Chapter 1
Introduction to Phantoms of Medical and Health Physics

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1.1 Introduction

Phantoms, devices that represent the human body, have been used in medical physics and health physics since the beginning. Soon after the discovery of X-rays, news of the medical benefits of radiation quickly spread. The first X-ray image of a human was taken of Prof. Wilhelm Roentgen's wife's hand in 1896 [1]. However, the harmful effects of high radiation doses became apparent as erythema and cell squamation were common side effects associated with the early use of medical radiation. People were reluctant to volunteer to receive radiation for experimental reasons. Consequently, physicists developed phantoms to simulate patients in order to make dosimetric measurements and to test the limitations of their systems.

The design and composition of a phantom are determined entirely by the purpose the phantom is to serve. A phantom that has been developed to evaluate the dose delivered to a patient during radiation therapy treatments will be drastically different from a phantom designed to test the imaging limits of a kilovoltage radiographic system. The purpose of the phantom will dictate the physical design of the phantom, such as the size, shape, composition, and other details of the phantom such as composition. It will also determine whether or not the phantom is to contain dosimeters (for example, TLDs or ion chambers) and what type of other elements would best suit the given situation.

The materials within a phantom are often intended to simulate human tissue. However, the properties of these materials vary with the energy of the radiation incident upon them. Thus, while something may be tissue equivalent over a given energy range, it may not be tissue equivalent over all energies. As a result, a phantom designed for use in megavoltage X-ray beams will often be made from different materials than a phantom designed for kilovoltage beams.

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Phantoms have become popular and are used in all aspects of medical physics applications. Simple, water-based phantoms exist to measure the output of megavoltage therapy beams. More complicated, anthropomorphic phantoms are used to test the ability of the megavoltage beams to accurately deliver a treatment. Imaging phantoms have been designed to test the limitations of X-ray imaging systems. These typically test the achievable resolution of the X-ray beam and the detector system, as well as the amount of contrast needed to distinguish objects from one another. Similar phantoms exist to test the same properties of ultrasound (US), computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET) systems. Computational phantoms have also been developed for use in computer simulations. Phantoms can also be designed to test the effects of positional errors and organ motion for both imaging and therapy applications. The various types of phantoms will be discussed in detail in the later chapters of this text.

1.2 History

Once the use of ionizing radiation became popular, the need for phantoms soon became apparent. Early in the twentieth century, it was recognized that in order to quantify the dose delivered to a tissue of interest, the measurement should be made on the tissue itself [2]. When the harmful effects of radiation were realized, the need for tissue substitutes became clear, and the concept of phantoms was born. The earliest phantoms were comprised of water or wax. The geometry of the phantoms remained fairly simple with water tanks and blocks of wax for measurements of radioactive sources or X-ray beams.

While water was (and still is) a very good approximation of the human tissues, wax presented a number of problems. Firstly, the formulations of wax varied significantly depending on the type of wax used. Thus, there was a lack of consistency among the early measurements. It was also soon discovered that wax deviated from tissue equivalency at the low energies. To alleviate this, materials with high atomic numbers were added to the wax mixtures. While this improved the radiological properties of the waxes, there was still a fair degree of variability that remained.

Wood was proposed as a potential tissue substitute and was fairly popular during the late 1930s, with use continuing in some capacities to the 1970s. There were similar problems with wood as there was with wax, as a degree of variability also exists among different samples of wood.

Around halfway through the twentieth century, an interest in developing geometrically realistic anthropomorphic phantoms occurred. A number of different anthropomorphic phantoms were developed which produced a variety of whole body phantoms as well as phantoms that covered smaller segments of the body. However, the inconsistency of tissue equivalent materials still presented a large obstacle at the time. In the 1960s, two advanced anthropomorphic phantoms were introduced. Stacey et al. [3] and Alderson et al. [4] both developed phantoms, known as the Temex™ phantom and the Rando® phantom, respectively, that contained real human skeletons embedded in a tissue substitute. The phantoms were sliced axially, and the Rando® phantom allowed for the insertion of thermoluminescent dosimeters (TLDs) into cavities to measure the dose distribution.

While the phantoms discussed up to this point have been designed for dosimetry of radiotherapy treatments, a number of phantoms were developed for imaging systems. In the 1970s, a number of mammography phantoms were developed along with phantoms for CT, radiography and image intensifier systems. However, some imaging phantoms were developed as early as the late 1940s. Improvements and variations of these early imaging phantoms have been developed, but their main purpose has remained to test the various aspects of image quality of the system in question. Phantoms were also developed for non-ionizing applications such as US and MRI. Like the phantoms designed for testing systems that make use of ionizing radiation, the main parameters of concern are the related to the quality of the image produced by the system.

Phantoms have become more complex and more reliable over time as the materials used to manufacture them have become more reliable and reproducible. New tissue substitutes like epoxy resins and polyurethanes have allowed for phantoms of higher quality and greater reproducibility. This progression has also led to the development of phantoms that accurately mimic tissues over a wider range of energies.

With the rise in popularity of computer simulations in the field of medical physics, there came a need to represent the human body in these simulations. The detail and complexity of the computational phantoms have increased with the increased computing capacity of the available technology. Advanced imaging modalities such as CT and MRI have aided in the creation of these complex computational phantoms. The development of these phantoms have been accompanied by the rise of complex radiation transport codes, and together they have led to improved radiation dosimetry and measurement. Doses can be calculated to a variety of different tissues using these mathematical phantoms, such as the Virtual Man [5].

1.3 Phantom Materials

The selection of the appropriate materials is critical to the design and function of any type of phantom. In most cases, a phantom is meant to simulate some form of tissue, such as muscle, bone, or lung. Another very common simulated material is water, as the use of liquid water can prove to be difficult and cumbersome in certain situations. The simulated tissues all have different properties, both physically and radiologically, and the goal of the phantom materials is to represent these physical and radiological properties as accurately as possible.

There are a number of properties that can be used as a measure of the tissue equivalence of a phantom. The physical density (ρ) and effective atomic number (Z_{eff}) can both be used as relatively crude assessments of a materials tissue equivalence. While these parameters provide insight into the physical properties of the material in question, they do little to describe the material's radiological properties. The electron density (ρ_e) of a material is a more detailed parameter that provides more insight into how a material will behave in a radiation field. The most widely used and commonly accepted parameter to gauge tissue equivalence is the mass energy-absorption coefficient (μ_{en}/ρ) as it gives an indication as to how much energy is deposited locally in the tissue of interest [6, 7]. Ideally, a material will accurately represent as many of the aforementioned properties of the tissue that is being simulated. However, this can be very difficult to achieve, and one should primarily aim to simulate the radiological properties of the tissue of interest.

In most cases, there are materials available that simulate tissues very accurately, yet there are a number of caveats that should be kept in mind when phantoms are being used. The radiological properties of a material are often highly dependent on the energy of the radiation incident upon it. Thus, a material may accurately simulate a tissue in a given energy range, but could differ significantly in other energy ranges. It is common to see phantom materials separated by the energy range in which they should be used, such as the kilovoltage (diagnostic) energies or the megavoltage (treatment) energies. There are also materials available that have been developed to simulate tissues in both the diagnostic and the treatment energy ranges. However, even within a given energy range, the spectrum of the beam being used is often very wide, causing error to always be present to some degree.

It should be noted that the previous discussion is in reference to phantoms that are to be used in fields of ionizing radiation. That mass energy-absorption coefficient of a material would not necessarily be an accurate measurement of tissue equivalence for MRI or US purposes as these two imaging modalities operate on different physical principles.

1.4 Dosimetry Phantoms

Dosimetry phantoms are used when there is a need to simulate the conditions of a procedure in order to measure dose at certain points of interest. It is clearly impractical and dangerous to place an actual human in the beam to take measurements, and perhaps even more impractical to place dosimeters inside a human to make the measurements. This was the impetus for the first dosimetry phantoms, as tanks of water or slabs of tissue equivalent materials were designed to hold dosimeters and allow for measurements "in tissue" without any unnecessary exposure to the people involved.

1.4.1 Phantom Construction

As discussed earlier, the first phantoms were fairly simple, consisting of slabs of wax or tanks of water. These phantoms, while seemingly unsophisticated in design, continue to be used in many aspects of dosimetry. While wax slabs have fallen out of use, slabs of other materials (e.g., epoxy-based materials), such as Virtual Water™ and Solid Water®, have remained popular. Their advantage lies in their simplicity and ease of reproducibility. Their position in a beam can be easily replicated, so measurements can be made under the same conditions at different institutions and at different times. Water tanks also allow for an essentially infinite number of locations at which to place a dosimeter. The tanks allow for scanning of the beam with ionization chambers. The advanced positioning systems have been developed in order to allow for precise movement of the dosimeters within the water tank. The slab phantoms, while obviously more rigid in their design, can also be modified to hold dosimeters at number of different locations. Other rather simplistic geometries also exist for various purposes. For example, a simple cylindrical phantom is commonly used for the measurement of the computed tomography dose index (CTDI) [8]. Similarly, a uniform spherical phantom is typically used for Gamma Knife® dosimetry [9] because these shapes match the device's natural symmetry.

As discussed in the previous section, as time progressed, the need for phantoms that more accurately simulate the human body became increasingly evident. This led to the development of anthropomorphic phantoms. These phantoms were designed to physically resemble a body part of interest. These phantoms provide a more accurate representation of a human body which allows for dose measurements that correlate much better with the dose distribution within the human body. Another aspect of simulating the body is simulating aspects of how it moves, and phantoms have been designed to simulate these motions.

Regardless of the physical shape of the phantom, there is often an interest in introducing inhomogeneities into the phantom. It intuitively follows that more complex anthropomorphic phantoms employ more complex material distributions. However, this is not always the case. The aforementioned Rando® phantom has a detailed physical shape, but the only materials simulated in the phantom are bone, lung, and soft tissue. Similarly, some phantoms with simple exterior geometries can contain detailed internal structures [10]. One could even use various thicknesses of different slab phantoms to create a slab phantom with planar inhomogeneities. Phantoms that are anthropomorphic in their outward physical shape do not necessarily contain anatomically accurate internal structures, such as the RSVP Phantom® Head made by The Phantom Laboratory or the Radiological Physics Center's (RPC) head and neck intensity-modulated radiation therapy (IMRT) phantom. Both of these phantoms have specific purposes and have been designed to optimally and efficiently make the measurements for which they are designed.

Phantom design and construction are dictated by the phantom's purpose. Reference phantoms tend to be simpler in design for ease of reproducibility.

Phantoms designed for treatment verification purposes tend to more accurately simulate a human patient, though this is certainly not always the case. In certain cases, a detailed internal anatomy would be superfluous, while in others detailed internal structures are necessary to accurately simulate the procedure of concern.

1.4.2 Dosimeters

Any dosimetry phantom must inherently contain at least one dosimeter in order to measure the dose within the phantom. There are a number of possible dosimeters that can be used in this instance and each possesses a number of advantages and disadvantages.

Ionization chambers are commonly used for a number of reasons, including stability, negligible energy response, and their calibration to primary standards [11]. While ionization chambers are capable of providing dose at point, that dose value is a result of volume averaging. The use of a chamber should be avoided in areas where there is a steep dose gradient to avoid averaging over a large range of doses. Smaller chambers can be used to minimize this effect, but this decreases the output signal of the chamber and can also introduce a number of other problems [12]. The presence of the chamber's air cavity in the phantom can alter the field compared to when the chamber is not present, which can affect the dose measurements at locations near the chamber. Also, irradiation of the chamber stem and cable can cause leakage current which can affect readings. Ultimately, the reliability and flat energy response of ion chambers makes them well suited for dosimetry measurements in phantom. One simply must be aware of the shortcomings of ion chambers and account for them appropriately.

TLDs are also used frequently in phantoms. These solid state, integrating detectors vary in size and shape but share certain characteristics. They are generally fairly small and can be made as small as $(1 \times 1 \times 1)\ mm^3$ cubes. This small size allows for high spatial resolution and for measurement of fairly steep dose gradients when used properly. Many TLD formulations are also approximately tissue equivalent, which eliminates the field perturbation concerns present with ion chambers as discussed above. Most TLDs remain fairly linear up to about 1 Gy [13]. TLDs can also exhibit a rather severe energy response, particularly at lower energies [14, 15]. The use of TLDs can be tedious as their use involves a reliable annealing process and careful handling. However, if handled properly, precision less than 5 % can be achieved [16]. TLDs are well suited to phantom dosimetry as they are small, reliable, and tissue equivalent, integrating dosimeters. One must be aware of the both the dose and energy response of the TLD formulation being used, so as to avoid making errors in the dosimetric measurement.

Film dosimeters are commonly used in order to obtain a dose distribution with high spatial resolution. The two types of film are used for dosimetry purposes are radiographic film and radiochromic film. Radiographic film has been used extensively for dosimetric purposes, and the American Association of Physicists in

Medicine (AAPM) Task Group 69 [17] has published a detailed report on the use of radiographic film. Radiographic film is straightforward to use and can provide excellent measurements of dose distribution due to its extremely high spatial resolution. However, the response of any particular film can vary quite drastically due to variations in the film production process. It has also been observed that fluctuations in processor conditions can have rather severe effects on the optical density of the film. Because most films are composed of silver halide, which has a high atomic number, there is a significant energy response that must be accounted for when using radiographic film for dosimetry purposes. Despite these potential pitfalls, radiographic film can be used reliably as long as the appropriate precautions and corrections are taken into account.

The primary advantages of radiochromic film are that it is approximately tissue equivalent, and it can provide excellent spatial resolution. Additionally, it does not require a processor in order to develop. The report of AAPM Task Group 55 [18] covers radiochromic film dosimetry in detail. In 2012, the AAPM approved Task Group 235 in order to update the report of TG-55 to include a more detailed review of the literature and further investigate radiochromic film dosimetry. Radiochromic film has been shown to have a number of problems, such as an orientation dependence and similar batch non-uniformities to those of radiographic films.

There are a number of other possible dosimeters that can be used in phantoms that are not discussed here. MOSFETs and diodes have been used for dose measurements at a point. There are a number of gels available that can provide three-dimensional dose distributions within a phantom. Each dosimeter has its own advantages and drawbacks. The proper choice of a dosimeter for use in a phantom requires a knowledge of quantity to be measured and an analysis of the advantages and disadvantages of each type of dosimeter being considered. One must always be conscious of the limitations of the dosimeter being used in order to obtain accurate and reliable dosimetric measurements. A thorough analysis of dosimeter choices has been performed by Low et al. [11], and the reader is referred there for further detail.

1.4.3 Computational Phantoms

Computer simulations of radiation treatments and measurements have become increasingly popular as computer technology has become more efficient. In order for these simulations to be relevant and useful, accurate representations of the irradiation conditions are necessary. Furthermore, if one desires to compare two different simulations, it is helpful if the same geometry is used. This has led to the development of computational phantoms. Computational phantoms can be as complex or as simple as the physical sample that they are trying to represent. They can simulate anything from a simple slab phantom to anatomically accurate humans.

In many situations, the calculations performed using the computational phantoms are compared to actual measurements. This can be useful to validate a Monte Carlo transport code, or if the code has already been validated, it can be used to verify a measurement technique or to generate correction factors. Generally, these types of simulations involve relatively simple geometries and are most commonly used in the realm of radiotherapy. The complex and detailed full body phantoms are used frequently in health physics applications. A number of whole body computational phantoms have been developed over the years. Recently, the International Commission of Radiological Protection (ICRP) has designed two reference computational phantoms, one male and one female [19]. The NORMAN phantom was developed from MRI data from a single patient by Dimbylow [20] and Xu et al. [5] developed the VIP-Man computational phantom. There are a number of other computational phantoms that have been developed, and comparisons have been performed to assess their performance relative to one another [21]. These are all typically used to assess organ dose and other quantities of interest in health physics. Computational phantoms are discussed in greater detail in Chaps. 12 and 13.

1.5 Imaging Phantoms

Since the 1980s, the amount of man-made radiation exposure per person has nearly doubled [22]. This is due in large part to the increased usage of diagnostic and interventional medical procedures. These systems have become a popular means to effectively and noninvasively diagnose a patient in almost any circumstance. However, this increased exposure has raised many concerns about the risks associated with medical imaging procedures. Ideally, it would be possible to minimize the dose to the patient while maintaining the image quality required to gather the necessary information. While dosimetric phantoms would be used to assess the dose from these procedures, most phantoms used in imaging systems provide an assessment of image quality.

There are a number of factors that determine whether or not an object will be visible in a medical image. From a simple radiograph to a CT scan, the size, shape, and radiation absorption properties of the structure and of the surrounding material affect whether or not that structure will be seen. Ultimately, the quantity of interest is the contrast of the structure, which is dependent upon the aforementioned factors. The spatial resolution of a system is also a quantity that is typically tested when evaluating performance.

Imaging phantoms need to address many of the same issues as dosimetry phantoms. Phantom materials must be chosen appropriately to properly simulate the tissues of interest. In order to generate any sort of useful image, at least two materials are needed. Many phantoms that wish to test the contrast limitations of a system will have a phantom which contains objects of various sizes and contrasts. These phantoms are often of relatively simple geometries and have been used for multiple imaging modalities. An example of a phantom of this type is the Catphan® phantom developed by The Phantom Laboratory for the assessment of performance of CT scanners. It contains objects of varying size and contrast in order to test the contrast resolution of the scanner. It also contains a line pair per cm gauge to test the spatial resolution of the system. There are a number of other tests this phantom is capable of performing. Phantoms such as these can be used not only to test the limitations of the CT equipment, but also the reconstruction algorithm being used [23]. Similar phantoms have been developed to test the limitations of radiography [24], MRI [25], PET [26], and US [27] systems.

In many imaging procedures, there is a desire to have a phantom that presents a more realistic situation. As a result, there are anthropomorphic phantoms that are shaped like human body parts, and they often contain highly detailed internal anatomy. The internal anatomy of these phantoms is often far more comprehensive than in dosimetric phantoms. This is because at the lower photon energies used in imaging procedures, smaller changes in material compositions have larger effects on attenuation properties. Thus, the difference between muscle and water may be relatively small at the megavoltage energies used in external beam therapy, but can be rather noticeable at the kilovoltage energies used in imaging. There are also anthropomorphic phantoms that are used to simulate dynamic procedures such as the injection of a contrast agent. Imaging phantoms have also been developed that contain unrealistic Fourier-based patterns to assess different properties of the imaging system such as the modulation transfer function. The various types and applications of imaging phantoms will be addressed in further detail in Chaps. 6–10.

1.6 Scope of the Text

This text is designed to provide an overview of the phantoms used in the past, present, and future of medical and health physics applications. There is a great deal of variety in both the physical design and the purpose of the phantoms used in the field. A brief overview of the topics to be covered in the text will be provided here, with detailed discussions to follow in later chapters.

1.6.1 Radiation Therapy Phantoms

Phantoms used in radiation therapy are almost always dosimetry phantoms although imaging phantoms are of increasing importance in therapy. The dosimetry phantoms include the water and epoxy-based slab phantoms that are used for reference purposes as well as the anthropomorphic phantoms that more accurately represent the human body. Some phantoms used in radiation therapy have been designed to simulate patient motion that occurs during radiotherapy treatments.

These can be used to assess the effectiveness of techniques designed to limit the effects of patient motion on treatment delivery.

Radiation therapy phantoms are used in brachytherapy applications. Dosimetry phantoms are used in order to characterize properties of brachytherapy seeds. These properties are later used for treatment planning purposes in clinical treatments. Because brachytherapy seeds are often of lower energy, the selection of the phantom material can have significant influence on how dose is distributed through the phantom. Thus, having a material that accurately mimics the material of interest is of critical importance. Deeper discussion of the phantoms used in radiation therapy will be provided in Chaps. 2–5.

1.6.2 X-ray Imaging Phantoms

A variety of phantoms are necessary to properly assess the characteristics of an imaging system. Conventional X-ray imaging, which includes radiography and fluoroscopy, and CT make use of phantoms of various designs and purposes. Anthropomorphic phantoms can be used to simulate patient images, which can be helpful when determining what X-ray tube settings should be used in a given situation or even when training new technologists or radiologists. Both conventional X-ray and CT systems must undergo acceptance testing and regular quality assurance (QA) procedures in order to ensure the systems are performing adequately and will continue to do so in the future. Phantoms have been designed to test all of the parameters necessary for assessing system performance. As these systems make use of ionizing radiation, the dose delivered to the patient during the procedure is of interest and is meant to be kept as low as possible. Dosimetry phantoms have been designed specifically to assess the dosimetric properties of both CT and conventional X-ray systems.

Mammography is a modality of particular concern for a number of reasons. It is a very common procedure as many women receive regular mammograms as a part of breast cancer screening. Also, breast cancer is the most common type of cancer in women [28], which magnifies the importance of a properly function screening system. Like the other X-ray imaging modalities, phantoms have been designed specifically for the assessment of mammography systems. Anthropomorphic phantoms, image quality phantoms, and dosimetry phantoms have all been developed specifically for use in mammography.

1.6.3 Non-ionizing Radiation Phantoms

While they may not make use of ionizing radiation, US and MRI systems must still be evaluated to ensure proper image quality is being maintained. Because these modalities make use of properties other than the radiological properties of the material, there are different considerations that must be taken into account when designing phantoms for these systems. The US application relies primarily on the speed of sound in a given material to produce its images and MRI relies on the relaxation rates of different tissues. Thus, tissue equivalency for US or MRI is defined quite differently than in imaging that utilizes ionizing radiation. Despite these differences in material properties, the physical design of phantoms and the techniques used to assess image quality and system performance of US and MRI can be quite similar to those of X-ray imaging modalities. Also, both US and MRI make use of anthropomorphic phantoms to simulate a medical procedure or experiment as accurately as possible.

1.6.4 Nuclear Medicine Phantoms

Nuclear medicine involves the injection of radioactive materials into the body for imaging or therapeutic purposes. Common procedures include heart perfusion scans, bone density scans, functional imaging of the brain, and thyroid cancer treatments. Nuclear medicine imaging systems undergo similar testing as that described for the other imaging modalities. Phantoms are used to test the system's detection limitations, its spatial resolution, and its uniformity [29]. Anthropomorphic phantoms have also been developed to simulate actual clinical procedures such as liver [30] or brain imaging [31]. Phantoms for nuclear medicine are unique in that they must be able to accommodate the injection of the radioactive material. Thus, phantoms are often designed to have cavities or inserts that hold the injected material during the imaging process. The phantoms used in medical imaging systems will be discussed in great detail in Chaps. 6–11.

1.6.5 Health Physics and Computational Phantoms

The field of health physics investigates the dangers to those other than the patient associated with ionizing radiation. Frequently, risk of cancer induction is assessed as function of radiation dose received. There are also endpoints that are evaluated such as organ toxicities or radiation sicknesses. Assessment of these endpoints can often involve measurements of small doses or over long periods of time. Consequently, health physicists often make use of computer simulations in order to aid in this process. These simulations make use of the computational phantoms described earlier in order to provide expedient and detailed results. The computational phantoms can be used to gain some understanding of the risks associated with occupational exposures, medical imaging procedures, or from out of field dose in radiation therapy treatments. Health physics also makes use of physical phantoms in many applications. The Rando® phantom is used frequently to evaluate doses for health physics purposes. The BOMAB phantom [32] has also been developed for use with whole body counters in an effort to simulate the incorporation of radioactive materials into the body. Chapters 12 and 13 provide more detail on the computational phantoms used for health physics and other applications.

1.7 Conclusion

Ultimately, the purpose of a phantom in medical physics applications is to simulate human tissue in a given procedure or experiment. While the shape and composition of a phantom can vary drastically, they generally fall into one of two categories, dosimetry phantoms and imaging phantoms. Dosimetry phantoms are designed to be able to quantify the amount of radiation received at a given point, whether it be during a therapy or imaging procedure. Imaging phantoms are used to test the limits of an imaging system and to assess the quality of the images being produced by that system.

The purpose of the phantom dictates both its form and its composition. When selecting or designing a phantom, one must carefully consider the materials to be used, the physical shape, and how these will affect what is trying to be measured in the situation of interest. There is an immense variety of phantoms available for any given application and proper selection of a phantom is dependent entirely on the situation in which it is to be used. New phantoms are continually being developed to utilize new technologies and being used in different ways to serve new and exciting purposes in the field of medical physics.

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