MONTE CARLO-BASED SPENCER–ATTIX AND BRAGG–GRAY TISSUE-TO-AIR STOPPING POWER RATIOS FOR ISO BETA SOURCES

T. Palani Selvam, S. Vandana*, A. K. Bakshi and D. A. R. Babu

Radiological Physics and Advisory Division, Health, Safety and Environment Group, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, India

*Corresponding author: vanash@barc.gov.in

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Spencer–Attix (SA) and Bragg–Gray (BG) mass-collision-stopping-power ratios of tissue-to-air are calculated using a modified version of EGSnrc-based SPRRZnrc user-code for the International Organization for Standardization (ISO) beta sources such as ^{147}Pm , ^{85}Kr , $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$. The ratios are calculated at 5 and 70 μm depths along the central axis of the unit density ICRU-4 element tissue phantom as a function of air-cavity lengths of the extrapolation chamber $l = 0.025\text{--}0.25\text{ cm}$. The study shows that the BG values are independent of l and agree well with the ISO-reported values for the above sources. The overall variation in the SA values is $\sim 0.3\%$ for all the investigated sources, when l is varied from 0.025 to 0.25 cm. As energy of the beta increases the SA stopping-power ratio for a given cavity length decreases. For example, SA values of ^{147}Pm are higher by $\sim 2\%$ when compared with the corresponding values of $^{106}\text{Ru}/^{106}\text{Rh}$ source. SA stopping-power ratios are higher than the BG stopping-power ratios and the degree of variation depends on type of source and the value of l . For example, the difference is up to 0.7% at $l = 0.025\text{ cm}$ for the $^{90}\text{Sr}/^{90}\text{Y}$ source.

INTRODUCTION

Quantity of interest in external beta radiation protection is the absorbed dose rate to tissue at a depth of 7 mg cm^{-2} (7 mg/cm^2) in a 4-element ICRU (International Commission for Radiation Units and Measurements) unit density phantom⁽¹⁾. International Organization for Standardization (ISO) 6980-2 provides guidelines to establish this quantity for beta emitters using an extrapolation chamber as a primary standard⁽¹⁾. ISO 6980 proposes two series of beta reference radiation fields, namely, series 1 and series 2⁽²⁾. Series 1 covers $^{90}\text{Sr}/^{90}\text{Y}$, ^{85}Kr , ^{204}Tl and ^{147}Pm sources used with a beam flattening filter and Series 2 covers radionuclide of series 1 in addition of ^{14}C and $^{106}\text{Ru}/^{106}\text{Rh}$ sources without a beam flattening filter.

An extrapolation chamber is usually made from polymethyl methacrylate (PMMA) and works on the principle of ionisation which provides the variable measuring volume by changing the plate separation (cavity length l) in the ISO-recommended range of $l = 0.25\text{--}2.5\text{ mm}$ ⁽¹⁾. In practice, current measurements are carried out at a series of l . These current values as a function of l are fitted to determine the slope at the limit of zero depth. $\dot{D}_t(7\text{ mg/cm}^2)$ is then determined using a set of correction factors and the Bragg–Gray (BG) relationship as described in ISO 6980-2 report⁽¹⁾. A complete description of the application of cavity theory to the use of the extrapolation chamber in beta radiation dosimetry is reported in the literature^(1–8).

Palani Selvam *et al.* reported Monte Carlo-based modelling of the response of the NRC's $^{90}\text{Sr}/^{90}\text{Y}$

primary beta standard⁽⁸⁾. In that work, authors compared the measured response of the National Research Council of Canada (NRC) extrapolation against the Monte Carlo calculations. The authors used the EGSnrc-based⁽⁹⁾ BEAMnrc⁽¹⁰⁾ user-code for this purpose. More recently, Behrens carried out EGSnrc Monte Carlo simulation of radiation fields of beta secondary standard BSS-2⁽¹¹⁾.

The Monte Carlo-based user-code SPRRZnrc which is originally distributed along with EGSnrc⁽⁹⁾ code system calculates the Spencer–Attix (SA) stopping-power ratios in a cylindrical RZ geometry. Although SA cavity theory is considered more accurate than BG cavity theory, the latter is sometimes still applied in radiation dosimetry studies⁽¹⁾. Because, SA cavity theory could account for the variation in the response measured as a function of cavity dimension^(12–15) whereas BG cavity theory could not. In radiotherapy dose measurements, SA cavity theory is employed⁽¹⁶⁾. Palani Selvam and Rogers modified the original SPRRZnrc code by including BG stopping-power ratios⁽¹⁷⁾.

The objective of this study is to calculate SA stopping-power ratios of tissue-to-air, $[(\bar{L}/\rho)(z, \Delta)]_a^t$ (z is depth in phantom, Δ is initial kinetic energy of the secondary electrons which is sufficient to cross the cavity, t and a denote tissue and air media, respectively), for the ISO beta sources such as ^{147}Pm , ^{85}Kr , $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$ using the modified version of SPRRZnrc code⁽¹⁷⁾. The SA stopping-power ratios are calculated as a function of l (0.025–0.25 cm). The study also includes calculation of BG stopping-power

ratios of tissue-to-air, $(S/p)_a^t$ for the above-mentioned sources and compares the same against the corresponding ISO-reported values⁽¹⁾.

MATERIALS AND METHODS

Beta sources

Beta Secondary Standard BSS-2 developed at Physikalisch Technische Bundesantalt (PTB), Braunschweig, Germany, is in worldwide use to irradiate devices with calibrated beta sources⁽¹¹⁾. ISO 6980-2 recommended sources are being used as standard sources and the reference dose rate $\dot{D}_t(7 \text{ mg/cm}^2)$ for these sources must be measured using an extrapolation ionisation chamber. Behrens⁽¹¹⁾ has provided the phase-space spectra data for ^{147}Pm , ^{85}Kr , $^{106}\text{Ru}/^{106}\text{Rh}$ and $^{90}\text{Sr}/^{90}\text{Y}$ with Mylar flattening filter except $^{90}\text{Sr}/^{90}\text{Y}$ for which the spectra are also made available without flattening filter. These spectra are determined using the Monte Carlo particle transport code BEAMnrc⁽¹⁰⁾ and are provided as electronic version. Both electrons and photons emitted from the radioactive material have been included in the simulations in order to obtain particle spectra of both the components separately. Behrens provided the separate spectra files for photons and electrons, respectively, as electronic version. The phase-space data are made available for ^{85}Kr , $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$ sources at 30 cm distance from these sources and at 20 cm distance for the ^{147}Pm source.

Monte Carlo calculations

The PEGS4 dataset needed for the Monte Carlo calculations is based on XCOM⁽¹⁸⁾ compilations. As the objective is to calculate SA stopping-power ratios as a function of l , PEGS4 data sets with different AE values are needed, where AE is the low-energy threshold for the production of knock-on electrons. For the range of l values ($l = 0.025\text{--}0.25 \text{ cm}$) the cord length L was calculated using the relation $L = 4 V/S$ ⁽¹⁵⁾, where V and S are the volume and surface area of the cylindrical air cavity of the chamber, respectively. Note that $L = V/S$ corresponds to the case of isotropic electrons. The radius of sensitive air cavity of the PTB extrapolation chamber is 1.5 cm. Therefore, the radius of air cavity used in the calculation of L is 1.5 cm. Using the L values, the corresponding values of Δ were obtained by using the CSDA⁽¹⁹⁾ range energy relationship. Thus for the above-mentioned range of l values, the values of AE are in the range 0.515–0.525 MeV (AE values include electron's rest mass energy).

In preparation of PEGS4 data sets for BG stopping-power ratios, the authors explicitly set IUNRST = 1 in the PEGS4 input file. This cannot be done from the egsgui and so the file must be created

manually. The IUNRST = 1 option provides a cross section data set (PEGS4 output) that includes just the unrestricted collision stopping powers. The values of AE and AP set are 0.512 MeV and 1 keV, respectively.

In the Monte Carlo calculations, on-axis $[(\bar{L}/\rho)(z, \Delta)]_a^t$ and $(S/p)_a^t$ values are calculated in a cylindrical unit density ICRU-4-element tissue phantom of 7 cm radius and 3 cm thick. The ratios are obtained at 5 and 70 μm depths in tissue, as the PTB extrapolation chamber has default entrance window of 5 μm and ISO 6980-2 recommends the measurements at 70 μm depth. The scoring radius and thickness used in the calculations are 1.5 cm and 1 μm . All the calculations utilised the PRESTA-II step length and EXACT boundary crossing algorithms. The photon transport cut-off energy PCUT is chosen at 1 keV in all calculations. Up to 2.5×10^6 particle histories are simulated. The 1σ statistical uncertainties on the calculated values are $\sim 0.01\%$.

RESULTS AND DISCUSSION

Tables 1–4 present the on-axis $[(\bar{L}/\rho)(z, \Delta)]_a^t$ values (calculated based on Δ values arrived at using the formula $L = 4 V/S$) at 5 and 70 μm depths in tissue, as a function of l for ^{147}Pm , ^{85}Kr , $^{90}\text{Sr}/^{90}\text{Y}$ (with Mylar) and $^{106}\text{Ru}/^{106}\text{Rh}$, respectively. In these calculations, the phase-space data are based on Mylar filter present between the source and the scoring plane. For ^{147}Pm and ^{85}Kr sources, the values of $[(\bar{L}/\rho)(z, \Delta)]_a^t$ are statistically identical at both the depths. Whereas for high energy sources such as $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$, for a given l , $[(\bar{L}/\rho)(z, \Delta)]_a^t$ value at 70 μm depth is higher than the corresponding value at 5 μm depth. For example, in the case of $^{106}\text{Ru}/^{106}\text{Rh}$

Table 1. Monte Carlo-calculated on-axis SA mass-collision-stopping-power ratio of tissue-to-air, $[(\bar{L}/\rho)(z, \Delta)]_a^t$, for ^{147}Pm source at 5 and 70 μm depths in tissue with mylar filter.

Cavity length l (cm)	$L = 4 V/S$ (cm)	Δ (keV)	AE = ECUT (keV)	$[(\bar{L}/\rho)(z, \Delta)]_a^t$	
				5 μm	70 μm
0.025	0.049	4.0	515	1.1294	1.1294
0.050	0.097	6.0	517	1.1281	1.1283
0.075	0.143	7.4	518	1.1277	1.1278
0.100	0.188	9.0	520	1.1271	1.1273
0.125	0.231	9.7	521	1.1269	1.1269
0.150	0.273	11.0	522	1.1266	1.1268
0.175	0.313	11.7	523	1.1264	1.1266
0.200	0.353	12.5	524	1.1262	1.1263
0.225	0.391	13.3	524	1.1262	1.1263
0.250	0.429	14.0	525	1.1261	1.1262

The statistical uncertainties associated with these values are $\pm 0.01\%$. The ratios are based on Δ values arrived at using the formula $L = 4 V/S$.

Table 2. Monte Carlo-calculated on-axis SA mass-collision-stopping-power ratio of tissue-to-air, for ^{85}Kr source at 5 and 70 μm depths in tissue with mylar filter.

Cavity length l (cm)	$L = 4 V/S$ (cm)	Δ (keV)	AE = ECUT (keV)	$[(\bar{L}/\rho)(z, \Delta)]_a^t$	
				5 μm	70 μm
0.025	0.049	4.0	515	1.1273	1.1273
0.050	0.097	6.0	517	1.1260	1.1261
0.075	0.143	7.4	518	1.1258	1.1258
0.100	0.188	9.0	520	1.1251	1.1252
0.125	0.231	9.7	521	1.1249	1.1249
0.150	0.273	11.0	522	1.1247	1.1247
0.175	0.313	11.7	523	1.1244	1.1244
0.200	0.353	12.5	524	1.1243	1.1242
0.225	0.391	13.3	524	1.1243	1.1242
0.250	0.429	14.0	525	1.1241	1.1242

The statistical uncertainties associated with these values are ± 0.01 %. The ratios are based on Δ values arrived at using the formula $L = 4 V/S$.

Table 3. Monte Carlo-calculated on-axis SA mass-collision-stopping-power ratio of tissue-to-air, $[(\bar{L}/\rho)(z, \Delta)]_a^t$, for $^{90}\text{Sr}/^{90}\text{Y}$ source at 5 and 70 μm depths in tissue with mylar filter.

Cavity length l (cm)	$L = 4 V/S$ (cm)	Δ (keV)	AE = ECUT (keV)	$[(\bar{L}/\rho)(z, \Delta)]_a^t$	
				5 μm	70 μm
0.025	0.049	4.0	515	1.1173	1.1182
0.050	0.097	6.0	517	1.1163	1.1172
0.075	0.143	7.4	518	1.1156	1.1168
0.100	0.188	9.0	520	1.1153	1.1163
0.125	0.231	9.7	521	1.1150	1.1161
0.150	0.273	11.0	522	1.1145	1.1158
0.175	0.313	11.7	523	1.1146	1.1156
0.200	0.353	12.5	524	1.1145	1.1152
0.225	0.391	13.3	524	1.1145	1.1152
0.250	0.429	14.0	525	1.1143	1.1152

The statistical uncertainties associated with these values are ± 0.01 %. The ratios are based on Δ values arrived at using the formula $L = 4 V/S$.

Table 4. Monte Carlo-calculated on-axis SA mass-collision-stopping-power ratio of tissue-to-air, $[(\bar{L}/\rho)(z, \Delta)]_a^t$, for $^{106}\text{Ru}/^{106}\text{Rh}$ source at 5 and 70 μm depths in tissue with mylar filter.

Cavity length l (cm)	$L = 4 V/S$ (cm)	Δ (keV)	AE = ECUT (keV)	$[(\bar{L}/\rho)(z, \Delta)]_a^t$	
				5 μm	70 μm
0.025	0.049	4.0	515	1.1082	1.1097
0.050	0.097	6.0	517	1.1071	1.1081
0.075	0.143	7.4	518	1.1065	1.1081
0.100	0.188	9.0	520	1.1066	1.1076
0.125	0.231	9.7	521	1.1058	1.1076
0.150	0.273	11.0	522	1.1057	1.1066
0.175	0.313	11.7	523	1.1056	1.1067
0.200	0.353	12.5	524	1.1053	1.1067
0.225	0.391	13.3	524	1.1053	1.1067
0.250	0.429	14.0	525	1.1052	1.1067

The statistical uncertainties associated with these values are ± 0.01 %. The ratios are based on Δ values arrived at using the formula $L = 4 V/S$.

source, depending upon the value of l , $[(\bar{L}/\rho)(z, \Delta)]_a^t$ values at 70 μm depths are higher by 0.08–0.16 % than at 5 μm . A similar comparison for the $^{90}\text{Sr}/^{90}\text{Y}$ source with Mylar and without Mylar shows deviations of 0.06–0.12 % and 0.08–0.15 %, respectively. The overall variation in the $[(\bar{L}/\rho)(z, \Delta)]_a^t$ values is only ~ 0.3 % when the l is varied from 0.025 to 0.25 cm. This is true for all the investigated sources.

Table 5 presents the $[(\bar{L}/\rho)(z, \Delta)]_a^t$ values (calculated based on Δ values arrived at using the formula $L = 4 V/S$) for $^{90}\text{Sr}/^{90}\text{Y}$ source, when Mylar is not present. A comparison of stopping-power ratios with and without Mylar for the $^{90}\text{Sr}/^{90}\text{Y}$ source shows that $[(\bar{L}/\rho)(z, \Delta)]_a^t$ values are higher with Mylar. For

example, depending upon the value of l , at 5 and 70 μm depths, $[(\bar{L}/\rho)(z, \Delta)]_a^t$ values with Mylar are higher by 0.15–0.19 % and 0.12–0.15 %, respectively, when compared with the corresponding values without Mylar. Note that when Mylar is present, the fluence-weighted mean energy of electrons is expected to be less than the case without Mylar. Simulations using the FLURZnrc user-code⁽²⁰⁾ show that the fluence-weighted mean energies of electrons with and without Mylar filter are 833 and 875 keV, respectively. These mean energies were calculated in a 1.5 cm radius $\times$ 0.01 cm thick air region. Above variation in the mean energy caused differences in the $[(\bar{L}/\rho)(z, \Delta)]_a^t$ with and without Mylar.

Table 5. Monte Carlo-calculated on-axis SA mass-collision-stopping-power ratio of tissue-to-air, $[(\bar{L}/\rho)(z, \Delta)]_a^t$, for $^{90}\text{Sr}/^{90}\text{Y}$ source at 5 and 70 μm depths in tissue without mylar filter.

Cavity length l (cm)	$L = 4 V/S$ (cm)	Δ (keV)	AE = ECUT (keV)	$[(\bar{L}/\rho)(z, \Delta)]_a^t$	
				5 μm	70 μm
0.025	0.049	4.0	515	1.1154	1.1169
0.050	0.097	6.0	517	1.1145	1.1157
0.075	0.143	7.4	518	1.1140	1.1152
0.100	0.188	9.0	520	1.1132	1.1149
0.125	0.231	9.7	521	1.1131	1.1142
0.150	0.273	11.0	522	1.1128	1.1143
0.175	0.313	11.7	523	1.1130	1.1139
0.200	0.353	12.5	524	1.1128	1.1139
0.225	0.391	13.3	524	1.1128	1.1139
0.250	0.429	14.0	525	1.1123	1.1137

The statistical uncertainties associated with these values are $\pm 0.01\%$. The ratios are based on Δ values arrived at using the formula $L = 4 V/S$.

Table 6. Comparison of Monte Carlo-calculated and ISO-quoted BG mass-collision-stopping-power ratio of tissue-to-air, $(S/p)_a^t$, at 5 and 70 μm depths in tissue phantom.

Sources	$(S/p)_a^t$ (MC calculated)		ISO quoted values ^a
	5 μm	70 μm	
^{147}Pm	1.125	1.126	1.124
^{85}Kr	1.122	1.122	1.121
$^{90}\text{Sr}/^{90}\text{Y}$ (with filter)	1.110	1.111	1.110
$^{90}\text{Sr}/^{90}\text{Y}$ (without filter)	1.110	1.110	1.110
$^{106}\text{Ru}/^{106}\text{Rh}$	1.103	1.103	1.102

^aReference⁽¹⁾.

Table 7. Ratio of on-axis SA and BG mass-collision-stopping-power ratio of tissue-to-air presented ^{147}Pm , ^{85}Kr , $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$ beta sources.

Cavity length l (cm)	^{147}Pm		^{85}Kr		$^{90}\text{Sr}/^{90}\text{Y}$ (with filter)		$^{90}\text{Sr}/^{90}\text{Y}$ (without filter)		$^{106}\text{Ru}/^{106}\text{Rh}$	
	5 μm	70 μm	5 μm	70 μm	5 μm	70 μm	5 μm	70 μm	5 μm	70 μm
0.025	1.0039	1.0030	1.0047	1.0047	1.0066	1.0065	1.0049	1.0062	1.0047	1.0061
0.050	1.0028	1.0020	1.0036	1.0037	1.0057	1.0056	1.0041	1.0051	1.0037	1.0046
0.075	1.0024	1.0016	1.0034	1.0034	1.0050	1.0052	1.0036	1.0047	1.0032	1.0046
0.100	1.0019	1.0012	1.0028	1.0029	1.0048	1.0048	1.0029	1.0044	1.0033	1.0042
0.125	1.0017	1.0008	1.0026	1.0026	1.0045	1.0046	1.0028	1.0038	1.0025	1.0042
0.150	1.0014	1.0007	1.0024	1.0024	1.0041	1.0043	1.0025	1.0039	1.0024	1.0034
0.175	1.0012	1.0005	1.0021	1.0021	1.0041	1.0041	1.0027	1.0035	1.0024	1.0034
0.200	1.0011	1.0003	1.0020	1.0020	1.0041	1.0038	1.0025	1.0035	1.0021	1.0034
0.250	1.0010	1.0002	1.0019	1.0020	1.0039	1.0038	1.0021	1.0033	1.0020	1.0034

The ratios are presented for different cavity lengths and for depths 5 and 70 μm in tissue. The SA ratios are based on Δ values arrived at using the formula $L = 4 V/S$.

Further analysis of data shows that as energy of the beta increases the $[(\bar{L}/\rho)(z, \Delta)]_a^t$ value for a given l decreases. For example, $[(\bar{L}/\rho)(z, \Delta)]_a^t$ values of ^{147}Pm are higher by $\sim 2\%$ when compared with the corresponding values of $^{106}\text{Ru}/^{106}\text{Rh}$ source. A similar comparison shows that $[(\bar{L}/\rho)(z, \Delta)]_a^t$ values of ^{147}Pm are higher by $\sim 1\%$ than that of the $^{90}\text{Sr}/^{90}\text{Y}$ source (with Mylar). The $[(\bar{L}/\rho)(z, \Delta)]_a^t$ data of ^{85}Kr and ^{147}Pm sources are comparable within 0.2%.

The Monte Carlo-calculated values of BG mass-collision-stopping-power ratio of tissue-to-air, $(S/p)_a^t$ do not show l dependent. Table 6 compares the Monte Carlo-calculated and ISO-quoted⁽¹⁾ values of $(S/p)_a^t$, at 5 and 70 μm depths in tissue for the investigated sources. The Monte Carlo-based values are in good agreement with the values reported in the ISO 6980-2 report⁽¹⁾. At both the depths, the values are almost constant. A comparison of $[(\bar{L}/\rho)(z, \Delta)]_a^t$ (calculated based on Δ values arrived at using the formula $L = 4 V/S$) and $(S/p)_a^t$ data for a given source suggests that the former values are higher than the latter (see Table 7). The degree of difference is source and l dependent. For a given source and depth in phantom, the difference decreases as l increases. The difference is up to 0.7% at $l = 0.025$ cm for the $^{90}\text{Sr}/^{90}\text{Y}$ source (with Mylar filter).

It is possible that high energy beta particles from $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$ sources may be in the forward direction and therefore will move straight across the air cavity of the chamber. In order to investigate this, the authors carried out auxiliary simulations by using Δ values corresponding to l . The values of Δ in this case range from 3 to 10 keV, when l varies from 0.025 to 0.25 cm. Table 8 presents the values of $[(\bar{L}/\rho)(z, \Delta)]_a^t$ (for the case when beta particles move across the cavity straight) for ^{147}Pm , ^{85}Kr , $^{90}\text{Sr}/^{90}\text{Y}$ (with and without Mylar filter) and $^{106}\text{Ru}/^{106}\text{Rh}$.

Table 8. Monte Carlo-calculated on-axis SA mass-collision-stopping-power ratio of tissue-to-air, $[(\bar{L}/\rho)(z, \Delta)]_a^t$, for ^{147}Pm , ^{85}Kr , $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$ sources at 5 and 70 μm depths in tissue.

Cavity length l (cm)	Δ (keV)	AE = ECUT (keV)	$[(\bar{L}/\rho)(z, \Delta)]_a^t$									
			^{147}Pm		^{85}Kr		$^{90}\text{Sr}/^{90}\text{Y}$ with filter		$^{90}\text{Sr}/^{90}\text{Y}$ without filter		$^{106}\text{Ru}/^{106}\text{Rh}$	
			5 μm	70 μm	5 μm	70 μm	5 μm	70 μm	5 μm	70 μm	5 μm	70 μm
0.025	2.8	514	1.1304	1.1306	1.1282	1.1283	1.1184	1.1191	1.1163	1.1177	1.1097	1.1106
0.050	4.0	515	1.1294	1.1294	1.1273	1.1273	1.1173	1.1182	1.1154	1.1169	1.1082	1.1097
0.075	5.0	516	1.1286	1.1288	1.1267	1.1268	1.1166	1.1177	1.1148	1.1163	1.1078	1.1093
0.100	6.0	517	1.1281	1.1283	1.1260	1.1261	1.1163	1.1172	1.1145	1.1157	1.1071	1.1081
0.125	7.0	518	1.1277	1.1278	1.1258	1.1258	1.1156	1.1168	1.1140	1.1152	1.1065	1.1081
0.150	8.0	519	1.1274	1.1275	1.1254	1.1254	1.1156	1.1164	1.1136	1.1149	1.1065	1.1081
0.175	8.6	520	1.1271	1.1273	1.1251	1.1252	1.1153	1.1163	1.1132	1.1149	1.1066	1.1076
0.200	9.0	520	1.1271	1.1273	1.1251	1.1252	1.1153	1.1163	1.1132	1.1149	1.1066	1.1076
0.225	9.7	521	1.1269	1.1269	1.1249	1.1249	1.1150	1.1161	1.1131	1.1142	1.1058	1.1076
0.250	10.0	521	1.1269	1.1269	1.1249	1.1249	1.1150	1.1161	1.1131	1.1142	1.1058	1.1076

The statistical uncertainties associated with these values are $\pm 0.01\%$. The ratios are based on Δ values when electrons cross the cavity parallel to the chamber axis.

sources at 5 and 70 μm depths in tissue. This investigation suggests that the calculated $[(\bar{L}/\rho)(z, \Delta)]_a^t$ value for a given source and given l is higher when compared with the corresponding value based on $L = 4 V/S$. For example, the difference is up to $\sim 0.14\%$ for $^{106}\text{Ru}/^{106}\text{Rh}$ source (for $l = 0.025\text{ cm}$ at 5 μm , $l = 0.05$ and 0.15 cm at 70 μm). However, most values are higher by $< 0.08\%$ for all the sources.

APPLICATION

In order to see the influence of SA cavity theory on the measured dose rate to tissue at 70 μm depth in the 4-element ICRU tissue phantom, the authors utilised previously measured response of ^{147}Pm (at 20 cm), ^{85}Kr (at 30 cm) and $^{90}\text{Sr}/^{90}\text{Y}$ (at 30 cm) sources (with Mylar filter)⁽⁴⁾. The measured currents corrected for cavity length dependent corrections including $[(\bar{L}/\rho)(z, \Delta)]_a^t$ were plotted against l to obtain the slope. The dose rate to tissue at 70 μm depth obtained by this approach is higher by 0.15, 0.24 and 0.35 %, respectively, for ^{147}Pm , ^{85}Kr and $^{90}\text{Sr}/^{90}\text{Y}$ sources, when compared with using the BG theory.

CONCLUSIONS

On-axis SA and BG mass-collision-stopping-power ratio of tissue-to-air are calculated at 5 and 70 μm depths in the unit density ICRU-4 element tissue phantom as a function of air-cavity lengths $l = 0.025\text{--}0.25\text{ cm}$ of the extrapolation chamber for the ISO beta sources such as ^{147}Pm , ^{85}Kr , $^{90}\text{Sr}/^{90}\text{Y}$ and

$^{106}\text{Ru}/^{106}\text{Rh}$. The BG values are independent of l and agree well with the ISO-reported values for the above sources. The overall variation in the SA stopping-power ratios is about 0.3 % when l is varied from 0.025 to 0.25 cm for all the investigated sources. SA stopping-power ratios are higher than the BG stopping-power ratios and the degree of variation depends on type of source and the value of l . For example, the difference is up to $\sim 0.7\%$ at $l = 0.025\text{ cm}$ for the $^{90}\text{Sr}/^{90}\text{Y}$ source. Application of SA cavity theory on previously measured response of PTB chamber enhanced dose rate to tissue at 70 μm depth in 4-element ICRU phantom, by 0.15, 0.24 and 0.35 %, respectively, for ^{147}Pm , ^{85}Kr and $^{90}\text{Sr}/^{90}\text{Y}$ sources. It is therefore recommended that the SA cavity theory may be applied in extrapolation chamber-based external beta dosimetry as it improves the accuracy of dose rate to tissue at the depth of 70 μm .

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