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DOSIMETRIC BEHAVIORS OF DIFFERENT TISSUE-EQUIVALENT MATERIALS. A MONTE CARLO SIMULATED STUDY

BY

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Abstract. Quality assurance and radiation protection are a very important factor in radiotherapy techniques. If in reference dosimetry (performed in primary and secondary standard laboratories) almost exclusively water phantoms are used, in relative dosimetry (in the non-reference conditions of the medical unit) phantoms of tissue-equivalent materials are used. In this paper we present a comparative simulated study for dosimetric behaviors of different tissue-equivalent materials.

Keywords: dosimetry; radiation therapy; tissue-equivalent materials; phantoms; Monte Carlo code.

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1. Introduction

Experts estimate that in the next decades, one of the three European citizens will suffer from cancer of one form or another. It should be noted that the term cancer indicates more than one hundred distinct tumors, which occur in various tissues and are diagnosed at different stages of development. Tumor cells are biologically similar to normal cells, currently therapeutic approaches are strictly limited by this fact. Most researchers are confident that, in the long term, significant advances in cancer healing will occur due to immunotherapy and gene therapy. However, research focused on these systemic treatments is slowly advancing, and for the next decades revolutionary discoveries for treating different forms of cancer are not expected, with medicine still relying on improvements to existing techniques (You and Henneberg, 2018).

Statistics show that currently in Europe 45% of all cancer patients are "cured", meaning that the cancerous disease does not manifest again within at least 5 years after treatment. Approximately 90% of the cured patients owe this to surgery and radiotherapy (accompanied in most cases by chemotherapy to prevent the spread of metastasis). Therefore, radiotherapy is one of the vital ways to cure cancer, which is based more on the local control of the tumor and the tumor site (Bray and Soerjomataram, 2015).

Although conventional radiotherapy (with photon and/or electron beams) has recently been added to new radiotherapy techniques (such as proton beam radiation or heavy ion radiation), there are still many challenges for physicians and physicists that are working in the field. Perhaps one of the most important is finding solutions to increase the dose absorbed by the tumor (thus increasing the degree of tumor control), while protecting the healthy tissues around or adjacent to the tumor site (Washington *et al*., 2019).

For these reasons, quality assurance and radiation protection is a very important factor in radiotherapy techniques. That is why radiotherapists and medical physicists collaborate on medical records to make treatment plans as effective and safe as possible for cancer patients. Phantoms play a vital role in these procedures, without them being unable to perform calibrations of clinical use beams, quality assurance tests, but also treatment planning (Gunderson and Tepper, 2015).

If in reference dosimetry (performed in primary and secondary standard laboratories) almost exclusively water phantoms are used, in relative dosimetry (in the non-reference conditions of the medical unit) phantoms of equivalent-tissue materials (such as PMMA or polystyrene) are used.

With their help the calibrations of the beams and the treatment plans are performed on the spot, or, also very important in the radiotherapeutic act, the modulation of the beams (through the bowls made of this type of materials). Most tissue-equivalent materials are made to have a high equivalence to water,

but there is also a fairly diverse range of materials made to mimic some specific types of tissue (such as bone or soft tissue).

The experimental data from literature (measurements and simulations) show that there is no perfect equality between the dose distributions in depth of the equivalent tissue materials. However, tissue-equivalent materials (especially those made from plastics) are used as substitutes for water and tissues in radiotherapy departments (Prakash *et al*., 2014).

The goal of this paper is to study (through simulations) the interactions of various beams used in radiotherapy with phantoms made of tissue-equivalent materials.

2. Methods

Phantoms have an important role in the dosimetry of the external beams used in radiotherapy, both in reference conditions and in non-reference conditions. Although The International Atomic Energy Agency (IAEA) recommends the use of phantoms from equivalent materials-only for reference measurements of low energy X-ray beams (up to about 10 MeV), the popularity of these materials is constantly increasing, being used in treatment conditions (non-reference conditions of the radiotherapy facility user).

The phantoms should extend at least 5 cm beyond all four parts of the largest field used at the depth of measurement. Also, there should be a limit of 5 g/cm^2 beyond the maximum depth of measurement.

When using phantoms of equivalent-tissue materials instead of reference ones, discrepancies (some quite significant) may occur in determining the dose for most types of beams. This is due to the fact that lots of tissue-equivalent materials represent very small variations in density, but also because the procedures for scaling the depths and the absorbed dose (or fluence), for example scaling the plastic to the water, have an approximate nature. It should be taken into account the density of the plastic measured for the plastic batch in use, and not the nominal value of the density provided by the manufacturer, as density differences of up to 4% have been reported.

The use of plastic phantoms in tablet form should include a determination of the average thickness and density for each tablet, the variation in thickness for each tablet, as well as radiographic investigations of the presence of air or vacuum bubbles in the plastic.

Plastic phantoms can also be used for routine quality assurance, provided that the relationship between the readings on the plastic dosimeter and in the water is determined for the user's beam at the time of calibration. This implies an extensive comparison with measurements in water, which should be made before the routine use of the phantom. Also, periodic checks are required at reasonable intervals to ensure the validity and consistency of the original comparative result (IAEA, 2008).

When using phantoms made from dielectric materials, users should be aware of the problems that may result from accumulating charges (loads).

This is especially important when using a sleeve chamber in a plastic phantom for electron beam measurements. Charges accumulation can also have a significant effect during the calibration of electron beams when using parallel-plane chambers. The effect can lead to a very large electric field around the chamber, directly influencing the distribution of the electron flow, consequently affecting the reading on the chamber.

To reduce this effect the phantoms should be made using thin plastic tablets, in no case exceeding 2 cm. As mentioned above, the actual thickness of each tablet and the variation of the thickness of each tablet should be measured, especially in the case of thin tablets. Also, the average density of each tablet should be determined. In addition, the layers of air between tablets should be avoided.

Measurements in non-reference conditions for megavoltage electron beams

The measurement of a depth distribution on the central axis must follow the precedence for measuring R_{50}:

$$\begin{aligned} R_{50} &= 1.029 R_{50,ion} - 0.060 g/cm^2 \,(R_{50} \le 10 g/cm^2) \\ R_{50} &= 1.059 R_{50,ion} - 0.37 g/cm^2 \,(R_{50} \ge 10 g/cm^2) \end{aligned} \tag{1}$$

If an ionization chamber is used, the ionization distribution in depth must be converted into a dose distribution in depth. For a R_{50} quality beam, this is achieved by multiplying the current or the ionization charge, from each depth z, with the ratios of the stopping powers $s_{w,air}$ from the respective depth.

It should be noted that this procedure neglects any variation of the disturbance factor with depth. The procedure is a good approximation for planar-parallel chamber models that are well screened. For the models of plane-parallel chambers that are not well screened, as well as for the cylindrical chambers, the changes that appear in the disturbance factor are significant and must be taken into account. Unfortunately, the existing data for the disturbance factors of these chamber models have been verified only at depths close to the reference depth, so they are not suitable for use at other depths, despite the fact that they are used regularly at these depths. In conclusion, the use of these chambers to determine the dose distribution in depth is discouraging.

For a given electron beam, the output factors should be measured at the depth of the maximum dose for field size and source-surface distances of non-reference used in the treatment of patients. Consideration should be given to the variation of the maximum dose depth, especially for small field dimensions or large energies.

For dosimeters such as diodes, diamonds, etc., the output factor should be appropriately approximated by reading on the dosimeter in non-reference

conditions with reading on the dosimeter in reference conditions. If an ionization chamber is used, the ratio of the measured ionization currents or charges must be corrected for the depth variation of the stopping power ratio.

Plastic phantoms can only be used for beam qualities $R_{50} < 4g/cm^2 (E_0 \leq 10MeV)$.

In a horizontal electron beam, the phantom window should have a thickness t_{window} between 0.2 cm and 0.5 cm. The thickness equivalent to the tissue (water) of the material must be taken into account when positioning the chamber at the desired measurement depth.

The depths in the plastic phantoms, expressed in g/cm^2, are obtained by multiplying the depth in centimeters with the density of the plastic ρ_{pl}, expressed in g/cm^3. The density of the plastic must be measured for each batch in use. Measurements made at depth z_{pl} in a plastic phantom are expressed according to the depth in water through the relationship:

$$z_{water} = z_{pl} c_{pl} \text{ g/cm}^2 \tag{2}$$

where c_{pl} represents the depth scaling factor.

Table 1

Values for the Scaling Factor with the Depth c_{pl}, the Scaling Factor with the Fluence h_{pl} and the Nominal Density ρ_{pl} for Certain Plastics

Plastic phantom	c_{pl}	h_{pl}	ρ_{pl} (g/cm^2)
Solid water (WT1)	0.949	1.011	1.020
Solid water (RMI-457)	0.949	1.008	1.030
Plastic water	0.982	0.998	1.013
Virtual water	0.946	–	1.030
PMMA	0.941	1.009	1.190
Pure polystyrene	0.922	1.026	1.060
White polystyrene	0.922	1.019	1.060
A-150	0.948		1.127

If a plastic phantom is used to measure the quality of the beam, the measured size represents the half-life of the plastic ionization depth distribution, $R_{50,ion,pl}$, $R_{50,ion}$ for water is determined using the equation:

$$R_{50,ion} = R_{50,ion,pl} c_{p1} \text{ g/ } cm^2 \tag{3}$$

The quality of the beam for water R_{50} is then determined by relationships (1).

To determine the absorbed dose in water at the reference depth using a plastic phantom, the chamber must be positioned in plastic at the scaled

reference depth $z_{ref,pl}$. This is determined from z_{ref} to water using the inverse form of the equation:

$$z_{ref,pl} = z_{ref} c_{p1} \text{ g/cm}^2 \tag{4}$$

In addition to scaling in depth, it must be scaled with the reading equivalent to the reference depth in water and the reading from the dosimeter to the plastic reference depth, using the relation:

$$M_Q = M_{Q,pl} h_{pl} \tag{5}$$

The values of the scaling factor with the fluence h_{pl} for some plastics were given in Table 1. The uncertainty associated with this scaling is precisely the main reason why plastic phantoms are not used very often.

The absorbed dose in water is then determined by the value M_Q given by Eq. (5) and by the use of the equation:

$$D_{W,Q} = M_Q N_{D,W,Q_0} k_{Q,Q_0} \tag{6}$$

When using a plastic phantom to determine the dose distribution in depth, each plastic measuring depth must be scaled, using Eq. (2), to obtain adequate depth in water. The reading on the dosimeter for each depth must also be scaled using Eq. (5). For depths greater than $z_{ref,pl}$ (as they are given by Eq. (4)) it is acceptable to use the value of h_{pl} at $z_{ref,pl}$ given in Table 1.

At shallow depths, this value for h_{pl} should be linearly decreased to a value equal to unity, at zero depth; thus, the effect of the differences of the back printing on the surface is ignored.

Measurements in non-reference conditions for hadron beams

As with conventional radiotherapy, the baseline of dosimetry and treatment planning are the measurements of dose distributions in water in depth.

Water is recommended by the IAEA as the main material for phantoms.

Because in the treatment planning the dose must be calculated not only for water but also for human tissues, which differ in density and energy absorption properties, tissue-equivalent materials are required to experimentally verify the theoretical path. For equivalent-tissue materials that are different than water, the calculated geometric path is corrected by using a search chart ("look-up table"- LUT), which converts CT Hounsfield units (HU) of equivalent-tissue material into a relative water-equivalent path length. The particle path in the equivalent-tissue material is then the scale with WEPL.

The Hounsfield unit scale represents a linear transformation of the measurement of the original linear attenuation coefficient into one in which the radiosensity of distilled water under standard pressure and temperature conditions is defined as zero Hounsfield units, and the density of air under the same conditions is defined as -1000 HU. For a material X having the linear attenuation coefficient μx, the corresponding HU value is given by the relation:

$$HU = \frac{\mu_x - \mu_{water}}{\mu_{water} - \mu_{air}} x1000 \quad (7)$$

where μ_{water} and μ_{air} are the linear attenuation coefficients in water and air, respectively (Table 2).

Thus, a modification of a Hounsfield unit represents a 0.1% change in the attenuation coefficient in water, because the attenuation coefficient in air is approximately zero. This definition is used for CT units calibrated in water. Note that the Hounsfield scale applies to conventional medical CT units, but not to conical beam computed tomography (CBCT). A practical application of this scale is the evaluation of tumors, where, for example, an adrenal tumor with a radiodensity of less than 10 HU is almost certainly a benign adrenal adenoma.

Table 2

HU Scale for Some Common Substances

The substance	HU
Air	-1000
Fat	-120
Water	0
Blood	Between +35 and +45
Muscle	+40
Bone	+400 or more

The procedure described above only takes into account variations in density. The other effects, caused by the different chemical compositions, which can lead to different effective sections of fragmentation, or to small variations of the stopping powers, are not considered in this procedure. Significant corrections may be needed especially for variations in primary particle fluxes.

To account for purely electromagnetic effects, a LUT is generated for a set of tissue-equivalent materials. Because Hounsfield units depend on CT parameters, the CT protocol for HU-LUT measurements must be fixed to the protocol used for treatment planning.

Because there is no unique relationship between the chemical composition of a material and the corresponding Hounsfield units, the materials of different chemical compositions may lead to the same HU and, consequently, the same WEPL in treatment planning, although the actual course in these substituents may be different. Thus, it is essential that the substituents used to establish HU-LUT be tissue-equivalent and in relation to their chemical structure.

For photon radiotherapy, tissue-equivalence is in some cases achieved by adding a small number of high Z (atomic number) materials.

Although the energy absorption in these substituents for photons may be equivalent to that of the actual tissue, this is not the case for hadrons. That is why phantom materials that have high-Z materials should not be used in hadron therapy.

A commonly used material for modulating the pathway in hadron radiation is PMMA, which has a WEPL of about 1.159 for protons and about 1.165 for carbon ions, with a generation uncertainty of about 3%. Although these values can be used to correct the course of hadrons in PMMA, PMMA should not be used as a phantom material when planning for CT-based treatment.

It is important to note that the WEPL obtained from HU-LUT using the HU value of PMMA will be different from the values mentioned above, because PMMA is not tissue-equivalent in terms of chemical structure. A dose calculation based on CT in PMMA will therefore lead to routes and doses that are not in line with reality, if HU-LUT is not manipulated to describe the PMMA.

As an alternative method of modifying the HU-LUT, the Hounsfield units in the CT data set can be manipulated so that the HU-LUT results characterize the correct WEPL.

Despite the possibility of correction of the pathway in PMMA, it must be taken into account that the chemical structure of PMMA with respect to water may also require corrections for fluence. Palmans and his other collaborators have shown that the differences between proton flux distributions are caused almost entirely by differences between effective sections of inelastic interactions of plastics and water.

For proton beams below 100 MeV, corrections for fluence are less than 1%, while over 200 MeV they increase to 2-5% for greater depths. Comparative measurements in the middle of very inhomogeneous cubic dose distributions in PMMA determined 1.5% deviations for carbon ions. Due to these corrections required for fluence, plastic phantoms are not recommended for reference dosimetry of proton or heavy ion beams.

The use of plastic phantoms for relative dosimetry of proton beams

As mentioned above, in many cases plastic phantoms cause discrepancies in dose determination. Plastic phantoms should not be used in reference dosimetry because they require a plastic fluence correction factor relative to water, a factor not known for proton beams.

However, when accurate positioning of the chamber in water is not possible, or when no impermeable ionization chamber is available, their use is allowed to measure dose distributions in depth, especially for low energy proton beams (approximately below 100 MeV).

In these cases, the reading on the dosimeter should be scaled to each plastic depth using the scaling factor of the fluence h_{pl}. It is assumed that h_{pl} has a constant value, equal to unity, for all depths.

Each depth of measurement in plastic z_{pl} must also be scaled to give the proper depth in the water, using the equation:

$$z_{water} = z_{pl} c_{pl} \text{ g/cm}^2 \quad (8)$$

where c_{pl} is the scaling factor of the depth.

For proton beams, c_{pl} can be calculated, with a good approximation, as the ratio of paths in water and plastic. The depth scaling factor, c_{pl}, has a value of 0.974 for PMMA and 0.981 for pure polystyrene.

If a plastic phantom is used to measure the beam quality, the measured size represents the residual path in the plastic, $R_{res,pl}$. The residual path R_{res} in water is also determined from Eq. (8).

The use of plastic phantoms for the relative dosimetry of heavy ion beams

Plastic phantoms should not be used for the reference dosimetry of heavy ion beams because the required water flow correction factors against the plastic are not known. In addition, the fluence of heavy ions, including fragmented particles, in a plastic phantom will be different from that of a water phantom.

However, plastic phantoms can be used in relative dosimetry, especially in routine measurements for quality assurance, provided that a transfer factor between plastic and water is established. For the determination of the dosimetric physical quantities, the procedure is the same as the one described above.

Simulated study of dosimetric characteristics of equivalent-tissue materials

The tissue-equivalent materials included in this study are listed in Table 3. "Solid water" and "plastic water" are terms that designate two types of epoxy resins, with different chemical structures.

Table 3
Elemental Composition by Relative Weight and Physical Density of Tissue-Equivalent Materials Used in our Study

	"Solid water" RMI-457	"Plastic water"	A150 (soft tissue equivalent)	B100 (bone tissue equivalent)
H	0.809	0.0925	0.1013	0.0654
C	0.6722	0.6282	0.7755	0.5369
N	0.0240	0.0100	0.0350	0.215
O	0.1984	0.1794	0.0523	0.0320
Cl	0.0013	0.0096		
Ca	0.0232	0.0795	0.018378	0.1765
Br		0.003		
F			0.01742	0.1674
ρ	**1.030**	**1.013**	**1.127**	**1.45**

As a tool for simulating the interactions of the beams with phantoms, the Fluka software was used, along with its interface, Flair.

Fluka is a Monte Carlo code-based software, used in calculations for the transport of particles and their interaction with the substance, covering a wide range of applications, such as screening and target design, calorimetry, dosimetry, detector design, cosmic rays, neutrino physics, radiotherapy, etc. Fluka can accurately simulate the interaction with the substance of over 60 different particles, including photons, electrons, hadrons, neutrons, muons (Battistoni *et al*., 2016).

It should be emphasized that the chemical structure and physical-chemical properties of the equivalent-tissue materials or which simulations were performed have been retrieved from the Fluka database.

The scaling coefficient with depth relative to the reference substance, cpl, was calculated from the ratio of the values of R_{50} (the depth at which the dose reaches 50% of its maximum value) in the case of electron beam simulations, and from the ratio of its powers z_{max} (depth of the maximum dose - the x-axis coordinate of the Bragg peak) for proton and heavy ion beams.

For these simulations, pencil beams of electrons, protons and carbon ions (with Z=6 and A=12) were used with the following energies:

- Electrons: 20 Mev and 40 Mev;
- Protons: 100 Mev and 130 Mev;
- Carbon ions: 250 Mev/u and 300 Mev/u.

The number of events (primary particles) was 2,000,000 events for each simulation. Note that Fluka runs each simulation as a 5-story cycle.

The target geometry of the phantom was simple, representing a rectangular parallelepiped (20 cm x 20 cm x 25 cm) surrounded by vacuum. The number of dose recording points ("scoring bins") was 200.

3. Results and Discussions

In Tables 4-9 we present the obtained results of our Fluka simulations. Also, for illustrative purposes, we have selected in Figs. 1-3 some data plots.

i) Electron beam simulations

Table 4
Simulated Results for Water Equivalent Materials Irradiated with Electron Beams

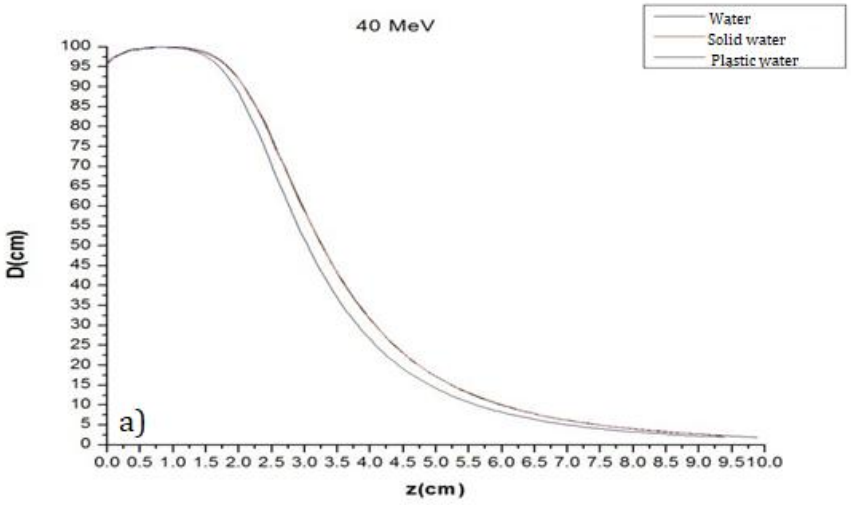
20 MeV	z_{max} (cm)	R_{50} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Water	0.63	2.06	–	1.000
Solid water	0.525	2.08	0.990	1.030
Plastic water	0.525	1.955	1.054	1.013

Table 4
Continuation

40 MeV	z_{max} (cm)	R_{50} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Water	0.8	3.29	–	1.000
Solid water	0.855	3.27	1.006	1.030
Plastic water	0.760	3.03	1.086	1.013

Table 5
Simulated Results for Soft Tissue and Bone Equivalent Materials Irradiated with Electron Beams

20 MeV	z_{max} (cm)	R_{50} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Soft tissue	0.64	2.155	–	1.000
A150	0.7	12.150	1.002	1.127
40 MeV	z_{max} (cm)	R_{50} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Soft tissue	0.88	3.5	–	1.000
A150	0.88	3.46	1.011	1.127
20 MeV	z_{max} (cm)	R_{50} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Bone	0.55	1.575	–	1.850
B100	0.63	1.750	0.9	1.450
40 MeV	z_{max} (cm)	R_{50} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Bone	0.8	2.440	–	1.850
B100	0.9	2.754	0.889	1.450



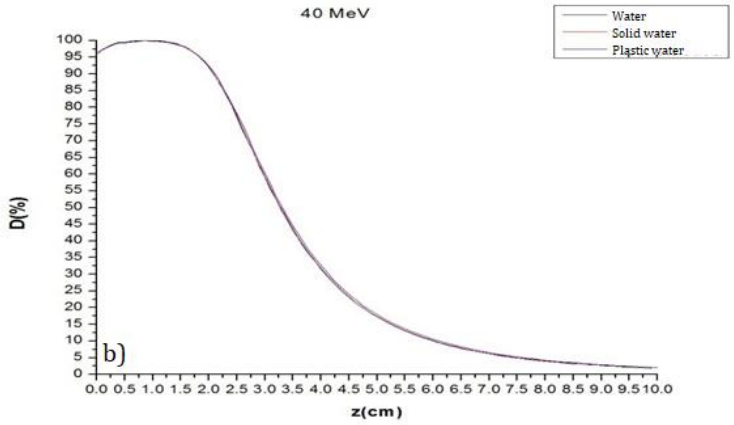


Fig. 1 – Unscaled (*a*) and scaled (*b*) dose distributions plots for data from Table 4.

ii) Proton beam simulations

Table 6
Simulated Results for Water Equivalent Materials Irradiated with Proton Beams

100 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Water	7.60	–	1.000
Solid water	8.32	0.913	1.030
Plastic water	8.55	0.973	1.013
130 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Water	12.09	–	1.000
Solid water	13.26	0.911	1.030
Plastic water	13.57	0.890	1.013

Table 7
Simulated Results for Soft Tissue and Bone Equivalent Materials Irradiated with Proton Beams

100 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Soft tissue	7.6	–	1.000
A150	6.685	1.136	1.127
130 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Soft tissue	12.09	–	1.000
A150	10.62	1.138	1.127
100 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Bone	4.425	–	1.850
B100	5.520	0.801	1.450
130 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Bone	7.040	–	1.850
B100	8.800	0.800	1.450

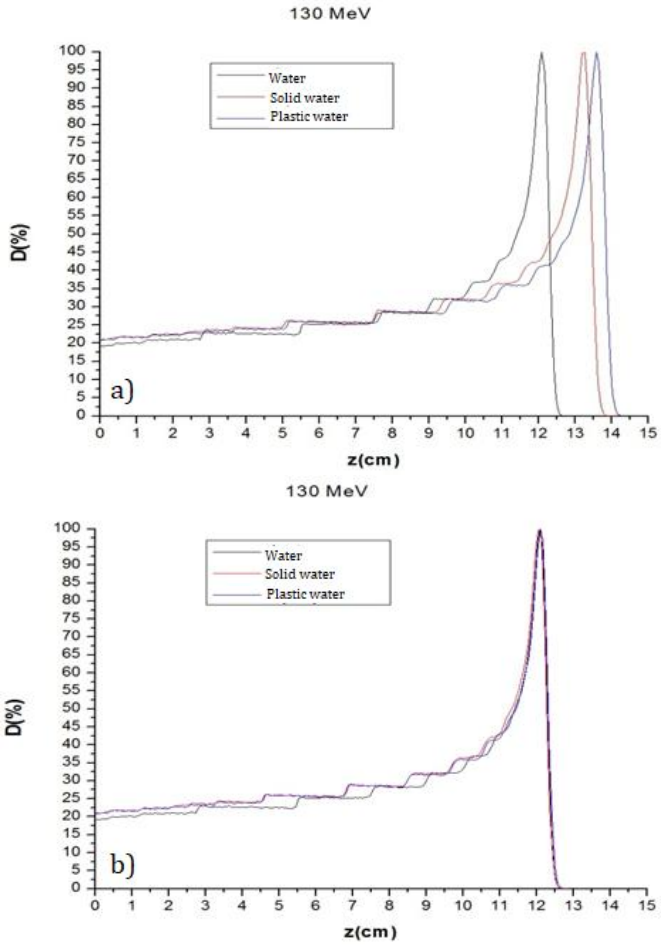


Fig. 2 – Unscaled (*a*) and scaled (*b*) dose distributions plots for data from Table 6.

iii) Carbon ions beam simulations

Table 8
Simulated Results for Water Equivalent Materials Irradiated with Carbon Ions Beams

250 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Water	12.46	–	1.000
Solid water	13.75	0.906	1.030
Plastic water	14.24	0.875	1.013
300 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Water	17.0	–	1.000
Solid water	18.6	0.914	1.030
Plastic water	19.2	0.885	1.013

Table 9

Simulated Results for Soft Tissue and Bone Equivalent Materials Irradiated with Heavy Ions Beams

250 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Soft tissue	12.46	–	1.000
A150	11.04	1.129	1.127
300 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Soft tissue	16.909	–	1.000
A150	14.819	1.141	1.127
250 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Bone	7.29	–	1.850
B100	9.12	0.799	1.450
300 MeV	z_{max} (cm)	c_{pl} (cm)	ρ (g/cm^3)
Bone	9.899	–	1.850
B100	12.450	0.795	1.450

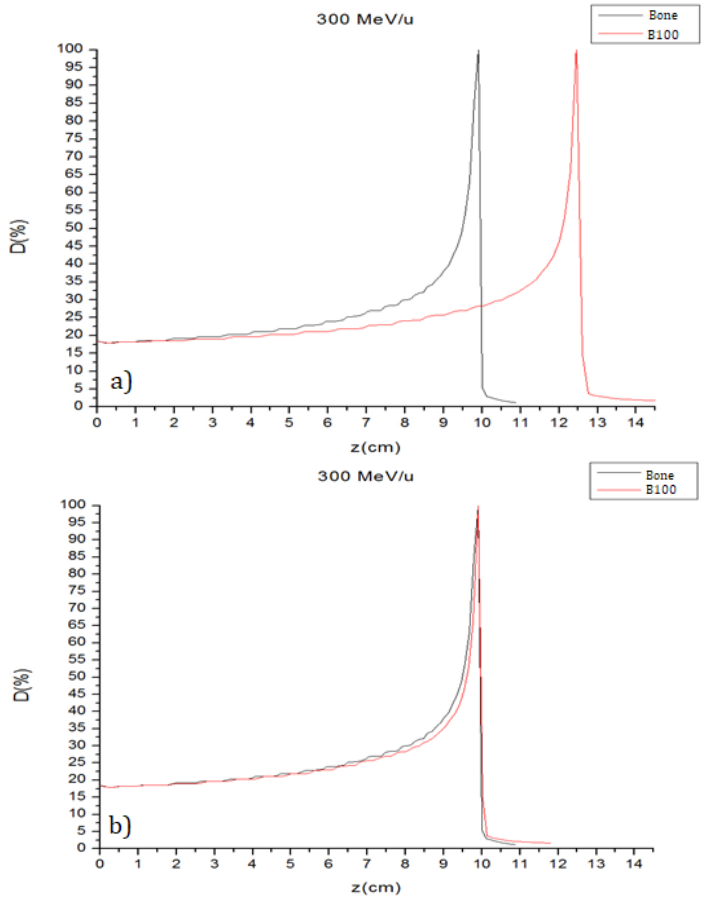


Fig. 3 – Unscaled (*a*) and scaled (*b*) dose distributions plots for data from Table 9.

Using the scaling factor with the depth, determined for each equivalent material-tissue, through the previous simulations, we can determine the degree of equivalence of a material with respect to the reference substance (water or tissue), calculating an equivalence factor ε with the following relation:

$$\varepsilon = \frac{\rho_{mat} \cdot \overline{c_{pl}}}{\rho_{ref}} \tag{9}$$

where ρ_{mat} is the density of the evaluated material, $\overline{c_{pl}}$ is the average scaling coefficient with depth relative to the reference substance, and ρ_{ref} is the density of the reference substance.

Thus, as ε the coefficient is closer to the unit, the dosimetric behavior of the evaluated material is closer to the dosimetric behavior of the reference substance. In Tables 10-13 we have summed up the dosimetric behaviors for the analyzed materials.

Table 10
Dosimetric Behavior of Solid Water

Beam	$\overline{c_{pl}}$ (cm) – *reference: water*	ε
Electrons	0.998	1.028
Protons	0.912	0.939
Carbon ions	0.91	0.937

Table 11
Dosimetric Behavior of Plastic Water

Beam	$\overline{c_{pl}}$ (cm) – *reference: water*	ε
Electrons	1.070	1.08
Protons	0.931	0.943
Carbon ions	0.88	0.89

Table 12
Dosimetric Behavior of A150

Beam	$\overline{c_{pl}}$ (cm) – *reference: soft tissue*	ε
Electrons	1.006	1.134
Protons	1.139	1.284
Carbon ions	1.138	1.283

Table 13
Dosimetric Behavior of B100

Beam	$\overline{c_{pl}}$ (cm) – *reference: bone*	ε
Electrons	0.889	0.697
Protons	0.800	0.627
Carbon ions	0.797	0.625

4. Conclusions

With the exception of B100, the tissue-equivalent materials studied have a dosimetric behavior close to that of the reference substances. For these reasons, solid water, plastic water and A150 are recommended by the IAEA for the manufacture of phantoms used in the relative dosimetry of the external beams used in radiotherapy.

All the evaluated materials have applications in medicine, with the absolutely necessary condition to take into account the factors of scaling in depth and of equivalence to the configuration of the phantoms used in radiotherapy.

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COMPORTAMENTELE DOZIMETRICE ALE MATERIALELOR ECHIVALENT-ȚESUT. UN STUDIU DE SIMULARE MONTE CARLO

(Rezumat)

Asigurarea calității și protecția împotriva radiațiilor ionizante sunt aspecte extrem de importante în procedurile de radioterapie. Dacă în cazul dozimetriei de referință (efectuată în laboratoare cu standarde primare și secundare) sunt folosite aproape exclusiv fantome din apă, în cazul dozimetriei relative (în condițiile clinice ale instituției medicale) se folosesc fantome din materiale echivalent-țesut. În această lucrare prezentăm un studiu comparativ de simulare a comportamentelor dozimetrice pentru materiale echivalent-țesut variate.