SHIELDING CONSIDERATIONS OF A BUNKER TO BE TAKEN INTO ACCOUNT BY THE REGULATORY BODY FOR AUTHORIZATION PURPOSES: *Case study of radiotherapy center in Mali.*

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Abstract

For radiation safety purposes, the barriers thicknesses must be designed to attenuate the primary beam and scatter radiations. The purpose of this work was to check the provided thicknesses by experts about bunker of the only radiotherapy center in Mali according to NCRP 151 recommendations. The obtained results proved that the thicknesses of primary barriers vary between 200 and 224 cm of concrete with a mean value equal to 216 cm and the secondary barriers vary between 84 and 138 cm of concrete with a mean value equal to 103 cm. Considering the different parameters and results such as provided thicknesses of the bunker by experts, conventional treatment techniques (workload), shielding design goals, use and occupancy factors; the regulatory body concluded this bunker will protect efficiently workers and public around its vicinity against ionizing radiations.

1. INTRODUCTION

Structural shielding design in a bunker of accelerator's installations aims to limit radiation exposures to members of the public and employees to an acceptable level, i.e., to reduce the effective dose coming from accelerator to a point outside the bunker as low as reasonably achievable. Shielding design is particularly concerned with attenuation of primary beam and secondary radiations in the form of head leakage of accelerator, patient and wall scatter. Thus, finding the optimum barrier thickness is an essential requirement for the safety of facilities [1-2]. Recommendations and technical information for the shielding design and evaluation for the accelerator facilities, using megavoltage x-ray and gamma-ray, are fully described in Report No. 151 of the National Council on Radiation Protection and Measurements (NCRP) [3] of the USA. This book is one of the most suitable documents to estimate shielding requirements in medical installations using linear accelerators.

The decree No 2014-0931/P-RM (of December 31st, 2014) fixing the rules of protection against ionizing radiations, safety and security of ionizing radiations sources [4], treats in general all aspects related to radiation protection in Mali especially: requirements to be fulfilled by facilities in order to be authorized, safety and security of workers exposed to ionizing radiations, protection of population and environment against harmful effects of ionizing radiations, etc.

For building any bunker able to host an accelerator for medical or research activities, the owner of facility in collaboration with a qualify expert, medical physicist and an architect must establish some detailed plans of facility with the different thicknesses of the bunker (in concrete or lead of primary and secondary barriers) and other areas close to this bunker. Those plans will define also the rooms, control boot, emergency buttons, offices of staff and the conduits (cables for ventilation or cooling, AC, calibration, cooling, etc.). It is in that same concept AMARAP studied the provided plan of radiotherapy center located inside the hospital of MALI in Moribabougou-Bamako for authorization purposes. This is the only radiotherapy center around the country. The objectives of this work were to:

- re-calculate the primary and secondary barrier thicknesses of the bunker of the only radiotherapy center in MALI according to the NCRP Report n°151 methods for authorization purposes;
- compare these calculated results to the provided results;
- understand protection systems implemented by the facility for radiological safety and security of workers and the population in vicinity.

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The shielding of the main door of the bunker was not included in this paper because it was provided with the LINAC by the manufacturer.

2. MATERIALS AND METHODS

The calculation methods to evaluate barriers thicknesses were carried out for a treatment room with a LINAC Elekta Compact, with maximum nominal energy of 6 MV. The LINAC isocenter located at 1 m from the radiation source and it was assumed a symmetric distribution of gantry treatment angles. NCRP methods are based on the tenth-value layer (TVL) concept. It was used, in this study, the TVL for ordinary concrete. The used workload in this work was weekly workload (W). In terms of use factor (U), occupancy factor (T) and shielding design goals (P), for workers and public members, it was used NCRP 151 approach (referred to the plans of the facility and NCRP values).

2.1. Information from Architectural Plan (Building Plan)

2.1.1. Description of the radiation treatment room (Bunker)

The radiation treatment room has a rectangular ground plot (7.65 x 4.90 m^2) with a maze-access and an altitude of 3.0 m (up to the suspended ceiling). The distance from ceiling to the ground is 3.1 m. Sliding motorized and shielded door is fixed to the main entrance of the radiation treatment room, Control room and other compartments are close to the bunker. See figure 1 for more details.

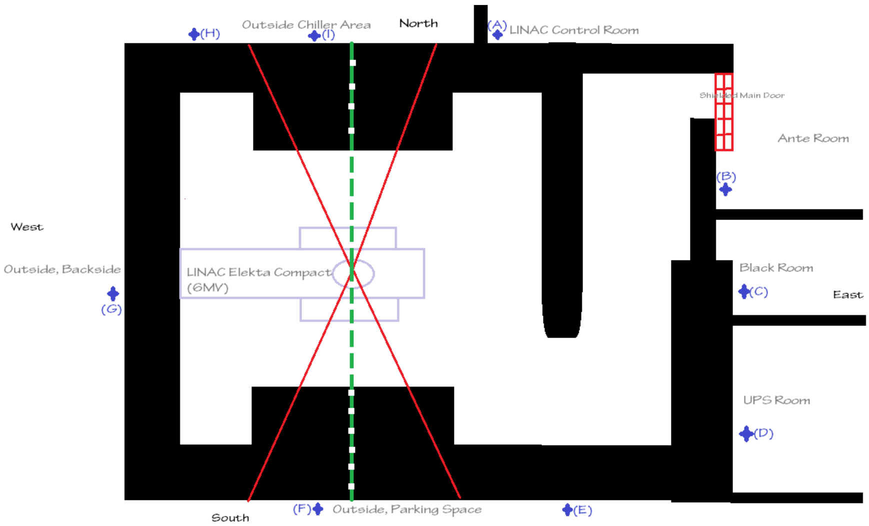

FIG. 1: Plan with measurement points plotted and designation of different compartments beside the radiation treatment room. Green line is the normal to the isocenter of the LINAC and red lines are the directions of primary beam.

2.1.2. Methods of Shielding calculations used by AMARAP (NCRP 151 methods)

Basic considerations: For any practice related to the use of ionizing radiation, the main objective for the shielding in terms of radiation protection is to reduce $I_{(out)}$ to the authorized values for public or workers (see figure 2).

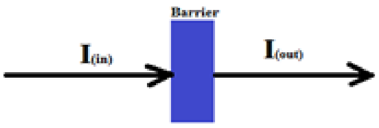

FIG. 2

$$B_{(x)} = \frac{I(out)}{I(in)} \qquad \text{Equation (2.1)}$$

B(x) is the barrier transmission factor to determine in order to know the thickness of specified barrier and I is the intensity of the radiation. For accelerator bunker, there are two (02) barriers called primary and secondary barriers.

TABLE 1. PARAMETERS BY ZONE[#)]

Position	Zone	P Shielding design Goal ($Sv.week^{-1}$)	Distance from LINAC Isocenter to the interest point (m)	Angle to the normal (°C)	Occupancy factor (T)	Use Factor (U)
A	Controlled	1.210^{-4}	3,3	30		
B	Controlled	1.210^{-4}	3,8	60		
C	Controlled	1.210^{-4}	4	90		
D	Controlled	1.210^{-4}	4,2	135		
E	Uncontrolled	2.10^{-5}	3,7	135	1	1
F	Uncontrolled	2.10^{-5}	3,3	0		
G	Uncontrolled	2.10^{-5}	3	90		
H	Uncontrolled	2.10^{-5}	3,2	315		
I	Uncontrolled	2.10^{-5}	3,1	0		
Ceiling	Uncontrolled	2.10^{-5}	3,4	60		

[#)] *Under the radiation treatment room (Bunker) is the basement of the building. Hence, there are no accessible areas below this room.*

2.1.3. Calculation of B(x) and thickness for primary barriers

The primary barrier is expected to adequately attenuate the dose equivalent beyond the barrier that results from secondary products of the photon beam. For an adequate barrier the ratio of the dose equivalent transmitted through the barrier to the shielding design goal (P) needs to be less than or equal to one. Hence the transmission factor of the primary barrier (B_{pri}) that will reduce the radiation field to an acceptable level is given by Equation (2.2).

$$\mathbf{B}_{(pri)} = \frac{\boldsymbol{Pd_{pri}^2}}{\boldsymbol{WUT}} \qquad \text{Equation (2.2)}$$

P is the shielding design goal (expressed as dose equivalent) beyond the barrier and is usually given for a weekly time frame (Sv.week–1), dpri is the distance from the x-ray target to the point protected(meters), W is the workload or photon absorbed dose delivered at 1 m from the x-ray target per week (Gy.week–1), U is the use factor or fraction of the workload that the primary beam is directed at the barrier in question, T is the occupancy factor for the protected location or fraction of the workweek that a person is present beyond the barrier. This location is usually assumed to be 0.3 m beyond the barrier in question (tabulated values)

The thickness of the barrier can then be determined using tenth-value layers (TVL) based on the energy of the accelerator and type of shielding material. In this case, the required number (n) of TVLs is given by Equation (2.3) and the barrier thickness (tbarrier) is given by Equation (2.4).

$$n = -\log(B_{pri}) \qquad \text{Equation (2.3)} \qquad\qquad t_{(barrier)} = TVL_1 + (n-1)TVL_e \qquad \text{Equation (2.4)}$$

where, TVL_1 and TVL_e are called tenth-value layer first and equilibrium respectively, these values are tabulated, (see appendix B, table B.2 of NCRP report N°151).

2.1.4. Calculation of B(x) and thickness for secondary barriers

Secondary barriers need to be designed to adequately protect individuals beyond the accelerator room from leakage radiation, scattered radiation from the patient, scattered radiation from the walls, and secondary radiations (including photo neutrons and neutron capture gamma rays) produced in the accelerator head or in scattering throughout the room.

Leakage radiation from the head of accelerator and scattered radiation from patient and walls of bunker can differ, the secondary-barrier requirements for each are typically computed separately and compared in order to arrive at the final recommended thickness.

The barrier transmission for scattered radiation by the patient (B_{ps}) is given by Equation (2.5).

$$B_{ps} = \frac{P}{a\,W\,T}\, d_{sca}^2 d_{sec}^2 \frac{400}{F} \qquad \text{Equation (2.5)}$$

where, d_{sca} and d_{sec} are the distance from the x-ray target to the patient or scattering surface and the distance from the scattering object to the point protected respectively (meters), a is a scatter fraction or fraction of the primary-beam absorbed dose that scatters from the patient at a particular angle (see table B.4 of NCRP 151), F is a field area at mid-depth of the patient at 1 m (40 x 40 cm^2).The value 400 assumes the scatter fractions are normalized to those measured for a 20 cm × 20 cm field size, P, W and T are defined in equation (2.2). The barrier thickness of scattered radiations (patient and walls) is given by Equation (2.6),

$$t_{(barrier)} = n \times TVL_s \qquad \text{Equation (2.6)}$$

and the TVL_s for the patient-scattered radiation values are given by NCRP report 151 (table B.5a of Appendix B).

The barrier thickness of scattered radiations (patient and walls) is given by equation (2.6) and the barrier transmission for leakage radiation by the head of accelerator (BL) is given by equation (2.7).

$$t_{(barrier)} = n \times TVL_s \qquad \text{Eq. (2.6)} \qquad\qquad B_L = \frac{1000\,P\,d_L^2}{W\,T} \qquad \text{Eq. (2.7)}$$

The amount of leakage radiation coming from the head of accelerator is assumed to be 0,1% of the workload (useful beam), d_L is the distance from head to the point of interest beyond the secondary barrier (meter). The barrier thickness of leakage from the head of LINAC (6 MV) is given by equation (2.8).

$$t_{(barrier)} = TVL_1 + (n-1)TVL_e \qquad \text{Equation (2.8)}$$

If the thickness of the required barrier is about the same for each secondary component: 1 HVL is added to the larger of the two barrier thicknesses. If the two thicknesses differ by a TVL or more, the larger barrier thickness is used.

3. RESULTS AND DISCUSSIONS

In Mali, the regulatory shielding design goals (dose equivalent) for public and workers from practices due to the ionizing radiation are respectively 1 mSv.year^{-1} (which is 2.10^{-5} Sv.week^{-1}) and 20 mSv.year^{-1} (this dose is optimized to 6 mSv.year^{-1} which is 1.210^{-4} Sv.week^{-1}) [3]. All the rooms or other location areas beside the bunker were considered to be fully occupied (occupancy factor is equal to 1) and the use factor of 1 was assumed for all adjacent areas.

According to the international requirements for calculation of radiation protection shielding, a workload of 1000 Gy.week^{-1} was assumed. The measurements are performed with the maximum field size of the collimator of 40 x 40 cm^2 at isocenter. The thickness of different barriers was expressed in centimeter of concrete.

TABLE 2. PRIMARY BARRIERS RESULTS

Location	Type of Zone	P (Sv.week^{-1})	d_{pri} (m)	W (Sv.week^{-1})	T	U	$B_{(pri)}$	n	TVL_1 (cm)	TVL_e (cm)	$t_{barrier}$ (cm)
F	Uncontrolled	2.00E-05	3.3	1000	1	1	2.2E-07	6.7	37	33	224
I	Controlled	1.20E-04	3.1	1000	1	1	1.2E-06	5.9	37	33	200
Ceiling	Uncontrolled	2.00E-05	3.4	1000	1	1	2.3E-07	6.6	37	33	223

TABLE 3. RESULTS FROM SCATTERED RADIATIONS FROM PATIENT AND WALLS

Location	Type of Zone	P $Sv.week^{-1}$	W $Sv.week^{-1}$	T	a (angle θ)	d_{sca} (m)	d_{sec} (m)	F	$B_{(pri)}$	N	TVL_s (cm)	$t_{barrier}$ (cm)
A	Controlled	1.20E-04	1000	1	2.77E-03	1	3.3	1600	1.18E-04	3.93	26	102.14
B	Controlled	1.20E-04	1000	1	8.24E-04	1	3.8	1600	5.26E-04	3.28	21	68.86
C	Controlled	1.20E-04	1000	1	4.26E-04	1	4	1600	1.13E-03	2.95	17	50.12
D	Uncontrolled	2.00E-05	1000	1	3.00E-04	1	4.1	1600	2.80E-04	3.55	15	53.29
E	Uncontrolled	2.00E-05	1000	1	3.00E-04	1	3.7	1600	2.28E-04	3.64	15	54.63
G	Uncontrolled	2.00E-05	1000	1	4.26E-04	1	3	1600	1.06E-04	3.98	17	67.60
H	Controlled	1.20E-04	1000	1	3.00E-04	1	3.2	1600	1.02E-03	2.99	15	44.85
Ceiling	Uncontrolled	2.00E-05	1000	1	8.24E-04	1	3.8	1600	8.76E-05	4.06	34	137.95

TABLE 4. RESULTS FROM LEAKAGE RADIATION FROM THE HEAD OF LINAC

Location	Type of Zone	P ($Sv.week^{-1}$)	W ($Sv.week^{-1}$)	T	d_L (m)	$B_{(pri)}$	n	TVL_1 (cm)	TVL_e (cm)	$t_{barrier}$ (cm)
A	Controlled	1.20E-04	1000	1	3.3	1.31E-03	2.9	34	29	88.63
B	Controlled	1.20E-04	1000	1	3.8	1.73E-03	2.8	34	29	85.08
C	Controlled	1.20E-04	1000	1	4	1.92E-03	2.7	34	29	83.78
D	Uncontrolled	2.00E-05	1000	1	4.1	3.36E-04	3.5	34	29	105.73
E	Uncontrolled	2.00E-05	1000	1	3.7	2.74E-04	3.6	34	29	108.31
G	Uncontrolled	2.00E-05	1000	1	3	1.80E-04	3.7	34	29	113.6
H	Controlled	1.20E-04	1000	1	3.2	1.23E-03	2.9	34	29	89.41
Ceiling	Uncontrolled	2.00E-05	1000	1	3.8	2.89E-04	3.5	34	29	107.64

TABLE 5. COMBINED RESULTS FROM SCATTERED AND LEAKAGE RADIATIONS

Location	t_{scat}	t_{Leak}	t_{Leak}- t_{scatt}	> TVL_e(29cm)	t_{new} (cm)
A	102.14	88.63	13.51	No	110.87
B	68.86	85.08	16.22	No	93.81
C	50.12	83.78	33.66	Yes	83.78
D	53.29	105.78	52.49	Yes	85.46
E	54.63	108.73	54.1	Yes	108.73
G	67.6	113.6	46	Yes	113.6
H	44.85	89.41	44.56	Yes	89.41
Ceiling	137.95	107.64	30.31	Yes	137.95

TABLE 5. COMBINED RESULTS FROM SCATTERED AND LEAKAGE RADIATIONS

Location	t_{scat}	t_{Leak}	t_{Leak}- t_{scatt}	> TVL_e(29cm)	t_{new} (cm)
A	102.14	88.63	13.51	No	110.87
B	68.86	85.08	16.22	No	93.81
C	50.12	83.78	33.66	Yes	83.78
D	53.29	105.78	52.49	Yes	85.46
E	54.63	108.73	54.1	Yes	108.73
G	67.6	113.6	46	Yes	113.6
H	44.85	89.41	44.56	Yes	89.41
Ceiling	137.95	107.64	30.31	Yes	137.95

TABLE 6. COMPARISON BETWEEN THE OBTAINED SHIELDING RESULTS BY AMARAP AND PROVIDED RESULTS BY ARCHITECT AND QUALIFIED EXPERTS

Thicknesses of Barrier in Concrete (cm)			
Location	AMARAP Results	Provided Results from experts of "Hôpital du Mali"[4]	Obervations
Primary Barriers			
F	224	235	
I	200	235	Good thickness
Ceiling	223	235	
Secondary Barriers			
A	110,87	141	Good thickness
B	93,81	60	Thickness should be completed by the shielding maze and door of bunker
C	83,78	60	
D	85,46	117	
E	108,73	141	
G	113,6	140	Good thickness
H	89,41	141	
Ceiling	137,95	141	

The thicknesses of primary barriers were calculated, and the results were expressed in table 2, the minimum and maximum values were respectively 200 to 224 cm of concrete with a mean value equal to 216 cm of concrete. The thicknesses of secondary barriers were calculated by combining the thicknesses from scattered radiations and leakage (see table 5); the minimum and maximum values were respectively 84 to 138 cm of concrete with a mean value around 103 cm of concrete.

Table 6 is the comparison between the calculated thicknesses by AMARAP and the provided values by experts. This comparison revealed that, the provided thicknesses (primary and secondary) of bunker by experts were acceptable except areas B (Ante room) and C (Black room). For these two (02) areas, the provided values (60 cm of concrete for both) were below the calculated values (around 94 cm of concrete for area B and 84 cm of concrete for area C). In the design plan, there is a maze before the barrier of areas B and C (see fig.1). In order to complete the missing thickness of these areas, the thickness of the maze must be around 34 cm of concrete. The main door (principal entrance) must be shielded in lead with a thickness equivalent to 94 cm of concrete.

4. CONCLUSIONS AND RECCOMMENDATIONS

The thicknesses of primary and secondary barriers for LINAC 6 MV Elekta-Compact bunker were calculated using NCRP report 151 by regulatory body (AMARAP) in order to check the provided thicknesses for authorization purposes. The results showed that, the calculated thicknesses of different locations were bigger than the ones provided except location B and C. But in the building plan, there is maze, and the thickness of this maze must around 40 cm of concrete. Before the beginning of the operation, some regulatory controls or inspections were carried out and they reported that the bunker protects efficiently workers and public around its vicinity against ionizing radiations.

The Direction of AMARAP listed the recommendations below to the responsible radiotherapy center of "Hôpital du MALI":

- inform in advance the direction of AMARAP of any modifications about shielding of bunker,
- inform in advance the direction of AMARAP about the acquisition of new LINAC whose the energy is high than 6 MV,
- inform in advance the direction of AMARAP for using others treatment techniques such as IMRT (Intensity Modulated radiation Therapy), TBI (Total Body Irradiation), etc. in order to recalculate the workload. These techniques provide more equivalent dose to the patient,
- make sure that all the conducts (cables for cooling, calibrations and others) carried out on the secondary barriers,
- do not touch to the integrity (shielding) of the primary barriers.

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