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RADIATION PROTECTION OF LINAC BUNKERS. A USER-FRIENDLY APPROACH

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A well-known but complex formalism for the calculation of the leakage dose at the entrance of the linac maze was considered and simplified. These simplifications were based partly on the literature and partly on the authors' own measurements. The authors have included photon scatter originating from the irradiated patient in the formalism. A formalism for two different types of bunkers was developed, and the authors have obtained simple formulas to calculate the dose at the maze entrance for both bunker types.

INTRODUCTION

Several publications describe leakage dose calculations(1, 2) at the entrance of a bunker maze. One of the most difficult issues to address in these calculations is the scattered radiation contribution from the bunker and maze to the maze entrance dose. The objective of this study was to make these calculations easy and user-friendly by introducing a simple formalism. Knowing this dose, one can assess the worst case yearly doses to relatives of the patients and the general public. Furthermore, one can predict the yearly doses to the staff. Two different types of bunkers are considered: one with and one without a 'nose' on the maze wall. Direct transmitted radiation(1) from the linac is not considered, and the transmission of room-scattered radiation and leakage through the maze and 'nose' walls are neglected based on radiation transmission calculations. The minimum wall thickness is 80 cm of ordinary concrete. Leakage radiation from the linac head and scattered radiation originating from the patient in the primary beam. Consequently, a dose dependency will exist on energy, field size, gantry angle and on whether there is a phantom/patient in the primary beam or not.

MATERIALS AND METHODS

Ambient photon doses were measured using an Inovision Monitor 451P, and ambient neutron doses were measured with an FHT 762 Wendy-2 monitor. It has been verified that these monitors give the correct dose measurements in a pulsed beam at the maze entrance(3, 4).

Measurements of photon and neutron ambient dose equivalents, $H^*(10)$, in two different bunker designs were performed, and the authors compared measured and calculated dose values. $H^*(10)$ is the equivalent dose that the radiation field would deposit at 10 mm depth in a tissue-equivalent sphere with a radius of 15 cm (an ICRU sphere), i.e. it corresponds approximately to the dose at 10 mm depth in a human being. In general, the authors' calculations were performed under reference conditions, i.e. the gantry angle of 0° with an energy of 15 MV and a 40 cm × 40 cm field with no scatter phantom. All the authors' measurements were corrected for background. The layouts of the bunkers are shown in (Figures 1 and 2). Besides having measured under reference conditions, the authors have also performed measurements with different field sizes, gantry angles and with a phantom in the primary beam. Based on these measurements, the authors modified their formalism to match realistic treatment situations. This is presented in 'Results and Discussion'.

In Figure 1, the point A is in the middle of the maze and only just visible from the isocenter. In Figure 2, the point A is also only just visible from the isocenter and is situated in the middle of the 'nose' duct. The points C are situated in the middle of the maze/'nose' duct and 1 m from the points A (Figure 2). The point B is in the middle of the corner where the 'nose' meets the maze (Figure 2).

Point D is located in the middle of the maze entrance.

Calculation of photon doses at the bunker entrance in bunkers without a 'nose'

Assumption: The leakage dose is 0.1 % of the primary dose(2). The total photon dose in the reference point D is therefore as the dose in the point C is 10 % of the dose in the point A(2):

$$D_{\mathrm{ph}}(D) = D(\mathrm{linac}) \times 10^{-3} \times 0.1 \times \left(\frac{1}{a}\right)^2 \times \left(\frac{1}{c}\right)^2,$$

where D(linac) is the dose measured at the depth of maximum dose ($d$max) in a water phantom at a source-to-surface distance of 1 m.

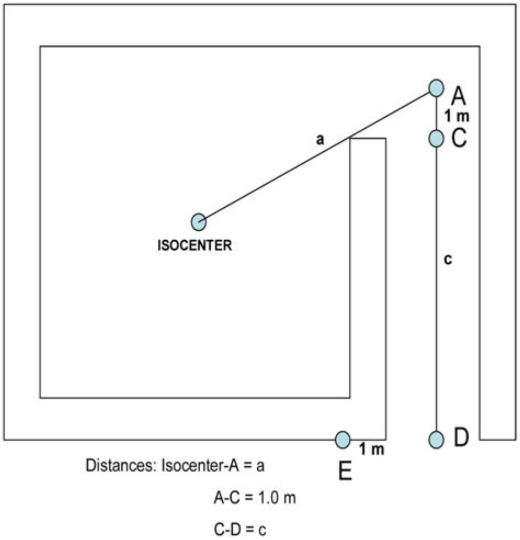

Figure 1. Bunker without a ‘nose’.

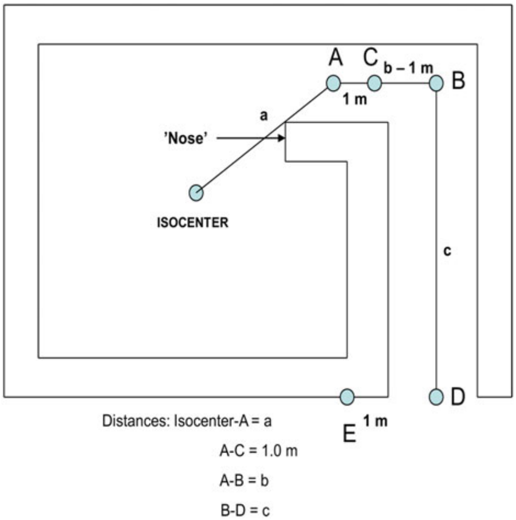

Figure 2. Bunker with a ‘nose’.

Consequently, the specific photon dose in the point D is as follows:

$$S_{\mathrm{ph}}(D) = \frac{100}{(a \times c)^2} \frac{\mu\mathrm{Sv}}{\mathrm{Gy}}, \tag{1}$$

where $S_{\mathrm{ph}}(D)$ is assumed to be the ambient dose equivalent $H^*(10)$. All distances are measured in metres (Figure 1).

Calculation of neutron doses at the bunker entrance in bunkers without a ‘nose’

In the authors’ calculations, they chose the neutron quality factor Q to be 10 and the neutron production to be 10^{-4}(2) giving the neutron dose equivalent of $Q \times 10^{-4} = 10^{-3}$ Sv Gy^{-1}. This choice of Q is also suggested in (5) for the neutron monitor the authors have used. S is the minimum cross section of the maze and $S_0 = 6$ m^2. The neutron dose at point D is(2):

$$D_{\mathrm{n}}(D) = 10^{-3} \times D(\mathrm{linac}) \times \left(\frac{1}{a}\right)^2 \times 10^{-[1+((c-2)/5)]} \times \frac{S}{S_0}.$$

The specific neutron dose at point D is thus:

$$S_{\mathrm{n}}(D) = \frac{1000}{a^2} \times \frac{S}{S_0} \times 10^{-[1+((c-2)/5)]} \frac{\mu\mathrm{Sv}}{\mathrm{Gy}}. \tag{2}$$

This formula is only valid for c of >2 m.

Calculation of photon doses at the bunker entrance in bunkers with a ‘nose’

The same assumptions as for bunkers without a ‘nose’ are used. A factor of 2 is used to compensate for maze corner scatter. This choice of the compensation factor is verified to be correct by the authors’ measurements.

$$D_{\mathrm{ph}}(D) = D(\mathrm{linac}) \times \left(\frac{(1-c)^2 \times 200}{[a \times (b-1)]^2}\right) \times 10^{-6}.$$

The specific photon dose in D is as follows:

$$S_{\mathrm{ph}}(D) = \frac{200}{[a \times (b-1) \times c]^2} \left(\frac{\mu\mathrm{Sv}}{\mathrm{Gy}}\right). \tag{3}$$

Calculation of neutron doses at the bunker entrance in bunkers with a ‘nose’

From (2), the specific neutron dose can be derived:

$$S_{\mathrm{n}}(D) = \frac{1000}{a^2} \times \frac{S}{S_0} \times 10^{-[1+((b+c-3)/5)]} \frac{\mu\mathrm{Sv}}{\mathrm{Gy}}. \tag{4}$$

This formula is only valid for $(b + c)$ of >3 m. All distances are measured in metres. The total dose in D for a bunker without a ‘nose’ is then the sum of Formulas (1) and (2). Similarly, the total dose in D for a bunker with a ‘nose’ is the sum of Formulas (3) and (4).

RESULTS AND DISCUSSION

The formulas mentioned above do not include phantom/patient scatter but include solely leakage.

Table 1. Modification factors.

Modification factors	Photons		Neutrons
	'safety'	Gantry/phantom	'safety'
Bunker without 'nose'	1.0	2.6	1.1
Bunker with 'nose'	1.5	1.2	1.2

The authors have performed measurements with and without a phantom (patient) for different gantry angles and field sizes for 15 MV. The average phantom scatter for different gantry angles (gantry/phantom factors) for maximum field size is listed in Table 1. The 'safety' factor is introduced with the purpose to correct for deviations between calculated and measured doses under reference conditions.

Applying these modification factors on the appropriate formulas and adding the photon and neutron contribution to the entrance dose, one gets the total dose in D (Formulas (1 + 2) and (3 + 4)):

Bunker without a 'nose' is as follows:

$$S_{\mathrm{tot}} = \frac{1000}{a^2} \times \left[\frac{0.26}{c^2} + 1.1 \times \frac{S}{S_0} \times 10^{-[1+((c-2)/5)]}\right] \frac{\mu\mathrm{Sv}}{\mathrm{Gy}}. \quad (5)$$

In Equation (5), the first addend in the bracket is achieved by multiplying the photon contribution in Equation 1 with the 'safety' factor (1.0) and the gantry/phantom factor (2.6), and the second addend, which represents the neutron contribution in Equation, 2 is multiplied with the 'safety' factor (1.1) listed in Table 1.

Bunker with a 'nose' is as follows:

$$S_{\mathrm{tot}} = \frac{1000}{a^2} \times \left[\frac{0.36}{[(b-1)\times c]^2} + 1.2 \times \frac{S}{S_0} \times 10^{-[1+((b+c-3)/5)]}\right] \frac{\mu\mathrm{Sv}}{\mathrm{Gy}}. \quad (6)$$

In Equation (6), the first addend in the bracket is achieved by multiplying the photon contribution in Equation 3 with the 'safety' factor (1.5) and the gantry/phantom factor (1.2), and the second addend, which represents the neutron contribution in Equation (4), is multiplied with the 'safety' factor (1.2) listed in Table 1.

Formulas (5) and (6) are also valid for the energies of <15 MV. This has been confirmed by the authors' measurements at 8 and 6 MV. However, the neutron contribution to the total dose (the second addend in the large square brackets in 5 and 6) should be modified in accordance with the neutron yield. For 15 MV, this yield is 0.1 %, 10 MV 0.03 %, and for energies of <10 MV, the yield is zero (the second addend is removed)(2).

One important result from the authors' measurements is that the 'nose' practically eliminates all the phantom/patient scatters (Table 1). Another important result of the authors' measurements is that the dose at the point E (Figures 1 and 2) at the staff's place is ~10 % of the photon dose in D. The neutron dose at E is at background level.

It should be emphasised that the neutron contribution in Formulas (5) and (6) could be increased with a factor of up to 1.3 in case that dynamic small field size techniques such as IMRT or VMAT are used at 15 MV. This small field effect has not been taken into account here.

If the bunkers are with a design similar to the designs sketched in Figures 1 and 2, wall thicknesses of ≥80 cm and the metric dimensions of the bunker do not deviate more than a few metres from 8 × 8 m, it is believed that a robust and simple method has been found to determine the dose at the bunker/maze entrance.

CONCLUSIONS

The authors have found a simple semi-empirical formalism that allows the calculation of the dose at the maze entrance by means of simple Formulas (5) and (6). Only the metric distances in the bunkers (Figures 1 and 2) and the leakage of the linac need to be known to calculate this dose for energies of 15 MV or lower. They have furthermore found an empirical method for calculating the dose at the operating area represented by the point E. When the calculated doses, the total yearly workload of the linac and the occupancy times are known the yearly doses to the staff (point E) and relatives of the patients (point D) can be estimated.

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