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Dose Equivalents per Unit Fluence for Tissue Equivalent Slab Phantoms for Electrons from 50 keV to 10 MeV

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Abstract - The MCNPE-BO and MCNP4 Monte Carlo electron-photon codes have been used to calculate the dose equivalent per unit fluence at various depths in tissue equivalent slab phantoms for broad parallel beams of mono-energetic electrons with energies from 50 keV to 10 MeV. The study is carried out in the framework of the activities of a ICRP/ICRU Joint Task Group with the support of EURADOS WG4 (Computational Dosimetry). Some preliminary results and comparisons as well as a general discussion on the performances of the codes are presented, which demonstrate a satisfactory agreement among the results obtained using the two codes and those of other authors.

1. INTRODUCTION

After the publication of the "1990 Recommendations of the International Commission on Radiological Protection" (ICRP 60) /1/, an ICRP/ICRU Joint Task Group has been created to revise the ICRP Publication 51 "Data for Use in Protection Against External Radiation" /2/. The aim is to include the new computational evaluations of effective doses as well as the new calculated values of the operational quantities.

In this framework particular interest has been focused on the need of updating data for electron and beta radiations. Currently available data can be derived at the moment from a limited number of scientific works that do not provide a complete and homogeneous set of data. A subgroup of the EURADOS WG4 (Computational Dosimetry) has been therefore created as a support to the ICRP/ICRU Joint Task Group with the specific aim of providing conversion factors for operational quantities for electron and beta radiations for individual monitoring. The ENEA contribution to the Task Group dealt with the Monte Carlo analyses of electron individual dose equivalents for slab phantoms of different compositions, which required an extended series of calculations to be carried out. The present paper summarises some preliminary results concerning the study, which is still underway. The complete results are going to be published in the near future.

2. DOSE EQUIVALENT CALCULATIONS IN SLAB PHANTOMS

The investigated quantity was the individual dose equivalent $H(d,\alpha)$ in a slab phantom, to produce a complete set of fluence-to-dose equivalent conversion factors :

-for electron energies ranging from 50 keV to 10 MeV

-for different angles of incidence from 0 degrees to 75 degrees

-for different phantom materials: water, PMMA and ICRU material

The incident electron beam was an aligned and expanded field impinging on a 30 cm * 30 cm *15 cm phantom and the dose equivalent values had to be calculated at the centre of the 30 cm * 30 cm y - z surface at the three typical depths of 0.07 mm, 3 mm and 10 mm. The scoring thickness at the three stated depths **d** was required to be Δ**d**=0.01 **d**.

Due to the limited range in water of the investigated energies, the contribution of the phantom edges to the response has been neglected and the irradiation geometry has been described in a one-dimensional fashion with y - z infinite dimensions and a 15 cm thick tissue material in the x direction. For symmetry reasons it has been demonstrated that y -z infinite scoring volumes embedded in the phantom irradiated by a point mono-directional beam provide the same results as the real finite slab with very small scoring volumes at the various depths when irradiated by an aligned and expanded field. The validity of the assumption was demonstrated by independent calculations in the finite and infinite configurations, for various incident angles obtaining a very satisfactory agreement. This approach allowed considerable computer time to be saved.

3. COMPUTATIONAL METHODS

All the calculations have been carried out using MCNPE-BO /3/-/6/ whilst MCNP4 /7/ was employed only for the energies below 1 MeV.

MCNPE-BO is a Monte Carlo code based on MCNP-3a for neutrons and photons and on the multi-scattering theory of Molière for electrons. This means that the electron transport is simulated by an artificial trajectory each step of which takes into account a multitude of collisions ('condensed history'). The steps, arbitrarily chosen, are subject to restrictions from the Molière theory in order to avoid steps with less than 20 collisions and angular deflections greater than one radian; moreover the energy deposition and boundary crossing algorithms are very sensitive to the step-length. Therefore an inappropriate choice of the step can cause non-physical numerical effects that strongly affect the calculated results, particularly at low energies. Therefore, when the electron transport was implemented, a new multi-scattering model /5/ was introduced into the code and original algorithms, such as the 'Correction Tables' /3/ were added, with the aim to allow a high level of step-length insensitivity. All the tests performed so far /6/ have confirmed this goal.

The electron transport of MCNP4 is based on a different multi-scattering theory, the Goudsmit-Saunderson theory, which relies on a pre-determined set of step-lengths assumed sufficiently small to permit a good simulation. On the one hand the code offers a more detailed description of the electron physics at low energies than MCNPE-BO - for example Auger electrons, shell vacancies and also a better treatment of bremsstrahlung. On the other hand, the energy deposition score (pulse-height and not track-length type) results excessively sensitive to the cell thickness and, when too few events occur in a cell, the calculations can have very strong statistical fluctuations.

Giving the lack of any experimental data, it was necessary to employ at least two reasonably independent calculational tools so that a degree of confidence could be attached to the results.

4. COMPUTATIONAL PROBLEMS AND MCNPE-BO - MCNP4 COMPARISON

The electron ranges vary in the three materials from about $4*10^{-3}$ cm at 0.050 MeV, to less than 5 cm at 10 MeV. It follows that:

- some scoring regions, at 0.007 cm for energies of 0.05 and 0.06 MeV and at 0.3 cm for 0.6 MeV, are outside the range of the primary electrons;
- the scoring thickness, 0.00007, 0.003 and 0.01 cm, required at the various depths are of the order of 10^{-2} - 10^{-5} of the range of the primary electrons.

Outside the range of the primary electrons the energy is transported by bremsstrahlung photons of which there are very few at low energies, 0.05 or 0.06 MeV, and which therefore produce still fewer secondary electrons. Due to the few particles arriving at depths greater than one range, the standard deviations are very poor and variance reduction methods are not effective because of the low analogue population. In MCNPE-BO, using a track-length tally, standard deviations are about 20-30% but results are very stable and probably not too far from the truth. The pulse-height tally of MCNP4 depends not on the tracks entering the cell but on the tracks that lead to a deposition of energy; unfortunately the probability that the few photons interact with matter in the cells is very small and the calculated results are very unstable, with no score at all or with standard deviations that forbid any interpretation. Figure 1 shows these effects quite clearly for electrons of 0.050 MeV frontally incident on a slab of water. The 'bremsstrahlung tail' becomes much smoother for higher energies, where there is a higher photon production and the standard deviations of both the codes decrease and become comparable.

Problems with very thin cells are common to all the multi-scattering codes, because the events of an electron interaction with creation of secondaries just inside rather than just outside the cell, radically change the energy deposited in the cell. MCNP4 pulse-height tally is even more sensitive to thin cells and when the cells become 10^{-2} range or less, the energy deposition increases showing non-physical peaks; unfortunately the standard deviations do not correctly indicate an anomaly. MCNPE-BO too shows some problems, though much less evident and only for cells that are 10^{-4} range or less; anyway, the results are always inside one standard deviation. Figure 2 shows this behaviour for electrons of 0.200 MeV incident at 30° on a slab of water. It is possible to reduce this effect considering larger cells and interpolating the data, because the curves are very smooth.

Taking the results of both codes as a whole and neglecting the specific problems outlined previously, we can feel confident concerning the quality of the results. The results are approximately inside one standard deviation for energies > 0.20 MeV, while the difference is outside the statistical confidence interval at lower energies. Notwithstanding at lower energies the results are still satisfactory considering the critical energy range and the different algorithms used by the two codes.

5. COMPARISONS WITH PREVIOUS CALCULATIONS

The entire depth dose curve has been calculated and it was possible to carry out some comparisons with fluence to dose conversion factors available in the literature for normally incident electron beams /8/-/10/. In Figure 3 we show a comparison of the maximal dose equivalent for water. It has to be pointed out that the energy deposited is an averaged quantity (that depends on the thickness of the scoring volume which, in our calculations, was taken as 1/10 of the range of the primary electrons). Figure 4 summarises the H(3mm, 0°) and H(10mm, 0°) values calculated by MCNPE-BO and Rogers /8/ for the ICRU material slab.

Whilst there is a systematic discrepancy of about 1-8 % with Rogers, the results obtained with MCNPE-BO and MCNP4 are in a very satisfactory agreement with the other authors.

6. DOSE DEPENDENCE ON ELECTRON BEAM INCIDENT ANGLE AT GIVEN DEPTH

An example of the dependence of the individual dose equivalent on the electron beam incident angle is shown in Figures 5 and 6 . Figure 5 summarises the angular dependence at 0.007 cm for electron energies ranging from 80 keV to 3 MeV, whilst Figure 6 supplies the values at 1 cm for electron energies ranging from 3 MeV to 10 MeV. The calculations presented were performed using MCNPE-BO in a water slab phantom.

We see that a build-up effect contributes to the response and a qualitative explanation of the different angular behaviours with the energy at the various depths can be made considering the effect of the attenuation of the primary electrons in the material before the scoring region (which is strongly energy and angle-dependent) and the frontal leakage from the slab (important at high incident angles of the source electrons).

7. CONCLUSIONS

A substantial agreement with previously published results has been obtained by both MCNPE-BO and MCNP4 calculations. The differences between the two codes can be attributed to the different multi-scattering theories underlying them.

An extensive and detailed report on the energy deposition distributions for all the proposed electron beam incident energies and angles as well as for the three tissue equivalent phantoms, will be published in the near future.

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Comparison between finite and infinite slab for broad parallel beams of electrons of 10 MeV incident at 75° on water

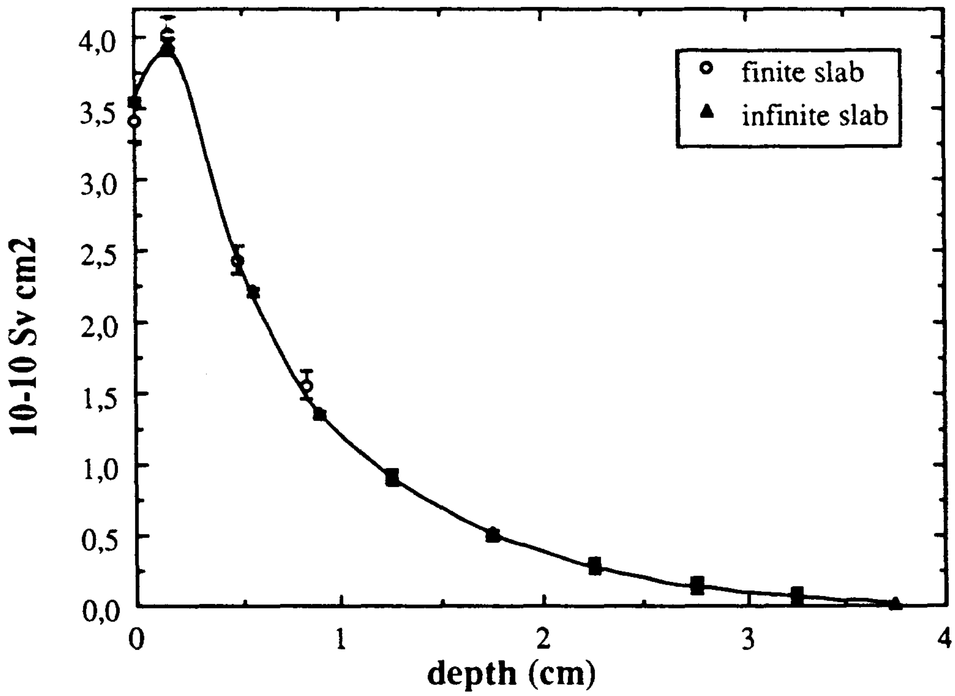


Fig.1 Dose equivalent per unit incident fluence for broad parallel beam of electrons of 0.05MeV incident normally on a slab of water

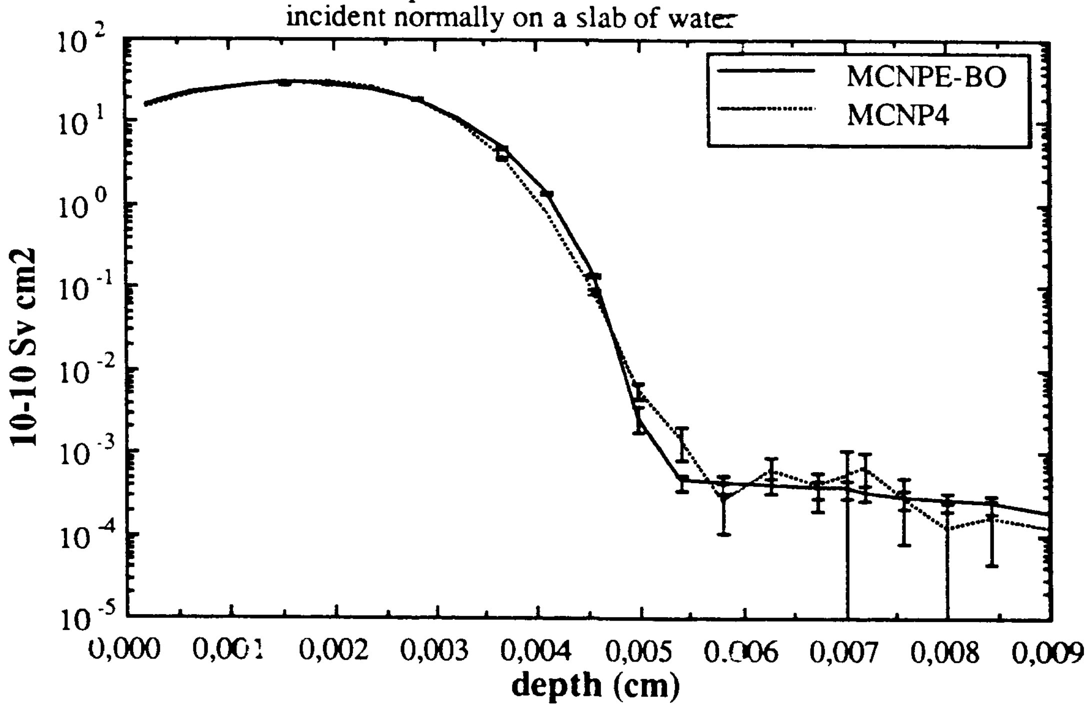


Fig.2 Dose equivalent per unit incident fluence for broad parallel beam of electrons of 0.2 MeV incident at 30° on a slab of water

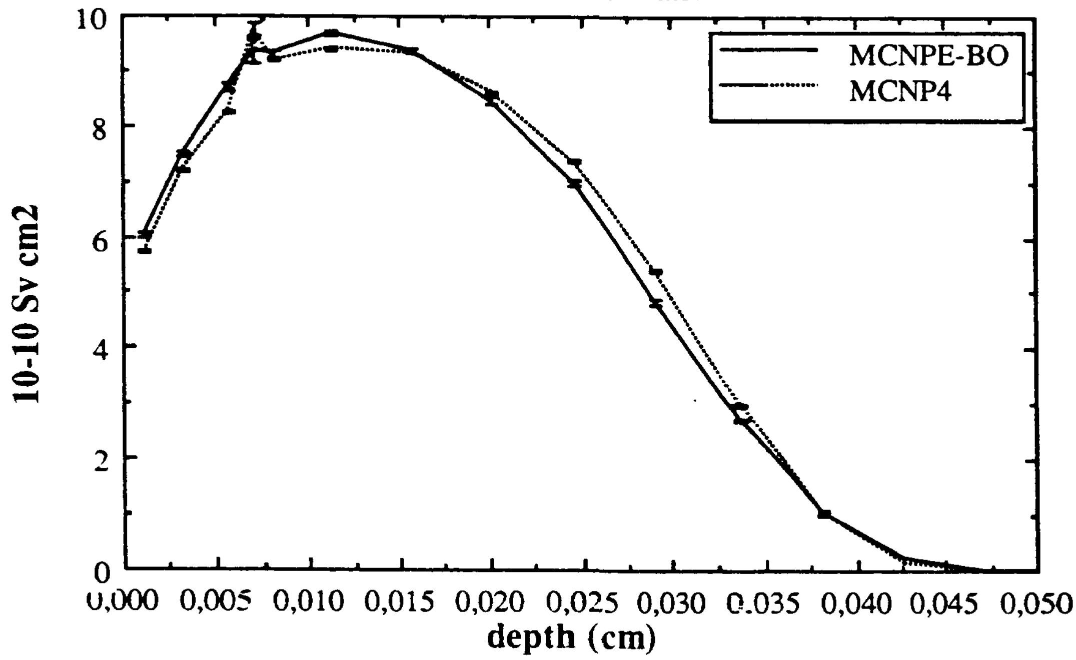


Fig.3 Maximal dose equivalent per unit incident fluence for broad parallel beams of electrons incident normally on a slab of water

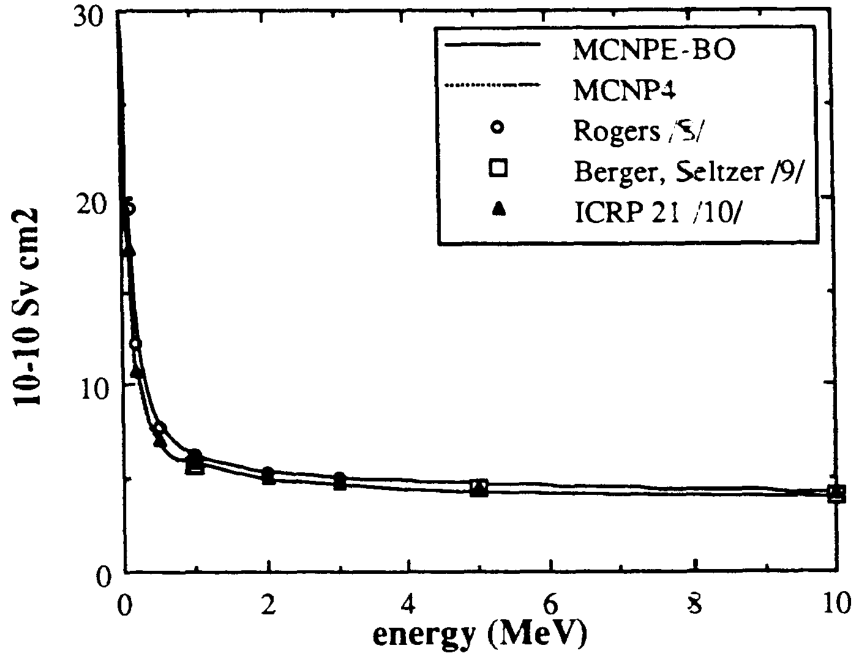


Fig.4 Dose equivalent per unit incident fluence for broad parallel beams of electrons incident normally on a slab of ICRU material at depth of 3 mm and 10 mm

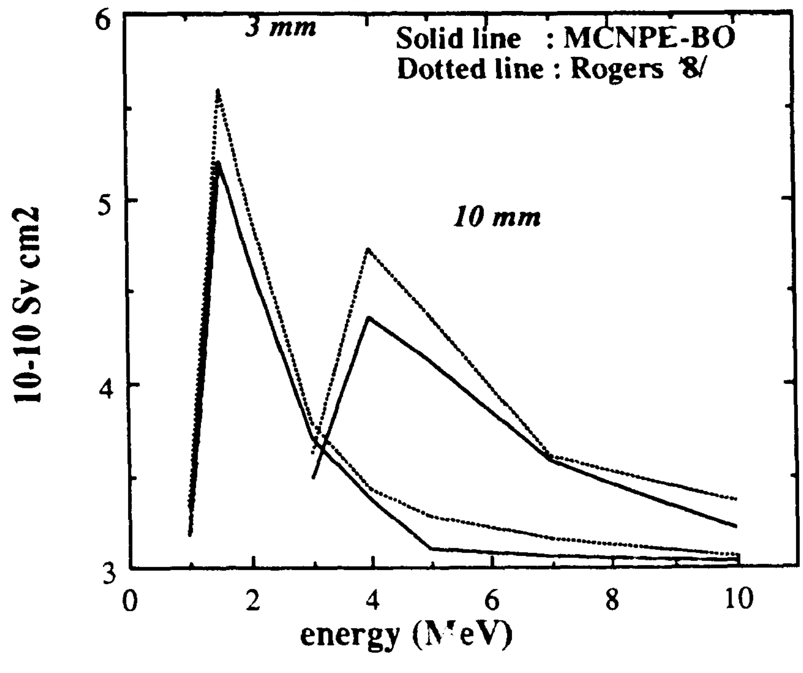


Fig.5 Angular dependence of the dose equivalent per unit incident fluence for broad parallel beams of electrons incident on a slab of water at a depth of 0.07 mm

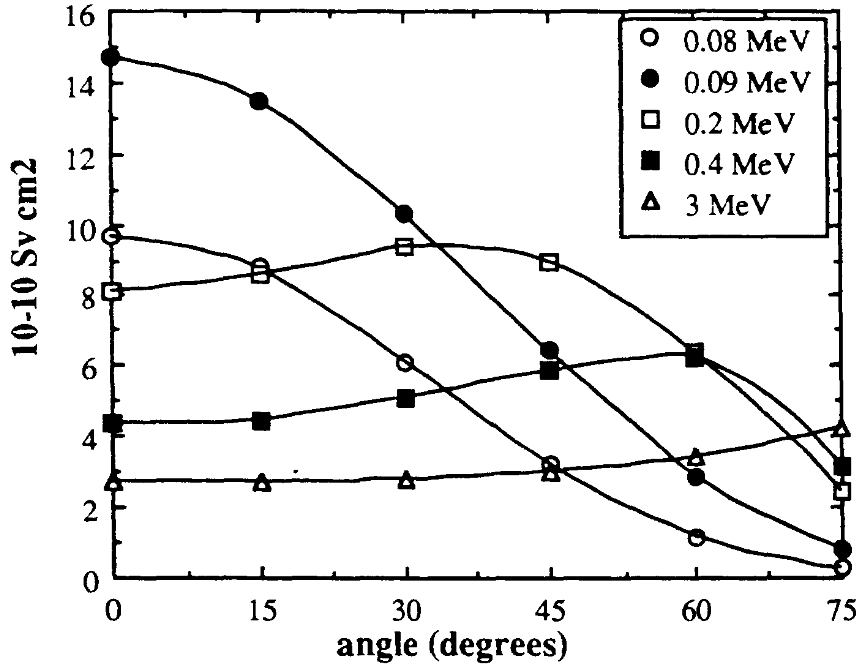
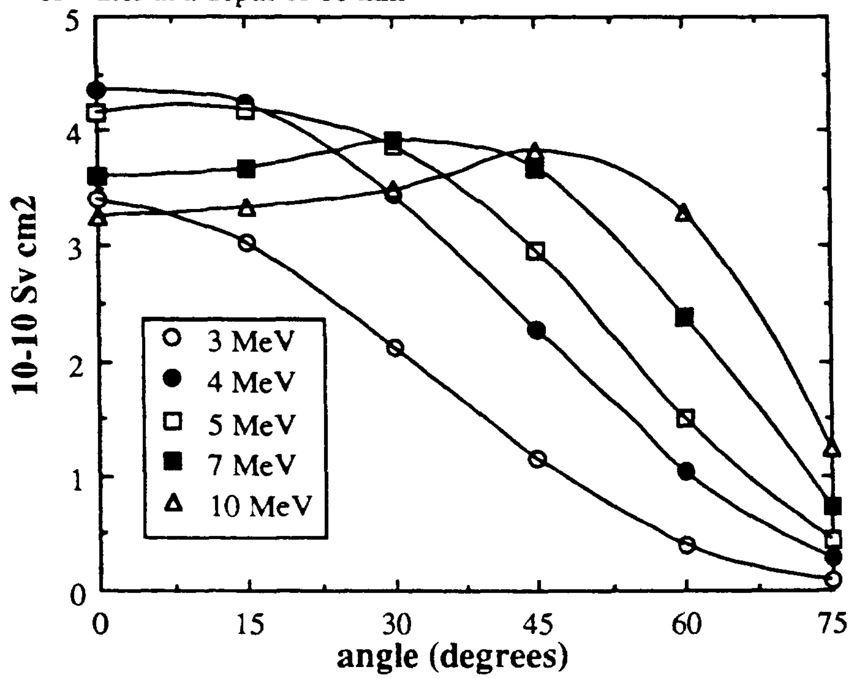


Fig.6 Angular dependence of the dose equivalent per unit incident fluence for broad parallel beams of electrons incident on a slab of water at a depth of 10 mm



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