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Infrared Radiography: Modeling X-ray Imaging Without Harmful Radiation

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Planar x-ray imaging is a ubiquitous diagnostic tool and is routinely performed to diagnose conditions as varied as bone fractures and pneumonia. The underlying principle is that the varying attenuation coefficients of air, water, tissue, bone, or metal implants within the body result in non-uniform transmission of x-ray radiation. Through the detection of transmitted radiation, the spatial organization and composition of materials in the body can be ascertained. In this paper, we describe an original apparatus that teaches these concepts by utilizing near infrared radiation and an up-converting phosphorescent screen to safely probe the contents of an opaque enclosure.

Motivation

Electromagnetic radiation and the electromagnetic spectrum are an important part of the introductory physics curriculum. The discussion of light interaction with matter is of special relevance to pre-health and life science students as many diagnostic techniques and research tools are based on it. The specific aim of the apparatus and accompanying laboratory exercise described in this paper is to demonstrate core physics principles underlying an essential medical imaging technique while promoting a conceptual understanding of properties of electromagnetic radiation, attenuation, and image formation through hands-on experimentation. The apparatus can serve as an introduction to radiography techniques and a platform to introduce more complex techniques, including computed tomography (CT). In addition to the application as a lab exercise, the construction of the apparatus can be assigned as a project for an upper-level undergraduate student and involves additional concepts including: circuit design, polarity driven solvent/solute interactions, and two-photon absorption processes. The apparatus and laboratory activities presented here are part of a larger effort to develop undergraduate physics curricula in a biomedical context.[1-5]

Apparatus

Using x-rays in an educational setting can be expensive and require considerable safety precautions. However, the concepts underlying radiography can be taught using safe and inexpensive visible or near infrared (IR) light sources.[5-6] Just as invisible x-ray radiation is used to image the human body, we use invisible IR radiation to image the inside of an opaque enclosure. Both imaging methods result in a two-dimensional projection of a three-dimensional volume. The two-dimensional image gives a profile of the objects, which cannot be seen with the human eye, and the intensity of radiation present at the detector is used to characterize the composition of the concealed materials through a comparison of relative attenuation characteristics.

The principle components of the apparatus are an IR light source, an IR detector, an attenuation slide, and an opaque enclosure, in which various objects can be placed (Fig. 1).[7]

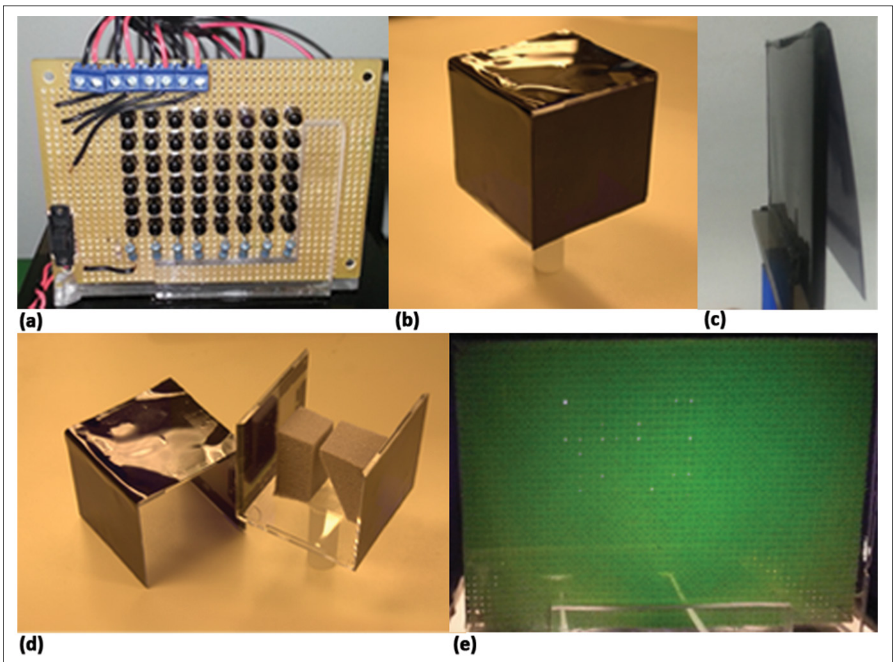

Fig. 1. Radiography apparatus components: (a) infrared LED array, (b) enclosure mostly opaque to visible light but mostly transparent to IR, (c) slide with various attenuation coefficients, (d) objects concealed within the enclosure, and (e) detector screen emitting green light upon excitation by infrared light.

1. Emitter The emissive source, an infrared LED array, was constructed using 48 SFH 4547 high-intensity LEDs (940 nm)[8] powered by four 9-V batteries in parallel. The peak emission of the LEDs was chosen such that it was invisible to the eye (like x-rays), not harmful (unlike x-rays), and matched well with the peak absorption wavelength of the up-converting phosphor of the detector: 952 nm. [see Fig. 1(a)].

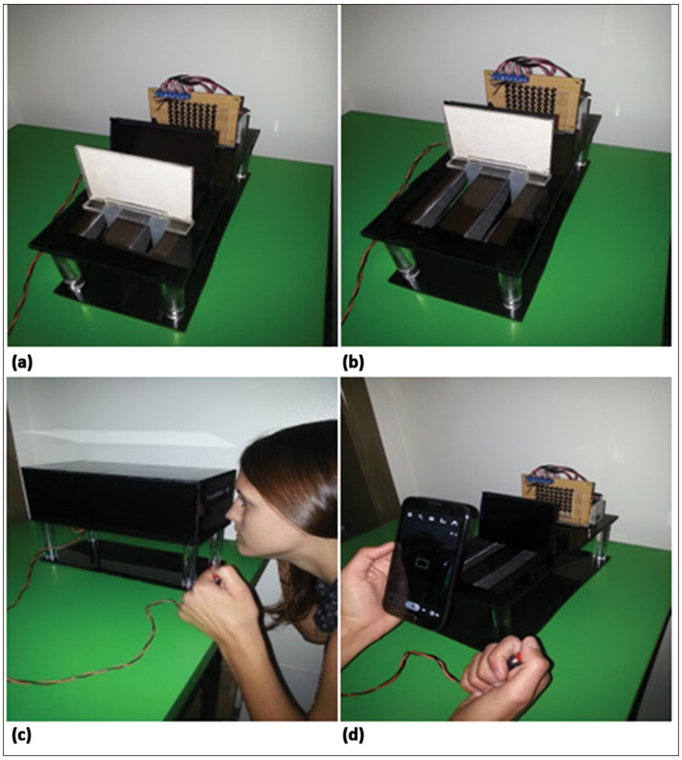

Fig. 2. Arrangement for examination of attenuation effects on transmission. (a) Place the detector and slide on the base. (b) Move the detector until it is against the slide. (c) Place the lid on the base, hold the button, and view the image through the slot. (d) Remove the lid and detector and view the image with a cellphone.

2. Detector To obtain a sufficiently large detector screen [see Fig. 1(e)], 1 g of IRUCG- IR phosphor[9] was suspended in 8 mL of polyurethane and subsequently applied to a piece of cloth (3 in x 2 in). The phosphor converts the invisible IR light and makes it visible to the observer through an anti-Stokes shift.[10] The IRUCG phosphor emits 552-nm photons. Due to the small size of the up-converting phosphor particles, an even distribution is achieved by suspension in a liquid and application to cloth or paper.

3. Enclosure The enclosure [3 in x 3 in x 3 in, see Fig. 1(b) and (d)] was constructed from a display case covered with Congo Blue filter #181, which is mostly opaque in the visible spectrum but largely transparent to IR.[11] The enclosure can be rotated so one can see how the projection of an object inside the container appears on the screen from different angles. The objects selected should have clearly defined edges and significantly differing profiles in order to produce clear images. In order for the demonstration to be performed in a well-lit room, we used a lid that fit over the apparatus with a viewing port near the detector [Fig. 2(c)].

4. Attenuation slide X-ray imaging is based on the different attenuation characteristics of different tissues in the human body. To demonstrate the effects of a material's composition on the transmission of radiation, an attenuation slide [see Fig. 1(c)] was constructed from two different kinds of

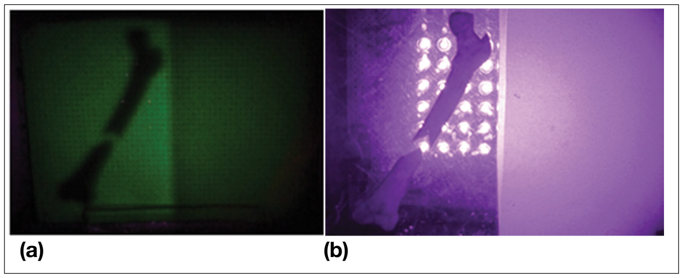

Fig. 3. (a) Image of the analog up-converting phosphor detector and (b) digital image taken with a cellphone, displaying differences in image intensity corresponding to varying attenuation coefficients of materials in the slide. The left half (Congo Blue) of the slide is most intense, the right half (tissue paper) appears dim, and the bone (construction paper) appears dark as all transmission is blocked.

paper and an optical filter. To conceal the arrangement, both sides of the slide were covered with the Congo Blue filter. One side has a removable flap so the arrangement can be examined after the exercise.

5. Alternative emitter and detector An alternative construction of the apparatus can be completed with an infrared flashlight and a digital camera. The silicon sensors of digital cameras are sensitive to near IR light at wavelengths lower than about 1000 nm. Digital cameras are therefore equipped with infrared filters, but these filters typically do not block all infrared light. The images in Figs. 3 and 4 were taken with a Samsung Note 2 cellphone camera. To boost the infrared sensitivity for many point-and-shoot cameras, the infrared filter can be removed.[12] The use of a camera with a weak or removed IR filter enables the demonstration to be performed in a well-lit room without requiring a lid or enclosure to block ambient light. This presents opportunities for instructor demonstrations to a larger group as well as student exploration of additional topics including the band gap of semiconductors, why silicon sensors are used in imaging, and the requirements for "night vision" and thermal imaging.

Experiment 1: Attenuation

In the first activity, students explore attenuation with a slide constructed from the Congo Blue filter and two pieces of paper (construction paper and vellum) (Fig. 2). This slide enables the student to visually observe the difference in radiation transmission through each material by comparing differing intensities at the phosphor screen. These varying intensities can be used to infer the relative attenuation coefficients of the various materials in the slide.

Students are asked to observe the intensity of infrared light seen on the detectors and compare them to each other as well as to analogous parts of the human body (Fig. 3). For example, the Congo Blue filter is largely transparent to IR light, similar to how skin tissue is largely transparent to x-rays. Conversely, the vellum used for the right half of the attenuation slide blocks a fraction of the light and resembles organs in radiological images. The construction paper used to cut out the shape of a bone in the attenuation slide blocks

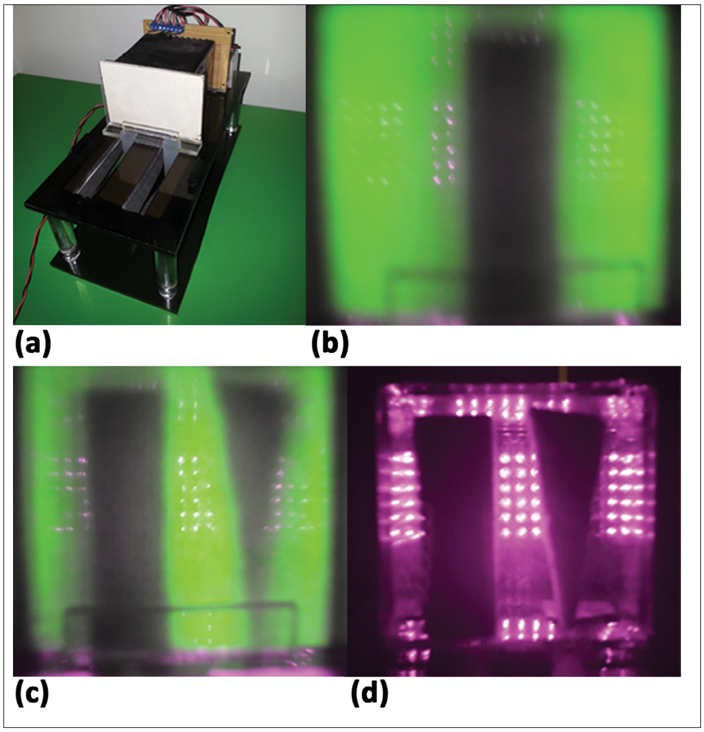

Fig. 4. Planar images of concealed objects similar to Fig. 1(d). (a) Experimental setup for the planar imaging activity. Figures (b) and (c) show how additional information about the objects can be attained by viewing from two angles. Figures (c) and (d) illustrate the differences between analog (phosphor screen) and digital (cellphone camera) detectors.

a majority of the emitted light, resulting in a dark area on the detector. This is analogous to bone and metal blocking x-ray transmission, resulting in unexposed areas on x-ray film.

Experiment 2: Planar imaging

In the second activity, students explore how three-dimensional objects appear in planar imaging. An enclosure surrounded by material that transmits infrared light but absorbs visible light causes the identity and position of any objects inside to be obscured from sight [Fig. 1(b)]. Students quickly discover that a two-dimensional image of a three-dimensional space is insufficient to determine the spatial arrangement of the unknown objects. For example, if two objects are in the enclosure, an image from only one angle will not provide a complete description of object orientation, number, and shape. By rotating the enclosure, students can view the contents of the box from multiple angles and thereby discern the shape and orientation of the objects contained within (Fig. 4). Students discuss what information they can obtain from each vantage point and sketch an image of the object before opening the enclosure. It is also possible to design the objects so that two exposures reveal only some of the spatial information, which demonstrates how more projections from multiple angles are necessary to get 3-D information of more complex objects. In this way, the activity can serve as an introduction to CT. Students can also discuss the limitations of planar images and weigh the benefit of full three-dimensional CT images against the cost of increasing radiation exposure that comes with imaging from multiple angles.

This exercise can lead to discussions of medical imaging techniques. For example, in radiological terms, Figs. 4(b) and 4(c) represent an analog to digital conversion. Specifically, the phosphor screen represents the x-ray sensitive plate while the digital image of the phosphor screen represents the digitization of x-ray images to a portable digital imaging file. Another imaging method is displayed in Fig. 4(d): images are taken without the analog phosphorous screen in place and represent direct capture of the radiation with a digital camera. Additionally, the methods of image formation using the presented apparatus and those in the medical field can be compared and contrasted. In the demonstration, photons from the emitter interact with the detector, visible light is produced, and the image of an object appears dark because it blocks transmission. This is the opposite of planar images taken with x-ray sensitive plates for medical diagnostics, where the detector is initially white and darkens upon exposure to x-rays.

Additional activities

Before conducting the lab, students are asked to calculate the energies of photons in the infrared, visible, and x-ray spectrums in both joules and electron volts. These energies are compared to energies involved in breaking atomic bonds and the implications are discussed; for example, DNA damage can occur through radiation having energy over a certain level. Students also calculate the energy of the Bremsstrahlung that occurs when electrons hit a tungsten target. The lab gives the opportunity to discuss how the attenuation coefficient is related to radiodensity as quantified by the Hounsfield Unit[13] in radiology. Throughout this exercise, students can compare analog and digital imaging through the use of the detector and their own cellphones, as well as compare the components of the apparatus to actual radiographic equipment. The construction of the apparatus can be assigned as a project for advanced undergraduate students and involves concepts covered later in a physics curriculum.

Conclusion

This device allows for safe, interactive, and engaging exploration of topics covered in undergraduate physics and biology courses for pre-health and life science majors without the high cost of specialized equipment and the danger associated with high-energy radiation. The hands-on demonstration renders the traditionally difficult and abstract concepts of electromagnetic radiation, attenuation, and planar projection approachable through use of a cost efficient device.

Acknowledgments

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Fermi Questions

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Question 1: Plane friends

What is the probability that you will recognize someone on your next airplane flight?

Question 2: Shaving time

How many people are shaving themselves right now? How much time do we spend shaving over our lifetime? (Include faces, armpits, legs, etc.)

Look for the answers online at *tpt.aapt.org*. Question suggestions are always welcome! For more Fermi questions and answers, see the now available *Guesstimation 2.0: Solving Today's Problems on the Back of a Napkin,* by Lawrence Weinstein (Princeton University Press, 2012).

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