Radiation Physics and Chemistry 112 (2015) 169–176

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Determination of tissue equivalent materials of a physical 8-year-old phantom for use in computed tomography

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HIGHLIGHTS

- A methodology to select tissue equivalent materials for use in CT was proposed.
- Physical properties of different materials were studied.
- TLDs dose and dose distribution were calculated for original and proposed materials.
- B-100 as bone, and water as soft tissue are best substitute materials at 80 kVp.
- Mass attenuation coefficient is determinant for selecting best tissue substitutes.

ARTICLE INFO

Article history:
Received 13 September 2014
Received in revised form
24 February 2015
Accepted 28 March 2015
Available online 30 March 2015

Keywords:
Physical phantom
Tissue equivalent material
Computed tomography
Physical properties
Dose determination

ABSTRACT

This paper reports on the methodology applied to select suitable tissue equivalent materials of an 8-year phantom for use in computed tomography (CT) examinations. To find the appropriate tissue substitutes, first physical properties (physical density, electronic density, effective atomic number, mass attenuation coefficient and CT number) of different materials were studied. Results showed that, the physical properties of water and polyurethane (as soft tissue), B-100 and polyvinyl chloride (PVC) (as bone) and polyurethane foam (as lung) agree more with those of original tissues. Then in the next step, the absorbed doses in the location of 25 thermoluminescent dosimeters (TLDs) as well as dose distribution in one slice of phantom were calculated for original and these proposed materials by Monte Carlo simulation at different tube voltages. The comparisons suggested that at tube voltages of 80 and 100 kVp using B-100 as bone, water as soft tissue and polyurethane foam as lung is suitable for dosimetric study in pediatric CT examinations. In addition, it was concluded that by considering just the mass attenuation coefficient of different materials, the appropriate tissue equivalent substitutes in each desired X-ray energy range could be found.

1. Introduction

Physical anthropomorphic phantoms have an important role in radiation dosimetry studies and quality assurance of medical imaging (Hintenlang et al., 2010). The conceptual basis lying behind the development of a physical or experimental phantom is to model an organ/tissue or the entire body with the aim to study the topics related to radiation dosimetry and radiological protection. This would permit a better understanding of how radiation interacts with biological tissues through various mechanisms of radiation interaction with matter and deposits energy (for radiation dosimetry applications) (Fisher, 2006).

The analysis of the dose in pediatric radiology is of interest since growing tissue is generally considered more sensitive to radiation and in most examinations, a larger portion of the child's body is included in the primary beam (NCRP, 1989). Age appropriate phantoms are required for accurate analysis of pediatric dosimetry. An adult phantom or even a scaled down version of an adult phantom is not appropriate for studying pediatric examinations or for comparing the results to those from mathematical modeling (Bower, 1997).

Hitherto, many physical anthropomorphic phantoms were developed in academic and corporate settings, but very few dynamic torso phantoms are commercially available. The majority of organ dose studies in diagnostic imaging utilize commercially available anthropomorphic phantoms such as RANDO (The Phantom Laboratory, Salem, NY) or ATOM phantoms (Computerized Imaging Reference Systems, Inc, Norfolk, VA). Unfortunately, the

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http://dx.doi.org/10.1016/j.radphyschem.2015.03.030
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widespread clinical use of these phantoms has been limited by their prohibitive costs (Winslow et al., 2009).

The design of an anthropomorphic phantom requires the careful selection of tissue substitute materials. The materials must closely match the volume, density and chemical composition characteristics of the represented tissue for a proper radiological response at the energy of interest. The materials chosen must be commercially available, relatively simple to fabricate and maintainable for a long period of time (Bower, 1997). Most tissue-equivalent materials have been designed to match tissue attenuation characteristics at relatively high energies (around 1 MeV and higher) as required by most of the early applications. Phantoms constructed of these materials are therefore expected to respond accurately at these energies, but may not have comparable tissue equivalence for X-rays with lower energies (Hintenlang et al., 2010).

Tissue-equivalent materials may be fabricated to simulate a wide variety of tissues and organs. For radiation dosimetry studies, at the current state of the art, the differing levels of attenuation and density do not significantly affect dosimetry results. A single soft-tissue material is therefore commonly used for all soft-tissues with the exception of the lung. The lung volume has a similar elemental composition, but much lower density ($<0.32\ \mathrm{g\ cm^{-3}}$) than other soft tissues ($<1.04\ \mathrm{g\ cm^{-3}}$). It is frequently considered based on similar soft-tissue mixtures with the addition of foaming agents to reduce the density. Skeletal structures are created that have a higher density. While not common, anatomical physical phantoms may also incorporate adipose tissues, based on soft-tissue substitute having a reduced density.

The basis for tissue-equivalent materials for many years has been mixtures based on common epoxy resins. The epoxy resin may be combined with a variety of other molecular compounds to achieve the desired mass attenuation coefficient and density, but it was difficult to work with. Some anatomical phantoms have made use of human skeletal tissues for the skeletal structure of the phantom. These materials are extracted from cadavers and provide precise bone anatomy for accurate anatomical detail, but since they have lost bone marrow contents, and dried considerably, they may not be an accurate tissue for healthy bone like some synthetic bone materials (Hintenlang et al., 2010).

According to the wide range of tissue equivalent materials used in physical phantom, which have different responses in diagnostic energy range, the goal of the current study is to introduce suitable tissue equivalent materials in diagnostic energy range for an 8-year-old phantom, so that we will be able to construct a physical phantom. Therefore, in addition to physical properties, absorbed dose and dose distribution in different tissue equivalent materials of UF 8-year-old phantom were calculated and compared with those of UF original materials. In this study, all organ dose calculations were performed using Monte Carlo simulation, which is the most reliable way to obtain accurate values of dose under CT imaging (de Marco et al., 2005; Lee et al., 2011). In this regard, TLDs were placed in different organs of UF phantom, and absorbed doses as well as dose distribution were evaluated by MCNP4C. Finally, for each of X-ray energies, based on their agreements with UF original tissues, the appropriate tissue equivalent materials for lung, soft tissue and bone were introduced. Determining the suitable tissue equivalent materials, we will construct an 8-year physical phantom in the next step.

The process described here to choose the suitable tissue equivalent material for CT examination, could easily be expanded to other phantoms, so a full series of phantoms could be constructed to assist many different aspects of radiation protection.

2. Materials and methods

Given that the majority of pediatric examinations are of children in their first decade of life; therefore, a phantom of an 8-year-old was considered for estimating the suitable tissue equivalent materials in diagnostic energy range. Therefore, UF 8-year old reference voxel phantom with the height of 126.4 cm and weight of 28.41 kg (developed at University of Florida) (Lee, 2006) was selected as a reference phantom.

In this study, three different set of materials were proposed as tissue substitutes. The materials consisted of a bone substitute (a homogeneous mixture simulating trabecular bone, cortical bone, active marrow, and inactive marrow), a soft tissue substitute (a common assumption is made that all soft tissue organ can be simulated by a single substitute material) and a lung substitute. Adipose tissue was not specifically considered. Thus, the proposed soft tissue equivalent materials comprised skeletal muscle as well as organs, connective tissue, and adipose tissue. Some materials, which might have the potential to be used as tissue equivalent materials as well as tissue substitutes introduced by other authors, were studied. Various composition of epoxy resin with different percentage of phenol (Hintenlang et al., 2010), K_2HPO_4 (Torikoshi et al., 2003), B-100 (Shonka et al., 1958), PVC, and bone material recommended in ICRP 70 (ICRP, 1995) were considered as the bone substitute material. A-150 (Shonka et al., 1958), polyurethane (Kim et al., 2006), methane based tissue-equivalent gas (MBTE), propane based tissue-equivalent gas (PBTE), the composition recommended by White (White, 1978), ethylene bis stearamide (EBS), polycarbonate (PC), polypropylene (PP), polymethylmethacrylate (PMMA), polyethylene and water (Constantinou et al., 1982) were investigated as substitutes for soft tissue. The proposed lung equivalent materials were polyurethane foam (Kim et al., 2006), composition cork (Chang et al., 2012) and lung composition recommended by White (White, 1978). The physical properties of these materials were studied. In addition, absorbed dose and dose distributions in UF 8-year old reference voxel phantom modeled by different tissue equivalent materials were evaluated using Monte Carlo simulation. For convenience, the different combinations of materials used for soft tissue, lung and bone were abbreviated with letter “M”.

2.1. Studying the physical properties of proposed materials

The tissue-equivalent substitutes should have similar physical properties to human tissue. The physical properties of proposed tissue materials including electron density, effective atomic number, CT number and attenuation properties in the diagnostic energy range were determined.

2.1.1. Effective atomic number and electron density

The electron density (number of electrons per gram) and effective atomic numbers of all proposed materials was calculated using their elemental compositions. The electron density ρ_e and effective atomic number Z_{eff} were specified using the following equations:

$$\rho_e = N_A \sum_i \frac{W_i Z_i}{A_i} \tag{1}$$

$$Z_{eff} = \frac{\sum_i \frac{W_i Z_i}{A_i}}{\sum_i \frac{W_i}{A_i}} \tag{2}$$

where N_A is Avogadro's number, and w_i, Z_i, and A_i are the weight fraction, the atomic number, and the atomic mass of each atom, respectively (Chang et al., 2012).