Radiotherapy bunker design as a function of treatment technique. Economic impact evaluation.

Victoria Corregidor
victoria.corregidor@tecnico.ulisboa.pt
Instituto Superior Técnico, Lisboa, Portugal

October 2018

Abstract

The main objective of a bunker used for external radiotherapy is to limit the radiation exposure of workers and public. When considering a radiotherapy bunker design, there are many parameters that should be taken into account as type of linear accelerator, intended techniques for treatment, type and energy of the beam to deliver those techniques, number of treatments, area available for construction, etc. Barrier thickness and door composition will depend also on the materials to be used: concrete or high density concrete for walls, and lead and borated polyethylene for doors. The choice of these materials will be reflected on the budget and on the space needed, which are usually limited. This work explores how the treatment techniques (3D-CRT, IMRT, SRS and TBI) and the energy of the photon beam used (6 and/or 15 MV) will affect the barriers of a bunker, and how they are reflected in both: volume and budget. The methodology followed is that described in the NCRP-151 report. Results obtained can be applied to real bunkers already installed a decade ago designed to perform 3D-CRT, the most used technique in radiotherapy in that time. Nowadays the same accelerator (and bunker) is also used to deliver IMRT or SRS techniques, and then, according to the results obtained, a re-evaluation of structural shielding design and a radiation survey should take place on those bunkers, since these changes introduce variations on barrier thicknesses, mostly due to the leakage radiation and neutron generation.

Keywords: NCRP-151, shielding design, radiation protection, radiotherapy room, leakage radiation, neutron shielding

1 Introduction

Fortunately, thanks to the technological advances made in radiation oncology jointly with the developments in other related specialties and the early detection strategies, the number of patients that have been treated and cured is rising. According to IAEA [1] about 50% of all cancer patients would require radiotherapy, and of all patients healed, about 40 % were treated by external radiotherapy (RT) techniques alone or in combination with other modalities.

According to Van Dyk *et at.* [2], RT is an affordable and feasible therapeutic treatment, despite the core investments required (capital and specialised human resources). Among the capital investment, the construction cost of the bunker is among the most important contribution. Available space and type of adjacent areas will affect the bunker design for radiotherapy purpose. Also, long-term maintenance or quick access to the patient should be also considered. The choice of barrier materials (e.g. concrete, lead, steel or polyethylene) will also influence the final costs and available space. Furthermore, the door complexity is closely related with the beam energy used since, above 10 MV photon beam, there is an increase probability of generating neutrons mainly due to the materials used in the accelerator head, which are difficult to block with a simple (and thin) barrier, leading then to heavy doors with associated additional maintenance and safety costs.

At the same time, the successful of RT is based on the use of the latest technical improvements which requires access to modern equipment and the latest RT treatments as intensity modulated radiotherapy (IMRT) or stereotactic radiotherapy (SRT) [3]. These improvements entails changes in parameters used to calculate the shielding needed in a bunker [4], which usually imply a reinforcement of the barriers. For example, IMRT is among the RT techniques with higher growth rate in most of the countries in the latest years, which imply an increment of the leakage workload by a factor between 2 and 5 when compared with 3D conformal radiotherapy (3D-CRT) technique, thus secondary barriers projected for 3D-CRT should be re-evaluated, and eventually increased. Other changes as energy of the primary beam or patient position for TBI (total body irradiation) technique will have an impact in the shielding parameters and, as a consequence, in the radiation protection of both, workers and public.

Given the investment needed to construct this type of rooms, it is desirable to achieve the thinnest possible structure consistent with the radiation protection goals. Throughout this work the methodology and nomenclature followed by the NCRP-151 report [5] will be used. "MV" will be used when referring to the endpoint energy of a bremsstrahlung spectrum of the x-rays, while "MeV" will be used when referring only to monoenergetic photons or electrons.

This work emerges as an effort to show how the RT techniques using 6 and 15 MV photon beam energies, and their patterns of usage, affect the bunker barriers (walls and door). Realistic situations, based on historical data available from Santa Maria Hospital in Portugal, were studied. The materials considered for the construction of the barriers were: ordinary and high density (HD) concrete for walls and a combination of lead (Pb) and borated polyethylene (BPE) for door.

2 Materials and Methods

The NCRP-151 report [5] presents recommendations and technical information related to the design and installation of structural shielding for megavoltage x- and gamma-ray radiotherapy facilities. This work follows the methodology described in that report for the calculation of primary, secondary barriers and door for both x-rays and neutrons, including also the calculi of TADR (time averaged dose equivalent rate) over a week (R_w) or over in-any-one-hour, R_h.

The methodology is based on the calculation of the transmission factor (B) through the barriers (primary and secondary) that will be used to assign the number of TVLs (tenth-value layer) or "n" of material needed, considering the relationship among them: $n = log_{10}\big(1/B\big)$.

Then, the thickness of the barrier (t) regarding primary, patient scattered or leakage radiation (t_{pri}, t_{ps}, t_L respectively), can be calculated as: $t = TVL_1 + (n-1)TVL_e$, where TVL_1 refers to the first TVL and TVL_e refers to the equilibrium TVL. The TVLs values depend on the primary beam energy, shielding material used, type of radiation to shield (primary, patient scattered or leakage) and scattering angles (values considered are those from Appendix A in the NCRP-151 report [5]). When more than a single radiation component arrive to a barrier, its final thickness is determined by the "two-source" rule [5], that is, if the thickness difference is larger than a TVL, the largest value is chosen, if not, a HVL is added to the largest thickness.

Finally, the thickness obtained should be evaluated in terms of time averaged dose equivalent rate over a week and over in-any-one-hour, and also the sum of dose equivalent from photon leakage and patient scattered radiation (H_{sum}) should be below the shielding design goal.

According to the shielding design goal beyond the barrier (P), the transmission factor depends on the square of the distance from the x-ray target to the point to be protected (d), and it is inversely proportional to the use factor (U), the occupancy factor of the space to be protected (T) and the workload (W).

The workload is the absorbed dose from photons at the beam isocenter averaged over one week, and depending on the barrier considered (primary or secondary) it can be split into [6]: primary workload (W_{pri}), leakage-radiation (W_L) and patient and wall scattered radiation workload (W_{ps}). These quantities, as well as the wall use factors, are dependent on the RT treatment to be delivered and they are summarized in table 1, considering that the RT techniques use the same LINAC.

Table 1: *Workloads, distances and use factors according to RT technique.*

Treatment technique	$\mathbf{W}_{pri}$	$\mathbf{W}_L$	$\mathbf{W}_{ps}$	$\mathbf{d}_{sca}$	$\mathbf{U}_{pri}$	$\mathbf{U}_L$
3D-CRT	W_{conv}*	W_{conv}	W_{conv}	1 m	0.25	1
IMRT	$W_{IMRT}=W_{conv}$	$C_{IMRT}\ W_{IMRT}$	W_{IMRT}	1 m	0.25	1
TBI	$W_{TBI}= 5\ N\ D_{TBI}\ d_{TBI}^2$	$C_{TBI}\ W_{TBI}$	W_{TBI}	$d_{TBI} \geq 4$m	1	1
SRS	$W_{SRS}= 5\ N\ D_{SRS}\ d_{sca}^2$	$C_{SRS}\ W_{SRS}$	W_{SRS}	1 m	0.25	1
QC	W_{QC}	W_{QC}	W_{QC}	1 m	0.25	1

* W_{conv}=*5 D N* (*Gy/week*). Assuming: a 5 working days-week; N: number of treatments/day; D: absorbed dose/treatment.
** QC: Quality control and calibration.

The primary workload will be the sum of primary radiation contributions from RT techniques towards a primary barrier (equation 1) and the leakage workload is the sum of radiation contributions towards any barrier (equation 2). Workload due to radiation scattered by patient is equal to the primary workload.

$$W_{pri} = W_{3DCRT} + W_{IMRT} + W_{TBI} + W_{SRS} + W_{QC} \tag{1}$$

$$W_L = W_{3DCRT} + C_{IMRT} \cdot W_{IMRT} + C_{TBI} \cdot W_{TBI} + C_{SRS} \cdot W_{SRS} + W_{QC} \tag{2}$$

The leakage workload for IMRT, TBI and SRS techniques are multiplied by the corresponding C factor, which is the ratio of the average monitor unit per unit of prescribed absorbed dose for this technique and the monitor unit per unit of absorbed dose for conventional treatment. These C factors are treatment dependent and are higher than 1 [6, 7].

The door design is treated under two separate cases due to the presence of neutrons at energies above 10 MV as described in the NCRP-151 report [5]. The dose equivalent at door, H_w, is then the sum of H_{tot} (dose equivalent beyond the door from photon leakage and patient scattered radiation), H_{cg} (dose equivalent due to the contribution of neutron capture gamma rays) and H_n (dose equivalent due to neutrons).

2.1 Bunker description

In figures 1 and 2 are shown the bunker layouts where primary (C, D and G), secondary barriers (A, B, E, F, H) and maze barrier are identified. Also, the movement and extension of the couch are indicated in figure 1. Following the IAEA recommendations [8] and since there is no space limitation, a 15 m x 14 m space was considered as starting point. The height is approximately 3 meters, and a dropped ceiling at 2.75 m was supposed in order to reduce the cross-section of neutrons and to accommodate the necessary auxiliary systems. The isocenter of accelerator is located at 5 m from the external E wall, 7 m from external D (or C) wall (see figure 1) and 1.3 m from floor.

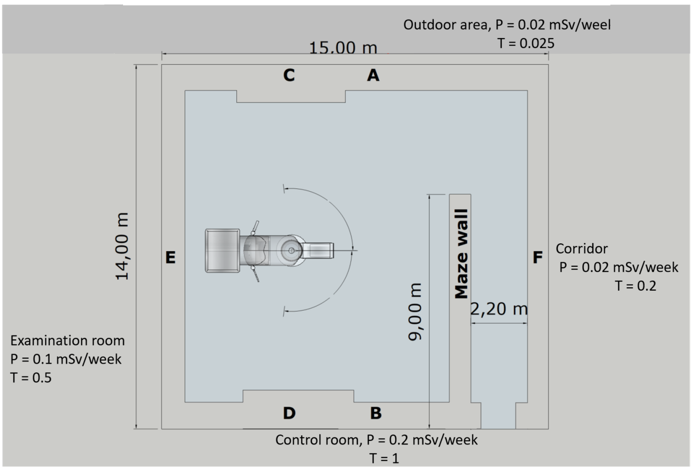


Figure 1: *Room layout and labels for primary (C, D), secondary barriers (A, B, E, F) and maze (top view).*

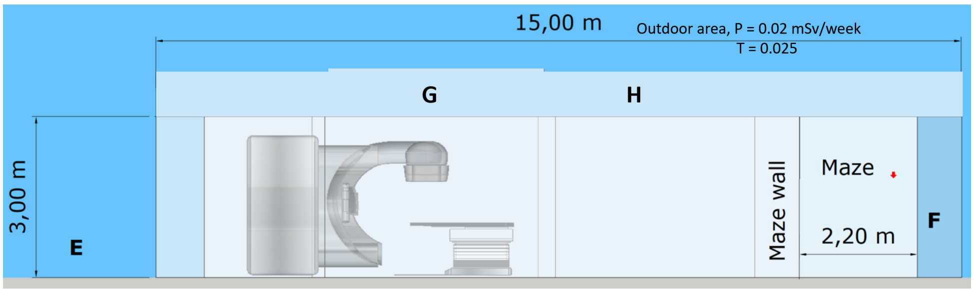


Figure 2: *Room layout and labels for primary (G), secondary barriers (E, F, H) and maze (front view).*

Since the work considers the use of 15 MV energy beam, the maze is almost mandatory to reduce the dose equivalent at the door. For this reason, a maze (9 m long and width of 2.2 m) was considered and also complying with height-to-width ratio between 1 and 2 and $2< d_{zz}/\sqrt{(maze\ width\ \cdot\ height)} <6$ [5].

Width of primary barriers was calculated considering the size of the diagonal of the largest beam (35 x 35 cm^2) at 1 m source-to-surface distance projected on the barrier C or D. And following the recommendations of the NCRP-151 report, the higher width is maintained over the primary-barrier region (barriers C, D and G), allowing simply arrangement during construction.

Distances from x-target to the point to be protected, which include the 0.3 m distance beyond the barrier, used to calculate the thicknesses of barriers are summarized in table 2, where there are also included the occupancy factor, use factor and scattering angle needed to calculate the thickness. Distance for barrier G (roof) changes according to the case study in order to maintain the height (3 m) constant in and it is calculated by an iterative approach [9].

Table 2: *Barriers parameters.*

Barrier	**Area description**	**Type**	**P, mSv/week**	**T**	**U**	**scat. angle**	**Distance, m**
C	Outdoor area	N.C.	0.02	0.025	0.25/ 1*	-	7.3
D	Control room	C.	0.1	1	0.25	-	7.3
G	Open space	N.C.	0.02	0.025	0.25	-	4.0**
A	Outdoor area	N.C.	0.02	0.025	1	21	7.9
B	Control room	C.	0.1	1	1	25	7.9
E	Examination room	C.	0.1	0.5	1	90	5.3
F	Corridor	N.C.	0.02	0.2	1	90	10.3
H	Open space	N.C.	0.02	0.025	1	∼46	∼4.5
Maze	Bunker corridor	C.	0.1	1	1	-	-

* Beam toward the Barrier C during TBI treatments.

** Distance is calculated for each scenario to maintain a 3 m height room.

N.C. for not controlled area; C. for controlled area.

No particular manufacturer or accelerator has been chosen. The LINAC considered is able to deliver photon energies of 6 and 15 MV, with a maximum absorbed-dose output rate at isocenter equals to 360 Gy/h and a maximum field size at isocenter of 40 x 40 cm^2. Additional data are those presented in Table B.9 from NCRP-151 [5]. Treatments parameters are based on historical data of the Radiotherapy Department at Santa Maria Hospital and they are summarized in table 3.

Table 3: *Treatment parameters.*

	3D-CRT	**IMRT**	**SRS**	**TBI**
Number of weeks (5 days) per year, week/y	50	50	50	50
Total number of treatments per week	250	250	60	40
Average number of patients per day per LINAC	50	50	12	8
Average number of patients per hour, $\bar{N}_h$	3.85	3.85	1.5	1
Maximum number of patients per hour	5	5	2	2
M (max. nº patients per hour/average patients per hour)	1.3	1.3	1.3	2
Distance x-ray target to patient, m	1	1	1	4
Mean absorbed dose per treatment, Gy	2.5	2.5	12.5	12
C factor	1	3.3	15	15

All secondary barriers are made of ordinary concrete (density of 2.35 g/cm^3) while for primary barriers is considered ordinary or high density (HD) concrete (3.2 g/cm^3). Prices (90 €/m^3 for ordinary concrete and 600 €/m^3 for HD concrete) were obtained from different estimations and budgets [10–12]. A swing door is considered with dimensions of 1.65 m x 2.15 m height, overlapping the wall at all sides 15 cm. Most of the shielded doors use layers of lead and borated (5%) polyethylene (BPE), which composition is calculated for each case-study, although the commercially available thicknesses will determine the final door composition [13, 14]. Price of lead is approximately 3.8 €/Kg [15].

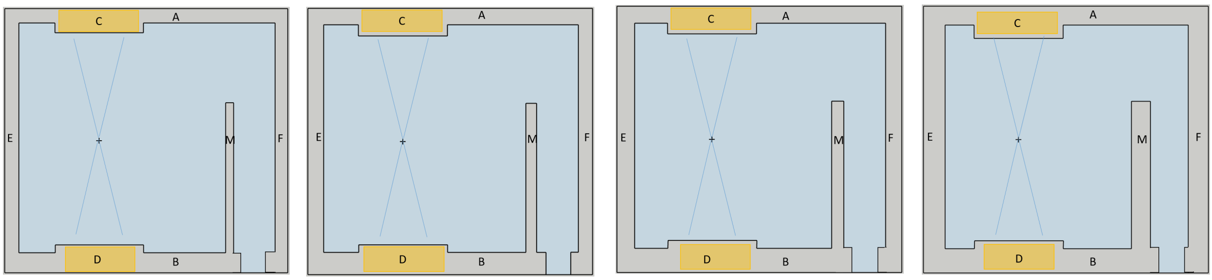
In this work, the limit imposed by some regulatory bodies, as the U.S. NRC [16], to the time averaged dose equivalent rate in-any-one-hour for uncontrolled areas (0.02 mSv) has been also extended to controlled areas. R_h depends on the average number of treatments per hour performed, the number of working hours per week (usually a 40-hour week), and the maximum number of treatments including the set-up time (see table 3).

3 Results and discussion

Different case studies have been considered, described as:

- Case 1. 100% of cases treated with 6 MV photons using 3D-CRT;
- Case 2. 25% of cases treated with 15 MV photons (3D-CRT) while at 6 MV x-rays are performed both techniques: IMRT (50%) and 3D-CRT (25 %).
- Case 3. 20% and 28% of treatments delivered using 3D-CRT and IMRT respectively at both energies while SRS (4%) is performed at 6MV.
- Case 4. All techniques are applied, 20% of treatments using 3D-CRT at both energies, 28% using IMRT at both energies, 1.6% using TBI technique and 2.4% using SRS technique, last two techniques with 6 MV photon beam.

Table 4 summarizes the workload values used for primary and secondary barrier calculations, where workload for quality control and calibration are included in the 3D-CRT data. Considering these values and those from tables 2 and 3, thicknesses obtained jointly with the R_h and H_{sum} values are summarized in table 5. Layouts of the bunkers using ordinary concrete for all barriers are shown in figure 3.



(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4

Figure 3: *Bunker layouts considering ordinary concrete for different radiotherapy techniques patters of usage.*

As can be observed the barriers become thicker as the leakage workload increases, which at the same time it is related to the type of RT treatment delivered due to the mean absorbed dose and mainly, due to the *C* factor. Distance for primary barriers C and D are the same (7.3 m) but in all cases (besides case 4) barrier D is thicker than C. This is related to the areas beyond them, while on the other side of

Table 4: *Workload (W) in Gy/week for the cases considered.*

		$6MV$	$15MV$	6 MV		15 MV	
		% treatments/week (nº of treatments)		W_{pri}	W_L	W_{pri}	W_L
Case 1	$3D-CRT$	100% (250)	0% (0)	625.0	625.0	-	-
	Total	250	-	**625.0**	**625.0**	**-**	**-**
Case 2	$3D-CRT$	25% (62)	25% (63)	155	155	157.5	157.5
	$IMRT$	50% (125)	0% (0)	312.5	1 031.3	-	-
	Total	187	63	**467.5**	**1 186.3**	**157.5**	**157.5**
Case 3	$3D-CRT$	20% (50)	20% (50)	125.0	125.0	125.0	125.0
	$IMRT$	28% (70)	28% (70)	175.0	577.5	175.0	577.5
	SRS	4% (10)	-	125.0	1 875.0	-	-
	Total	130	120	**425.0**	**2 577.5**	**300**	**702.5**
Case 4	$3D-CRT$	20% (50)	20% (50)	125	125	125	125
	$IMRT$	28% (70)	28% (70)	175	577.5	175	577.5
	SRS	2.4% (6)	-	75	1 125	-	-
	TBI	1.6% (4)	-	768*	11 520	-	-
	Total	130	120	**375****	**13 347.5**	**300**	**702.5**

* Beam is only towards Barrier C during TBI treatments.

** $W=W_{3D-CRT}+W_{IMRT}+W_{SRS}+W_{TBI}$; $W_{pri,C}\cdot U_C = 375\cdot 0.25 + 768\cdot 1 = 861.8$ Gy/week

barrier C there is an untended parking with a low occupancy factor (T=0.025), beyond barrier D is the control room, a controlled area with the maximum occupancy factor (T=1). Similarly, barriers C and G protect uncontrolled areas with equal occupancy factor (0.025), but due to the distance considered (7.3 m and about 3.5 m respectively) barrier G is always thicker than barrier D. In general, the lowest values of R_h and H_{sum} are obtained for barrier D.

Similar behaviour is observed for secondary barriers, thickness increases with the leakage workload. Among the secondary barriers, barrier B is the thickest one in all cases (again protecting the workers in the control room), but it also presents (jointly with barrier E, another controlled area), the highest values of H_{sum}. In some cases, the sum of the dose equivalent from patient scattered and leakage radiation would represent more than half of the maximum dose equivalent allowed in one week (0.1 mSv), and eventually addition of a HVL to these barriers should be considered.

Maze barrier also increases as the workload increases affecting the total dose equivalent at the door, H_w, see table 6. To protect from neutrons, produced at 15 MV, it is necessary to use BPE whose thickness will depend on the workload at this energy. As can be observed in table 6, the BPE thickness increases as the workload at 15 MV increases. In fact, case 4 and case 5 present the same BPE thickness and same workload, nevertheless H_n is slightly different due to the dependence of this dose-equivalent on internal distances and maze entrance cross-sectional area (which depends on the barrier A thickness), being lower in case 4. Also, the thickness of lead sheets needed increases with the workload, mainly due to the photon leakage and patient scattered radiation (H_{tot}) contribution, while the contribution due to neutron capture gamma rays (H_{cg}) is almost negligible in all cases (except case 1).

A doorless bunker can be easily achieved for the case 1. If maze barrier increases up to 66 cm the dose equivalent H_w is reduced up 42.5 µSv/week. A doorless entry improves the access and also avoids the cost of heavy shielding doors, although additional safety systems should be installed to avoid unauthorized entry into the room while the beam is on.

Table 5: *Results obtained for the bunkers considered (primary and secondary barriers). Thickness, (t) in m, R_h and H_{sum} in μSv/week.*

			Primary barriers			Secondary barriers					
			C	D	G	A	B	E	H	F	M
Case 1	Concrete	t	1.28	1.48	1.45	0.76	1.06	0.75	0.61	0.67	0.43
		R_h	13.0	3.2	13.0	14.2	1.7	2.9	10.1	0.9	-
		H_{sum}	0.5	0.2	0.03	10.9	53.2	45.1	11.2	9.1	-
	HD concrete	t	0.98	1.13	1.13						
		R_h	13.0	3.2	13.0						
		H_{sum}	4.3	3.6	0.5						
Case 2	Concrete	t	1.45	1.57	1.53	0.86	1.17	0.83	0.70	0.75	0.56
		R_h	9.5	4.5	18.3	9.7	1.4	3.4	9.6	1.0	-
		H_{sum}	0.5	0.3	0.04	7.5	43.6	52.9	11.4	10.5	-
	HD concrete	t	0.90	1.06	1.06						
		R_h	16.4	3.8	15.3						
		H_{sum}	13.6	15.0	2.0						
Case 3	Concrete	t	1.45	1.69	1.64	0.89	1.27	0.93	0.80	0.85	0.64
		R_h	15.1	3.8	15.2	12.8	1.2	4.3	10.7	1.3	-
		H_{sum}	0.9	0.3	0.04	9.9	38.3	65.8	13.1	12.8	-
	HD concrete	t	0.97	1.05	1.13						
		R_h	11.0	5.4	10.5						
		H_{sum}	13.9	35.9	2.6						
Case 4	Concrete	t	1.69	1.69	1.76	0.99	1.27	1.14	1.00	1.06	0.79
		R_h	10.8	5.7	11.3	15.1	2.4	4.8	19.0	2.4	-
		H_{sum}	0.4	0.8	0.04	7.6	48.3	47.8	9.5	9.5	-
	HD concrete	t	1.13	1.13	1.13						
		R_h	15.0	3.9	15.5						
		H_{sum}	13.6	58.5	7.8						

Table 6: *Total dose equivalent at the door, H_w in μSv/week, and contributions: H_{tot} (dose equivalent beyond the door from photon leakage and patient scattered radiation), H_{cg} (dose equivalent due to the contribution of neutron capture gamma rays) and H_n (dose equivalent due to neutrons), for the cases studied.*

	H_{tot}	H_{cg}	H_n	H_w	Door description
Case 1	95.5	-	-	95.5	1.98 mm Pb
Case 2	62.8	1.2	127.3	191.3	0.39 mm Pb + 2.54 cm BPE + 0.39 mm Pb
Case 3	78.1	5.4	594.4	674.9	0.79 mm Pb + 5.08 cm BPE + 0.79 mm Pb
Case 4	371.3	4.7	514.4	890.4	3.17 mm Pb + 5.08 cm BPE + 3.17 mm Pb

Regarding the use of HD concrete for primary barriers, it could be a wise choice if there is space limitation. As can be seen in table 5, primary barriers made of HD concrete are thinner, and contrary to those made of ordinary concrete, they do not present too much increment between then when compared with case 1, even more, in cases 2 and 3 they are thinner than in case 1. The high values obtained for H_{sum} for these barriers are related to the lack of data available (TVL for leakage and patient scattered radiation) for this material, and then, data from ordinary concrete, which are higher than real, were considered.

Although space available is an important limitation, budget should be also considered. The use of HD concrete in primary barriers means that the bunker will cost (without considering the door) more than twice that if only ordinary concrete is used for both, primary and secondary barriers (see figure 4). In figure 4 are also shown the volumes needed for these barriers for both materials and prices for each case, including the door. It should be highlighted that only costs attributed to material construction have been considered.

Case 4 exhibits the highest volume (303 m^3 for secondary barriers and 164 m^3 for primary barriers using ordinary concrete, or 106 m^3 if HD concrete is used) and then, the highest price, mainly due to barrier C, which during TBI treatment has a use factor (U) equals to 1, and to the high leakage workload (13 348 Gy/week), affecting also the lead needed for door.

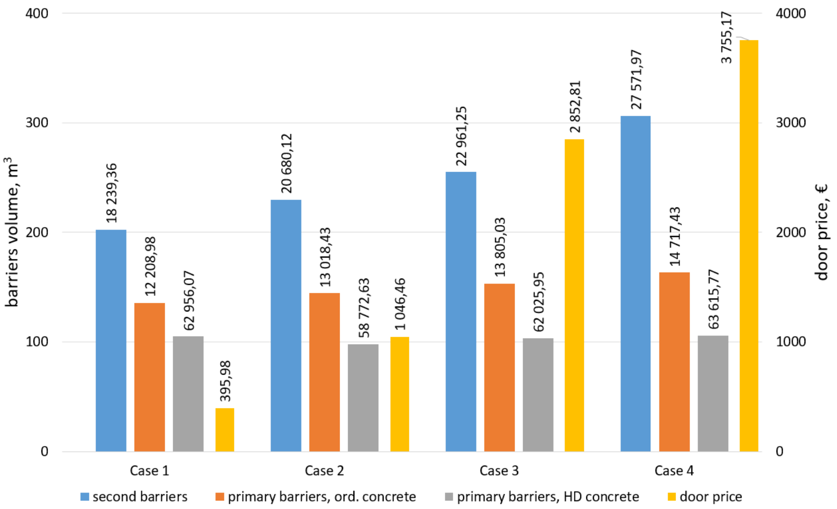


Figure 4: *Volume, in* m^3*, and prices, in €, for the studied bunkers.*

4 Conclusions

A study of the thickness of shielding barriers for bunkers to deliver different RT treatments (3D-CRT, IMRT, SRS and TBI) with two beam energies (6 and 15 MV) have been carried out, following the methodology of NCRP-151 report. These changes in barrier thicknesses are correlated with the volume of material needed and also with the budget.

The cheapest bunker is the one dedicated to 3D-CRT at 6 MV, and prices increase with the increment of the leakage radiation related to the RT techniques. In general, the use of HD concrete for primary barriers implies an average budget 4.6 times higher than the budget needed when using ordinary concrete, and about 2.4 times higher considering primary and secondary barriers (without considering the door). This extra investment can be justified if constrains, as space, exist. Furthermore, the use of photons with energy of 15 MV involves expensive doors, mainly due to the need of using borated polyethylene, a costly material to protect from neutrons generated at this energy.

When a bunker has been designed and constructed under well determined conditions, as RT technique to be delivered and beam energy, the introduction of new techniques affecting the initial usage pattern will be reflected in the wall thicknesses needed to protect from radiation produced. Adding IMRT or SRS techniques will increase mainly the volume of secondary barriers. The introduction of TBI technique will affect both, primary and secondary barriers, being the primary barrier towards the beam is pointing the one with the highest increment, while the secondary barriers, due to the leakage and patient scattered radiation will also increase.

The limit imposed to the time averaged dose equivalent in-any-one-hour (R_h) is relatively easy to comply, in fact the limit to the dose equivalent due to patient and leakage radiation (H_{sum}) is more important to determine the final barrier thickness, especially when close values to the shielding design goal are achieved in controlled areas.

Results obtained using the NCRP-151 methodology should be compared with calculations obtained from Monte Carlo simulations and, when possible, with experimental measurements.

Finally, as it has been shown, there is a relationship between the RT techniques implemented in a bunker and the barrier thicknesses. Most of the LINACs installed a decade ago to perform only 3D-CRT are nowadays performing IMRT and SRS techniques without any change in the bunker. A survey should be performed to check if the barriers are appropriate or if a reinforcement is needed.

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