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Occupational Radiation Protection: Assessment of Bunker Shielding in Radiotherapy Department

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Abstract

Intensity Modulation Radiation Treatment (IMRT) technique increases significantly head leakage and the workload is also affected compared with Conventional treatment. The equivalent dose from medical Linear Accelerator (LINAC) System must be limited to prevent occupational and public exposure to radiation. Therefore, the shielding design must be adequate. The aim of this study was to reassess the shielding of our LINAC room designed for conventional treatment if we planned to treat 30% of the patients with IMRT technique at Aristide Le Dantec hospital. We propose a method to evaluate the equivalent dose by using empirical formulas from the report 151 of the National Council of Radiation Protection (NCRP151). We estimate the transmission factor for all barriers using the wall thicknesses. Equivalent doses for all surrounded areas were calculated and compared with those found during measurement. The doses observed here are below annual dose limit for occupational and public even when IMRT technique will be used for treatment of 30% of the patients in a LINAC room entirely shielded for conventional treatment. The results show also that the shielding was overestimated by at least a factor of 2. Adequacy of secondary shielding will depend on the IMRT patient workload. For conventional facilities that are being assessed for IMRT therapy, existing primary barriers will typically prove adequate. Accurate and conservative shielding design is essential for radiation protection professionals in clinical practice.

Keywords

Shielding, IMRT, Leakage Radiation, Conformal Therapy, Doses, Barriers

1. Introduction

The incidence of cancer throughout the world is increasing with the prolonged life expectancy that has resulted from improvements in standards of living. About half of all cancer patients receive radiation therapy, either as part of their primary treatment or in connection with recurrences or palliation. Radiation therapy is a method of treatment that uses ionizing radiations to destroy cancer cells. This could be done by radioactive sources or by X-rays emitting device called a linear accelerator (LINAC). Patients can undoubtedly obtain enormous benefit from these treatments, although the ionizing nature of the X-rays means that their use is not entirely without risk. The damage that ionizing radiation can cause has been known from observations made on the pioneers of radiology, such as radiologists and physicists [1] [2]. Following an upsurge in erythema and radiation-induced cancer in the ranks of the scientific community, the International Commission for Radiological Protection (ICRP) was created in 1928. Exposure to ionizing radiation can have, even at low doses, effect on health, hence the importance of applying radiation protection measures and principles. ICRP suggested general principles of radiation protection with three key words: justification, optimization and dose limit [3]. In respect to these principles and mainly for optimization and dose limit, the radiotherapy room must be shielded to reduce the effective dose from a 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. When a medical linac is introduced at a facility, finding the optimum barrier thickness is an essential requirement for the safety of radiotherapy facilities to prevent public exposure to radiation [4]. Given the potential impact on public health, bunker configuration is achieved by following clear and stringent guidelines from national or international regulatory organizations (IAEA, ICRP, NCRP) that deal with radiation protection. Thanks to shielding theory and recommendations summarized in publications from these groups [4] bunker design is a well understood branch of medical physics, where research focuses on optimizing the configuration of the room with increasingly sophisticated tools. The Basic Safety Standard (BSS) define a dose constraint as “prospective and source related restriction on the individual dose delivered by the source which serves as a bound in the optimization of protection and safety of the source.” When planning for the construction of a radiotherapy facility, the dose constraints for occupational and public exposures will be the doses in, respectively, controlled and supervised areas for which the facility is designed. Two principles of radiation protection and safety on which the BSS are based and that must be considered when choosing appropriate dose constraints are optimization of protection and dose limitation [3]. The BSS provide a simplified rendering of the principle of limitation: “individual doses due to the combination of exposures from all relevant practices should not exceed specified dose limits.” Therefore, dose constraints need to be selected so that, in addition to meeting the requirement for optimization, limits on individual doses from occupational and public exposures are not exceeded. Shielding protocols should be constantly reviewed to allow for new techniques and improvements in accuracy. In the last decade, the technology of treatment delivery for radiation oncology patients has undergone tremendous change and of great interest. Many studies have been carried out because of the rapid evolution of radiotherapy treatment technology. Most of the studies published about the fact that the shielding parameters can vary depending on the geometrical structure of the linear accelerators (LINAC), treatment techniques, and beam energies. P.H. McGinley observed that radiation shielding requirements of the room housing radiotherapy equipment (e.g., 6MV Accelerator, Tomotherapy, Cyberknife, Halcyon) may vary even for the same photon beam energy, source to point of interest, shielding martials of protective barrier, and allowed dose limit [5].

Recently, Dong Hyeok Choi *et al.* introduce the O-ring type Radiation therapy equipment Shielding Evaluation (ORSE) program which allows for the shielding evaluation results to the clinical environment of each institution based on patient data.

The program evaluates the radiation shielding and calculates the maximum number of treatable patients, using the Digital Imaging and Communications in Medicine Radiation Therapy (DICOM RT) plan files of the actual treated patients [6] [7].

James Rijken *et al.* found that the current shielding protocol does not describe adequately the methodology for the shielding of a stereotactic-only radiotherapy LINAC bunker.

In that sense, Price RA *et al.* developed formalism for evaluating the shielding in an existing vault to be used for IMRT [8].

In particular, multi leaf collimator-based intensity modulated radiation therapy (IMRT), in its various versions, has been found relatively inefficient compared to conventional treatment methods in term of shielding. IMRT is a technique which gives more monitor unit than conformal therapy, so more head leakage. The ratio, C, of the number of MU to dose (number of cGy) at the isocenter has been found to range [9] [10] from 2 to 10, with some proposed methods going even higher [4] [11]. This increased MU load means the leakage radiation from the accelerator assembly has increased by a factor of approximately C and raises concern about the adequacy of radiation protection afforded by existing facilities now embarking on IMRT as well as how to design new shielded vaults for IMRT.

At Aristide Le Dantec hospital, the bunker was shielded with assumptions based on a workload of conventionally fractionated patients and the plan was to start IMRT treatment technique for some tumor localization. The impact of IMRT on shielding design has been investigated from as early as 2001 through application of a nominal machine output (monitor units) to patient dose ratio for a portion of the IMRT workload. This IMRT factor C is used to scale the leakage contribution. While some studies have demonstrated application of this factor to the entire workload for evaluation of secondary barriers increasing secondary barriers by as much as 1 TVL [11]-[13]. Kairn *et al.* have shown that this is unnecessary and leads to potentially costly overestimations [14]. Therefore, this study aimed to reevaluate the assumptions made during the construction of the facility to see if the leakage radiation could exceed the primary one and if the theoretical hypotheses were observed before starting the IMRT treatment technique. Shielding design for medical radiation therapy facilities is based on simple empirical equations reported in IAEA and NCRP documents [4] [10].

2. Materials and Methods

The annual dose received by the staff for a Linac room exclusively designed for 3D conformal therapy and in which a new treatment technique named IMRT is planned to be start was evaluated at Aristide Le Dantec hospital, Joliot Curie Cancer Institute in the radiotherapy department. The measurements were performed with a 6MV variant unique Linear accelerator equipped with 120 multi leaves collimator. This method entirely applies the evaluation of the multiple reflections that may occur because of head leakage, patient and wall scattering.

The room shielding design and the limit of radiation depend on the classification of the surrounded area. The designation of areas as controlled or supervised areas may sometimes be defined in terms of the dose rate at the boundary. In this study, the controlled and uncontrolled areas were defined as in the BSS [3].

The following picture (**Figure 1**) shows the layout of the radiotherapy department in which there are two controlled areas (treatment console and physicist room) and four public areas (street outside, technical room, secretary office and the waiting room).

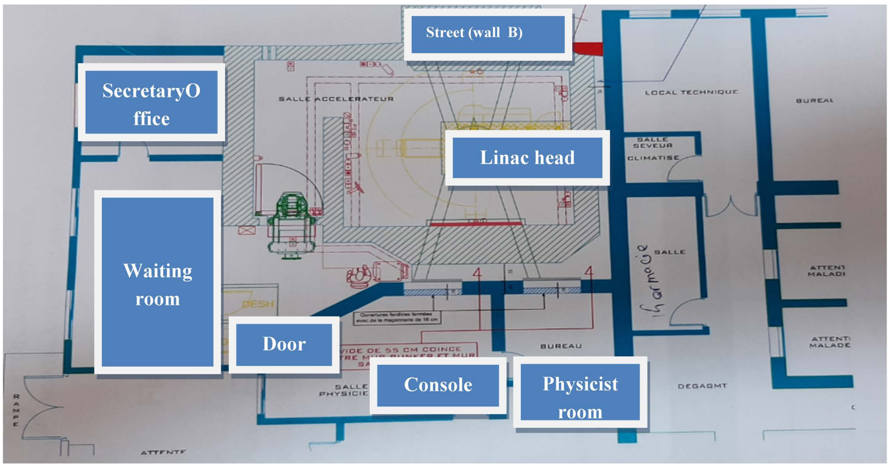


Figure 1. The layout of the radiotherapy department.

As shown in the layout, the street and the physicist room are located behind the primaries wall and there are for both areas free space between the wall and the areas itself. There are three principal sources of ionizing radiation incident on protective barriers direct, leakage and scatter. These radiations have in general different penetrating qualities and tenth value layer (TVL). In order to handle the problem increased leakage radiation produced by IMRT treatment, three types of workload were defined (direct, leakage and scatter). Scatter and direct workload are equal. Radiation treatment facilities are comprised of primary and secondary barriers. Where the main radiation beam strike the wall roof, a primary barrier is required. If the facility is located above any accessible area, the floor will need to be a primary barrier. It should be much thicker than the remaining walls, which are called secondary scattered and leakage radiation. In our RT department, there is no accessible area under and above the bunker room, this implies that the floor and the ceiling were not taken as barriers. The primary barrier is expected to adequately attenuate the dose equivalent beyond the barrier that results from secondary products of photon beam.

2.1. Transmission Factor (*B*)

B represents the transmission factor of the x rays beam through the shielding wall calculated using the tenth value layer of the shielding material and the shielding thickness. Knowing the later, the transmission factor for all the barriers were calculated using the following equation:

$$B = 10^{-\left\{1+\left[\frac{t-\text{TVL1}}{\text{TVLe}}\right]\right\}} \tag{1}$$

where TVL1 and TVLe are respectively the first and equilibrium Tenth Value Layer which is defined as the absorber thickness which attenuates the beam intensity to 10% and t is the thickness of the wall which we want to calculate the transmission factor. In this study, the material for radiation shielding is concrete.

2.2. Equivalent Dose for Primary Barrier

Protective barriers are designed to ensure that the dose equivalent received by any individual does not exceed the applicable maximum equivalent value. Hence the design dose (P) equivalent limit (some fraction 1/20 of the annual regulatory limit) for the site being protected start with the following equation:

$$P = \frac{B * W * U * T}{d^2} \tag{2}$$

here B is the barrier transmission factor calculated above, W is the radiation workload in term of total dose delivered at the isocenter (1 m from the X ray target) per year (Gy/year), d is the distance from the X ray target to the point protected (meters), U is the use factor or fraction of the workload that the primary beam is directed at the barrier in question and T is the occupancy factor for the protected location or fraction of time that a person is present beyond the barrier.

The direct workload receives contributions from the conventional treatment delivery and the quality assurance activities which include calibration and other physics research activities. In average 60 patients are treated every day in around 250 working day with 2.5 Gy in average to account for larger dose per fraction for some palliative treatments. The occupancy factors T were taken from NCRP 151 for the concerned areas as shown in Table 1.

$$W_{dir} = \left(\frac{2.5\ \text{Gy}}{\text{patient}} * 250\ \text{working day} * 60\ \text{patients/day} \right) + 20\%\text{QC} \quad (3)$$

Table 1. Occupancy and use factors for areas towards the primary barriers from NCRP 151 and the different distances and thicknesses for the concerned areas.

Primary Barriers	Use factor (U)	Occupancy factor (T)	Distances (m)	Thickness (m)	Concrete	
					TVL1	TVLe
Treatment console	0.25	1	2.7	1.20	37	33
Physicist room	0.25	0.05	2.7	1.68	37	33
Street outside	0.25	0.025	2.64	2.10	37	33

2.3. Equivalent Dose for Secondary Barrier

Similar formulas for determining the dose for secondary barrier thickness requirement stemming from the leakage and patient scatter are also proportional to the workload.

$$P = \frac{B * W_L * L * T}{d^2} \quad (4)$$

The IMRT treatment delivery technique contributes more to the leakage per unit dose at the isocenter than the direct radiation by a factor C which ranges from 2 to 10. A factor of 5 is often used in calculations.

$$W_L = W_{dir} + 5 * W_{IMRT} \quad (5)$$

A hypothesis that 30% of the patients will be treated with IMRT was done. The leakage attenuation factor L is by regulation not to exceed 0.1% (IEC Safety standard). The use factor was taken equal to 1 since scatter and leakage are assumed with isotropic emission. The occupancy factors T were taken from NCRP 151 for the concerned areas as shown in Table 2 [4].

Table 2. Occupancy and use factors for different areas taken from NCRP 151 (Leakage radiation) and the different distances and thicknesses for the concerned areas.

Secondary Barriers (Leakage)	Use factor (U)	Occupancy factor (T)	Distances (m)	Thickness (cm)	Concrete	
					TVL1	TVLe
Treatment console	1	1	2.7	1.20	34	29
Physicist room	1	0.05	2.7	1.68	34	29
Street outside	1	0.025	2.64	2.10	34	29
Secretary office	1	1	3.4	0.76	34	29
Waiting room	1	0.5	6.1	0.76	34	29
Technical local	1	0.05	1.65	0.64	34	29

The equivalent dose for scatter from the patient shielding is given by the following equation:

$$P = \frac{F}{400} * \frac{a * W * B * T}{d_{scat}^2 * d_{sec}^2} \quad (6)$$

F is the area of the beam at the scattering point at mid-depth of the patient at 1 m (cm[2]), d_{scat} and d_{sec} are respectively the distance from the source to the patient and the distance from patient to point of interest, a represents the scatter fraction at 1 m from a human-size phantom, target-to-phantom distance of 1 m, and field size of 400 cm[2] [15] [16].The scatter workload is determined by the dose at the isocenter received by the patient or phantom. A conservative and simplifying procedure would be to set:

$$W_{sca} = W_{dir} \quad (7)$$

The following table (**Table 3**) summarizes the different parameters used to estimate the workload for the scatter radiation.

Table 3. Occupancy and use factors for different areas taken from NCRP 151 (Scatter radiation) and the different distances and thicknesses for the concerned areas.

Secondary Barriers (Scatter)	Use factor (U)	Occupancy factor (T)	d_{sec} (m)	Thickness (m)	Concrete TVL	d_{scat} (m)	Angle (˚)	a	F
Treatment console	1	1	2.7	1.68	34	1	90	4.26E−04	1600
Physicist room	1	0.05	2.7	1.68	34	1	90	4.26E−04	1600
Street outside	1	0.025	2.64	2.10	34	1	90	4.26E−04	1600
Secretary office	1	1	3.4	0.76	34	1	30	2.77E−03	1600
Waiting room	1	0.5	6.1	0.76	34	1	30	2.77E−03	1600
Technical room	1	0.05	1.65	0.64	34	1	30	2.77E−03	1600

The total dose rate at the entrance of the maze arises from the scattered primary beam from the bunker wall, the scatter from the patient, the scatter of the head leakage radiation from the bunker walls and from the transmission of head leakage radiation through the maze wall when the beam is pointed at the wall B which is in front of the maze. It was calculated using the following equation:

$$H_B = fS_S + S_p + L + L_d \quad (8)$$

with f the fraction of beam transmitted by the patient body (≈0.26 for 6 - 10 MV). Adding the contributions when the beam is pointing in all 4 directions, the total dose rate to the maze entrance is obtained. As a rule (from NCRP151) total dose rate is obtained with this following equation:

$$H_{Tot} = 2.64 * H_B \quad (9)$$

And the required door shielding design dose is given by:

$$P = B * H_{Tot} \quad (10)$$

The dose rate at the maze entrance (S_s) arises from the scattered primary beam from the Bunker Wall (the nearest to the maze) and is given by:

$$S_s = \frac{W * U_B * \alpha_1 * A_1 * \alpha_2 A_2}{\left(d_i * d_{r1} * d_{r2}\right)^2} \tag{11}$$

where W is the radiation workload, U is the use factor toward the wall B, α_1 is the reflection coefficient at first scattering surface (the wall A_1), α_2 is the reflection coefficient for second surface (the wall A_2), A is the area filled by the beam at each reflection and d is the distances as shown in Figure 2(a).

The dose rate at the maze entrance (S_p) from the patient scatter was calculated using the following equation:

$$S_p = \frac{a * W * U_B * \frac{F}{400} * \alpha_1 * A_1}{\left(d_{sca} * d_{sec} * d_s\right)^2} \tag{12}$$

where a is the patient scatter fraction, W is the radiation workload, U is the use factor toward the wall B, F is the area of the beam in the plane of the patient, α is the reflection coefficient at the wall, A is the area filled by the beam at the reflection and d are distances as shown by Figure 2(b).

The dose rate at the maze entrance (L) from the scatter of head leakage radiation from the Bunker Walls was calculated using this formula:

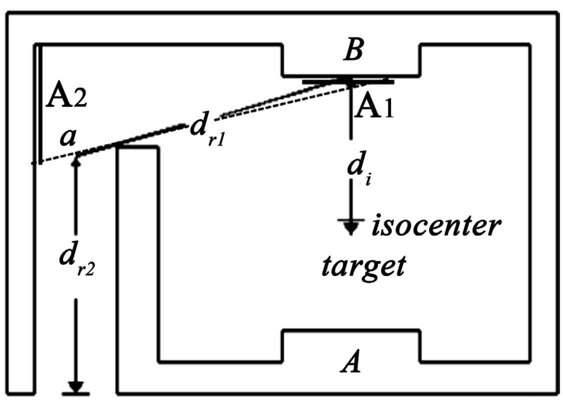
$$L = \frac{L_0 * w * U_B * \alpha_1 * A_1}{\left(d_s * d_1\right)^2} \tag{13}$$

where L_0 is the leakage factor, W is the radiation workload, U is the use factor toward the wall B, α is the reflection coefficient at the wall, A is the area filled by the beam at the reflection and d are distances as shown in Figure 2(c).

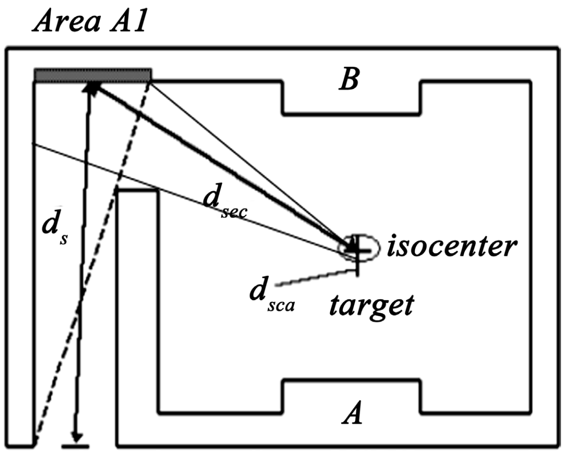
The dose rate at the maze entrance (L_d) from the transmission of head leakage radiation through the maze wall is given by this equation:

$$L_d = \frac{L_0 * W * U_B * 10^{-(t/\mathrm{TVL})}}{\left(d_1 - d\right)^2} \tag{14}$$

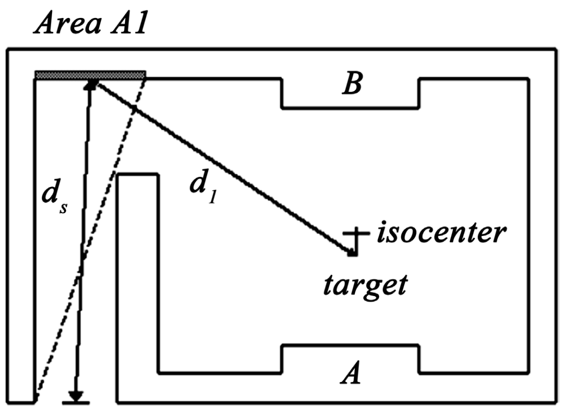
But it was not computed because the transmission of scatter radiation has the lowest mean energy compared to leakage radiation.



(a)



(b)



(c)

Figure 2. (a) Scatter of the primary beam from the bunker wall, (b) Scatter from the patient and (c) Scatter of head leakage radiation from the bunker walls.

In this study, all the calculations were done using the empirical equation and factors from NCRP151 to meet the requirements for designing the shielding.

Microsoft excel software was used to handle the data and R statistical software for the comparison of means and to calculate the p values. Statistical significance was defined as $p < 0.05$.

To verify the method and validate the calculations, the results were evaluated by a comparison with measured doses in all the concerned areas using a detector.

Measurements have been done using a Fluke Biomedical ion chamber survey meter. The maximum field size (40*40 cm^2) was used with a solid phantom (PMMA) on the table to simulate the scatter.

3. Results

In this study, we present a method to determine the annual dose received by the staff for a Linac room designed at the beginning exclusively for 3D conformal therapy and in which IMRT is planned to be started for 30% of the patients. For that, the transmission factor for different barriers was calculated depending on the surrounded area. The later were classified into controlled and uncontrolled as defined in the BSS. The dose for different location was estimated with empirical equation from NCRP 151 and presented here.

Using the thicknesses for the different barriers (primary and secondary), the transmission factor was calculated for all of them and given in the following table (**Table 4**) respectively for primary and secondary barriers. The later were calculated separately for leakage and for scatter. Part of the radiation dose at the point of interest behind the secondary barrier is produced by the scatter of primary photon incident on a patient or phantom located at the isocenter. For scatter radiation, the calculations were performed considering scatter angle of 30 and 90 since the scatter fraction is energy and angle dependent.

Table 4. Transmission factor (B) for the primary barriers and for the secondary barriers (Leakage and scatter).

Barriers	Transmission factor (B)		
	Primary	Secondary	
		Leakage	Scatter
Technical room	-	9.24E−03	3.46E−03
Secretary office	-	3.56E−03	1.19E−03
Patient waiting	-	3.56E−03	1.19E−03
Console	1.07E−05	1.08E−04	8.73E−08
Physicist room	1.07E−05	2.39E−06	1.31E−10
Street (Outside)	5.72E−07	8.53E−08	4.43E−13

Table 5 shows the workloads for the different type of radiation: direct, leakage and scatter (W, W_L and W_s) at 1m from the isocenter. The workload of the leakage radiation take accounts the percentage of patient that will be treating with IMRT. The workload from scatter radiation is the same than the direct radiation.

Table 5. Workloads for the different type of radiation.

workloads (Gy/yr at 1 m)	Direct (W)	Leakage (W_L)	Scatter (W_s)
	45,000	105,000	45,000

The relative exposures of the staff in term of permissible doses outside the shielding barriers are summarized in **Table 6**. The results show that the scatter radiation exceed the leakage for certain areas. As expected the permissible dose behind the primary barriers are higher than those from the secondary. It means that the primary barriers can shield also the secondary one because the dose from the latter is lower.

Table 6. Equivalent dose per year for the primary and for the secondary barriers (Leakage and scatter).

Barriers	Permissible dose (*P*) (Sv/yr)		
	Primary	Secondary	
		Leakage	Scatter
Technical room	-	3.36E−03	5.97E−03
Secretary office	-	1.44E−02	2.29E−02
Patient waiting	-	3.07E−03	4.89E−03
Console	3.35E−03	3.16E−04	1.86E−07
Physicist room	1.68E−04	3.49E−07	1.40E−11
Street (Outside)	4.05E−06	5.64E−09	2.14E−14

The Monitor Unit requires to deliver IMRT treatment are higher than those required for conventional treatment which means more scatter and leakage radiation will arrive at the door. The role of the maze is to attenuate these radiations as much as possible so as not to weigh down the door. That's why we estimated the dose at the entrance. Table 7 shows a comparison of the equivalent dose per year at the entrance of the maze between the calculated and the measured value. The mean difference being 41% and shows a statistical significance (p = 0.0029).

Table 7. Equivalent dose per year at the entrance of the maze.

Entrance of the maze	H_B	f	S_s	S_p	L	H_{tot} (mSv/yr)	Measured (mSv/yr)	p value
	1.45	0.26	4.4	0.22	0.0804	3.8	2.23	0.0029

4. Discussions

Initial assessment of linac bunker has been carried out to estimate the permissible dose received by the staff to see if the shielding remains adequate when a new technique will be started.

4.1. Permissible Dose from Primary and Secondary Barriers

The results show that the primary barrier are sufficiently wide, that's means they will also shield small angle scattered radiation and no additional thickness is needed to shield the scatter radiation. In this case the calculated doses for scatter exceed the leakage for these areas technical room, secretary office and waiting room but are below the leakage dose for console, physicist room and street. These differences can be explained by the fact that the scatter fraction is higher for the three first areas. The scatter fraction increases when the scatter angle decreases and here we use small scatter angle for the areas which don't face the primary beam and higher scatter angle for the one that face the primary beam to be more conservative. The barrier for the primary beam is wider than the barrier for secondary.

4.2. Equivalent Dose Comparison

The measurements were done in the worse condition to be more conservative using the biggest open field (40*40 cm^2) with the highest dose rate (600 UM/min). The tests performed on the data between the calculated and the measured equivalent dose show that there is no significant difference between the means value for the following areas: patient waiting room and console with p values greater than 0.05. For the other areas, the results show a significant difference with p values less than 0.05. Figure 3 shows the equivalent dose comparison in terms of histogram for all the areas.

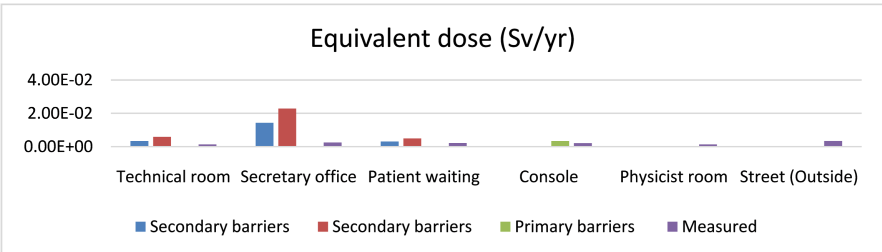


Figure 3. Comparison of Effective doses given by calculation and measured by an ion chamber survey.

An investigation was performed to examine the equivalent dose in a radiotherapy room when a new technique has to be started. The results show that the secondary radiation could not exceed the primary one. For console, physicist room and street, the equivalent doses were estimated considering these areas as primary and secondary barrier at the same time and the found value for the latter are negligible compared to the primary one.

These calculations indicated that primary shielding for conventional therapy is already conservative, with conformal-therapy size fields yielding relative exposure rates outside the room a factor of two less than inside the room. The use of 40*40 cm^2 broad-beam transmission data to determine barrier thickness, even if appropriate considerations are made for the tumor dose, may yield overestimates in the required barrier thickness. This is consistent with a common understanding that a 40*40 cm^2 field size is a conservative estimate used for shielding calculations.

For all barriers considered as secondary in this study, the scatter doses exceed the leakage doses, this can be explained by the fact that the Linac head is well shielded by the manufacturer.

The secondary shielding barrier thickness will increase due to the increase in monitor units required to deliver IMRT treatments. Followill *et al.* [6] estimated that the MUs required for IMRT treatments are about a factor of two greater than those required for conventional therapy [17]. In this study, a factor of 5 was used to be more conservative. The increase in shielding requirements will be proportional to the increase in total delivered monitor units which is a function of the mix of conventional and IMRT patient loads.

An estimate of the barrier thickness must account for the expected distribution of IMRT and conventional patients. MUTIC *et al.* found that conventional primary barriers are adequate for both dynamic MLC and serial tomotherapy IMRT [11]. All the equivalent doses presented here are lower than their corresponding annual limit for workers and for public except the secretary who should be considered as public. This can be explained by the fact that the equivalent dose used in design calculations was occupational since that office was occupied first by the therapist. There are different shielding design goals for controlled and uncontrolled areas. Shielding design goals (P) are levels of dose equivalent (H) used in design calculations and evaluation of barriers constructed for the protection of workers and public. The design dose from the annual dose limit for occupational and public exposure, the workload of the department, the occupancy and use factors and the distances between the target isocenter and the different walls should be taken depending on the surrounded areas. Due to the fact that the machine used in this study is monoenergetic with 6MV, neutron shielding for high-energy photon IMRT was not investigated.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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