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PHOTON ENERGY-FLUENCE CORRECTION FACTOR IN LOW-ENERGY BRACHYTHERAPY

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ABSTRACT

The AAPM TG-43 brachytherapy dosimetry formalism has become a standard for brachytherapy dosimetry worldwide; it implicitly assumes that charged-particle equilibrium (CPE) exists for the determination of absorbed dose to water at different locations. At the time of relating dose to tissue and dose to water, or vice versa, it is usually assumed that the photon fluence in water and in tissues are practically identical, so that the absorbed dose in the two media can be related by their ratio of mass energy-absorption coefficients. The purpose of this work is to study the influence of photon energy-fluence in different media and to evaluate a proposal for energy-fluence correction factors for the conversion between dose-to-tissue (D_{tis}) and dose-to-water (D_w) .State-of-the art Monte Carlo (MC) calculations are used to score photon fluence differential in energy in water and in various human tissues (muscle, adipose and bone) in two different codes, MCNP and PENELOPE, which in all cases include a realistic modeling of the ^{125}I low-energy brachytherapy seed in order to benchmark the formalism proposed. A correction is introduced that is based on the ratio of the water-to-tissue photon energy-fluences using the large-cavity theory. In this work, an efficient way to correlate absorbed dose to water and absorbed dose to tissue in brachytherapy calculations at clinically relevant distances for low-energy photon emitting seed is proposed. The energy-fluence based corrections given in this work are able to correlate absorbed dose to tissue and absorbed dose to water with an accuracy better than 0.5% in the most critical cases.

1. INTRODUCTION

The AAPM TG-43 brachytherapy dosimetry formalism, introduced in 1995 and modified subsequently in various publications [1, 2, 3, 4], has become a standard for brachytherapy dosimetry worldwide. This formalism implicitly assumes that a seed is embedded in an infinite water medium and, consequently, charged-particle equilibrium (CPE) exists. Absorbed dose can, therefore, be approximated by collision kerma. Monte Carlo and experimentally derived TG-43 consensus datasets for both high- and low-energy seed models have been extensively derived in the literature based on these approximations [5, 6, 7].

Currently, most of the clinical experience is mainly based on TG-43, i.e., absorbed dose-to-water in water. However, it is well known that the TG-43 assumptions may not be accurate in some clinical situations [8]. This is particularly true for the combination of low-energy photons (< 100 keV) and some tissues as bone, for which the ratio of mass energy-absorption coefficients are significantly different from unity. The high-Z elements found in bone structures make the photoelectric effect to be the predominant interaction, leading to a higher absorption of low-energy photons and therefore hardening the photon spectrum as it goes deeper on the body [9]. Body-air interfaces, like those observed in breast or lung lesions, are another clinical situation where TG-43 assumptions are not valid [10, 11, 12].

In this context, state-of-the-art model-based dose calculations algorithms (MBDCAs) [13] such as Monte Carlo (MC) and analytical models like ACE (Advanced Calculation Engine – Nucletron – an Elekta Company, Veenendaal, The Netherlands) and ACUROS^{TM} (Transpire Inc., Gig Harbor, WA), both for HDR applications with ^{192}Ir, have become available in brachytherapy. They are considered by the AAPM Radiation Therapy Committee Task Group 186 (TG-186) as potential replacements of the TG-43 formalism. MBDCAs are capable of handling tissue compositions/densities and other treatments complexities leading to the determination of dose-to-tissue.

The relation between dose-to-tissue and dose-to-water, or vice versa, has been the subject of some recent publications in order to associate all previous clinical experience based on dose-to-water with the new methodologies based on dose-to-tissue [13,14,15,16].

Usually, absorbed dose calculations are performed using cavity theory in which the cavity dimensions are compared to the ranges of secondary electrons [17]. When the cavity is larger than the range of secondary electrons the absorbed dose to non-water tissue is estimated using ratios of mass energy-absorption coefficients between water and tissue [8,10], on the assumption that the photon energy-fluence at the point of interest is practically the same for water and for the different human tissues.

The purpose of this work is to study the influence of photon energy-fluence in different media and to evaluate a proposal for energy-fluence correction factors for the conversion between dose-to-tissue and dose-to-water. For this goal, Monte Carlo simulations using MCNP (Monte Carlo N-Particle) and PENELOPE codes for a subset of human tissues of interest in brachytherapy for ^{125}I - low energy brachytherapy seed has been performed.

2. MATERIALS AND METHODS

This section describes the methodology employed to convert absorbed dose to a tissue (D_{tis}) into absorbed dose to water (D_w) using the large-cavity theory and how Monte Carlo calculations have been carried out.

2.1. Relation between D_w and D_{tis}

At this point it should be emphasized that the conversion between D_{tis} and D_w is required mainly due to:

(i) most treatment planning systems (TPS) calculate D_w, hence available clinical experience is based on D_w;

(ii) advanced developments in absorbed dose calculation methods determine accurately D_{tis} assuming that a valid characterization of tissues from dual-CT procedures or from a lookup density-tissue table has been made;

(iii) a comparison between D_{tis} obtained by Monte Carlo calculations with D_w calculated with conventional TPS, and their transfer method, is necessary to update D_w-based previous clinical experience.

TG-43 photon brachytherapy dosimetry assumes that:

1) The source is located in an infinite water medium and charged particle equilibrium (CPE) exists (except in the vicinity of the source capsule).
2) The absorbed dose to a tissue located in such a water infinite medium, D_{tis}, at a point is approximated by the collision kerma, $(K_{col})_{tis}$, at the same point, i.e.:

$$D_{tis} \overset{CPE}{=} (K_{col})_{tis} = \Psi_{tis}(\bar{\mu}_{en}/\rho)_{tis} \tag{1}$$

where $(\bar{\mu}_{en}/\rho)_{tis}$ is the mass energy-absorption coefficient, averaged over the photon energy-fluence spectrum, and $\Psi_{tis} = \int_E \Psi_E^{tis} dE$ is the total photon energy-fluence, with:

$$\Psi_E^{tis} = \left.\frac{d\Psi}{dE}\right|_{tis} = E\Phi_E^{tis} = E\left.\frac{d\Phi}{dE}\right|_{tis} \tag{2}$$

Φ_E^{tis} being the photon fluence spectrum, differential in energy, at the point of interest.

3) The relation between dose-to-water, D_w, and dose-to-tissue D_{tis} can therefore be written as

$$\frac{D_w}{D_{tis}} = \frac{\Psi_w}{\Psi_{tis}}\frac{(\bar{\mu}_{en}/\rho)_w}{(\bar{\mu}_{en}/\rho)_{tis}} = \frac{\Psi_w}{\Psi_{tis}}(\bar{\mu}_{en}/\rho)_{tis}^w = \Psi_{tis}^w(\bar{\mu}_{en}/\rho)_{tis}^w \tag{3}$$

where Ψ_{tis}^w is the ratio of the total photon energy-fluences in water and in tissue, and $(\bar{\mu}_{en}/\rho)_{tis}^w$ is the ratio of mass energy-absorption coefficients of water and tissue, averaged over the local photon energy-fluence.

4) Assuming, as is widely done, that the photon energy-fluence at the point of interest is practically the same in tissue and in water, i.e. that $\Psi_{tis}^w \cong 1$, eq. (3) becomes:

$$\frac{D_w}{D_{tis}} = (\bar{\mu}_{en}/\rho)^w_{tis} \quad (4)$$

5) If, on the other hand, the photon energy-fluence depends on the medium at the point of interest, the ratio Ψ^w_{tis} needs to be taken into account, so that eq. (3) becomes:

$$\frac{D_w}{D_{tis}} = \Psi^w_{tis}(\bar{\mu}_{en}/\rho)^w_{tis} \quad (5)$$

where Ψ^w_{tis} is the ratio of the total photon energy-fluence in water and tissue, which in this work is termed the water-to-tissue photon energy-fluence correction factor.

This work explores the relations (4) and (5) for various human body tissues in the energy region of interest for an ^{125}I low energy brachytherapy source.

2.2. Monte Carlo calculations

Monte Carlo (MC) calculations were performed using the MCNP6 (Monte Carlo N-Particle) code version 1.0 [18,19] and Penelope MC system version 2014 [20], which accurately model photon and electron interactions in an arbitrary material for the energy range of interest in this work.

MCNP6 calculations uses the ENDF/B cross section photon library [21, 22] which is consistent with the NIST database, as stated by previous studies [23]. All calculations were performed using the MCPLIB84 photon cross-section library and EL03 for electrons [18].

Penelope2014 photon cross-sections are based on the EPDL97 cross sections library including binding effects [24, 25] and additionally include the Impulse Approximation to account for Doppler broadening. Photoelectric cross-sections have been calculated with the program *photoabs* [26]. Electron cross-sections are directly calculated by the Penelope data generation code *pendbase* and, for this work.

A comparison of mass energy-absorption coefficients for different materials using the photon dataset of Penelope and values from other libraries (e.g., the NIST database, used by MCNP) has been described by Andreo et al. [27].

2.2.1. Low energy brachytherapy seed

The brachytherapy low-energy seed has been investigated in this study is model 6711 ^{125}I source (GE Healthcare, IL. Marketed by Oncura, Inc). The seed was modeled according to published descriptions [5] and the primary radionuclide spectrum were obtained from the USA National Nuclear Data Center (NNDC) [28]. The mean photon energy is 28.5 keV.

2.2.2. Materials and geometry of the Monte Carlo calculations

Figure 1 shows the geometric modeling used for the study, which consists of an "infinite" water sphere (R = 30 cm) containing a spherical shell detector of thickness Δx = 2 mm (hatched area) with the seed located at its center. In this study, two different "detector" locations were used. In the first one, the detector was located at a distance r = 1 cm of the seed center, and in the second one at a distance r = 5 cm. These detectors were used to score photon energy-fluence spectra differential in energy and absorbed doses in the MC calculations.

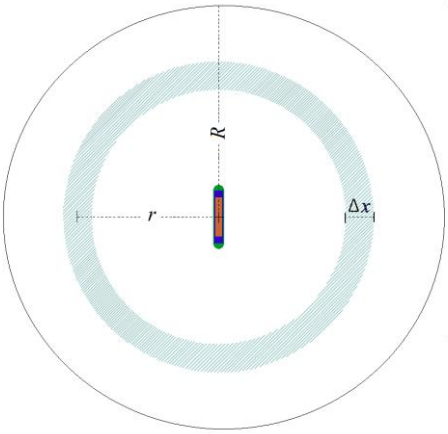

Figure 1: Schematic illustration of the simulation geometry, the size of the phantom is a water sphere with R = 30 cm, the thickness of the detectors is $\Delta x = 0.2$ cm, and the source - center to detector distance *r* is 1 cm or 5 cm (figure not to scale).

Water and four human tissues of interest in brachytherapy were considered in the spherical detectors: muscle and adipose tissue composition from ICRP Report 110 [29] and skeletal bone from ICRU Report 46 [30]. The atomic composition and mass density of each material are given in table 1.

Table 1: Materials compositions (in fraction by weight) and relevant atomic properties

Material	Water	Muscle	Adipose Tissue	Bone$_{(ICRU)}$
H	$1.12\ 10^{-1}$	$1.01\ 10^{-1}$	$1.19\ 10^{-1}$	$6.39\ 10^{-2}$
C	-	$1.08\ 10^{-1}$	$6.37\ 10^{-1}$	$2.78\ 10^{-1}$
N	-	$2.77\ 10^{-2}$	$7.97\ 10^{-3}$	$2.70\ 10^{-2}$
O	$8.80\ 10^{-1}$	$7.55\ 10^{-1}$	$2.32\ 10^{-1}$	$4.10\ 10^{-1}$
Mg	-	$1.90\ 10^{-4}$	$2.00\ 10^{-5}$	$2.00\ 10^{-3}$
P	-	$1.80\ 10^{-3}$	$1.60\ 10^{-4}$	$7.00\ 10^{-2}$
S	-	$2.41\ 10^{-3}$	$7.30\ 10^{-4}$	$2.00\ 10^{-3}$
Cl	-	$7.90\ 10^{-4}$	$1.19\ 10^{-3}$	-
K	-	$3.02\ 10^{-3}$	$3.20\ 10^{-4}$	-
Ca	-	$3.00\ 10^{-5}$	$2.00\ 10^{-5}$	$1.47\ 10^{-1}$
Others	-	$6.00\ 10^{-5}$	$5.00\ 10^{-4}$	$1.00\ 10^{-4}$
Density (g/cm³)	1.0	1.04	0.92	1.85

The *I*-values of each material in the codes are given in table 2.

Table 2: I – values in eV for different tissues used in PENELOPE and MCNP codes

	I-value (eV)			
	Water	Muscle	Adipose Tissue	$Bone_{(ICRU)}$
Penelope	78	75.3	63.2	91.9
MCNP	75.3	75.6	63.2	91.9

Photons and electrons were transported down to an energy cut-off of 1 keV in all simulations. The number of incident photons was set to 10^9 for all calculations, so that the Type A standard uncertainty of the MC-scored absorbed dose and total fluence was of the order of 0.5%.

2.2.3. Estimators of photon energy-fluence spectra and absorbed dose

Two tallies were employed:

1. Average photon Track length spectra – The "*F4 + DE/DF" cards in MCNP, which associate the trach length with the (μ_{en}/ρ) for water and each tissue by NIST; and the "tallyFluenceTrackLength" in Penelope to calculate the average photon track-length spectra within the detector volume, whose output is given multiplied by the detector volume, $V\Phi_E$, V being the detector volume (the score was subsequently divided by V). The *mutren* code of Penelope was used to calculate (μ_{en}/ρ) for water and each tissue for the energy of each bin, E_i.

   Photon fluence spectra Φ_E in water and in each tissue, were scored for n energy bins from $E_{\min}$ to $E_{\max}$ the minimum and the maximum energies of each incident seed spectrum (using n=158). Subsequently, the energy-fluence differential in energy Ψ_E was determined from Φ_E (see eq. (2)).
2. Absorbed dose - The "*F8" in MCNP and "tallySphericalDoseDistribution" in Penelope was used to score the absorbed doses D_w and D_{tis} inside the two detector volumes.

2.3. Ratios of mass energy-absorption coefficients of water and tissue and photon energy-fluence spectra

Using the equations given in section 2.1 together with the MC-scored quantities obtained as described in section 2.2, the energy-fluence weighted average mass energy-absorption coefficient ratios of water and tissue $(\overline{\mu_{en}/\rho})_{tis}^{w}$ were evaluated according to:

$$(\bar{\mu}_{en}/\rho)^{w}_{tis} = \frac{\dfrac{\int_{E_{min}}^{E_{max}} \Psi_{E}^{w}\left(\mu_{en}/\rho\right)_{w} dE}{\int_{E_{min}}^{E_{max}} \Psi_{E}^{w} dE}}{\dfrac{\int_{E_{min}}^{E_{max}} \Psi_{E}^{tis}\left(\mu_{en}/\rho\right)_{tis} dE}{\int_{E_{min}}^{E_{max}} \Psi_{E}^{tis} dE}} \cong \frac{\dfrac{\sum_{i=1}^{n} \Psi_{E_i}^{w}\left(\mu_{en}(E_i)/\rho\right)_{w}}{\sum_{i=1}^{n} \Psi_{E_i}^{w}}}{\dfrac{\sum_{i=1}^{n} \Psi_{E_i}^{tis}\left(\mu_{en}(E_i)/\rho\right)_{tis}}{\sum_{i=1}^{n} \Psi_{E_i}^{tis}}} \tag{6}$$

where $\Psi_{E_i}^{w}$ and $\Psi_{E_i}^{tis}$ are the energy-fluence distributions in water and tissue, respectively.

Following the same procedure, the values of the Ψ_{tis}^{w}-ratios were calculated using:

$$\Psi_{tis}^{w} = \frac{\int_{E_{min}}^{E_{max}} \Psi_{E}^{w} dE}{\int_{E_{min}}^{E_{max}} \Psi_{E}^{tis} dE} \cong \frac{\frac{1}{n}\sum_{i=1}^{n} \Psi_{E_i}^{w}}{\frac{1}{n}\sum_{i=1}^{n} \Psi_{E_i}^{tis}} \tag{7}$$

3. RESULTS AND DISCUSSION

The calculated mass energy-absorption coefficients of the human tissues relative to those of water are shown in Figure 2(a). For comparison, the quotient between the data from Penelope 2014 and the corresponding NIST-values used by MCNP is presented in figure 2(b). It should be noted that the differences shown are not solely due to the photoeffect cross sections in each dataset, re-normalized in Penelope 2014 and non-re-normalized in NIST, but also to the use of the Impulse Approximation and its account for Doppler broadening in Penelope whereas the NIST data uses the Klein-Nishina kinematics relationship for the scattered photon (Compton line). Both datasets incorporate binding effects.

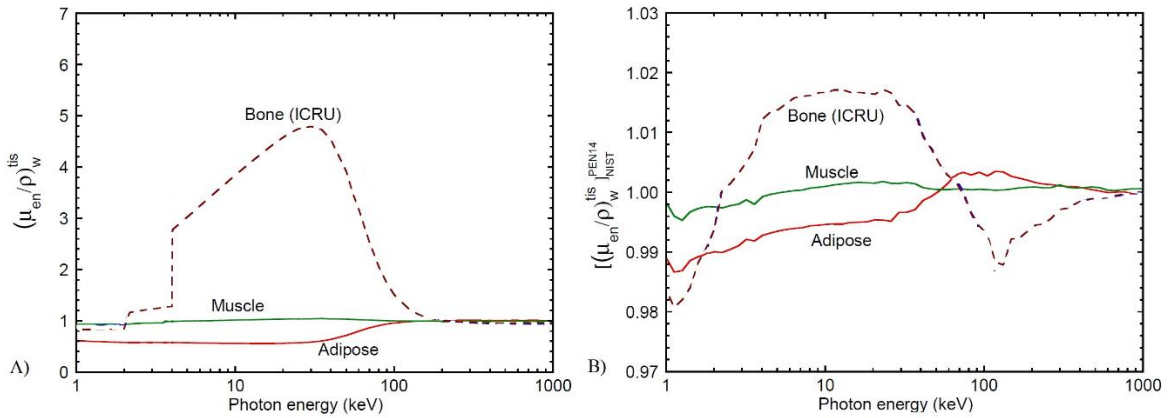

Figure 2: (a) Mass energy-absorption coefficients of various human tissues relative to water calculated in this work using the *mutren* code of the PENELOPE MC system. (b) ratio of the PENELOPE 2014 quotients to the corresponding NIST values.

The mass energy-absorptions coefficients values have been used in combination with the photon energy-fluence spectra calculated in the "detectors" at a distance of 1 cm and 5 cm from the seed center. The energy-fluence weighted average mass energy-absorption coefficients ratios were calculated according to equation (6) using the $E_{\min} = 0.5\,\text{keV}$ and $E_{\max} = 35.492\,\text{keV}$ are summarized in table 3.

Table 3: Energy-fluence weighted average mass energy-absorbed coefficients of different tissue, and their ratio relative to that of water, evaluated for ^{125}I spectra.

	PENELOPE				**MCNP**			
	1 cm		**5 cm**		**1 cm**		**5 cm**	
Materials:	$(\bar{\mu}_{en}/\rho)$ (cm²/g)	$(\bar{\mu}_{en}/\rho)^{w}_{tis}$	$(\bar{\mu}_{en}/\rho)$ (cm²/g)	$(\bar{\mu}_{en}/\rho)^{w}_{tis}$	$(\bar{\mu}_{en}/\rho)$ (cm²/g)	$(\bar{\mu}_{en}/\rho)^{w}_{tis}$	$(\bar{\mu}_{en}/\rho)$ (cm²/g)	$(\bar{\mu}_{en}/\rho)^{w}_{tis}$
Water	0.218	1.000	0.212	1.000	0.215	1.000	0.213	1.000
Muscle	0.227	0.961	0.220	0.961	0.223	0.963	0.219	0.972
Adipose	0.125	1.734	0.122	1.729	0.124	1.728	0.122	0.174
Bone (ICRU)	1.016	0.214	0.982	0.216	0.980	0.219	0.954	0.223

Energy-fluence ratios Ψ^{w}_{tis} obtained using equation (7) are given in table 4, where it can be seen that only the muscle/water ratios are approximately close to one. For the two distances, in adipose tissue the energy-fluence ratio to water varies within about -3% and -1%, but it varies up to within 20% and 50% for the ICRU bone composition. Such large differences show that the common assumption of considering approximately equal the fluences in water (or in a soft

tissue like muscle) and in bone, that provides the basis for a dose ratio equal to that of the mass energy-absorption coefficients (see eq. 4), is not acceptable for high-Z tissues.

Table 4. Energy-fluence weighted average mass photon total energy-fluence and energy-fluence correction factors for different tissues evaluated for ^{125}I spectra.

	PENELOPE				MCNP			
Materials:	1 cm		5 cm		1 cm		5 cm	
	Ψ (eV/cm^2)	Ψ_{tis}^{w}	Ψ (eV/cm^2)	Ψ_{tis}^{w}	Ψ (eV/cm^2)	Ψ_{tis}^{w}	Ψ (eV/cm^2)	Ψ_{tis}^{w}
Water	917.2	1.000	14.19	1.000	896.8	1.000	13.84	1.000
Muscle	915.6	1.002	14.14	1.003	895.2	1.002	13.80	1.003
Adipose	930.0	0.986	14.48	0.979	909,2	0.986	14.13	0.980
Bone (ICRU)	742.1	1.236	10.89	1.302	725.1	1.237	10.66	1.298

The proposal of this work is therefore to include a photon energy-fluence correction factor Ψ_{tis}^{w} to account for the fluence difference in two media according to eq. (5). This correction parallels the proposal made by Andreo et al. [31] for megavoltage photon beams, where an electron fluence correction was introduced for the tissues used in the present work. The correction factors are however, substantially larger in the case of low-energy photons used in brachytherapy than in megavoltage photons.

Results for the approximations relating the MC ratio, with the corresponding eq. (4) and eq. (5) at 1 cm and 5 cm, for the spectrum from the ^{125}I source are given in tables 4 and 5, respectively. It can be seen that the correction of eq. (5) provides dose ratios close to one within a few tenths of a per cent. The results are displayed in Figure 3 for easier visualization.

Table 4. Data of the approximations relating the MC ratio $\frac{D_{tis}}{D_w}$ with the corresponding Eq. (4), $\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)_{tis}^{w}$, and Eq. (5), $\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)_{tis}^{w}\Psi_{tis}^{w}$ for ^{125}I spectrum at 1 cm.

	1 cm					
	PENELOPE			**MCNP**		
Materials:	$\frac{D_{tis}}{D_w}$	$\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)_{tis}^{w}$	$\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)_{tis}^{w}\Psi_{tis}^{w}$	$\frac{D_{tis}}{D_w}$	$\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)_{tis}^{w}$	$\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)_{tis}^{w}\Psi_{tis}^{w}$
Muscle	1.038	0.997	0.999	1.037	0.999	1.001
Adipose	0.585	1.015	1.001	0.587	1.015	1.002
Bone (ICRU)	3.761	0.806	0.996	3.726	0.818	1.012

Table 5. Data of the approximations relating the MC ratio $\frac{D_{tis}}{D_w}$ with the corresponding Eq. (4), $\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)^w_{tis}$, and Eq. (5), $\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)^w_{tis}\Psi^w_{tis}$ for ^{125}I spectrum at 5 cm.

	5 cm					
	PENELOPE			MCNP		
Materials:	$\frac{D_{tis}}{D_w}$	$\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)^w_{tis}$	$\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)^w_{tis}\Psi^w_{tis}$	$\frac{D_{tis}}{D_w}$	$\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)^w_{tis}$	$\frac{D_{tis}}{D_w}(\bar{\mu}_{en}/\rho)^w_{tis}\Psi^w_{tis}$
Muscle	1.037	0.997	0.999	1.035	1.006	1.009
Adipose	0.591	1.022	1.001	0.593	1.031	1.010
Bone (ICRU)	3.548	0.766	0.997	3.519	0.786	1.020

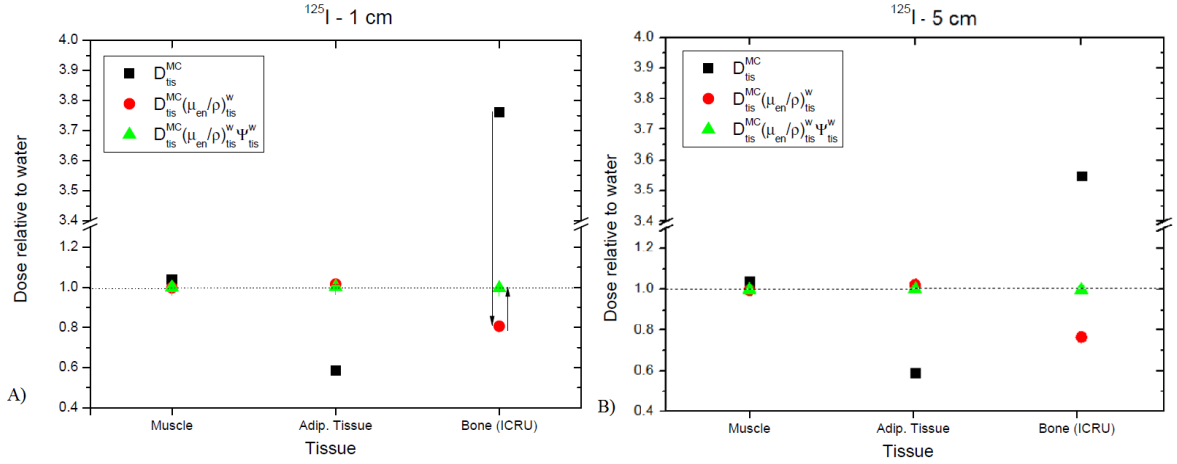

Figure 3: Ratio between D_{tis} and D_w corrected with the approximations given by equations (4) and (5) calculated by MCNP code. The ratios of the Monte Carlo-scored D_{tis} and D_w are shown as black squares. The use of the ratio of mass energy-absorption coefficients of water and tissue is shown as red circles. Adding to this ratio the energy-fluence corrections proposed in this work yields the results shown as green triangles. Type A uncertainties for all the absorbed dose ratios are of the order of 0.5%. The arrows in the top-left panel illustrate the trend of dose relative to water when the two different corrections are applied.

The different dose ratios have been analyzed at 1 cm (the typical prescription distance) and 5 cm (a typical distance for the organs at risk) from the source center in order to distinguish whether the proposed corrections could be used for clinically relevant distances, less than 5 cm from the source.

As expected, significant differences between D_w and D_{tis} can be observed for all sources and tissues, especially for bone tissues. D_{tis} values can be approximately 3.5 times higher than D_w for the bone tissue. The energy-fluence based correction proposed in Eqs. (5) and (7) provides

an excellent estimation of the correction needed to the ratio $\frac{D_w}{D_{tis}}$ for the ^{125}I source used in this work and for all clinically relevant distances with an agreement better than 0.5%.

4. CONCLUSIONS

A photon energy-fluence based correction has been proposed that represents a straightforward and efficient procedure to correlate absorbed dose to water and absorbed dose to tissue in brachytherapy calculations for clinically relevant distances. Its rationale is that photon fluence varies in different media, particularly between water and high-Z tissues like bone; for adipose tissue, the differences are much smaller but still worth correcting for. The corrections provided can be implemented in any treatment planning system and be easily extended to other distances, sources and/or radionuclides by performing a detailed Monte Carlo simulation following the procedures outlined in this work. For the new MBDCA calculation techniques, photon fluence estimators can be included in the calculation process so that both absorbed dose and photon fluence are scored simultaneously; outputs can then be given in terms of dose to tissue and of dose to water in an accurate way.

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