Tissue-equivalence of 3D-printed plastics for medical phantoms in radiology

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Abstract: The paper describes measurement of the linear attenuation coefficients for 59.5 keV, 122.0 keV and 344.5 keV photons and Hounsfield units for 80 kVp and 120 kVp computed tomography imaging of a large set of commercially 3D-printed test samples of different plastic materials aiming to provide a basis for a selection of a suitable and available material for 3D printing of medical phantoms used in radiology, and specifically for imaging in targeted radionuclide therapy. The results were compared to ICRU44 skeletal muscle and adipose tissues. The results also showed large differences between photon attenuation properties of the same type of plastic material printed by different companies on different printers using filaments from different manufacturers. As a result, it is highly recommended to print a medical phantom on the same printer, with the same settings, and with the same filament as the test sample.

Keywords: Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Instrumentation for gamma-electron therapy

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1 Introduction

In the last years there has been an increase in Europe in the development and use of radiopharmaceuticals for treating cancer in the field of radiotherapy called molecular radiotherapy (MRT) that is also known as ‘targeted radionuclide therapy’, or ‘nuclear medicine therapy’. In spite of the growing acceptance that an accurate knowledge of the radiation absorbed dose to critical tissues would provide a more effective targeted use of MRT, most patient treatments were till lately performed by administering a nominal activity of the radiopharmaceutical.

This historical practice is being now abandoned owing to the implementation of the Council Directive 2013/59/EURATOM, Article 56, [1] which states that doses to critical tissues must be individually planned and verified for all radiotherapy (including MRT) in European Union Member States by February 2018. Hence the clinical dosimetry should be performed for all treatments leading to full personalisation and optimisation of targeted radionuclide therapy.

To support this effort, a joint research project 15HLT06 “Metrology for clinical implementation of dosimetry in molecular radiotherapy” (MRTDosimetry; [2]) supported by the European Metrology Programme for Innovation and Research (EMPIR) began in June 2016 and runs for three years, finishing in May 2019. It brings together expertise in metrology and nuclear medicine research in order to provide the metrology support for the clinical implementation of absorbed dose calculations in MRT and reduce the uncertainties associated with every step of the absorbed dose determination.

One of the objectives of the project is the development of a range of 3D-printed quasi-realistic anthropomorphic phantoms for MRT applications used to mimic measurements of real patients.
The reason is that there is currently no commercial phantom available that is able to provide a clinically realistic representation of patients with varying diseases and disease distributions. The developed phantoms will contain compartments fillable with known activities of radioactive liquid or standardized sealed radioactive test sources, having a range of geometrical complexity for validation of multimodal quantitative imaging or absorbed dose assessment, and for estimation of uncertainties.

3D printing techniques experienced rapid development of in recent years. It allows to utilize a large scale of materials as well as the ability to customize the printed object with the desired geometrical properties. It is therefore not striking that the method was quickly adopted in medicine. A summary on the current methods and medical applications are provided in, e.g., [3–5]. Specific examples of its use in radiology may include the comparison of computed tomography (CT) and positron emission tomography (PET) scans of a commercial and 3D-printed rod imaging phantom [6], 3D-printed spine-shaped phantoms for stereotactic radiotherapy [7], and a 3D-printed anthropomorphic thorax phantom for X-ray based imaging quality evaluation [8]. There is literature dealing with characterization of materials for 3D printing of medical phantoms for radiology (e.g., [9, 10]). However, the goal of this study was to test materials available from commercial companies as the authors do not dispose own suitable 3D printer or 3D printing workshop.

A wide range of plastic materials potentially suitable for 3D printing of medical phantoms in radiology was tested aiming to provide a basis for a selection of a suitable and available material specifically for a 3D printing of a neck phantom developed within the project and subsequently used for calibrations and verifications in thyroid cancer MRT treatment. The searched material should mimic the radiological properties of soft tissue [11]. The radiological tissue equivalence can be determined by comparison of relevant physical characteristics to the given tissue, e.g., mass density, electron density, elemental composition, or effective atomic number. As summarized in [12], there are various methods used by different authors for testing for the radiological tissue equivalence, for example relative dosimetry measurements, transmission measurements of photon attenuation, determination of CT Hounsfield units (HU) or electron densities, measurement of the mass-energy absorption coefficients, or Monte Carlo calculations. In this study, the authors used HU values from CT scans and γ-ray transmission measurements.

2 Materials and methods

The work was focused on the measurement of the linear attenuation coefficient, $\mu$, and the determination of Hounsfield units, $HU$, of 3D-printed test samples of plastic materials and their comparison to the ones of skeletal muscle tissue and adipose tissue. These two tissues were selected as typical representatives of soft tissues in human body. As the materials are aimed to be used for phantoms for validation of quantitative imaging in radionuclide therapy, the study investigates $\mu$ in the lower photon energy range, specifically between 60 and 350 keV. In addition, density of the test samples was determined. On the other hand, no work effort was invested 1) to estimation of stopping and scattering power because the scope of the study is focused more on phantoms for imaging and not dosimetry, and 2) to estimate elemental composition of the samples because the plastics for 3D printing usually include additives and the exact composition of a given plastic may vary batch-to-batch.
2.1 Test samples

Samples of different 3D-printed plastics were obtained from three commercial companies in the Czech Republic. Test samples marked as “A” in the latter text were printed by Elvira s.r.o. (ABC3D), Prague, samples “B” come from Open Innovations s.r.o. (MakersLab), Prague, and samples “C” were obtained from Parzlich s.r.o. (Fillamentum), Hulin, all from the Czech Republic. The companies were asked to print one sample of each available kind of printable plastic material. The sample was a block with the dimensions of 1.0 cm $\times$ 1.5 cm $\times$ 2.0 cm, 200 $\mu$m layer thickness, and 100% filling. In addition, the producers were requested to provide a sample of each filament and an information about the used 3D printer and printing temperature. In total 32 samples were received for testing but a filament sample or printer information was provided for some of them only. The selection of test samples is depicted in figure 1, the list of plastic materials tested is presented in table 1, and the summary information about all samples materials, filament producers, 3D printers, and printing temperature used is presented in table 2. The samples are listed according to the type of the material in order to visually get an overview about variations between samples made of the same material more easily. Samples A9 and A11 to A14 were printed from the same filament, on the same printer and with the same printer settings, but independently in different time periods to get an information about reproducibility of the printing. In addition, the layers in the samples A12 and A14 were printed perpendicularly to the largest side to assess the potential differences resulting from orientation of the layers.

![Figure 1. Selection of 3D-printed test samples of different plastic materials.](image)

2.2 Mass density determination

The mass density of test samples was determined by weighting the rectangular samples on calibrated analytical balances Sartorius 1602 MP 8-1 (Göttingen, Germany) and measuring their dimensions. Every dimension was measured by two people five times in total to obtain the uncertainty estimate. The combined standard uncertainty of the test samples density was obtained from the standard deviation of the measured dimensions according to [13], section 5.1.2, assuming no correlation between uncertainty components. The mass density of filaments was obtained by a liquid pycnometer method according to ISO 1183-1:2012 [14] and using the water density of 0.99717 g/cm$^3$ at 24.5°C [15]. The combined standard uncertainty of the filaments density was obtained also based on [13], section 5.1.2, taking into account the following uncertainty components $u$: filament sample mass: $u(m_S) = 0.002$ g, water density: $u(\rho_w) = 0.0005$ g/cm$^3$, mass of the water inside the pycnometer without ($m_1$) and with ($m_2$) a sample: $u_{rel}(m_1) = u_{rel}(m_2) = 0.01\%$.
Table 1. Acronyms of the tested material.

| Acronym | Material                        |
|---------|---------------------------------|
| ABS     | Acrylonitrile butadiene styrene |
| ASA     | Acrylonitrile styrene acrylate  |
| CPE MM  | Chlorinated polyethylene, white |
| CPE HG  | Chlorinated polyethylene, natural |
| FLEXFILL 98A | Thermoplastic polyurethane |
| HIPS    | High impact polystyrene        |
| PC      | Polycarbonate                   |
| PET     | Polyethylene terephthalate      |
| PLA     | Polylactic acid                 |
| PMMA    | Polymethyl methacrylate         |
| PVA     | Polyvinyl alcohol               |
| TIMBERFILL | Biodegradable material based on wood |

2.3 Linear attenuation coefficient

Linear attenuation coefficient, $\mu$, of test samples was obtained from $\gamma$-spectrometric measurements with narrow collimated photon beams from Eu-152 and Am-241 radionuclide sources. The detector used was a high-purity germanium detector IGC 25 (Princeton Gamma Tech Instruments, Inc., U.S.A.) with 25% relative efficiency and 0.89 keV full-width at half maximum energy resolution at 122 keV energy (detector datasheet). The measurement set-up is presented in figure 2. The $\mu$ was calculated from the difference of net peak areas per unit measurement live-time in pulse-height spectra obtained without a sample, $n_b$, and with a sample, $n_s$, and normalized per unit sample thickness, $x$, according to equation (2.1).

$$\mu = \frac{1}{x} \ln \left( \frac{n_b}{n_s} \right).$$

Although, in principle, it was possible to obtain the $\mu$ for a large number of energies ranging from 40 keV to 1.4 MeV, the evaluation focused only on the energies 59.5 keV (Am-241), 122.0 keV, and 344.5 keV (both Eu-152) with the highest counting statistics. Chosen energies fit the energetic range of CT scanners and photon energy range of the most common radionuclides used in nuclear medicine examination (Tc–99m, I-131). The typical counting rates without a sample were 95, 8 and 5 counts/s for above mentioned photon energies, respectively, and the typical measurement time was 10 min with Am-241 and 60 min with Eu-152.

2.4 Tissue equivalence

The measured $\mu$ of 3D-printed test samples were compared to the tabulated ones of skeletal muscle tissue and adipose tissue taken from [16]. Table 4, Tissue, Soft (ICRU-44), and Muscle, Skeletal (ICRU-44). Their chemical composition was obtained from the ICRU-44 publication [11].

\(^{1}\)Table 4, “Tissue, Soft (ICRU–44)” and “Muscle, Skeletal (ICRU–44)” at https://physics.nist.gov/PhysRefData/XrayMassCoef/tab4.html.
Table 2. 3D-printed samples.

| Sample | Material\(^{(1)}\) | Producer | Printer            | \(t\) \((^\circ\text{C})\)\(^{(2)}\) |
|--------|---------------------|----------|--------------------|----------------------------------|
| A1     | ABS                 | eco 3D filament | Flasforge Finder   | 240                              |
| A7     | ABS                 | 3D systems      | CubePro            | 240                              |
| A8     | ABS                 | Collorilla     | BCN3D Sigma        | 240                              |
| A9, A11, A13 | ABS            | Omni 3D        | Factory 2.0        | 240                              |
| A12\(^{(3)}\), A14\(^{(3)}\) | ABS       | Omni 3D        | Factory 2.0        | 240                              |
| B1     | ABS                 | Plasty Mladeč  | Rebelix            | 230                              |
| C1\(^{(3)}\) | ABS              | Fillamentum    | N/A                | N/A                              |
| A5     | PLA                 | FlashForge     | Flasforge Finder   | 210                              |
| B5     | PLA                 | Plasty Mladeč  | Rebelix            | 210                              |
| C5\(^{(3)}\) | PLA              | Fillamentum    | N/A                | N/A                              |
| A2     | HIPS                | eco 3D filament | Flasforge Finder   | 235                              |
| B2     | HIPS                | Fillamentum    | Rebelix            | 245                              |
| C2\(^{(3)}\) | HIPS            | Fillamentum    | N/A                | N/A                              |
| A3     | NYLON               | 3D systems      | CubePro            | 260                              |
| B3     | NYLON               | BRIDGE          | Rebelix            | 215                              |
| C3\(^{(3)}\) | NYLON           | Fillamentum    | N/A                | N/A                              |
| C4\(^{(3)}\) | NYLON           | Fillamentum    | N/A                | N/A                              |
| C6\(^{(3)}\) | NYLON         | Fillamentum    | N/A                | N/A                              |
| A4     | PET                 | eco 3D filament | Flasforge Finder   | 205                              |
| B4     | PET                 | Taulman3D       | Rebelix            | 240                              |
| A6     | PVA                 | 3D systems      | CubePro            | 205                              |
| B6     | PVA                 | Plasty Mladeč  | Průša i3 M1        | 195                              |
| B7     | PMMA                | Herz GMBH       | Průša i3 M2        | 255                              |
| B8     | PC                  | Bendlay         | Rebelix            | 240                              |
| C7\(^{(3)}\) | CPE MM          | Fillamentum    | N/A                | N/A                              |
| C8\(^{(3)}\) | CPE HG          | Fillamentum    | N/A                | N/A                              |
| C9\(^{(3)}\) | ASA              | Fillamentum    | N/A                | N/A                              |
| C10\(^{(3)}\) | FLEXFILL       | Fillamentum    | N/A                | N/A                              |
| C11\(^{(3)}\) | TIMBERFILL     | Fillamentum    | N/A                | N/A                              |

\(^{(1)}\) See table 1 for acronym description.
\(^{(2)}\) Printing temperature.
\(^{(3)}\) The layers were printed perpendicularly to the largest side.
Muscle tissue has the density of $1.05 \text{g/cm}^3$ and it consists of elements H (10.2%), C (14.3%), N (3.4%), O (71.0%), Na (0.1%), P (0.2%), S (0.3%), Cl (0.1%), and K (0.4%), and adipose tissue has the density of $0.95 \text{g/cm}^3$ and it consists of elements H (11.4%), C (59.8%), N (0.7%), O (27.8%), Na (0.1%), S (0.1%), and Cl (0.1%) all in weight %. The value of $\mu_t$ for the energies of 60 keV, 122 keV, and 345 keV was obtained with a log-log interpolation between the tabulated data [16] resulting in the values of $0.2159 \text{cm}^{-1}$, $0.1671 \text{cm}^{-1}$, and $0.1170 \text{cm}^{-1}$ in muscle tissue, respectively, and $0.1881 \text{cm}^{-1}$, $0.1513 \text{cm}^{-1}$, and $0.1069 \text{cm}^{-1}$ in adipose tissue, respectively. The relative uncertainty was assumed to be 1.0%.

For an assessment of the level of 3D-printed sample equivalence to a specific tissue, a weighted average relative difference, $\overline{RD}$, between the samples $\mu$ and the given tissue $\mu_t$ was determined according to equation (2.2).

$$\overline{RD} = \frac{\sum E \left[ RD(E) \cdot u^2 (RD(E)) \right]}{\sum E \left[ 1/u^2 (RD(E)) \right]} ; \quad RD(E) = \frac{\mu}{\mu_t} - 1 . \quad (2.2)$$

Similarly to the weighted least squares method, the weights are the inverse squared uncertainties $u$ of the individual relative differences $RD(E)$ for photon energy $E$. The $\overline{RD}$ is determined from $\mu$ for all three photon energies $E$: 60 keV, 122 keV, and 345 keV.

2.5 Hounsfield units

The Hounsfield unit is used in medical CT scans and represents the value of $\mu$ recalculated into the linear scale where $\mu_{\text{water}} = 0$ and $\mu_{\text{air}} = -1000$ [17]. The HU values of all test samples were obtained from the CT study performed on Philips Brilliance CT Big Bore radiotherapy simulator (Philips, U.S.A.) at 80 kVp and 120 kVp (figure 3). A bottle of demineralized purified water was scanned together with the samples in order to recalibrated all results (avoid internal setting of the scanner). The average HU value and its uncertainty for every sample was obtained from at least 5000 voxels (excluding borders) from reconstructed CT images.
3 Results and discussion

Firstly, the measured mass density of filaments and printed samples is described, followed by summarization of the samples measured $\mu$, and finally presentation of the comparison of the samples $\mu$ with the $\mu_t$ of the two tissues.

3.1 Mass density

Table 3 provides the measured mass density of filaments and 3D-printed samples. Except for two ABS samples (A1 and B1), the density of printed samples is lower typically by 10% but reaching the relative difference up to 19% in some cases. However, it should be noted that specifically for samples B3, B4, B7 and B8 the large reduction of density was contributed also by poor printing quality. It resulted in layer separation or even improper adhesion of inner layers to side walls of the sample which created air gaps inside the sample reducing the average mass density. A CT slice of one of such samples is presented in figure 4. Inhomogeneity of the material is clearly visible. The defect was caused by improper adhesion of inner layers to side walls of the sample during printing. Such errors have to be avoided during printing of a full phantom. The higher density of some of the printed ABS samples compared to their filament was not studied further.

Figure 4. Example of inhomogeneity inside a sample (pointed by an arrow), compared to homogeneous printing (right), and water (left), as visualized by a CT scan.

Higher uncertainty of the density of PVA filaments compared to other materials is given by the measurement method. Because PVA is soluble in water, the pycnometer method could not be used. Instead, the density was obtained from the weight, length and thickness of the filament. The uncertainty of the density was dominated by the contribution of the latter parameter.
Table 3. Mass density of filaments, \( \rho_f \), and 3D-printed samples, \( \rho_p \), linear attenuation coefficients of the samples across printed layers, \( \mu_s \), at 60 keV, 122 keV, and 344 keV, and HU values of the samples. Combined standard uncertainties are stated at the coverage factor \( k = 1 \). The numerical value in the brackets expresses the uncertainty of the last digits.

| Sample | Material\(^{(1)}\) | \( \rho_f \) (g/cm\(^3\))\(^{(2)}\) | \( \rho_p \) (g/cm\(^3\))\(^{(3)}\) | \( RD \)'s\(^{(4)}\) | \( \mu_s \) (cm\(^{-1}\))\(^{(5)}\) | \( HU \) |
|--------|-----------------|------------------|------------------|----------------------|------------------|------------------|
| —      | Muscle\(^{(5)}\) | —                | 1.05             | —                    | 0.216            | 0.167            |
| —      | Adipose\(^{(5)}\) | 1.045(11)        | 1.163(8)         | 11.3 ± 1.4           | 0.188            | 0.151            |
| A1     | ABS             | 0.965(10)        | N/A              | 0.181(3)             | 0.147(5)         | 0.093(6)         |
| A7     | ABS             | N/A              | 0.942(6)         | 1.01(3)              | 0.136(5)         | 0.099(6)         |
| A8     | ABS             | 0.956(4)         | N/A              | 1.037(8)             | 0.153(5)         | 0.106(6)         |
| A9     | ABS             | 0.956(4)         | N/A              | 0.179(3)             | 0.148(5)         | 0.105(7)         |
| A11    | ABS             | 0.956(4)         | N/A              | 0.182(3)             | 0.148(5)         | 0.105(7)         |
| A12    | ABS             | 0.956(4)         | N/A              | 0.179(3)             | 0.144(5)         | 0.104(6)         |
| A13    | ABS             | 0.956(4)         | N/A              | 0.181(3)             | 0.151(4)         | 0.105(5)         |
| A14    | ABS             | 0.956(4)         | N/A              | 0.179(4)             | 0.148(5)         | 0.105(7)         |
| A15    | ABS             | 0.956(4)         | N/A              | 0.209(4)             | 0.154(6)         | 0.106(8)         |
| B1     | ABS             | 0.956(4)         | N/A              | 0.209(3)             | 0.167(4)         | 0.118(4)         |
| B3     | ABS             | 0.956(4)         | N/A              | 0.211(14)            | 0.139(6)         | 0.086(5)         |
| B5     | PLA             | 1.125(10)        | 1.112(5)         | 3.4 ± 1.3            | 0.204(9)         | 0.154(6)         |
| B7     | PLA             | 0.948(2)         | N/A              | 0.174(2)             | 0.146(4)         | 0.106(6)         |
| C1     | ABS             | 0.948(5)         | N/A              | 0.181(2)             | 0.148(4)         | 0.103(4)         |
| A2     | HIPS            | 0.929(11)        | 0.93 ± 1.5       | 0.187(4)             | 0.155(6)         | 0.117(7)         |
| C2     | HIPS            | 0.948(5)         | 0.7 ± 1.4        | 0.175(4)             | 0.145(6)         | 0.115(8)         |
| A3     | NYLON           | 1.01(13)         | 0.96 ± 1.8       | 0.189(4)             | 0.151(6)         | 0.103(8)         |
| C3     | NYLON 25C       | 0.840(1)         | N/A              | 0.165(2)             | 0.134(3)         | 0.088(4)         |
| C4     | NYLON AF80      | 0.852(3)         | N/A              | 0.172(3)             | 0.134(3)         | 0.095(4)         |
| C6     | NYLON CF15      | 0.736(3)         | N/A              | 0.138(2)             | 0.111(3)         | 0.075(4)         |
| A4     | PET             | 1.234(8)         | 0.55 ± 1.1       | 0.234(4)             | 0.185(6)         | 0.127(8)         |
| B4     | PET             | 1.054(10)        | 0.177 ± 1.3      | 0.202(4)             | 0.168(6)         | 0.113(8)         |
| A6     | PVA             | 0.996(5)         | 0.173 ± 0.9      | 0.191(4)             | 0.146(6)         | 0.109(8)         |
| B6     | PVA             | 1.182(7)         | 0.67 ± 5.2       | 0.235(4)             | 0.190(6)         | 0.142(8)         |
| B7     | PMMA            | 0.956(10)        | 0.181 ± 1.2      | 0.181(4)             | 0.150(6)         | 0.111(8)         |
| B8     | PC              | 1.043(16)        | 0.119 ± 1.6      | 0.197(4)             | 0.170(6)         | 0.111(8)         |
| C7     | CPE MM          | 1.067(4)         | N/A              | 0.209(3)             | 0.167(4)         | 0.118(4)         |
| C8     | CPE HG          | 1.117(3)         | N/A              | 0.211(3)             | 0.167(4)         | 0.114(4)         |
| C9     | ASA             | 0.969(2)         | N/A              | 0.187(3)             | 0.149(4)         | 0.102(4)         |
| C10    | FLEXFILL        | 1.033(2)         | N/A              | 0.190(3)             | 0.154(4)         | 0.104(4)         |
| C11    | TIMBERFILL      | 1.047(2)         | N/A              | 0.202(3)             | 0.164(4)         | 0.112(4)         |

\(^{(1)}\)See table 1 for acronym description.

\(^{(2)}\)Filament density.

\(^{(3)}\)Printed sample density.

\(^{(4)}\)Relative difference, \( RD = 100 \times (\rho_p/\rho_f - 1) \).

\(^{(5)}\)Values taken from Error: reference source not found.

\(^{(6)}\)Poor print quality, see text.

\(^{(7)}\)Density was determined from the size and weight of the filament.
3.2 Linear attenuation coefficients and Hounsfield units

Linear attenuation coefficients of the samples measured across, $\mu_x$, printed layers are presented in table 3, for photon energies of 60 keV, 122 keV, and 344 keV. The $\mu_y$ along the layers is not presented, however, the relative differences of $\mu_x$ and $\mu_y$ of all samples lie within the measurement uncertainties. The average relative difference over all samples is below 0.7% for each of three photon energies therefore it can be concluded that the photon attenuation properties of all studied 3D-printed plastic materials are isotropic. The uncertainties of $\mu_x$ and $\mu_y$ vary between 2% and 10% and they are given by the counting statistics that is influenced by source activity, photon yield, detection efficiency, measurement time, and sample attenuation. The results for 344 keV photons have the largest uncertainties because of the lowest detection efficiency and photon yield. The actual thicknesses of printed samples were used in the attenuation coefficients assessment.

The measured $HU$ values of the samples are presented in table 3 as well. Large uncertainties of $HU$ values of samples B4 and B7 were caused by inhomogeneous material distribution in the samples caused by the printing.

For the three photon energies, the comparison of measured $\mu_k$ of printed samples and tabulated $\mu$ for muscle tissue and adipose tissue [16] is summarized in table 4.

Correlation of $HU$ values with samples $\mu$ for 60 keV photons and samples mass density and is depicted in figure 5, respectively. Because the $HU$ values are uniquely related to $\mu$, the differences from a straight line in figure 5 on the right side are given by the measurement uncertainties of both $HU$ values (CT scan) and $\mu$ (gamma spectrometry).

![Figure 5. Correlation between $HU$ values of 3D-printed samples obtained from 80 kVp (circles) and 120 kVp (triangles) CT scans and their linear attenuation coefficient for 60 keV photons (left) and mass density (right).](image)

Determination of the 3D-printed samples equivalence to each of the two soft tissues was performed by determination of the weighted average relative difference between $\mu$ of the samples and the given soft tissue according to the equation (2.2). Averaging was performed over each of three photon energies. The results summarized in figure 6 show the tested materials sorted from the largest negative difference with respect to the $\mu_l$ of each of the two soft tissues.

The highest level of the equivalence to muscle tissue according to the selected criteria show the materials CPE (samples C7 and C8), PLA (B5 and C5), PET (B4), ABS (B1), and TIMBERFILL (C11). Focusing on adipose tissue, the highest level of the equivalence to this tissue show the
Table 4. Relative difference, \( RD \), between linear attenuation coefficients of the 3D-printed samples across printed layers, \( \mu_s \), and of muscle tissue and adipose tissue, \( \mu_t \). \( RD = 100 \times (\mu_s/\mu_t - 1) \). \( SD \) is the combined standard uncertainty at the coverage factor \( k = 1 \).

| Sample | Material\(^{(1)}\) | **Muscle tissue; \( RD \pm SD \) (%)** |  | **Adipose tissue; \( RD \pm SD \) (%)** |  |
|--------|-----------------|------------------------------------------|---|------------------------------------------|---|
|        |  | 60 keV | 122 keV | 344 keV | 60 keV | 122 keV | 344 keV |
| A1     | ABS             | 8.9 ± 2.2 | 3.9 ± 3.9 | 14.6 ± 7.1 | 25.0 ± 2.5 | 14.7 ± 4.3 | 25.5 ± 7.8 |
| A7     | ABS             | −16.2 ± 1.7 | −12.3 ± 3.4 | −20.7 ± 5.5 | −3.8 ± 2.0 | −3.2 ± 3.7 | −13.2 ± 6.0 |
| A8     | ABS             | −20.8 ± 1.7 | −18.6 ± 3.2 | −16.5 ± 5.3 | −9.1 ± 1.9 | −10.2 ± 3.5 | −8.6 ± 5.8 |
| A9     | ABS             | −17.2 ± 1.7 | −8.3 ± 3.2 | −9.0 ± 5.2 | −4.9 ± 1.9 | 1.2 ± 3.5 | −0.4 ± 5.7 |
| A11    | ABS             | −15.8 ± 1.6 | −10.9 ± 2.6 | −8.8 ± 4.4 | −3.4 ± 1.8 | −1.6 ± 2.8 | −0.2 ± 4.8 |
| A12    | ABS             | −17.0 ± 1.6 | −14.0 ± 3.1 | −11.2 ± 5.2 | −4.8 ± 1.8 | −5.1 ± 3.5 | −2.8 ± 5.7 |
| A13    | ABS             | −16.2 ± 1.6 | −9.4 ± 2.8 | −10.1 ± 4.6 | −3.9 ± 1.8 | 0.0 ± 3.1 | −1.6 ± 5.0 |
| A14    | ABS             | −17.2 ± 1.9 | −11.6 ± 3.3 | −10.4 ± 6.0 | −4.9 ± 2.1 | −2.4 ± 3.7 | −1.9 ± 6.6 |
| B1     | ABS             | −3.4 ± 2.2 | −7.6 ± 4.0 | −9.4 ± 7.3 | 10.9 ± 2.5 | 2.0 ± 4.4 | −0.8 ± 8.0 |
| C1     | ABS             | −16.2 ± 1.2 | −11.1 ± 2.4 | −11.9 ± 3.6 | −3.7 ± 1.4 | −1.9 ± 2.6 | −3.5 ± 4.0 |
| A5     | PLA             | −12.4 ± 2.1 | −16.9 ± 3.8 | −8.0 ± 7.0 | 0.6 ± 2.4 | −8.3 ± 4.2 | 0.8 ± 7.7 |
| B5     | PLA             | −4.5 ± 2.1 | −1.6 ± 3.9 | 2.0 ± 7.1 | 9.7 ± 2.4 | 8.7 ± 4.3 | 11.7 ± 7.7 |
| C5     | PLA             | 0.5 ± 1.5 | 8.3 ± 2.4 | 5.5 ± 3.7 | 15.3 ± 1.8 | 19.6 ± 2.7 | 15.5 ± 4.0 |
| A2     | HIPS            | −13.5 ± 1.9 | −7.0 ± 3.6 | 0.1 ± 6.5 | −0.6 ± 2.2 | 2.6 ± 3.9 | 9.7 ± 7.1 |
| B2     | HIPS            | −18.8 ± 2.1 | −12.9 ± 3.9 | −1.5 ± 7.2 | −6.8 ± 2.4 | −3.9 ± 4.3 | 7.9 ± 7.9 |
| C2     | HIPS            | −19.3 ± 1.4 | −12.9 ± 2.3 | −9.6 ± 3.6 | −7.4 ± 1.6 | −3.8 ± 2.6 | −1.0 ± 4.0 |
| A3     | NYLON           | −12.4 ± 2.1 | −9.9 ± 3.9 | −11.6 ± 7.1 | 0.6 ± 2.4 | −0.5 ± 4.3 | −3.3 ± 7.8 |
| B3\(^{(2)}\) | NYLON         | −8.1 ± 2.1 | 2.1 ± 3.9 | −3.5 ± 7.1 | 5.6 ± 2.4 | 12.7 ± 4.3 | 5.7 ± 7.7 |
| C3     | NYLON 25C       | −23.5 ± 1.2 | −19.8 ± 2.1 | −24.5 ± 3.6 | −12.2 ± 1.4 | −11.5 ± 2.3 | −17.4 ± 3.9 |
| C4     | NYLON AF80      | −20.4 ± 1.4 | −19.6 ± 2.1 | −19.1 ± 3.6 | −8.6 ± 1.6 | −11.3 ± 2.3 | −11.4 ± 4.0 |
| C6     | NYLON CF15      | −36.1 ± 1.1 | −33.4 ± 2.0 | −35.8 ± 3.6 | −26.7 ± 1.3 | −26.4 ± 2.2 | −29.7 ± 3.9 |
| A4     | PET             | 8.6 ± 2.2 | 10.9 ± 3.9 | 8.8 ± 7.1 | 24.6 ± 2.5 | 22.4 ± 4.3 | 19.2 ± 7.8 |
| B4\(^{(2)}\) | PET            | −6.3 ± 2.1 | 0.3 ± 3.9 | −3.7 ± 7.1 | 7.5 ± 2.4 | 10.7 ± 4.3 | 5.4 ± 7.8 |
| A6     | PVA             | −11.4 ± 2.1 | −12.8 ± 3.8 | −7.3 ± 7.0 | 1.7 ± 2.4 | −3.7 ± 4.2 | 1.6 ± 7.7 |
| B6     | PVA             | 9.0 ± 2.2 | 13.7 ± 3.9 | 21.2 ± 7.0 | 25.1 ± 2.5 | 25.5 ± 4.3 | 32.7 ± 7.7 |
| B7\(^{(2)}\) | PMMA          | −16.1 ± 2.1 | −10.5 ± 3.9 | −4.9 ± 7.2 | −3.7 ± 2.4 | −1.1 ± 4.3 | 4.1 ± 7.9 |
| B8     | PC              | −8.6 ± 2.1 | 1.8 ± 4.0 | −4.8 ± 7.2 | 4.9 ± 2.5 | 12.4 ± 4.4 | 4.2 ± 7.9 |
| C7     | CPE MM          | −3.1 ± 1.5 | −0.1 ± 2.4 | 0.4 ± 3.6 | 11.3 ± 1.7 | 10.3 ± 2.6 | 10.0 ± 4.0 |
| C8     | CPE HG          | −2.1 ± 1.5 | −0.1 ± 2.4 | −2.3 ± 3.6 | 12.4 ± 1.8 | 10.3 ± 2.6 | 7.0 ± 4.0 |
| C9     | ASA             | −13.4 ± 1.5 | −11.0 ± 2.4 | −12.6 ± 3.6 | −0.6 ± 1.7 | −1.8 ± 2.6 | −4.3 ± 4.0 |
| C10    | FLEXFILL        | −12.2 ± 1.5 | −7.6 ± 2.4 | −11.2 ± 3.6 | 0.8 ± 1.7 | 2.0 ± 2.6 | −2.7 ± 4.0 |
| C11    | TIMBERFILL      | −6.4 ± 1.5 | −1.6 ± 2.4 | −4.7 ± 3.7 | 7.5 ± 1.7 | 8.6 ± 2.6 | 4.4 ± 4.0 |

\(^{(1)}\)See table 1 for acronym description.

\(^{(2)}\)Poor print quality caused higher uncertainty of \( \mu_s \) values, see text.
materials NYLON (sample A3), PVA (A6), FLEXFILL (C10), HIPS (A2), ASA (C9), PLA (A5), PMMA (B7), and ABS (A7, A9, A11–A14, C1). The listed samples have the weighted relative difference of $\mu_x$ within 5% of the $\mu_t$ of the given tissue.

The different plastic materials may be selected for phantoms where the aim is to mimic both soft tissues separately. However, the final choice of the material should also take into account the price of the filament and printing time, possibility and ease of printing of large objects, and chemical and mechanical properties of the printed samples like separation of layers, water, thermal, and chemical resistance, which may be more or less important depending on the intended application of the phantom.

The results also showed large differences between photon attenuation properties of the same type of plastic material printed by different companies on different printers using filaments from different manufacturers. Also, quality and chemical reproducibility of filaments from one manufacturer may vary in time and so it can be recommended to use high quality filaments from established producers that can guarantee reproducibility of chemical composition and stability of filament physical properties. Another critical parameter is a printing quality as already presented in figure 4. As a result, it is highly recommended to print a medical phantom on the same printer, with the same settings, and with the same filament as the selected test sample.

### 3.3 Reproducibility of the 3D printing

Reproducibility of 3D printing of ABS samples with respect to attenuation properties of the material is presented in figure 7. Relative differences between measured $\mu$ at different photon energies of samples A9 and A11–A14 and the average value over these samples are within measurement uncertainties. The same results were obtained by testing the measured HU values. Numerical values for individual samples are presented in table 3.

The results cannot be generalized to all studied materials, printers and companies, but it can be concluded that at least one of the studied plastic materials, specifically ABS, can be printed by
a commercial company with the reproducibility better than 2%, as determined from measurement uncertainties of $\mu$ at 60 keV photon energy.

4 Conclusions

Linear attenuation coefficients for 59.5 keV, 122.0 keV and 344.5 keV photons and Hounsfield units obtained with 80 kVp and 120 kVp CT scans were determined for a large set of 3D-printed test samples of different plastics obtained from different commercial companies. The values were compared to ICRU-44 skeleton muscle tissue and adipose tissue aiming to get an overview about tissue equivalence of 3D-printed plastics. The results will be used as a basis for the selection of a suitable material for 3D print of a neck phantom intended for calibrations and verifications in thyroid cancer treatment using targeted radionuclide therapy.

Quasi-realistic anthropomorphic phantoms developed within the MRTDosimetry project and the use of 3D printing will introduce a very powerful capability to phantom design and construction and should significantly enhance the ability of clinics to investigate difficult situations where MRT dosimetry, and quantitative imaging in particular, are the most challenging.

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