Application of the Monte Carlo Method to Estimate the Tenth-value Thickness for X-rays in Medical Electron Accelerators

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Abstract

DIN-6847 is the most suitable standard to estimate shielding requirements in medical radiotherapy installations using linear electron accelerators. Its calculation method is based on the tenth-value thickness concept for which values given by curves and tables are recommended in DIN-6847. These parameters have been estimated for both primary and secondary X-ray beams using the MCNP code based on the Monte Carlo method. Results show that DIN-6847 values are conservative for secondary X-ray beam, but not always for direct radiation. The methodology used has been tested using the mentioned code and results are well consistent.

I. INTRODUCTION

There is a great number of medical installations using particle accelerators for radiotherapy. The importance of an accurate estimation of the doses due to these installations that can be received by health workers, patients or public is obvious. The lower limits of doses established in the new ICRP recommendations [1] imply a recalculation of items concerning such installations [2].

There are only two known standards [3], [4] to estimate shielding requirements in medical installations using linear accelerators, i. e. NCRP-51 and DIN-6847. The last one is more suitable for this type of calculations. NCRP-51 is incomplete and difficult to apply, while DIN-6847 is fairly comprehensive and easy to apply [2], [5]. However, it is based on various semiempirical approaches which should be adequately verified. In the paper, the tenth-value thickness included in DIN-6847 for various materials for primary and secondary X-rays produced in electron accelerators has been verified using the MCNP code based on the Monte Carlo method [6].

II. CALCULATION METHODOLOGY

A. Shielding Calculation

In DIN-6847 standard [4], the shielding thickness is given by the following expression:

$$s_i = z_i \log_{10}\left(\frac{W_A\ U\ T\ K_i\ q_i}{H_w}\right) \tag{1}$$

where, s_i is the shielding thickness for the ith radiation, referring to electrons, X-rays (primary, secondary, leakage, tertiary) or neutrons (primary and scattered beam); z_i is the tenth-value thickness; W_A is the weekly workload at the reference distance of a_0 meters (Gy/week); U is the use factor; T is the occupancy factor; K_i is the reduction factor; q_i is the quality factor; and H_w is the equivalent weekly dose.

The calculation scheme is as follows: (a) establish the geometrical features of the reference point; (b) identify all types of radiation involved in the calculation; and (c) obtain the shielding thickness s_i, from the general equation (1) and the actual variations according to the type of radiation.

For *primary X-ray beam*, q_i = 1 and the reduction factor is given by:

$$K_i = \frac{a_0^2}{a_n^2} \tag{2}$$

where, a_o is the reference distance (1 m) and a_n is the distance in meters from the source to the shielding. The tenth-value thickness, $z_i = z_r$, depending on the shielding material can be obtained from curves recommended by DIN-6847 that are reproduced in Figure 1, it is seen that the same curve is used for aluminum and concrete, and also for iron and copper.

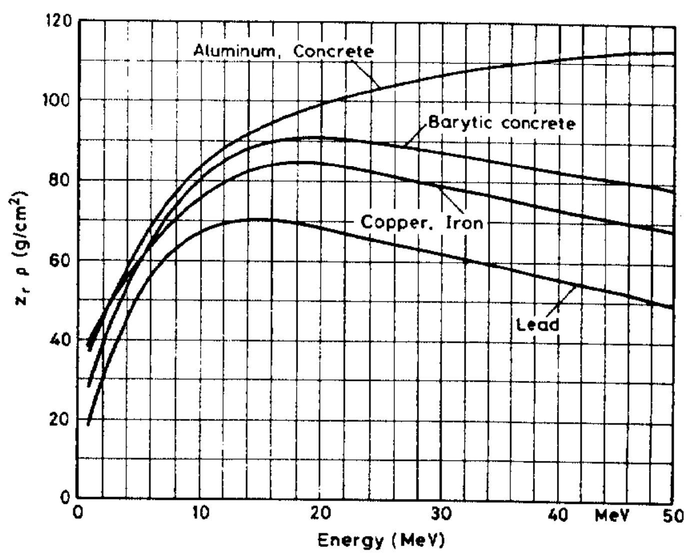

Figure 1. Mass tenth-value thickness for primary X-rays.

For the *scattered X-ray beam*, the use factor is U = 1; the tenth-value thickness, $z_i = z_s$, obtained from DIN-6847 (see Table 1) does not depend on energy; and the reduction factor K_s is given by:

$$K_s = \frac{10^{-2}\ F_n\ k}{a_s^2} \quad (3)$$

where, F_n is the illuminating surface (normally ~ 0,04 m^2); k equals 1 for X-rays; and a_s is the distance from the scatterer to the reference point.

Table 1
Mass Tenth-value Thickness for Secondary X-rays.

Material	Concrete	Barytic concrete	Iron	Lead
$z_s\rho$	37	29	38	17

B. Tenth-value Thickness Estimation

The following expression for the equivalent dose rate H_w can be obtained from eq. (1):

$$H_w = \frac{C}{a_n^2} \left(\frac{1}{10}\right)^{\frac{s}{z}} \quad (4)$$

where C includes all the terms depending on the installation and radiation involved.

In order to verify the adequacy of eq. (4) a photon source produced by Bremsstrahlung in aluminum from monoenergetic 23 MeV electrons has been considered. With a lineal spectrum taken from Chilton [7], MCNP calculates doses for shielding thickness from 0 up to 130 cm. The correlation coefficient between log(H_w a_n^2) and s has been found and it is equal to 0.999613. Therefore, they are linearly related and consequently the tenth-value thickness can be estimated in terms of dose rates calculated for two different values of shielding thickness and related distances, as follows:

$$z = -\frac{s_2 - s_1}{\log_{10} \dfrac{H_{2W}\ a_2^2}{H_{1W}\ a_1^2}} \quad (5)$$

MCNP code has been used to determine doses at distances considered, for various energy values up to 50 MeV and materials of interest. The photon source was point isotropic and monoenergetic, with all the particles being emitted inside a small solid angle (cos α = 0.9997) to avoid the leakage radiation. Surface counters have been used, placed in maximal dose zones. Cell importance has been the only variance reduction technique used, due to geometric features of the problem and the type of counters used.

The photon interaction cross sections come from the Storm and Israel [8] plus ENDF/B evaluations and cover the energy range from 0.001 to 100 MeV. MCNP takes account of incoherent (using an inverse fit rather than a rejection scheme on the Klein-Nishina distribution) and coherent scattering, the possibility of fluorescent emission following photoelectric absorption, and absorption in pair production with local emission of the annihilation quanta.

III. RESULTS

Calculation has been carried out for a radiotherapy room with two perpendicular walls made of the same material. The first one that receives primary beam is located at 500 cm away from the radiation source and the second one where falls in the scattered beam is 350 cm away from the source. MCNP has been run for energies from 0,5 up to 50 MeV for direct radiation and from 5 up to 50 MeV for the scattered one.

Shielding thickness values have been taken in such a way that for each energy the doses obtained differ by a magnitude order at least. 100,000 photons for direct radiation and 200,000 for the scattered one for each energy have been generated. Concrete, barytic concrete, aluminum, iron, copper and lead have been considered for primary beam and all except aluminum and copper for the scattered one.

Results are shown in Figure 2 for *direct radiation*. Comparing this figure with Figure 1, one can see that values obtained by MCNP match reasonably with those from DIN-6847 except for lead. At the lowest energy (0.5 MeV) the Monte Carlo values are slightly lower than the DIN ones, but for higher values of energy they are higher too: always for concrete, up to 40 MeV for aluminum, up to 10 MeV for barytic concrete, and up to 15 MeV for iron and copper. For the rest of energy values, the Monte Carlo obtained values are lower, but differences are small.

For lead the behavior is completely opposite and we think that the Monte Carlo calculated values should be discarded for this material. MCNP does not include the transport of photoelectrons, Compton electrons and electron-positron pairs. At higher energies these electrons collide with hard atomic nuclei producing the electromagnetic radiation (Bremsstrahlung) obviously not considered by the code. These phenomena are very important in lead and the calculated tenth-value thicknesses are clearly lower than those of the guide, they might be less safe.

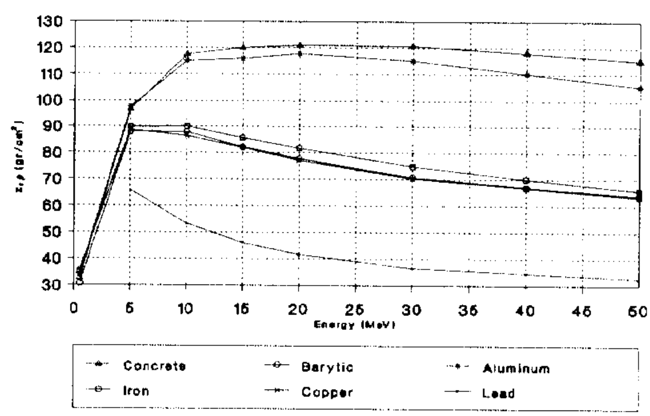

Figure 2. MCNP results for direct radiation.

Concordance would has been better if we had considered a continuous actual spectrum rather than a monoenergetic source, but unfortunately we could not get these data from manufacturers.

Thus, DIN-6847 is less conservative for direct radiation than expected, as it was discussed by authors in an early paper [9] comparing tenth-value thickness from DIN-6847 with those from NCRP-49 [10] for concrete, up to 10 MeV.

On the other hand, the obtained curves for concrete and aluminum are very similar, furthermore the curves not only for iron and copper but also for barytic concrete match very well.

For the *scattered radiation* the Monte Carlo results are shown in Figure 3. Note that the obtained tenth-value thicknesses are practically constant, always lower than the DIN-6847 recommended values although differences are less significant.

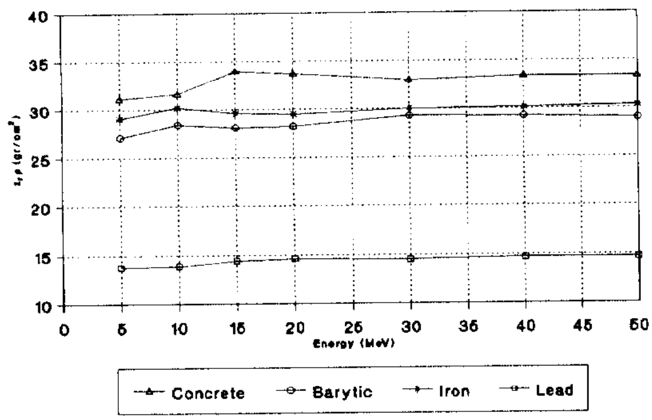

Figure 3. MCNP results for scattered radiation.

MCNP determines error for each calculated dose. With these data a statistical analysis has been performed to prove that results are significant, practically at 100% for relative error of 5%.

IV. CONCLUSIONS

Monte Carlo method has been used to estimate tenth-value thickness for X-ray direct and scattered beams in medical electron accelerators. Results have been compared with values recommended by the DIN-6847 standard.

It has been verified for primary radiation that without significant errors the same curve may be used for different materials, in particular for concrete and aluminum and for barytic concrete, iron and copper, respectively, though "a priori" it did not look very logical.

For secondary radiation, results proved that the single table given by the guide is sufficient to obtain tenth-value thickness independently of incident beam energy. Furthermore, the Monte Carlo obtained data are very similar to those proposed by the guide.

Since the primary beam spectrum in an accelerator is generally unknown, a monoenergetic source has been considered. For a continuous actual spectrum there should be used the maximal value of z within the spectrum energy range. If the spectrum is well known, the tenth-value thickness can be obtained by decomposition.

In order to get more conservative shielding barriers the Monte Carlo calculated values for the primary beam may be used, except for lead for which the DIN-6847 curve has to be used. For the scattered beam, values recommended by DIN-6847 may be safely used.

V. REFERENCES

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