Chapter 3
Anthropomorphic Phantoms for Radiation Oncology Medical Physics

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3.1 Introduction

The use of phantoms in radiation oncology by medical physicists as a substitute for human tissue has been in use for many decades. The various types of phantoms used have evolved with time in terms of shape, material and composition. Basic calibration and output constancy phantoms used in the clinic have been simple blocks of wood, solid plastic cubes, solid acrylic or polystyrene plastic phantoms cut into slabs, water tanks of all sizes and currently a variety of water equivalent plastics. Regardless of the number of solid phantoms available to the medical physicist, since 1983 with the publication of the Task Group report 21 [1], the liquid water phantom has been the preferred phantom for calibrations and dosimetry measurements (as described in Chap. 2). No other readily available phantom comes closer to simulating actual human soft tissue than the liquid water phantom.

Even though the water phantoms used for calibration simulate most human soft tissues and is easy to use, it does not provide a realistic representation of the shape of the human body, differences in tissue densities and the spatial mass density distributions between different organ sites within the body. As such, anthropomorphic phantoms were built and reported on as early as 1924. These early phantoms were humanoid in shape and contained different tissue equivalent materials such as "wax-plastic", bags of talc, plywood, Mix D plastic and sawdust and rice [2–6]. The ICRU report 44 on "Tissue Substitutes in Radiation Dosimetry and Measurement" and ICRU report 48 on "Phantoms and Computational Models in Therapy, Diagnosis and Protection" give a detailed history of the early and current anthropomorphic phantoms [7, 8]. The version of the anthropomorphic phantom used today was developed over 50 years ago which was described by

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Stacey et al. in 1961 [9] and Alderson et al. back in 1962 [10]. The term "anthropomorphic" is defined as "ascribing human form and/or attributes to an object that is not human". Most all anthropomorphic phantoms are normally designed and made to closely resemble the shape and size of the human body, whether male, female, adult or child. In addition, these anthropomorphic phantoms have to be constructed of materials that not only simulated human tissue densities, but also the radiation interactions within the tissue equivalent materials.

Since these phantoms are designed for dosimetry measurements they had to have the ability to accommodate radiation dosimeters in multiple locations. These anthropomorphic phantoms are not recommended for routine dosimetry measurements of actual patients due to the variability between the phantoms and the patients, but they are excellent phantoms to verify a particular new treatment process, dose calculation algorithm or to make dose measurements at locations far from the treatment fields. This verification process may include some if not all of the following components:

1. imaging of a heterogeneous human-like phantom,
2. transfer of the images to the treatment planning system,
3. contouring targets and organs at risk (OAR),
4. dosimetry data in the planning system,
5. dose calculation algorithm used by the planning system,
6. transfer of the treatment plan to the treatment unit, and
7. delivery of the planned doses.

This verification process is also known as an, "end to end", treatment verification.

3.2 Anthropomorphic Body Phantoms

There are currently three versions of the anthropomorphic cross sectional dosimetry body phantoms available to the radiotherapy medical physicist. The first is the "Alderson Radiation Therapy phantom (ART phantom)" offered by Radiology Support Devices (Long Beach, CA). This phantom is a modified version of the earlier original Alderson RANDO phantom built and described by Alderson et al. back in 1962 10]. The second body phantom is the "RANDO®" body phantom offered by The Phantom Lab (Salem, NY) and this phantom is very similar in design to the original Alderson RANDO phantom. The third body phantom is the "ATOM®Dosimetry Phantom" offered by Computerized Imaging Reference Systems, Inc (CIRS) (Norfolk, VA). The ATOM phantom is unique in that it can be provided in different sizes ranging from a newborn to adult. All three of the commercially available types of body phantoms are designed to hold various types of radiation dosimeters depending on the needs of the medical physicist.

3.2.1 ART Phantom

As mentioned above, the ART anthropomorphic body phantom (Fig. 3.1) (Radiology Support Devices Inc., Long Beach, CA) is the descendant of the original Alderson RANDO phantom [10]. This phantom can be supplied either as a male (175 cm tall, 73.5 kg) or female (155 cm, 50 kg). The phantom includes cross sectional slices from the apex of the head to just below the groin. Several key improvements over the original Alderson RANDO phantom have been made and they include using tissue equivalent materials that follow the ICRU 44 specifications in terms of a stable homogeneous composition in the desired anatomical shape that has both non-radiation properties (electrical conductivity, thermal and mechanical properties) and radiation related properties (appropriate attenuation and scatter properties) to simulate human tissue (ICRU 1989). The human skeleton has been replaced with a skeleton that comes from a highly detailed polymer molding from a human skeleton which reproduces the shape, mass density, and attenuation coefficient of cortical bone and spongiosa. The replacement of the human skeleton with a manufactured one allows for more continuity between phantoms. Campbell and Almond compared the location and size of the human skeleton in 3 Alderson RANDO phantoms and found a considerable difference between the 3 phantoms [11]. The molded bone equivalent material also takes care of the reduced bone density problem associated with human skeletons due to the loss of the marrow [12]. The lungs are molded from syntactic foam and have an average density of 0.3 g/cm^3. The soft tissue equivalent material conforms to the ICRU standards and where necessary is cut away to generate air cavities such as in

Fig. 3.1 Alderson radiation therapy phantom (*ART* phantom) provided by radiology support devices (*RSD*)

the nasal cavity region. Various realistically shaped breast sizes are provided that can be attached to the female phantom or if a large female is desired, the male phantom can be made to accommodate breasts.

The ART phantoms are cut in 2.5 cm cross sectional slices. Matrices of holes in either a 3 × 3 or 1.5 × 1.5 cm grid can be drilled to accommodate TLD capsules. The holes, when they do not contain TLD, are filled with bone-, lung- or soft tissue-equivalent pins. The phantom plastics are rigid enough to be drilled to custom fit an ion chamber if the medical physicist so desires.

3.2.2 RANDO® Phantom

The RANDO® phantom (Fig. 3.2) (The Phantom Laboratory, Salem, NY) closely simulates the original Alderson Rando phantom. This phantom can be supplied either as a male (175 cm tall, 73.5 kg) or female (163 cm, 54 kg). The phantom includes cross sectional slices from the apex of the head to just below the groin.

Fig. 3.2 RANDO® Phantom provided by the phantom laboratory

Unlike the ART phantom, each RANDO® phantom contains a human skeleton. These human skeletons provide the asymmetry in the bony structure and distorted joints normally found in a patient. However, because the skeletons are not all the same size, they are adjusted slightly to fit in the phantom mold when each phantom is made. The lungs are hand molded and custom placed in each ribcage for each phantom. They have the same effective atomic number as the soft tissue equivalent material, but with a density equal to that of median respiratory rate ($\sim$0.35 g/cm^3). The soft tissue equivalent material is a urethane formulation that is equivalent to muscle with randomly distributed fat. Similar to the ART phantom, the female or male RANDO® phantom can be accommodated with naturally shaped breasts, ranging in sizes from A through E.

The RANDO® phantoms are cut in 2.5 cm cross sectional slices. Film can be sandwiched between slices if desired. Matrices of holes can also be custom drilled or the medical physicist can accept the standard grid sizes of either 3×3 or 1.5×1.5 cm. Holes are never drilled where there is bone and the holes can be 2, 5, or 6 mm in diameter. Mix D plugs are offered to fill the holes when dosimeters are not inserted. The phantom plastics are rigid enough to be drilled to custom fit an ion chamber or other dosimeter if the medical physicist so desires.

3.2.3 ATOM® Dosimetry Phantom

The ATOM® phantoms (Fig. 3.3) (CIRS, Inc., Norfolk, VA) come in six different sizes; adult male (173 cm tall, 73 kg), adult female (160 cm, 55 kg), pediatric

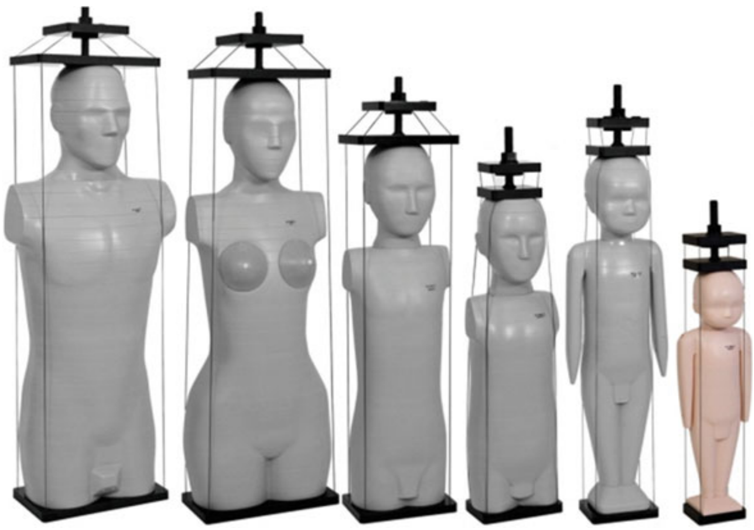

Fig. 3.3 The ATOM® phantoms provided by computerized imaging reference systems (*CIRS*), Inc

newborn (51 cm, 3.5 kg), pediatric 1 year (75 cm, 10 kg), pediatric 5 years (110 cm, 19 kg) and pediatric 10 years (140 cm, 32 kg). Of the three commercial providers of body phantoms, these are the only pediatric body phantoms offered [13]. The phantoms includes cross sectional slices from the apex of the head to just below the groin except for the newborn and pediatric 1 year phantoms which include the legs and arms. Leg and arm attachments are also available upon request for the other 4 ATOM® phantoms. All ATOM® phantoms are made from the CIRS tissue equivalent epoxy resins. The bone tissue equivalent material is homogeneous and customized to vary in density from 1.41 g/cm^3 for the newborn to 1.6 g/cm^3 for the adult phantoms depending on the phantom simulated age since human skeleton density varies as a person ages. Human skeletons are not used. The ATOM® phantoms are all constructed of CIRS tested proprietary tissue equivalent materials. The linear attenuation coefficients for soft/bone tissue equivalent and lung equivalent materials are within 1 and 3 % of actual soft tissue/bone and lung tissue, respectively. The lung equivalent tissues are made to be low density inhale (0.2 g/cm^3), but higher densities are available on special order. Similar to the other body phantoms, the female or male ATOM® phantom can be accommodated with naturally shaped breasts, ranging in sizes of 190 or 350 cm^3 for the female phantom and 350 cm^3 for the male phantom. In addition, supine breasts, shaped as when a patient would be lying on their back are available in three sizes: small (400 cm^3 B–C cup), medium (800 cm^3 D cup) and large (1,200 cm^3 DD cup).

The ATOM® phantoms are cut in 2.5 cm cross sectional slices. CIRS has identified on each slice a mapping of the average location of 22 different radiosensitive organs. This allows the medical physicist to customize the placement of the dosimeter holes to only those locations that are crucial and desired. In addition to the customized dosimeter hole placement, the medical physicist can also have a standard grid of either 3 $\times$ 3 or 1.5 $\times$ 1.5 cm of holes drilled in each slice. The holes can be 2, 5, 7 or 10 mm in diameter. Holes are filled, when not containing a dosimeter, with custom plugs made of the appropriate tissue equivalent material depending on where the holes are located and what dosimeters are being used. The ATOM ®phantoms can be prepared to hold a variety of dosimeters including various shaped and sized TLD, OSLD nanoDots, MOSFETs, film, ion chambers or diodes. The medical physicist simply needs to discuss the specific requirements needed for the phantom with the CIRS staff.

3.2.4 Custom Body Phantoms

While the three anthropomorphic body phantoms described in detail above are precisely made and are very human-like, they do have disadvantages. They are extremely expensive, may not be configured in every possible manner and when assembled are very heavy. A clinic should clearly define the benefits and need for purchasing an anthropomorphic body phantom and compare these against the price of the phantom. Not only will the phantom be expensive, but does the clinic have the equipment and knowledge to analyze the dosimeters normally placed in the body phantoms, i.e., TLD. The dosimetry system may be an extra cost.

There have been other researchers who have developed anthropomorphic body phantoms in an attempt to bypass the disadvantages listed above. Hasanzadeh and Abedelahi built their own anthropomorphic body phantom using a human skeleton and paraffin (plus NaCl) that would accommodate TLD at various locations [14]. Lehmann et al. [15] developed and reported on an anthropomorphic body phantom called the "radiation phantom with humanoid shape and adjustable height (RPHAT)". The unique characteristic of this body phantom was designed to have an adjustable thickness to address the range of patient thicknesses encountered in the clinic. The height adjustment comes from the fact that the phantom is sliced in the coronal direction instead of the axial direction. The phantom had additional coronal phantom slices that could be inserted in the center of the phantom to increase the thickness as needed [15]. Commercial phantoms may be sliced in the sagital or coronal direction but only by special order. Despite the expense of the commercial body phantoms, and with a few exceptions, they appear to be the standard anthropomorphic body phantom that the medical physics community continues to use. The need for ideal tissue equivalent materials and the capability to modify the phantoms to the user's specifications seems to outweigh the cost of these phantoms.

3.3 Anthropomorphic Body-Part Phantoms

Instead of purchasing a complete body phantom, there is often the need to have an anthropomorphic phantom for just a section or part of the body to assess a specific treatment modality or treatment target. Examples of this would be the need for only a head phantom for stereotactic radiotherapy for brain lesions or a thorax for the evaluation of a moving target in a low density organ to evaluate the heterogeneity corrected dose calculations for an SBRT treatment. To address this need for smaller more specific anthropomorphic phantoms, numerous anthropomorphic body-part phantoms have been developed. All of these smaller phantoms have the same requirements as the larger body phantoms such as appropriate tissue equivalent materials and the ability to contain dosimeters of various types depending on the need of the medical physicist. The vast majority of these anthropomorphic body-part phantoms are solid and are primarily made of tissue equivalent plastics. However, there are some body-part phantoms that have plastic shells and are water filled where there might be soft tissue. There are two classifications of anthropomorphic body-part phantoms: those that can commercially purchased for individual use and those that were developed by a quality assurance (QA) service organization or by an individual institution for their own QA purposes.

3.3.1 *Commercially Available Anthropomorphic Body-Part Phantoms*

Similarly to the anthropomorphic body phantoms, the body-part phantoms are available from a variety of vendors, for several body-parts and that will accommodate various dosimeters. In Table 3.1, a list of the primary vendors and body-part phantoms available from each is listed. The manufacturers of the large body phantoms capitalized on their specific expertise and experience with their own specific tissue equivalent materials when designing and building the smaller body-part phantoms.

Some of the common features for the body-part phantoms listed in Table 3.1 are that they all can accommodate multiple dosimeters depending on the accessories purchased with the phantom. The CIRS, SI, RSD and Modus phantoms are solid and the Phantom Lab is liquid filled. All of the phantoms can hold either TLD or film with the exception of the Modus QUASAR™ phantom which only has inserts for ion chambers. The CIRS and SI phantoms can accommodate 3D dosimeters (gels), diodes, MOSFETs and ion chambers with the exception of the CIRS SRS Head phantom, which can not accommodate diodes or MOSFETs. The Phantom Lab phantoms have inserts for TLD, gels, film and ion chambers.

All of the anthropomorphic body-part phantoms that are commercially available are made of appropriate tissue equivalent materials. Some are more heterogeneous than others, but that is by design depending on the body part and the number of heterogeneous tissue structures located within that body-part. All of these phantoms will serve the medical physicist's need, however it is critical that the physicist be capable of taking the dosimeter readings and precisely being able to determine dose from those readings. The most sophisticated and expensive anthropomorphic phantom will be useless if the physicist can not perform the measurements and dosimeter analysis correctly.

Table 3.1 Major commercial providers of anthropomorphic body-part phantoms

Vendor	Body-part			
	Head	Thorax	Moving thorax	Pelvic
Radiology support devices (RSD)	SRS head phantom	–	Dynamic breathing phantom	–
The phantom lab	SRS RSVP phantom™ head	–	–	IMRT RSVP Phantom™ Pelvis
Comp. imaging ref. sys. (CIRS)	SRS head	Thorax phantom	Dynamic thorax phantom	IMRT pelvic 3D phantom
Modus medical devices	–	QUASAR™ body phantom	QUASAR™ body phantom	QUASAR™ body phantom
Standard imaging (SI)	LUCY® 3D QA phantom	–	–	–

3.3.2 *Anthropomorphic Body-Part Phantoms Developed by a QA Service Organization or Institution for Their Own QA Purposes*

Typically this class of anthropomorphic phantom was designed with a single purpose in mind. For example, the Radiological Physics Center (RPC) developed its IMRT spine phantom with the sole purpose of credentialing institutions for participation in a specific spine metastases clinical trial, while de Almeida et al. [16] developed a gynecological pelvic phantom for dose delivery verification and education at their institution. These phantoms are normally not available for purchase, but may be used by many institutions and medical physicists as a part of the QA service being offered.

One such organization that provides phantoms for a service, specifically for NCI funded clinical trial QA, is the RPC. The RPC uses lightweight mailable anthropomorphic phantoms (Fig. 3.4) to evaluate treatment delivery at institutions wanting to participate in NCI sponsored clinical trials. The phantoms simulate lesions to be treated in the brain, head and neck, prostate, liver, spine or lung areas, and allow verification of 3D-CRT, SBRT and IMRT plans. The RPC currently has 65 anthropomorphic body-part phantoms in use. The brain, head and neck, pelvis, spine and thorax RPC phantoms have been described in detail [17–20]. The phantoms contain imageable targets as well as organs at risk whose location and densities are similar to the tissues within the body-part being simulated as seen in Fig. 3.5. Densities and dimensions provide realistic conditions for dose constraints used during the planning and delivery process. A reciprocating table, which is able to reproduce different breathing cycles, is also included when a technique to account for target motion, as might be seen with lung or liver targets, is required for credentialing. Participating institutions are instructed to image the phantom, plan a treatment following guidelines, perform all the QA procedures used in clinic and deliver the plan as if it were a patient.

Fig. 3.4 The RPC IMRT H&N, pelvis and lung phantoms

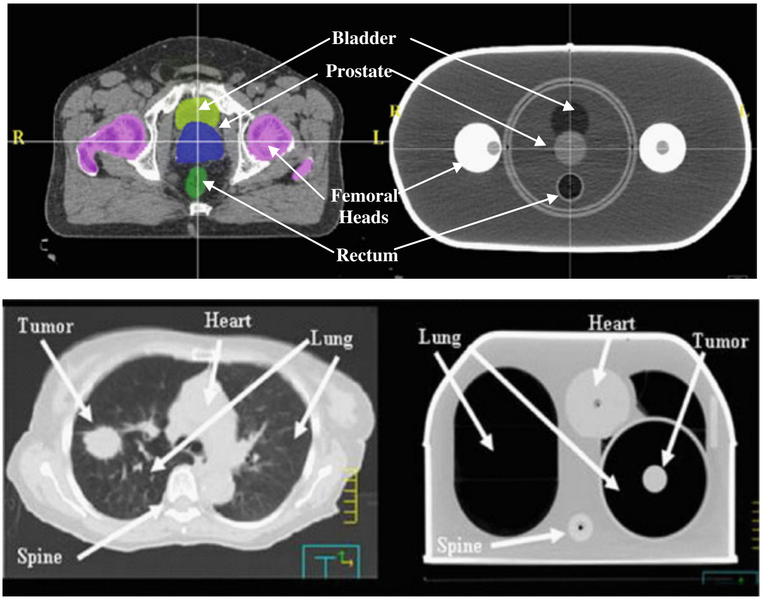

Fig. 3.5 RPC pelvis and lung phantoms with corresponding patient anatomy

The RPC is not the only QA service to use anthropomorphic body-parts. Harrison et al. [21] described the use of a pelvic phantom for an Australian multicenter radiotherapy dosimetry comparison [22]. The Australian pelvic phantom was a solid phantom that had structures representing bone, organ and backfill and it could accommodate the placement of TLD and an ion chamber at various locations. The gynecological pelvic phantom described by de Almeida et al. was a water filled acrylic phantom modeled after the pelvic region of the female Alderson Rando phantom. The unique characteristic of this phantom was that it allowed the placement of tandem and ovoids along with an insert for an ion chamber so that it could be placed at the bladder, rectum and point A locations. Another IMRT head and neck phantom, different from the RPC design, was developed and used by a Belgian-French task group called Groupe Oncologie Radiotherapie Tete Et Cou (GORTEC) to perform a multicenter IMRT dosimetry audit of IMRT delivery. The GORTEC phantom was a solid homogeneous dedicated head and neck polystyrene phantom where ion chambers could be placed at seven different locations coinciding with target and OAR locations. The anthropomorphic body-part phantoms listed above are just a few of the many that are developed at individual institutions for the purpose of performing their own end to end QA of a specific treatment or to verify their treatment planning system's dose calculation accuracy.

With the recent increase in the number of proton radiotherapy centers, the delivery of accurate proton doses to patients has become a topic of concern within the clinical trial community. The RPC has developed three anthropomorphic body-part phantoms to be used as end to end quality audits for proton therapy of sites in the brain, lung and pelvis. These phantoms are nearly identical to the RPC's other phantoms with the exception that the head phantom is solid and all three phantoms contain proton equivalent plastics. Unlike photon and electron radiotherapy where the planning system dose calculation depends on the CT number versus electron density curve, proton therapy planning system dose calculations depend on the CT number versus relative stopping power (RSP) Ratio. As such the plastics that were good tissue equivalent materials for photons and electrons may not be appropriate for protons because they do not fall on the CT number versus RSP for human tissues. An example of this is the use of high impact polystyrene for photons as a soft tissue substitute, however for protons polystyrene has an RSP that is approximately 10 % different than soft tissue of the same CT number. The RPC and Moyers et al. [23] have made numerous measurements of various plastics to determine which ones are suitable tissue equivalents for proton therapy. Plastics that fall on or very near to the curve representing real human tissues are viewed as being tissue equivalent for proton therapy. Therefore, caution is necessary when using current commercial or QA service anthropomorphic phantoms for proton therapy dosimetry verification. The incorrect plastics can result in large errors in dose and dose distribution.

3.4 Summary

As described, there are numerous options available to the radiotherapy medical physicist in terms of anthropomorphic phantoms. The choice of which to use is highly dependent on the specific needs of the physicist and the specific treatments to be verified. Decisions have to be made as to whether a body phantom is necessary or perhaps a body-part phantom is all that is needed. The type of dosimeter to be placed within the phantom that the physicist knows how to analyze correctly may also play a role as to which phantom is the best fit for your clinic. Regardless of the many variables to choose from, there is no better human substitute than an anthropomorphic phantom for verifying, by means of dose measurements, the complete "end to end" dose delivery process.

Future anthropomorphic phantoms will become even more complex. As radiation oncology enters the era of adaptive radiation therapy (ART), phantoms will be needed to verify the delivery of a radiation dose to a moving or changing target using the imaging systems found on therapy units. These phantoms will not only have structures that can be visualized with kV and MV X-rays, but will have to include some aspect of target position change with time and be able to accommodate dosimeters. The introduction of 3D dosimetry will pose additional challenges in that they are not always tissue equivalent. Finally, the use of charged particle therapy, i.e., protons and carbon ions, will require further investigations as to the suitability of the phantom materials to be used as tissue substitutes.

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