FF

KEK - 1 2 3
su 8402

KEK Preprint 93-123
September 1993
R

CERN LIBRARIES, GENEVA

P00019773

CALCULATION OF ABSORBED DOSE AT
0.07-, 3.0- and 10.0-mm- DEPTHS IN A SLAB
PHANTOM FOR MONOENERGETIC ELECTRONS

H. HIRAYAMA

*KEK, National Laboratory for High Energy Physics
Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan*

(to be published in Radiat. Prot. Dosim.)

© National Laboratory for High Energy Physics, 1993

KEK Reports are available from:

Technical Information & Library
National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi
Ibaraki-ken, 305
JAPAN

Phone: 0298-64-1171
Telex: 3652-534 (Domestic)
(0)3652-534 (International)
Fax: 0298-64-4604
Cable: KEK OHO
E-mail: LIBRARY@JPNKEKVX (Bitnet Address)
library@kekvax.kek.jp (Internet Address)

1. INTRODUCTION

A Joint ICRP/ICRU Task Group is currently preparing a revised ICRP Publication 51 by investigating data concerning quantities for Radiation Protection and their relationships. To take into account the 1990 Recommendations of the ICRP, calculations must be performed for neutrons, photons and electrons in order to provide new sets of conversion factors between the field quantities and operational quantities or anthropomorphic quantities. Desirable calculations for electrons had been defined by members of the "Electron Data" subgroup of the EURADOS WG4 at a meeting held in PTB Braunschweig on the 1st July, 1992^[1]. These are summarized in second section.

The general-purpose electron gamma shower Monte Carlo code EGS4^[2] has been used to calculate the required quantities. The third section presents a brief overview of the EGS4 system, the user code written for these calculations and the cut-off parameters. The last section discusses the depth vs the absorbed dose and the dependence of the absorbed doses at each depth on the incident electron energy, incident angle and phantom material.

2. REQUIRED QUANTITIES

The required quantity is $D(d, \alpha)$, the absorbed dose at a depth of d (in mm) in a slab phantom ($30\text{ cm} \times 30\text{ cm} \times 15\text{ cm}$) irradiated by a parallel electron beam, and impinging at an incident angle of α . The phantom is surrounded by a vacuum. The electron energy varies from 50 keV to 10 MeV. Depths (d) of 0.07, 3.0 and 10.0 mm are required and the scoring thickness at each depth in the phantom is recommended to be $\Delta d = 0.01d$. The incident angle (α) varies from 0° to 75° with increments of 15° . To see the dependence of the incident angle in detail, the absorbed doses for 85° - and 89° -incidence electrons were also calculated. The polymethyl methacrylate (PMMA)^[3], water and ICRU 4-element tissue^[4] (tissue) are being considered as materials for the slab phantom. The elemental compositions of these three materials are shown in Table 1 together with their density. Depths of 7° -, 300° - and 1000-mg cm^{-2} are also required for PMMA^[5]. Water and PMMA are supposed to be selected as the phantom material easily available in the form of liquid and solid, respectively.

CALCULATION OF ABSORBED DOSE AT 0.07-, 3.0- and 10.0-mm- DEPTHS IN A SLAB PHANTOM FOR MONOENERGETIC ELECTRONS

H. HIRAYAMA

ABSTRACT

The general-purpose electron gamma shower Monte Carlo code EGS4 has been used to calculate absorbed doses at 0.07° -, 0.3° - and 10.0-mm-depts per unit fluence for broad parallel beams of mono-energetic electrons impinging at an incident angle of α on a slab phantom ($30\text{cm} \times 30\text{cm} \times 15\text{cm}$) of polymethyl methacrylate (PMMA), water and ICRU 4-element tissue required by EURADOS WG4 for a revision of ICRP Publication 51. Absorbed doses at 7° -, 300° - and 1000-mg cm^{-2} were also calculated for PMMA. The electron kinetic energy range covered is 50 keV to 10 MeV. The incident angle (α) varies from 0° to 75° with an increment of 15° .

The calculated results are presented in tables. The depth vs the absorbed dose curves and dependence of absorbed dose at each depth on the incident electron energy, incident angle and phantom material are also presented and discussed.

3. CALCULATION

Calculations were carried out using the general-purpose electron gamma shower code EGS4. This code considers all of the physical processes believed to be important in the transport of electrons or positrons above a few tens of keV or photons above a few keV. In photon transport, the code considers Compton scattering (Klein-Nishina cross section applied to free electrons), pair production (with an approximate treatment of triplet production), and the photoelectric effect (photoelectrons are tracked but fluorescence X-rays, and Auger electrons are considered to be deposited locally). Rayleigh scattering, which is important in the low-energy region below 100 keV, can be included as an option. Electron-positron transport is simulated using the condensed history technique with energy-loss fluctuations accounted for through the random nature of elastic scattering events. Bremsstrahlung production, positron annihilation in flight and at rest, elastic Moller and Bhabha scattering from electrons and Molière multiple scattering from atomic nuclei are all taken into account.

An EGS4 user code called UCICRP was developed for the required calculations. It considers a finite plate having a $30\text{ cm} \times 30\text{ cm}$ area and a 15 cm -depth of arbitrary material which can be divided into regions along the depth axis to calculate the dose at the required depth. The broad parallel beam is accomplished by considering an incident pencil beam at the center of the phantom and scoring the total energy deposited in a broad slice within the depth from $0.995d$ to $1.005d$ at each depth (d). The PRESTA^[6] algorithm was used to get accurate results without setting a very small step size. The energy cutoffs used in the calculations are summarized in Table 2. The meanings of the cutoff parameters in the table are as follows:

- AE: energy threshold for delta-ray production (total energy in MeV); interactions, which would produce secondaries below AE, are treated as a continuous restricted energy loss.
- AP: lower cut-off energy of photon transport (in MeV); bremsstrahlung reactions, which would produce photons below AP, are treated as a continuous energy loss.
- ECUT: energy threshold for electron- or positron-tracking (total energy in MeV); when a particle becomes below Ecut, its kinetic energy is

deposited locally at that place.

PCUT: energy threshold for photon tracking (in MeV); when a photon becomes below PCUT, its energy is deposited locally at that place.

The material data used in EGS4 are calculated with PEGS4 (Preprocessor for EGS4). The APRIM option^[7] and the EPSTAR option^[8] are used in PEGS4 to produce a stopping power identical to that presented in ICRU-37.^[3] The IRAYL option to produce Rayleigh-scattering related data is also used for all of the materials.

The CSDA ranges of water and PMMA presented in ICRU-37^[3] are shown in Figure 1. The difference between PMMA and water is mainly due to its density. From this figure, it is clear that 50 or 60 keV electrons can not reach a depth of 0.07 mm. In this situation, energy depositions at 0.07-mm-depth are caused by bremsstrahlung photons produced by primary electrons. The effective atomic number of considered materials is small and the electron energy is much lower than the critical energy of each material. Therefore, the bremsstrahlung reaction cross section is very small in this case, and the statistics of the calculated results at 0.07 mm become very poor. To obtain good statistics in this case, the bremsstrahlung splitting option developed and implemented in the EGS4 system by A. F. Bielajew was used. Splitting ON in Table 2 means that the bremsstrahlung splitting option is used at that calculation.

Rogers and Bielajew^[9] and Cross et al.^[10] compared the calculated dose distributions for normally incident mono-energetic electrons on water between EGS4 and ETRAN or SANDYL. From these detailed comparisons, the results of EGS4, ETRAN and SANDYL agree well each other within the estimated errors except at near the CSDA range.

All calculations were carried out with several kinds of UNIX workstations. The CPU-time per case by DEC Station 5000/200 for electrons normally incident on tissue, for each incident energy, is also given in Table 2.

1. RESULTS AND DISCUSSION

The results shown in Tables 3, 4, 5 are $D(0.07 \text{ mm}, \alpha)$, $D(0.3 \text{ mm}, \alpha)$ and $D(10.0 \text{ mm}, \alpha)$ for the three materials, respectively. $D(7 \text{ mg cm}^{-2}, \alpha)$, $D(300 \text{ mg cm}^{-2}, \alpha)$ and $D(1000 \text{ mg cm}^{-2}, \alpha)$ for PMMA are given in Table 6, 7 and 8, respectively. The standard deviation of the mean (σ) was obtained by considering a single set of N numbers, their mean value $\bar{D}$, and the N squared residuals, $\sum (D_i - \bar{D})^2$, by the following equation:

$$\sigma = \sqrt{\frac{1}{N-1} \sum (D_i - \bar{D})^2} = \sqrt{\frac{N}{N-1} (\bar{D}^2 - \bar{D}^2)}.$$

All of the results were given as an absorbed dose in terms of the gray per unit fluence of electron (Gy cm^2).

4.1. DEPTH-DOSE CURVES

Figures 2 and 3 show the depth vs the absorbed dose curves of water for normally incident and 75° -incident electrons, respectively. The absorbed dose for normally incident electrons gradually increases with an increase in the depth, and becomes maximum at about the half thickness of the CSDA range as mentioned in the reference 10. The absorbed dose at the surface decreases with an increase in the electron energy. This corresponds to the energy dependence of the restricted stopping power. Beyond the CSDA range, energy depositions are mainly caused by bremsstrahlung photons produced by primary electrons, and are far smaller than those at depths within the CSDA range. On the other hand, the absorbed dose for 75° -incidence electrons decreases with an increase in the depth except the 10 MeV case. The decrease tendency near the CSDA range is more gradual than that of the normal incidence due to the contributions of electrons scattered to the side direction. To see these situations more clearly, tracks of particles produced in tissue with 100 incident electrons are shown in Figure 4. In this figure, charged particle and photon tracks are depicted as solid and dotted lines, respectively. The general tendency of the depth-dose curves is similar within the three phantom materials.

4.2. ELECTRON ENERGY DEPENDENCE

Figure 5 shows the calculated absorbed doses per unit incident fluence for normal incidence on the phantom as the function of the incident electron energy at 0.07-, 3.0- and 10.0-mm-depths, respectively. $D(d, 0^\circ)$ increases rapidly at a certain energy, at which energy the CSDA range exceeds depth d ; the results of PMMA differ significantly at this region from the those of other two materials. This difference comes mainly from the shorter CSDA range of PMMA than that of other two materials due to the difference of its density. After this region, $D(d, 0^\circ)$ gradually changes and the results of three materials become almost the same. $D(0.07, 0^\circ)$ has a peak value at around 100 keV, at which a maximum energy deposition exists near to 0.07 mm. Above 4 MeV, the absorbed doses at the above three depths are nearly the same, as can be seen from the depth dose curve shown in Figure 2.

4.3. INCIDENT ANGLE DEPENDENCE

The incident angle dependence of the absorbed doses ($D(d, \alpha)$) in the case of tissue is shown in Figure 6 as ratios to $D(d, 0^\circ)$ at each depth. The number of electrons incident on unit area of the phantom decreases by the factor $\cos \alpha$ with an increase in incident angle (α). On the other hand, the effective thickness of the scoring region from the primary electrons increases $1/\cos \alpha$ times. Therefore, the decrease in the number of electrons incident on unit area is nearly cancelled by an increase in the effective thickness of the scoring region if the CSDA range of incident electrons is longer than $d/\cos \alpha$. In this situation, $D(d, \alpha)/D(d, 0^\circ)$ is larger than 1.0 and increases with an increase in α due to the contribution of electrons scattered to the side direction. This can be seen for above the 0.7 MeV case at 0.07-mm-depth, for above the 4.0 MeV case at 0.3-mm-depth and for above the 7.0 MeV case at 10-mm-depth. If the incident electron does not have a sufficient range, the decrease in the number of electrons entering the scoring region affects the results, and $D(d, \alpha)/D(d, 0^\circ)$ becomes less than 1.0 and decreases with an increase in α .

4.4. MATERIAL DEPENDENCE

The absorbed dose dependencies on the material used as the phantom are shown in Figure 7 as ratios to the results for tissue. The water results agree better than the PMMA results in all cases. The differences due to the material used are significant at the energy region at which region the CSDA range is close to d . The absorbed doses of the PMMA phantom are smaller than those of water and tissue in this energy region. After this energy region, the results for the three materials agree within 10% in the case of 0° . $D(d, 75^\circ)$ of PMMA is smaller than that of the other materials at all energy considered especially for the 3 mm and 10 mm cases. Figure 8 shows the results at 7-, 300- and 1000-mg cm^{-2} -depth as ratios to those for tissue. All results agree well within 10% except in the energy region, at which the CSDA range is close to d . In this energy region, the PMMA results are larger than the tissue ones. This is the opposite tendency seen at 0.07-, 3.0- and 10.0-mm-depths.

From the results shown above, it is concluded that PMMA and water can be used as a substitute phantom material of tissue for electrons concerning the absorbed dose at 7-, 300- and 1000-mg cm^{-2} -depth except in the energy region, at which the CSDA range is close to d .

4.5. ACCURACY

The statistical uncertainty on the absorbed doses was kept to less than 1% for the electron energy, at which the CSDA range is larger than the specified depth, for the incident angle from 0° to 75° . It was about 5% if the CSDA range is smaller than the specified depth. This comes from the fact that the energy deposition causes by bremsstrahlung photons produced by incident electrons in this situation. The uncertainty in the photon cross section data is likely closer to 1% and that in the electron stopping powers is of the order of 1% by using the APRIM and EPSTAR options. The overall uncertainty in the calculation is therefore in the range 3 – 7%.

REFERENCES

1. Chartier, J. L., 30 July, 1992, private communication.
2. Nelson, W. R., Hirayama, H. and Rogers, D. W. O., *EGS4 Code System*, SLAC-265, Stanford Linear Accelerator, 1985
3. ICRU, Report No.37, *Radiation Quantities and Units*, Washington, D.C., 1984.
4. ICRU, Report No.33, *Radiation Quantities and Units*, Washington, D.C., 1980.
5. Chartier, J. L., 29 March, 1993, private communication.
6. Bielajew, A. F. and Rogers, D. W. O., *PRESTA: The Parameter Reduced Electron-Step Transport Algorithm for Electron Monte Carlo Transport*, Nucl. Instr. and Meth., **B18**, 165-181 (1987).
7. Rogers, D. W. O., Duane, S., Bielajew, A. F. and Nelson, W. R., *Use of ICRU-37/NBS Radiative Stopping Power in the EGS4 System*, NRCC, Ottawa, Report PIRS-0177, 1989.
8. Duane, S., Bielajew, A. F. and Rogers, D. W. O., *Use of ICRU-37/NBS Collision Stopping Power in the EGS4 System*, NRCC, Ottawa, Report PIRS-0173, 1989.
9. Rogers, D. W. O. and Bielajew, A. F., *Differences in electron depth-dose curves calculated with EGS and ETRAN and improved energy-range relationships*, Med. Phys., **13**, 687-694 (1986).
10. Cross, W. G., Wong, P. Y. and Freedman, N. O., *Dose Distributions for Electrons and Beta Rays Incident Normally on Water*, Radiat. Prot. Dosim., **35**, 77-91 (1991).

Table 1 Elemental Weight Percent Abundance.

Element	ICRU 4-Element tissue	PMMA	Water
H	10.1	8.05	11.19
C	11.1	59.98	
N	2.6		
O	76.2	31.96	88.81
Density $g\ cm^{-3}$	1.0	1.19	1.0

Table 2 Parameters used in calculation

	Energy (keV)					
	50	60	70	80	90	100
Histories	2000000	2000000	2000000	2000000	100000	100000
AE	0.516	0.516	0.516	0.516	0.516	0.516
AP	0.001	0.001	0.001	0.001	0.001	0.001
ECUT	0.516	0.516	0.516	0.516	0.516	0.516
PCUT	0.001	0.001	0.001	0.001	0.001	0.001
Splitting*	On	On	On	On	Off	Off
CPU-time**	4.20E-3	5.38E-3	6.21E-3	7.98E-3	7.67E-3	8.38E-3
	Energy (MeV)					
	0.2	0.4	0.6	0.7	0.8	1.0
Histories	100000	100000	500000	500000	500000	100000
AE	0.516	0.516	0.516	0.516	0.516	0.516
AP	0.001	0.001	0.001	0.001	0.001	0.001
ECUT	0.516	0.516	0.516	0.516	0.516	0.516
PCUT	0.001	0.001	0.001	0.001	0.001	0.001
Splitting	Off	Off	On	On	On	On
CPU-time	1.07E-2	1.80E-2	4.20E-2	4.27E-2	5.45E-2	7.71E-2
	Energy (3MeV)					
	1.5	2.0	3.0	4.0	7.0	10.0
Histories	500000	500000	100000	100000	100000	100000
AE	0.516	0.516	0.516	0.516	0.516	0.516
AP	0.001	0.001	0.001	0.001	0.001	0.001
ECUT	0.516	0.516	0.516	0.516	0.516	0.516
PCUT	0.001	0.001	0.001	0.001	0.001	0.001
Splitting	On	On	Off	Off	Off	Off
CPU-time	1.33E-1	1.35E-1	7.85E-1	9.33E-2	1.25E-1	1.62E-1

* Bremsstrahlung Splitting.

** seconds per case for Tissue by DEC Station 5000/200

*** Read as 4.20×10^{-3} Table 3(a) $D(0.07; 0^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^{-2})$

Material	Energy (keV)			
	50	60	70	80
PMMA	$1.43E-14 \pm 8.88E-16$	$2.07E-14 \pm 9.14E-16$	$2.62E-14 \pm 9.21E-16$	$3.27E-14 \pm 1.79E-12$
WATER	$2.20E-14 \pm 1.06E-15$	$2.82E-14 \pm 1.21E-15$	$3.33E-14 \pm 1.07E-15$	$4.08E-14 \pm 2.53E-12$
TISSUE	$2.00E-14 \pm 1.04E-15$	$2.78E-14 \pm 1.17E-15$	$3.22E-14 \pm 1.19E-15$	$3.92E-14 \pm 2.57E-12$
Material	Energy (MeV)			
	0.1	0.2	0.4	0.7
PMMA	$1.53E-09 \pm 1.14E-11$	$8.71E-10 \pm 6.60E-12$	$4.61E-10 \pm 4.26E-12$	$3.49E-10 \pm 1.70E-12$
WATER	$1.71E-09 \pm 1.22E-11$	$8.76E-10 \pm 6.96E-12$	$4.83E-10 \pm 4.61E-12$	$3.66E-10 \pm 1.86E-12$
TISSUE	$1.70E-09 \pm 1.21E-11$	$8.50E-10 \pm 6.67E-12$	$4.04E-10 \pm 4.20E-12$	$3.63E-10 \pm 1.82E-12$
Material	Energy (MeV)			
	2.0	3.0	4.0	7.0
PMMA	$2.79E-10 \pm 1.27E-12$	$2.74E-10 \pm 2.93E-12$	$2.70E-10 \pm 2.82E-12$	$2.69E-10 \pm 2.72E-12$
WATER	$2.92E-10 \pm 1.39E-12$	$2.79E-10 \pm 2.88E-12$	$2.74E-10 \pm 2.78E-12$	$2.74E-10 \pm 2.94E-12$
TISSUE	$2.84E-10 \pm 1.30E-12$	$2.83E-10 \pm 3.03E-12$	$2.76E-10 \pm 2.90E-12$	$2.71E-10 \pm 2.87E-12$

*Read as 1.43×10^{-14} .Table 3(b) $D(0.07; 15^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^{-2})$

Material	Energy (keV)			
	50	60	70	80
PMMA	$1.43E-14 \pm 6.40E-16$	$1.74E-14 \pm 8.40E-16$	$2.04E-14 \pm 1.21E-15$	$4.51E-10 \pm 1.63E-12$
WATER	$2.08E-14 \pm 9.36E-16$	$2.84E-14 \pm 1.00E-15$	$3.19E-10 \pm 9.34E-13$	$9.63E-10 \pm 2.38E-12$
TISSUE	$2.01E-14 \pm 9.75E-16$	$2.67E-14 \pm 1.11E-15$	$3.48E-10 \pm 2.03E-12$	$9.98E-10 \pm 2.40E-12$
Material	Energy (MeV)			
	0.1	0.2	0.4	0.7
PMMA	$1.41E-09 \pm 1.08E-11$	$8.87E-10 \pm 6.50E-12$	$4.66E-10 \pm 4.04E-12$	$3.57E-10 \pm 1.69E-12$
WATER	$1.61E-09 \pm 1.20E-11$	$9.00E-10 \pm 6.97E-12$	$4.93E-10 \pm 4.49E-12$	$3.78E-10 \pm 1.91E-12$
TISSUE	$1.60E-09 \pm 1.17E-11$	$8.81E-10 \pm 6.83E-12$	$4.89E-10 \pm 4.67E-12$	$3.74E-10 \pm 1.90E-12$
Material	Energy (MeV)			
	2.0	3.0	4.0	7.0
PMMA	$2.84E-10 \pm 1.28E-12$	$2.75E-10 \pm 2.80E-12$	$2.77E-10 \pm 2.84E-12$	$2.67E-10 \pm 2.63E-12$
WATER	$2.96E-10 \pm 1.35E-12$	$2.85E-10 \pm 2.93E-12$	$2.84E-10 \pm 3.04E-12$	$2.77E-10 \pm 2.86E-12$
TISSUE	$2.90E-10 \pm 1.31E-12$	$2.86E-10 \pm 3.10E-12$	$2.72E-10 \pm 2.62E-12$	$2.73E-10 \pm 2.82E-12$

*Read as 1.43×10^{-14} .

Table 3(c) $D(0.07; 30^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^2)$

Material	Energy (keV)			
	50	60	70	80
PMMA	1.22E-14 $\pm$ 5.49E-16	1.45E-14 $\pm$ 7.30E-16	2.03E-14 $\pm$ 7.92E-16	2.72E-14 $\pm$ 1.21E-15
WATER	1.97E-14 $\pm$ 9.02E-16	2.60E-14 $\pm$ 1.08E-15	3.60E-14 $\pm$ 6.11E-15	5.00E-14 $\pm$ 1.91E-15
TISSUE	1.96E-14 $\pm$ 9.04E-16	2.34E-14 $\pm$ 8.83E-16	7.29E-14 $\pm$ 6.91E-15	6.99E-14 $\pm$ 1.94E-15
Material	Energy (MeV)			
	0.1	0.2	0.4	0.7
PMMA	1.12E-09 $\pm$ 9.39E-12	9.52E-10 $\pm$ 6.86E-12	5.31E-10 $\pm$ 4.52E-12	3.88E-10 $\pm$ 1.71E-12
WATER	1.30E-09 $\pm$ 1.02E-11	9.62E-10 $\pm$ 7.06E-12	5.40E-10 $\pm$ 4.59E-12	4.04E-10 $\pm$ 1.86E-12
TISSUE	1.30E-09 $\pm$ 1.02E-11	9.54E-10 $\pm$ 7.11E-12	5.33E-10 $\pm$ 4.58E-12	4.00E-10 $\pm$ 1.87E-12
Material	Energy (MeV)			
	2.0	3.0	4.0	7.0
PMMA	2.95E-10 $\pm$ 1.24E-12	2.84E-10 $\pm$ 2.66E-12	2.78E-10 $\pm$ 2.64E-12	2.70E-10 $\pm$ 2.44E-12
WATER	3.08E-10 $\pm$ 1.31E-12	2.92E-10 $\pm$ 2.76E-12	2.89E-10 $\pm$ 2.79E-12	2.79E-10 $\pm$ 2.64E-12
TISSUE	3.06E-10 $\pm$ 1.33E-12	2.93E-10 $\pm$ 2.88E-12	2.88E-10 $\pm$ 2.79E-12	2.78E-10 $\pm$ 2.68E-12

*Read as 1.22×10^{-14} .Table 3(d) $D(0.07; 45^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^2)$

Material	Energy (keV)			
	50	60	70	80
PMMA	9.22E-15 $\pm$ 4.36E-16	1.13E-14 $\pm$ 5.88E-16	1.55E-14 $\pm$ 6.76E-16	1.09E-14 $\pm$ 7.01E-16
WATER	1.40E-14 $\pm$ 6.00E-16	1.91E-14 $\pm$ 8.31E-16	1.44E-14 $\pm$ 2.84E-15	3.45E-14 $\pm$ 1.27E-15
TISSUE	1.36E-14 $\pm$ 8.44E-16	1.78E-14 $\pm$ 9.67E-16	1.93E-14 $\pm$ 3.23E-15	3.65E-14 $\pm$ 1.30E-15
Material	Energy (MeV)			
	0.1	0.2	0.4	0.7
PMMA	7.00E-10 $\pm$ 6.94E-12	8.69E-10 $\pm$ 6.15E-12	6.14E-10 $\pm$ 4.78E-12	4.49E-10 $\pm$ 1.77E-12
WATER	8.79E-10 $\pm$ 7.94E-12	9.23E-10 $\pm$ 6.58E-12	6.24E-10 $\pm$ 4.75E-12	4.63E-10 $\pm$ 1.86E-12
TISSUE	8.60E-10 $\pm$ 7.63E-12	9.13E-10 $\pm$ 6.59E-12	6.14E-10 $\pm$ 4.69E-12	4.60E-10 $\pm$ 1.90E-12
Material	Energy (MeV)			
	2.0	3.0	4.0	7.0
PMMA	3.21E-10 $\pm$ 1.18E-12	3.07E-10 $\pm$ 2.60E-12	2.96E-10 $\pm$ 2.50E-12	2.83E-10 $\pm$ 2.47E-12
WATER	3.39E-10 $\pm$ 1.32E-12	3.21E-10 $\pm$ 2.87E-12	3.08E-10 $\pm$ 2.73E-12	2.92E-10 $\pm$ 2.50E-12
TISSUE	3.32E-10 $\pm$ 1.29E-12	3.13E-10 $\pm$ 2.74E-12	3.01E-10 $\pm$ 2.55E-12	2.93E-10 $\pm$ 2.53E-12

*Read as 9.22×10^{-15} .Table 3(e) $D(0.07; 60^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^2)$

Material	Energy (keV)			
	50	60	70	80
PMMA	5.66E-15 $\pm$ 3.47E-16	7.31E-15 $\pm$ 3.91E-16	9.01E-15 $\pm$ 4.26E-16	2.54E-15 $\pm$ 2.89E-16
WATER	8.60E-15 $\pm$ 4.84E-16	1.06E-14 $\pm$ 4.51E-16	1.67E-14 $\pm$ 8.03E-16	1.20E-14 $\pm$ 6.41E-16
TISSUE	8.92E-15 $\pm$ 4.14E-16	1.00E-14 $\pm$ 6.47E-16	2.49E-14 $\pm$ 9.75E-16	1.29E-14 $\pm$ 6.62E-16
Material	Energy (MeV)			
	0.1	0.2	0.4	0.7
PMMA	3.15E-10 $\pm$ 1.03E-12	3.97E-10 $\pm$ 4.48E-12	5.92E-10 $\pm$ 4.10E-12	3.37E-10 $\pm$ 1.80E-12
WATER	4.36E-10 $\pm$ 1.84E-12	6.45E-10 $\pm$ 4.89E-12	6.23E-10 $\pm$ 4.37E-12	5.59E-10 $\pm$ 1.93E-12
TISSUE	4.39E-10 $\pm$ 1.78E-12	6.39E-10 $\pm$ 4.75E-12	6.11E-10 $\pm$ 4.20E-12	5.49E-10 $\pm$ 1.89E-12
Material	Energy (MeV)			
	2.0	3.0	4.0	7.0
PMMA	3.74E-10 $\pm$ 1.17E-12	3.42E-10 $\pm$ 2.33E-12	3.29E-10 $\pm$ 2.26E-12	3.10E-10 $\pm$ 2.13E-12
WATER	3.87E-10 $\pm$ 1.32E-12	3.38E-10 $\pm$ 2.36E-12	3.47E-10 $\pm$ 2.46E-12	3.30E-10 $\pm$ 2.24E-12
TISSUE	3.83E-10 $\pm$ 1.23E-12	3.50E-10 $\pm$ 2.41E-12	3.39E-10 $\pm$ 2.38E-12	3.17E-10 $\pm$ 2.22E-12

*Read as 5.66×10^{-15} .Table 3(f) $D(0.07; 75^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^2)$

Material	Energy (keV)			
	50	60	70	80
PMMA	2.12E-15 $\pm$ 1.81E-16	3.04E-15 $\pm$ 1.80E-16	3.59E-15 $\pm$ 1.95E-16	2.87E-15 $\pm$ 2.02E-16
WATER	3.65E-15 $\pm$ 1.90E-16	4.29E-15 $\pm$ 2.37E-16	1.22E-13 $\pm$ 1.63E-14	2.27E-13 $\pm$ 2.04E-13
TISSUE	3.26E-15 $\pm$ 2.10E-16	4.06E-15 $\pm$ 2.82E-16	1.65E-13 $\pm$ 1.82E-14	2.51E-13 $\pm$ 2.15E-13
Material	Energy (MeV)			
	0.1	0.2	0.4	0.7
PMMA	8.38E-11 $\pm$ 1.52E-12	2.28E-10 $\pm$ 2.05E-12	2.75E-10 $\pm$ 2.10E-12	3.47E-10 $\pm$ 1.13E-12
WATER	1.35E-10 $\pm$ 2.02E-12	2.52E-10 $\pm$ 2.24E-12	2.93E-10 $\pm$ 2.22E-12	3.75E-10 $\pm$ 1.24E-12
TISSUE	1.35E-10 $\pm$ 1.98E-12	2.48E-10 $\pm$ 2.20E-12	2.93E-10 $\pm$ 2.22E-12	3.75E-10 $\pm$ 1.24E-12
Material	Energy (MeV)			
	2.0	3.0	4.0	7.0
PMMA	4.55E-10 $\pm$ 1.18E-12	4.40E-10 $\pm$ 2.50E-12	4.20E-10 $\pm$ 2.36E-12	3.76E-10 $\pm$ 1.99E-12
WATER	4.74E-10 $\pm$ 1.25E-12	4.53E-10 $\pm$ 2.61E-12	4.33E-10 $\pm$ 2.48E-12	3.85E-10 $\pm$ 2.05E-12
TISSUE	4.67E-10 $\pm$ 1.22E-12	4.52E-10 $\pm$ 2.65E-12	4.29E-10 $\pm$ 2.45E-12	3.87E-10 $\pm$ 2.08E-12

*Read as 2.12×10^{-15} .

Table 3(e) $D(0.07; 85^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^{-2})$

Material	Energy (keV)				
	50	60	70	80	90
PMMA	5.32E-16 $\pm$ 4.31E-17	6.66E-16 $\pm$ 4.92E-17	8.49E-16 $\pm$ 6.86E-17	3.11E-13 $\pm$ 1.37E-14	5.59E-12 $\pm$ 2.41E-13
WATER	7.91E-16 $\pm$ 6.15E-17	1.04E-15 $\pm$ 7.03E-17	8.20E-15 $\pm$ 2.07E-13	3.25E-12 $\pm$ 4.47E-14	1.90E-11 $\pm$ 3.92E-13
TISSUE	7.37E-16 $\pm$ 6.75E-17	8.95E-16 $\pm$ 7.55E-17	1.37E-14 $\pm$ 2.86E-13	3.71E-12 $\pm$ 4.84E-14	1.55E-11 $\pm$ 4.28E-13
Material	Energy (MeV)				
	0.1	0.2	0.4	0.7	1.0
PMMA	1.53E-11 $\pm$ 3.80E-13	4.89E-11 $\pm$ 5.80E-13	5.79E-11 $\pm$ 5.89E-13	7.28E-11 $\pm$ 2.90E-13	8.74E-11 $\pm$ 7.09E-13
WATER	2.75E-11 $\pm$ 5.54E-13	5.24E-11 $\pm$ 6.13E-13	6.23E-11 $\pm$ 6.35E-13	7.78E-11 $\pm$ 3.08E-13	9.13E-11 $\pm$ 7.80E-13
TISSUE	2.63E-11 $\pm$ 5.24E-13	5.26E-11 $\pm$ 6.24E-13	6.24E-11 $\pm$ 6.19E-13	7.85E-11 $\pm$ 3.11E-13	9.49E-11 $\pm$ 7.70E-13
Material	Energy (MeV)				
	2.0	3.0	4.0	7.0	10.0
PMMA	1.41E-10 $\pm$ 4.35E-13	1.93E-10 $\pm$ 1.20E-12	2.40E-10 $\pm$ 1.41E-12	3.56E-10 $\pm$ 1.87E-12	4.22E-10 $\pm$ 2.06E-12
WATER	1.51E-10 $\pm$ 4.64E-13	2.06E-10 $\pm$ 1.30E-12	2.55E-10 $\pm$ 1.48E-12	3.75E-10 $\pm$ 1.97E-12	4.43E-10 $\pm$ 2.16E-12
TISSUE	1.51E-10 $\pm$ 4.64E-13	2.07E-10 $\pm$ 1.29E-12	2.55E-10 $\pm$ 1.48E-12	3.71E-10 $\pm$ 1.94E-12	4.41E-10 $\pm$ 2.20E-12

*Read as 5.32×10^{-16} Table 3(f) $D(0.07; 89^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^{-2})$

Material	Energy (keV)				
	50	60	70	80	90
PMMA	8.32E-17 $\pm$ 6.75E-18	1.04E-16 $\pm$ 9.38E-18	1.19E-16 $\pm$ 1.13E-17	3.78E-14 $\pm$ 2.09E-15	6.98E-13 $\pm$ 3.91E-14
WATER	1.16E-16 $\pm$ 8.77E-18	1.22E-16 $\pm$ 1.06E-17	1.49E-15 $\pm$ 4.32E-16	4.14E-13 $\pm$ 7.26E-15	1.86E-12 $\pm$ 6.59E-14
TISSUE	1.06E-16 $\pm$ 9.59E-18	1.42E-16 $\pm$ 1.11E-17	2.49E-15 $\pm$ 6.18E-16	4.71E-13 $\pm$ 7.64E-15	1.95E-12 $\pm$ 6.73E-14
Material	Energy (MeV)				
	0.1	0.2	0.4	0.7	1.0
PMMA	1.93E-12 $\pm$ 6.20E-14	3.80E-12 $\pm$ 8.91E-14	6.48E-12 $\pm$ 8.77E-14	7.67E-12 $\pm$ 4.21E-14	9.14E-12 $\pm$ 1.08E-13
WATER	3.39E-12 $\pm$ 8.42E-14	6.45E-12 $\pm$ 9.80E-14	7.08E-12 $\pm$ 9.74E-14	8.41E-12 $\pm$ 4.74E-14	9.75E-12 $\pm$ 1.14E-13
TISSUE	3.43E-12 $\pm$ 8.50E-14	6.50E-12 $\pm$ 9.88E-14	6.93E-12 $\pm$ 9.42E-14	8.39E-12 $\pm$ 4.65E-14	9.84E-12 $\pm$ 1.13E-13
Material	Energy (MeV)				
	2.0	3.0	4.0	7.0	10.0
PMMA	1.41E-11 $\pm$ 6.49E-14	1.91E-11 $\pm$ 1.81E-13	2.41E-11 $\pm$ 2.12E-13	3.82E-11 $\pm$ 3.00E-13	5.29E-11 $\pm$ 3.87E-13
WATER	1.51E-11 $\pm$ 6.92E-14	2.04E-11 $\pm$ 1.94E-13	2.53E-11 $\pm$ 2.24E-13	4.10E-11 $\pm$ 3.22E-13	5.61E-11 $\pm$ 4.11E-13
TISSUE	1.51E-11 $\pm$ 6.90E-14	2.03E-11 $\pm$ 1.92E-13	2.56E-11 $\pm$ 2.26E-13	4.09E-11 $\pm$ 3.23E-13	5.71E-11 $\pm$ 4.18E-13

*Read as 8.32×10^{-17} .Table 4(a) $D(3; 0^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^{-2})$

Material	Energy (MeV)		
	0.6	0.8	1.0
PMMA	2.23E-14 $\pm$ 2.86E-16	1.06E-12 $\pm$ 3.58E-14	1.53E-10 $\pm$ 1.13E-12
WATER	3.06E-14 $\pm$ 3.73E-16	3.20E-11 $\pm$ 2.44E-13	2.87E-10 $\pm$ 1.61E-12
TISSUE	3.08E-14 $\pm$ 4.32E-16	3.83E-11 $\pm$ 2.67E-13	2.96E-10 $\pm$ 1.61E-12
Material	Energy (MeV)		
	2.0	3.0	4.0
PMMA	4.80E-10 $\pm$ 7.50E-13	3.80E-10 $\pm$ 1.25E-12	3.35E-10 $\pm$ 9.87E-13
WATER	4.95E-10 $\pm$ 7.86E-13	3.89E-10 $\pm$ 1.29E-12	3.44E-10 $\pm$ 1.03E-12
TISSUE	4.88E-10 $\pm$ 7.78E-13	3.83E-10 $\pm$ 1.29E-12	3.40E-10 $\pm$ 1.04E-12

*Read as 2.23×10^{-14} .Table 4(b) $D(3; 15^\circ)$ for a parallel beam of electrons impinging a slab phantom $(Gy\ cm^{-2})$

Material	Energy (MeV)		
	0.6	0.8	1.0
PMMA	2.16E-14 $\pm$ 2.80E-16	7.57E-13 $\pm$ 2.90E-14	1.34E-10 $\pm$ 1.06E-12
WATER	3.04E-14 $\pm$ 4.23E-16	2.64E-11 $\pm$ 2.17E-13	2.59E-10 $\pm$ 1.32E-12
TISSUE	2.91E-14 $\pm$ 3.63E-16	3.17E-11 $\pm$ 2.40E-13	2.67E-10 $\pm$ 1.53E-12
Material	Energy (MeV)		
	2.0	3.0	4.0
PMMA	4.73E-10 $\pm$ 7.50E-13	3.95E-10 $\pm$ 1.35E-12	3.45E-10 $\pm$ 1.07E-12
WATER	4.94E-10 $\pm$ 8.01E-13	4.06E-10 $\pm$ 1.41E-12	3.55E-10 $\pm$ 1.13E-12
TISSUE	4.87E-10 $\pm$ 7.88E-13	3.98E-10 $\pm$ 1.37E-12	3.51E-10 $\pm$ 1.12E-12

*Read as 2.16×10^{-14} .

Table 4(c) $D(3; 30^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	0.6	0.8	1.0
PMMA	$1.87E-14 \pm 2.45E-16$	$3.47E-13 \pm 1.80E-14$	$8.63E-11 \pm 8.20E-13$
WATER	$2.59E-14 \pm 3.15E-16$	$1.46E-11 \pm 1.53E-13$	$1.81E-10 \pm 1.23E-12$
TISSUE	$2.52E-14 \pm 3.74E-16$	$1.76E-11 \pm 1.68E-13$	$1.89E-10 \pm 1.25E-12$
Material	Energy (MeV)		
	1.5	3.0	4.0
PMMA	$4.25E-10 \pm 7.06E-13$	$4.17E-10 \pm 1.48E-12$	$3.82E-10 \pm 1.33E-12$
WATER	$4.60E-10 \pm 7.68E-13$	$4.35E-10 \pm 1.57E-12$	$3.92E-10 \pm 1.36E-12$
TISSUE	$4.55E-10 \pm 7.62E-13$	$4.31E-10 \pm 1.59E-12$	$3.86E-10 \pm 1.35E-12$

*Read as 1.87×10^{-14} .

Table 4(d) $D(3; 45^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	0.6	0.8	1.0
PMMA	$1.47E-14 \pm 2.03E-16$	$9.23E-14 \pm 7.23E-15$	$3.79E-11 \pm 4.96E-13$
WATER	$2.04E-14 \pm 2.64E-16$	$5.33E-12 \pm 8.22E-14$	$9.66E-11 \pm 8.39E-13$
TISSUE	$1.99E-14 \pm 2.62E-16$	$6.56E-12 \pm 9.18E-14$	$1.00E-10 \pm 8.48E-13$
Material	Energy (MeV)		
	2.0	3.0	4.0
PMMA	$3.16E-10 \pm 5.83E-13$	$3.91E-10 \pm 1.47E-12$	$4.09E-10 \pm 1.50E-12$
WATER	$3.56E-10 \pm 6.49E-13$	$4.22E-10 \pm 1.61E-12$	$4.32E-10 \pm 1.61E-12$
TISSUE	$3.54E-10 \pm 6.45E-13$	$4.21E-10 \pm 1.59E-12$	$4.29E-10 \pm 1.61E-12$

*Read as 1.47×10^{-14} .

Table 4(e) $D(3; 60^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	0.6	0.8	1.0
PMMA	$9.64E-15 \pm 1.44E-16$	$2.37E-14 \pm 1.88E-15$	$1.09E-11 \pm 2.25E-13$
WATER	$1.30E-14 \pm 2.12E-16$	$1.14E-12 \pm 3.09E-14$	$3.55E-11 \pm 4.36E-13$
TISSUE	$1.26E-14 \pm 2.05E-16$	$1.43E-12 \pm 3.52E-14$	$3.70E-11 \pm 4.44E-13$
Material	Energy (MeV)		
	2.0	3.0	4.0
PMMA	$1.72E-10 \pm 3.86E-13$	$2.57E-10 \pm 1.08E-12$	$3.16E-10 \pm 1.24E-12$
WATER	$2.03E-10 \pm 4.37E-13$	$2.86E-10 \pm 1.20E-12$	$3.47E-10 \pm 1.35E-12$
TISSUE	$2.02E-10 \pm 4.36E-13$	$2.86E-10 \pm 1.19E-12$	$3.47E-10 \pm 1.36E-12$

*Read as 9.64×10^{-15} .

Table 4(f) $D(3; 75^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	0.6	0.8	1.0
PMMA	$4.03E-15 \pm 6.80E-17$	$7.23E-15 \pm 1.63E-16$	$1.69E-12 \pm 6.30E-14$
WATER	$5.35E-15 \pm 8.16E-17$	$1.36E-13 \pm 7.45E-15$	$7.25E-12 \pm 1.43E-13$
TISSUE	$5.44E-15 \pm 9.88E-17$	$1.89E-13 \pm 8.86E-15$	$7.95E-12 \pm 1.49E-13$
Material	Energy (MeV)		
	2.0	3.0	4.0
PMMA	$5.48E-11 \pm 1.66E-13$	$8.85E-11 \pm 4.89E-13$	$1.19E-10 \pm 5.84E-13$
WATER	$6.74E-11 \pm 1.92E-13$	$1.03E-10 \pm 5.52E-13$	$1.37E-10 \pm 6.70E-13$
TISSUE	$6.80E-11 \pm 1.93E-13$	$1.04E-10 \pm 5.54E-13$	$1.37E-10 \pm 6.70E-13$

*Read as 4.03×10^{-15} .

Table 4(a) $D(3; 85^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	0.6	0.8	1.0
PMMA	$9.16E-16 \pm 2.26E-17$	$1.57E-15 \pm 3.28E-17$	$2.24E-13 \pm 1.34E-14$
WATER	$1.17E-15 \pm 3.03E-17$	$1.67E-14 \pm 1.45E-15$	$1.12E-12 \pm 3.28E-14$
TISSUE	$1.16E-15 \pm 3.06E-17$	$2.14E-14 \pm 1.70E-15$	$1.20E-12 \pm 3.35E-14$
Material	Energy (MeV)		
	2.0	3.0	4.0
PMMA	$1.01E-11 \pm 4.31E-14$	$1.68E-11 \pm 1.30E-13$	$2.23E-11 \pm 1.58E-13$
WATER	$1.26E-11 \pm 5.04E-14$	$1.96E-11 \pm 1.47E-13$	$2.57E-11 \pm 1.78E-13$
TISSUE	$1.28E-11 \pm 5.06E-14$	$1.99E-11 \pm 1.49E-13$	$2.63E-11 \pm 1.82E-13$

*Read as 9.16×10^{-16} .

Table 4(b) $D(3; 89^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	0.6	0.8	1.0
PMMA	$9.93E-17 \pm 2.82E-18$	$1.74E-16 \pm 4.17E-18$	$2.29E-14 \pm 1.90E-15$
WATER	$1.27E-16 \pm 3.30E-18$	$1.18E-15 \pm 1.61E-16$	$1.09E-13 \pm 4.49E-15$
TISSUE	$1.35E-16 \pm 3.32E-18$	$1.88E-15 \pm 2.15E-16$	$1.19E-13 \pm 4.73E-15$
Material	Energy (MeV)		
	2.0	3.0	4.0
PMMA	$9.82E-13 \pm 6.14E-15$	$1.62E-12 \pm 1.89E-14$	$2.12E-12 \pm 2.25E-14$
WATER	$1.27E-12 \pm 7.41E-15$	$1.91E-12 \pm 2.16E-14$	$2.48E-12 \pm 2.60E-14$
TISSUE	$1.27E-12 \pm 7.35E-15$	$1.93E-12 \pm 2.16E-14$	$2.46E-12 \pm 2.58E-14$

*Read as 9.93×10^{-17} .

Table 5(a) $D(10; 0^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	2.0	2.5	3.0
PMMA	$1.27E-13^* \pm 1.52E-14$	$3.30E-11 \pm 3.11E-13$	$2.06E-10 \pm 1.60E-12$
WATER	$1.49E-12 \pm 6.63E-14$	$1.36E-10 \pm 6.41E-13$	$3.23E-10 \pm 2.02E-12$
TISSUE	$2.30E-12 \pm 8.45E-14$	$1.45E-10 \pm 6.51E-13$	$3.29E-10 \pm 2.00E-12$
Material	Energy (MeV)		
	4.0	7.0	10.0
PMMA	$4.07E-10 \pm 1.97E-12$	$3.63E-10 \pm 1.38E-12$	$3.26E-10 \pm 1.11E-12$
WATER	$4.55E-10 \pm 2.13E-12$	$3.67E-10 \pm 1.36E-12$	$3.35E-10 \pm 1.20E-12$
TISSUE	$4.50E-10 \pm 2.11E-12$	$3.63E-10 \pm 1.38E-12$	$3.32E-10 \pm 1.17E-12$

*Read as 1.27×10^{-13} .

Table 5(b) $D(10; 15^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	2.0	2.5	3.0
PMMA	$1.21E-13^* \pm 1.31E-14$	$2.63E-11 \pm 2.73E-13$	$1.78E-10 \pm 1.48E-12$
WATER	$1.18E-12 \pm 5.94E-14$	$1.15E-10 \pm 5.84E-13$	$2.87E-10 \pm 1.89E-12$
TISSUE	$1.67E-12 \pm 6.84E-14$	$1.24E-10 \pm 5.92E-13$	$2.95E-10 \pm 1.88E-12$
Material	Energy (MeV)		
	4.0	7.0	10.0
PMMA	$3.81E-10 \pm 1.92E-12$	$3.73E-10 \pm 1.48E-12$	$3.32E-10 \pm 1.14E-12$
WATER	$4.38E-10 \pm 2.11E-12$	$3.79E-10 \pm 1.51E-12$	$3.41E-10 \pm 1.23E-12$
TISSUE	$4.33E-10 \pm 2.10E-12$	$3.73E-10 \pm 1.48E-12$	$3.36E-10 \pm 1.19E-12$

*Read as 1.21×10^{-13} .

Table 5(c) $D(10; 30^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	2.0	2.5	3.0
PMMA	$1.08E-13 \pm 1.16E-14$	$1.28E-11 \pm 1.82E-13$	$1.14E-10 \pm 1.14E-12$
WATER	$5.22E-13 \pm 3.63E-14$	$6.92E-11 \pm 4.30E-13$	$2.03E-10 \pm 1.55E-12$
TISSUE	$7.30E-13 \pm 4.00E-14$	$7.53E-11 \pm 4.43E-13$	$2.09E-10 \pm 1.54E-12$
Material	Energy (MeV)		
	4.0	7.0	10.0
PMMA	$2.95E-10 \pm 1.66E-12$	$3.89E-10 \pm 1.65E-12$	$3.54E-10 \pm 1.34E-12$
WATER	$3.53E-10 \pm 1.86E-12$	$4.05E-10 \pm 1.79E-12$	$3.64E-10 \pm 1.38E-12$
TISSUE	$3.51E-10 \pm 1.83E-12$	$4.00E-10 \pm 1.69E-12$	$3.60E-10 \pm 1.40E-12$

*Read as 1.08×10^{-13} .

Table 5(d) $D(10; 45^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	2.0	2.5	3.0
PMMA	$8.95E-14 \pm 1.00E-14$	$3.39E-12 \pm 8.28E-14$	$4.99E-11 \pm 7.10E-13$
WATER	$1.95E-13 \pm 1.80E-14$	$2.87E-11 \pm 2.54E-13$	$1.06E-10 \pm 1.05E-12$
TISSUE	$2.38E-13 \pm 1.77E-14$	$3.08E-11 \pm 2.61E-13$	$1.09E-10 \pm 1.04E-12$
Material	Energy (MeV)		
	4.0	7.0	10.0
PMMA	$1.74E-10 \pm 1.21E-12$	$3.45E-10 \pm 1.61E-12$	$3.84E-10 \pm 1.64E-12$
WATER	$2.24E-10 \pm 1.38E-12$	$3.79E-10 \pm 1.78E-12$	$4.03E-10 \pm 1.73E-12$
TISSUE	$2.28E-10 \pm 1.41E-12$	$3.76E-10 \pm 1.74E-12$	$3.97E-10 \pm 1.69E-12$

*Read as 8.95×10^{-14} .

Table 5(e) $D(10; 60^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	2.0	2.5	3.0
PMMA	$7.31E-14 \pm 9.38E-15$	$6.03E-13 \pm 2.77E-14$	$1.27E-11 \pm 2.93E-13$
WATER	$8.94E-14 \pm 1.03E-14$	$7.06E-12 \pm 1.07E-13$	$3.60E-11 \pm 5.36E-13$
TISSUE	$8.20E-14 \pm 3.59E-15$	$7.95E-12 \pm 1.13E-13$	$3.81E-11 \pm 5.36E-13$
Material	Energy (MeV)		
	4.0	7.0	10.0
PMMA	$6.94E-11 \pm 6.79E-13$	$1.95E-10 \pm 1.08E-12$	$2.93E-10 \pm 1.39E-12$
WATER	$1.02E-10 \pm 8.32E-13$	$2.34E-10 \pm 1.27E-12$	$3.29E-10 \pm 1.57E-12$
TISSUE	$1.03E-10 \pm 8.50E-13$	$2.35E-10 \pm 1.27E-12$	$3.28E-10 \pm 1.55E-12$

*Read as 7.31×10^{-14} .

Table 5(f) $D(10; 75^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	2.0	2.5	3.0
PMMA	$2.53E-14 \pm 3.24E-15$	$8.64E-14 \pm 5.31E-15$	$1.73E-12 \pm 7.98E-14$
WATER	$3.34E-14 \pm 4.39E-15$	$9.40E-13 \pm 2.77E-14$	$6.32E-12 \pm 1.58E-13$
TISSUE	$3.31E-14 \pm 4.85E-16$	$1.02E-12 \pm 2.85E-14$	$7.10E-12 \pm 1.68E-13$
Material	Energy (MeV)		
	4.0	7.0	10.0
PMMA	$1.44E-11 \pm 2.29E-13$	$3.68E-11 \pm 4.57E-13$	$9.63E-11 \pm 6.22E-13$
WATER	$2.49E-11 \pm 3.08E-13$	$7.16E-11 \pm 5.25E-13$	$1.16E-10 \pm 7.08E-13$
TISSUE	$2.52E-11 \pm 3.07E-13$	$7.18E-11 \pm 5.23E-13$	$1.17E-10 \pm 7.17E-13$

*Read as 2.53×10^{-14} .

Table 5(g) $D(10:85^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	2.0	2.5	3.0
PMMA	$9.06E-15 \pm 1.47E-13$	$1.34E-14 \pm 1.21E-13$	$2.03E-13 \pm 1.60E-14$
WATER	$7.70E-15 \pm 1.01E-15$	$9.64E-14 \pm 4.83E-15$	$9.22E-13 \pm 3.70E-14$
TISSUE	$7.18E-15 \pm 1.34E-16$	$1.19E-13 \pm 5.69E-13$	$9.16E-13 \pm 3.71E-14$
Material	Energy (MeV)		
	4.0	7.0	10.0
PMMA	$2.00E-12 \pm 5.09E-14$	$9.28E-12 \pm 1.08E-13$	$1.60E-11 \pm 1.50E-13$
WATER	$3.88E-12 \pm 7.21E-14$	$1.24E-11 \pm 1.33E-13$	$2.00E-11 \pm 1.75E-13$
TISSUE	$3.07E-12 \pm 7.19E-14$	$1.24E-11 \pm 1.30E-13$	$2.00E-11 \pm 1.80E-13$

*Read as 9.06×10^{-15} .

Table 5(h) $D(10:80^\circ)$ for a parallel beam of electrons impinging a slab phantom
($Gy\ cm^2$)

Material	Energy (MeV)		
	2.0	2.5	3.0
PMMA	$5.68E-16 \pm 1.25E-16$	$1.68E-15 \pm 1.86E-16$	$1.89E-14 \pm 2.24E-15$
WATER	$6.06E-16 \pm 1.32E-16$	$8.48E-15 \pm 6.72E-16$	$8.34E-14 \pm 5.02E-15$
TISSUE	$7.28E-16 \pm 1.59E-17$	$9.92E-15 \pm 6.58E-16$	$8.56E-14 \pm 4.82E-15$
Material	Energy (MeV)		
	4.0	7.0	10.0
PMMA	$1.93E-13 \pm 7.12E-15$	$8.63E-13 \pm 1.52E-14$	$1.47E-12 \pm 2.11E-14$
WATER	$3.59E-13 \pm 9.62E-15$	$1.14E-12 \pm 1.85E-14$	$1.82E-12 \pm 2.40E-14$
TISSUE	$3.71E-13 \pm 1.01E-14$	$1.18E-12 \pm 1.84E-14$	$1.83E-12 \pm 2.46E-14$

*Read as 5.68×10^{-16} .

Table 6 $D(7mg\ cm^{-2}; \alpha)$ for a parallel beam of electrons impinging a slab phantom of PMMA
($Gy\ cm^2$)

α	Energy (keV)				
	50	60	70	80	90
0°	$1.64E-14 \pm 8.49E-16$	$2.53E-14 \pm 1.09E-15$	$3.21E-10 \pm 1.51E-12$	$1.24E-09 \pm 2.63E-12$	$1.63E-09 \pm 3.89E-12$
15°	$1.63E-14 \pm 8.00E-16$	$2.21E-14 \pm 9.83E-16$	$2.59E-10 \pm 1.33E-12$	$1.13E-09 \pm 2.48E-12$	$1.52E-09 \pm 3.73E-12$
30°	$1.25E-14 \pm 6.76E-16$	$1.83E-14 \pm 7.91E-16$	$1.32E-10 \pm 9.12E-13$	$8.04E-10 \pm 3.01E-12$	$1.19E-09 \pm 3.20E-12$
45°	$1.11E-14 \pm 5.11E-16$	$1.40E-14 \pm 6.41E-16$	$4.11E-11 \pm 4.66E-13$	$4.25E-10 \pm 1.36E-12$	$1.41E-10 \pm 2.37E-12$
60°	$6.57E-15 \pm 3.31E-16$	$8.70E-15 \pm 3.75E-16$	$6.31E-12 \pm 1.55E-13$	$1.84E-10 \pm 7.09E-12$	$3.35E-10 \pm 1.38E-12$
75°	$2.84E-15 \pm 1.59E-16$	$3.89E-15 \pm 2.71E-16$	$4.73E-13 \pm 3.14E-14$	$3.05E-11 \pm 2.30E-13$	$9.00E-11 \pm 5.30E-13$
α	Energy (MeV)				
	0.1	0.2	0.4	0.7	1.0
0°	$1.68E-09 \pm 3.73E-12$	$7.91E-10 \pm 2.00E-12$	$4.47E-10 \pm 2.13E-12$	$3.46E-10 \pm 1.76E-12$	$3.12E-10 \pm 3.19E-12$
15°	$1.60E-09 \pm 3.61E-12$	$8.25E-10 \pm 2.06E-12$	$4.63E-10 \pm 2.16E-12$	$3.52E-10 \pm 1.73E-12$	$3.14E-10 \pm 3.14E-12$
30°	$1.32E-09 \pm 3.17E-12$	$9.00E-10 \pm 2.12E-12$	$5.19E-10 \pm 2.30E-12$	$3.81E-10 \pm 1.77E-12$	$3.38E-10 \pm 3.30E-12$
45°	$8.95E-10 \pm 2.44E-12$	$8.88E-10 \pm 2.01E-12$	$6.03E-10 \pm 2.31E-12$	$4.38E-10 \pm 1.82E-12$	$3.76E-10 \pm 3.21E-12$
60°	$4.58E-10 \pm 1.53E-12$	$6.34E-10 \pm 1.48E-12$	$6.31E-10 \pm 2.16E-12$	$5.27E-10 \pm 1.83E-12$	$4.46E-10 \pm 3.12E-12$
75°	$1.40E-10 \pm 6.30E-13$	$2.53E-10 \pm 7.06E-13$	$3.13E-10 \pm 1.15E-12$	$3.78E-10 \pm 1.24E-12$	$4.11E-10 \pm 2.57E-12$
85°	$2.76E-11 \pm 5.17E-13$	$5.36E-11 \pm 6.11E-13$	$6.30E-11 \pm 6.18E-13$	$8.02E-11 \pm 3.14E-13$	$9.76E-11 \pm 7.82E-13$
89°	$3.45E-12 \pm 8.10E-14$	$6.50E-12 \pm 9.61E-14$	$6.98E-12 \pm 9.23E-14$	$8.60E-12 \pm 4.71E-14$	$1.01E-11 \pm 1.16E-13$
Material	Energy (MeV)				
	2.0	3.0	4.0	7.0	10.0
0°	$2.79E-10 \pm 1.35E-12$	$2.71E-10 \pm 2.93E-12$	$2.68E-10 \pm 2.88E-12$	$2.65E-10 \pm 2.84E-12$	$2.62E-10 \pm 2.64E-12$
15°	$2.82E-10 \pm 1.34E-12$	$2.73E-10 \pm 2.80E-12$	$2.69E-10 \pm 2.73E-12$	$2.71E-10 \pm 2.93E-12$	$2.63E-10 \pm 2.63E-12$
30°	$2.95E-10 \pm 1.28E-12$	$2.78E-10 \pm 2.63E-12$	$2.73E-10 \pm 2.68E-12$	$2.70E-10 \pm 2.63E-12$	$2.67E-10 \pm 2.58E-12$
45°	$3.20E-10 \pm 1.26E-12$	$2.96E-10 \pm 2.47E-12$	$2.94E-10 \pm 2.62E-12$	$2.81E-10 \pm 2.38E-12$	$2.77E-10 \pm 2.40E-12$
60°	$3.68E-10 \pm 1.20E-12$	$3.44E-10 \pm 2.45E-12$	$3.23E-10 \pm 2.27E-12$	$3.11E-10 \pm 2.27E-12$	$2.99E-10 \pm 2.16E-12$
75°	$4.55E-10 \pm 1.19E-12$	$4.35E-10 \pm 2.54E-12$	$4.05E-10 \pm 2.22E-12$	$3.72E-10 \pm 2.00E-12$	$3.57E-10 \pm 1.91E-12$
85°	$1.54E-10 \pm 4.68E-13$	$2.11E-10 \pm 1.31E-12$	$2.60E-10 \pm 1.49E-12$	$3.78E-10 \pm 1.96E-12$	$4.36E-10 \pm 2.12E-12$
89°	$1.54E-11 \pm 6.99E-14$	$2.09E-11 \pm 1.94E-13$	$2.59E-11 \pm 2.29E-13$	$4.23E-11 \pm 3.32E-13$	$5.81E-11 \pm 4.25E-13$

*Read as 1.64×10^{-14} .

Table 7 $D(300mg\ cm^{-2}; \alpha)$ for a parallel beam of electrons impinging a slab phantom of PMMA
($Gy\ cm^{-2}$)

α	Energy (MeV)			
	0.6	0.8	1.0	1.5
0°	2.73E-14 $\pm$ 3.40E-16	5.96E-11 $\pm$ 3.31E-13	3.29E-10 $\pm$ 1.65E-12	5.10E-10 $\pm$ 8.25E-13
15°	2.51E-14 $\pm$ 3.19E-16	5.03E-11 $\pm$ 2.99E-13	2.97E-10 $\pm$ 1.55E-12	4.88E-10 $\pm$ 8.07E-13
30°	2.28E-14 $\pm$ 2.96E-16	2.88E-11 $\pm$ 2.15E-13	2.13E-10 $\pm$ 1.29E-12	4.12E-10 $\pm$ 7.26E-13
45°	1.75E-14 $\pm$ 2.35E-16	1.08E-11 $\pm$ 1.18E-13	1.17E-10 $\pm$ 8.93E-13	2.87E-10 $\pm$ 5.79E-13
60°	1.10E-14 $\pm$ 1.72E-16	2.40E-12 $\pm$ 4.60E-14	4.35E-11 $\pm$ 4.69E-13	1.47E-10 $\pm$ 3.69E-13
75°	4.60E-15 $\pm$ 7.62E-17	2.97E-13 $\pm$ 1.13E-14	9.16E-12 $\pm$ 1.38E-13	4.55E-11 $\pm$ 1.56E-13
85°	9.89E-16 $\pm$ 2.08E-17	3.46E-14 $\pm$ 2.19E-15	1.36E-12 $\pm$ 3.53E-14	8.22E-12 $\pm$ 3.95E-14
89°	1.15E-16 $\pm$ 3.74E-18	3.41E-15 $\pm$ 3.12E-16	1.41E-13 $\pm$ 5.11E-15	8.17E-13 $\pm$ 5.70E-15
α	Energy (MeV)			
	2.0	3.0	4.0	10.0
0°	4.58E-10 $\pm$ 7.31E-13	3.61E-10 $\pm$ 1.18E-12	3.26E-10 $\pm$ 1.01E-12	2.95E-10 $\pm$ 7.65E-13
15°	4.62E-10 $\pm$ 7.41E-13	3.73E-10 $\pm$ 1.25E-12	3.32E-10 $\pm$ 1.01E-12	2.98E-10 $\pm$ 8.13E-13
30°	4.43E-10 $\pm$ 7.35E-13	4.09E-10 $\pm$ 1.49E-12	3.65E-10 $\pm$ 1.23E-12	3.03E-10 $\pm$ 7.98E-13
45°	3.53E-10 $\pm$ 6.31E-13	4.08E-10 $\pm$ 1.53E-12	4.08E-10 $\pm$ 1.50E-12	3.22E-10 $\pm$ 9.21E-13
60°	2.05E-10 $\pm$ 4.32E-13	2.87E-10 $\pm$ 1.12E-12	3.49E-10 $\pm$ 1.36E-12	3.92E-10 $\pm$ 1.35E-12
75°	6.86E-11 $\pm$ 1.91E-13	1.04E-10 $\pm$ 5.44E-13	1.38E-10 $\pm$ 6.61E-13	3.17E-10 $\pm$ 1.23E-12
85°	1.28E-11 $\pm$ 3.01E-14	1.96E-11 $\pm$ 1.46E-13	2.61E-11 $\pm$ 1.78E-13	6.64E-11 $\pm$ 3.64E-13
89°	1.28E-12 $\pm$ 7.30E-15	1.93E-12 $\pm$ 2.15E-14	2.48E-12 $\pm$ 2.55E-14	6.08E-12 $\pm$ 5.24E-14

*Read as 2.73×10^{-14} .

Table 8 $D(100mg\ cm^{-2}; \alpha)$ for a parallel beam of electrons impinging a slab phantom of PMMA
($Gy\ cm^{-2}$)

α	Energy (MeV)			
	2.0	2.5	3.0	
0°	6.51E-12 $\pm$ 1.41E-13	1.80E-10 $\pm$ 7.04E-13	3.48E-10 $\pm$ 1.99E-12	
15°	4.74E-12 $\pm$ 1.18E-13	1.54E-10 $\pm$ 6.39E-13	3.14E-10 $\pm$ 1.89E-12	
30°	2.05E-12 $\pm$ 7.24E-14	9.76E-11 $\pm$ 4.95E-13	2.28E-10 $\pm$ 1.58E-12	
45°	5.20E-13 $\pm$ 3.03E-14	4.19E-11 $\pm$ 2.98E-13	1.20E-10 $\pm$ 1.05E-12	
60°	1.13E-13 $\pm$ 8.18E-15	1.09E-11 $\pm$ 1.30E-13	4.42E-11 $\pm$ 5.70E-13	
75°	3.85E-14 $\pm$ 2.95E-15	1.46E-12 $\pm$ 3.32E-14	7.92E-12 $\pm$ 1.74E-13	
85°	6.78E-15 $\pm$ 1.08E-16	1.66E-13 $\pm$ 6.91E-15	1.07E-12 $\pm$ 3.63E-14	
89°	7.58E-16 $\pm$ 4.10E-17	1.55E-14 $\pm$ 8.84E-16	1.04E-13 $\pm$ 5.44E-15	
α	Energy (MeV)			
	4.0	7.0	10.0	
0°	4.39E-10 $\pm$ 2.02E-12	3.46E-10 $\pm$ 1.30E-12	3.20E-10 $\pm$ 1.08E-12	
15°	4.22E-10 $\pm$ 1.96E-12	3.57E-10 $\pm$ 1.38E-12	3.25E-10 $\pm$ 1.15E-12	
30°	3.53E-10 $\pm$ 1.78E-12	3.84E-10 $\pm$ 1.63E-12	3.41E-10 $\pm$ 1.28E-12	
45°	2.34E-10 $\pm$ 1.40E-12	3.73E-10 $\pm$ 1.69E-12	3.81E-10 $\pm$ 1.59E-12	
60°	1.07E-10 $\pm$ 8.32E-13	2.38E-10 $\pm$ 1.26E-12	3.30E-10 $\pm$ 1.52E-12	
75°	2.67E-11 $\pm$ 3.13E-13	7.41E-11 $\pm$ 5.38E-13	1.19E-10 $\pm$ 7.16E-13	
85°	4.15E-12 $\pm$ 7.35E-14	1.27E-11 $\pm$ 1.32E-13	2.04E-11 $\pm$ 1.70E-13	
89°	3.81E-13 $\pm$ 1.00E-14	1.17E-12 $\pm$ 1.88E-14	1.84E-12 $\pm$ 2.39E-14	

*Read as 6.51×10^{-12} .

Fig. 1 CSDA range of water and PMMA.

Fig. 2 Depth dose for a broad parallel beam of electrons normally incident on water.
a) 50, 80 and 400 keV, b) 0.8, 2.0 and 10 MeV.

Fig. 4 EGS4-generated tracks of particles produced with 100 incident electrons in tissue. The charged particle and photon tracks are depicted as solid and dotted lines, respectively.

28

Fig. 3 Depth dose for a broad parallel beam of electrons with an incident angle 75° on water. a) 50, 80 and 400 keV. b) 0.8, 2.0 and 10 MeV.

27

Fig. 5 Absorbed doses as a function of the incident electron energy.
a) $D(0.07 \text{ mm}, 0^\circ)$, b) $D(3.0 \text{ mm}, 0^\circ)$, c) $D(10.0 \text{ mm}, 0^\circ)$

Fig. 6 Absorbed doses of tissue as a function of the incident angle (α). The results are plotted as ratios to $D(d, 0^\circ)$ at each depth.
a) $D(0.07 \text{ mm}, \alpha)$, b) $D(3.0 \text{ mm}, \alpha)$, c) $D(10.0 \text{ mm}, \alpha)$.

Fig. 7 Comparison of the absorbed dose ($D(d, \alpha)$) calculated for different materials.
The results are plotted as ratios to the values of tissue.
a) $D(0.07, \alpha)$, b) $D(3.0, \alpha)$, c) $D(10.0, \alpha)$.

Fig. 8 Comparison of the absorbed dose ($D(d, \alpha)$) calculated for different materials. The results are plotted as ratios to the values of tissue.
a) $D(7 \text{ mg cm}^{-2}, \alpha)$, b) $D(300 \text{ mg cm}^{-2}, \alpha)$, c) $D(1000 \text{ mg cm}^{-2}, \alpha)$.