

ORIGINAL RESEARCH ARTICLE

Shielding design calculations for a radiotherapy vault of a 6 and 10-megavoltage medical linear accelerator operating with or without a flattening filter

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Abstract

This study focuses on upgrading the shielding design of a Co-60 radiotherapy unit to accommodate a linear accelerator operating at 6 and 10 megavoltage, which can function in both flattening filter (FF) and flattening filter-free (FFF) modes. Shielding calculations were performed using analytical methods from the National Council on Radiation Protection and Measurements Report No. 151 and International Atomic Energy Agency Safety Reports Series No. 47, considering standard (40 patients/day) and heavy (60 patients/day) workloads. Barrier thicknesses were determined to ensure the instantaneous dose rate (IDR) behind primary barriers is $\leq 7.5 \mu\text{Sv/h}$ in FF mode and $\leq 20 \mu\text{Sv/h}$ in FFF mode, as recommended in the Institute of Physics and Engineering in Medicine Report No. 75. Results showed that workload had no significant effect on the primary barrier thickness. Moreover, strict adherence to the IDR criteria increased shielding demands ranging from 11% to 46% while reducing the personal equivalent dose to 1.2 – 13.4% of the dose constraints. This highlights a potential overdesign that could substantially increase raise construction costs. Therefore, applying the IDR criteria violates the radiation protection principles, namely, “optimization.” An alternative approach has been proposed to optimally use the IDR criteria by including the patient’s transmission factor in the current IDR criteria or by adopting higher values of IDR strictly to verify the shielding efficiency. Higher IDR adoption would result in lower linear accelerator vault costs and more realistic shielding calculations consistent with operating conditions.

Keywords: Medical linear accelerator; Radiotherapy; Flattening filter; Shielding calculations; Instantaneous dose rate; Optimization

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1. Introduction

Megavoltage (MV) photon beams produced by linear accelerators at various energies are the most commonly used radiation sources in modern radiation oncology and radiotherapy. The primary goal in treatment planning is to deliver an appropriate dose to the tumor while minimizing exposure to surrounding tissues and organs at risk. This objective has been progressively enhanced using different radiotherapy techniques, such as three-dimensional conformal radiotherapy, intensity-modulated radiotherapy

(IMRT), and volumetric-modulated arc therapy (VMAT). In recent years, IMRT and VMAT have increasingly replaced three-dimensional conformal radiotherapy.

Conventionally, it was believed that an ideal photon beam used in treatment planning should be uniform across the treatment field. This uniformity is obtained using a flattening filter (FF) positioned in the linear accelerator (linac) head. However, the widespread adoption of non-uniform beam distribution has challenged this assumption. Removing the FF results in flattening filter-free (FFF) beams, now widely used for stereotactic and non-stereotactic radiotherapy treatments. As a result, advanced treatment techniques prefer FFF beams over FF beams.¹⁻⁶

Numerous studies^{3,4,7-12} have thoroughly examined the main dosimetric properties of FFF beams, the precision of dose calculations, and the quality of treatment plans for IMRT with unflattened beams. The FFF beams exhibit distinct characteristics compared to standard FF beams, specifically in terms of high dose rate and a profile shape that is peaked along the beam's central axis. Moreover, removing the FF significantly lowers the leakage radiation from the treatment head and softens the photons' energy spectrum.¹³⁻¹⁶ Furthermore, since the FF is a source of photoneutrons, its removal reduces neutron production from the linac's head.

The main objective of the radiation protection program in medical linear accelerator facilities is to protect workers, the general public, and the environment from the harmful effects of ionizing radiation (gamma rays and photoneutrons) transmitted outside the linac's vault. Thus, shielding requirements are defined by the dosimetric characteristics of the clinically applied MV photon beams – more precisely, by the beam modality used during treatment (FF or FFF). In all cases, shielding design should avoid unnecessary overestimation. A balanced approach must be taken, considering both the actual shielding needs under normal operating working conditions and the associated construction cost.

This study aims to present a case analysis evaluating the shielding requirements for an existing Co-60 radiotherapy bunker intended to adequately accommodate an Elekta Versa HD medical linear accelerator operating at 6 and 10 MV, with and without an FF. The shielding evaluation considers both a standard operating workload (40 patients/day) and an overload (60 patients/day) of 50% for each accelerator energy. The final thicknesses of the primary barriers were determined such that the expected instantaneous dose rate (IDR) behind the barriers does not exceed 7.5 $\mu\text{Sv/h}$ for FF mode and 20 $\mu\text{Sv/h}$ for FFF mode, in accordance with the recommendations of the Institute

of Physics in Medicine and Engineering Report No. 75 (IPEM 75).¹⁷ The shielding evaluation and determination were performed for the existing vault using the analytical equations listed in the International Atomic Energy Agency Safety Reports Series No. 47 (IAEA SRS-47)¹⁸ and the National Council on Radiation Protection and Measurements Report No. 151 (NCRP 151).¹⁹ Both primary and secondary barriers were assessed, with a particular focus on primary barriers that are directly exposed to the beam. The impact of applying the IDR criteria on shielding design has not been extensively studied. In this work, the thicknesses of the primary barriers obtained with and without adhering to the above-mentioned IDR criteria were analyzed in detail and evaluated in the context of fundamental radiation protection principles, with particular emphasis on the “optimization” principle. The necessary recommendations were proposed regarding using the IDR criteria in its current form or modifying its use to suit the working conditions in radiation therapy units without overestimating the barriers' thicknesses. This study represents a step-by-step, comprehensive, practical guide for determining shielding requirements for a real linac bunker, with detailed explanations for each step.

2. Methods

2.1. Bunker description and shielding upgrade approach

Figure 1 represents the linac's bunker before and after the shielding upgrade. The existing primary barrier thickness (1.35 m) is inadequate for 6 or 10 MV linacs. One of the primary barriers is adjacent to the public waiting area, that is, fully occupied, and fortunately, there is enough space to extend it using ordinary concrete (density = 2.35 g/cm^3). The same situation applied to the primary ceiling, and it is also possible to extend the ceiling's shielding since the bunker's roof is dedicated to the linac's chillers and the hospital's heating, ventilation, and air conditioning system. The other primary barrier is adjacent to the maze of another bunker, that is, partially occupied, and the space is very limited for implementing any concrete shielding beyond this barrier. Therefore, the necessary shielding extension will be partially implemented using ordinary concrete inside the bunker; the largest thickness available for this internal extension is 0.5 m \times 3.12 m. This internal shielding extension is very advantageous to support the ceiling's shielding extension from a structural engineering point of view. The remaining shielding extension will be implemented using high-density material, such as iron, outside the bunker.

The left secondary barrier of the bunker's maze is comparatively short and thin (0.95 m). This results in a

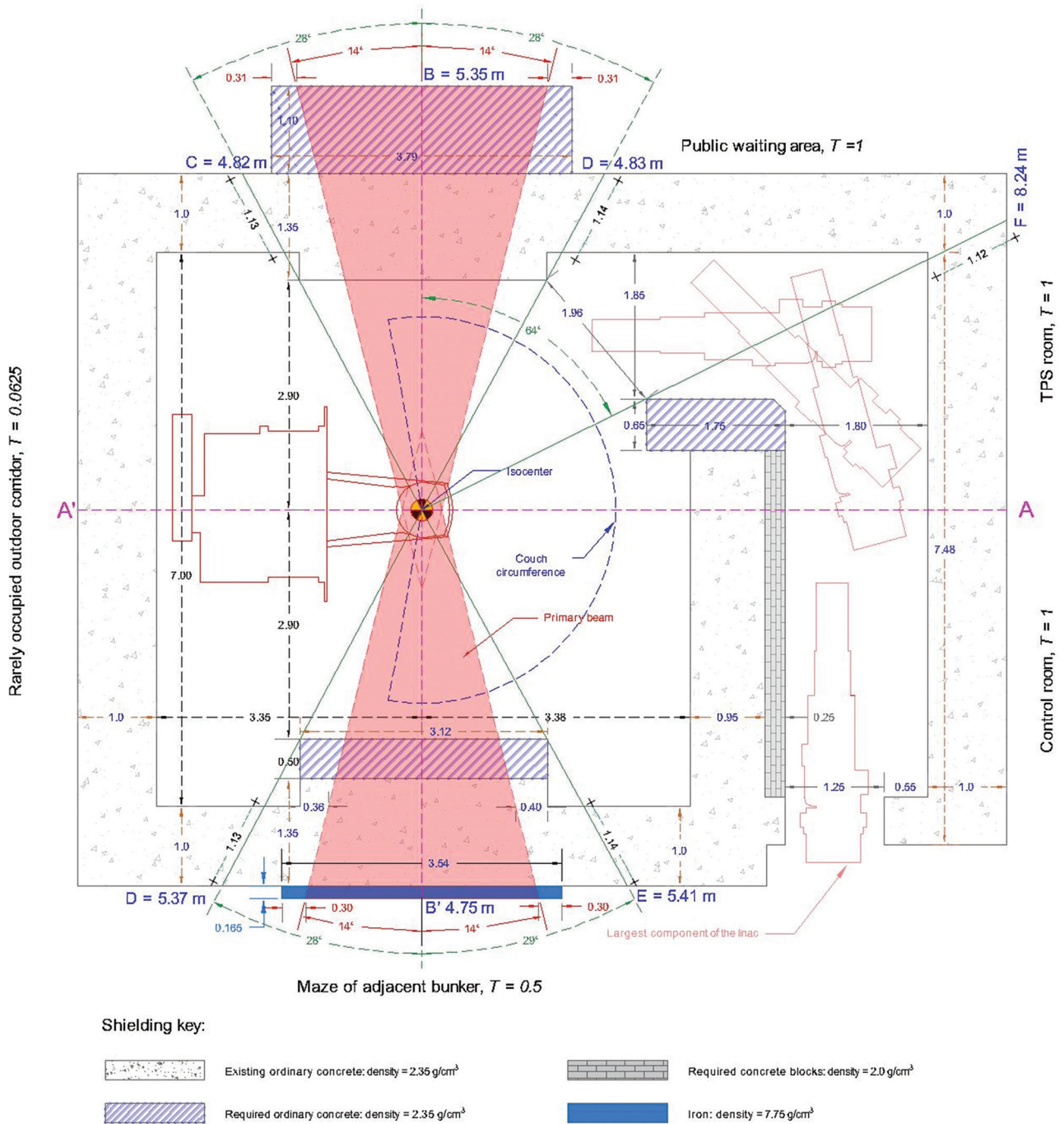


Figure 1. Vault design for a 6 and 10 MV linear accelerator with one primary barrier made from ordinary concrete while the other comprises ordinary concrete and iron. Image created by the author. Abbreviation: TPS: Treatment Planning System room.

wide cross-section of the inner maze entrance, raising the radiation levels (neutrons and gamma) at the bunker's door. To increase this barrier's thickness, 25 cm of concrete blocks with a density of at least 2.0 g/cm³ – equivalent to

21 cm of concrete – will be added, making the barrier's total effective thickness approximately 116 cm of ordinary concrete. Concrete blocks were utilized since concrete cannot be easily poured at a thin thickness (25 cm).

In addition, the inner maze entrance was modified by adding a shielding extension of ordinary concrete, with dimensions of 1.75 m × 0.65 m. This alteration effectively converted the original single-leg maze into a two-leg configuration, significantly reducing the radiation (gamma and neutrons) within the maze. As a result, radiation dose behind the right-side barrier of the maze where two rooms are fully occupied, namely, the treatment planning system and control rooms, are also expected to decrease.

The internal shielding extensions were designed based on two criteria, as illustrated in Figure 1: first, to allow free movement of the linac treatment couch without any obstacles while maintaining sufficient space for the linac operator to position patients comfortably, and second, to allow for the safe and free maneuvering of the largest component of the Elekta Versa HD linac through the inner maze entrance.

Given that the minimum slant path through the shielding is approximately 114 cm, the thicknesses of the other secondary barriers (1.0 m) were left unaltered. This design assumption will be validated through calculations and radiation measurements.

2.2. The national council on radiation protection and measurements report no. 151 and safety reports series no. 47 shielding calculation approach

The weekly dose constraint (P_w) received by a person behind a primary barrier is determined by Equation I.

$$P_w = \frac{B_0 \times W \times U \times T}{d + SAD} (\mu\text{Sv} / \text{week}) \quad (\text{I})$$

The dose constraint (P_w) received by a person behind a secondary barrier is determined by the sum of the doses received due to secondary radiation, namely, head leakage [P_L] and patient scatter [P_p], as in Equations II and III,

$$P_w = P_L + P_p (\mu\text{Sv}/\text{week}) \quad (\text{II})$$

$$P_w = \frac{B_L \times W^* \times T}{1000 \times d} + \frac{B_p \times a \times W \times T \times (F / 400)}{d_{sca} \times d_{sec}} (\mu\text{Sv} / \text{week}) \quad (\text{III})$$

Where W is the weekly workload (Gy/week) at the isocenter, W^* is the weekly workload (Gy/week) produced by the linac, T is the occupancy factor, a is the scatter fraction from the patient, U is the wall use factor, F is field size incident on the patient, and SAD is the source to isocenter distance. B_0 is the barrier transmission against primary radiation, d is the distance from the isocenter to the calculation point, B_L is the barrier transmission against leakage radiation, d_{sca} is the distance from the source to the patient, B_p is the barrier transmission against patient

scatter radiation, and d_{sec} is the distance from the patient to the calculation point.

The designed dose constraint (P_w) behind a particular primary barrier is achieved at a specific value of the transmission factor B_0 of that barrier. This transmission factor is achieved using a particular thickness of the barrier of specific density that can attenuate the radiation dose to the designed dose constraint. The required transmission factor B_0 could be determined using Equation IV,

$$TVLs = \log_{10} \left(\frac{1}{B_0} \right) \quad (\text{IV})$$

Where $TVLs$ are the number of the tenth value layers (TVLs) required to achieve the designed B_0 . The transmission factor B_0 of that barrier is then given in Equation V,

$$B_0 = \left(\frac{P_0 \times (SAD + d)^2}{D_0} \right) \quad (\text{V})$$

Where D_0 is the dose rate at the isocenter, and P_0 is the equivalent dose rate constraint behind the barrier. IPEM 75¹⁷ proposed $P_0 = 7.5 \mu\text{Sv}/\text{h}$ when testing the transmission factor at the FF modality and $20 \mu\text{Sv}/\text{h}$ in the case of the FFF beam modality. In this study, all parameters, as mentioned earlier, were retrieved from the NCRP 151 except the TVLs, which were extracted from the IAEA SRS-47 because the TVL values reported therein are more consistent with the experimental data results in recent studies.^{20,21}

Exposure to the radiation from the linac vault represents planned exposure controlled within the framework of dose constraints to ensure that the radiation exposure is as low as reasonably achievable.²² Accordingly, the shielding design calculations are carried out using the following assumptions: (i) annual dose limit [P_o] = 20 (1) mSv/year for occupational (public) and (ii) annual dose constraints [P] = 6 (1) mSv/year for occupational (public). This means the weekly dose constraints [P_w] = 120 (20) $\mu\text{Sv}/\text{week}$.

The thicknesses of the primary and secondary barriers are determined so that the weekly dose constraints are not exceeded.

2.3. Workload considerations

Two workload cases have been considered in this study; the first one is 40 patients/day, representing the standard workload in all literature. The number 40 patients/day means five patients are treated in 1 h along an 8-h working day. Another case represents an overloaded facility with 60 patients/day, which means that seven to eight patients are treated in an hour or the working day is longer than 8 h.

Many of the radiotherapy facilities in Egypt are operating at an overload, with an average of 60 patients per day. Table 1 summarizes the two cases of workload distribution during the working week.

3. Results

3.1. Primary barrier at point B (public waiting area)

This barrier is made entirely of ordinary concrete. The unshielded weekly dose behind this primary barrier is determined as in Equation VI,

$$W \times T \times U / ((d+0.3) + SAD)^2 \tag{VI}$$

Where, the occupancy factor $T = 1$, the use factor $U = 0.25$, dose constraint = $20 \mu\text{Sv/week}$, $d = 5.35$, and $SAD = 1 \text{ m}$.

3.1.1. Case 1: Working load of 40 patients/day

The weekly unshielded dose at 10 MV (20 patients) is presented in Equation VII.

$$360 \times 1 \times 0.25 / 6.65^2 = 2.04 \text{ Sv/week} \tag{VII}$$

To reduce this value to the weekly dose constraints for the public ($20 \mu\text{Sv/week}$), the transmission factor becomes $B = 9.83 \times 10^{-6}$. Accordingly, the number of TVLs needed to achieve this value is 5.0; considering that the TVL at 10 MV is 38.9 cm, the primary barrier should be 1.95 m thick.

The weekly unshielded dose at 6 MV (20 patients) is presented in Equation VIII.

$$360 \times 1 \times 0.25 / 6.65^2 = 2.04 \text{ Sv/week} \tag{VIII}$$

To reduce this value to the weekly dose constraints for the public ($20 \mu\text{Sv/week}$), the transmission factor becomes

$B = 9.83 \times 10^{-6}$. Accordingly, the number of TVLs needed to achieve this value is 5.0; considering that the TVL at 6 MV is 34.3 cm, the primary barrier should be 1.72 m thick.

The difference between the two thicknesses is 23 cm. This difference reduces the weekly dose at 6 MV to $4.26 \mu\text{Sv/week}$, making the total weekly dose $24.6 \mu\text{Sv}$. Therefore, one half-value layer (HVL) of 10 MV will be added to the total thickness to ensure that the weekly dose rate is $<20 \mu\text{Sv/week}$; the final thickness of the primary barrier will be 2.07 m. The total weekly dose from the two energies at this final thickness is $11.94 \mu\text{Sv/week}$.

However, in the case of 10 MV FF beam modality, to fulfill the IDR of $\leq 7.5 \mu\text{Sv/h}$ at a dose rate of 600 MU/min at the linac's isocenter, the primary barrier thickness should be 2.35 m. In addition, in the case of 10 MV FFF beam modality, to fulfill the IDR criteria of $\leq 20 \mu\text{Sv/h}$ at a dose rate of 2,400 MU/min at the linac's isocenter, the primary barrier thickness should be 2.42 m. Accordingly, the highest value will be considered. Consequently, using IDR criteria necessitates that the primary barrier thickness for the workload of 40 patients/week should be increased by 17.0%.

The expected equivalent dose behind the primary barrier at the final thickness, 2.42 m, equals $1.434 \mu\text{Sv/week}$ or $71.7 \mu\text{Sv/year}$, which means that the use of IDR criteria reduces the equivalent dose to just 7.17% of the annual dose constrain, that is, 1 mSv/year.

3.1.2. Case 2: Working load of 60 patients/day

The weekly unshielded dose at 10 MV (40 patients) is presented in Equation IX.

Table 1. Details of weekly workload distribution for a 6 and 10-MV linear accelerator

Planned weekly workload using 6 and 10 MV linear accelerator	Energy (treatment modality)	Patients per day	Dose fraction (Gy/patient)	Weekly workload (Gy/week)	Total dose at isocenter Gy/week	IMRT ratio	Total dose produced by linear accelerator (Gy/week)
Case 1: 40 patients/day	10 (3D)	10	3	180	360	1	855
	10 (IMRT)	5	3	90		5	
	10 (VMAT)	5	3	90		2.5	
	6 (3D)	10	3	180	360	1	
	6 (IMRT)	5	3	90		5	
	6 (VMAT)	5	3	90		2.5	
Case 2: 60 patients/day	10 (3D)	20	3	360	720	1	1,710
	10 (IMRT)	10	3	180		5	
	10 (VMAT)	10	3	180		2.5	
	6 (3D)	10	3	180	360	1	
	6 (IMRT)	5	3	90		5	
	6 (VMAT)	5	3	90		2.5	

Abbreviations: 3D: Three-dimensional; IMRT: Intensity-modulated radiotherapy; VMAT: Volumetric-modulated arc therapy.

$$720 \times 1 \times 0.25/6.65^2 = 4.07 \text{ Sv/week} \quad (\text{IX})$$

To reduce this value to the weekly dose constraints for the public (20 μSv/week), the transmission factor becomes $B = 4.91 \times 10^{-6}$. Accordingly, the number of TVLs needed to achieve this value is 5.31; considering that the TVL at 10 MV is 38.9 cm, the primary barrier should be 2.07 m thick.

The weekly unshielded dose at 6 MV (20 patients) is presented in Equation X.

$$360 \times 1 \times 0.25/6.65^2 = 2.5 \text{ Sv/week} \quad (\text{X})$$

To reduce this value to the weekly dose constraints for the public (20 μSv/week), the transmission factor becomes $B = 9.83 \times 10^{-6}$. Accordingly, the number of TVLs needed to achieve this value is 5.0; considering that the TVL at 6 MV is 34.3 cm, the primary barrier should be 1.72 m thick.

The difference between the two thicknesses is 34.7 cm; this difference reduces the weekly dose at 6MV to 1.94 μSv/week, which makes the total weekly dose 21.94 μSv/week. Therefore, one HVL of 10 MV will be added to the total thickness to ensure that the weekly dose rate is <20 μSv/week and the final thickness of the primary barrier will be 2.18 m. The total weekly dose from the two energies at this final thickness is 10.88 μSv/week.

Since the primary barrier thickness is 2.42 m based on the IDR criteria mentioned above, the primary barrier thickness for the workload of 60 patients/week must be increased by 10.73%.

The expected equivalent dose behind the primary barrier at the final thickness, 2.42 m, equals 2.684 μSv/week or 134.2 μSv/year, which means that the use of IDR criteria reduces the equivalent dose to just 13.4% of the annual dose constrain, that is, 1 mSv/year. For this primary barrier (B), it is worth noting that the IDR in the FF case decreases from 7.5 μSv/h at 2.35 m to 5 μSv/h at 2.42 m, the thickness required in the FFF case.

3.2. Primary barrier at point B'

This barrier is made partially of ordinary concrete, and any additional thickness is made of iron. At this point, the occupancy factor $T = 0.5$, the use factor $U = 0.25$, and the dose constraint = 120 μSv/week.

3.2.1. Case 1: Working load of 40 patients/day

The weekly unshielded dose at 10 MV (20 patients) is presented in Equation XI.

$$360 \times 0.25 \times 0.5/6.05^2 = 1.23 \text{ Sv/week} \quad (\text{XI})$$

To reduce this value to the weekly dose constraints for the workers (120 μSv/week), the transmission factor becomes $B = 9.76 \times 10^5$. Accordingly, the number of TVLs

needed to achieve this value is 4.0; considering that the TVL at 10 MV is 38.9 cm, the primary barrier should be 1.56 m thick.

The weekly unshielded dose at 6 MV (20 patients) is presented in Equation XII.

$$360 \times 0.25 \times 0.5/6.05^2 = 1.23 \text{ Sv/week} \quad (\text{XII})$$

To reduce this value to the weekly dose constraints for the workers (120 μSv/week), the transmission factor becomes $B = 9.76 \times 10^5$. Accordingly, the number of TVLs needed to achieve this value is 4.0; considering that the TVL at 6 MV is 34.3 cm, the primary barrier should be 1.38 m thick.

The difference between the two thicknesses is 18.4 cm; this difference reduces the weekly dose at 6 MV to 34.78 μSv/week, which made the total weekly dose 154.78 μSv/week. Therefore, one HVL of 10 MV will be added to the total thickness to ensure the weekly dose rate is < 120 μSv/week. Hence, the final thickness of the primary barrier will be 1.68 m. The total weekly dose from the two energies at this final thickness is 75.85 μSv/week.

In the case of 10 MV FF beam modality, to fulfill the IDR criteria of ≤7.5 μSv/h at a dose rate of 600 MU/min at the linac's isocenter, the primary barrier thickness should be 2.38 m. In the case of 10 MV FFF beam modality, to fulfill the IDR criteria to be ≤20 μSv/h at a dose rate of 2,400 MU/min at the linac's isocenter, the primary barrier thickness should be 2.45 m. Accordingly, the highest value will be considered. Consequently, using IDR criteria necessitates that the primary barrier thickness for the workload of 40 patients/week must be increased by 46%.

The expected equivalent dose behind the primary barrier at the final thickness, 2.45 m, equals 1.429 μSv/week or 71.45 μSv/year, which means that the use of IDR criteria reduces the equivalent dose to just 1.91% of the annual dose constrain, that is, 6 mSv/year.

3.2.2. Case 2: Working load of 60 patients/day

The weekly unshielded dose at 10 MV (40 patients) is presented in Equation XIII.

$$720 \times 0.25 \times 0.5/6.05^2 = 2.46 \text{ Sv/week} \quad (\text{XIII})$$

To reduce this value to the weekly dose constraints for the workers (120 μSv/week), the transmission factor becomes $B = 4.88 \times 10^{-5}$. Accordingly, the number of TVLs needed to achieve this value is 4.31; considering that the TVL at 10 MV is 38.9 cm, the primary barrier should be 1.68 m thick.

The weekly unshielded dose at 6 MV (20 patients) is presented in Equation XIV.

$$360 \times 0.25 \times 0.5/6.05^2 = 1.23 \text{ Sv/week} \quad (\text{XIV})$$

To reduce this value to the weekly dose constraints for the workers (120 $\mu\text{Sv/week}$), the transmission factor becomes $B = 9.76 \times 10^5$. Accordingly, the number of TVLs needed to achieve this value is 4.0; considering that the TVL at 6 MV is 34.3 cm, the primary barrier should be 1.38 m thick.

The difference between the two thicknesses is 30 cm; this difference reduces the weekly dose at 6 MV to 15.84 $\mu\text{Sv/week}$, which made the total weekly dose 135.84 $\mu\text{Sv/week}$. Therefore, one HVL of 10 MV must be added to the total thickness to ensure the weekly dose rate is <120 $\mu\text{Sv/week}$. The final thickness of the primary barrier will be 1.8 m. The total weekly dose from the two energies at this final thickness is 67.21 $\mu\text{Sv/week}$.

Since the primary barrier thickness is 2.45 m based on the IDR criteria mentioned above, there is a 36.45% increase in the barrier thickness. Notably, for this primary barrier (B'), the IDR of the FF decreases from 7.5 $\mu\text{Sv/h}$ at 2.38 m to 5 $\mu\text{Sv/h}$ at 2.45 m, which is the thickness of the FFF case.

The expected equivalent dose behind the primary barrier at the final thickness, 2.45 m, equals 2.679 $\mu\text{Sv/week}$ or 134 $\mu\text{Sv/year}$, indicating that the use of IDR criteria reduces the equivalent dose to just 2.23% of the annual dose constrain, that is, 6 mSv/year.

Given that only 185 cm of concrete exists, the remaining required thickness of the primary barrier (60 cm) should be compensated with a high-density material due to the limited space available. This required 60 cm thickness corresponds to 1.54 TVL at 10 MV. Considering that the TVL at 10 MV for iron is 10.5 cm, a 16.2 cm layer of iron should be used. Hence, for practical reasons, 16.5 cm of iron will be implemented.

Figure 2 represents the primary barrier's final design with an additional iron thickness. As shown, there are two options: (i) use one iron layer weighing approximately 16.9 tons or (ii) use multilayers of iron with different thicknesses and dimensions. In this case, calculations were conducted in 40 cm steps in horizontal and vertical directions. This was done because the layers will be arranged and fixed on the wall using 40 cm \times 40 cm tiles of iron, which will be well welded together. The thickness of each layer is determined based on its distance from the isocenter and the slant path of radiation inside the concrete, as shown in Figure 2. Using the multi-layers of iron requires only 13 tons, saving about 3.6 tons. Notably, the thickness of the existing (1.35 m) and new concrete (0.5 m) is adequate if the IDR criteria were not applied.

The ceiling shielding calculations at point G were performed similarly to those followed in primary barriers B and B'. Although the occupancy factor of the roof is very small, the final thickness is determined based on 20 $\mu\text{Sv/h}$ criteria at 10 MV (FFF).

Table 2 summarizes the shielding calculation results obtained for the two workload cases. Notably, the maximum barrier's thickness is obtained when IDR criteria were applied at 10 MV (FFF), that is, ≤ 20 $\mu\text{Sv/h}$, regardless of any thickness obtained at 6 MV or 10 MV (FF). Table 3 summarizes the expected equivalent dose received by personnel behind the primary barriers B and B'.

3.3. Secondary barriers at points C, D, E, F, and G

Points C, D, E, and F have the same scattering angle ($28^\circ - 29^\circ$) and the same slant radiation path inside the concrete (approximately 1.13 cm). Accordingly, the following observations are made:

- (i) The distances of points C and D from the isocenter are longer than those of E and F
- (ii) The occupancy factor at C and E is greater than that at points E and F
- (iii) The dose constraint at points C and E is less than at points E and F.

Thus, the shielding requirements at points C and D are greater than those needed for E and F. Similarly, the shielding requirements at point G are less than those required at points C and D since its distance from the isocenter is much longer (8.24 m) and its scattering angle is greater (65°). Therefore, if the existing thickness (1.0 m) of all secondary barriers is adequate at points C or D, it will also be sufficient at E, F, and G. The shielding requirement at point C is presented by evaluating the leakage and patient scatter at this barrier.

The use factor for leakage radiation is 1, given that it hits all barriers regardless of the linac's head angle. Secondary barriers adjacent to the primary barriers receive significant patient scatter radiation only when the primary beam is directed at the primary barriers. Thus, assuming that the use factor at points C, D, E, and F equals 0.25, that is, the same use factor as primary barriers will be reasonable. Using a use factor of 1 for an adjacent secondary barrier exaggerates conservatism. This study uses this assumption and verifies its validity through an experimental radiation survey at a later stage. Notably, the use factor for secondary barriers adjacent to the primary barriers in NCRP 151, SRS 47, and IPEM 75 equals unity.

Although the average field size used in treating patients daily is $20 \times 20 \text{ cm}^2$, the same approach mentioned in NCRP

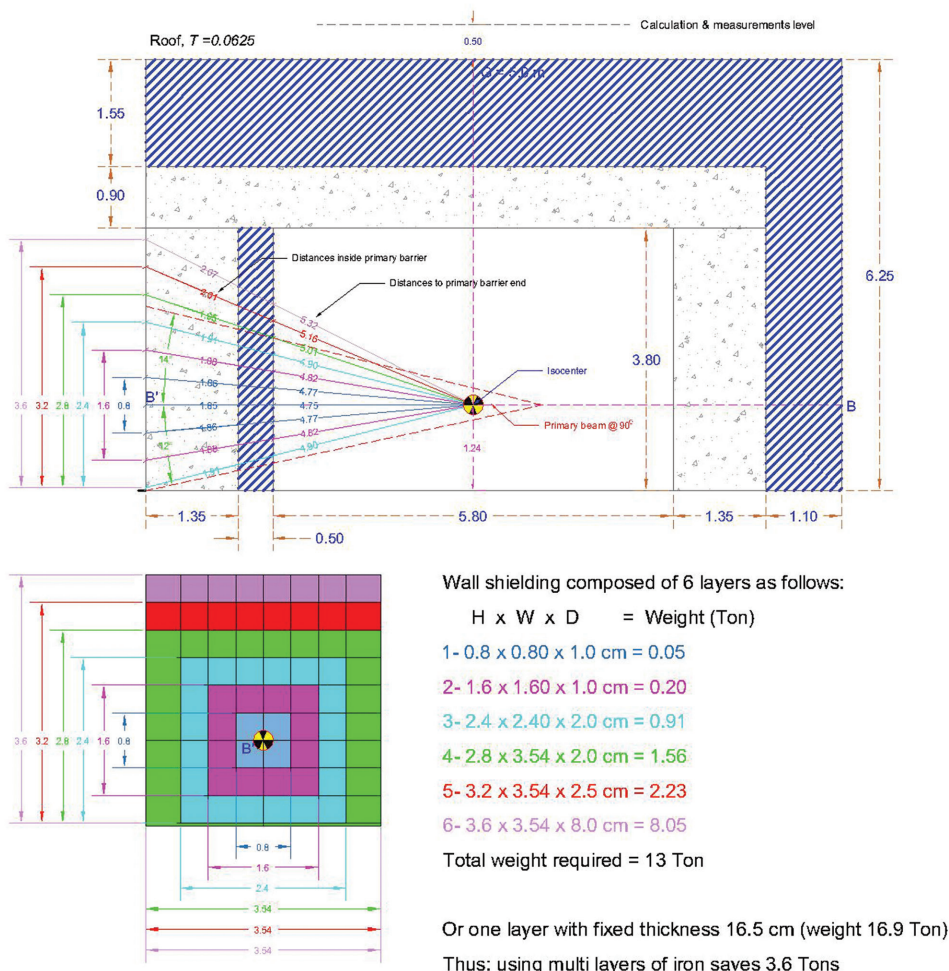


Figure 2. Primary barrier detail design composed of ordinary concrete and multi-layers of iron with different dimensions. Image created by the author.

Table 2. Summary of the shielding calculation results for primary barriers

Barrier thickness demands (in m)	Workload (No. patient/day)	Criteria, concrete thickness (m), and no. TVL			% Increment in shielding thickness due to using IDR criteria, $\frac{b-a}{a}$
		^a Weekly dose constraints	IDR=7.5 μ Sv/h (10 MV FF)	^b IDR=20 μ Sv/h (10 MV FFF)	
Point B	40 patients/day	2.07 m no. TVL=5.3	2.35 m no. TVL=6.04	2.42 m no. TVL=6.21	17.01
	60 patients/day	2.18 m no. TVL=5.61	2.35 m no. TVL=6.04	2.42 m no. TVL=6.21	10.73
Point B' (maze of the adjacent bunker)	40 patients/day	1.68 m no. TVL=4.31	2.38 m no. TVL=6.11	2.45 m no. TVL=6.29	45.96
	60 patients/day	1.75 m no. TVL=4.61	2.38 m no. TVL=6.11	2.45 m no. TVL=6.29	36.45

Abbreviations: FF: Flattening filter; FFF: Flattening-free filter; IDR: Instantaneous dose rate; MV: Megavoltage; TVL: Tenth-value layer.

151, SRS 47, and IPEM 75 will be followed, i.e., a field size of $40 \times 40 \text{ cm}^2$ will be used as a conservative measure, despite it being overly conservative.

In summary, it was deemed unjustified to apply two overly conservative assumptions simultaneously when calculating shielding requirements for secondary barriers:

Table 3. The expected equivalent dose received by personnel behind the primary barriers B and B'

Barrier	Dose limit	Dose constraint	Expected annual dose	% of annual dose constraint
B	1 mSv/year	1 mSv/year	40 patient/day: 71.7 μSv 60 patients/day: 134.2 μSv	100×71.1/1,000=7.17 100×134.2/1,000=13.42
B'	20 mSv/year	6 mSv/year	40 patient/day: 71.45 μSv 60 patients/day: 134 μSv	100×71.1/6,000=1.191 100×134.2/6,000=2.23

(i) using a 40 × 40 cm field size instead of the average 20 × 20 cm and (ii) assigning a use factor of 1 for secondary barriers adjacent to primary barriers. Therefore, the first assumption was retained, while the second was revised to reflect practical clinical conditions better, as previously indicated.

3.3.1. Case 1: Working load of 40 patients/day

The weekly unshielded leakage dose at 10 MV (20 patients) is presented in Equation XV.

$$855 \times 0.001/5.12^2 = 32.6 \text{ mSv/week} \quad (\text{XV})$$

The transmission factor was deemed as $B = 6.13 \times 10^{-4}$ to reduce this value to the weekly dose constraints for the public (20 μSv/week). Accordingly, the number of TVLs needed to achieve this value is 3.21; considering that the TVL leakage for 10 MV is 30.5 cm, the secondary barrier should be 0.98 m thick.

The weekly unshielded leakage dose at 6 MV (20 patients) is presented in Equation XVI.

$$855 \times 0.001/5.12^2 = 32.6 \text{ mSv/week} \quad (\text{XVI})$$

Similarly, the transmission factor becomes $B = 6.13 \times 10^{-4}$ to reduce the obtained value. The number of TVLs needed to achieve this value is 3.21; considering that the TVL leakage for 6 MV is 27.9 cm, the secondary barrier should be 0.90 m thick. A simple calculation shows that the total leakage radiation from 6 and 10 MV at the existing slant thickness (1.14 m) equals 5.95 μSv/week.

The weekly unshielded patient scatter dose at 10 MV (20 patients) is presented in Equation XVII.

$$W \times T \times U \times a \times F^2/400 \times d^2 = 360 \times 1 \times 0.25 \times 3.18 \times 10^{-3} \times 1,600/400 \times 5.12^2 = 43.7 \text{ mSv/week} \quad (\text{XVII})$$

To reduce this value to the weekly dose constraints for the public, the transmission factor becomes $B = 4.57 \times 10^{-4}$. Accordingly, the number of TVLs needed to achieve this value is 3.34; taking into consideration that the TVL leakage for 10 MV is 27.5 cm, the secondary barrier should be 0.92 m thick.

The weekly unshielded patient scatter dose at 6 MV (20 patients) is presented in Equation XVIII.

$$W \times T \times U \times a \times F^2/400 \times d^2 = 360 \times 1 \times 0.25 \times 2.77 \times 10^{-3} \times 1,600/400 \times 5.12^2 = 38 \text{ mSv/week} \quad (\text{XVIII})$$

To reduce this value to the weekly dose constraints for the public, the transmission factor becomes $B = 4.28 \times 10^{-4}$. Accordingly, the number of TVLs needed to achieve this value is 3.28; considering that the TVL leakage for 6 MV is 26.1 cm, the secondary barrier should be 0.86 m thick. A simple calculation shows that the total patient scatter radiation from 6 and 10 MV at the existing slant thickness (1.14 m) equals 4.75 μSv/week.

Accordingly, the total weekly dose from leakage and scatter radiation at point C equals 10.7 μSv, less than the weekly dose constraints, 20 μSv/week. Hence, the existing thickness is adequate for the workload of 40 patients/day.

3.3.2. Case 2: Working load of 60 patients/day

The weekly unshielded leakage dose at 10 MV (40 patients) is presented in Equation XIX.

$$1,710 \times 0.001/5.12^2 = 65.2 \text{ mSv/week} \quad (\text{XIX})$$

To reduce this value to the weekly dose constraints for the public, the transmission factor becomes $B = 3.06 \times 10^{-4}$. Accordingly, the number of TVLs needed to achieve this value is 3.51; considering that the TVL leakage for 10 MV is 30.5 cm, the secondary barrier should be 1.07 m thick.

The weekly unshielded dose at 6 MV (20 patients) is presented in Equation XX.

$$855 \times 0.001/5.12^2 = 32.6 \text{ mSv/week} \quad (\text{XX})$$

The transmission factor becomes $B = 6.14 \times 10^{-4}$ to reduce this value to the weekly dose constraints for the public. Hence, the number of TVLs needed to achieve this value is 3.21. Given that the TVL leakage for 6 MV is 27.9 cm, the secondary barrier should be 0.90 m thick. A simple calculation shows that the total leakage radiation from 6 and 10 MV at the existing slant thickness is 14.57 μSv/week.

The weekly unshielded patient scatter dose at 10 MV (40 patients) is presented in Equation XXI.

$$720 \times 1 \times 0.25 \times 3.18 \times 10^{-3} \times 1,600/400 \times 5.12^2 = 87.3 \text{ mSv/week} \quad (\text{XXI})$$

To reduce this value to the weekly dose constraints for the public, the transmission factor becomes $B = 2.3 \times 10^{-4}$. Accordingly, the number of TVLs needed to achieve this

value is 3.64; considering that the TVL leakage for 10 MV is 27.5 cm, the secondary barrier should be 1 m thick.

The weekly unshielded patient scatter dose at 6 MV (20 patients) is presented in Equation XXII.

$$360 \times 1 \times 0.25 \times 2.77 \times 10^{-3} \times 1,600/400 \times 5.12^2 = 38 \text{ mSv/week} \quad (\text{XXII})$$

The transmission factor becomes $B = 4.28 \times 10^{-4}$ to reduce this value to the weekly dose constraints. Hence, the number of TVLs needed to achieve this value is 3.28; considering that the TVL leakage for 6 MV is 26.1 cm, the secondary barrier should be 0.86 m thick. A simple calculation shows that the total scatter radiation from 6 and 10 MV at the existing slant thickness equals 7.87 $\mu\text{Sv/week}$.

Accordingly, the total weekly dose from leakage and scatter radiation at point C is 22.44 μSv . Given that the total dose of 22.44 μSv is only slightly greater than the weekly dose constraint, 20 μSv , the existing thickness is left unaltered. Since the existing secondary barrier at point C, with a thickness of 1 m, is considered adequate, the secondary barriers at points D, E, F, and G are also regarded as adequate.

4. Discussion

The shielding calculations performed, particularly for primary barriers B and B', showed that the final thickness of the barriers is determined solely by the IDR criteria at 10 MV in FFF mode. Specifically, the barrier thickness must ensure that the IDR does not exceed 20 $\mu\text{Sv/week}$ at the maximum dose rate at the isocenter. In practical terms, neither the standard workload (40 patients/day) nor the heavy workload (60 patients/day) influences the determination of barrier thickness. Furthermore, the IDR criteria for 6 MV, whether in FF or FFF mode, are irrelevant in this context, as their IDRs are inherently lower than those for 10 MV. This leads to several important questions:

- (i) If the thickness of the primary barrier can be determined in a single calculation step, what is the practical value of performing extensive and time-consuming calculations shown above?

- (ii) Although applying the IDR criterion significantly reduces the personal equivalent doses behind the barrier, does it truly satisfy the core radiation protection principles, namely optimization; in other words, is the thickness justified and well optimized?
- (iii) Do the IDR criteria reflect the same parameters and conditions used in evaluating the barrier thickness by the equations mentioned in NCRP 151 or SRS 47?

Certainly, applying the IDR criteria does not comply with the optimization principle. Applying the dose constraint principle provides a significant safety factor to protect personnel in radiotherapy facilities. In addition, the analytical equations listed in NCRP 151 and SRS 47 for primary barriers, in particular, are highly conservative as they are formulated without accounting for the presence of patients or phantoms in the path of the radiation. Moreover, the IDR criteria do not consider use or occupancy factors, which are fundamental in traditional shielding design. This omission leads to overly conservative estimates, resulting in exaggerated barrier thicknesses. Therefore, the current application of the IDR criteria in determining the final barrier thickness should be reconsidered, or its intended role should be more clearly defined.

In this context, it is important to present the expected IDR behind the primary barriers based on the barrier thicknesses determined using the analytical equations provided in NCRP 151 and SRS 47. Table 4 shows the expected dose rate for both FF and FFF modes at the actual barrier thicknesses obtained at the workloads of 40 and 60 patients per day. The expected weekly equivalent dose and its percentage to the weekly dose constraint are also included. Based on the table, all the IDRs for FF listed significantly exceed 7.5 $\mu\text{Sv/h}$, and all the IDR values of FFF exceed 20 $\mu\text{Sv/h}$. Despite these exceedances, the expected equivalent doses behind the barrier remain well below the weekly dose constraint. Therefore, the current approach to applying IDR (FF/FFF) criteria should be reconsidered. The following recommendations are proposed to optimize their usage:

Table 4. IDR of FF and FFF behind the primary barriers B and B' at the thicknesses obtained using NCRP 151 analytical equations

Barrier ID (patients/day)	Thickness (m)	IDR (FF) 600 MU/min	IDR (FFF) 2,400 MU/min	P_w , weekly dose constraint	P_{cw} , weekly equivalent dose	P_{cw}/P_w (%)
B (60)	2.12	20 $\mu\text{Sv/h}$	80 $\mu\text{Sv/h}$	20 μSv	10.88 μSv	54.4
B (40)	2.07	40 $\mu\text{Sv/h}$	160 $\mu\text{Sv/h}$	20 μSv	11.94 μSv	59.7
B' (60)	1.95	240 $\mu\text{Sv/h}$	960 $\mu\text{Sv/h}$	120 μSv	67.22 μSv	56.02
B' (40)	1.68	480 $\mu\text{Sv/h}$	1,920 $\mu\text{Sv/h}$	120 μSv	75.85 μSv	63.21

Abbreviations: FF: Flattening filter; FFF: Flattening-free filter; IDR: Instantaneous dose rate; NCRP 151: National Council on Radiation Protection and Measurements Report No. 151.

- (i) The IDR (FF/FFF) criteria could only be used after incorporating the patient transmission factor and verified experimentally using appropriate phantoms
- (ii) Since no patient or phantoms are used while applying the IDR (FF/FFF) criteria, these criteria should be used exclusively for shielding effectiveness verification and validation
- (iii) The IDR (FF/FFF) values should not be used to determine the equivalent dose behind the barriers; instead, they should verify the barriers' transmission factor and refine the expected equivalent dose only when barrier densities differ from that used in calculations
- (iv) During shielding verification, it is sufficient to use IDR only in FF mode, as these dose rates are lower than those in FFF mode
- (v) High dose rate measurements using IDR (FF/FFF) should be acknowledged only in the context of shielding effectiveness.

Therefore, it is necessary to enhance the safety culture and professional awareness among workers in radiotherapy units and regulatory bodies. There must be a clear understanding that the operational context of medical linacs in radiotherapy fundamentally differs from that of nuclear medicine. Radiation measurements using the IDR (FF/FFF) reflect testing conditions, not working conditions. High radiation levels observed during these tests are not indicative of typical staff exposure but rather a tool to validate the adequacy of structural shielding.

Certainly, regulatory authorities can set a reasonable maximum level for IDR (FF/FFF) during shielding efficiency tests based on the occupancy factor and the personnel behind the primary barriers. However, the higher it is, the lower the degree of overestimation in the required wall thickness. In any case, shielding efficiency tests and the expected high radiation readings can be performed safely under a strict radiation protection program and the supervision of a qualified radiation protection expert.

5. Conclusion

This study represents a case study for upgrading the shielding of an existing Co-60 radiotherapy bunker to accommodate a medical linac operating at 6 MV and 10 MV in FF and FFF modes. Shielding calculations were performed systematically using analytical equations listed in NCRP 151, SRS 47, and IPEM 75.

The shielding evaluation took into account a standard operating workload (40 patients/day) and an overload (60 patients/day) of 50% for each accelerator energy, with the final wall thickness restricted so that the expected IDR

behind the primary barriers in FF and FFF modes do not exceed 7.5 $\mu\text{Sv/h}$ and 20 $\mu\text{Sv/h}$, respectively.

Results showed that adhering to the IDR criteria yields an increment in shielding demands ranging from 11% to 46% depending on the dose constraints (public or occupational) as well as on the occupancy factor of the adjacent areas. This will be significantly reflected in the cost of the linac vault. Moreover, complying with IDR criteria reduces the expected equivalent dose behind barriers ranging from 1.2% to 13.4% of the dose constraints. The results proved that applying the IDR criteria yields a violation of the radiation protection principles, in particular, optimization. On the other hand, non-complying with the IDR criteria, the expected weekly equivalent dose behind barriers still shows conservative values ranging from 54% to 63% of the weekly dose constraints.

Thus, this study presents an alternative approach to use the IDR criteria optimally. This study concludes that the current values of IDR, that is, $\leq 7.5 \mu\text{Sv/h}$ at FF and $\leq 20 \mu\text{Sv/h}$ at FFF, can be used provided that the patient's transmission factor is included, or higher values of IDR are used only when testing the shielding efficiency; the higher the IDR adopted, the lower the cost of the linac vault.

Some workers may not accept the newly adopted high IDR due to their lack of understanding of how shielding requirements of a linac bunker are obtained. The workers, staff, and regulatory bodies should recognize that such high IDRs are expected only at extreme conditions used to verify the shielding effectiveness measurements. Such measurements are made occasionally, just after shielding implementations, and never be experienced during daily working normal conditions. Such high dose rates could be measured safely remotely under the supervision of a professional radiation protection expert, considering all protective measures.

Therefore, the safety culture and professional awareness regarding the working, inspecting or authorizing linac's bunker should be raised and flourished among working staff and regulatory bodies, particularly in developing countries.

Further studies should focus on evaluating the actual personal equivalent doses received by individuals behind shielding barriers in different radiotherapy units and comparing them with the thickness of those barriers. These studies should focus on linac-based radiotherapy units that use the FFF technology with different workloads that cover different treatment protocols and modalities. Relevant international institutions, especially the International Commission on Radiological Protection, could launch a task group to reconsider the concept of IDR

in radiotherapy units – how to use it, and the purpose of its use – followed by necessary recommendations to ensure achieving an actual balance between the cost of shielding barriers and the expected equivalent personal doses behind these barriers. The experimental validation of the shielding calculations presented in this study will be reported in a separate article.

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All data are presented within the manuscript.

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