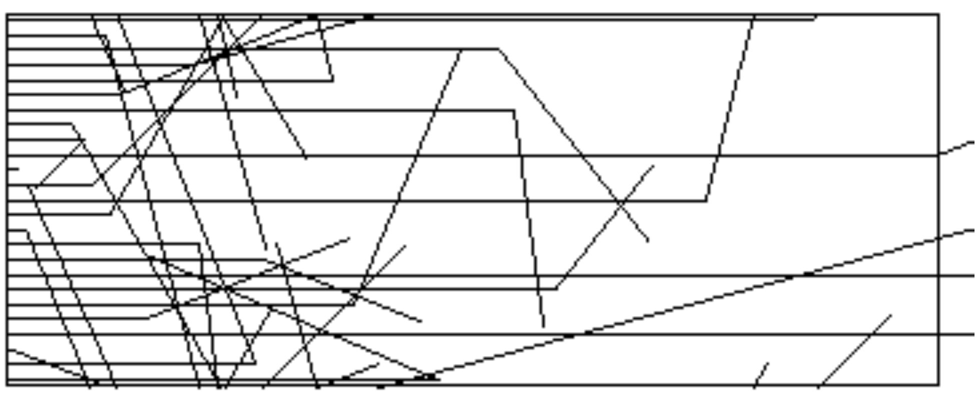
Instructor's Guide

for

MacDose

Version 2.1

December 31, 1989



Russell K. Hobbie
School of Physics and Astronomy
University of Minnesota
Minneapolis, MN 55455
(612) 62608920
hobbie@umn.edu

Please send corrections or suggestions to

Russell K. Hobbie
University of Minnesota
School of Physics and Astronomy
116 Church St. SE
Minneapolis, MN 55455

(612) 626-8920
hobbie@umn.edu

ACKNOWLEDGEMENTS

MacDose is based on a simulation program written originally by Tao-qu Chen as part of the requirements for a Master of Science degree in physics. It has also been made possible by an equipment grant from Apple Computer through Project MinneMac.

Table of Contents

License Agreement, Warranties and Limitations

MacDose is designed for teaching concepts of radiological physics. It is not accurate enough to be used for calculations of dose or buildup factors.

Introduction

This Instructor's Guide reproduces the exercises in the *User's Manual and Exercises for MacDose* and provides the results which I obtained when I tried them. Since many of the results are random, you will get slightly different values unless you use the same random number seed. However, these answers show the intent of each exercise.

The statement of the problem in the Exercise Manual is shown in italics.

Random Numbers

The simulation in MacDose is based on a series of "random" numbers generated by the computer. These are actually a sequence of pseudo-random numbers, generated by a mathematical algorithm. One starts with a number called the "seed. Each calculation of a pseudo-random number in the sequence also generates the seed for the next calculation. If one starts with the same seed, the same sequence of pseudo-random numbers is generated. With a different seed one gets a different sequence. The initial seed used in MacDose is the number 2. The seed can be changed in the **Set Parameters** dialog.

Photon Interactions

Three types of photon interactions are simulated: the photoelectric effect, Compton scattering, and pair production. In the photoelectric effect, the photon is absorbed by an atom and an electron emerges. Using an (in, out) notation, this can be called a (γ, e) reaction. Compton scattering is a $(\gamma,\gamma' e)$ reaction: a photon is incident and both a photon and electron emerge. Pair production is a (γ,e^+e^-) reaction. The program ignores coherent scattering, which is a (γ,γ) reaction, since coherent scattering does not produce any ionizing electrons and hence does not contribute to the dose. Coherent scattering occurs at energies where the photoelectric effect is important.

The simulation of Compton scattering is reasonably accurate. The Compton cross section, multiplied by solid angle $2\pi \sin\theta\, \Delta\theta$ for scattering into the cone $(\theta, \Delta\theta)$, is divided by the total Compton cross section and compared to a random number in the range (0, 1) to determine which of 24 angular bins contains the scattered photon.

Photoelectric effect and pair production simulations are less accurate. All photoelectrons are emitted in the forward direction. This gives an inaccurate simulation when the length of the sample along the beam is comparable to the range of the photoelectron.

For the pair production simulation, the positron is assumed to have kinetic energy distributed randomly and uniformly between 0.3E and 0.8E, where E is the sum of the kinetic energies of the electron and positron, $E = h\nu - 2m_ec^2$. Electrons all are assumed to travel in straight lines whose length is equal to the range calculated in the Continuous-Slowing-Down-Approximation .

Subsequent Interactions

MacDose allows the student to simulate subsequent interactions of photons that are produced in the interactions. These can make a very significant contribution to the total dose. The program has been written so that the primary interactions use the same sequence of random numbers whether or not subsequent interactions are being considered. Thus, if the student makes two runs, one with and one without subsequent interactions, and remembers to start with the same random number seed, the pattern of primary interactions will be the same. This feature makes it much easier to investigate the effects of subsequent interactions.

Exercises

Exercise 1. The kinds of photon interactions

This exercise introduces you to the three fundamental kinds of photon interactions: the photoelectric effect, Compton scattering, and pair production. You will discover that each dominates in a particular energy range. (Coherent scattering is not included in the simulation, since it does not contribute to the dose.)

Photon tracks are drawn as narrow lines; electron tracks are thicker. On a color monitor or printer, the electron tracks are red. In the photoelectric effect, the photon track stops. An electron track emerges, but unless the sample is microscopic in dimensions, the electron moves such a short distance that its track is not seen. In Compton scattering, a scattered photon emerges at some angle. For small values of length along the beam, the recoil electrons can be seen. In pair production two thick tracks emerge, one for the electron and one for the positron.

The program is initially set to simulate 100 keV (1.00 E5 eV) photons. Run two or three times at this energy, one screen at a time. Print each screen after you have run it, using ***Print Current Results****. Identify photoelectric and Compton interactions. Estimate the fraction of the interactions of each kind.*

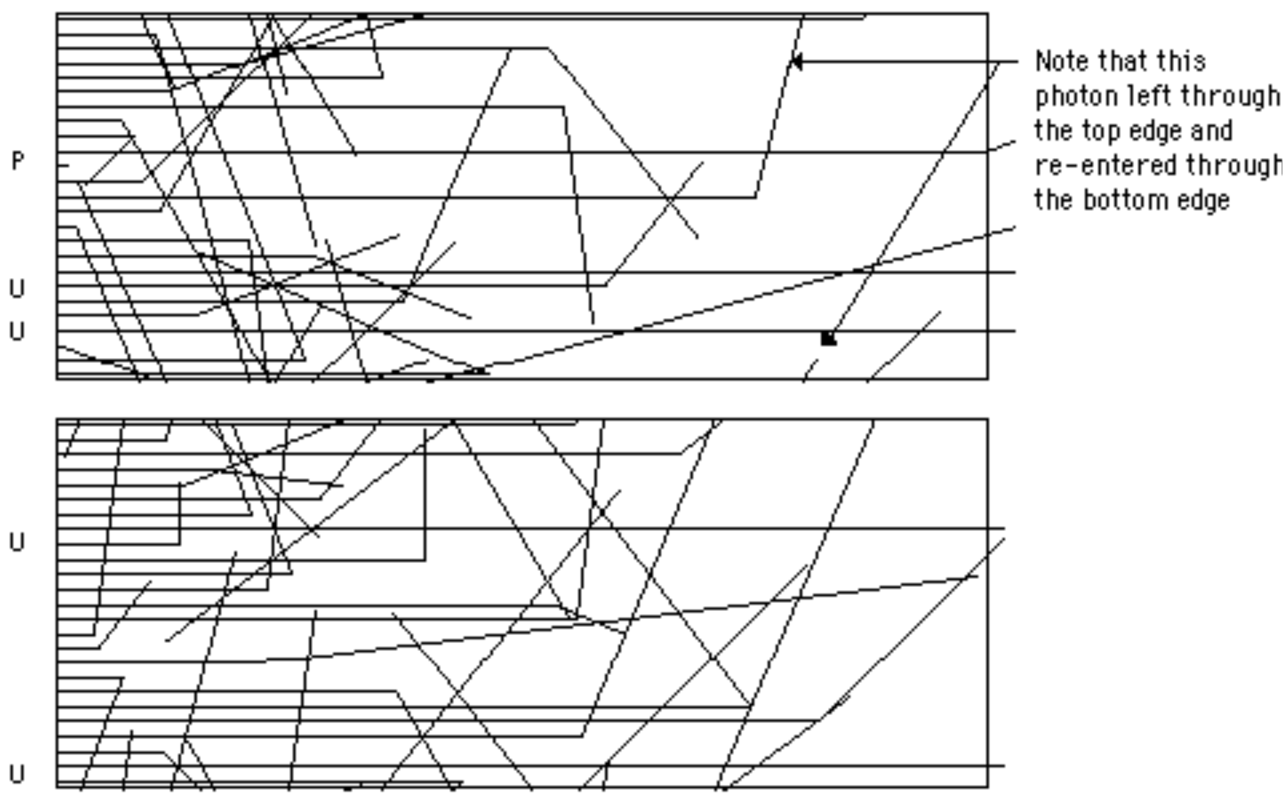


Figure 1. Two simulations with 100-keV photons. All are Compton scattering except for P, which is photoelectric effect and U, which is unattenuated.

For 100-keV photons, shown in Fig. 1, 4 out of 50 (8%) are unattenuated. Only 1 out of 46 is photoelectric effect; the rest are Compton scattering. (In some cases the photons leave the top or bottom edge of the sample; they enter again from the other edge, to represent interactions which took place in the medium above or below the sample.)

*Repeat the same process for 20-keV (2.00 E4) and 10-MeV (1.00 E7) photons. Note how the fraction of interactions of each kind changes with energy. You can change the energy with **Set Parameters** in the **Program** menu.*

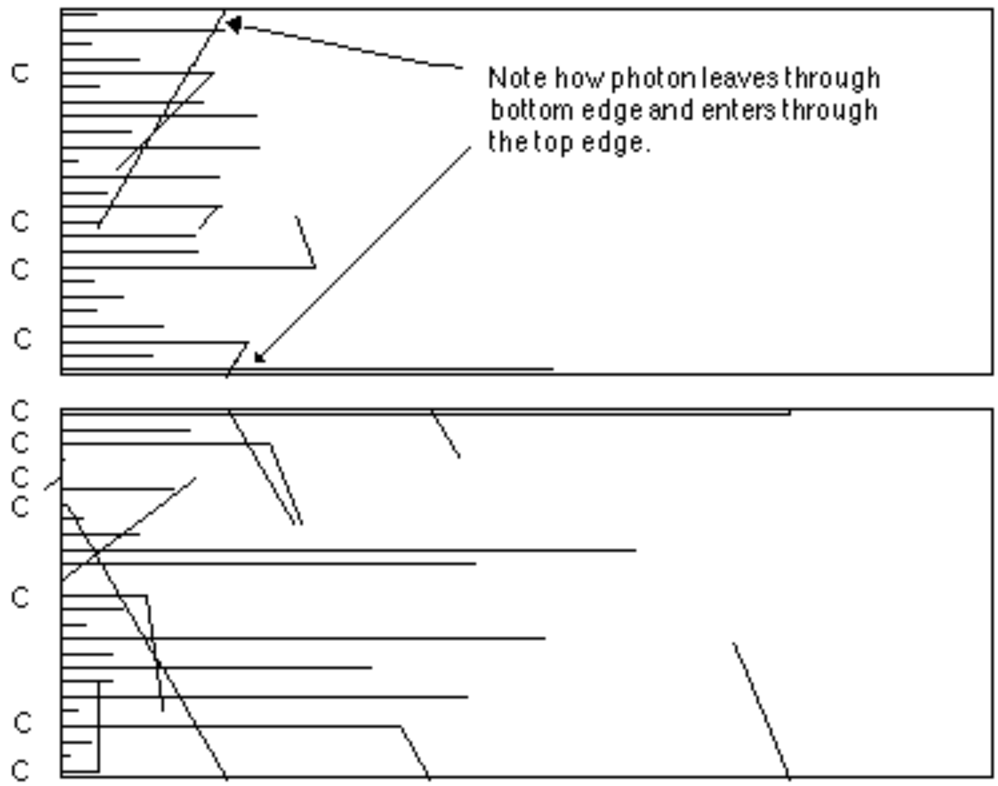


Figure 2. Two simulations for 20-keV photons. All interactions are the photoelectric effect, except for those labelled C, which are Compton scattering.

Figure 2 shows two runs at 20 keV. The photoelectric interactions show no scattered photons. The Compton-scattered photons are clearly visible. Out of 50 interactions, 11 (22%) are Compton scattering and 39 (78%) are photoelectric effect. None of the photons penetrate the 0.1-meter-long sample.

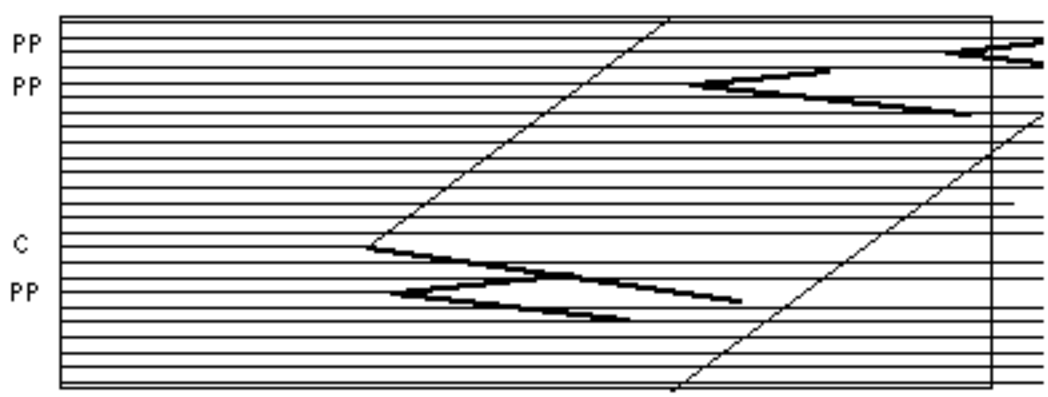


Figure 3a. The first of two simulations with 10-MeV photons. C marks Compton scattering. PP shows pair production. The electrons and positrons have lines of double thickness. On a color display or printer (such as an Imagewriter II with a color ribbon) they are red.

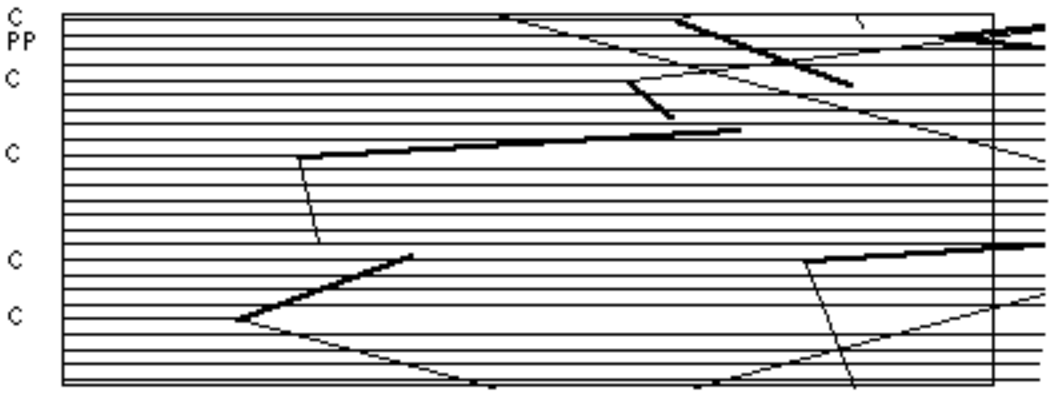


Figure 3b. The second of two simulations with 10-MeV photons. C marks Compton scattering. PP shows pair production. The electrons and positrons have lines of double thickness. On a color display or printer (such as an Imagewriter II with a color ribbon) they are red.

At 10 MeV, shown in Fig. 3, 80% are unattenuated in 0.1 meter. Of the 10 that interact, 40% are pair production and 60% are Compton scattering.

Exercise 2. The random nature of photon interactions.

You can explore the random nature of the photon interactions. Different screens look different. You can explore quantitatively the fluctuations in the number of photons emerging from the sample unattenuated.

Set the energy at 250 keV. ***Run One Screen*** *10 times and tabulate the fraction unattenuated. Plot a histogram of the fraction unattenuated, and calculate the mean and the standard deviation. (If you have access to statistical software, you could open a Log File to record these results. However, each run must be done using* ***Run One Screen****, so that the results are reset and each individual run is shown in the Log File.)*

Dose Simulation Log File on Sun, Jul 17, 1988 at 2:46:40 PM

Incident energy =	250 keV	
Sample length along beam =	1.00e-1	meters
Thickness perp to screen =	1.00e-1	meters

Subsequent interactions Ignored

Number	Fraction Unattenuated
2.50e+1	0.00
2.50e+1	0.00
2.50e+1	0.28
2.50e+1	0.32
2.50e+1	0.28
2.50e+1	0.24
2.50e+1	0.20
2.50e+1	0.16
2.50e+1	0.32
2.50e+1	0.48

Mean =	0.23
Std. Deviation =	0.15

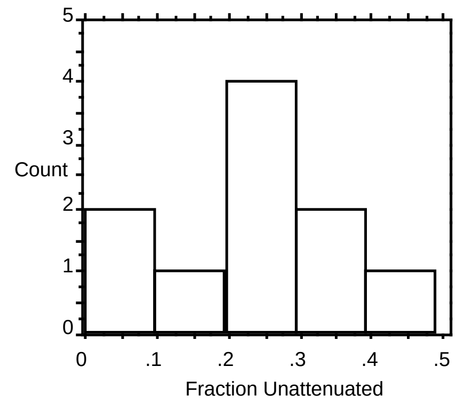


Figure 4. Histogram of the number of simulations vs. the fraction unattenuated.

*Turn on the Log File (or open a different one, if you had one open for the preceding task). Run 1000 photons (****Run a Given Number of Photons*** *with the default value.) What is the fraction unattenuated? Use the Log File to plot the fraction attenuated vs. the number of photons in the simulation. Note that the fraction unattenuated fluctuates about the average value, and that the size of the fluctuations decreases as the number of photons in the simulation increases.*

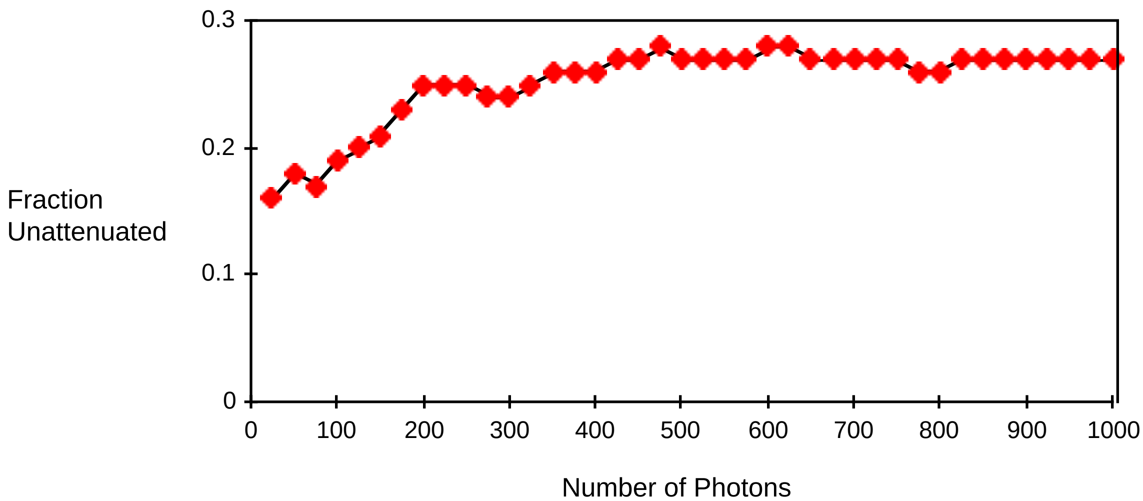


Figure 5. The fraction of photons unattenuated vs. the total number of photons in a sequence of runs of 25 photons each. The fraction fluctuates around a value given by $e^{-\mu L}$.

In Fig. 5, notice how the fraction unattenuated settles down and fluctuates about some value, with the size of the fluctuations becoming smaller as the number of photons increases. Though not asked for in the exercise, the result for 10,000 incident photons is shown in Fig. 6. This was a different series of random numbers, and the details of the curve are different.

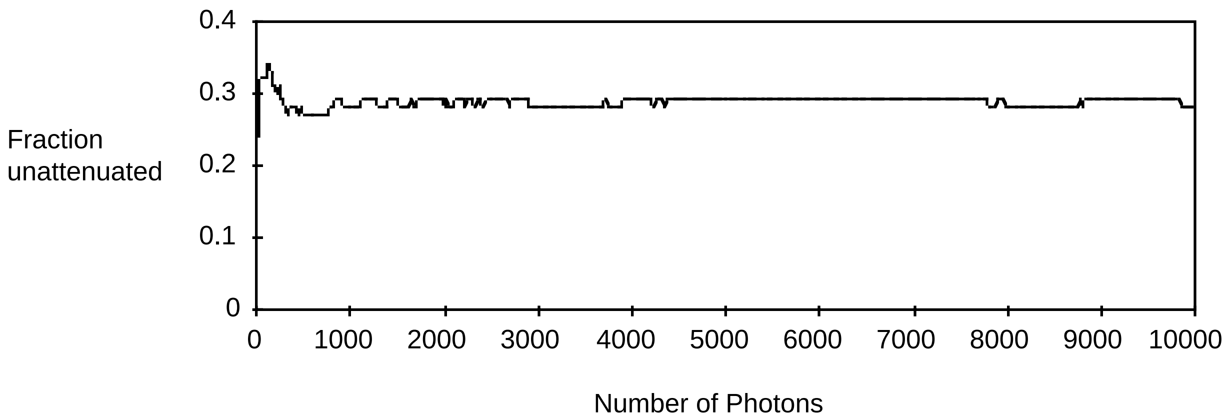


Figure 6. The fraction of photons unattenuated vs. number of photons for a much longer simulation.

The Results window shows the value of the attenuation coefficient. How does $e^{-\mu L}$ compare to the average fraction unattenuated for the ten runs (250 photons)? To the value for 1000 photons?

$e^{-(\mu/\rho)\,\rho L} = e^{-(0.0127)(1000)(0.1)} = e^{-1.27} = 0.28$ The fluctuations are about this value.

Vary the thickness of the sample (length along the beam). Plot the fraction unattenuated vs. thickness.

Here are the results of simulations with different thicknesses. Fig. 7 shows linear and semi-log plots of the results. Because the interactions are random, the unattenuated fraction fluctuates about $e^{-\mu L}$.

Thickness (m)	Fraction unattenuated
0.00	1.00
0.01	0.88
0.02	0.77
0.03	0.65
0.04	0.59
0.05	0.52
0.06	0.44
0.07	0.42
0.08	0.34
0.09	0.30
0.10	0.28

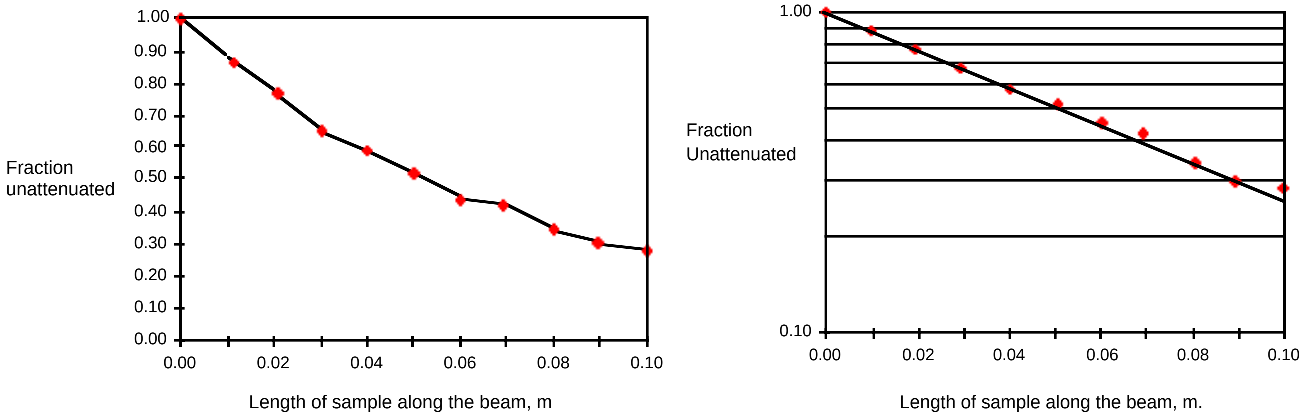


Figure 7. Fraction of photons unattenuated vs. thickness of a sample along the beam , in linear and semi-log plots. Because of the random interactions, the fraction fluctuates about the line given by $e^{-\mu L}$.

Exercise 3. The difference between energy transferred and energy absorbed.

Set the energy at 60 keV. Use the default 0.1-m thick sample. Run one screen and record the Energy Transferred to electrons and the Energy Absorbed in the sample. Are they the same?

Run one screen again. Are the numbers the same as the previous set? Why or why not? Are they the same as each other? Why or why not?

For my first run I obtained Energy Transferred to Electrons = Energy Absorbed in the sample = 2.39 x 10^{-14} J. They are the same because the length of the sample is large compared to the range of the electrons, so all of the energy transferred to electrons is absorbed in the sample. Fig. 8 is a picture of one screen. The range of the recoil electrons is too small to be seen.

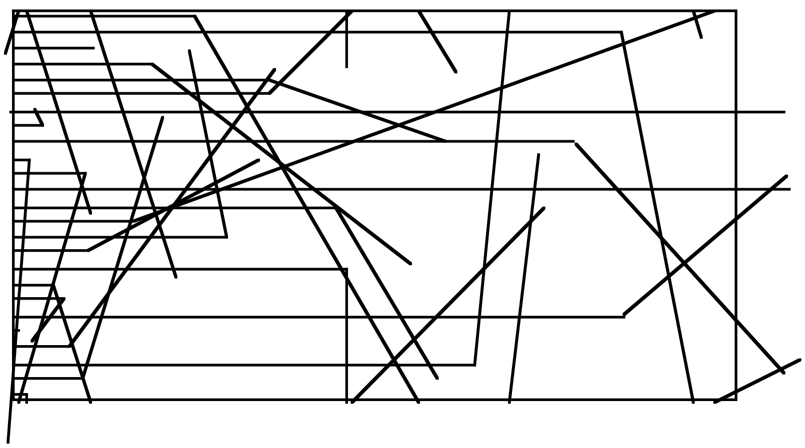


Figure 8. A screen showing the interactions. The electron range (distance travelled) is negligible compared to the length of the sample along the beam.

When I repeated the simulation with a different seed, I got different values: Energy Transferred to Electrons = Energy Absorbed in the sample = 1.44 x 10^{-12} J. The two runs differed because the interactions are random, and each group of photons gives slightly different results. Fig. 9 shows a histogram of the energy transferred to electrons in a series of 25-photon runs.

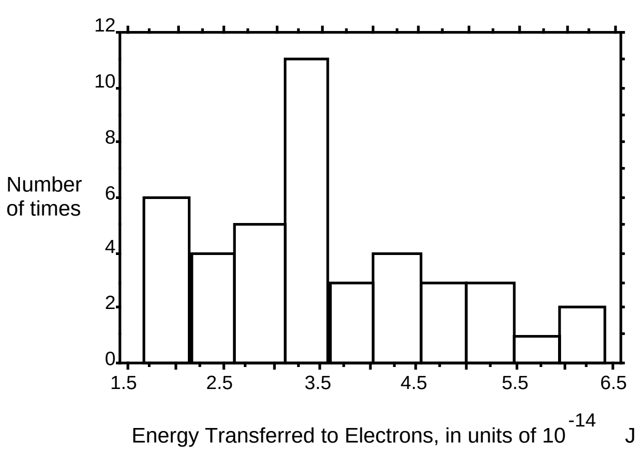


Figure 9. Histogram of the number of occurrences vs. the Energy Transferred to Electrons, for a series of simulations with 60-keV photons striking a sample of length 0.1 m along the beam.

Repeat this for two single-screen runs with 2 MeV photons and the same sample thickness. Explain what you observe now.

In this case, the results are very different. One simulation is shown In Fig. 10. Many photons pass through the sample.

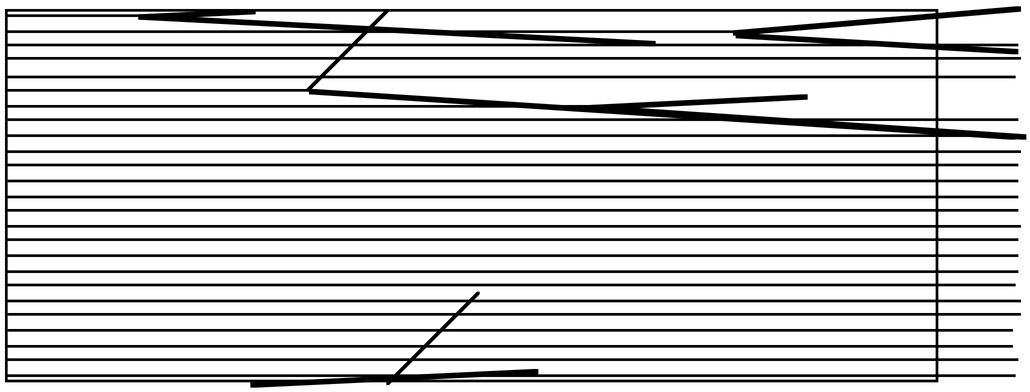


Figure 10. Simulation for 2-MeV photons in a 0.1-m thick sample.

Those that interact do so by either Compton scattering or pair production. A significant fraction of the electrons leave the sample with appreciable kinetic energy. This energy is not absorbed in the sample, so the energy transferred to the electrons is greater than the energy absorbed in the sample. For this screen the energy transferred to electrons was 12.1 x 10^{-12} J, and the energy absorbed in the sample was only 8.66 x 10^{-12} J, 72% of the former. When I repeated this with another single-screen run, I got different values: 5.63 x 10^{-12} and 2.25 x 10^{-12}, a 40%ratio. Fig. 11 shows a histograms of the Energy Transferred to electrons and the Energy Absorbed in the sample.

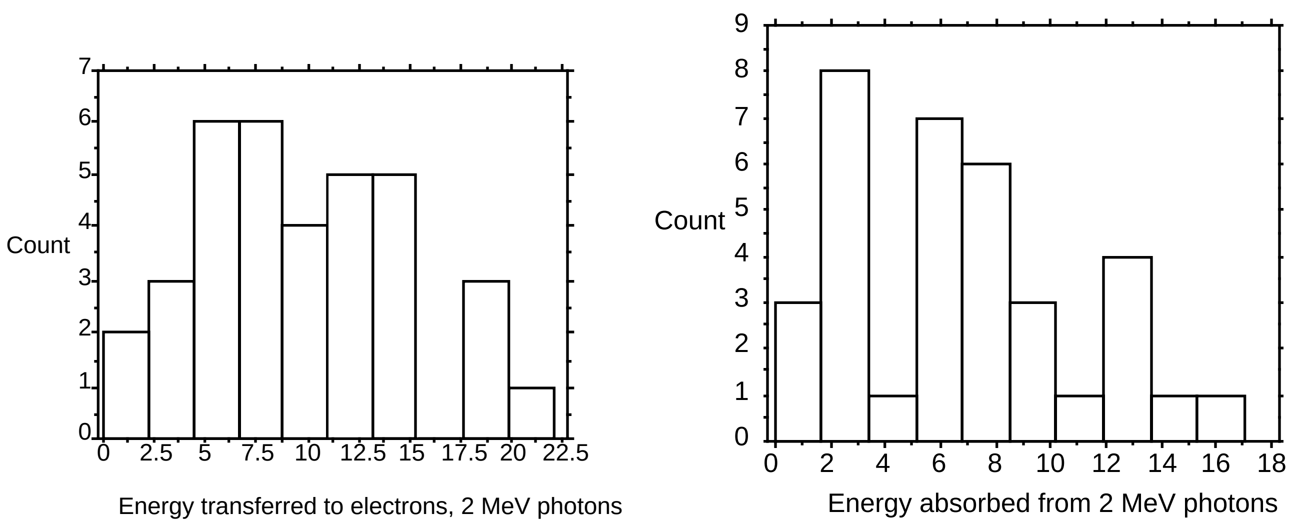


Figure 11. Histograms of the Energy Transferred and the Energy Absorbed for a series of simulations in which 2-MeV photons strike a sample of length 0.1 m. The energy is in units of 10^{-12} J

Using some long runs (1000 - 10,000 photons, depending on the time you have available), study the ratio of Energy Absorbed to Energy Transferred for a 0.1 m sample at 100 keV, 300 keV, 1 MeV, 3 MeV, and 10 MeV.

Fig. 12 shows plots of the ratio of Energy Absorbed to Energy Transferred vs. photon energy for samples of two different thicknesses. The higher the energy (and the greater the range of the electrons) or the thinner the sample, the smaller the ratio of Energy Absorbed to Energy Transferred.

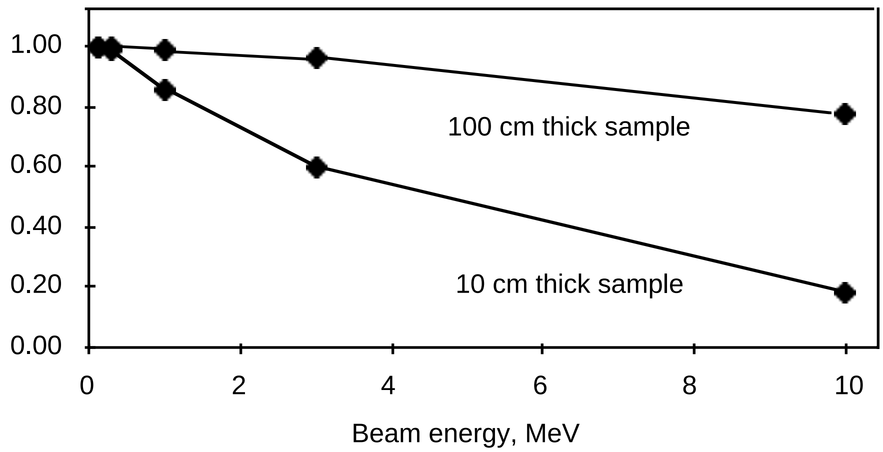


Figure 12. Ratio of Energy Absorbed in the sample to Energy Transferred to electrons within the sample as a function of photon energy, for samples of two different thicknesses.

Exercise 4. The energy absorbed per unit mass for a thin sample.

Using 100 keV photons on a 1-mm thick target (1.00 E-03 m), turn on the Log File and record the energy absorbed in the target vs. the number of photons which strike. Run for 10,000 incident photons. How does energy absorbed depend on number of photons? Are there statistical fluctuations?

Fig. 13 shows a plot, for 100 keV photons striking a 1-mm thick target, of the energy absorbed in the target vs. the number of photons which strike. We expect this to increase linearly. Note how the energy absorbed fluctuated about the straight line, because of the random nature of the interactions.

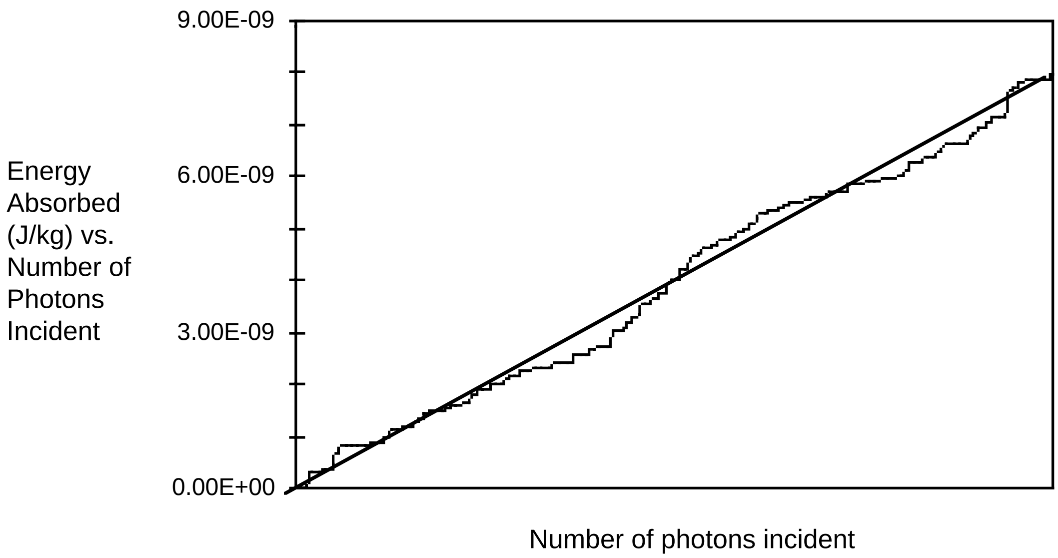


Figure 13. Plot of Energy Absorbed vs. the number of 100-keV photons striking a sample 1 mm thick.

Exercise 5. The difference between entrance collision kerma and average collision kerma.

Using 60-keV photons and a 1-mm thick sample, compare the Energy Absorbed per unit mass to the Average Collision Kerma. Use 4,000 photons and plot the results vs. number of photons with the aid of the Log File. Can you explain the nature of the graph?

The *collision kerma* (Kinetic Energy Released in the Medium) at a point is the *average* or *expectation value* of the net energy transferred to charged particles per unit mass in a small region around that point. (We say net energy transferred because it is possible for some of the energy transferred to electrons to be converted back to photons, through bremsstrahlung or annihilation of positrons in flight.)

The collision kerma is related to the energy fluence and the mass energy absorption coefficient by $K_c = \Psi\ (\mu_{en}/\rho)$. Fig. 14 shows the ratio of energy absorbed to collision kerma, as a function of the number of 60-keV photons that struck a sample 1-mm thick. The value of $e^{-\mu x}$ is 0.981; that means that for 4000 incident photons, only 76 have actually interacted in the sample. This explains the abrupt increases and slow decays in the curve. One or two interactions during a string of 25 photons causes a large increase in the energy absorbed. The next few hundred photons do not interact at all, but they increase K_c as Ψ increases, and therefore they decrease the ratio.

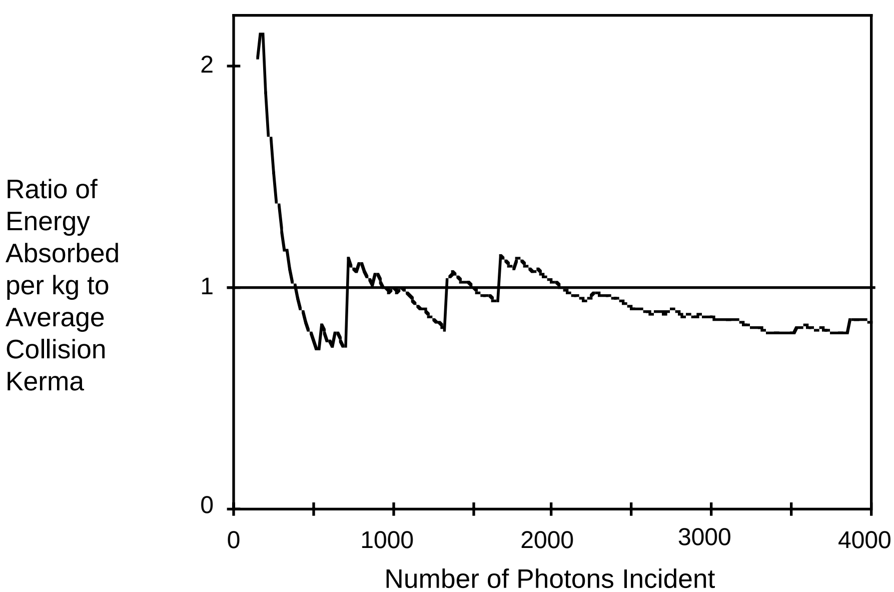


Figure 14. The ratio of Energy Absorbed per unit mass to Average Collision Kerma vs. the number of photons striking a thin sample. The photons energy is 60 keV. The sample thickness is 1 mm.

Then do a continuous run of 1000 photons at 60 keV with an 0.1-m thick sample. Notice from the Results Window that the entrance collision kerma is 7.94×10^{-12} J kg^{-1} while the average collision kerma is only 3.44×10^{-12} J kg^{-1}. Can you explain the difference by looking at the simulation?

The energy fluence is largest at the entrance to the sample and decreases exponentially. Therefore, the collision kerma decreases exponentially through the sample. Fig. 15 shows one screen of 25 photons. A dot has been placed at each photon interaction. You can see that 13 photons interacted in the first half of the sample compared to 8 in the second half. [On average, the number interacting in the first half is $25(1 - e^{-\mu x})$. The value of μx is $(\mu/\rho)(\rho x) = (1.99 \times 10^{-2})(10^3)(0.05) = 0.995$; $e^{-0.995} = 0.370$; $25(1 - 0.370) = 15.7$.]

Quantitatively, the energy fluence is $\Psi = \Psi_0 e^{-\mu x}$ where μ is the attenuation coefficient. The average kerma is the total energy absorbed in the sample divided by the total mass. From this one can show that

$$(K_c)_{average} = \left(\frac{\mu_{en}}{\rho}\right)\left(\frac{(1 - e^{-\mu L})}{\mu L}\right)\Psi$$

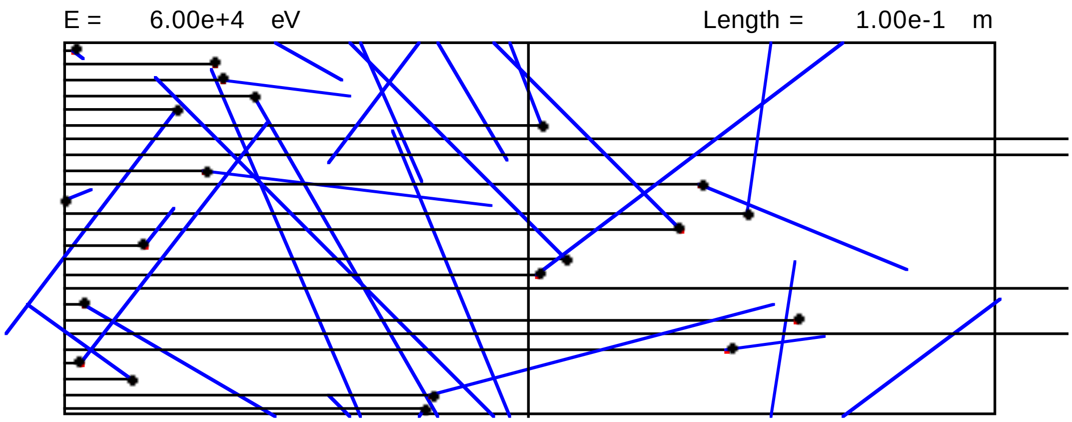


Figure 15. A simulation of 60 keV photons in a sample of length 0.1 m. More photons interact in the first half of the sample, so the kerma is larger there.

Fig. 16 shows how the average energy absorbed per unit mass fluctuates around the average collision kerma.

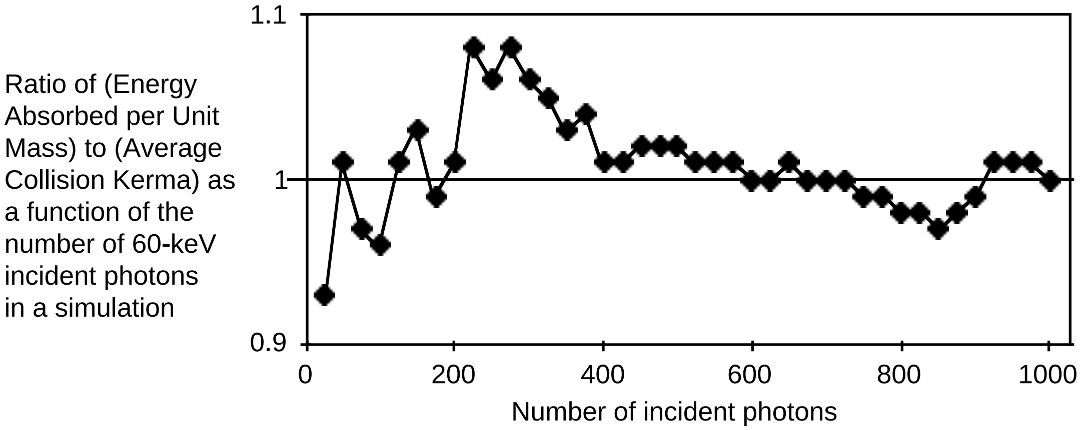


Figure 16. The ratio of (Energy Absorbed per Unit Mass) to (Average Collision Kerma) for 60-keV photons incident on a 0.1-m thick sample.

Exercise 6. Study of plots of energy absorbed and energy transferred vs. depth in the sample.

The energy transferred to electrons in a slice at a given depth in the sample will not be the same as the energy absorbed in that slice, unless the range of the electrons is small compared to the thickness of the slice.

Refer to your work from Exercise 3 and consider the ratio of energy absorbed to energy transferred. At 100 keV you will find that they are the same. Repeat your simulation for 10 MeV photons in samples of thickness 1 m, 0.2 m and 0.1 m. How do energy transferred and energy absorbed compare vs. depth?

Fig. 17 shows a plot for a 1-m thick sample. The energy absorbed and the energy transferred fall exponentially, reflecting the decrease in photon energy fluence: $\Psi = \Psi_0 e^{-\mu x}$. The energy absorbed may be slightly less than the energy transferred in the first slice because electrons created in the first slice move downstream and lose part of their energy in the second slice. In downstream slices, if the energy of electrons moving in from upstream is greater than the energy of electrons leaving, the energy transferred is slightly greater than the energy absorbed.

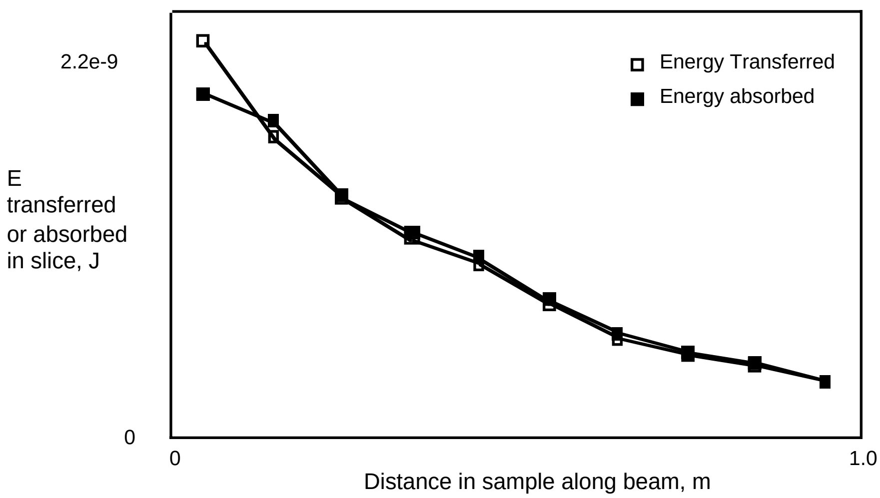


Figure 17. Graph of Energy Transferred and Energy Absorbed vs depth for 10-MeV photons in a 1-m sample.

Fig. 18 shows a sample that is 20 cm thick. We can see the fluctuations around exponential decay of the energy transferred, and the buildup of energy absorbed with depth.

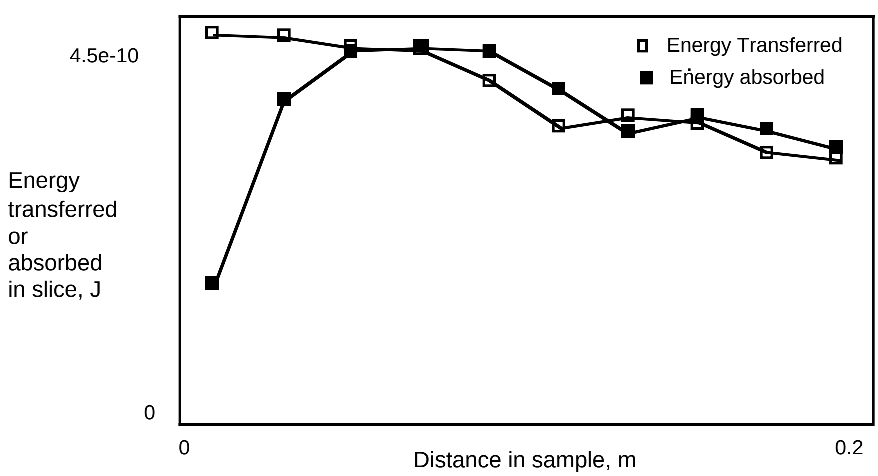


Figure 18. Graph of Energy Transferred and Energy Absorbed vs depth for 10-MeV photons in a 20-cm-thick sample.

Fig. 19 shows a 10-cm-thick sample. The dose buildup region can be seen even more clearly. It occurs over a distance of about 2.5 cm. This is about the range of a 5-MeV electron. (The range of a 10 MeV electron in water is about 5 cm. Few of the electrons have the full energy of the incident photon.)

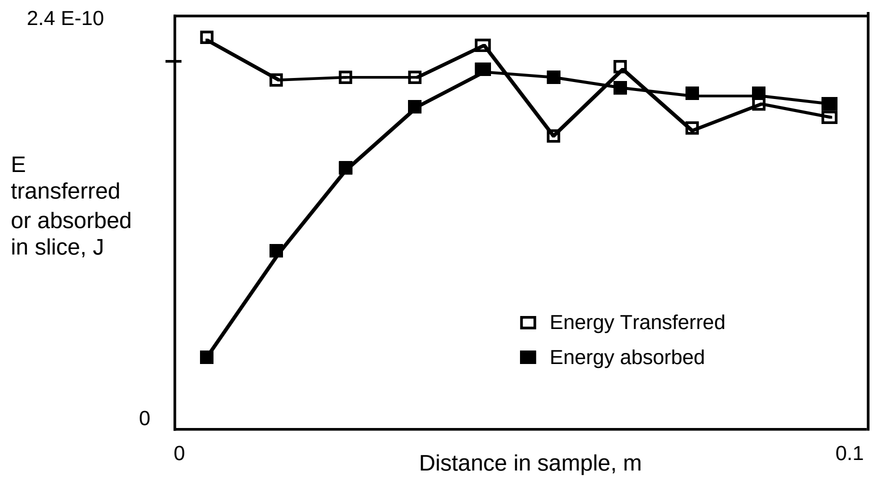


Figure 19. Graph of Energy Transferred and Energy Absorbed vs depth for 10-MeV photons in a 10-cm-thick sample.

Repeat the simulation for 2 MeV photons and a sample 2 cm thick. Use 10000 photons. The range of a 1-MeV electron is 0.44 cm. Do you think you will see a buildup region?

Fig. 20 shows the energy transferred and energy absorbed for the 2-MeV photons in a 2-cm thick sample. The buildup indeed takes place over a distance corresponding roughly to the range of an electron with half the energy of the incident photons.

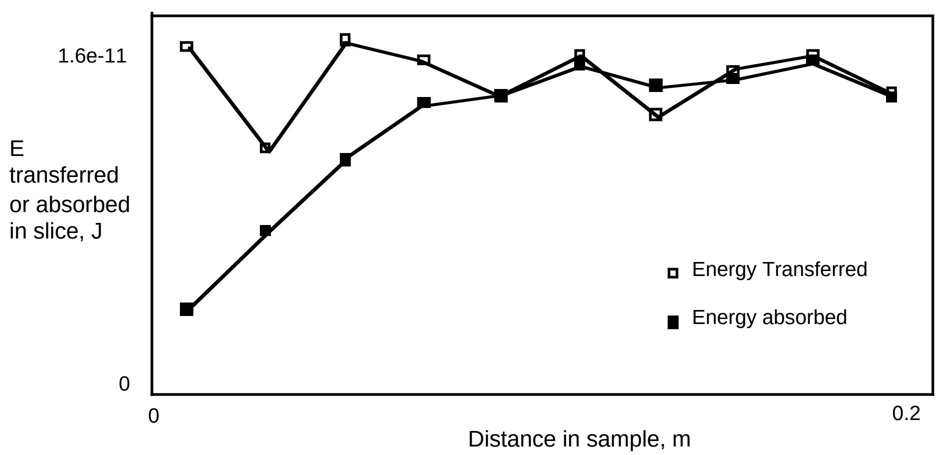


Figure 20. Graph of Energy Transferred and Energy Absorbed vs depth for 2-MeV photons in a 20-cm thick sample.

Run with 50 keV photons in a 20-cm thick sample. Do you expect to be able to see any difference between energy transferred and energy absorbed?

The electron range is now so small that we do not see any difference between the two curves in Fig. 21.

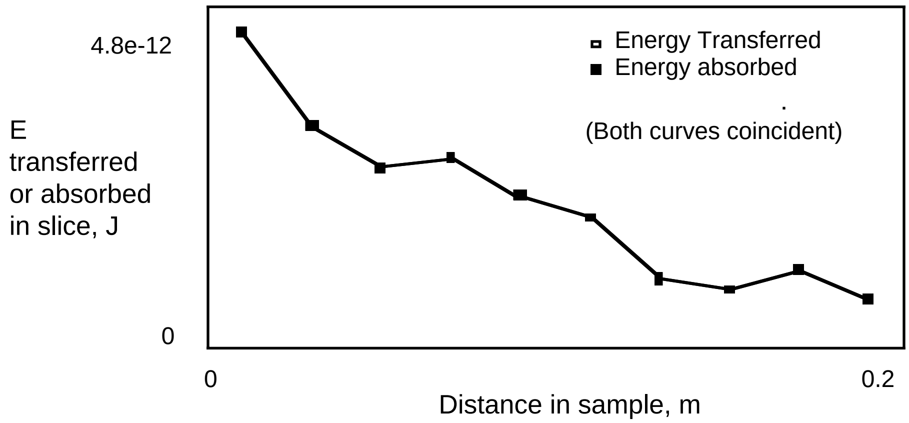


Figure 21. Graph of Energy Transferred and Energy Absorbed vs depth for 50-eV photons in a 20-cm thick sample.

Exercise 7. The effect of subsequent interactions.

Analytic calculations of energy transferred usually ignore the interactions of subsequent photons. Usually these are Compton scattered photons, though they may also be fluorescence or annihilation radiation. An option in the ***Set Parameters*** *dialog box allows you to follow subsequent photons until there are no further interactions in the sample.*

The simulation in MacDose is based on a series of "random" numbers generated by the computer. These are actually a sequence of pseudo-random numbers, generated by a mathematical algorithm. One starts with a number called the "seed." Each calculation of a number in the sequence also generates the seed for the next calculation. Thus, with the same initial seed, you will get exactly the same result. A different seed will allow you to see the effects of random fluctuations. The initial seed used in MacDose is the number 2.

Use ***Set Parameters*** *to make sure the random number seed is 2. Run a single screen. Print the result. Reset the seed to 2 and run again. The results should be exactly the same.*

The program has been written so that the primary interactions use the same sequence of random numbers whether or not subsequent interactions are being considered. Thus, if you make two runs, one with and one without subsequent interactions, and you remember to start with the same random number seed, the pattern of primary interactions will be the same.

Use ***Set Parameters*** *to set the number of photons per run to 4. Make a series of runs at 100 keV, 1 MeV and 10 MeV with 4 photons each. Run first without subsequent interactions included, and then with subsequent interactions included. Each time reset the seed to 2. Print your results. Compare the simulations. What is the total energy transferred to electrons in each case? How many additional interactions are there for each incident photon? For the 10 MeV run, which heavy tracks represent electrons? Which are positrons?*

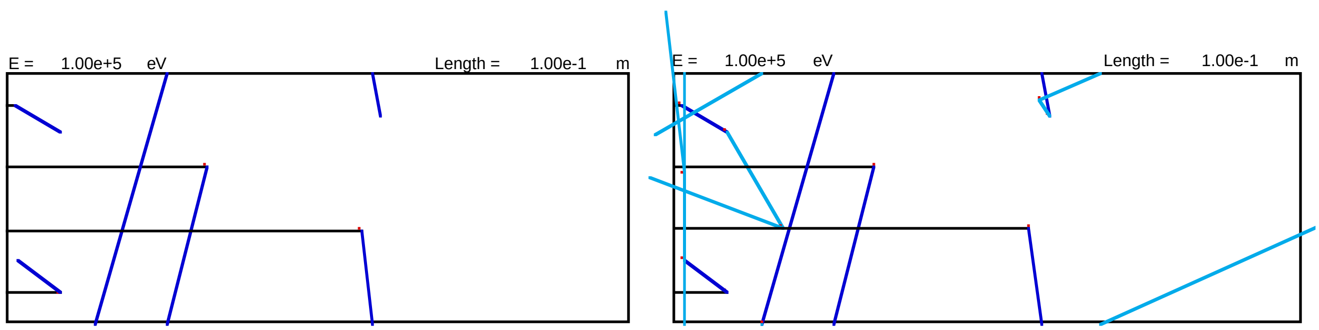


Figure 22. Four 100-keV photons with and without subsequent interactions.

At 100 keV (Fig. 22) the energy transferred is 1 x 10^{-14} J and 2 x 10^{-14} J in each case. On the right, where subsequent interactions are included, from top to bottom there are 2, 1, 2 and 2 additional interactions. (The fourth photon scatters upward perpendicular to the beam, leaves the sample, enters again from the bottom, and finally scatters upstream out of the sample.)

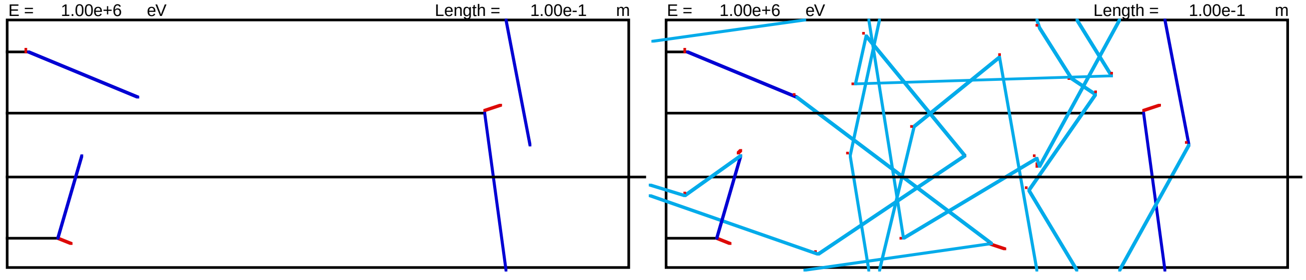


Figure 23. Four 1-MeV photons with and without subsequent interactions.

For the 1 MeV beam, the energy transferred is 2.15 x 10^{-13} and 4.15 x 10^{-13} J. Each photon has 2, 16, 0, and 2 additional interactions.

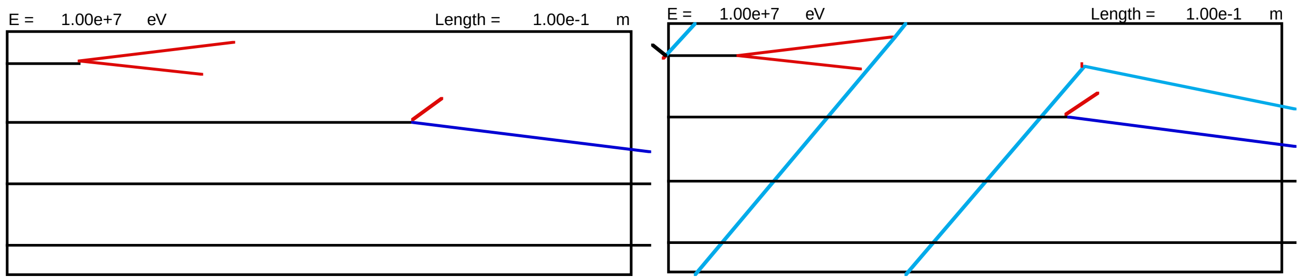


Figure 24. Four 10-MeV photons with and without subsequent interactions.

At 10 MeV (Fig. 24) the energy transferred is 1.64 x 10^{-12} and 1.71 x 10^{-12} J in each case. The first photon underwent pair production, and the second was Compton scattered. There are therefore two electron tracks and one positron track. We cannot tell which is the positron until we look at subsequent interactions. The positron annihilates. One photon travels up and to the right, re-entering at the bottom of the sample and Compton scattering before it leaves through the right edge. The other photon travels down and to the left, re-entering at the top and Compton scattering at the left edge.

Exercise 8. Energy transfer vs. depth with subsequent interactions.

Use 100 keV photons. Run for at least 1000 primary photons. Print the results. Repeat the run with a different random number seed. Plot the buildup facto, B, which is the total energy transferred to electrons in each slice with subsequent interactions included, divided by the energy transferred by primary interactions. Compare your plots to a calculation based on $K_C = \Psi\, (\mu_{en}/\rho)$? (You must include appropriate attenuation.) What is the buildup factor at the surface? Why is it not unity?

The results shown here are for 67,550 photons. If subsequent interactions are ignored, the energy transferred to electrons in a slice is the collision kerma times the mass of the slice:

$$K_C m = K_C \rho S \Delta x$$

where m is the mass of the slice, ρ the density, S is the area perpendicular to the beam, and $\Delta x = 0.1/10 = 0.01$ m. The area perpendicular to the beam is determined from

$$S = \frac{\text{Number of photons}}{\text{Number fluence}} = \frac{67750}{1.69 \times 10^7} = 3.997 \times 10^{-3}\ \text{m}^2$$

The collision kerma vs. depth is given by

$$K_C(x) = \Psi\,(\mu_{en}/\rho) = \Psi_0\, e^{-\mu x} \left(\frac{\mu_{en}}{\rho}\right)$$

Numerical values are

Total number:	67,550	
Incident energy	10^5 eV	(From Results Table)
Number fluence	1.69×10^7 m^{-2}	(From Results Table)
S	3.997×10^{-3} m^2	(From total number/number fluence)
Energy fluence	2.7×10^{-7} J m^{-2}	(From Results Table)
μ_{atten}	0.0168 m^{-1}	(From Results Table)
μ_{en}	0.00243 m^{-1}	(From Results Table)

Fig. 25 shows a plot of the energy transferred vs. depth The line marked "calculated" is from $\Psi_0 e^{-\mu x}$ (μ_{en}/ρ). The ratio of actual energy transfer to that calculated for the primary beam is called the *buildup factor*, B(x). It is listed in the table below, and is plotted in Fig. 26. The levelling off occurs at relatively small values of $\mu_{atten}x$ because the sample is finite; in a thicker sample there would be more backscattered secondary photons.

Mid-slice depth x, in m	E transferred in slice (including subsequent interactions)	E transferred in slice (primary interactions only)	$\mu_{atten}x$	Buildup factor, B
0.005	4.40E-11	2.37E-11	0.084	1.86
0.015	4.61E-11	1.97E-11	0.252	2.34
0.025	4.56E-11	1.67E-11	0.42	2.73
0.035	4.45E-11	1.44E-11	0.588	3.09
0.045	4.26E-11	1.22E-11	0.756	3.49
0.055	3.90E-11	1.03E-11	0.924	3.79
0.065	3.49E-11	8.59E-12	1.092	4.06
0.075	3.19E-11	7.39E-12	1.26	4.32
0.085	2.76E-11	6.48E-12	1.428	4.26
0.095	2.20E-11	5.23E-12	1.596	4.21

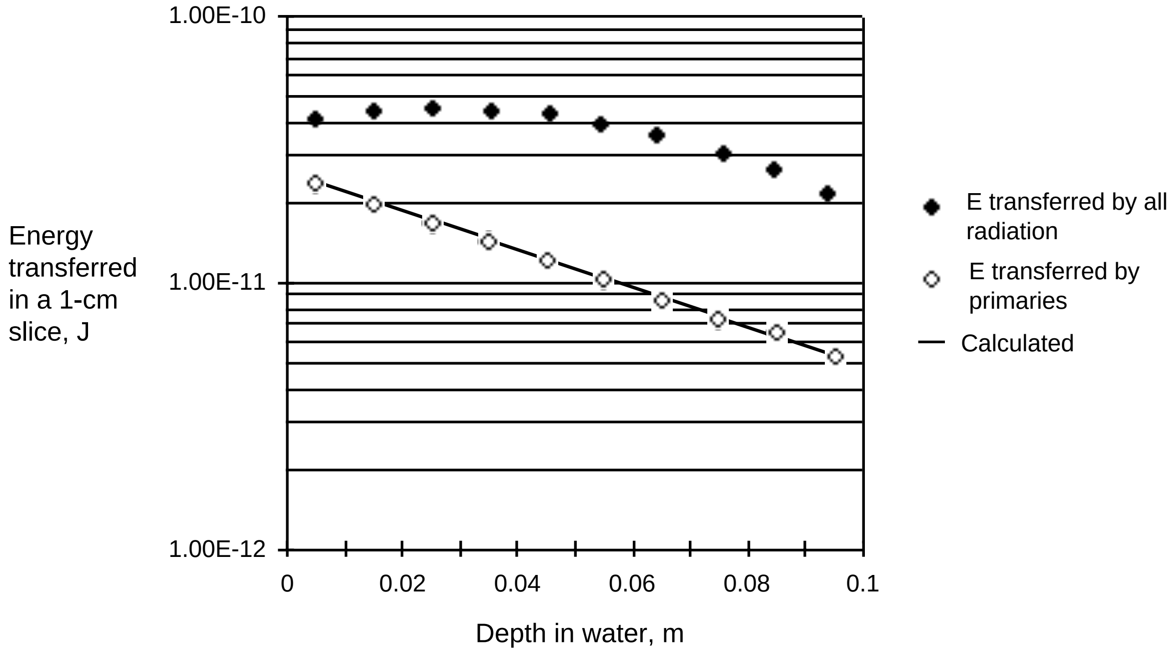


Figure 25. Energy transferred to electrons by all radiation and by primary radiation for 100-keV photons. The line marked "calculated" is from $\Psi_0 e^{-\mu x}$ (μ_{en}/ρ).

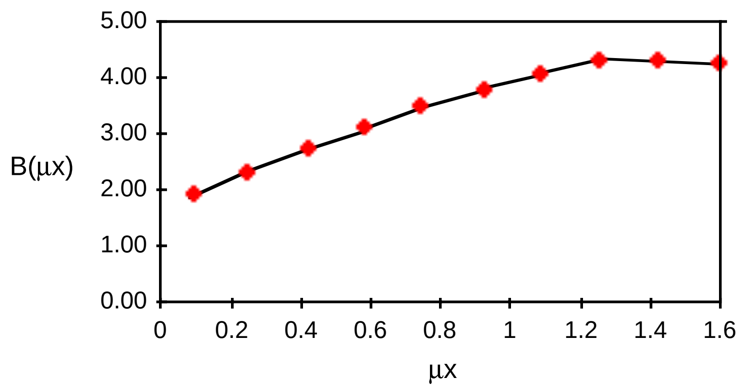


Figure 26. Plot of the buildup factor B vs. µx for 100 keV photons on water.

Figures 27 and 28 show plots of B(µx) vs. µx for thicker samples, compared to the curves from Goldstein that are given in Attix.[1] Two runs were done at each energy to show the random nature of the simulation. When µx = 8, if there were 10^4 incident photons, only 3 remain in the primary beam. Thus, the statistical accuracy of B is quite poor.

[1] Attix, H. *Introduction to Radiological Physics and Radiation Dosimetry*. New York, Wiley-Interscience, 1986, p. 54

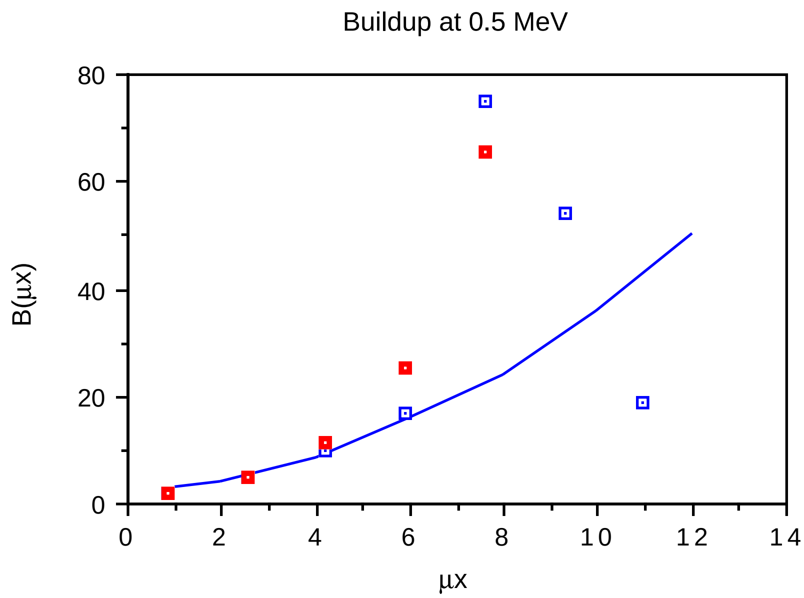


Figure 27. Buildup factor vs. depth for 0.5-MeV photons. The curve is from Attix.

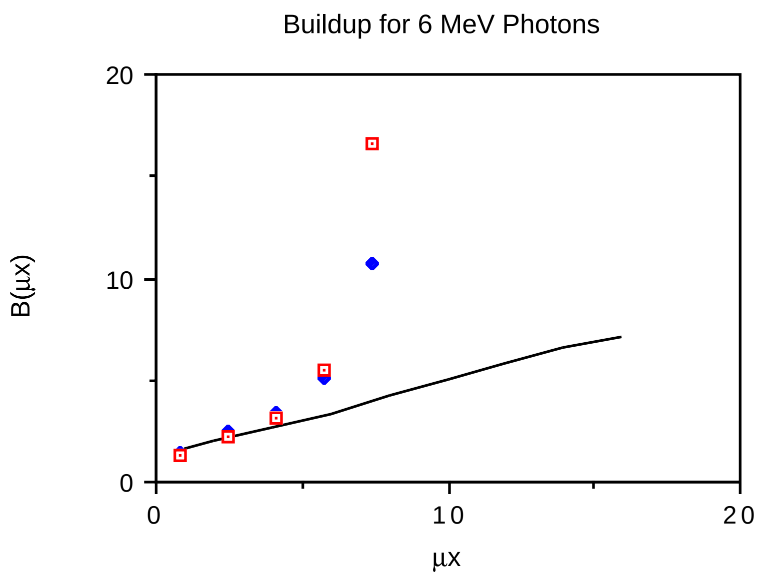


Figure 28. Buildup factor vs. depth for 6-MeV photons. The curve is from Attix.

Exercise 9. The effect of subsequent interactions vs. photon energy.

Run for 1000 photons at 10 keV through 5 MeV, with subsequent interactions considered. Use a sample thickness such that μL is about 5. How does the buildup factor for the first slice change with energy? Why?

The runs were done for 1000 photons each, always starting with a random number seed of 2 and using a thickness such that the value of μx for the first slice was about 0.25. The buildup is plotted below. It is largest when Compton scattering is important, peaking at about 2 near 100 keV. The value greater than unity is due to backscattered photons.

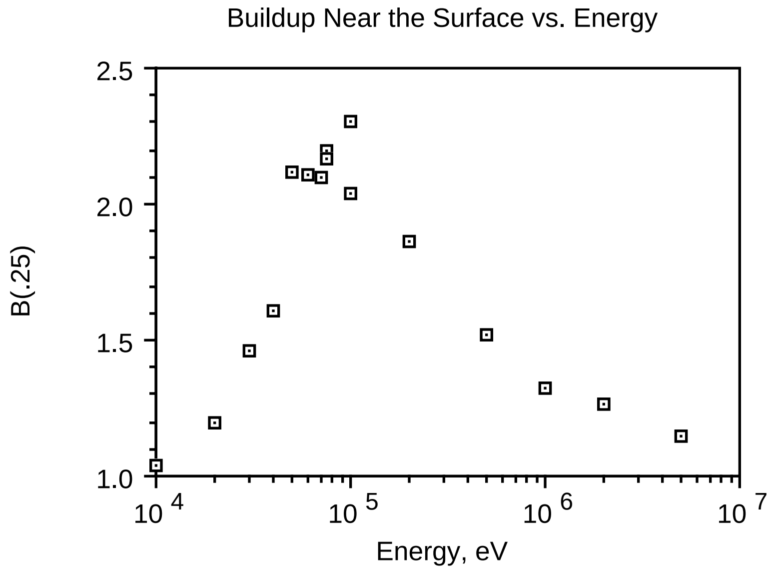


Figure 29. Buildup factor near the surface vs. energy.

Index