Shielding Evaluation for a Radiotherapy Bunker by NCRP 151 and Portuguese Regulation on Radiation Safety

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ABSTRACT

NCRP Report No. 151 (2005) concerned with radiation safety is one of the most suitable documents for structural shielding design and evaluation in modern radiotherapy facilities. For radiation safety purposes, the barriers thicknesses must be designed to attenuate the primary, leakage and scatter radiations. The purpose of this work was to establish a comparison between the primary and secondary barrier thicknesses calculated according to NCRP 151 recommendation and the current Portuguese Regulation (DL 180/2002), which recommends the German Standard DIN-6847 for a radiotherapy bunker with a linear accelerator.

The calculation methods performed are based on the tenth-value layer (TVL) concept, and in this study were used the TVL values recommended in each norm for the same shielding material, the ordinary concrete. For both standards, the calculation was carried out for a treatment room with Elekta-Synergy linear accelerator, maximum nominal energy of 15 MV, and for three-dimensional conformal radiation therapy treatment technique.

The results obtained by both standards show that the maximum deviations for the primary and secondary barriers were up to 16 % and 19 %, respectively. When using the same shielding design goals, occupancy and use factors, the deviations between both norms for the primary and secondary barriers were up to 5 % and 29 %, respectively.

Some reasons for the discrepancies between both methods are the TVL values. Differently from DIN-6847, the NCRP´s TVL is a function of the energy and radiation scattering angle. Another source of discrepancy is that DIN method takes into account the neutron contribution for the secondary barriers.

KEY WORDS

Shielding calculation, radiotherapy bunker, radiation safety

1. INTRODUCTION

Structural shielding design in medical radiotherapy installations aims to limit radiation exposures to members of the public and employees to an acceptable level, i.e. to reduce the effective dose from a linear accelerator (linac) to a point outside the radiotherapy bunker as low as reasonably achievable. Shielding design is particularly concerned with attenuation of the primary beam and secondary radiation in the form of head leakage, patient and wall scatter. Thus, finding the optimum barrier thickness is an essential requirement for the safety of radiotherapy facilities. Recommendations and technical information for the shielding design and evaluation in modern radiotherapy facilities, using megavoltage x-ray and gamma-ray, are fully described in Report No. 151 of the National Council on Radiation Protection and Measurements (NCRP) [1]. NCRP 151 is one of the most suitable documents to estimate shielding requirements in medical installations using linear accelerators. Decree-Law No. 180/2002 of 8 August 2002 (DL) [2] is the current Portuguese Regulation that establishes safety standards for the workers and public members, against the dangers arising by using ionizing radiation in diagnostic and therapeutic purposes. For the calculations of the barriers thicknesses, for a radiotherapy bunker with a linac, DL 180/2002 recommends the German Standard DIN-6847 of November 1977 (DIN) [3]. However, the calculations shown in DIN-6847 only includes conventional treatment techniques, thus excluding the modern treatment techniques, that required others parameters in the shielding calculation. The purpose of this work was to establish a comparison between the primary and secondary barrier thicknesses calculated according to NCRP recommendation and DL 180/2002 using DIN methodology, for three-dimensional conformal radiation therapy treatment techniques (3D-CRT). The comparison of door shielding evaluation by both norms was not included in this paper.

2. MATERIAL AND METHODS

The calculation methods to evaluate barrier thicknesses were carried out for a treatment room with Elekta-Synergy linac, with maximum nominal energy of 15 MV, and 3D-CRT. The linac isocenter located at 1 m from the radiation source and it was assumed a symmetric distribution of gantry treatment angles. NCRP and DIN methods are based on the tenth-value layer (TVL) concept. It was used, in this study, the TVL values recommended in each norm, NCRP and DIN, for the same shielding material, the ordinary concrete. For both cases, was used the same weekly workload (W).

In terms of use factor (U), occupancy factor (T) and shielding design goals (P), for workers and public members, it was used two different approaches. The first approach using the U, T and P values specified in each norm, NCRP and DL. For the second approach it was used the same U, T and P values, which were based on NCRP recommendations.

2.1. Shielding Calculation Methodology

The scheme used to calculate the barrier thickness for both norms include: a) establish the geometrical features of the reference point; b) identify all types of radiation involved in the calculation; c) the barrier thickness calculation based on TVL concept; and d) only for NCRP, the time averaged dose-equivalent rates (TADR). TADR is the barrier attenuated dose-equivalent rate averaged over a specified time or period of accelerator operation. The periods of operation frequently used in radiation protection are the week and the hour. For controlled areas, it is used the weekly time averaged dose-equivalent rate, where its maximum value is equal to shielding design goal (Sv/week), and for uncontrolled areas, the dose equivalent from external sources should not exceed $20 \times 10^{-6} Sv$ in-any-one-hour.

2.1.1. NCRP 151 method

According to NCRP the barrier thickness can be estimated by the following formula:

$$t = TVL_1 + (n-1)TVL_e \quad (1)$$

with

$$n = \log_{10}\left(\frac{1}{B}\right) \quad (2)$$

where t is the barrier thickness; TVL_1 and TVL_e are the first and equilibrium tenth-value layers, respectively; n is the number of TVLs required for the shield; and B is the attenuation factor of the barrier that will reduce the radiation field to an acceptable level.

For primary beam TVL value is function of the energy of the radiation beam and the type of shielding material, and its attenuation factor (B_{pri}) is given by:

$$B_{pri} = \frac{P\, d_{pri}^2}{W\, U\, T} \quad (3)$$

where P is the shielding design goal 0.30 m beyond the barrier (Sv/week); d_{pri} is the distance from the x-ray target to the point protected (m); W is the weekly workload at the reference distance of 1 m (Gy/week); U is the use factor; and T is the occupancy factor.

For leakage radiation, as well as primary barrier, the TVL values depending on the energy of the accelerator and type of shielding material. Its attenuation factor (B_L) is given by the following equation:

$$B_L = \frac{P\, d_L^2}{10^{-3}\, W_L\, T} \quad (4)$$

where d_L is the distance from the isocenter to the point protected (m); W_L is the workload for leakage radiation at the reference distance of 1 m (Gy/week); and the factor 10^{-3} arises from the assumption that leakage radiation is 0.1 % of the useful beam.

For scattered radiation, the TVL values beside of shielding material also are a function of the linac energy and radiation scatter angle. Its attenuation factor (B_{ps}) is given by the following equation:

$$B_{ps} = \frac{P\, d_{sca}^2\, d_{sec}^2}{a\, W\, U_{ps}\, T\, (F/400)} \tag{5}$$

where d_{sca} is the distance from the x-ray target to the patient or scattering surface (m); d_{sec} is the distance from the scattering object to the point protected (m); a is the scatter fraction; U_{ps} is the use factor for patient scattered radiation; F is the field area at mind-depth of the patient at 1 m (cm^2); and the factor 400 assumes the scatter fractions are normalized to those measured for $20\ cm\ \times 20\ cm$ field size.

2.1.2. DIN-6847 method (used to apply the Portuguese Regulation DL 180/2002)

For DIN the barrier thickness is given by the following formula:

$$s_i = z_i \times n_i \tag{6}$$

with

$$n_i = \log_{10}\left(\frac{1}{B}\right) = \log_{10}\left(\frac{W\, U\, T\, K_i\, q_i}{H_w}\right) \tag{7}$$

where i is the radiation component index; s is the shielding thickness (cm); z is the first tenth-value layer thickness (TVL); n is the number of TVLs required for the shield; B is the attenuation factor of the barrier; W is the weekly workload at the reference distance of a_0 meters (mGy/week); U is the use factor; T is the occupancy factor; K is the reduction factor; q is the quality factor (for photons $q = 1\, Sv/Gy$ and for neutrons $q = 10\, Sv/Gy$); and H_w is the weekly dose equivalent (mSv/week).

For primary beam TVL value (or $z_r$value) is function of the energy of the radiation beam and the type of shielding material. Its reduction factor follows the inverse square law of the distance and is given by:

$$K_r = \frac{a_0^2}{a_n^2} \tag{8}$$

where a_0 is the reference distance (1 m) and a_n is the distance from the x-ray target to the point protected (m).

For leakage radiation the TVL value is the same of the primary radiation (z_r), but its reduction factor is given by:

$$K_0 = \frac{\dot{D}_0}{\dot{D}_r} \times \frac{a_0^2}{a_n^2} \tag{9}$$

where $\dot{D}_0$ is the leakage radiation dose rate and $\dot{D}_r$ is the x-ray dose rate at the reference point.

For scattered radiation the TVL value (z_s) depends only of the type of shielding material, and its reduction factor is given by:

$$K_s = 10^{-2}\ k\ \frac{F_n}{a_s^2} \tag{10}$$

where the factor k is equals 1 for x-rays; F_n is the maximum radiation field area at 1 m from the divergence point (m^2); a_s is the distance from the scattering surface to the point protected (m); and the factor 10^{-2} arises from the assumption that scatter radiation fraction at 1 m from the patient for conventional accelerators is 1 % of useful beam.

According to DIN methodology, it is considered in the calculation of the secondary barrier thicknesses, in addition to leakage and scattered photons contributions, the direct neutrons contributions, while NCRP considers them to the maze and door calculations. So, for direct neutron radiation the TVL value (z_d) depends only of the type of shielding material, and its reduction factor is given by:

$$K_d = \frac{\dot{D}_n}{\dot{D}_r} \times \frac{a_0}{a_d} \tag{11}$$

where $\dot{D}_n$ is the direct neutrons radiation dose rate; $\dot{D}_r$ is the x-ray dose rate at the reference point; and a_d is the distance from the direct neutron source to the point protected (m).

2.2. Identification of shielding barriers

The shielding calculations, for both norms, were performed for a radiotherapy bunker located in the radiotherapy facility of the Santa Maria Hospital in Lisbon. Figure 1 shows the bunker design and the protected point's location.

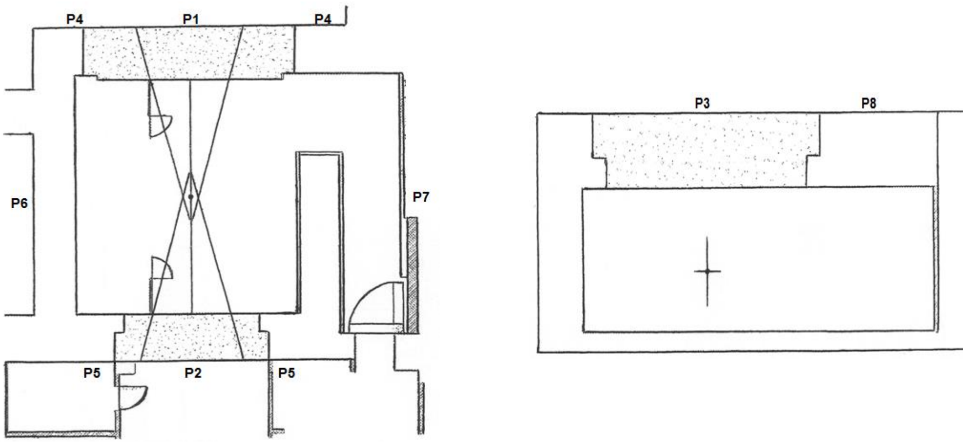

Figure 1. On the left: bunker design and identification of the protected points. On the right: vertical section of the installation and identification of the protected points.

Table 1 shows the identification, in terms of radiation protection, of the shielding barriers in this bunker and its protected point. The identification of the barriers in primary or secondary is related to their function: primary barriers are those that intercept the primary radiation (useful beam) and secondary barriers are those that intercept secondary radiation (scatter, leakage and depending on the norm used, neutron radiation). The protected point is the location of shielding design goal which is 0.30 m from the barrier.

Table 1. Identification of the shielding areas.

Protected Point	Classification of the Barrier	Area	Area Type
P1	Primary Barrier	Outdoor area	Uncontrolled
P2	Primary Barrier	Treatment control area	Controlled
P3	Primary Barrier	Ceiling - Outdoor area	Uncontrolled
P4	Secondary Barrier	Outdoor area	Uncontrolled
P5	Secondary Barrier	Treatment control area	Controlled
P6	Secondary Barrier	Braquiterapia bunker	Controlled
P7	Secondary Barrier	Adjacent treatment bunker	Controlled
P8	Secondary Barrier	Ceiling - Outdoor area	Uncontrolled

2.3. Input Data

Workload calculation was based on the treatments performed on 2011 in one linac of the Radiotherapy Department and was 737.18 $Gy/week$ at 1 m from the radiation source. The P, U, and T values were chosen according to the specification in item 2, using two approaches. As the shielding designs goals (P) depend on the type of the area outside the shielding barrier, whether is controlled or an uncontrolled area. For controlled areas, NCRP and DL recommend a weekly dose equivalent of 0.1 mSv/week and 0.4 mSv/week, respectively. For uncontrolled areas, both NCRP and DL, recommend a weekly dose equivalent of 0.02 mSv/week. Table 2 identifies the use (U) and occupancy factors (T), for the protected points described in table 1, that were used in the calculations of the barriers thicknesses for each norm.

Table 2. Use (U) and occupancy (T) factors.

Protected Point	NCRP 151		DL 180/2002	
	U	T	U	T
P1	0.25	1/40	0.25	1/16
P2	0.25	1	0.25	1
P3	0.25	1/40	0.25	1/16
P4	1	1/40	1	1/16
P5	*	1	1	1
P6	1	1/2	1	1
P7	1	1/2	1	1
P8	*	1/40	1	1/16

* For P5 and P8, the use factor assumed two different values: one for leakage radiation which was 1 and the other for scattered radiation (U_{ps}) which was 0.25 (scatter angle = 30º).

Note: Use factor value for P3 (Ceiling - Outdoor area) was obtained from DIN-6847 standard, because the DL 180/2002 does not include this information.

3. RESULTS AND DISCUSSION

Results obtained using the two different approaches (see item 2) are shown in table 3, where it is possible to start identifying differences between DL and NCRP standards regarding the calculated thicknesses of the primary and secondary radiation barriers.

Table 3. Difference between the barriers thicknesses calculated according to DL 180/2002 and NCRP 151, using two approaches for input data.

Protected Point and Barrier	First Approach	Second Approach
	Difference (%)	Difference (%)
P1.Primary barrier	+ 16	+ 5
P2.Primary barrier	- 8	+ 5
P3.Primary barrier	+ 15	+ 5
P4.Secondary barrier	- 8	- 29
P5.Secondary barrier	- 19	+ 1
P6.Secondary barrier	- 4	+ 11
P7.Secondary barrier	+ 7	+ 13
P8.Secondary barrier	+ 16	+ 3

From the results of the primary barriers, one can see in table 3 that discrepancies were greater (up to 16 %) for the first approach, when P, U and T values were applied following the recommendation in each norm. For this approach, the positive variations associated with the points P1 and P3, located in an uncontrolled area, occur because of the greater occupancy factor values associated with DL, which led to an increase of these barriers thicknesses for this norm. For P2, located in a controlled area, the shielding design goal for DL is greater than the one for NCRP, making the barrier for DL less thick than that calculated according to NCRP.

In the second approach, the differences of 5% (see table 3) between the two norms for primary barriers occur because of the differences in the TVL concept used to calculate the final barrier thickness in each of them, according to equations 1 and 6. In NCRP both TVLs, the equilibrium tenth-value layer for primary barrier (TVL_e) and the first tenth-value layer (TVL_1), are considered in the thickness calculation, whereas DIN uses only the first tenth-value layer. For ordinary concrete and a photon beam with 15 MV, $TVL_1\ was\ 44\ cm$ and $TVL_e\ was\ 41\ cm.$

In order to understand the differences concerning the secondary barriers, the parameters that contribute for the discrepancies in each barrier were analyzed independently. For P4, even though the T value would lead to an increase of the barrier thickness calculated according to DL, the results in table 3 shows a barrier less thick than the one calculated with NCRP because the calculation was performed considering scattering angle of 30° that led to increasing scatter fraction and U_{ps}, consequently increasing the barrier thickness.

In the first approach, for P5, the P value decreased the calculated thickness for DL, but in the second approach the U_{ps} value for photon scattered radiation (see table 2) used in NCRP calculations caused the largest discrepancy, that led to a decrease in the resultant thickness, but did not affect the resultant thickness calculated according to DL because in this case, the thickness was obtained from the leakage and neutrons contributions. If U_{ps} was 1 in both norms, the differences between them, applying the second approach for P5, would be 16 %. This is also valid for P8, and therefore the discrepancies would be 18 %. For P8, the positive variation in first approach occurred because of the differences in T value for uncontrolled area in both norms.

For P6 and P7, the P and T factors affected the barriers thicknesses calculation. Besides that, as will be discussed later, P6 results were also changed by TADR considerations in NCRP calculations and P7 results were affected by neutrons considerations in DIN method (DL). Regarding the second approach, for P6 and P7, their thicknesses calculated with DL were greater than the ones using NCRP because of the large scattering angles incident in that barriers.

In order to understand the discrepancies between the two norms, DL (using DIN) and NCRP, regarding the calculated secondary barrier thickness, it was necessary to analyze separately some components that have different approaches in both standards. The components studied were TADR, leakage, photon scattered and neutron radiation. Table 4 shows the difference between the barriers thicknesses for leakage and photon scattered radiation calculated according to DL 180/2002 and NCRP 151, using the input data: U, T and P values, specified in each norm.

Table 4. Difference between the thicknesses, for secondary barriers, calculated according to DL and NCRP for leakage and photon scattered radiation.

Protected Point	**Leakage Radiation**	**Photon Scattered Radiation**	
	Difference (%)	**Scatter angles (º)**	**Difference (%)**
P4	+ 56	38	- 57
P5	- 13	30	- 61
P6	+ 9	90	- 4
P7	+ 4	90	- 4
P8	+ 58	30	- 39

According to table 4, for leakage radiation, the discrepancies between two norms were mainly due to the TVLs in each norm, and can be seen in the results for P4, P6, P7 and P8. NCRP considers the equilibrium and first tenth-value layer for the thickness calculation, thus for leakage radiation, ordinary concrete and 15 MV, the $TVL_e\ is\ 33\ cm$ and $TVL_1 is\ 36\ cm.$ In DIN method, the first TVL for leakage radiation is the same TVL as for primary radiation $(so, TVL_1\ is\ 44\ cm)$. Exception was verified for P5 where barrier thickness for leakage radiation calculated according to DL resulted in a less thick barrier than the one according to NCRP. This fact was mainly because of its shielding design goal and the differences related to the distances to the protected point in both norms, d_L and a_n, equations (4) and (9), respectively, that led to increasing the barrier thickness when using NCRP.

Concerning photon scattered radiation, the results in table 4 shows that the difference between the two methods were greater for small scattering angles. This occurred because of the TVL values in DL, for photon scattered radiation, that are dependent on the type of shielding material only (so, ordinary concrete $TVL\ is\ 17\ cm$), while NCRP takes into account also the linac energy and radiation scattering angles, so TVL values decrease with the increasing of the scattering angles (e.g. for ordinary concrete and 15 MV: $TVL_{30^\circ}\ is\ 31\ cm$ and $TVL_{90^\circ}\ is\ 18\ cm$). So, for large scattering angles (90º), the TVLs in both norms are similar, leading to a reduction of the differences between both methods, as can be seen in table 4 for P6 and P7 barriers.

The final barrier thickness calculation, for NCRP method, is estimated based on the difference between the calculated thicknesses for leakage and photon scattered radiation, while DIN method takes into account also the direct neutron radiation contribution. Considering that, table 5 shows the results of the difference of final thicknesses calculated with DL and NCRP, for secondary barriers, using the first approach for input data, for three situations: 1) comparison between DIN method without neutron consideration and NCRP method; 2) comparison between DIN method which includes neutrons considerations and NCRP method; and 3) comparison between DIN method and NCRP method without TADR considerations.

Table 5. The results of the difference of final thicknesses calculated with DL 180/2002 (DIN) and NCRP 151, for secondary barriers, and for three different situations.

Protected Point	DIN-6847 method without neutron consideration vs NCRP 151	DIN-6847 vs NCRP 151	DIN-6847 vs NCRP 151 without TADR considerations
	Difference (%)	Difference (%)	Difference (%)
P4	- 18	- 8	- 8
P5	- 28	- 19	- 19
P6	- 4	- 4	+ 9
P7	- 11	+ 7	+ 7
P8	+ 16	+ 16	+ 16

According to table 5, the results obtained regarding neutron contribution, as expected when using DIN method, showed an increase of the secondary barrier thicknesses that can be seen for P4, P5 and P7. Exception were verified for P6 and P8, they both were not affected for neutron consideration, once the calculated thicknesses for leakage radiation prevail over the others. Regarding the results in table 5, for point P6, one can note that TADR considerations in NCRP, led to an increase of the barrier thickness calculated according to this norm, because it was the only point where the difference between leakage and scattered radiation in NCRP method was superior than a TVL, which means that the calculated thickness was the one obtained from leakage radiation. In this case, the calculated thickness was not sufficient to ensure the weekly TADR. In order to accomplish the weekly TADR it was added one half-value layer (HVL) to the calculated thickness, which led to an increase of the barrier thickness calculated according to NCRP. The other barriers, P4, P5, P7 and P8, were not affected for TADR considerations.

4. CONCLUSIONS

The thicknesses of primary and secondary radiation barriers for a 15 MV linac bunker were calculated using the NCRP 151 and DL 180/2002 norms, where the last one is based on DIN-6847 method. The results obtained with both norms showed that the main cause of the discrepancies for the primary barriers was due to the use of the first TVL for DIN method; whereas NCRP takes into account both the first TVL and equilibrium TVL. For secondary barriers, the main reasons for discrepancies between both norms were the TVLs related to each norm and the neutrons considerations in DIN method. For DIN, the TVL for leakage radiation is the same as the TVL for primary radiation, which is greater than the TVL for leakage radiation in NCRP. And differently from DIN method, the NCRP's TVL for photon scattered radiation is a function of the energy and radiation scattering angle.

In conclusion, when considering conventional treatment techniques, and using the shielding design goals, use and occupancy factors specified in each norm, the differences for primary and secondary radiation barriers can be quite important. In some cases, as for secondary radiation barrier, the calculated thicknesses were underestimated, particularly when the calculations were based on Portuguese Regulations. This situation can be even more critical if one considers IMRT techniques, because of the increasing leakage-radiation that is taken into account by the IMRT factor in the workload calculations for the secondary barriers in NCRP but not in DL.

5. REFERENCES

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