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Development of a Cost-Effective Head and Neck Anthropomorphic Phantom for Use in Radiation Dosimetry Studies

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Abstract

Background and Aims: Anthropomorphic phantoms are essential for accurate radiation dosimetry but are often prohibitively expensive, limiting their use in resource-constrained settings. Our aim was to manufacture a low-cost head and neck anthropomorphic phantom using commercially accessible materials for use in radiation dosimetry studies.

Methods: This phantom was generated from 1 mm slice thickness CT scan images of an adult female, utilizing 3D Slicer and Autodesk Inventor software. In accordance with ICRU-44 report, two tissue-equivalent materials for soft tissue and bone tissue are plexiglass (polymethyl methacrylate) and polytetrafluoroethylene (PTFE), respectively. The physical and radiological characteristics of different types of plexiglass and PTFE were evaluated, and the most suitable materials were selected. Then, the 5mm-thick plates of plexiglass and PTFE were laser-cut and arranged according to the specifications. Moreover, thermoluminescent dosimeter (TLD) holes (3 mm in diameter and 5 mm in depth) were incorporated within each layer in a 3 cm × 3 cm grid for dose measurements. Finally, these plates were placed on top of each other and secured using two rods.

Results: The evaluated properties of selected soft tissue and bone tissue-equivalent materials were closely aligned with the reference values. It was found that the cost of the manufactured female phantom was about 8 times lower than commercially available phantoms.

Conclusion: In this study, we successfully manufactured an anthropomorphic phantom using commercially available materials with low expenses. Its dosimetric performance will be validated in future studies. It can facilitate more dosimetric research and quality control of radiation equipment in various radiology/radiotherapy centers.

Keywords: Cost-effective anthropomorphic phantom, Dosimetry, Ionizing Radiation, Radiology, Radiotherapy.

1. Introduction

The accurate measurement of radiation dose deposited in human tissues is a cornerstone of both diagnostic radiology and radiotherapy. In diagnostic imaging, the fundamental principle of maintaining radiation exposure As Low As Reasonably Achievable (ALARA) necessitates a precise understanding of the dose delivered to radiosensitive organs to optimize protocols and minimize stochastic risks such as cancer induction. Conversely, in radiotherapy, the objective is the deliberate delivery of a high, tumoricidal dose to eradicate cancerous cells while meticulously sparing the surrounding healthy tissues. In both fields, dose measurement in body tissues subjected to various radiation sources is critical.[1]

The challenge of accurate dosimetry stems from the complex, heterogeneous nature of the human body. A photon with a certain energy deposits various doses in media of different densities.[2] Human tissue is not a uniform water-equivalent medium; it is a composite of structures with vastly different physical densities and atomic compositions, ranging from low-density lung tissue and air cavities to high-density cortical bone.[3] This heterogeneity significantly perturbs the radiation beam, causing effects like differential attenuation and scatter, which lead to a complex, heterogeneous dose distribution throughout the irradiated volume.[4] Consequently, the dose calculated for a homogeneous water phantom can substantially differ from the dose actually absorbed in a specific organ or tumor within the patient. Therefore, accurate calculation of the amount of absorbed dose in the treatment area is not merely a technical detail but a factor that will significantly influence the outcome of cancer radiotherapy, impacting both tumor control probability and normal tissue complication probability.[5]

To address this challenge, various dosimetric tools and methodologies have been developed. Physical phantoms provide a practical tool by enabling direct and reliable dose measurements without requiring complex inputs, offering significant advantages for experimental dose evaluations.[6] Among these, anthropomorphic phantoms are considered the gold standard for realistic dosimetry. These phantoms are constructed from tissue-equivalent materials substances designed to mimic the radiological properties (e.g., mass density, electron density, effective atomic number) of specific human tissues like soft tissue, bone, lung, and fat. A well-designed anthropomorphic phantom can offer a practical physical depiction of an individual's anatomy and the attenuation properties of body tissues,[7,8] allowing for the validation of radiation delivery under clinically representative conditions. They are indispensable for tasks such as patient-specific quality assurance, commissioning of new radiotherapy units, and developing and verifying new treatment techniques like intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT).[8]

Parallel to physical measurements, dose calculation algorithms play an important role in dose estimation for radiotherapy treatment planning.[9,10] Modern treatment planning systems (TPS) employ sophisticated algorithms, from simple pencil-beam models to more advanced convolution/superposition and Monte Carlo-based methods, to predict dose distribution within a patient's computed tomography (CT)-derived anatomical model. Nonetheless, these algorithms may be deficient in precise dose calculation in settings characterized by extreme heterogeneity or complex geometry, such as the head and neck region with its intricate bone structures and air cavities.[11-13] Small errors in calculation can be magnified in these regions, potentially leading to under-dosing of the target or over-exposure of critical organs at risk.

Another advanced approach for estimating dose values in body tissues is the utilization of computational phantoms, also known as virtual phantoms. These are digital representations of human anatomy, often based on CT or magnetic resonance imaging (MRI) data, used within radiation transport simulations like Monte Carlo methods. While incredibly powerful and flexible, their accuracy is contingent upon an accurate understanding of the photon energy spectrum and radiation geometry. Furthermore, the setup and computational duration required for high-fidelity Monte Carlo simulations can be considerable and may be prone to uncertainties related to the modeling of physics processes and anatomical boundaries.[14] Considering these issues, direct dose measurement in physical anthropomorphic phantoms offers several tangible advantages over computational phantoms, especially in more complex geometries, as they account for the full complexity of radiation scattering and interactions in a real, physical object.[7]

As mentioned earlier, assessing the dose values in body tissues during cancer radiotherapy is crucial. However, direct dose measurement in vivo in body tissues is almost impossible for obvious ethical and practical reasons. Moreover, the rapid global expansion of radiology/radiotherapy centers and the continual advent of modern, complex diagnostic and therapeutic instruments necessitate robust, precise, and reliable quality control and commissioning procedures for these instruments. Utilizing physical anthropomorphic phantoms appears to be a viable and comprehensive solution to address these issues, bridging the gap between theoretical calculations and actual delivered dose.

A significant barrier to the widespread adoption of these essential tools is their prohibitive cost. Commercially available physical anthropomorphic phantoms, such as the RANDO® phantom, are typically expensive, often costing tens of thousands of dollars. This high cost severely limits their accessibility, particularly in low- and middle-income countries (LMICs) and smaller clinics, potentially creating a disparity in the quality and safety of radiation care.[15] This financial constraint hinders dosimetric research, routine quality assurance, and the safe implementation of new technologies in these settings. Therefore, there is a pressing need for affordable, high-fidelity alternatives. In response to this need, this study aimed to design and fabricate a cost-effective head and neck anthropomorphic phantom utilizing commercially accessible tissue-equivalent materials, thereby making sophisticated dosimetric validation a more accessible endeavor for a broader range of healthcare and research institutions.

2. Methods

2.1. Phantom design

The dimensions of the phantom for an adult female were initially determined based on International Commission on Radiological Protection (ICRP)-89 report.[16] Subsequently, CT scan images of head and neck region of a female patient were acquired from the medical database of the radiology department at Shahid Beheshti Hospital in Kashan, Iran, depicting a subject whose characteristics closely aligned with the standard specifications. The original CT scans were acquired with a slice thickness of 1 mm and reconstructed using a standard kernel. The CT images were imported into 3D-Slicer software; then, the three-dimensional skeletal structure, outer shell (representing the skin or the area surrounding the phantom) and the air cavities (such as sinuses, oral cavity, etc.) were extracted in format of Stereolithography (STL) files and imported into CATIA software. Next, point cloud extraction from the STL files was done using commands in CATIA, and Standard for the Exchange of Product Data (STP) files were exported. The STP files were imported into Autodesk Inventor for design purposes. Then, the final model was sectioned into 5 mm thick cross-sections, which were sequentially numbered starting with top of the head as 1, and the overall phantom structure was formed. Two support rods were used to maintain the phantom's overall form. For dosimetric purposes, TLD holes (3 mm in diameter and 5 mm in depth) were included in a 3 cm × 3 cm grid in each slice.

2.2. Material selection

In the present study, two tissue-equivalent materials were chosen based on the recommendations of the ICRU-44 report.[17] In this regard, Plexiglass (polymethyl methacrylate) and Polytetrafluoroethylene (PTFE) were selected as substitutes for soft tissue and bone, respectively.

To select the most suitable ones, different types of Plexiglass and PTFE materials were prepared and their characteristics including elemental compositions, physical density, electron density, electron density per volume, effective atomic number and Hounsfield unit (CT number) were obtained and compared with those in ICRU-44 report.

2.2.1. Elemental compositions

The elemental weight fractions of the evaluated materials were obtained using CHNSO elemental analyzer and EDAX-EDS analyzer.

2.2.2. Physical density

To measure the physical density of the materials, three various volumes/dimensions of 0.5×0.5×0.5, 0.5×0.5×1.5 and 0.5×0.5×2 cm^3 were set as references. For each referenced value, twelve pieces of each material were cut. Then, their physical densities were determined by dividing the mass of each piece, measured using an analytical balance with 0.1 mg precision, by its volume.

2.2.3. Electrons per gram (ρ~e~):

The electron densities (number of electrons per gram) of the materials were calculated using the formula below:[18]

$$\rho_e = N_A \, . \, \sum \frac{W_a . Z_a}{A_a} \qquad (1)$$

where N_A, W_a, Z_a and A_a are the Avogadro number, elemental weight fraction, atomic number and the atomic mass of each atom, respectively.

2.2.4. Electron density per volume

We calculated the electron density per volume (EDV or numbers of electrons/cm^3) parameter for the materials using the formula below:[18]

$$\text{EDV} = \text{Physical density} \times \rho_e \qquad (2)$$

2.2.5. Effective atomic number

The effective atomic number of the materials was given by:[18]

$$Z_{eff} = \frac{\sum \frac{W_a . Z_a}{A_a}}{\frac{W_a}{A_a}} \qquad (3)$$

2.2.6. CT number

For determining CT number, the materials were scanned using a CT scanner at 120 kVp and standard dose settings. For each material, 50 points were randomly selected on the resulting images of the evaluated materials. Of note, the reported values are the average of these 50 points.

2.3. Phantom assembly

After selecting the most appropriate equivalent materials for soft tissue and bone, plexiglass and PTFE plates with a 5mm thicknesses were acquired and laser-cut according to the predetermined design. The slice numbers were also inscribed by laser on each slice. Moreover, the TLD holes were filled by the containers made from a tissue-equivalent resin.

Results

The human body is a heterogeneous medium with tissues of different densities, leading to various radiological responses following radiation exposure. Accurate dose estimation for specific organs is essential in radiology and radiotherapy; however, direct measurement in vivo is nearly impossible. In this study, we successfully designed and constructed a head and neck anthropomorphic phantom to address this challenge using commercially available tissue-equivalent materials.

Figure 1 shows a general view of the assembled phantom, while Figure 2 presents a topogram of the constructed phantom. To ensure anatomical accuracy, the phantom was generated from CT scan images of an adult female acquired with a slice thickness of 1 mm and reconstructed using a standard kernel.

Figure 1. A general view of the assembled cost-effective head and neck anthropomorphic phantom. The phantom is constructed from stacked 5 mm thick laser-cut plates of plexiglass (soft tissue-equivalent) and polytetrafluoroethylene (PTFE, bone-equivalent), secured with alignment rods.

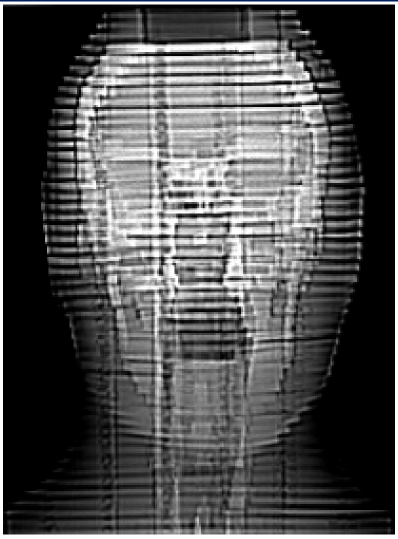

Figure 2. A topogram (scout view) of the constructed head and neck phantom, demonstrating its overall anatomical proportions and external contour.

Our material evaluation focused on identifying optimal tissue substitutes. Two materials - plexiglass (representing soft tissue) and polytetrafluoroethylene (PTFE, representing bone) - were selected based on ICRU-44 recommendations. Various types of these materials were characterized, and those most closely matching reference values were utilized in phantom fabrication.

Table 1 summarizes the physical properties and elemental composition of plexiglass compared to ICRU-44 soft tissue standards. Our plexiglass sample showed excellent agreement in physical density (1.18 vs. 1.17 g/cm^3), electron density per gram (3.17×10^{23} vs. 3.247×10^{23}), and electron density per volume (3.74×10^{23} vs. 3.8×10^{23} electrons/cm^3). While the effective atomic number showed a slight deviation (4.22 vs. 3.61), the overall dosimetric properties aligned well with soft tissue standards.

Table-2 presents corresponding data for PTFE compared to ICRU-44 bone standards. Our PTFE sample demonstrated close agreement in all measured parameters: physical density (2.2 vs. 2.1 g/cm^3), electron density per gram (2.9×10^{23} vs. 2.89×10^{23}), electron density per volume (6.38×10^{23} vs. 6.07×10^{23} electrons/cm^3), and effective atomic number (7.76 vs. 8.0).

Table 3 shows the average CT numbers obtained for both materials scanned at 120 kVp. The values (plexiglass: 105 HU; PTFE: 804 HU) appropriately represent soft tissue and cortical bone, respectively.

The phantom incorporates TLD holes (3 mm in diameter and 5 mm in depth) arranged in a 3×3 cm grid within each 5 mm-thick slice [Figure-3], providing high spatial resolution for dose measurements. The total manufacturing cost was approximately eight times lower than commercially available phantoms (such as RANDO phantom).

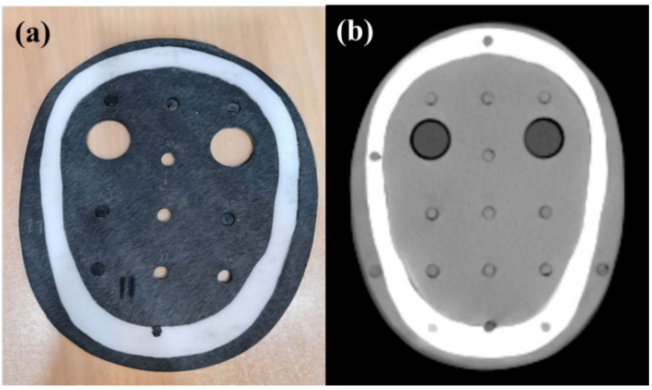

Figure 3. A cross-sectional view of slice number 11 from the constructed phantom (a) and its corresponding CT scan image acquired at 120 kVp (b). The image clearly shows the spatial distribution of the bone-substitute (PTFE, white arrows) and soft tissue-substitute (plexiglass) materials. The grid of TLD holes (3 mm diameter, 5 mm depth) is also visible.

Table 1. Physical properties and elemental compositions of Plexiglas as the tissue-substitute material for soft tissue.

Physical properties	ICRU-44	Our study
Physical density (g/cm^3)	1.17	1.18
EDG (ρ_e)	3.247×10^{23}	3.17×10^{23}
EDV (electrons/cm^3)	3.8×10^{23}	3.74×10^{23}
Effective atomic number	3.61	4.22
Elemental composition (weight %)		
C	60	63.04
H	8	5.28
N	-	0.85
S	-	1.65
O	32	29.18

Table 2. Physical properties and elemental compositions of PTFE as the tissue-substitute material for bone.

Physical properties	ICRU-44	Our study
Physical density (g/cm^3)	2.1	2.2
EDG (ρ_e)	2.89×10^{23}	2.9×10^{23}
EDV (electrons/cm^3)	6.07×10^{23}	6.38×10^{23}
Effective atomic number	8	7.76
Elemental composition (weight %)		
C	24	30.51
O	-	1.23
F	76	68.26

Table 3. Average CT number of the tissue-substitute materials used in the construction of head and neck phantom.

Material	CT number (HU)
PTFE	804
Plexiglass	105

Discussion

This study successfully demonstrates the development and preliminary validation of a cost-effective head and neck anthropomorphic phantom constructed from commercially available materials. The primary innovation of this work lies not in the creation of a phantom *per se*, but in its radical cost-effectiveness achieving production costs approximately one-eighth of commercial alternatives while striving to maintain critical dosimetric accuracy through a rigorous process of material selection and thoughtful design. This addresses a significant and often overlooked barrier in global radiation medicine: the inequitable access to high-quality dosimetric tools necessary for patient safety and treatment efficacy.[15,19]

The foundation of any reliable anthropomorphic phantom is the radiological fidelity of its constituent materials. Our comprehensive characterization results confirm that the selected plexiglass (PMMA) and polytetrafluoroethylene (PTFE) samples closely match the ICRU-44 reference values for soft tissue and bone equivalents, respectively. The excellent agreement observed in physical density, electron density per gram (ρ_e), and electron density per volume (EDV) is particularly crucial. These parameters are fundamental drivers of photon interaction probabilities through Compton scattering, which is the dominant interaction mechanism in the diagnostic and therapeutic megavoltage energy range.[20] The slight deviation observed in the effective atomic number (Zeff) for plexiglass (4.22 vs. 3.61) is noteworthy but unlikely to significantly impact photon dosimetry, especially within the orthovoltage and megavoltage ranges central to radiotherapy. The photoelectric effect, which is highly dependent on Zeff (proportional to Z^3), diminishes in importance at higher energies. Therefore, the strong concordance in electron density and CT number the latter being a direct indicator of a material's linear attenuation coefficient at a specific beam energy provides greater confidence in the material's performance for its intended dosimetric role.[21] The measured CT numbers of 105 HU for plexiglass and 804 HU for PTFE at 120 kVp are entirely appropriate for representing soft tissue and cortical bone, ensuring that the phantom will interact with diagnostic and planning CT beams in a anatomically realistic manner.

Beyond material properties, the structural design of the phantom incorporates several advantageous features that enhance its practical utility. A key innovation is the use of a 5 mm slice thickness with TLD holes arranged in a 3×3 cm grid. This design provides superior spatial resolution for dose mapping compared to many commercially available phantoms, such as the RANDO® phantom, which typically employs 10 mm or even 25 mm thick slices.[22] This enhanced resolution is not merely an academic improvement; it is particularly valuable for modern radiotherapy techniques like IMRT and VMAT, which are characterized by steep dose gradients at the boundaries between targets and organs at risk (OARs).[23] The ability to measure dose with high spatial density is critical for verifying the accuracy of these complex treatments. Furthermore, the use of a tissue-equivalent resin to fill the TLD holes is a critical detail often overlooked in homemade phantom designs. This practice ensures minimal perturbation of the radiation field during measurements, preventing the introduction of air cavities or non-equivalent materials that could scatter or attenuate the beam and lead to erroneous readings.[8] The CT imaging presented in the results confirms the successful integration of both materials and the TLD holders, demonstrating appropriate spatial relationships and material representation that faithfully recreates the heterogeneities of the head and neck region.

Despite these strengths, several limitations of the current phantom design must be acknowledged to contextualize its application and guide future development. Firstly, the current iteration lacks specific internal organ delineation (e.g., spinal cord, parotids, larynx, mandible). While the phantom accurately represents bulk tissue heterogeneities (soft tissue vs. bone vs. air), it does not allow for organ-specific dose assessment. This is a common trade-off in cost-effective designs. Future iterations could incorporate these structures using 3D-printing technologies with different tissue-equivalent filaments or by molding specific organs from compatible materials.[24] Secondly, the rigidity of the selected materials (plexiglass and PTFE) prevents the simulation of patient movement or tissue deformation. This means the phantom is unsuitable for evaluating techniques that account for motion, such as 4D radiotherapy or the impact of breathing on dose distribution in lower neck targets. Additionally, the materials cannot simulate the changes in electron density associated with anatomical changes, a factor increasingly important with the adoption of adaptive radiotherapy workflows.[25]

The most critical next step for this research is the comprehensive dosimetric validation of the phantom. Future work will include rigorous testing against both treatment planning system (TPS) calculations and direct measurements in a established commercial phantom. This validation should involve irradiating the phantom under a variety of clinical scenarios (e.g., open fields, IMRT/VMAT plans for head and neck cancer) and comparing the measured TLD doses with those predicted by the TPS. Discrepancies can reveal insights into both the phantom's performance and potential limitations of the TPS algorithm in heterogeneous regions. Furthermore, end-to-end tests, from CT simulation to plan delivery and dose measurement, should be conducted to assess the phantom's suitability for overall quality assurance programs.[8]

Despite these limitations, the methodology established here, developed in consultation with an experienced anatomist to ensure anatomical fidelity, provides a robust and adaptable framework. The same process utilizing patient CT data, CAD software for slicing, and laser-cutting of characterized materials can be employed to create a suite of various anthropomorphic models, including pediatric, adult male, and female-specific pelvic phantoms. This scalability significantly enhances the impact of the approach. The potential of this cost-effective phantom to facilitate advanced dosimetric research, routine quality control of radiation systems, and independent validation of treatment planning algorithms, particularly in resource-limited settings, is substantial.[26] By lowering the financial barrier to entry, it empowers more clinics to engage in a higher standard of patient safety and technical excellence, helping to bridge the global inequity gap in radiation medicine.

Conclusions

In this study, we successfully developed a low-cost head and neck female anthropomorphic phantom using commercially available materials. Comprehensive material validation confirmed that the selected plexiglass and PTFE closely match the radiological properties of soft tissue and bone as specified in the ICRU-44 report. The production cost of the phantom is estimated to be approximately one-eighth of commercially available phantoms (such as RANDO phantom), making it a highly accessible and practical tool. The incorporation of TLD holes in a 3 cm × 3 cm grid within 5 mm slices provides enhanced spatial resolution for dosimetric measurements. This cost-effective phantom shows significant potential for advancing dosimetric research, quality control of radiation systems, and validation of treatment planning algorithms in various radiology/radiotherapy centers, particularly those with limited resources. Future work will focus on the comprehensive dosimetric validation of this phantom against established standards.

Acknowledgment

None.

Competing interests

The authors declare that they have no competing interests.

Abbreviations

As Low As Reasonably Achievable: ALARA; Magnetic Resonance Imaging: MRI; Intensity-Modulated Radiotherapy: IMRT; Volumetric Modulated Arc Therapy: VMAT; Treatment Planning Systems: TPS; Computed Tomography: CT; Magnetic Resonance Imaging: MRI; Low- And Middle-Income Countries: LMICs; International Commission on Radiological Protection: ICRP; Stereolithography: STL; Polytetrafluoroethylene: PTFE; Electron Density per Volume: EDV; Organs At Risk: OARs; Treatment Planning System: TPS.

Authors' contributions

All authors read and approved the final manuscript. All authors take responsibility for the integrity of the data and the accuracy of the data analysis.

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Availability of data and materials

The data used in this study are available from the corresponding author on request.

Ethics approval and consent to participate

The study was conducted in accordance with the Declaration of Helsinki.

Consent for publication

By submitting this document, the authors declare their consent for the final accepted version of the manuscript to be considered for publication.

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