductory physics class, the perception of relevance of the course material actually decreased as the semester progressed (Kortemeyer, 2007). These same students identified that medically related topics would be strongly preferred by students (of all the quantitative items of the course-specific survey, pre-medical students ranked their preference for the examples of applications of physics in medicine as the strongest suggestion for inclusion for the class). When this suggestion is implemented, it is shown to have a positive effect on students. For students pursuing programs in life sciences, studies have shown that introductory physics for life sciences (IPLS) courses may be more successful when they showcase physics concepts using examples from life sciences. By using these types of examples, educators have shown an increase in student interest, performance, and positive attitudes for the IPLS learning material (Crouch, Wissittanawat, Cai, & Renninger, 2018). Medical physics topics offer a wealth of content that highlights this relevance for students.

Critical thinking and problem solving in physics have long been foundational skills required of physics and engineering students, and IPLS students also require these competencies. The Medical College Admission Test (MCAT) is a standardised, multiple-choice, computer-based exam administered by the Association of American Medical Colleges. The exam is used to assess prospective medical students prior to admission to medical school, and is used in Australia, Canada, the United States, and Caribbean Islands. The exam is scored in four sections, of which one is chemical and physical foundations of biological systems (AAMC, 2023). Analyses of MCAT exam questions using a Bloom's Taxonomy framework demonstrated that MCAT questions required students to engage in critical thinking, well beyond simple recall for "plug and chug" style physics questions (Meredith & Bolker, 2012; Zheng, Lawhorn, Lumley, & Freeman, 2008). Medical physics problems often involve both complex physics concepts drawn from multiple areas of physics, as well as a practical use of a range of analytical and computational tools. By integrating these types of problems into physics courses, educators encourage students to continue developing problem-solving skills in a real-world context.

By incorporating medical physics topics into their physics classrooms, educators can encourage students to wrestle with socio-scientific issues. Socio-scientific issues (SSI) are complex, open-ended, and real-world topics that involve scientific, social, and ethical components. Previous work has shown that SSI-based classroom instruction advances students' critical reasoning, science literacy, and interest in the curricula (Namdar & Namdar 2021). Students in UK secondary schools using bioethics, physics, and ethics online modules found open-ended ethical dilemma questions and thought experiments unexpectedly rewarding (Green & Wishart, 2008). Topics in cancer healthcare, including those in medical physics, offer a wealth of relevant, concrete, and timely questions to challenge students. Available SSI-based subject matter directly related to medical physics includes disparate patient population access to technology such as MRI or proton therapy, risks of negative quality of life outcomes following radiation treatments, historic radiobiology research such as the Saenger total body irradiation experiments, financial toxicity of diagnosis and treatment for cancer patients and their families, and financial and environmental implications of treatment and diagnosis of disease.

Lastly, introducing medical physics in the introductory physics classroom may serve to inspire students to study physics with the goal of working in medical physics, or adjacent fields, as an eventual career. Most secondary and lower-level university students have not heard of medical physics. Though students can understand that careers in healthcare may be a rewarding profession, when surveyed high school students were asked to identify three job opportunities within a hospital, they struggled to identify any options aside from physician or nurse (Buckley, 2016). Clearly, many of these surveyed students have not been introduced to the range of positions in healthcare science available as future job opportunities. Clinical medical physics, just one of these many possibilities, can be used as an example career to interest students in physics. Medical physicists describe finding their field rewarding, often reporting high levels of career satisfaction (Chen, Arnone, Sillanpaa, Yu, & Mills, 2015). However, students interested in physics early in their studies may not be aware of the existence of this field, or of the possibility to pursue medical physics as a career. Integrating topics in medical physics into the curricula may then serve two purposes: first, it may stimulate learning as a relevant and connected topic to students' prior knowledge and interests; and second, it may inspire students to consider pursuing physics as a serious topic of study in preparation for a possible career opportunity.

Examples of medical physics topics

At the graduate university level, formal medical physics education is often well defined and rigorous, with dedicated training programs available (Loughery et al., 2017). As previously discussed, introducing medical physics topics in more introductory-level physics classes can also provide benefits for students, including at the secondary and undergraduate university levels. Previous work has shown success for incorporating these types of programs at the secondary level, in which lesson plans were developed to connect to the topics already addressed in the standard science curriculum (Buckley, 2016).

At the undergraduate level, previous publications describe the experience at small, liberal arts colleges in the U.S., including at Carleton College (Christensen, 2001) and Haverford College (Amador, 1994). Carleton College is a private U.S. college with an undergraduate enrolment of approximately 2,000 students at the time of that publication. For this program, an intermediate-level physics class devoted solely to medical physics topics was developed. The ten-week course was shown to attract both physics majors and pre-medical students. It included field trips to Medtronic Corporation (a biomedical manufacturing company), the Department of Radiology at the University of Minnesota, a local ophthalmologist practice, and the Department of Biomedical Engineering at the Mayo Clinic. At Haverford College, an introductory-level physics course was designed as a two-semester freshman introductory physics class for pre-medical students. The course was purely algebra-based (and did not require calculus as a prerequisite for the course). Topics of the course included fibre optic scopes; laser surgery and photodynamic therapy; radioactivity and radiobiology; radiation therapy; and radiography, ultrasound, PET, CT, and MR imaging. The course used a lecture-based format, with either a laboratory or an outside professional visitor coming to the classroom approximately every other week. Both publications describe the lack of a comprehensive, single textbook at the appropriate difficulty level available for this type of course; however, many resources are available for educators interested in incorporating medical physics topics into the introductory physics classroom. Even without a dedicated textbook at that time, these educators and others have found a wealth of possibilities for medical physics topics as suitable content for this audience. Possible topics include using radioactive decay to explore basic statistical processes and distributions, magnetic resonance imaging to discuss introductory topics in quantum mechanics and electricity and magnetism, and medical ultrasound to delve into topics including oscillations and waves. Three concrete examples of medical physics-based lesson plans are included below, using real clinical data. These lesson plans have been implemented at a US-based public university with an enrollment of approximately 12,000 students, in an elective physics course. Prerequisites for the course included three quarters of introductory physics coursework (either the calculus-based series or the non-calculus-based series) and two quarters of calculus. Prior to introducing these topics, some introductory radiation physics is covered in class, including a basic introduction to photon interactions (the photoelectric effect, coherent scattering, Compton scattering, and pair production), and a class session on radiation exponential attenuation when traversing a medium.

Exploring the inverse square law with linear accelerator data

Linear accelerators are large machines that generate high-energy radiation for the purpose of targeting cancer cells. They work by accelerating electrons close to the speed of light, and then crashing these particles into a target, resulting in high-energy photon ionizing radiation. Patients treated with linear accelerators are treated using external beams of radiation, meaning that beams are aimed from the outside of the patient to the target to kill cancer cells at the convergence of those beams. Therapy medical physicists take many precision measurements of various aspects of clinical linear accelerators, to ensure that the accelerators are operating as expected and within safe tolerances for patient treatments.

A type of tool that medical physicists use with linear accelerators is a radiation detector called an ionization chamber. Ionization chambers can be used to measure charge collected as a result of incoming radiation. As the detector is moved to different positions, different amounts of signal will be collected. If the detector is positioned directly in the beam path, then the signal collected is a function of the distance from the radiation source as well as various characteristics of the beam (including energy and field size). As the distance between the detector and the source is increased but no other characteristic of the beam is modified, the signal decreases proportional to the square of the distance between the source and the detector. Collecting this data is a trivial exercise in the clinic but can be instrumental in having students personally derive the inverse square law. At the university level, many students will be familiar with inverse square relationships through previous learning (including Coulomb’s Law and Newton’s Law of Gravitation). By deriving this relationship in a practical setting, students can build connections to prior learning and experience.

Analysing radiation attenuation and penetration characteristics using a shielding study

When high-energy, ionizing radiation passes through a medium, some of it may penetrate the medium, and some of it may be attenuated. The intensity of a given beam passing through a medium declines exponentially with distance from the initial intensity at the medium surface. This relationship can be expressed in terms of an attenuation coefficient. When radiation therapy is delivered in hospital and clinical settings, it is often in the setting of large bunkers called vaults that are lined with materials such as concrete, lead, and steel. These construction materials are used for their attenuating properties–it is important to include these shielding considerations in the construction of vaults for the health and safety of people located in areas surrounding the vaults. Various regulatory bodies such as the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NRCP) make recommendations about safe levels of radiation protection and maximum recommended radiation exposure levels for members of the public (including patients and other hospital visitors) as well as radiation occupational workers (including those working within a radiation therapy department or radiology practice).

For a laboratory exercise focused on an important health physics topic, students can explore concepts of radiation attenuation and penetration by analysing actual clinical blueprints of vaults to determine required thicknesses of concrete and lead to shield an imaging or treatment vault. The type of equipment included within the vault could vary–for example, there are lower shielding requirements for a CT scanner than for a linear accelerator, but both result in ionizing radiation and both must have shielding assessments completed to assure safe operation of the equipment.

Examining three-dimensional image space and Fourier analysis using CT image reconstruction

Although three-dimensional datasets and vectors are often introduced at the secondary education level, surveys of incoming introductory university level students show that students still struggle with these concepts (Nguyen & Meltzer, 2003). Reviewing and manipulating CT image datasets allows students to adjust the window and level settings, rotate, and otherwise practice manipulating real three-dimensional datasets in real time. Resources such as the web-based platform eContour, available at http://eContour.org (Panjwani et al., 2019), offer a library of real, anonymous patient CT data for a variety of anatomical sites. Students can practice identifying various anatomical landmarks as well as common imaging artifacts such as those caused by dental restorations, such as crowns and fillings. Image datasets of specialised quality assurance test objects called phantoms can be used by students. For example, the CatPHAN (The Phantom Laboratory, Salem, NY, USA) is a cylindrical phantom that includes embedded objects that are used by medical physicists to assess various aspects of image quality (Husby, Svendsen, Andersen, & Martinsen, 2017). Most radiation therapy and radiology departments have access to similar commercially available or in-house phantoms, and a CT image dataset of such a test object can be used for students to learn to use basic image dataset tools including measuring in three dimensions and comparing views in different planes. This type of dataset can also be used to develop foundational skills in three-dimensional geometrical problems, such as by using embedded wires installed at known angles within the CatPHAN to calculate the axial slice thickness by leveraging basic trigonometry relationships.

For more advanced students, conversations involving CT image reconstruction, or the process in which a raw image dataset is reconstructed into a useable image dataset, can be an informative starting point for an introduction to Fourier analysis (Fagerstrom, 2020), tying in to learning material advanced undergraduate students may have seen previously in the context of quantum mechanics.

Strategies for including medical physics topics in the physics classroom

Physics educators have made great strides in incorporating medical physics topics in some introductory physics classrooms. These include innovative new curricula, such as new IPLS courses specifically designed for students interested in life sciences. In addition to introducing new topics and content in introductory physics classrooms, educators may also be interested in innovative methods and learning strategies for these courses. Previous work has shown that traditional university physics course formats (including lectures, whiteboard work, and laboratories) are inefficient at reversing student misconceptions (Johnston & Miller, 2000). Active learning is a type of teaching that attempts to avoid passive student and active teacher roles–common in lecture-based courses (Megawa & Zimanyib, 2019). Instead, courses centred around active learning strategies endeavour to incorporate student hands-on participation, collaboration, and discovery learning, with the goal to encourage students to reach higher levels of Bloom's Taxonomy of Learning (Bloom, 1969), including critical thinking and the ability to apply knowledge. By incorporating active learning strategies, educators can lean into a learner-centred approach. New modes of active learning delivery demonstrate that the flipped classroom format can be used with success for these types of topics (Bawaneh & Moumene, 2020), as can e-learning (Woo & Ng, 2003). Medical physics instruction has been used with project-based learning (Howell et al., 2013), practice-based learning (Kapur, 2015), and peer instruction (Starkschall, 2009).

As one example of these possible active learning environments, the flipped classroom approach has been shown to improve student achievement in general physics courses when compared to lecture-based courses. Related courses, such as introductory astronomy, have also shown favorable outcomes when switching from a traditional lecture-based format to a flipped classroom. As a case study, Lazendic-Galloway, Fitzgerald, and McKinnon (2016) adjusted a first year elective astronomy course, which had been taught for the previous sixteen years as a traditional lecture/laboratory course, to a flipped classroom studio-based course. The traditional format had relied on three one-hour lectures and one two-hour laboratory session per week, for a cohort of >200 students per term. The revised format was structured as two, two-hour workshops per week. This change involved preparing pre-class modules, including reading materials, educational videos, and multiple-choice required questions. Instead of lectures, class time was spent running workshops, beginning with a 10-15 minute introductory/reminder "mini lecture," then activities using simulations, actual astronomical data, and paper-based problems. Following class, students were required to complete assignments as well as a course project. Students taking the flipped classroom version of the course demonstrated statistically significant increases in test scores and decreases in overall course failure rates compared to those who had taken the traditional version of the course.

The flipped classroom approach has also been used specifically for teaching medical physics. Bawaneh and Moumene (2020) described a university course on core concepts in medical physics that introduced students to topics including radiology, radiation oncology, nuclear medicine, electrocardiography, laser surgery, MRI, and ultrasound. They compared a conventionally taught lecture-based version of the course to a flipped classroom version taught concurrently. For the flipped classroom version of the course, video and audio passages were uploaded through the institution's electronic learning management system, and students were required to review these materials prior to class. During class time, students were divided into small groups and worked together to complete concept questions. For some of the class periods, a short (15-20 minute) lecture was included to address content students found especially challenging, based on results of integrated formative assessment. The amount of class time devoted to the mini lectures and small group work in the flipped classroom was the same as for the traditional lecture-based class. Pre- and post-test results showed greater statistically significant gains in concept understanding for the students taking the course in the flipped format, compared to the traditional lecture-based format.

In summary, there may exist advantages for students enrolled in introductory physics classes when medical physics topics are incorporated into the curricula. Medical physics-focused lesson plans can be designed with the appropriate complexity for both secondary education physics courses as well as an introductory university physics series. At the university level, these topics may serve life science students in the IPLS classroom as well as early-career physics and engineering students. By including these types of topics, students benefit from curricula that they may see as less abstract and more concretely applicable to real life. They may also develop problem-solving skills and be inspired to engage in SSI-based topics. After working with medical physics problems, some students may even be motivated to explore additional physics courses as a gateway to a potential career.

Acknowledgements

Sincere thanks to Krista Burton and Sukhjit Kaur for their informative discussions on these topics.

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