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Geant4 Simulation of Gamma-Ray Transmission Buildup Factors for Human Tissues

Abdulrahman A. Alfuraih[1,*] and Omrane M. Kadri[1,*,2]

Abstract

Quantification of scattered photons in addition to unscattered primary particles, under realistic exposure scenario, is best dealt with a parameter called "Buildup factor". The aim of this work is to simulate the transmission buildup factor (BUF) of gamma-ray in the energy range .15–15 MeV for 20 human tissues and organs using the Geant4 (version 10.5) Monte Carlo simulation followed by a geometrical progression (GP) parameterization procedure. Firstly, we verified the accuracy of Geant4 ability to predict the effective transmitted dose according to published data. Also, a comparison of simulated BUF for different geometrical configurations was carried out for some tissues and source energies. Then, we checked out the linear dependency of the K parameter (BUF is function of K) function of mean free path (mfp). Finally, we developed a fitting procedure according to GP method for BUF corresponding to 20 tissues and organs and different mfp (from 1 to 8) for energy range .15–15 MeV. We found a good agreement with previous published data. Proper comprehension of BUF for tissues leads to carefully controlling the energy absorption in the human body. Consequently, provided BUF could be of great interest for estimating safe dose levels in medical imaging and radiation therapy.

Keywords

geant4, buildup factor, effective transmission dose, geometrical progression fitting, human tissues

Introduction

Nowadays, gamma-ray is commonly used for medical imaging and radiation treatment over the world.[1] Thus, the ultimate need to accurately investigate and to enhance our knowledge on radiation protection is obvious. Especially, the proper knowledge of the interaction of ionizing radiation with human tissues and organs is necessary to avoid unsafe outcomes. For studying such interaction, the buildup factor (BUF) was introduced to improve the prediction of transmitted beam, through a given medium, for realistic cases, using the modified Beer-Lambert law.[2,3] Such factor estimates the contribution of primary and scattered photon beam along its attenuation within a given barrier.

Tissue equivalent materials respond to incident ionizing radiation in the same manner as human tissues. These phantoms are commonly used in medical applications including radiation therapy, diagnostic radiology, radiation protection, and radiobiology for calibration purposes and depth-dose estimation. On the other hand, there are 3 main categories of BUFs: absorbed dose, exposure, and dose-equivalent buildup factors, which are based on energy absorption, kerma, and equivalent dose responses, respectively. Hence, the importance of BUF factors for biological tissues is needed.

Gamma-ray BUF accurately measured is not always allowed. Therefore, studies of gamma-ray buildup factors were

[1]Department of Radiological Sciences, College of Applied Medical Science, King Saud University, Riyadh, Saudi Arabia
[2]National Center for Nuclear Sciences and Technologies, Tunis, Tunisia

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*A. Alfuraih and O. Kadri have contributed equally to this research.

Corresponding Author:
Abdulrahman A. Alfuraih, Department of Radiological Sciences, King Saud University, Riyadh 11451, Saudi Arabia.
Email: aalfuraih@ksu.edu.sa

Table 1. Elemental composition (%), Atomic Density (g/cm^3) and Equivalent Atomic Number (*Zeq*), at Different Energies in MeV, for Studied HDRK-Man Organs/Tissues (* stand for organ contents). RBM Means Red Bone Marrow.

	Elemental Composition						Zeq		
Tissue	H	C	N	O	Remaining	d(g/cc)	0.150	1.500	15.000
Lung	10.134	10.238	2.866	75.752	1.010(Na,Mg,Si,P,S, Cl,K,Ca,Fe,Zn,Rb)	.296	7.721	6.661	6.569
Adipose	11.400	59.800	.700	27.800	.30(Na,S,Cl)	.920	6.486	5.560	5.507
Adrenal	10.500	25.600	2.700	60.200	1.000(Na,P,S,Cl,K)	1.020	7.424	6.337	6.251
RBM	10.500	41.400	3.400	43.900	.800(P,S,Cl,K,Fe)	1.030	7.282	6.050	5.956
GallC	10.500	25.600	2.700	60.200	1.000(Na,P,S,Cl,K)	1.030	7.424	6.337	6.251
Heart	10.400	13.900	2.900	71.800	1.000(Na,P,S,Cl,K)	1.030	7.628	6.564	6.474
Oral	8.430	57.400	1.610	24.550	8.010(Mg,Cl)	1.030	7.413	6.218	6.130
IntestineC	10.600	11.500	2.200	75.100	.600(Na,P,S,Cl,K)	1.030	7.507	6.550	6.469
ColonC	10.600	11.500	2.200	75.100	.600(Na,P,S,Cl,K)	1.040	7.507	6.550	6.469
Oesophagus	10.500	25.600	2.700	60.200	1.000(Na,P,S,Cl,K)	1.040	7.424	6.337	6.251
Muscle	10.200	14.300	3.400	71.000	1.100(Na,P,S,Cl,K)	1.040	7.673	6.586	6.494
StomachC	10.600	11.500	2.200	75.100	.600(Na,P,S,Cl,K)	1.050	7.507	6.550	6.469
Kidneys	10.300	13.200	3.000	72.400	1.100(Na,P,S,Cl,K,Ca)	1.050	7.660	6.591	6.501
Thyroid	10.400	11.900	2.400	74.500	.800(Na,P,S,Cl,K,I)	1.050	8.702	6.736	6.516
Liver	10.200	13.900	3.000	71.600	1.300(Na,P,S,Cl,K)	1.060	7.690	6.604	6.512
HeartC	10.200	11.000	3.300	74.500	1.000(Na,P,S,Cl,K,Fe)	1.060	7.795	6.651	6.552
Pancreas	10.600	16.900	2.200	69.400	.900(Na,P,S,Cl,K)	1.060	7.505	6.474	6.390
Spleen	10.300	11.300	3.200	74.100	1.100(Na,P,S,Cl,K)	1.060	7.690	6.627	6.536
Skin	10.000	20.400	4.200	64.500	.900(Na,P,S,Cl,Na)	1.090	7.397	6.445	6.369
Bone	7.337	25.475	3.057	47.893	16.238(F,Na,Mg,Si,P,S, (Cl,K,Ca,Fe,Zn,Rb,Sr,Pb)	1.34	11.534	8.641	8.031

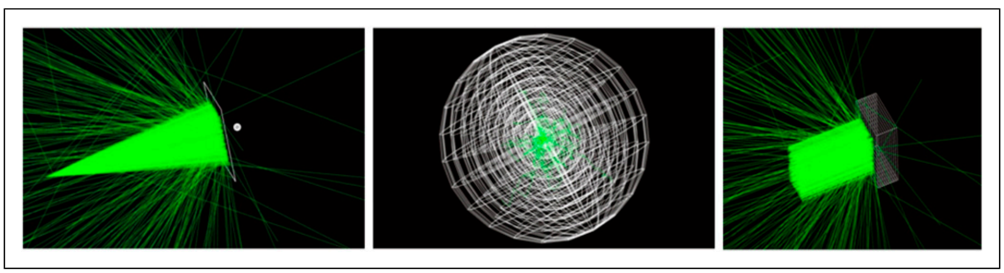

Figure 1. Visualization of Geant4 simulated setup using HepRAPP[26] package for different typical geometries used to acquire transmitted beam: (left) isotropic point source in planar configuration; (middle) isotropic point source in stratified spherical layers; (right): parallel unidirectional plane beam in planar shielding.

carried out using Monte Carlo simulation,[4,5] invariant embedding,[6] geometric progression (GP) fitting,[7-9] and other methods.

However, on the basis of our knowledge and the available literature, there is no more precise dataset of buildup factors than those tabulated by ANSI/ANS-6.4.3-1991.[10] This dataset provides five GP fitting parameters of BUF for 23 elements and three compounds in the energy range of .015–15 MeV at penetration depths up to 40 mean free paths (mfp). Although, generally, proposed data concern the specific case of unidirectional parallel beam impinging on planar stratified shielding and a correction factor was given to take into account spherical geometries. Moreover, there is no data base including BUF values directly derived from Monte Carlo simulations for all human body corresponding to isotropic point source with stratified spherical layers medium, which can be considered valuable to the scientific research community, as it could be easily included into point kernel-based programs. Furthermore, the Geometry ANd Tracking version (Geant4) Monte Carlo toolkit[11,12] has not been used to fully simulate buildup factors, except for recently published work in which the mass energy attenuation coefficients were simulated and used with the GP parameters[2] and our previous work attempt.[4] In order to address previous enumerated questions, we provide a BUF database and its corresponding parameterization for photon point isotropic sources and realistic

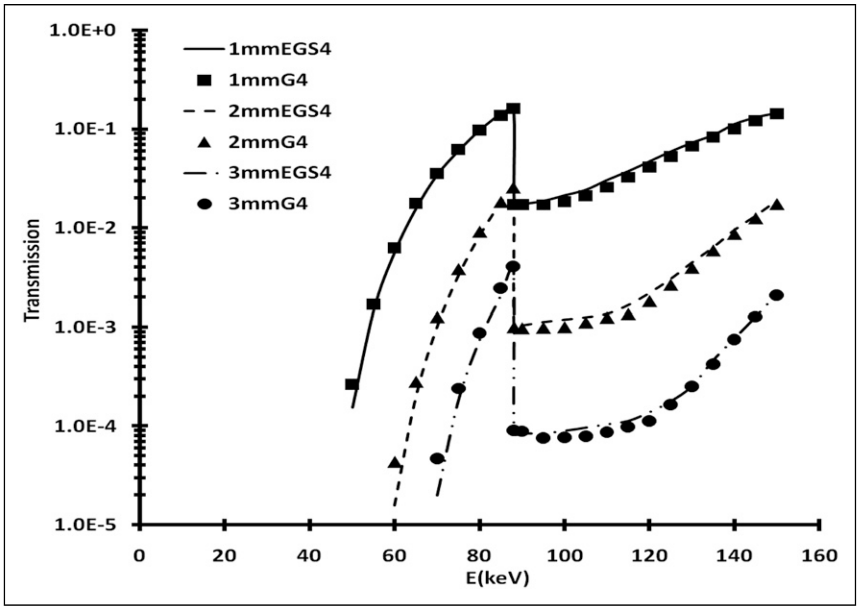

Figure 2. Geant4 simulated effective transmitted dose through lead material against EGS4[18] data for different thickness of 1, 2, and 3 mm.

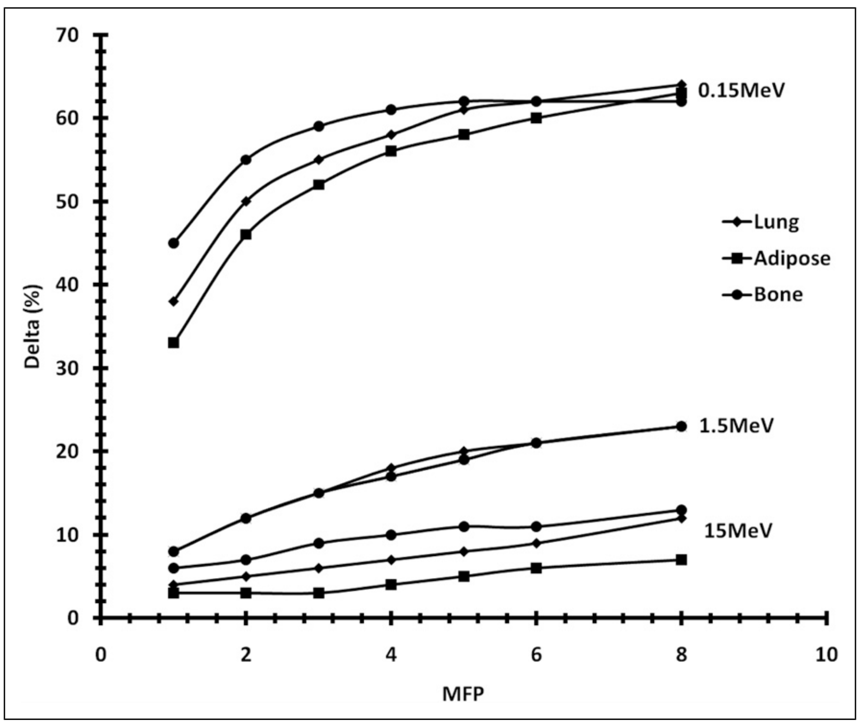

Figure 3. Difference of BUF simulated using Geant4, for isotropic source and spherical layers (extracted from ANSI/ANS-6.4.3[10,30]) and for parallel beam and parallel sheets, for Bone, Adipose, and Lung tissues for .15, 1.5, and 15 MeV photon source function of mean free path. (Delta(%) = 100*(1-Parallel/Isotropic)).

penetration through selected materials. At our knowledge, this is the first time using the Geant4 Monte Carlo simulation to fully compute the buildup factors for 20 human body tissues followed by parametric search of the well-known geometric progression formula and thus providing necessary materials for point kernel calculation applied to the High-Definition Reference Korean-Man (HDRK-Man).[13-15] Our previous work mainly focused on using GP parameters to compute BUFs, for all human tissues and organs, with a simple verification of Geant4 ability to predict the exposure buildup

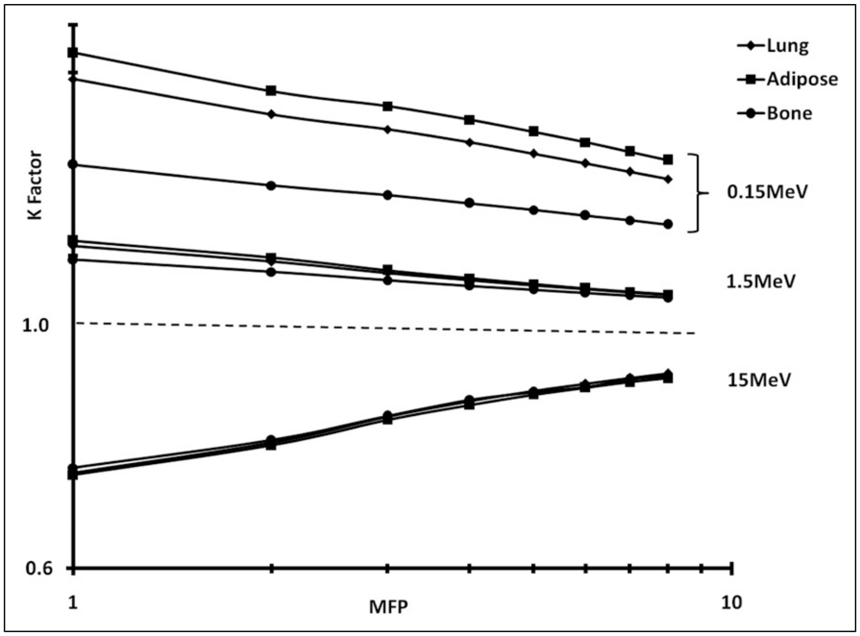

Figure 4. Linear dependency of the *K* factor function of mfp for Bone, Adipose, and Lung tissues for .15, 1.5, and 15 MeV isotropic spherical photon source.

factor of water for a photon energy of .1 MeV and penetration depths up to 10 mfp.[4] Also, the work carried out by Jarrah et al.[16] focused on the energy absorption buildup factor simulations of some ICRU tissue-like using MCNP5 code. Moreover, Kurudirek et al.[8] estimated the energy absorption buildup factors of some human tissues using GP parameters with a benchmark of MCNP6.1 simulation of EABF for soft tissue and water at .662, 1.173, and 1.25 MeV photon source, against GP fitting method. Also, the work carried out by Rafiei et al.[17] simulated the EABF for water and some tissue-equivalent materials for 356, 662, 1173, and 1332 keV gamma-ray energy up to depths of 10 mfp, using MCNPX code. Hence, this work can be considered as a continuation to those efforts, as we used Geant4 simulations of BUF for all HDRK-man tissues and the proposition of an in-house GP-like fitting method.

Our goal can be summarized as follows: (i) benchmark of Geant4 against EGS4 results for a given case study, (ii) perform BUF simulations, and (iii) search and propose of GP fitting parameters. Thus, after checking the ability of our computation to reproduce the transmission beam through Pb material previously published by Kato et al.,[18] we carried out the simulation of BUF for 3 standard photon energies .15, 1.5, and 15 MeV for some selected penetration depths (1–8 mfp, with a step of 1mfp). For each case study, we adopted and isotropic point source located at the center of 10 mfp sphere layered into 9 shells (the outer one has a thickness of 2 mfp to minimize backscattering effects). Then, we started by checking the linear behavior of the geometric progression factor function of mfp and terminated by a mathematical minimization procedure to search for the other GP fitting parameters. Finally, a verification of the ability of the fitting procedure to reproduce directly simulated data was carried out. The results of this study can be considered as an enhancement, to the large community of radiation physics researchers, of current point kernel-based techniques used to estimate the transmitted dose other than the dose distribution mapping for radiotherapy treatment planning and radiation diagnosis purposes based on the energy range and the medium thickness investigated.

As this study focused on simulating (Geant4) and computing (C++ fitting procedure) BUFs for HDRK-man tissue-like at only three photon energies of .15, 1.5, and 15MeV and for penetration depth up to only 8mfp, a straightforward extension of this work to cover energy and depth ranges, to be consistent with ANS standard tables, is feasible unless having the appropriate computing facilities (parallel works, large CPU workstations).

Methods

Elemental compositions of HDRK-man tissues and organs were taken from previous works[4,13] and given in Table 1.

After showing a brief introduction of BUF theoretical basics, we will describe the simulation and the derived fitting procedures carried out, as follows:

BUF Theoretical Frame

The effective transmitted dose, for an incident photon with energy E, through an absorber medium with x thickness in cm,

Table 2. Simulated Buildup GP Fitting 3 Parameters for Photon Point Isotropic Source in Spherical Geometry With Energy .15 MeV.

Medium	b	a	c
Lung	2.394	−.104	1.77262
Adipose	2.433	−.111	1.87942
Adrenal	2.403	−.106	1.79775
RBM	2.409	−.107	1.81289
GallC	2.403	−.106	1.79783
Heart	2.397	−.105	1.78048
Oral	2.404	−.107	1.80172
IntestineC	2.4	−.106	1.78946
ColonC	2.4	−.106	1.78919
Oesophagus	2.403	−.106	1.79763
Muscle	2.395	−.105	1.778
StomachC	2.4	−.106	1.78934
Kidneys	2.396	−.105	1.77838
Thyroid	2.372	−.101	1.72251
Liver	2.395	−.105	1.77655
HeartC	2.392	−.104	1.76816
Pancreas	2.401	−.106	1.79059
Spleen	2.395	−.105	1.77563
Skin	2.404	−.107	1.79904
Bone	2.243	−.063	1.4666

is defined as the ratio of the kerma measured in presence of the absorber, $\varepsilon(x,E)$, to that value in absence of the medium, $\varepsilon(0,E)$, at the same detector location[19]

$$T(x,E) = \frac{\varepsilon(x,E)}{\varepsilon(0,E)} \tag{1}$$

with

$$\varepsilon(x,E) = \sum_i \varphi(E_i) \times E_i \times \left(\frac{\mu_{en}}{\rho}\right)(E_i) \times k(E_i) \tag{2}$$

where $\varphi(E_i)$, $(\mu_{en}/\rho)(E_i)$, and $k(E_i)$ are the fluence in *photons/cm²*, the mass energy absorption coefficient in cm2/*g* (available from Hubbell and Seltzer[20] and XCOM program[21]) and the effective dose per air kerma free-in-air conversion coefficient in *Sv/Gy* (available from ICRP74[22,23] and ICRP116[24] with the adoption of rotational exposure scenario), respectively.

Also, we can rewrite *T(x,E)* in the following way

$$T(x,E) = B(x,E) \times \exp(-\mu(E) \times x) \tag{3}$$

where *B(x, E)* and $\mu(E)$ refer to BUF and linear attenuation coefficient, respectively.

Thus, using previous equations, we can deduce BUF value for a given E and x as follows

$$B(x,E) = \frac{\varepsilon(x,E)}{\varepsilon(0,E)} \times \exp(-\mu(E) \times x) \tag{4}$$

Simulation Procedure

Mainly managed and developed by the CERN organization (European Center for Nuclear Research), the versatile Monte Carlo simulation platform Geant4 has well known and verified capabilities able to mimic the transport of the majority of particle types (photons electron, ion, neutron, short-lived particle, etc…), covering large range of particle source energy (from eV to TeV) and modeling complicated and realistic setup configurations. It was used to compute mass attenuation coefficients leading to indirectly benchmark ANSI data based on calculated GP fitting parameters.[25] In our previous work,[4] we attempted to initiate a direct computation of buildup factors of water medium. Here, we advanced such computation for 20 human tissues and organs of the HDRK-man anthropomorphic phantom. Moreover, Table 1 illustrates their density and elemental composition as fully described elsewhere.[4,13] During this work, Geant4 version 10.5 was used to simulate the transport of gamma rays isotropically emitted from a point source through a given medium. The geometry of the problem consists of a monoenergetic point source located at the center of ten concentric spheres, separated by one mfp for each step. As, we were limited to only eight mfp thickness, for all studied media and three photon energy of .15, 1.5, and 15 MeV and in order to minimize the boundary effect, we added an outer sphere with two mfp for each case study. We tracked gamma rays through the setup to compute the photon flux crossing each shell/surface of the medium. Then, to be more consistent, we internally (within *SteppingAction* class) converted each crossed photon energy into kerma using the equation (2) and based on the *Log-Log* interpolations of *k(E)* and *μ(E)*, as described above. Such procedure was repeated with replacing the medium with air in order to accomplish the ratio formula given by equation (4). Finally, we can determine the overall BUF database for all studied cases including data extracted (*ε(x,E)* and *ε(0,E)*) numbered as $20 \times 3 \times 8 \times 2 = 960$ values. In this study, the buildup factor was computed for 10^9 gamma rays by run. We activated all the physical processes for electrons and photons (Photoelectric, Compton, Pair production effects for photon and Ionization, Bremsstrahlung for electron). We used the *G4EmStandardPhysics_option3* built-in physics library with a cutoff of 1 keV for electrons and photons. The overall statistical uncertainty does not exceed 1 % for all runs.

There are three geometrical configurations used for this work. As seen in Figure 1, the left one describes the setup used to verify again our simulation regarding to the data found by EGS4 code[18] to compute the effective transmitted dose through different thickness of lead of photon with different energies. Also, a visualization of the actual BUF simulation scenario by Geant4 is shown in the middle of Figure 1. Finally, the right part of Figure 1 shows the monodirectional parallel-plane source impinging on stratified shields, used for comparison purposes.

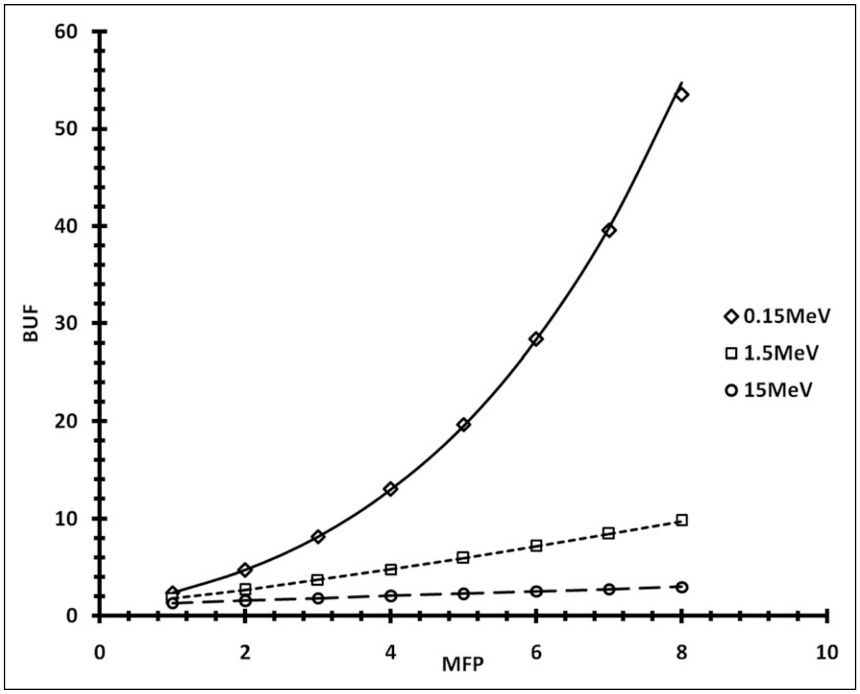

Figure 5. Simulated and fitted BUF for Heart tissue for .15, 1.5, and 15 MeV isotropic spherical photon source.

Fitting Procedure

According to the GP fitting method, we have

$$\frac{B(X)-1}{B(1)-1}=\frac{K^X-1}{K-1} \quad \text{, if } K\neq 1 \tag{5}$$

if $K = 1$, the second term of the equality will be reduced to X, only.

X is expressed in mean free paths: $1mfp = 1/(\mu\times\rho)$, with μ and ρ correspond to the linear attenuation coefficient and the mass density.For X ≤ 40 mfp

$$K = c\times X^a + d\times\frac{\tanh((X/X_k)-2)-\tanh(-2)}{1-\tanh(-2)} \tag{6}$$

where, c, a, d, X_k and $b = B(1)$ are the 5 fitting parameters.

As described by Harima,[7,27] for $X \leq X_k$ we can limit our study to the first part including the linear behavior of *Log(K)* as a function of *Log(x)*, as we have

$$\text{Log}(K) = a\times\text{Log}(X)+\text{Log}(c) \tag{7}$$

Moreover, as we limited our study to penetrations up to 8 mfp (medical applications) and due to the fact that the second term of the right side of equation (6) was included in order to take into account the *Log(K)* deviation from linearity beyond 15 mfp up to about 40 mfp with a tangent-hyperbolic function, we are concerned with only 3 fitting parameters (a, b, and c) along this procedure. Therefore, the buildup factor for a given isotropic point source located at the center of spherical material geometry will be fitted using the following formula

$$B(X,E) = 1+(b-1)\times\frac{(cX^a)^X-1}{cX^a-1} \tag{8}$$

Thus, our main goal is focused on searching the 3 fitting parameters: *a*, *b,* and *c*, for 20 human tissues and organs, in spherical geometry setup and for isotropic point source of gamma-ray with energy: .15, 1.5, and 15 MeV.

Results and Discussion

Geant4 Verification

Figure 2, shows a global good agreement between actual results and previously published data by Kato et al.[18] for the effective transmission dose through 1, 2, and 3 mm Pb shield thickness, as function of photon source energy. Also, the effect of 88 keV transmission corresponding to the characteristic peak of lead, is clearly seen, as we have the corresponding linear attenuation coefficient of lead material at 87.9 and 88.1 keV of 21.7 and 87.2 cm^{-1}, respectively.

Furthermore, we confirmed previous conclusion conducted by Rasouli et al. and Lin et al.[28,29] claiming that the effect of changing the geometry setup from parallel plane to spherical layer and the source from unidirectional plane parallel beam to isotropic point source can be explained by the boundary effect.

Figure 3, shows a large deviation decreasing from .15 to 15 MeV photon energy for tissues having low, medium, and high equivalent atomic number (Lung, Adipose, and Bone) as function of mfp. Such decrease can be explained by the close behavior of both setups at large thickness, as the mfp becomes

Table 3. Simulated buildup GP fitting 3 Parameters for Photon Point Isotropic Source in Spherical Geometry With Energy 1.5 MeV.

Medium	b	a	c
Lung	1.777	−.053	1.22571
Adipose	1.78	−.059	1.24002
Adrenal	1.776	−.054	1.22698
RBM	1.777	−.056	1.23067
GallC	1.776	−.054	1.22727
Heart	1.775	−.054	1.22533
Oral	1.776	−.055	1.22781
IntestineC	1.776	−.054	1.22635
ColonC	1.776	−.054	1.22564
Oesophagus	1.776	−.055	1.22807
Muscle	1.775	−.054	1.22503
StomachC	1.776	−.054	1.22471
Kidneys	1.775	−.054	1.22586
Thyroid	1.772	−.051	1.21687
Liver	1.775	−.053	1.22312
HeartC	1.775	−.054	1.22378
Pancreas	1.776	−.054	1.22622
Spleen	1.775	−.053	1.22351
Skin	1.776	−.055	1.22799
Bone	1.760	−.041	1.18892

Table 4. Simulated buildup GP fitting 3 Parameters for Photon Point Isotropic Source in Spherical Geometry With Energy 15 MeV.

Medium	b	a	c
Lung	1.33	.109	.741611
Adipose	1.327	.107	.738369
Adrenal	1.328	.107	.738578
RBM	1.328	.107	.737985
GallC	1.329	.107	.738172
Heart	1.329	.109	.734879
Oral	1.328	.107	.738434
IntestineC	1.329	.11	.734434
ColonC	1.329	.11	.734107
Oesophagus	1.329	.111	.73406
Muscle	1.329	.11	.735559
StomachC	1.329	.112	.732928
Kidneys	1.329	.112	.732986
Thyroid	1.328	.109	.737708
Liver	1.329	.110	.734528
HeartC	1.330	.109	.735474
Pancreas	1.329	.110	.735011
Spleen	1.330	.111	.734022
Skin	1.329	.111	.734825
Bone	1.332	.101	.749609

larger at higher photon energy. Also, the effect of *Zeq*, for each energy, on such deviation as function of penetration, is seen resulting to the variation of bremsstrahlung and multiple scattering effects.

Table 5. Buildup Correction Factor For Plane Parallel and Plane Isotropic Distribution Accordingly to Isotropic Point Source for Water Medium.

E(MeV)	Thickness(mfp)	Iso_Plane/ Iso_Sphere	Para_Plane/ Iso_Sphere
0.15	.5	1.72	1.30
	1	1.65	1.00
	2	1.63	.72
	3	1.60	.57
	4	1.58	.48
	5	1.55	.43
	6	1.53	.39
	7	1.53	.36
	8	1.54	.34
1.5	.5	1.38	1.07
	1	1.44	1.01
	2	1.48	.92
	3	1.51	.87
	4	1.52	.84
	5	1.53	.82
	6	1.56	.81
	7	1.56	.80
	8	1.59	.80
15	.5	1.15	1.10
	1	1.16	1.09
	2	1.18	1.09
	3	1.19	1.08
	4	1.19	1.08
	5	1.20	1.07
	6	1.20	1.07
	7	1.20	1.06
	8	1.21	1.06

Fitting Parameters

Deducing of the three fitting parameters from tabulated BUF was carried out using an in-house C^{++} program able to proceed with the multidimensional nonlinear fitting opportunity of the GNU Scientific Library (GSL).[31] Moreover, Figure 4 confirms the hypothesis of the linear dependency of the *K* parameter function of mfp, for the range in concern. From the same figure, we can see that such parameter continues to be more and more unique for all tissues and organs when the energy increased, which is obvious.

It can be observed that the value of K can be greater than one with downward trend or less than one with upward trend, as function of the source energy. For .15 and 1.5 MeV photon energy, the effect of backscattering at distance closer to the source is dominant, however, for 15 MeV, the dominant contribution concerns the bremsstrahlung effect. Also, Tables 2–4 tabulated found GP fitting 3 parameters for photon point isotropic source in spherical geometry with energy .15, 1.5, and 15 MeV. We remarked the slow variation (can be of the order of one hundredth) of each parameter for a given energy.

In order to check the fitting procedure, we plotted, as an example, fitted and directly simulated BUF for Heart organ. As an overall deviation of BUF fitted to directly simulated values, for all studied cases, we found an average value of .5 ± .6 % (Figure 5).

Finally, we can consider that the actually provided parameters database can be of great interest to medical physicist community, however, we were limited to only a thickness of eight mfp and photon particles and energy no more than 15 MeV. Also, our next work will be focused on the simulations of BUF for spherical multilayers.

Moreover, the implemented spherical geometry, here, is not similar to that used in brachytherapy or open radionuclide sources, where quasi-infinite media are employed during dose delivery and calculation. Basically, these BUFs differ from the point spread functions used in kernel-based algorithms to calculate dose under realistic setup and conditions.[32,33] Meanwhile, Table 5 shows the buildup correction factor when passing from isotropic point source to plane parallel or isotropic planar source distribution, where we extracted data from Takeuchi and Tanaka[33] for water medium.

Conclusion

Transmission photon buildup factor for 20 human tissues and organs has been simulated by Geant4 Monte Carlo toolkit for point isotropic source included within concentric spherical layers with different thickness. Covered photon source energy and thickness range were .15–15 MeV and 1–8 mfp, respectively. Among the analysis of simulated BUF values, it was verified that the K parameter behaves linearly as function of the thickness (in *Log-Log* scale) allowing us to derive a 3 fitting parameters according to the GP method for all studied cases. Such parameterization accurately reproduced the directly simulated BUF with an error less than 1 %. Nevertheless, the current study is limited to previous studied cases, the straight forwardly extension to other particles (neutron, beta, alpha…) and other source geometry and energy can be carried out. It is the main goal of this work to propose a BUF data base able to improve the accuracy of practical tools for medical imaging and treatment planning based on point kernel codes.

Declaration of Conflicting Interests

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ORCID iD

Abdulrahman A. Alfuraih https://orcid.org/0000-0003-3010-0136

References

1. Ogundare FO, Olarinoye IO, Obed RI. Estimation of patients' organ and conceptus doses from selected x-ray examinations in two Nigeria x-ray centers. *Radiat Prot Dosim*. 2009;132(4):395-402.
2. Mann KS, Korkut T. Gamma-ray buildup factors study for deep penetration in some silicates. *Ann Nucl Energy*. 2013;51:81-93.
3. Singh PS, Singh T, Kaur P. Variation of energy absorption buildup factors with incident photon energy and penetration depth for some commonly used solvents. *Ann Nucl Energy*. 2008;35:1093-1097.
4. Kadri O, Alfuraih A. Photon energy absorption and exposure buildup factors for deep penetration in human tissues. *Nucl Sci Tech*. 2019;30:176.
5. Sardari D, Abbaspour A, Baradaran S, Babapour F. Estimation of gamma- and x-ray photons buildup factor in soft tissue with monte carlo method. *Appl Radiat Isot*. 2009;67:1438-1440.
6. Shimizu A, Hirayama H. Calculation of gamma-ray buildup factors up to depths of 100 mfp by the method of invariant embedding, (II) improved treatment of bremsstrahlung. *J Nucl Sci Technol*. 2003;40:192-200.
7. Harima Y, Sakamoto Y, Tanaka S, Kawai M. Validity of the geometric progression formula in approximating gamma ray buildup factors. *Nucl Sci Eng*. 1986;94:24-35.
8. Kurudirek M, Kurucu Y. Estimation of energy absorption buildup factors of some human tissues at energies relevant to brachytherapy and external beam radiotherapy. *Int J Radiat Biol Sep*. 2019;95:1685-1695.
9. Mehmet B, Kurudirek M. Radiological properties of healthy, carcinoma and equivalent breast tissues for photon and charged particle interactions. *Int J Radiat Biol*. 2018;94(1):70-78.
10. American Nuclear Society. *Gamma Ray Attenuation Coefficient and Buildup Factors for Engineering Materials*. Report ANSI/ANS-6.4.3, USA (1991).
11. Agostinelli S, Allison J, Amako K, et al. Geant4-a simulation toolkit. *NIMA*. 2003;506(3):250-303.
12. Allison J, Amako K, Apostolakis J, et al. Recent developments in Geant4. *NIMA*. 2016;835(1):186-225.
13. Kim CH, Choi SH, Jeong JH, Lee C, Chung MS. HDRK-Man: a whole-body voxel model based on high-resolution color slice images of a Korean adult male cadaver. *Phys Med Biol*. 2008;53(15):4093-4106.
14. Alfuraih A, Kadri O, Alzimami K. Investigation of SPECT/CT cardiac imaging using Geant4. *Nucl Sci Tech*. 2018;29:7.
15. Kadri O, Manai K, Alfuraih A. Monte Carlo study of the cardiac absorbed dose during x-ray examination of and adult patient. *Radiat Prot Dosim*. 2016;171(4):431-437.
16. Jarrah I, Radaideh MI, Kozlowski T, Rizwan-uddin R. Determination and validation of photon energy absorption buildup factor in human tissues using Monte Carlo simulation. *Rad Phys Chem*. 2019;160:15-25.
17. Rafiei MM, Tavakoli-Anbaran H, Kurudirek M. A detailed investigation of gamma-ray energy absorption and dose buildup factor for soft tissue and tissue equivalents using Monte Carlo simulation. *Rad Phys Chem*. 2020;177:109118.

18. Kato H. Effective dose transmission of diagnostic x-rays through concrete and lead shields. *Jpn Soc Radiol Technol*. 2003;59(8):965-975.
19. Kharrati H, Agrebi A, Karaoui M-K. Monte Carlo simulation of x-ray buildup factors of lead and its applications in shielding of diagnostic x-ray facilities. *Med Phys*. 2007;34:1398-1404.
20. Hubbell JH, Seltzer SM. Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients from 1 keV to 20 MeV for Elements Z = 1 to 92 and 48 Additional Substances of Dosimetric Interest. NISTIR 5632. (July 2004).
21. Berger MJ, Hubbell JH. *XCOM: Photon Cross Sections Database. Web Version 3.1*. Gaithersburg, MD 20899, USA: National Institute of Standards and Technology, available at http://physics.nist.gov/xcom, August 1999. Originally published as NBSIR 87-3597, XCOM: Photon Cross Sections on a Personal Computer (July 1999) 1987-1999.
22. ICRP. Conversion coefficients for use in radiological protection against external radiation. International Commission on Radiological Protection; 1996, ICRP Publication 74. Ann ICRP 26(3-4).
23. Endo A. Calculation of fluence-to-effective dose conversion coefficients for the operational quantity proposed by ICRU RC26. *Radiat Prot Dosim*. 2017;175:378-387.
24. ICRP. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. *International Commission on Radiological Protection, ICRP Publication 116*. ICRP Publication 116, Ann. ICRP 40(2-5).
25. Harima Y. A historical review and current status of build-up factor calculations and applications. *Radiat Phys Chem*. 1993;41:631-672.
26. John A, Laurent G, Akinori K, et al. The Geant4 visualization system-a multi-driver graphics system. *Int J Model Simul Sci*. 2013;04(supp 01):1340001.
27. Harima Y, Kurosawa N, Sakamoto Y. Parameter search of geometric-progression formula for gamma-ray isotropic point source buildup factors up to depths of 100 mfp, including contribution of secondary radiations. *Prog Nucl Sci Tech*. 2014; 4(4):548-552.
28. Rasouli A, Tavakoli-Anbaran H. Study of relation between the gamma flux buildup factors and source geometry by M-C simulation. *Nucl Sci Tech*. 2017;28:136.
29. Lin UT, Jiang SH. A dedicated empirical formula for γ-ray buildup factors for a point isotropic source in stratified shields. *Rad Phys Chem*. 1996;48(4):389-401.
30. Durani L. *Update to ANSI/ANS-6.4.3-1991 for low-Z and compound materials and review of particle transport theory*. UNLV Theses, Dissertations, Professional Papers, and Capstones, 43; 2009.
31. Galassi M, Davies J, Theiler J, et al. *GNU Scientific Library Reference Manual*. 2nd ed. Godalming, UK: Network Theory Ltd, 0954161734
32. Trubey DK, Harima Y. *New Buildup Factor Data for Point Kernel Calculations*. United States: American Nuclear Society; 1987.
33. Takeuchi K, Tanaka Si. Buildup factors of gamma rays including bremsstrahlung and annihilation radiation for water, concrete, Iron, and Lead. *Nuclear Sci Eng*. 1984;87(4): 478-489.