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ORIGINAL RESEARCH ARTICLE

Suitability of Different Materials as Human Tissue Simulating Materials in Co-60 Radiation Energy Beam

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ABSTRACT

Radiotherapy calibration for precise dose delivery traditionally relies on water phantom systems, but this approach poses challenges of heterogeneous corrections or the use of anthropomorphic phantoms which most underdeveloped nations find expensive. In this study, the suitability of some tissue simulating materials were investigated within the Co-60 photons energy range. This study explores the identification of locally sourced materials to simulate human tissue behavior in Co-60 energy beams. By considering effective atomic numbers and physical densities, we evaluate materials for simulating soft tissue, lung, and bone. Water, aluminum metal, and polystyrene (Styrofoam) were selected for simulating soft tissue, bone, and lung, respectively, as they have values 7.96 and 1.00 g/cm^3; 13.00 and 2.6989 g/cm^3; and 6.01 and 0.016 g/cm^3 respectively for their effective atomic numbers and densites. This research provides valuable insights for resource-constrained regions aiming to improve radiotherapy calibration methods.

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KEYWORDS

Radiotherapy, Phantoms, Effective Atomic Number, Co-60

INTRODUCTION

Traditionally, radiotherapy machines are calibrated to ensure accurate dose delivery using water phantom systems. In the case of external beam radiation therapy (EBRT), the calibration is carried out in the beam with the same photon and electron energy range as to be used clinically. The use of water phantom is only sustained by developing and underdeveloped nations of the world as most developed nations have since moved to having scenario-based calibration where they employ different inhomogeneity correction factors for different organs under treatment or use of anthropomorphic phantom (AAPM, 2004). These anthropomorphic phantoms are expensive and not within reach of these underprivileged nations; thus, the need to identify materials that can be sourced locally and effectively simulate the behaviour of some tissues of the human body in a Co-60 energy beam.

Phantoms are designed principally to simulate the radiological properties of various body tissues. Appropriate materials are critical to "the design and function of any type of phantom". The design and composition of any phantom will be determined by the purpose it is designed to serve. Any phantom designed to evaluate dose delivery in radiotherapy will undoubtedly differ from the one designed for imaging systems. The purpose of any phantom determines its physical design, composition, and whether the phantom will have ports for accommodating dosimeters (DeWerd and Lawless, 2014).

The properties of the simulating materials vary with the energy of the incident radiation, with some being appropriate over a given energy range and inappropriate at others. Thus, a phantom designed for use in a kilovoltage energy range will be made of different materials from a phantom made for megavoltage usage.

Water, wax, and wood were among the early materials for human tissue simulation with fairly simple geometry: water tanks for water and blocks for wood and wax. While water is still in common use to date, wax and wood present a number of problems. They deviate from tissue equivalency at low energies, and their compositions differ significantly depending on the type used, and this consequently brought about inconsistency in the early

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measurements (DeWerd and Lawless, 2014; Frigo, 2014). According to Frigo (2014), water is still in common use because it is a major constituent of human tissue and is suitable for calibration standards. Water has a uniform composition and is also readily available.

Several other materials have, however, been reportedly used by several other authors (Blomquist and Karlsson, 1998; da Rosa *et al.*, 2010; Jeong *et al.*, 2011; Senthilkumar and Ramakrishnan, 2011; Senthilkumar, 2014) for the various body tissue simulation. The basic properties considered in virtually all of them are the materials' physical density (ϱ), electron density (ϱ_e), and effective atomic number (z_{eff}), which is a combination of the materials' percentage elemental composition and their electron densities.

Jeong *et al.* (2011) used equations 1-2 to calculate the effective atomic number (z_{eff}) of the following materials for various tissue simulations: Polystyrene, polyethylene, polytetrafluoroethylene (PTFE), and polyurethane foam (PU-F).

$$Effective\ atomic\ number\ (Z_{eff}) = A_{eff}\left[\sum w_i \frac{Z_i}{A_i}\right] \qquad (1)$$

Where:
w_i is the atomic weight fraction of the ith element; Z_i is the atomic number of the ith element; A_i is the atomic mass number of the ith element; and A_{eff} is the effective atomic mass number of the material as a whole.

$$A_{eff} = \sum_i w_i A_i \qquad (2)$$

The materials identified above by Jeong *et al.* (2011) were used to simulate muscle, fat, bone, and lung tissue, respectively, as illustrated in Table 1.

Senthilkumar (2014) designed a heterogeneous human equivalent thorax phantom using bee's wax as the soft-tissue simulating material, with cork and Teflon as lung and spine-simulating materials, respectively. Those materials have densities of 0.99, 0.2, and 2 g/cm^3 respectively. The main aim of the study was to design a low-cost homogeneous and heterogeneous thorax simulating phantom for tissue inhomogeneity dose correction as well as assess the dose accuracy of Treatment Planning Systems (TPS) calculated values for different lung treatment dosimetry using Thermoluminescent Dosimeter (TLD) measurement.

Table 1: Physical Properties of Human Body Tissues and Selected Materials (Jeong *et al.*, 2011)

Body Tissues	ϱ (g/cm^3)	Z_{eff}	Selected Materials	ϱ (g/cm^3)	Z_{eff}
Muscle	1.04	7.71	Polystyrene	1.05	6.00
Fat	0.95	6.63	Polyethylene	0.94	5.95
Bone	1.92	11.18	Polytetrafluoro-ethylene	2	8.31
Lung	0.26	7.80	Polyurethane Foam	0.28	6.94

METHODOLOGY

Selection of Tissue Simulating Materials

The effectiveness of materials in simulating human tissues in photon beams was based on the material's effective atomic number and physical densities (DeWerd and Lawles, 2014). Phantom materials were selected for the following body tissues: Soft tissue, Lungs, and Bone (rib bone and the spine).

a. Effective Atomic Number Z_{eff}

The effective atomic numbers (Z_{eff}) of the materials were calculated using equations 1 and 2. The elemental compositions of the body tissues and their simulating materials were obtained from the National Institute of Standards and Technology (NIST) online database and presented in Tables 2, 3, 4 and 5.

b. Materials Physical Density (ϱ)

Also investigated were the tissues simulating materials' physical densities, ϱ, the majority of which were also obtained from the NIST online database. The rest were calculated using Equation 3.

$$\rho = \frac{\text{mass of material}}{\text{volume of the material}} \qquad 3$$

Table 2: Elemental Composition of Soft Tissue

Body Tissue Simulated	Density (g/cm^3)	Elemental Composition	Fractional Composition
Soft tissue	1.00	H	0.104472
		C	0.23219
		N	0.02488
		O	0.630238
		Na	0.00113
		Mg	0.00013
		P	0.00133
		S	0.00199
		Cl	0.00134
		K	0.00199
		Ca	0.00023
		Fe	0.00005
		Zn	0.00003

Table 3: Elemental Composition of Lung

Body Tissue Simulated	Density (g/cm^3)	Elemental Composition	Fractional Composition
Lung	0.01 - 1.00*	H	0.101278
		C	0.10231
		N	0.02865
		O	0.757072
		Na	0.00184
		Mg	0.00073
		P	0.0008
		S	0.00225
		Cl	0.00266
		K	0.00194
		Ca	0.00009
		Fe	0.00037
		Zn	0.00001

* Sourced from Aarup et al. (2009)

Table 4: Elemental Composition of Bone

Body Tissue Simulated	Density (g/cm^3)	Elemental Composition	Fractional Composition
Bone	1.85	H	0.047234
		C	0.14433
		N	0.04199
		O	0.446096
		Mg	0.0022
		P	0.10497
		S	0.00315
		Ca	0.20993
		Zn	0.0001

Table 5: Radiological Properties of Tissue Simulating Materials

Selected Tissue Simulating Material	Density (g/cm³)	Elemental Composition	Fraction Composition
Water	1.00	H	0.111894
		O	0.888106
Styrofoam (Polystyrene)	-	H	0.077418
		C	0.922582
Aluminum metal	2.6989	Al	1.00

RESULTS AND DISCUSSION

The computed values for Z_{eff} and ϱ for the selected materials, alongside the corresponding values for actual human tissues, are presented in Table 6. These values provide the needed insights into the materials' ability to simulate the radiological properties of soft tissue, lung, and bone (rib and spine).

Table 6: Comparison of the Radiological Properties of Body Tissues and their Simulating Materials

Body Tissue	Density (g/cm³)	Z_{eff}	Selected Material	Density (g/cm³)	Z_{eff}
Soft tissue	1.00	7.69	Water	1.00	7.96
Lung	0.01 - 1.00*	7.81	Styrofoam (Polystyrene)	0.016	6.01
Bone	1.85	11.13	Aluminum metal	2.6989	13

* Sourced from Aarup et al. (2009)

Material Selection for Tissue Simulation

Based on the results, we made informed choices for materials suitable for simulating specific human tissues in radiotherapy phantoms:

Soft Tissue Simulation: Water was chosen as the preferred material for simulating soft tissue. Its Z_{eff} and ϱ values were found to be in close alignment with those of actual soft tissue, indicating its ability to accurately mimic soft tissue behavior within the specified energy range. Moreover, the availability and cost-effectiveness of water make it an attractive option for this purpose.

Lung Tissue Simulation: Styrofoam (Polystyrene) was selected for simulating lung tissue, despite some density variations compared to actual lung tissue. This choice considers the extremes of lung density corresponding to deep inspiration and deep expiration, as identified by Aarup et al. (2009). Styrofoam's Z_{eff} value aligns reasonably well with that of lung tissue, making it a practical and cost-effective choice for lung tissue simulation.

Bone (Rib and Spine) Simulation: Aluminum metal was chosen as the material of choice for simulating bone tissues, both rib and spine. It demonstrated a Z_{eff} Value that closely resembled the radiological properties of bone, thus providing an effective means of replicating bone behavior under the Co-60 radiation beam.

Practical Considerations

In addition to the aforementioned radiological properties, practical considerations played a pivotal role in our material selection. Factors such as local availability and cost-effectiveness were crucial, especially for resource-constrained settings. Water's status as a readily available and budget-friendly material made it a compelling option for soft tissue simulation.

While our choices for simulating lung and bone tissues may exhibit slight density variations compared to actual tissues, these variations are within acceptable limits. Furthermore, considering the extreme cases of lung density during different respiratory phases, Styrofoam (Polystyrene) is considered a suitable material for lung tissue simulation.

CONCLUSION

Our study underscores the importance of carefully selecting materials for simulating human tissues in radiotherapy phantoms. The materials chosen must replicate the radiological properties accurately and be practical in terms of availability and cost. Water, Styrofoam (Polystyrene), and aluminum metal have emerged as viable options for simulating soft tissue, lung, and bone under the specified energy range. These findings contribute to the ongoing efforts to improve the precision and accessibility of radiotherapy calibration methods, particularly in regions with limited resources. Further research and refinement of material selection criteria will continue to advance the field of radiotherapy calibration.

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