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NOTE

TEMPy: a toolkit for the modeling of weighted tissue equivalent material in diagnostic imaging

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Abstract

Objective. Accurate simulation of human tissues is imperative for advancements in diagnostic imaging, particularly in the fields of dosimetry and image quality evaluation. Developing Tissue Equivalent Materials (TEMs) with radiological characteristics akin to those of human tissues is essential for ensuring the reliability and relevance of imaging studies. This study presents the development of a mathematical model and a new toolkit (TEMPy) for obtaining the best composition of materials that mimic the radiological characteristics of human tissues. The model and the toolkit are described, along with an example showcasing its application to obtain desired TEMs. *Approach.* The methodology consisted of fitting volume fractions of the components of TEM in order to determine its linear attenuation coefficient as close as possible to the linear attenuation coefficient of the reference material. The fitting procedure adopted a modified Least Square Method including a weight function. This function reflects the contribution of the x-ray spectra in the suitable energy range of interest. TEMPy can also be used to estimate the effective atomic number and electron density of the resulting TEM. *Main results.* TEMPy was used to obtain the chemical composition of materials equivalent to water and soft tissue, in the energy range used in x-ray imaging ($10 - 150$ keV) and for breast tissue using the energy range (5–40 keV). The maximum relative difference between the linear attenuation coefficients of the developed and reference materials was $\pm 5\%$ in the considered energy ranges. *Significance.* TEMPy facilitates the formulation of TEMs with radiological properties closely mimicking those of real tissues, aiding in the preparation of physical anthropomorphic or geometric phantoms for various applications. The toolkit is freely available to interested readers.

1. Introduction

Modeling physical aspects of the interactions of ionizing radiation with human tissues using non-biological materials has been a challenging issue in medical physics in the last century (DeWerd and Kissick 2014). This challenge is associated with the intrinsic characteristics of the interaction of ionizing radiation with matter and with the goal of using this radiation for patient imaging or treatment. These materials, hereafter called tissue-equivalent materials (TEMs), are typically used for manufacturing device commonly referred in the literature as phantoms.

The field of phantoms is constantly evolving, with efforts to push the boundaries of tissue representation beyond conventional materials (Manohar *et al* 2024). Independently of the adopted design, these phantoms must be constructed using TEMs that adequately represent the tissues they should mimic, taking into account the different mechanisms of the interaction of the radiation with matter. In the present work, the focus of the developed method and the presented results are consistent with imaging applications. However, they can also be extended and validated to other energy ranges (White 1978b, DeWerd and Kissick 2014).

TEMs must mimic both the physical and radiological properties of the tissues they should represent. Mass density and effective atomic number can describe physical quantities, while radiological characterization can be described by the linear attenuation coefficient (White 1978a, Singh and Badiger 2014). Recent literature is plenty in information regarding the developments of TEMs and phantoms for different applications. For example, for the x-ray imaging range of energies, Vedanthan (2017) published a complete demonstration of the influence of physical quantities on the design of TEMs. The author's approach considers physical properties such as the mass attenuation coefficient, effective atomic number and electron density of mixtures and compounds and their impact on the design of TEMs for different applications in medical imaging.

Specific applications and availability of TEMs and phantoms for x-ray image quality evaluation and dose assessment have also been published (Tomal and Costa 2017). For example, Ng and Yeong (2014) summarize the available options for conventional x-ray imaging phantoms including anthropomorphic and quality control/accreditation models. Similar aspects of mammography (Tomal 2014, Sarno *et al* 2023) and computed tomography (Costa 2014) phantoms are also described in the literature. In each case, details of the nature of the materials adopted for an adequate representation of the human tissues and anatomic-morphologic construction of the phantoms for dosimetry applications are presented. The proper design and choice of the TEMs are essential for a good performance of these devices.

Nowadays, the popularization of the additive manufacture (3D printing) of objects has been changing the perspectives on the production of phantoms for medical applications (Cho *et al* 2015, Bliznakova *et al* 2022, Dukov *et al* 2022, Okkalidis *et al* 2022, Varallo *et al* 2022). Nonetheless, in the case of anthropomorphic phantoms, besides being printed using TEMs with attenuation properties as similar as possible to the respective target-tissues, the modeling has to produce the correct association of the TEM to the anatomic part of the human body (Bliznakova *et al* 2018). This kind of approach was published by Varallo *et al* (2022) and Mainprize *et al* (2020) considering anthropomorphic phantoms for breast imaging, by Hatamikia *et al* (2023) for Cone Beam CT, Tino *et al* (2022) for chest CT and Okkalidis *et al* (2022) for bones.

In this work we introduce TEMPy (**T**issue **E**quivalent **M**aterial in **Py**thon), a web application that uses the Least Squares Method (LSM) as a tool to optimize the formulation of TEMs. This application is based on a mathematical method that minimize the difference of the linear attenuation coefficient of the composition and the target material using a weighting function. As illustrative examples, we used TEMPy to obtain samples of water-equivalent, soft tissue-equivalent and breast TEMs in the energy range used in mammography (5–50 keV) and x-ray radiography or CT imaging (10–150 keV).

2. Methods

2.1. Mathematical modeling

The determination of human-tissue-equivalent compounds for radiology was performed using the methodology developed by Mariano and Costa (2017), which is based on the LSM. In this method, the volumetric fractions of the combined materials used to prepare the intended compounds are determined by minimizing the difference between the linear attenuation coefficient, $\mu(E)$, of the formulations and the linear attenuation coefficient of the reference material, $\mu_{\text{ref}}(E)$.

The model function to be fitted is obtained by approximating the linear attenuation coefficient of a mixture with the linear attenuation coefficient of the material to be developed.

$$q_1\mu_1(E) + q_2\mu_2(E) + \ldots + q_n\mu_n(E) = \mu_{\text{ref}}(E). \tag{1}$$

The volume fractions of the ith materials within the mixture, q_i, are the parameters to be adjusted in accordance with the condition,

$$q_1 + q_2 + \ldots + q_n = 1. \tag{2}$$

The hypothesis that the uncertainties in the attenuation coefficients, σ_j, are not covariant and are calculated as a percentage of the coefficient value itself, was also adopted in the calculations. The uncertainties are normalized by dividing by the square root of the normalized intensity of the corresponding energy point in the spectrum. This normalization process ensures that the uncertainties are appropriately scaled relative to the intensity of the x-ray beam at each energy level. To maximize the quality of fitting procedure in the energy range of x-rays that corresponds to the expected application of the TEM, the model adopts the energy spectrum of the x-ray beam, $w(E)$, as a weight function. Therefore, the equation to be minimized is:

$$Q = \sum_{j=1}^{N} w(E_j)\left(\frac{\mu_{\text{sample}}(q_i, \mu_i, E_j) - \mu_{\text{ref}}(E_j)}{\sigma_j}\right)^2 \tag{3}$$

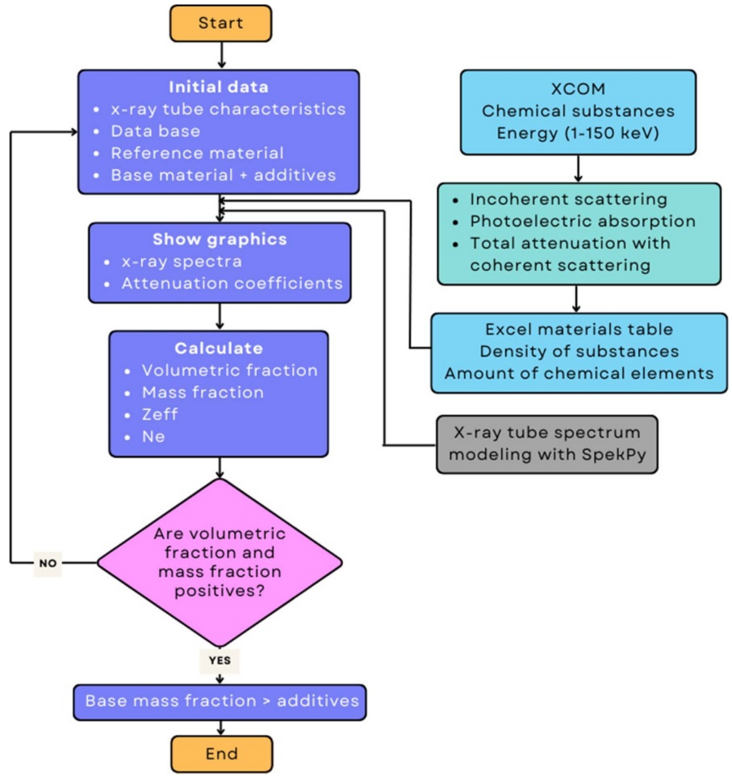

Figure 1. Flow chart of the TEMPy toolkit. Initial data includes selection of x-ray tube characteristics (anode material, additional filtration and kilovoltage peak), data base for calculation of beam parameters (NIST ou Penelope), reference material, base material and additives to form the tissue-equivalent material (TEM). The attenuation coefficients of the reference materials and additives are obtained from XCOM database and stored in an Excel materials table along with their densities and chemical composition. Following a click of the 'Show graphics' button, x-ray spectra, several beam qualifiers obtained through Spekpy and attenuation coefficients are presented. Volumetric and mass fraction are obtained through the Least Squares Method using matrix formalism. Mass density, effective atomic number and electron density for the formulated material are also shown. A TEM is obtained when volumetric and mass fraction of base and additives are positives.

where N is number of points in the energy spectrum. The index i varies from 1 to the number of materials in the mixture.

The minimization was implemented in Python using matrix formalism. The code utilizes three defined functions which are crucial components of the procedure. The first one is responsible for calculating a data vector. This function involves nested iterations over the model parameters, representing the volumetric fractions that serve as weights assigned to different materials in the mixture. Similarly, another function is designed to calculate a matrix, with nested iterations over pairs of model parameters and applying identical weighting and normalization factors. The inverse of the resulting matrix is then computed using the NumPy library, transforming it into a matrix inversion problem. This inversion yields a key component for solving the system of equations. Finally, the last function utilizes the obtained inverse matrix along with the data vector to compute the volumetric fractions, solving the system efficiently through matrix multiplication.

2.2. About the TEMPy toolkit

To implement and validate the presented mathematical method, the TEMPy computational routine was built using Streamlit (https://streamlit.io/), a Python-based tool (Python Software Foundation) for developing web applications. The described modeling was integrated to the web interface, enabling users to input data and obtain estimations. The toolkit also makes use of libraries such as 'NumPy', 'Pandas', 'SciPy' and 'Plotly'.

The software also uses the *SpekPy* toolkit (Bujila *et al* 2020, Poludniowski *et al* 2021), which is available from a public repository (https://bitbucket.org/spekpy/spekpy_release) to generate the x-ray spectra. Through SpekPy, the user can create and manipulate the initial spectrum model for an x-ray tube by applying filters composed by different materials. It also provides access to spectrum parameters, including average and effective energy, first HVL and homogeneity index. TEMPy is available online free-of-charge at https://tempy.if.usp.br. Figure 1 shows the flow chart to illustrate the calculation procedure.

2.3. Procedure for obtaining TEM formulations

The first step is to introduce the initial data for the program to run. These include selection of x-ray tube characteristics such as anode material, additional filtration and kilovoltage peak (kVp). The energy range of interest according to the application of the proposed TEM is also requested. After that, the user is asked to select a database for the linear attenuation coefficients used for beam filtering and half-value-layer determination. The 'NIST' option uses the NIST XCOM database (Berger and Hubbell 1987) and 'PENE' uses the data from the Penelope (PENetration and Energy Loss of Positrons and Electrons) Monte Carlo code (Salvat *et al* 2008). Then, the user has to select the reference material to be simulated and specify the substances to be combined which will result on a TEM. This selection of substances combines two categories of useful materials: a base material, usually the most abundant in the TEM, and one or more additives to be combined to improve the properties of the resulting material. The base materials and additives available in the current version are shown in supplementary materials. Introducing new materials requires knowledge of their composition and density, and can be included through requests to the authors.

The attenuation coefficients of the materials involved (reference, base and additives materials), that appear in equation (3), are accessed through an Excel spreadsheet (Microsoft Corporation—Redmond, Washington, USA). In this Excel spreadsheet the values of the mass attenuation coefficients for incoherent scattering, photoelectric interaction and total attenuation with coherent scattering from XCOM database (Berger and Hubbell 1987), chemical compositions and densities of each material were organized to serve as input data for the TEMPy app. The energy spectrum of the x-ray beam $w(E)$ in equation (3), is modeled by *SpekPy* using the parameters requested in the initial data. Following a click of the 'Show graphics' button, results are presented within a few seconds.

Several beam qualifiers obtained through *SpekPy* are presented: the mean and effective energy of the x-ray spectrum in keV, the first half-value layer in mm of Al and the homogeneity coefficient. Parameter adjustment by LSM was implemented using a matrix method in Python. The methodology organizes the pertinent parameters into matrices and vectors as described in section (2.1). Through NumPy libraries, operations and computations that manipulate these matrices and vectors are made to derive the optimal volume fractions minimizing the discrepancy between the sample and reference materials attenuation coefficients. The volumetric and mass fraction of the materials in the mixture are shown along with the attenuation coefficients and mass density of the formulated material. Effective atomic number and electron density for the TEM as a function of energy, calculated by Manohara´s method (Manohara *et al* 2008) (see supplementary materials), are also shown. If the imposed constraint (volumetric and mass fraction of base and additives must be positive) is respected, the optimized TEM material for the desired application is obtained. A screenshot of the main page of the TEMPy toolkit for obtaining a soft tissue simulating material using epoxy resin and calcium carbonate is shown in figure 2.

2.4. Production of TEMs samples and linear attenuation coefficient measurements

To objectively assess the practical value of TEMPy and test formulations performance, mixtures obtained with TEMPy were produced and their linear attenuation coefficients were experimentally determined. Samples with polypropylene as base material were produced using hot extrusion method while samples employing epoxy resin were prepared in laboratory. To ensure proper homogenization and avoid air bubbles, the mixtures were continuously stirred. The chemical compounds used included calcium carbonate ($CaCO_3$), sodium chloride (NaCl), and titanium dioxide (TiO_2) from Basile Química Ltda (São Paulo, Brazil), magnesium oxide (MgO) from Labsynth (São Paulo, Brazil) and epoxy resin (C_2H_3O) from Química Ltda (São Paulo, Brazil).

The linear attenuation coefficients, $\mu(E)$, were determined experimentally using the exponential attenuation law with a polyenergetic narrow beam. All x-ray measurements were conducted with a Philips MCN 421 x-ray tube, featuring a tungsten (W) target and a 2.2 mm beryllium (Be) window. A narrow beam was achieved using a 28 mm thick, 1.5 mm diameter cylindrical lead (Pb) collimator, positioned 14 cm from the x-ray tube's focal spot, associated to a collimation set incorporated to the spectrometer detector. Preliminary measurements were done without any sample between the x-ray tube and the detector in order to register the primary spectrum. After these measurements, samples were placed one by one between the x-ray tube and the detection system to measure the transmitted spectra. The tube voltage was set at 180 kV in order to generate x-ray spectra ensuring a high photon counting within the 15–150 keV range. This procedure minimizes measurement uncertainty. The detection system consisted on $3 \times 3 \times 1$ mm^3 Cadmium Telluride (CdTe) spectrometer (model XR-100T, Amptek, Inc, EUA) with the PX4 digital pulse processor. The linear attenuation coefficients were calculated according to the exponential attenuation law through measurements of incident and transmitted spectra through a thickness of the samples. A detailed description of the experimental setup and the procedure used to calculate $\mu(E)$ was previously described by Boiset *et al* (2023).

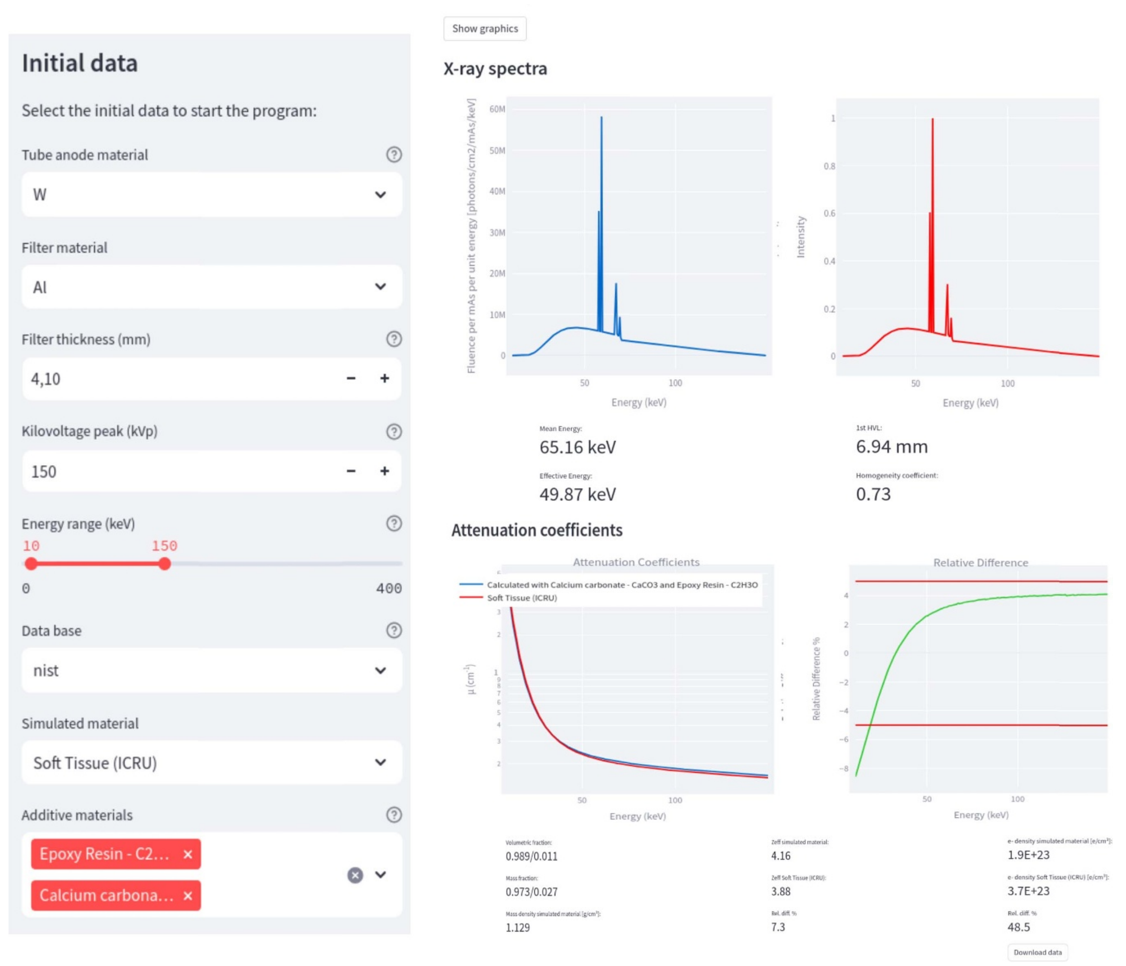

Figure 2. TEMPy toolkit main page. As an example, the obtaining of a material equivalent to soft tissue using epoxy resin and calcium carbonate in the energy region of 10–150 keV is shown.

3. Results

3.1. Generation of TEMs of dosimetric interest

The functionality of TEMPy was illustrated by generating TEMs of interest for x-ray imaging techniques, with epoxy resin and polypropylene as base materials. Table 1 presents the formulations of water-equivalent materials (W1, W2), breast TEMs (BR1, BR2) and soft TEMs (ST1, ST2) calculated according to the presented model using the TEMPy toolkit. The additive column shows the calculated percentage (by mass) of the additive material to be mixed on the base material in order to obtain the expected TEM with the best performance on the selected range of energy. The mass percentage corresponding to base material in each sample is obtained by subtracting this value from 100%. Water and soft TEMs were generated using a tungsten anode x-ray tube filtered by 4.10 mm of aluminum at 150 kV. For breast equivalent materials, a molybdenum anode x-ray tube filtered by 0.03 mm of molybdenum at 30 kV was used.

3.2. Comparative results with reference materials

Figures 3–5 shows the linear attenuation coefficient for the sample formulations calculated using the Mariano&Costa method through TEMPy toolkit and the values for reference material obtained by XCOM database. Below each chart, it is possible to see the relative difference of the attenuation coefficients, where two parallel dashed lines, represent $\pm 5\%$ difference values indicated on ICRU 44 (Goldstone 1990) for a composition to be considered as TEM.

In order to evaluate the quality of the formulations obtained in terms of its similarity to reference materials, samples were produced and the linear attenuation coefficients were estimated according to the attenuation law. Figures 3–5 also shows these results.

The calculated effective atomic numbers at different energies were compared with the values obtained by the Auto-Zeff (Taylor *et al* 2012) and Phy-X/ZeXTRA (Özpolat *et al* 2020) softwares. The results for Water and formulation W2 are available in the supplementary materials.

Table 1. Mass density (ρ), effective atomic number (Z_{eff}) for the energy spectrum used, electron density (ρ_e), percentage (by mass) of the additive material and elemental composition for the TEMs obtained using polypropylene as base material for samples W1 and W2. The base material for the other samples was epoxy resin.

Sample	P (g cm^{-3})	Z_{eff}	ρ_e (10^{23} e cm^{-3})	Additive (% in mass)[a]	Elemental composition (fraction by weight)			
					H	C	O	$Z > 8$
W1	1.036	3.4	2.7	MgO (19)	0.116	0.694	0.075	Mg (0.115)
W2	0.939	3.3	2.2	NaCl (8)	0.132	0.788	—	Na (0.031); Cl (0.049)
BR1	1.129	6.2	3.6	MgO (3)	0.068	0.541	0.372	Mg (0.018)
BR2	1.115	6.5	3.1	NaCl (1)	0.070	0.552	0.368	Na (0.004); Cl (0.006)
ST1	1.124	4.1	1.8	TiO_2 (2)	0.069	0.547	0.372	Ti (0.012)
ST2	1.130	4.2	1.9	$CaCO_3$ (3)	0.068	0.545	0.375	Ca (0.012)

[a] The percentage (by mass) of the additive material, calculated by TEMPy, was rounded to always give an integer value.

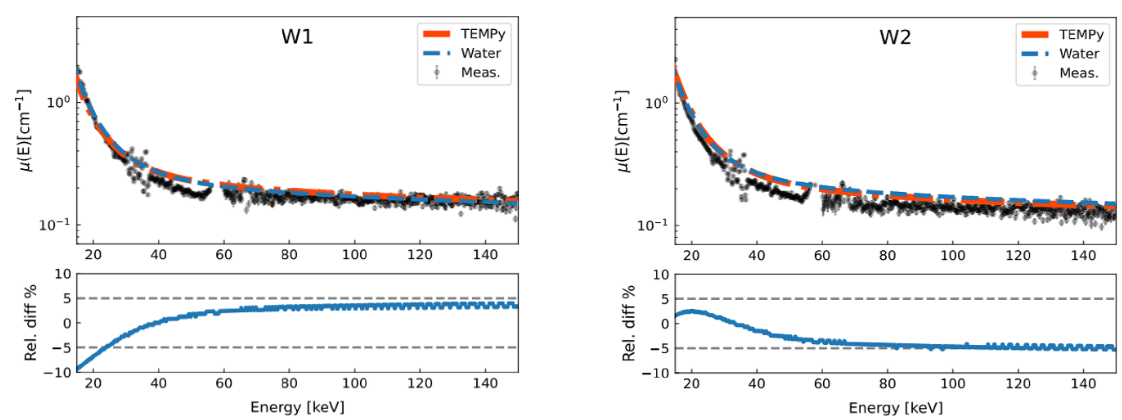

Figure 3. Linear attenuation coefficients of water (dashed blue line) and of the TEM (W1 and W2) whose chemical composition was calculated using TEMpy to mimic water (dashed red line). Both were calculated using XCOM database. The black dots represent the experimentally determined linear attenuation coefficients for the produced prototypes. The relative percentage difference of the TEMPy result against reference material is shown below each plot, with the horizontal dashed lines corresponding to ±5%.

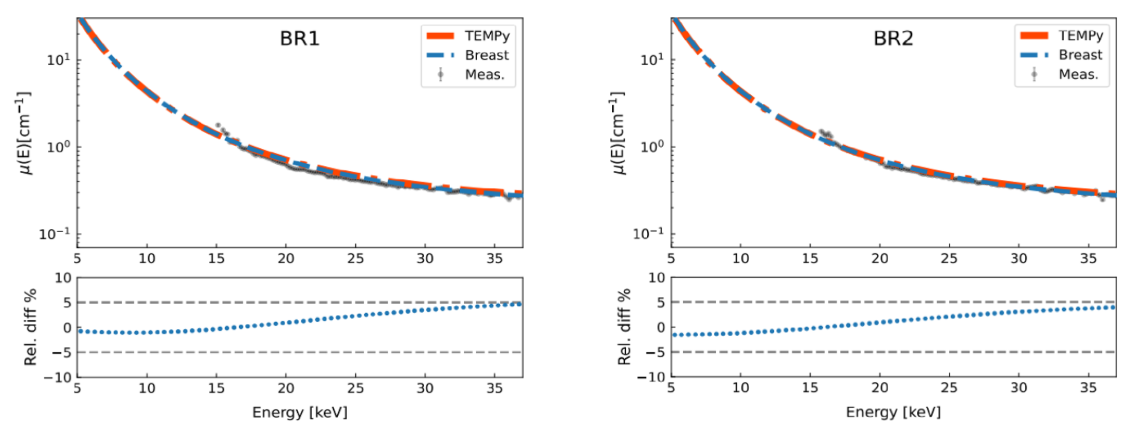

Figure 4. Linear attenuation coefficients of breast tissue (dashed blue line) and of the TEM (BR1 and BR2) whose chemical composition was calculated using TEMPy to mimic breast tissue (dashed red line). Both were calculated using XCOM database. The black dots represent the experimentally determined linear attenuation coefficients for the produced prototypes. The relative percentage difference of the TEMPy result against reference material is shown below each graph, with the horizontal dashed lines corresponding to ±5%.

4. Discussion

For a material to be considered tissue-equivalent, it must exhibit radiation transmission behavior, depending on thickness, that closely resembles that of the reference material. The attenuation of radiation as a function of the energy of the photons and the medium in which they interact can be expressed in terms of the linear attenuation coefficient. Several ways of obtaining TEMs have been proposed in the literature (Hermann *et al* 1985, 1986, Jennings 1993, Homolka *et al* 2002, Yohannes *et al* 2012). Most of these methods equally consider

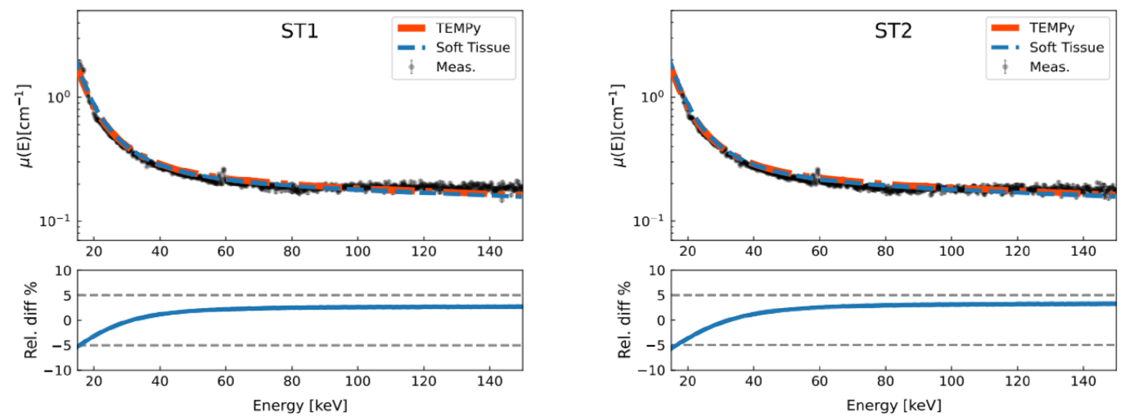

Figure 5. Linear attenuation coefficients of soft tissue (dashed blue line) and of the TEM (ST1 and ST2) whose chemical composition was calculated using TEMPy to mimic soft tissue (dashed red line). Both were calculated using XCOM database. The black dots represent the experimentally determined linear attenuation coefficients for the produced prototypes. The relative percentage difference of the TEMPy result against reference material is shown below each graph, with the horizontal dashed lines corresponding to ±5%.

the energy region of interest and are based on equalizing the attenuation coefficient of the developed and the reference material at just two or three different energies with the exception to the Homolka *et al* (2002) approach. The main problem when equally considering the energy region of interesting, occurs at the beginning of the energy range, between 10 and 20 keV. In a typical x-ray imaging beam, a large part of the low-energy x-rays are filtered, as they contribute strongly to the absorbed dose. However, it is at the lower energy range of the x-ray spectra that the contributions to the composition of the phantom material are more relevant, since it is in this region that the photoelectric effect predominates. Therefore, when developing TEMs in the diagnostic imaging range of energies, this filtration must be taken into account.

The TEMPy web application adopt the LSM as a tool to optimize the formulation of TEMs (Mariano and Costa 2017). The core innovation of TEMPy lies in its enhanced application of the weighted least squares method (WLSM) tailored specifically for the formulation of TEMs with radiological properties akin to human tissues over specified energy ranges. This weight function helps to prioritize that the attenuation coefficient of the TEM is closest to the attenuation coefficient of the reference material in the region that contains the greatest number of photons in the energy spectrum to which this phantom will be used in quality assurance or dosimetry applications. If this phantom will be used to obtain images, the weight function prioritizes the events that contribute most to the formation of the image. While the WLSM itself is a widely utilized algorithm, TEMPy differentiates through several technical advancements and functional enhancements that set it apart from prior works, as those by Homolka *et al* (2002) and Yohannes *et al* (2012).

Homolka *et al* (2002) developed a method for optimizing the composition of phantom materials primarily for computed tomography. Their approach focused on adjusting the x-ray attenuation properties of polymers mixed with mineral components to approximate the attenuation coefficients of various tissues. While effective, their methodology was constrained by the need for predetermined base polymers and additives, which limited flexibility. Additionally, the algorithm employed by Homolka *et al* did not incorporate spectral weighting tailored to specific diagnostic applications, which is a key feature of TEMPy. TEMPy offers the possibility of modeling, through integration with SpekPy (Bujila *et al* 2020, Poludniowski *et al* 2021), molybdenum and rhodium anodes (20–50 kV) and tungsten anode spectra (20–300 kV). This means that x-ray tubes relevant to mammography, radiography, low- and medium-energy x-ray radiotherapy, and industrial testing can be simulated and used as weight function. This integration ensures that the resulting TEMs are optimized not only for general use but also for specialized scenarios. Furthermore, TEMPy also introduces a user-friendly web interface, significantly lowering the barrier for users to input data, run simulations, and visualize results compared to the more technically demanding interfaces or standalone applications used in previous methods. This ease of use is complemented by the toolkit's ability to handle a wide range of materials and additives, allowing users to tailor the TEMs to their specific needs rather than relying on a limited set of components. The functionality of TEMPy was illustrated by generating some formulations of interest for x-ray imaging techniques.

Figures 3–5 show the linear attenuation coefficient variation of the formulated materials in the photon energy range of interest for diagnostic imaging. The variation in $\mu(E)$ can be explained by partial photon interaction processes, which result in the dependence of the total atomic cross-section on atomic number and photon energy. The cross-section of the photoelectric effect is dominant in the regions between ~5 and

50 keV and strongly depends on the atomic number of the material. At the same time, the cross-section of the Compton effect is dominant between 50 and 150 keV and varies almost linearly with the atomic number of the material. Thus, the lower-energy region of the spectra is much more dependent on the atomic number than the higher-energy region, making the match with the reference material coefficient more difficult in this region. These facts highlight the importance of using the Mariano&Costa methodology, compared to other methods presented in the literature to obtain adequate TEMs in a wide range of energies. In figures 3–5 it is possible to see that there is a wide range of energies in which the maximum relative μ difference between the formulated and reference material attenuation coefficients is less than 5% as recommended by ICRU 44 (Goldstone 1990). Samples of the formulated materials were produced and the comparative of the μ results indicated that the developed samples match well with the intended reference material. The mean difference between the measured and the reference $\mu(E)$ was lower than 7.3%.

It is important to acknowledge that TEMPy, like any modeling tool, has limitations. While TEMPy excels at formulating TEMs that mimic the attenuation behavior of target tissues, it does not explicitly account for all factors influencing radiation transport within the human body. TEMPy primarily focuses on the inherent material properties of the TEM itself. In real-world scenarios, scattered radiation within the body can influence the overall attenuation behavior. Phantoms are often composed of different materials besides the TEM itself, such as filler materials used to embed the TEM or create specific anatomical features. TEMPy does not currently factor in the potential interactions between the TEM and these surrounding materials. Future developments in the toolkit could explore methods to account for these effects.

Despite these limitations, TEMPy's versatility in formulating TEMs makes it a helpful and feasible tool for phantom development. Its ability to handle multiple materials and their varying proportions allows for the formulation of phantoms with heterogeneous material compositions, mimicking the complex tissue found in the human body. This feature is particularly valuable for simulating organs and tissues with distinct material properties. TEMPy's versatility extends beyond traditional radiography and computed tomography. Its ability to optimize TEM formulations for specific x-ray beam spectra makes it suitable for designing phantoms for innovative techniques such as breast computed tomography, spectral computed tomography and phase contrast imaging that demands phantoms that faithfully replicate tissue characteristics (Endrizzi 2018, Greffier *et al* 2023). Through meticulous formulation facilitated by TEMPy, researchers achieve intricate control over material compositions, thereby enabling the accurate simulation of tissue behaviors under diverse imaging modalities. Moreover, the possibility of combining materials compatible with additive manufacturing through TEMPy empowers the generation of anatomically complex structures within phantoms, enabling comprehensive validation and optimization of imaging modalities ensuring safer and more reliable advances in the medical and diagnostic imaging fields.

While TEMPy demonstrates significant potential for TEM design, it is valuable to recognize the existing tools and approaches (Okkalidis and Bliznakova 2022, Varallo *et al* 2022). One relevant study by Zhang *et al* (2018) describes the creation of a heterogeneous mouse phantom for multimodality medical imaging. Both TEMPy and the work by Zhang *et al* shares a similar application background in simulating TEMs. Zhang *et al* employ a multi-step experimentation approach to obtained the desire materials. TEMPy, on the other hand, could achieves this by formulating TEM compositions that match the attenuation coefficients of reference tissues across a broad energy spectrum in a faster way. TEMPy's ability to formulate precise material compositions could be leveraged in studies for similar purposes to that conducted by Zhang *et al.*, to optimize designed phantoms by potentially improving their accuracy in replicating tissue attenuation behavior. This complementarity aspect emphasizes the relevance of encouraging new research on this topic in order to improve the realism of the phantoms for medical imaging and dosimetry applications.

5. Conclusion

In this work, a methodology developed by Mariano&Costa based on the LSM, for the formulation of materials radiologically equivalent to human tissues, was integrated into web application called TEMPy. The methodology was applied to obtain TEMs of interest in the energy range between 10–150 keV. These findings highlight the utility of the application to obtain formulations of tissue-equivalents for fabricating anthropomorphic phantoms with accessible materials. Given the importance of Z_{eff} in the identification and differentiation of tissues in diagnostic imaging, TEMPy can also be employed to calculate Z_{eff} in a wide range of photon energies.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

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Conflict of interest

The authors have no conflicts to disclose.

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