EVALUATION OF SHIELDING DESIGN FOR A LINEAR ACCELERATOR (LINAC) FACILITY

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DECLARATION

Candidate's Declaration

This thesis is the result of research work undertaken by BELLAMECH NASSER DINE towards the Degree of M.Phil. Nuclear Science and Technology in the Department of Medical Physics, School of Nuclear and Allied Sciences, University of Ghana, under the supervision of Prof. CYRIL SCHANDORF and Dr. DENNIS K. ADOTEY.

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Supervisor's Declaration

We hereby declare that the preparation and presentation of this thesis was supervised in accordance with guidelines on supervision of thesis laid down by the University of Ghana.

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ABSTRACT

The main goal of this work is to assess the adequacy of the structural shielding design for the linear accelerator at the Mauritania Oncology Center to protect occupationally exposed workers, and general public due to the anticipated increased workload. A retrospective evaluation was done to verify whether those occupationally exposed and the public are adequately protected from the harmful effect of radiation exposure during the treatment procedures at the facility. National Council on Radiation Protection and Measurements (NCRP) Report No. 151 methodology was used for the evaluation of structural shielding adequacy for a LINAC. The thickness of the primary barrier was calculated to be 168 cm and that of secondary barrier was 82 cm. the existing thickness were 305 cm and 165 cm respectively for the primary barrier and secondary barrier respectively. The existing thickness (primary and secondary) provide adequate protection for the occupationally exposed workers and the public. The total dose equivalent at the door is 2.02 mSv week^{-1}, of which ≈ 86 % is from neutrons, 6 % from low-energy scattered and transmitted leakage photons, and 8 % from neutron capture gamma rays. The dose rate measurement shows that the shielding provided by the entrance door is not adequate so an additional shielding is required for the door or the workload should be constrained to a value that will enable compliance with the designed goal.

DEDICATION

This research work is dedicated to my lovely family (my wife, Amal; and daughters, Hanan and Bouchra). Dedicated also to my father, EL Ghassem Ahmedou, my mother, Maryem Maymoutt, my sister and my brothers, and to all my friends.

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List of Abbreviations and Symbols

α	reflection coefficient
β	transmission factor for neutrons that penetrate the head shielding
θ	angle for patient-scattered radiations
σ	cross section for thermal neutron reaction
φ_A	total neutron fluence at a point per unit absorbed dose of X rays at the isocenter (n cm^{-2} h^{-1})
A_0	beam area at the first scattering surface
A_1	area of wall that can be seen from maze door
A_z	cross sectional area of maze inner entry projected onto the maze wall from the perspective of the irradiated primary barrier
$a(\theta)$	scatter fraction or fraction of the primary-beam absorbed dose that scatters from the patient at a particular angle
ALARA	as low as reasonably achievable
B	Transmission factor or barrier transmission
B_L	barrier transmission of leakage radiation
B_{pri}	Transmission factor of the primary barrier
B_{ps}	barrier transmission for radiation scattered by the patient
D	absorbed dose
$\dot{D}_0$	absorbed-dose output rate at 1 m (Gy h^{-1})
d_H	distance from the radiation source to wall H, in m
d_i	distance from the radiation source to the maze centerline;
d_m	centerline distance along the maze.

d_P	distance from the source to the center of wall P.
d_r	distance from where the central axis of the radiation beam strikes wall *H* to the center of the maze opening *r*, in m;
d_z	distance from point *r* to the maze entrance, in m.
d''	distance from the center of wall P to the maze entrance;
d_t	distance from the radiation source to the maze entrance;
f	fraction of the primary beam transmitted through the patient
Gy	gray
H	dose equivalent
$H^*(10)$	ambient dose equivalent at a depth of 10 mm
h_φ	dose equivalent from neutron capture gamma rays at the outside maze entrance per unit absorbed doseof X rays at the isocenter
H_{cg}	weekly dose equivalent at maze door due to neutron capture gamma rays
H_{LS}	dose equivalent per week due to head-leakage photons scattered by the room surface
H_{LT}	dose equivalent per week due to leakage radiation which is transmitted through the inner maze wall.
H_n	neutron dose equivalent per week

$H_{n,D}$	neutron dose equivalent at maze entrance per unit absorbed dose of X rays at the isocenter
H_P	dose equivalent from patient-scattered radiation at the maze entrance
H_{PS}	dose equivalent per week due to primary beam scattered from the patient
$\bar{H}_{pt}$	average dose equivalent per patient treatment at 30 cm beyond the penetrated barrier
H_S	dose equivalent per week due to scatter of the primary beam from the room surface
H_w	total weekly dose equivalent at external maze entrance (leakage and scattered radiation, neutron capture gamma rays, and neutrons)
HVL	half-value layer
IDR	instantaneous dose-equivalent rate with the accelerator operating at maximum output at 30 cm beyond a barrier
IDR_L	instantaneous dose-equivalent rate measured at a point located 30 cm beyond the secondary barrier in the absence of phantom at the isocenter
IDR_{ps}	instantaneous dose-equivalent rate measured at a point located 30 cm beyond the secondary barrier due to patient-scattered radiation
IDR_{tot}	instantaneous dose-equivalent rate measured at a point located 30 cm beyond

	the secondary barrier in the presence of a phantom
K	ratio of the neutron capture gamma-ray dose equivalent to the total neutron fluence
M	maximum number of patient treatments in-any-one-hour divided by the average number of patients treatments per hour
n	number of tenth-value layers
NCRP	National on Radiation Protection and Measurements
P	Shielding design goal
Q_n	neutron source strength in neutrons emitted from the accelerator head per Gray of X-rays absorbed dose at the isocenter
S_0	inner maze entrance cross-sectional area
S_1	cross-sectional area along the maze
S_r	surface area of the treatment room
t	barrier thickness
t_s	slant thickness
T	occupancy factor
TADR	time averaged dose-equivalent rate

t_{pri}	thickness of primary barrier
TVD	ten-value distance
TVL	ten-value layer
TVL_1	first tenth-value layer
TVL_e	equilibrium tenth-value layer
U	use factor
U_{pri}	use factor for the primary barrier
U_{ps}	use factor the gantry orientation used during the measurements
W	workload
W_L	workload for leakage radiation
W_{pri}	primary barrier weekly workload
W_{ps}	patient-scattered radiation workload

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND

1.1.1. CANCER

Cancer is a set of diseases characterized by the uncontrolled expansion and spread of irregular cells. If the spread is not very well controlled, it can lead to death. Usually external and internal factors are the cause of cancer, external factors such as infectious organisms, tobacco, and an unhealthy diet, and internal factors, such as immune conditions, hormones, and inherited genetic mutations. These factors might act together to cause cancer. Mostly cancer begins in one part of the body and spreads to other parts.

Based on estimations from the International Agency for Research on Cancer (IARC), there were 14.1 million new cancer cases in 2012 worldwide, 8 million of these cases occurred in economically developing countries, which contain about 82% of the world’s population. The corresponding estimations for total cancer deaths in 2012 were 8.2 million which is about 22,000 cancer deaths daily) – 2.9 million in economically developed countries, and 5.3 million in economically developing countries [1].

Treatment for cancer usually depends on several factors, such as the level and localization of the tumor or cancer. Treatments for cancer mostly include one or a combination of the following:

- radiotherapy
- surgery
- chemotherapy

Linear accelerators (LINACs) are used in external-beam radiation therapy for treatment of cancer. Low-energy LINACs are used principally for the treatment of different types of tumors especially neck, head, breast and bone cancer. High-energy LINACs are used for treatment of deep cancers and tumors of the pelvis and thorax. Generally radiations are used for the treatment of more than one half of all cancer cases.

1.1.2. LINEAR ACCELERATOR (LINAC)

LINACs produce a defined beam of uniformly intense x-ray photon radiation and electron beams as well of different energies, there is a large range of energies depending on the type of accelerator and each accelerator has its own specifications.

The electron beam produced by a linear accelerator can be directed to a metallic target for the production of x-rays and can also be used for medical treatment purposes depending on stage and location of tumors or cancer.

Higher energy LINACs (6-18 MV) are commonly used in radiotherapy. Often, either 6 MV or 18 MV in LINACs is more preferable for cancer treatment. As a result, the production of unwanted fast neutrons due to the increase in photon energy can infect the therapeutic beam and also give an addition to the patient dose.

1.1.3. RADIATION ISSUES

Exposure to radiation during a medical treatment needs to be justified by comparing the benefits and the damages that may occur. In case of optimization, the practitioners have to confirm that the minimum amount of radiation is used to realize the planned objective. The use of radiotherapy has generally social benefit, but the high exposure to radiation during radiotherapy process may cause harm to patients and to the staff and to members of the public if unwanted radiation exposure occurs.

The radiation oncologist is the one responsible for the safety and protection of the patient in the prescription and delivery of radiotherapy. This person is required to make sure that the dose given to the patient is justified and optimized. The protection of occupationally exposed staff and members of public is the main aspect for optimization of the use of radiation in medical field. Particular concern in radiation protection is given to children, and pregnant females.

The occupationally exposed staff can be protected based on the general principles of radiation protection [2]. For each method the management of the treatment facility and devices needs special consideration. Activated devices and air in the treatment room should be carefully controlled when using high energy LINACs for radiotherapy purpose to avoid exposure of staff members by radiation. The patient family members also shouldn't be exposed to radiation.

1.1.4. SHIELDING DESIGN

The review of shielding design in medical radiotherapy installations is important after certain years of usage to make sure that the radiation exposures to staff and members of the public is within the acceptable level, i.e. to ensure the effective dose from a linear accelerator to a location outside the radiotherapy bunker is as low as reasonably achievable. Shielding design is mainly concerned with attenuation of the primary beam and secondary radiation in the form of head leakage, patient and wall scatter. Thus, finding the optimum barrier thickness is an important requirement for the safety of radiotherapy facilities. Recommendations and technical information for the shielding design and evaluation in modern radiotherapy facilities, using megavoltage x-ray and gamma-ray, are fully described in Report No. 151 of the National Council on Radiation Protection and Measurements (NCRP) [3], IAEA Safety Report Series No. 47, Radiation Protection in the Design of Radiotherapy Facilities [4] and IAEA Safety Report Series No 38, Applying Radiation Safety Standards in Radiotherapy [2]. The NCRP Report No.151 is one of the most suitable documents on structural shielding and design and evaluation for mega voltage x- and gamma -ray radiotherapy facilities.

1.2. STATEMENT OF THE PROBLEM

In Nouakchott Oncology Centre there is only one linear accelerator used for radiotherapy which started operating since 2010. The Centre was set up by the Mauritanian government with the help of IAEA. Due to its location; Senegal, Mali and other countries in the region have benefited from its services. This regional collaboration may have contributed to an increase in the workload not considered in the original design. In view of the anticipated higher workload and in future there is the urgent need to re-assess the adequacy of the shielding design.

The primary beam of the LINAC is used to treat the patients while the leakage radiation and scattered radiation are not useful and may contribute to worker and the public exposure.

The motivation for this work is therefore to perform a retrospective evaluation to verify whether those occupationally exposed and the public are adequately protected from the harmful effect of radiation exposure during the treatment procedures at the facility.

1.3. OBJECTIVES

The main objective of this work is to assess the adequacy of the structural shielding design for the linear accelerator at the Mauritania Oncology Center to protect workers, and general public due to the increased workload since 2010. .

The specific objective is to:

a. Estimate the workload spectrum for the linear accelerator facility

b. Estimate the thicknesses for the primary and the secondary barriers.

c. Assess whether the design dose levels for the protection of the worker and the public are being met during the operations of the accelerator

d. Make relevant recommendations from the findings

1.4. RELEVANCE AND JUSTIFICATION

Due to the harmful effects of ionizing radiation produced by high energy linear accelerator, shielding designs should be provided to decrease the radiation exposure to appropriate levels. The purpose of radiation shielding is to protect workers and the general public from the harmful effects of ionizing radiation.

Three principles used in operational radiation protection include; increasing the distance to the source of radiation exposure, decreasing the time spent in the radiation field and using appropriate shielding material and design to reduce the radiation exposure [5]. The three approaches can be used in combination to achieve the desired optimization of radiation protection.

Shielding must be designed by a competent expert to guarantee that the required degree of radiation protection is achieved. Any radiation exposure may have an associated level of risk, it is important that the competent expert assesses the completed facility design to make sure that all expected exposures are consistent with the ALARA principle.

Before any facility is authorized by the Regulatory Authority the licensee must demonstrate that the shielding and design requirements have been met and periodically re-evaluation done especially when workload data changes.

1.5. SCOPE AND LIMITATION

This work seeks to do a retrospective evaluation of the adequacy of the structural shielding design for the linear accelerator facility at the Nouakchott Oncology Center of Mauritania using workload and other relevant data since the facility started operating in 2010.

The study focuses on the protection of staff and members of the public.

This work doesn’t consider practically the measurements of neutrons radiations because there was not available instrument for the measurements at the regulatory authority and the hospital.

1.6. STRUCTURE OF THESIS

Chapter One introduces the background, the objectives, relevance and scope and limitation of the work. Chapter Two presents the literature review on the methodologies, structural shielding and evaluation for a linear accelerator. The materials and methods are described in Chapter Three. Chapter four summarizes the results and the relevant discussions on the findings. Finally, Chapter Five provides the conclusions and some recommendations to the relevant stakeholders.

CHAPTER TWO

LITERATURE REVIEW

This chapter reviews the literature relevant to the methodologies for structural shielding and evaluation for linear accelerators.

2.1. INTRODUCTION

The use of radiation facilities for health care purposes may potentially increase the dose rates to levels above the recommended design limits. Thus it is necessary to continuously conduct an assessment to establish if additional shielding is needed to reduce and control exposures of employees and members of the public to acceptable level of radiation.

The proper shielding of LINACs facility rooms play an important role for the protection of workers and the members of the public. The IAEA Safety Reports Series No. 47, Radiation Protection in the Design of Radiotherapy facilities and the National Council on Radiation Protection and Measurements (NCRP) Reports 51 and 151, present guidelines for medical LINAC shielding; these form important documents for most countries in the shielding and design of LINACs facilities.

2.2. DESIGN FEATURES

2.2.1. LOCATION

Radiotherapy facilities are generally located on the boundary of the Oncology Centers to avoid radiation protection issues coming from radiotherapy rooms being adjacent to high occupancy areas [4]. As mentioned in NCRP 49 [6], when a radiotherapy facility is being located many factors should be considered. These are operational efficiency, cost, as well as provision for future expansion and / or increased workload [7].

For underground rooms, the reduction in shielding costs for floors and outside walls should be compared with the expense of digging, watertight sealing and of providing access. For rooms on or above ground level, always shielding of outside walls is always required.

The required thickness of each barriers of the treatment room will depend on the amount of time that the adjacent areas are used. Areas with high occupancy levels will require greater shielding, while areas with low occupancy levels will require lower shielding. Whenever possible, the treatment rooms should be surrounded with rooms that have low occupancy [3].

2.2.2. ACCESS

Access to the room for the delivery and replacement of the treatment unit and subsequently by patients must be considered. Entrance to the room is generally through a shielded door or via a maze [8]. If there is no need for a door, for security purpose, the access of public during the treatment should be restricted. It is important to include in the room design an open access conduit for dosimetry equipment cables. This dosimetry duct should always be through a secondary barrier so that the primary beam can never strike it. Ideally it should run at an angle through the barrier to the treatment control area [4].

2.2.3. ROOM SIZE

The room dimensions (length, width and height) are provided by the manufacturer's manual. The room should be large enough to allow full extension of the couch in all directions, the staff should have large space to do their work freely, and moreover the accessory devices for patient treatments are usually stored inside the room, so the operator should be able to walk for it [4]. Generally the size of the room depends upon the type of treatments used by the facility. The room may need to be larger.

2.2.4. MAZES

In order to reduce the radiation dose near the entrance, a restricted access passageway leading to the room may be added in the design. This passageway is called the maze. The maze should be relatively longer with a small cross-section if possible. The minimum width may be determined by the dimensions for the facility that will be used for the treatment purpose and also by the hospital bed. A maze will reduce the need of heavy shielding for the door and also will assure that radiation won't reach the entrance door without having been attenuated with it. If the length of the maze is sufficient, or if there are enough bends, there may be no need for a radiation protection door at the maze entrance [3]. It is recommended that a gate be installed at the entrance of the maze to discourage entry to the room during patient treatment if a shielded door is not required. Another advantage of a maze is a route for ventilation ducts and electrical conduits without compromising the shielding.

2.2.5. DOORS AND INTERLOCKS

The treatment room containing the radiotherapy equipment should be an Access Controlled Area (ACA) according to the BSS [9]. It is recommended that a gate be installed at the entrance to the maze to restrict access during patient treatment. When a shielding door is required to reduce dose rates at the entrance, a motorized door may be necessary, and also an emergency means by which the motion of the door is stopped should be there. Moreover, if the motorized door is too heavy to be stopped manually it should have sensors that stop the door to prevent any accident [4].

All doors, gates, photoelectric beams and motion detectors must be interlocked to the treatment unit to prevent an exposure if a door is open. The interlock must also ensure that when the door is opened there is no radiation at all [7].

2.2.6. TREATMENT CONTROL AREA

The treatment control area is where the operators control the accelerator. Usually this area is close to the door of the treatment room so that the operators can monitor the entrance area. The control area should be large enough to accommodate the treatment unit control console and others devices [8].

2.2.7. PATIENT OBSERVATION AND COMMUNICATION

The operators should be able to monitor the patient during treatment. Two cameras are recommended [10]. These should be situated 15° off and above the gantry rotation axis for optimum observation of the patient on the treatment couch. The cameras should be located far away from the radiation source. There should also be provision for two way audio communication between the treatment control area and the room. A patient activated alarm may be required for patients unable to give an audible call.

2.2.8. PENETRATION OF DUCTS

Shielding of ducts and cable of conduits between LINAC room and outside the room is also important. This includes ducts for cables necessary to control LINAC facility, ventilation ducts, ducts for physics equipment and other service ducts. It is recommended that ducts do not penetrate primary barriers of the treatment room meanwhile they can penetrate the secondary barriers [4]. The ducts should be placed in such a way that radiation passing through them will require the least amount of compensation for the barrier material it displaces. No duct should run orthogonally through a radiation barrier. It could either run at an angle through the barrier or have one or more bends in it so that the total length of the duct is greater than the thickness of the radiation barrier [3]. If required, lead or steel plates are suitable materials to compensate for the displaced shielding. To shield the scattered radiation that passes along the duct, it is better to place the additional shielding outside the treatment room, where the radiation has a lower average energy and therefore, less shielding material is needed.

2.2.8.1. Shielding around ducts above the maze entrance for high energy machines

The photon and neutron dose equivalent rates at the maze door where the ducts penetrate the barrier may be estimated using the method described in NCRP-151 report method [3]. Since the penetration area should be located about 3 m or more above the floor, the scattered radiation to a person is further reduced. McGinley [7] has shown that for 18 MV photons, the need for additional shielding depends strongly on the length of the maze. For a maze 5 m in length, the total dose at the outer maze entrance is low and it usually requires no additional shielding around the duct. However, for a maze less than 3 m long, a shielding baffle may be needed to reduce the dose. Duct shielding is usually unnecessary for rooms with more than one bend.

2.2.9. WARNING SIGNS AND LIGHTS

BSS [9] requires registrants and licensees to display a warning symbol, such as that recommended by the International Organization for Standardization (ISO) [11] …at access points and other appropriate locations within controlled areas. It is recommended that an illuminated warning sign be displayed at the entrance to the maze or treatment room as well as inside the treatment room. These signs should be mounted at eye level (1650 mm above the floor level) and interlocked with the treatment unit control [4]. The illuminated signs may have two or three stages. For a two stage sign, the first stage will be illuminated when there is power to the treatment unit, and the second stage will illuminate when the treatment is going on. For a three stage sign, stage one will be illuminated when there is power to the treatment unit, stage two will light when the treatment unit is ready to start the treatment and stage three will illuminate when the treatment has started already. A warning sign should indicate the nature of the hazard. [16]

2.3. MATERIALS FOR SHIELDING

For buildings new LINACs facilities, concrete is the best material for shielding since it is the least expensive. However, higher density materials maybe necessary when the space is at a premium. Table 2.1 lists typical building materials that can be used for shielding with their densities [4].

Table 2.1: Building Materials and their Densities

Building material	**Density (kg·m^{-3})**	**Comment**
Concrete	2350	-Will vary with mineral content
Barytes concrete	3400–3500	-A bit expensive but commonly used.
Iron ore	4000–5400	-Range of densities depend of ore mixture to sand
Clay bricks	1600	-Generally used for shielding of X rays installations up to 500 kV with additional lead or steel.
Breeze blocks	1100–1400	
Earth	1600	-Used when the treatment room is below ground level
Steel	7900	-Normally used as supplementary shielding on an existing treatment room.
Lead (solid)	11 340	

The most common density of concrete used for LINACs facilities shielding is 2350 kg·m^{-3}. For concrete of different density an adjustment will be needed to determine the required barrier thickness. For therapy installations operating over 500 kV, Compton scattering dominates and the shielding material will absorb the radiation according to the density of material. The density of concrete varies according to the local aggregate that has been used. For example, in the United Kingdom, the normal density is

2300 kg·m^{-3}, but this will vary over the country from 2250 kg·m^{-3} (gravel) up to 2450 kg·m^{-3} (dense limestone or granite). If a design density is specified that cannot be made locally, then the cost will go up. The increase in cost is due mainly to the cost of transporting large volumes of aggregates. Concrete density can usually be achieved to within 50 kg·m^{-3} of that specified. It is most cost effective to determine the density of concrete that can be produced locally and determine the necessary barrier thicknesses accordingly, working on the lower limit of the density range specified [12].

Concrete is normally specified by strength, with density being of secondary importance. Strength is increased by increasing the proportion of cement in the mix, while increasing the proportion of aggregate increases density. Increasing the amount of water in the mix will reduce the overall density as air pockets may be left as the mix dries out [12]. To guard against air pockets it is customary to vibrate the concrete mix as it is poured. Each barrier should be formed in one pour to avoid seams between different layers. Pre-formed concrete blocks only have a density of 2000 kg·m^{-3}, but some special dense building bricks are available. Examples of such bricks are barites, or barium and magnetite bricks, which have a density of around 3000 kg·m^{-3}. If using dense bricks, it is important to use heavy mortars to avoid shine paths between the bricks. Ordinary sand mortar only has a density of 2000 kg·m^{-3}. If space is at a premium, then special high density concretes or high density materials such as steel or lead can be used. Steel plate is often used in existing rooms that need to be upgraded. The steel plate is usually formed in

10 mm thick sheets and fixed one layer at a time to the existing wall, taking care that the fixings do not overlie each other. For therapy installations operating above 10 MV, shielding against neutrons must be considered. Concrete contains relatively high hydrogen

content and is therefore efficient at shielding against fast neutrons. The tenth value layer (TVL) for the primary X ray beam is approximately double that for the photo-neutrons produced by medical linear accelerators, so any shield designed as a primary barrier against X rays will be more than adequate against photo-neutrons.

The fast neutrons are reduced in energy by elastic scattering interactions with hydrogen. After a number of collisions they become slow neutrons, which undergo capture reactions with many materials and penetrating capture gamma rays are emitted. The capture gamma ray spectrum in concrete extends to greater than 8.0 MeV and the average energy is 3.6 MeV. The capture of slow neutrons by hydrogen in concrete results in a pronounced peak in the photon spectrum at 2.21 MeV. Boron and cadmium have large cross-sections for the capture of slow neutrons. Boron is incorporated into polyethylene, which has high hydrogen content to form an efficient neutron shield. Slow neutron capture in the boron results in the production of a low energy gamma ray of 0.473 MeV. A 5% composition by weight of boron in polyethylene is commonly used in neutron shielding doors in treatment rooms.

2.4. SHIELDING DESIGN PARAMETERS

2. 4.1. Shielding design goal (P)

The main objective of radiation shielding is to reduce the effective equivalent dose from a LINAC facility to a sufficiently low level at a point outside the treatment room. This level is determined by the regulatory authority and it depends on the states where the LINAC is operated but is generally 0.02 mSv per week for uncontrolled area and 0.1 mSv per week for controlled areas that is occupied only by workers.

2.4.2. Use and Occupancy factors (U, T)

A use factor (*U*) is the fraction of the time during which the radiation beam is directed at a particular barrier. Use factors may depend on the use of the facility and also on the energy of the accelerator.

If a LINAC uses a conventional technique for the treatment the NCRP Report 49 [6] recommends 1.0 as use factor for the floor when the beam is exactly pointed down and 0.25 for walls and ceiling when there are no specific values.

Basically U = 0.25 for lateral barriers, ceiling barriers, and floor

U = 0.1 for thin portions of ceiling barrier [3]

Table 2.2: Use factor's values for both intervals 45° and 90°

90^{o} gantry angle intervals	
Angle Interval Center	U (%)
0° (down)	31.0
90° and 270°	21.3 (each)
180° (up)	26.3

45^{o} gantry angle intervals	
Angle Interval Center	U (%)
0° (down)	25.6
45° and 315°	5.8 (each)
90° and 270°	15.9 (each)
135° and 225°	4.0 (each)
180° (up)	23.0

The occupancy factor (*T*) is a fraction of time spent by an individual at a location adjacent to the treatment room when the beam is on. If the area is below the ground level the occupancy factor is zero since the area is not occupied. The occupancy factor is slightly greater when area is occasionally occupied, such as corridors, and an area such as an office is higher. If an occupied area is adjacent to the treatment room it will require more shielding. The occupancy factor then can be defined as the fraction of an 8 hour per day or 2000 hour per year for which an individual may occupy a location [3].

Table 2.3: Occupancy factor's values for different locations

Location	Occupancy factor
a) Areas occupied all the working time by an individual) e.g. administrative offices, treatment planning rooms, control rooms,	T=1
b) Rooms adjacent to the treatment room, adjacent patient examination rooms	T=1/2
c) Corridors, employee rooms, resting rooms for the workers	T = 1/5
d) Treatment vault doors	T = 1/8
e) Public toilets, unattended vending rooms, storage areas disregarded waiting rooms.	T = 1/20
f) Unattended parking	T = 1/40

2.4.3. Instantaneous Dose Rates and Time Averaged Dose Rates

When designing radiation shielding barriers we can still suppose that the workload is distributed throughout the year. Therefore, it will be possible to design a barrier that will meet only one-fiftieth of the annual shielding design goal (NCRP, 2004) per week.

The greater shielding requirements are met when shorter time intervals are used. In the United Kingdom, the shielding design for radiotherapy rooms is based on the instantaneous dose rate (IDR).

This is the direct reading from the dosimeter, averaged over one minute. The IDR can also be calculated to be compared with the direct reading from the dosimeter after the facility has been installed.

Definitely, the measured *IDR*, with maximum output from the facility, does not properly represent the true operating conditions. However it is more suitable taking into account the workload and the use factor with the measured or calculated *IDR* when evaluating the shielding adequacy of a barrier [3].

The TADR is the barrier attenuated dose-equivalent rate averaged over a period of operation.

2.4.3.1 Weekly Time Averaged Dose-Equivalent Rate (R_w)

It is the TADR at the specified location averaged over a 40 h workweek which is 8h × 5d. For primary barrier it is given by equation 2.1:

$$R_w = \frac{IDR\, W_{pri}\, U_{pri}}{\dot{D}_0} \tag{2.1}$$

R_w = the weekly TADR (Sv/week);

IDR = instantaneous dose-equivalent rate (SV/h) it is measured or calculated at 0.3 m beyond the barrier, and for LINAC measurement it is averaged over 20s to 1 minute depending on the type of accelerator;

$\dot{D}_0$ = output dose rate at 1 m (Gy h^{-1})

W_{pri} = weekly workload for primary barrier (Gy $week^{-1}$)

U_{pri} = use factor

For secondary barrier, R_w has contribution from both leakage and patient-scattered radiation

$$R_w = \left(IDR_L \frac{W_L}{\dot{D_0}}\right) + \left(IDR_{ps} \frac{W_{ps}\, U_{ps}}{\dot{D_0}}\right) \qquad (2.2)$$

$$IDR_{ps} = IDR_{tot} - IDR_L \qquad (2.3)$$

2.4.3.2. In-Any-One-Hour Time Averaged Dose-Equivalent Rate

Some radiation authorities set a limit for the time dose equivalent in-any-one-hour (R_h) in uncontrolled area. The U.S. Nuclear Regulatory Commission (NRC) set a limit of the dose equivalent in any uncontrolled area not to pass 0.02 mSv in-any-one-hour (NRC, 2005a). R_h arises from the maximum number of patients that can be performed in-any-one-hour including the set up procedure time of the patient [3].

$$R_h = N_{max}\, \overline{H}_{pt} \qquad (2.4)$$

N_{max} = maximum number of patients that can be treated in-any-one-hour including the set up procedure time of the patient.

$\overline{H}_{pt}$ = the average dose equivalent given per patient at 0.3 m outside the barrier

But $\overline{H}_{pt}$ is also equal to the time averaged dose equivalent per week (R_w) divided by the average number of patient treatments per week ($\overline{N}_w$).

2.5. SHIELDING PROVIDED BY MAZES DESIGN

An understanding of the scattering characteristics of X-rays is demanded when designing a maze, the scatter can be either by the patient or the walls of the room. For low energy LINACs units below 10 MV, the scatter and transmission of primary, leakage and scattered radiation must be considered. For high energy LINACs above 10 MV the neutron and neutron capture gamma rays must be considered [4]. For the design shown in figure 2.1, where the gantry rotation axis is perpendicular to the maze axis (this case).

The total dose at the door D_d is given by:

$$D_d = \sum_G D_p + \sum_G f \times D_w + \sum_G D_L + \sum_G D_T \tag{2.5}$$

Where

$\sum_G$ integrates over all gantry angles;

D_p = dose from patient scattered radiation;

f = transmission factor for the patient;

D_w = dose from radiation scattered by walls into the maze door;

D_L = dose from leakage radiation scattered to the entrance;

D_T = dose from leakage radiation transmitted through the maze wall.

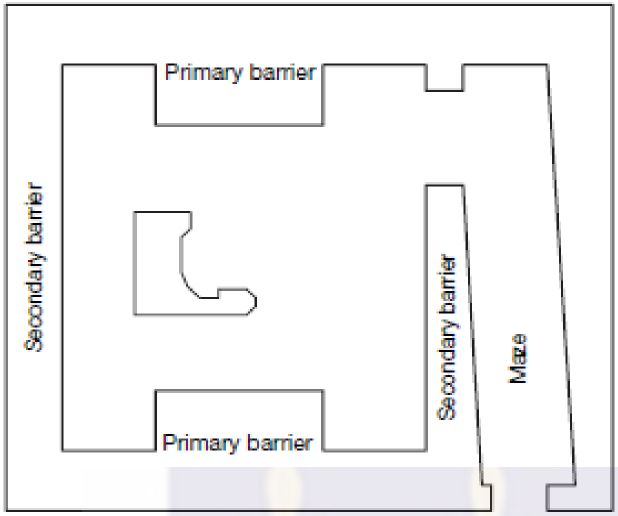

Figure 2.1: Typical room layout where the gantry rotation axis is perpendicular to the maze axis.

2.5.1. Dose arising from scatter by patient D_{pH}

The scatter at the maze door can be estimated for X rays below 10 MV and is given in NCRP Report No. 51 [13].

In Figure 2.2, the dose D_p at the maze door due to patient scatter can be estimated using equation 2.6.

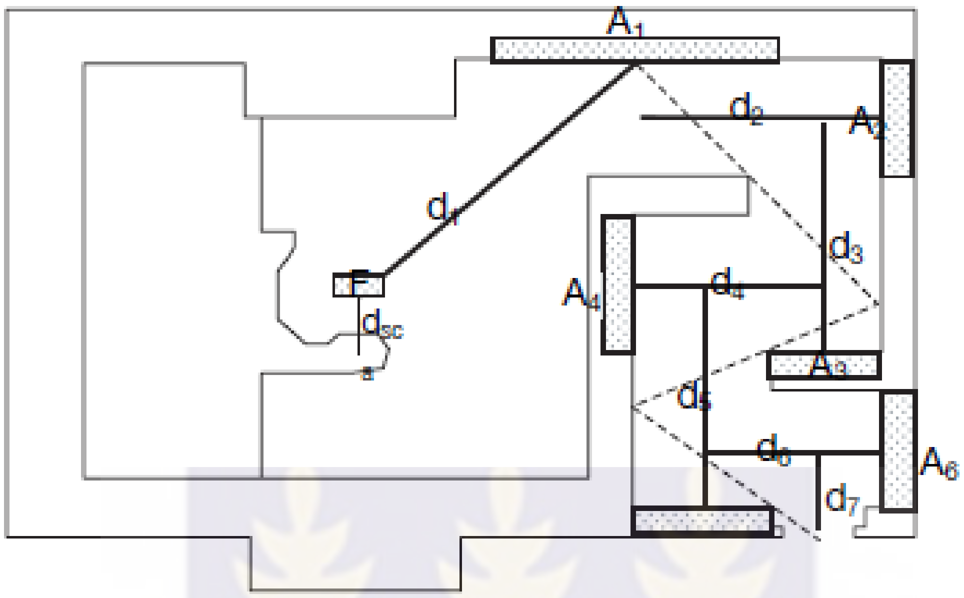

Figure 2.2: Schematic diagram to show the scatter paths to the maze entrance.

$$D_p = \frac{W\,U_0\,a\,\left(F/_{400}\right)(\alpha_1\,A_1)\ldots(\alpha_{n-1}\,A_{n-1})}{(d_{sca} \times d_1 \ldots d_n\,)^2} \qquad (2.6)$$

Where

W = workload, in Gy/week;

U_0 = Use factor (generally supposed to be 0.25 for lateral barriers).

a = scatter fraction at the patient [3].

α_1, α_2, etc., are the wall reflection coefficients for 0.5 MeV [4].

F = field size area, in cm^2.

A_1, A_2, etc., areas of walls that scattered radiation can reach the maze entrance.

d_{sca} = distance from radiation source to the patient, in meters.

$d_{1 \ldots dn}$ = distances to the next scattering surface, in m.

2.5.2. Dose arising from the primary beam scattered by the wall *Dw*

In Figure 2.3, D_w will result from the scatter of the primary beam by wall *H* down to the maze and its given by:

$$D_w = \frac{W\, U_H}{{d_H}^2} \times \frac{\alpha_H\, A_H\, \alpha_r\, A_r}{{d_r}^2 \times {d_z}^2} \qquad (2.7)$$

Where

W = workload, in Gy/ week;

U_H = wall *H* use factor, in most cases is 0.25;

α_H = reflection coefficient from wall *H*;

A_H = maximum field size projected onto wall *H*, in m^2;

α_r = reflection coefficient of the wall;

A_r = cross-sectional area of the inner maze, in m^2;

d_H = perpendicular distance from the source to the wall H, in m;

d_r = distance from where radiation beam strikes wall *H* to the center line of the maze, in m;

d_z = distance from point *r* to the door, in m.

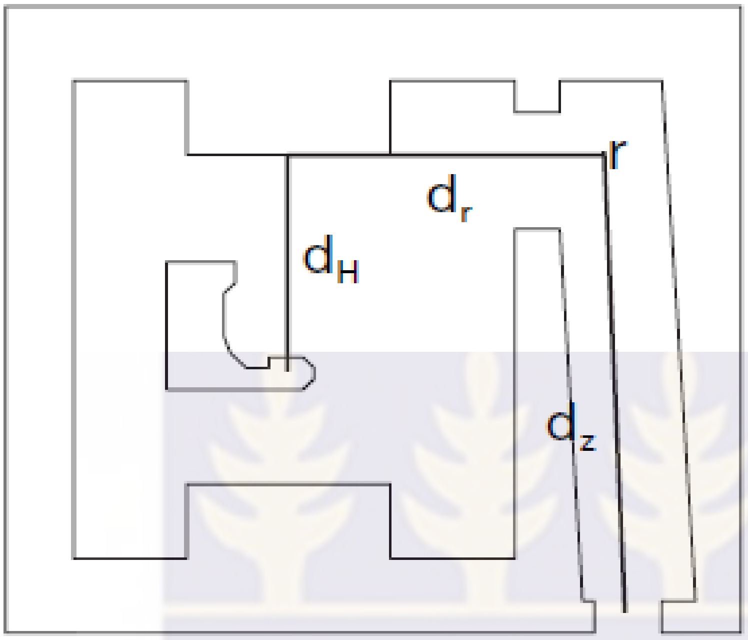

Figure 2.3: Schematic diagram showing the scatter path for the primary radiation beam to the maze entrance (gantry rotation axis perpendicular to the maze axis).

In Figure 2.4, D_w will result from leakage from the head of the accelerator transmitted through the maze wall to the maze door

$$.D_w = \frac{W\,U_m\,B_{pr}\,\alpha_p\,A_p}{(d_p\,d'')^2} \tag{2.8}$$

where

W = workload, in Gy/week;

$\mathbf{U_m}$ = is Use factor for the beam directed at the maze wall (usually 0.25);

$\mathbf{B_{pr}}$ = transmission factor of the beam through the maze wall;

d_P = distance from radiation source to the center of wall P;

d = distance from the center of wall P to the door;

α_P = wall reflection coefficient at wall P;

A_P = field size area projected to wall P, in m^2.

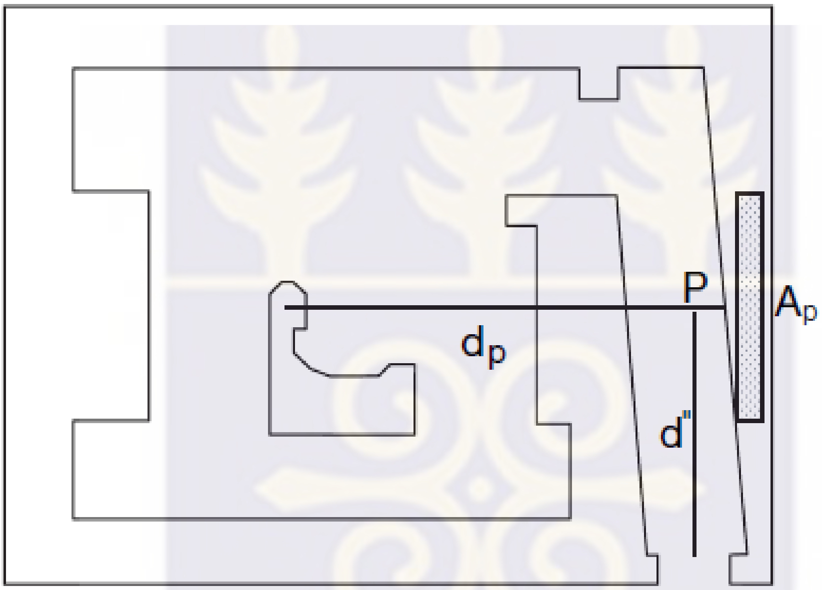

Figure 2.4: Schematic diagram showing the scatter path for the primary radiation beam to the maze entrance (gantry rotation axis parallel to the maze axis).

2.5.3. Dose arising from head leakage scatter to the maze entrance D_L

In figure 2.5, the radiation dose D_L at the maze entrance from the scattered head leakage is given by:

$$D_L = \frac{L_0\, W\, \alpha_1\, A_1}{(d_i\, d_m)^2} \qquad (2.9)$$

Where

L_0 is assumed to be 10^{-3}, which is approximately 0.1% of the useful beam;

W = workload, in Gy/week;

α_1 = wall reflection coefficient;

A_1 = area of wall that can be seen from the maze entrance;

d_i = distance from the target to where the centerline at the surface A_1;

d_m = distance from centerline at A_1 to the maze door.

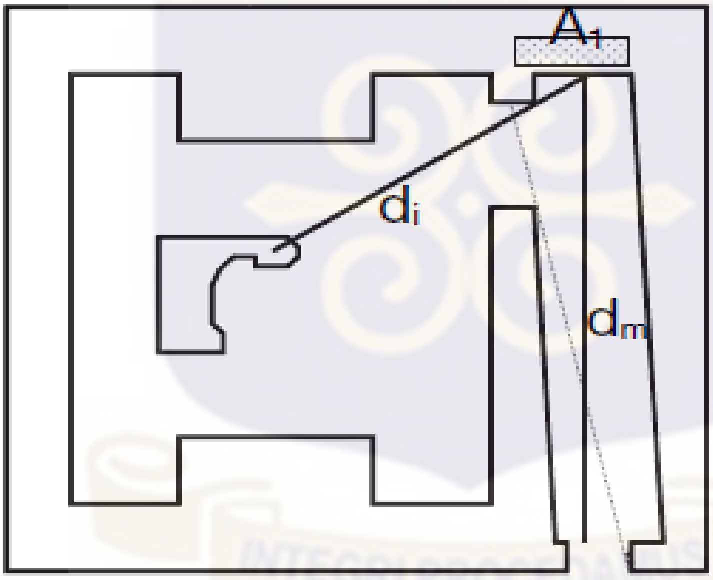

Figure 2.5: Schematic diagram showing path of scattered head leakage to the maze entrance.

2.5.4. Head leakage transmission to the maze entrance *D_T*

In Fig. 2.6, the radiation dose at the maze door from head leakage transmitted through the maze wall is given by equation 2.10:

$$D_T = \frac{L_0\, W\, B}{(d_t)^2} \qquad (2.10)$$

Where

d_t = distance from the target to the maze door;

B = transmission factor.

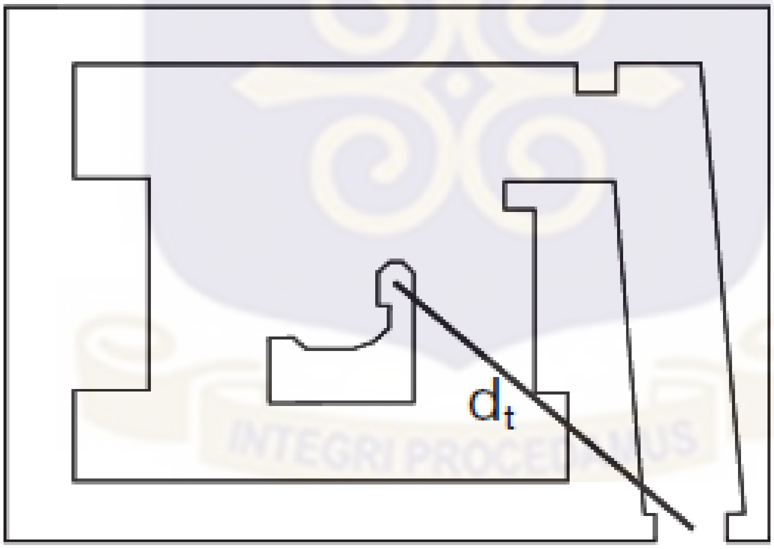

Figure 2.6: Schematic diagram showing the path of head leakage radiation transmitted through the maze wall to maze entrance.

The total dose at the maze door is the product of 2.64 and the sum of the doses calculated above.

$$D_{Tot} = 2.64\left(D_{pH} + f \times \ D_{wH} + D_{LH} + D_{TH} \right) \qquad (2.11)$$

Where *f is* the transmission of radiation scattered by the patient [4].

2.6. DOORS

After calculating the dose at the end of the maze the necessity of a door for radiation safety purposes can be ascertained. This will depend on the design dose limit from the regulatory authority. Division of the design goal limit by the calculated value of dose at the maze entrance will give the attenuation required in a door. To define the required TVL of lead are data tabulated in [4]. If there is no need for a door of protection it is still suggested to have a physical barrier at the end of the maze to dishearten entry.

2.7. NEUTRONS IN HIGH ENERGY LINEAR ACCELERATOR ROOMS

The production of neutrons is important only when high energy medical linear accelerator (LINACs) is used, this is above 10 MV. The production of photo-neutrons occurs when photons or electron beams interact with collimators, target, and other material during the treatment. The materials with high atomic number (*Z*) such us lead and tungsten are effective for photons shielding, but not effective for neutrons shielding. The total neutron fluence at the inner maze entrance is [4]:

$$\varphi_A = \frac{\beta\, Q_n}{4\pi d_1^2} + \frac{5.4\, \beta\, Q_n}{2\pi S_r} + \frac{1.3\, Q_n}{2\pi S_r} \qquad (2.12)$$

β = transmission factor for neutrons penetrating the head shielding (1 for lead and 0.85 for tungsten)

d_1 = distance from the isocenter to location A in figure 3.4 (meters)

Q_n = neutron source strength at the isocenter

S_r = treatment room area (m^2)

And 1/ (2π) in the scattered and thermal neutron terms account for the fraction of the neutron that enter the maze.

Usually materials that have high hydrogen content are generally good and efficient for attenuation of fast neutrons. Concrete is one of the materials that have relatively high hydrogen content (water content is 4–5% by weight) and the TVL of 0.34 MeV photo-neutrons in concrete is about half of the value of TVL in concrete for high energy X-rays (10–25 MeV) [3]. Therefore, the shielding for photons is more than adequate to shield against neutrons. If lead or iron is used in part of the shielding design, there will be a need for a moderator material to capture and slowed down the neutrons in the metal. Evaluation for neutron shielding must be performed carefully for safety of the staff and the public.

2.8. CAPTURE GAMMA AND NEUTRON DOSES AT THE MAZE ENTRANCE

A typical maze design is used for a linear accelerator treatment room to reduce the dose at the door entrance so that heavy shielding for the door is not necessary. This type of design is very important when the energy of the accelerators is higher, that is above 10 MV because of scatter neutrons and the capture gamma photons generated by neutrons interacting with the maze door and the maze wall [4].

CHAPTER THREE

MATERIALS AND METHOD

This chapter outlines the materials and methods used to conduct the research work on the structural shielding and design evaluation of the linear accelerator used for treatment of cancer at the Nouakchott Oncology Center, Mauritania.

3.1. MATERIALS

3.1.1. Description of LINAC facility and irradiation conditions

A Varian CLINAC DHX dual energy linear accelerator is used for the treatment of the patients at the Nouakchott Oncology Center, Mauritania. It produces two energies 6 and 18 MV X-ray beams and also able to produce different electron beams 6 MeV, 9 MeV, 12 MeV, 15 MeV, and 18 MeV energies for treatment purposes.

Figure 3.1.Shows the room layout of the LINAC at Nouakchott Oncology Center.

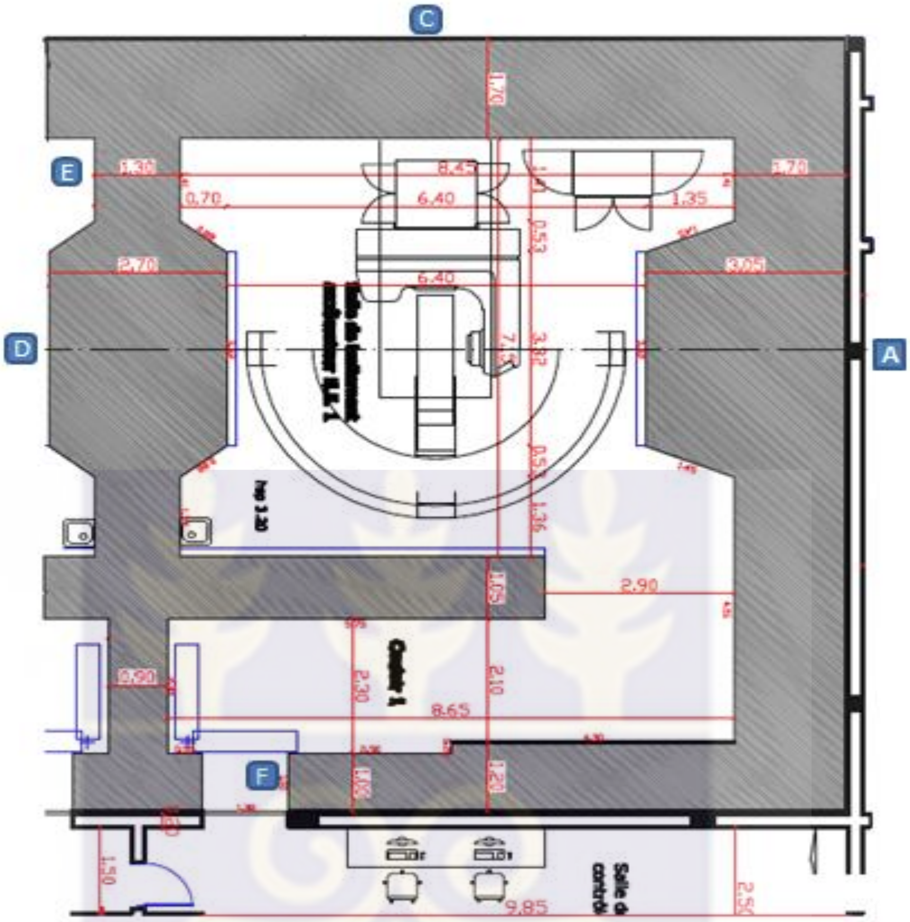

Figure 3.1: Room layout of the LINAC at Nouakchott Oncology Center

Locations A, B, C, D, E and F are where shielding evaluation calculations, dose rate measurements and calculations were done.

3.1.2. Description of Survey meter

The survey meter used is Thermo Scientific FH40G-L10 available at the Nuclear Regulatory Authority with following specifications:

- Ambient equivalent dose rate Range 10 nSv/h to 100mSv/h
- Energy Range : 30keV to 4.4 Mev

- capable of measuring Ambient equivalent $H^*(10)$

The Thermo Scientific FH 40 G is an appropriate digital gamma survey meter with wide range for all measurement tasks concerning ionizing radiation. It is shown in Figure 3.2

Figure 3.2: FH 40 G Multi-Purpose Digital Survey Meter

3.2. METHODS

3.2.1. WORKLOAD ESTIMATION

The workload of the facility was estimated by collecting the following data

- Use and occupancy factors for all locations (controlled or uncontrolled) around the treatment room

- Number of patients treated per week at the specified low (6MV) and high (18MV) beam energy and the averaged dose per patient within the same week.

3.2.2. DATA COLLECTIONS

Data for the number of patients treated per day and the given doses for each patient were collected for 8 months in 2016. The workload for high and low energy for each week of the month and maximum workload for each month has been considered for a conservative safe design. The average of the eight months workloads was also determined.

The workload (W) was calculated by using the equation:

$$\mathrm{W(Energy)} = \frac{\text{absorbed dose}}{\text{patient}} \,\mathrm{x}\, \frac{\text{number of patients}}{\text{week}} \;\; \mathrm{Gy/Week} \qquad (3.1).$$

3.2.3. STRUCTURAL SHIELDING EVALUATION

National Council on Radiation Protection and Measurements (NCRP) Report No.151 [3] provides recommendations on methods for the evaluation of structural shielding adequacy for a LINAC. This review covers methods for the evaluation of structural shielding adequacy against (i) primary radiation (ii) secondary radiation and (iii) neutrons

3.2.3.1. Primary barriers shielding evaluation

Primary barriers are designed to reduce the photon beam arising from the treatment facility. It is also expected to sufficiently reduce the dose equivalent outside the barrier that results from secondary products of the photon beam.

The transmission factor for the primary barrier, B_{pri} is given by equation 3.2:

$$B_{pri} = \frac{P\, d_{pri}^2}{W\ U\ T} \qquad (3.2)$$

Where

P = shielding design goal beyond the barrier and the unit is (Sv/week)

$\mathbf{d_{pri}}$ =distance from x-ray target to a point outside the barrier (in meters), the point is located at least 30 cm from the surface of the outside of the barrier

W = workload of the facility at 1 m from the x-ray source (Gy/week)

U = use factor

T = occupancy factor

Re-arranging any of the barrier transmission equations, one gets the dose equivalent beyond the barrier.

$$H_{pri} = \frac{W\ U\ T\ B_{pri}}{d^2} \qquad (3.3)$$

The thickness of the barrier can be calculated using equation 3.4 and 3.5 [3]:

$$t = TVL_1 + (n-1)TVL_e \ \ldots.. \quad (3.4) \qquad \text{with} \qquad \mathrm{n} = \log_{10}(\frac{1}{\mathrm{B}}) \ \ldots \quad (3.5)$$

Where t is the barrier thickness; TVL_1 is the first equilibrium tenth-value layer; TVL_e is the equilibrium tenth-value layer; n is the number of TVLs required for the shield; and B is the attenuation factor of the barrier that needed to decrease the radiation emanating from the source to an acceptable level.

Assuming that $t > TVL_1$, the total transmission factor (B) is given by equation 3.6:

$$B = 0.1 \times 10^{\left[-\frac{t - TVL_1}{TVL_e}\right]} \qquad (3.6)$$

3.2.2.2. Secondary barriers shielding evaluation

Sources of secondary radiation include: (1) leakage radiation from the head, (2) scattered radiation from the patient, (3) scattered radiation from the walls; and (4) secondary radiation (photo-neutrons and neutron capture gamma rays).

Secondary barriers have to be designed adequately against individual's exposition beyond the room of treatment to secondary radiation.

The transmission factor required for the patient scattered radiation (Bps) is given by the equation 3.7:

$$B_{ps} = \frac{P\, d_{sca}^2\, d_{sec}^2}{a\, W\, U_{ps}\, T(F/400)} \qquad (3.7)$$

Where;

$\boldsymbol{d_{sca}}$ is the distance from the source to the patient (m);

d_{sec} is the distance from the patient to the point protected (m);

a is the scatter coefficient;

U_{ps} is the use factor for patient scattered radiation;

F is the field size at mind-depth of the patient at 1 m (cm^2); and the factor 400 means the scatter fractions are normalized to those measured for a field size of 20 $cm \times 20$ cm (Figure 3.3)

The transmission factor for leakage radiation alone (B_L) is given by the equation 3.8:

$$B_L = \frac{P\, d_L^2}{10^{-3} W_L\, T} \tag{3.8}$$

Where:

d_L is the distance from the source to the point protected (m);

W_L is the workload for leakage radiation at 1 m (Gy/week); and the factor 10^{-3} appear from the assumption that leakage radiation is about 0.1 % of the useful beam.

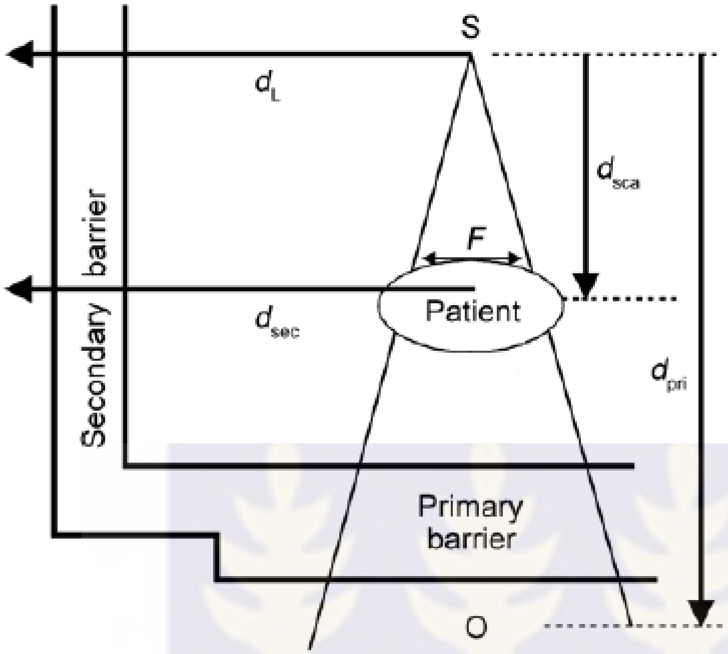

Figure 3.3: Room layout showing distance associated with patient-scattered (dsca, dsec) and leakage radiation (d_L).

The evaluation of shielding design will be to compare the calculated thicknesses of primary and secondary barrier with the existing thicknesses shown in the fig. 3.1 and see whether there is a need for additional shielding or not.

3.2.4. NEUTRON AND CAPTURE GAMMA DOSES EQUIVALENTS CALCULATIONS

3.2.4.1. High-Energy Accelerators

The weekly dose equivalent at the entrance due to neutron captures gamma rays:

$$H_{cg} = W_L \left\{ K \, \varphi_A 10^{-\left(\frac{d_2}{TVD}\right)} \right\} \qquad [3] \qquad (3.9)$$

K= dose equivalent ratio of the neutron capture gamma-ray to the total neutron fluence at location A in figure 3.4 (approximately 6.9 × 10^{-16}Sv m^2 per unit neutron fluence) this value was based on 22 accelerators facilities measurements.

$\boldsymbol{\varphi_A}$= total neutron fluence (m^{-2}) at location A per unit absorbed dose (gray) of X-rays at the isocenter (chapter two gives more information about it)

$\mathbf{d_2}$ = distance from point A to the entrance (meters)

TVD = tenth-value distance having approximate value of ~5.4 m for the X-ray beam in between18 to 25 MV, and approximate value of ~3.9 m for 15 MV x-ray beams

The weekly dose equivalent at the entrance due to neutrons [3]:

$$H_n = W_L \left\{ 2.4 \times 10^{-15} \varphi_A \sqrt{\frac{S_0}{S_1}} \left[1.64 \times 10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)} \right] \right\} \qquad (3.10)$$

$\mathbf{H_n}$ = dose equivalent for neutrons at the maze entrance in (Sv /gray) at the isocenter

$\mathbf{S_0/S_1}$ = ratio of the cross-sectional area of the inner maze to the cross sectional area along the maze (fig 3.4)

TVD = tenth-value distance (meters),$TVD = 2.06\sqrt{S1}$ and W_L is the weekly leakage-radiation workload

The weekly dose equivalent at the external maze entrance (H_w):

$$H_w = H_{tot} + H_{cg} + H_n \qquad (3.11)$$

$\boldsymbol{H_{tot}}$ is the weekly dose equivalent at maze entrance due to scatter and leakage radiation from low energy linear accelerator.

For most mazes, where energies above 10 MV are used, $\boldsymbol{H_{tot}}$ is an order of magnitude smaller than the sum of $\boldsymbol{H_{cg}}$ and $\boldsymbol{H_n}$, and is therefore negligible [3].

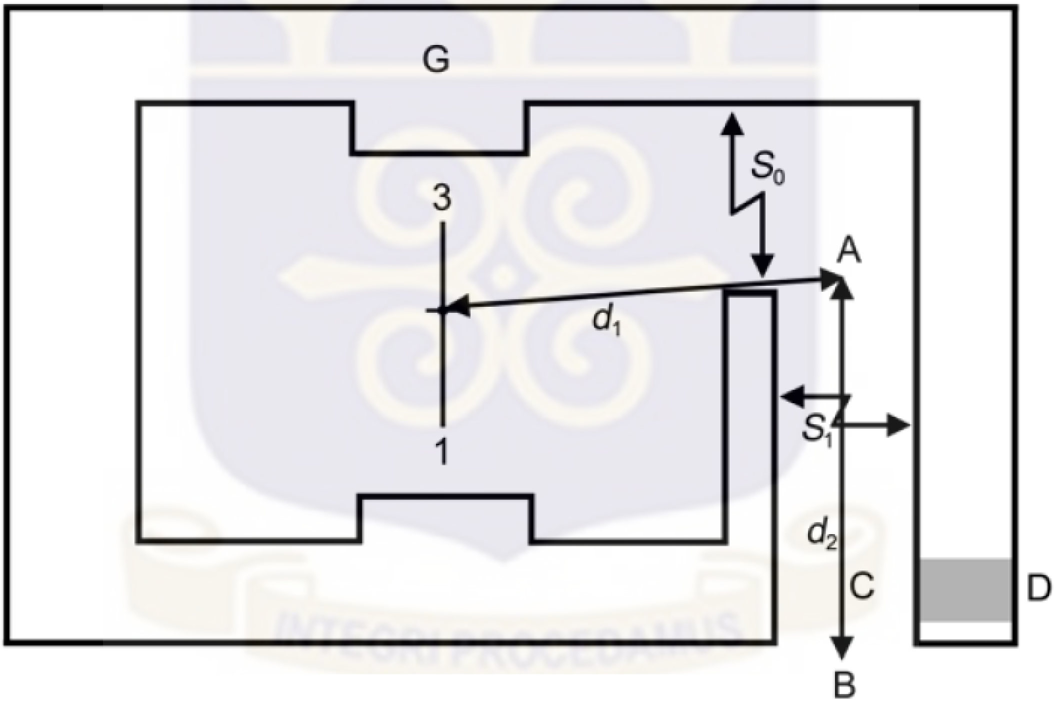

Figure 3.4: Room layout for calculating neutron capture gamma-ray and neutron dose equivalents at the maze door.

3.2.4.2. Low-Energy Accelerators

A maze such us the one shown in Fig. 3.5 is commonly used to moderate the radiation level at the accelerator room entrance, thus high shielding of the door is not required.

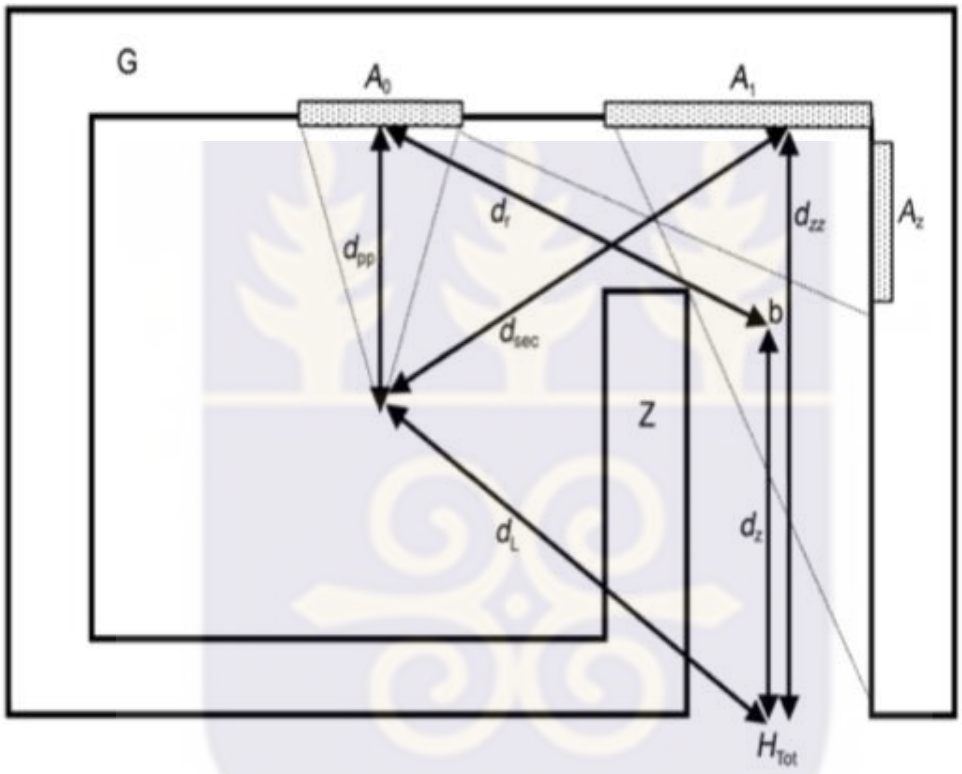

Figure 3.5:.General room layouts for definition of parameters used in maze door shielding.

The dose equivalent at the maze entrance is evaluated first when the beam is perpendicular to the wall G of Figure 3.5. The radiation reaching the maze entrance is due to scatter of radiation from the room surfaces and from the patient and also from the head-leakage through the maze barrier Z [4].

These components are given as follows:

H_S = weekly dose equivalent due to scatter of the primary beam from the surface of the room

H_{LS} = weekly dose equivalent from head-leakage photons scattered by the surface of the room

H_{PS} = weekly dose equivalent from the primary beam when it scattered by the patient

H_{LT} = weekly dose equivalent from leakage radiation transmitted through the maze wall Z.

Wall-scattered radiation component, H_S:

$$H_S = \frac{W\, U_G\, \alpha_0 A_0\, \alpha_Z A_Z}{(d_h d_r d_z)^2} \tag{3.12}$$

H_S = weekly dose equivalent from the scatter of the primary beam by the wall G

W = workload (Gy week^{-1})

U_G = wall G use factor

α_0 = reflection coefficient at the surface A_0

A_0 = beam area (m^2)

α_Z = reflection coefficient for second reflection at the surface A_z (an energy of 0.5 MeV is usually assumed)

A_Z = cross-sectional area

d_h = distance from the target to the surface A_0 (d_{pp} + 1 m) supposed to be perpendicular

d_r = distance from surface A_0 to a point b on the mid-line of the maze (meters)

d_Z = distance from point b to the entrance (m).

Head-leakage wall-scattered radiation component, **H_{LS}**:

$$H_{LS} = \frac{L_f W_L U_G \, \alpha_1 A_1}{(d_{sec} d_{zz})^2} \tag{3.13}$$

H_{LS} = weekly dose equivalent at the entrance due to scattered radiation from the head-leakage

L_f = head leakage radiation ratio 1/1000 or 0.1%

W_L = workload (Gy week^{-1})

U_G = use factor

α_1 = head leakage reflection coefficient from the first scattering

A_1 = wall G area that can be seen from the entrance (m^2)

d_{sec} = distance from the target to the maze

d_{zz} = distance from surface A_1 to the maze entrance (m)

Patient-scattered radiation component, H_{PS}:

$$H_{PS} = \frac{a(\theta)\, W\, U_G \left(\frac{F}{400}\right) \alpha_1 A_1}{(d_{sca} d_{sec} d_{zz})^2} \tag{3.14}$$

H_{PS} = weekly dose equivalent at the maze entrance from the scattered radiation by the patient

$a(\theta)$ = scatter fraction for radiation that scattered by the patient at angle θ (table B4 appendix B)

W = workload of primary beam (Gy week^{-1})

U_G = use factor, F = field size (cm^2)

α_1 = reflection coefficient

A_1 = area that can be seen from the door (m^2)

d_{sca} = distance from the target to the patient (m)

d_{sec} = distance from the patient to the surface A_1 at the maze centerline (m)

d_{zz} = distance from surface A_1 to the maze entrance (m).

Head-leakage radiation through Maze Wall component, H_{LT}:

$$H_{LT} = \frac{L_f W_L U_G\, B}{(d_L)^2} \qquad (3.15)$$

H_{LT} = weekly dose equivalent at the door from leakage radiation that transmitted through the maze wall Z.

L_f = head leakage radiation ratio 1/1000 or 0.1%

W_L =leakage radiation workload (Gy $week^{-1}$)

U_G = use factor

B = wall Z transmission factor

d_L= distance from the target to the center of the maze entrance (m).

After calculating each of the individual components, the total dose equivalent (H_{tot}) at the maze entrance is as follow [10]:

$$H_{tot} = 2.6$$

$$4\ (f\ H_S + H_{LS} + H_{PS} + H_{LT}) \qquad (3.16)$$

Where f is the transmission factor of radiation scattered by the patient [4].

CHAPTER FOUR

RESULTS AND DISCUSSIONS

Included in this chapter are basically the results of the work done and discussions related to these results. Operational workloads were estimated and used for thicknesses calculations of the primary and secondary barriers. An account is given of the calculations of doses equivalents from scatter and leakage radiation, neutron capture gamma and neutrons at the maze door entrance.

4.1. Workloads Estimation

The average workload over eight months and the summary workload data are presented in Table 4.1.

Table 4.1: Estimation of Workloads

Energy	**W (Gy /Week)**							
	March	**April**	**May**	**June**	**July**	**August**	**September**	**October**
W (6 MV)	194	166	190	190	184	152	190	194
W (18 MV)	164	222	156	166	168	146	150	114

The average weekly load estimated for the 6MV photon beam, W (6 MV) = 183 Gy/week corresponding to 19 patients per day averagely

The average weekly load estimated for the 18MV photon beam, W (18MV) = 161 Gy/week corresponding to 16 patients per day averagely

4.2. Location A

4.2.1. Primary Barrier Thickness at Location A

To determine the thickness of the barrier at location A, corridor, the equation (3.2) was used:

Table 4.2: Primary barrier thickness calculations at location A

Parameters	**Values**	**Comments**
P	20×10^{-6} Sv week^{-1}	Design goal
d_A	6.55 m	Distance to location A
W (18MV) W (6MV)	161 Gy week^{-1} 183 Gy week^{-1}	Workloads high and low energy
U T	0.25 0.2	Use factor Occupancy factor
TVL_1 TVL_e	45 cm 43 cm	First and equilibrium tenth value layers (appendix B.1)
B_{pri}	1.41×10^{-4}	Transmission factor
$n = \log_{10}\left(\frac{1}{B}\right)$	3.85	Required TVLs
$t = TVL_1 + (n-1)TVL_e$	168 cm	Thickness of the primary barrier

To check whether this barrier thickness is adequate for the additional workload from 6 MV X rays

H (6 MV) = B_{pri} W U T $(1 + d_A)^{-2}$	1.3 $\mu Sv\ week^{-1}$	dose equivalent per week at location A

This 6 MV dose equivalent per week of 1.3 μSv is only about 6.5 % of shielding design goal and would not affect the primary barrier thickness. It must now be determined if the maximum dose equivalent in-any-one-hour limit is satisfied.

4.2.2 Time Average Dose Equivalent Rate Considerations at Location A

Table 4.3: Time average dose equivalent rate consideration for location A

Parameters	Values	Comments
$\dot{D}_0$	12 Gy $\min^{-1}$ or 720 Gy h^{-1}	maximum absorbed-dose output rate at the isocenter (1m from the source)
IDR (18 MV)	1.78×10^{-3} Sv h^{-1}	Instantaneous dose rate for 18 MV
R_{w} (18 MV)	99.6×10^{-6} Sv $week^{-1}$	the weekly TADR at location A from 18 MV
IDR (6 MV)	1.02×10^{-4} Sv h^{-1}	Instantaneous dose rate for 6 MV
R_w (6 MV)	6.51×10^{-6} Sv $week^{-1}$	the weekly TADR at location A from 6 MV

A reasonable estimate is that no more than 10 patients can be treated in an hour. Since the average number of patients treated per hour is 4.4 (35 patients d^{-1} / 8 h d^{-1}), the value of M needed to calculate R_h is 10/4.4 = 2.27.

$R_h = (M / 40)\, R_w$ (total)	6.02 μSv	Well under the 20 μSv TADR limit.

4.2.3 Patient-Scattered Radiation Considerations at Location A

Table 4.4: Patient-scattered radiation consideration at location A

Parameters	Values	Comments
$t_{pri}(A)$	168 cm	-Primary barrier thickness
d_{sca} d_{sec}	1 m 6.55 m	-From target to the patient -From isocenter to location A
a (18 MV)	1.42×10^{-2}	-Scatter through 10 degrees at 2.5 cm depth (Table B.2, Appendix B) [3].
a (6MV)	1.04×10^{-2}	-Scatter through 10 degrees at 2.5 cm depth (Table B.2, Appendix B) [3].

W (18 MV) = 161 Gy week^{-1}, W (6MV) = 183 Gy week^{-1}, T= 1/5 = 0.2, U = 0.25, F = (40 × 40) cm^2 (the maximum field size is used to be conservatively safe)

Parameters	Values	Comments
TVL_{sca} (6 MV)	35 cm	-At 10 degrees approximately, Table B.3, Appendix B [3].
TVL_{sca} (18 MV)	45 cm	

The maximum transmitted patient-scattered dose equivalent at location A from both energies:

Parameters	Values	Comments
B_{sca} (6 MV) = $10^{-t/TVL}$	1.58×10^{-5}	-Transmission factor
$H_{sca}(6\ MV)$	0.14 µSv week^{-1}	-Patient-scattered dose equivalent
B_{sca} (18 MV) = $10^{-t/TVL}$	1.84×10^{-4}	-Transmission factor
$H_{sca}(18\ MV)$	2.04 µSv week^{-1}	-Patient-scattered dose equivalent

4.2.4. Leakage Radiation Consideration at Location A

To determine the thickness of the barrier required for shielding against leakage radiation at A, equation $B_L = \frac{P\, d_L^2}{10^{-3}\, W_L\, T}$ was used.

Table 4.5: Leakage radiation consideration at location A

Parameters	**Values**	**Comments**
$t_{pri}(A)$	168 cm	Primary barrier thickness
d_L	6.55 m	From the source to location A

W (18 MV) = 161 Gy week^{-1}, W (6MV) = 183 Gy week^{-1}, T= 1/5 = 0.2

TVL_1 (18 MV)	36 cm	Approximate values from Appendix B Table B.4 [3].
TVL_e (18 MV)	34 cm	
$H_L(6\ MV)$	2.04 × 10^{-3} µSv week^{-1}	Neither of these dose equivalents is significant compared to the shielding design goal.
$H_L(18\ MV)$	9.84 × 10^{-3} µSv week^{-1}	

Therefore, the shielding requirement for leakage radiation is adequate by the primary barrier thickness.

4.3. Location B

4.3.1. Leakage and patient-Scattered-Radiation Considerations for Location B

Leakage and patient-scattered radiations are the only radiation considered here, since this is secondary barrier and thus there is no primary radiation directed toward location B. Location B is 30 degrees of the beam centerline and, as a conservatively safe assumption, the minimum scatter angle of 30 degrees is used from Table B.2, Appendix B [3].

Table 4.6: Secondary barrier thickness calculations for location B

Parameters	**Values**	**Comments**
P	20×10^{-6} Sv week^{-1}	Design goal
d_{sca}	1 m	From source to the patient Distance
d_{sec}	7.35 m	from patient to location B
W (18MV)	161 Gy week^{-1}	Workloads high and low energy
W (6MV)	183 Gy week^{-1}	
a (18 MV)	2.53×10^{-3}	Table B.2, Appendix B, for 6 and 18 MV at 30 degrees and 2.5 cm depth [3].
a (6 MV)	2.77×10^{-3}	
T	0.2	Occupancy factor
F	(40×40) cm^2	maximum field size to be conservatively safe
TVL_{sca} (6 MV)	26 cm	30 degrees scatter, Table B.3, Appendix B [3].
TVL_{sca} (18 MV)	32 cm	

Table 4.6: Secondary barrier thickness calculations for location B Continued…

Parameters	**Values**	**Comments**
d_L	7.35 m	Distance from source to point B
TVL_1 (18 MV)	36 cm	First and equilibrium value layers for leakage radiations
TVL_e (18 MV)	34 cm	
TVL_1 (6 MV)	34cm	First and equilibrium value layers for leakage radiations
TVL_e (6 MV)	29 cm	

For calculation of necessary thickness of the barrier for patient-scattered radiation, equation (3.7) is used and U = 0.25 and a (30 degrees).

Parameters	**Values**	**Comments**
B_{ps}(18 MV)	1.33×10^{-2}	18 MV Patient transmission factor
N	1.88	Required TVLs
$t_{s,sca}$ (18 MV)	≈ 61 cm	required barrier slant thickness
B_{ps}(6 MV)	1.06×10^{-2}	6 MV Patient transmission factor
$t_{s,sca}$ (6 MV)	≈ 52 cm	required barrier slant thickness

Combination of these two barrier requirements lead to adding 1 HVL (a conservatively safe value for 18 MV) to the larger of the two values. Thus:

Parameters	**Values**	**Comments**
$t_{s,sca}$(total)	≈ 71 cm	Thickness for patient scattered radiation

For leakage radiation at 18 MV, using leakage equation (3.8)

Table 4.6: Secondary barrier thickness calculations for location B Continued…

Parameters	**Values**	**Comments**
B_L (18 MV)	3.38×10^{-2}	Leakage transmission factor
$t_{s,L}$ (18 MV)	≈ 52 cm	Thickness for leakage radiation
B_L (6 MV)	2.95×10^{-2}	Leakage transmission factor
$t_{s,L}$(6 MV)	≈ 52 cm	Thickness for leakage radiation

Combining the requirement for leakage radiation from both energy components gives:

$t_{s,L}$ (total)	≈ 63 cm	Thickness for leakage radiation from both energy

Finally, the scatter and leakage radiation barrier requirements (71 cm and 63 cm, respectively) are comparable and thus the total barrier slant thickness is given by the higher value plus one thickness of the highest HVL:

$t_{s,Tot}$	≈ 82 cm	Slant thickness of the secondary barrier

4.3.2 Time Average Dose Equivalent Rate (in-any-one-hour) Considerations for Location B

Table 4.7: Time average dose equivalent rate consideration for location B

Parameters	Values	Comments
$\dot{D}_0$	12 Gy min^{-1} or 720 Gy h^{-1}	Maximum absorbed-dose output rate at the isocenter (1m from the source)
IDR_{ps} $(18\ MV)$	3.2×10^{-4} Sv h^{-1}	Instantaneous dose rate (patient)
IDR_L $(18\ MV)$	5.16×10^{-5} Sv h^{-1}	Instantaneous dose rate (leakage)
IDR (18 MV)	3.72×10^{-4} Sv h^{-1}	Instantaneous dose rate for 18 MV
IDR_{ps} $(6\ MV)$	8.7×10^{-5} Sv h^{-1}	Instantaneous dose rate (patient)
IDR_L $(6\ MV)$	2.52×10^{-5} Sv h^{-1}	Instantaneous dose rate (leakage)
R_w (18 MV)	8.32×10^{-5} Sv week^{-1}	The weekly TADR at location B from 18 MV (equation 2.2)
R_w (6 MV)	2.85×10^{-5} Sv week^{-1}	the weekly TADR at location B from 6 MV (equation 2.2)

The total TADR in-any-one-hour, using M = 2.27

$R_h = (M / 40)\ R_w$ (total)	6.34 µSv	Well under the 20 µSv TADR limit.

Therefore, the maximum dose equivalent in-any-one-hour of 6.34 µSv is below the TADR limit of 20 µSv in-any-one-hour

4.4 Location D

4.4.1 Primary Barrier at Location D

To determine the thickness of the barrier at location D, second LINAC room, the equation (3.2) was used.

Table 4.8: Primary barrier thickness calculations at location D

Parameters	**Values**	**Comments**
P	100×10^{-6} Sv week^{-1}	Design goal
d_D	6.2 m	Distance to location D
W (18MV) W (6MV)	161 Gy week^{-1} 183 Gy week^{-1}	Workloads high and low energy
U T	0.25 0.5	Use factor Use and Occupancy factors
TVL_1 (18 MV) TVL_e (18 MV)	45 cm 43 cm	First and equilibrium tenth value layers (Appendix B.1)
TVL_1 (6 MV) TVL_e (6 MV)	37 cm 33 cm	First and equilibrium tenth value layers (Appendix B.1) [3].
B_{pri}	2.58×10^{-4}	Transmission factor
n= $\log_{10}\left(\frac{1}{B}\right)$	3.6	Required TVLs
$t = TVL_1 + (n-1)TVL_e$	157 cm	Thickness of the primary barrier

To determine whether this barrier thickness is adequate for the additional workload from 6 MV X rays, the following are used:

H (6 MV) = B_{pri} W U T $(1 + d_A)^{-2}$	10.19 $\mu Sv\ week$	dose equivalent per week at D

This 6 MV dose equivalent per week of 10.19 µSv is about 10 % of shielding design goal value and would not affect the primary barrier thickness effectiveness.

It must now be determined if the maximum dose equivalent in-any-one-hour limit is satisfied.

4.4.2 Time Average Dose Equivalent Rate Considerations at Location D

Table 4.9: Time average dose equivalent rate consideration for location D

Parameters	**Values**	**Comments**
$\dot{D}_0$	12 Gy min^{-1} or 720 Gy h^{-1}	maximum absorbed-dose output rate at the isocenter (1m from the source)
IDR (18 MV)	3.6×10^{-3} Sv h^{-1}	Instantaneous dose rate for 18 MV
R_w (18 MV)	200×10^{-6} Sv week^{-1}	the weekly TADR at location D from 18 MV
IDR (6 MV)	3.2×10^{-4} Sv h^{-1}	Instantaneous dose rate for 6 MV
R_w (6 MV)	20.33×10^{-6} Sv week^{-1}	the weekly TADR at location D from 6 MV

The total TADR in-any-one-hour, using M = 2.27

$R_h = (M / 40)\, R_w$ (total)	12.5 µSv	Well under the 20 µSv TADR limit.

4.5. Location E

4.5.1. Leakage and patient-Scattered-Radiation Considerations for Location E

Table 4.10: Secondary barrier thickness calculations for location E

Parameters	Values	Comments
P	100×10^{-6} Sv week^{-1}	Design goal
d_{sca} d_{sec}	1 m 6.4 m	From source to the patient Distance from patient to location E
W (18MV) W (6MV)	161 Gy week^{-1} 183 Gy week^{-1}	Workloads high and low energy
a (18 MV) a (6 MV)	2.53×10^{-3} 2.77×10^{-3}	Table B.2, Appendix B, for 6 and 18 MV at 30 degrees and 2.5 cm depth [3].
T F	0.5 (40×40) cm^2	Occupancy factor maximum field size to be conservatively safe
TVL_{sca} (6 MV)	26 cm	30 degrees scatter, Table B.3, Appendix B [3].
TVL_{sca} (18 MV)	32 cm	
d_L	6.4 m	Distance from source to point E
TVL_1 (18 MV)	36 cm	First and equilibrium value layers for leakage radiations
TVL_e (18 MV)	34 cm	
TVL_1 (6 MV)	34cm	First and equilibrium value layers for leakage radiations
TVL_e (6 MV)	29 cm	

For calculation of necessary thickness of the barrier for patient-scattered radiation, equation (3.7) is used and U = 0.25 and a (30 degrees).

B_{ps}(18 MV)	2.01×10^{-2}	18 MV Patient transmission factor
N	1.7	Required TVLs
$t_{s,sca}$ (18 MV)	≈ 55 cm	required barrier slant thickness
B_{ps}(6 MV)	1.62×10^{-2}	6 MV Patient transmission factor
$t_{s,sca}$ (6 MV)	≈ 47 cm	required barrier slant thickness

Combination of these two barrier requirements lead to adding 1 HVL (a conservatively safe value for 18 MV) to the larger of the two values. Thus:

$t_{s,sca}$ (total)	≈ 65 cm	Thickness for patient scattered radiation

For leakage radiation at 18 MV, using leakage equation (3.8)

B_L (18 MV)	5.01×10^{-2}	Leakage transmission factor
$t_{s,L}$ (18 MV)	≈ 46 cm	Thickness for leakage radiation
B_L (6 MV)	4.48×10^{-2}	Leakage transmission factor
$t_{s,L}$ (6 MV)	≈ 46 cm	Thickness for leakage radiation

Combining the requirement for leakage radiation from both energy components gives:

$t_{s,L}$(total)	≈ 57 cm	Thickness for leakage radiation from both energy

Finally, the scatter and leakage radiation barrier requirements (65 cm and 57 cm, respectively) are comparable and thus the total barrier slant thickness is given by the higher value plus one thickness of the highest HVL:

$t_{s,Tot}$	≈ 76 cm	Slant thickness of the secondary barrier

4.5.2. Time Average Dose Equivalent Rate (in-any-one-hour) Considerations for Location E

Table 4.11: Time average dose equivalent rate consideration for location E

Parameters	Values	Comments
$\dot{D}_0$	12 Gy min^{-1} or 720 Gy h^{-1}	maximum absorbed-dose output rate at the isocenter (1m from the source)
IDR_{ps} (18 MV)	7.5 × 10^{-4} Sv h^{-1}	Instantaneous dose rate (patient)
IDR_L (18 MV)	1.17 × 10^{-4} Sv h^{-1}	Instantaneous dose rate (leakage)
IDR (18 MV)	8.67 × 10^{-4} Sv h^{-1}	Instantaneous dose rate for 18 MV
IDR_{ps} (6 MV)	2.33 × 10^{-4} Sv h^{-1}	Instantaneous dose rate (patient)
IDR_L (6 MV)	0.63 × 10^{-4} Sv h^{-1}	Instantaneous dose rate (leakage)
IDR (6 MV)	2.96 × 10^{-4} Sv h^{-1}	Instantaneous dose rate for 6 MV
R_w (18 MV)	1.94 × 10^{-4} Sv week^{-1}	the weekly TADR at location E from 18 MV (equation 2.2)
R_w (6 MV)	5.92 × 10^{-5} Sv week^{-1}	the weekly TADR at location E from 6 MV (equation 2.2)

The total TADR in-any-one-hour, using M = 2.27

$R_h = (M / 40)\, R_w$ (total)	14.36 μSv	Well under the 20 μSv TADR limit.

Therefore, the maximum dose equivalent in-any-one-hour of 14.36 μSv is below the TADR limit of 20 μSv in-any-one-hour

4.6. Location C

4.6.1. Leakage and patient-Scattered-Radiation Considerations for Location C

Table 4.12: Secondary barrier thickness calculations for location C

Parameters	**Values**	**Comments**
P	20×10^{-6} Sv week^{-1}	Design goal
d_{sca} d_{sec}	1 m 5.58 m	From source to the patient Distance from patient to location C
W (18MV) W (6MV)	161 Gy week^{-1} 183 Gy week^{-1}	Workloads high and low energy
a (18 MV) a (6 MV)	1.89×10^{-4} 4.26×10^{-4}	Table B.2, Appendix B, for 6 and 18 MV at 90 degrees and 2.5 cm depth [3].
T F	0.05 (40 × 40) cm^2	Occupancy factor maximum field size to be conservatively safe
TVL_{sca} (6 MV)	17 cm	90 degrees scatter, Table B.3, Appendix B [3].
TVL_{sca} (18 MV)	19 cm	
d_L	5.75 m	Distance from source to point C
TVL_1 (18 MV)	36 cm	First and equilibrium value layers for leakage radiations
TVL_e (18 MV)	34 cm	
TVL_1 (6 MV)	34cm	First and equilibrium value layers for leakage radiations
TVL_e (6 MV)	29 cm	

For calculation of necessary thickness of the barrier for patient-scattered radiation, equation (3.7) was used and U = 1 and a (90 degrees).

Table 4.12: Secondary barrier thickness calculations for location C **(Continued…)**

Parameters	Values	Comments
B_{ps}(18 MV)	1.02×10^{-1}	18 MV Patient transmission factor
N	0.99	Required TVLs
$t_{s,sca}$ (18 MV)	≈ 32 cm	required barrier slant thickness
B_{ps}(6 MV)	4×10^{-2}	6 MV Patient transmission factor
$t_{s,sca}$ (6 MV)	≈ 37 cm	required barrier slant thickness

Combination of these two barrier requirements lead to adding 1 HVL (a conservatively safe value for 18 MV) to the larger of the two values. Thus:

$t_{s,sca}$(total)	≈ 47 cm	Thickness for patient scattered radiation

For leakage radiation at 18 MV, using leakage equation (3.8)

B_L (18 MV)	7.73×10^{-2}	Leakage transmission factor
$t_{s,L}$ (18 MV)	≈ 40 cm	Thickness for leakage radiation
B_L (6 MV)	6.8×10^{-2}	Leakage transmission factor
$t_{s,L}$ (6 MV)	≈ 40 cm	Thickness for leakage radiation

Combining the requirement for leakage radiation from both energy components gives:

$t_{s,L}$(total)	≈ 51 cm	Thickness for leakage radiation from both energy

Finally, the requirements for scatter and leakage radiation barrier were 47 cm and 51 cm respectively. Note that the leakage radiation thicknesses are thicker than scattered radiation thicknesses. These thicknesses are comparable and thus the total barrier slant thickness is given by the higher value plus one thickness of the highest HVL:

$t_{s,Tot}$	≈ 62 cm	Slant thickness of the secondary barrier

4.6.2. Time Average Dose Equivalent Rate (in-any-one-hour) Considerations for Location C

Table 4.13: Time average dose equivalent rate consideration for location C

Parameters	Values	Comments
$\dot{D}_0$	12 Gy min^{-1} or 720 Gy h^{-1}	maximum absorbed-dose output rate at the isocenter (1m from the source)
IDR_{ps} (18 MV)	2.02×10^{-4} Sv h^{-1}	Instantaneous dose rate (patient)
IDR_L (18 MV)	3.97×10^{-4} Sv h^{-1}	Instantaneous dose rate (leakage)
IDR (18 MV)	6×10^{-4} Sv h^{-1}	Instantaneous dose rate for 18 MV
IDR_{ps} (6 MV)	1.62×10^{-4} Sv h^{-1}	Instantaneous dose rate (patient)
IDR_L (6 MV)	2.5×10^{-4} Sv h^{-1}	Instantaneous dose rate (leakage)
IDR (6 MV)	4.12×10^{-4} Sv h^{-1}	Instantaneous dose rate for 6 MV
R_w (18 MV)	1.34×10^{-4} Sv week^{-1}	the weekly TADR at location C from 18 MV (equation 2.2)
R_w (6 MV)	1.05×10^{-4} Sv week^{-1}	the weekly TADR at location C from 6 MV (equation 2.2)

The total TADR in-any-one-hour, using M = 2.27

$R_h = (M / 40)\ R_w$ (total)	13.56 µSv	Well under the 20 µSv TADR limit.

Therefore, the maximum dose equivalent in-any-one-hour of 13.56 µSv is below the TADR limit of 20 µSv in-any-one-hour

4.7 Door Calculations

4.7.1 Leakage and Scattered Radiation at the Maze Door

For high-energy accelerator, the contributions of leakage and scattered radiations reaching the maze entrance are generally relatively low compared with the neutron capture gamma-ray and neutron dose equivalent components.

The room layout shown in Figure 3.1 and Equation (2.11) was used:

$$H_{tot} = 2.64 \left(D_{pH} + f \times D_{wH} + D_{LH} + D_{TH} \right)$$

4.7.1.1 Wall-Scattered Radiation Component, D_{wH}.

Table 4.14: Wall-Scattered Radiation Component Calculations

Parameters	**Values**	**Comments**
W (18MV)	161 Gy week^{-1}	Workloads high and low energy
W (6MV)	183 Gy week^{-1}	
U_H	0.25	Wall H use factor
d_H	4.2 m	Distance from source to wall H (Figure 2.3)
d_r	5.68 m	
d_z	4.4 m	
α_H (18 MV)	1.6×10^{-3}	Table B.5, Appendix B, normal incidence, 75 degree angle of reflection)
α_H (6 MV)	2.7×10^{-3}	
α_r	8×10^{-3}	75 degree angle of reflection, 0.5 MeV
$A_H = F\ (d_H/\ 1\text{m})^2$	3.1 m^2	area of the maximum field size
A_r	7.66 m^2	cross-sectional area
$\boldsymbol{D_{wH}}$	**2.95 µSv week^{-1}**	Wall scattered radiation

4.7.1.2 Head-Leakage Wall-Scattered Radiation Component, D_{LH}.

Table 4.15: Head-Leakage Wall-Scattered Radiation Component Calculations

Parameters	Values	Comments
W (18MV)	161 Gy week^{-1}	Workloads high and low energy
W (6MV)	183 Gy week^{-1}	
U_H	0.25	Wall H use factor
d_i	6.7 m	Figure 2.5
d_m	7.32 m	
α_1 (18 MV)	4.5×10^{-3}	Table B.6 (Appendix B) 45 degree incidence, zero degree angle of reflection
α_1 (6 MV)	6.4×10^{-3}	
L_0	10^{-3}	(assumed same for 6 MV and 18 MV x rays)
$A_1 = 3.15 \text{ m} \times 3.65 \text{ m}$	11.5 m^2	area of the maximum field size

The total dose equivalent at the maze door from head-leakage radiation scattered by the wall G is:

D_{LH}	**9.04 µSv week^{-1}**	Head-Leakage Wall-Scattered Radiation

4.7.1.3 Patient-Scattered Radiation Component, D_{pH}.

Table 4.16: Patient-Scattered Radiation Component Calculations

Parameters	**Values**	**Comments**
W (18MV) W (6MV) U_H	161 Gy week^{-1} 183 Gy week^{-1} 0.25	Workloads high and low energy Wall H use factor
d_1 d_m	7.17 m 7.32 m	See Figure 2.2
a (18 MV)	8.64×10^{-4}	Table B.2, Appendix B, scatter fraction for 6 MV at 45 degree scatter angle
a (6 MV)	1.39×10^{-3}	
F	(40×40) cm^2	maximum field size
$A_1 = 3.15$ m × 3.65 m	11.5 m^2	area of the maximum field size projected onto wall *H*
α_1	2.2×10^{-2}	concrete wall reflection coefficient
D_{PH}	36.14 µSv week^{-1}	Patient-Scattered Radiation

4.7.1.4 Head-Leakage Radiation through Maze Wall, D_{TH}.

Table 4.17: Head-Leakage Radiation through Maze Wall Calculations

Parameters	**Values**	**Comments**
W (18MV) W (6MV) U_H	161 Gy week^{-1} 183 Gy week^{-1} 0.25	Workloads high and low energy Wall H use factor
d_t	7.17 m	distance from the target source to the maze door
TVL_1 (18 MV)	36 cm	First and equilibrium value layers for leakage radiations
TVL_e (18 MV)	34 cm	
L_0	10^{-3}	(assumed same for 6 MV and 18 MV x rays)
$t_s = 1.05/\cos(30)$	1.22 m	The oblique maze wall slant thickness
B	2.95×10^{-4}	transmission through the maze wall
D_{TH}	0.92 µSv week^{-1}	Head-Leakage Radiation through Maze Wall

Finally, from equation **(2.11)** the total dose equivalent is:

$$\boldsymbol{H_{tot} = 2.64\,(\,D_{pH} + f \times\, D_{wH} + D_{LH} + D_{TH}\,)}$$

$f = 0.34$ (from Table B.7, Appendix B) [4]

$H_{tot} = 2.64$ (36.14 µSv week^{-1} + 0.34 × 2.95 µSv week^{-1} + 9.04 µSv week^{-1} + 0.92 µSv week^{-1})

H_{tot} **= 124.35 µSv week^{-1}**

4.7.2 Neutron Capture Gamma-Ray Dose Equivalent at the Maze door

4.7.2.1 Capture Gamma-Ray Dose Equivalent at the Maze door

Photoneutron production and, hence, the neutron capture gamma-ray dose equivalent is proportional to the leakage radiation workload of high-energy [3]. To determine the neutron capture gamma-ray dose equivalent (H_{cg}), equation (3.9) is used:

Table 4.18: Capture Gamma-Ray Dose Equivalent at the Maze door Calculations

Parameters	**Values**	**Comments**
φ_A	1.31×10^{10} neutrons m^{-2}	The total neutron fluence at the inner maze
Q_n	1.22×10^{12}	neutrons per X-ray gray at isocenter 18 MV machine (Varian Model DHX)
A	1	accelerator head is lead
d_1 d_2	6.1 m 5.19	from the isocenter to the inner maze The length of the maze
S_r	235 m^2	the surface area of the room
H_{cg}	159 µSv week^{-1}	Capture Gamma-Ray Dose Equivalent at the Maze door

4.7.2.2 Neutron Dose Equivalent at the Maze door

Two methods will be used to estimate the neutron dose equivalent at the maze entrance. The areas of the inner maze opening S_0, and the cross-sectional area of the maze S_1, as shown in fig 3.4, are needed for both methods.

Table 4.19: Neutron Dose Equivalent at the Maze door Calculations

Parameters	**Values**	**Comments**
S_0 S_1	10.58 m2 7.66 m2	Areas shown in fig 3.4
d_0 d_1	1.41 m 6.1 m	Distance shown in fig 3.4
$H_{n,D} = H_0 \left(\frac{S_0}{S_1}\right)\left(\frac{d_0}{d_1}\right)^2 10^{-\left(\frac{d_2}{5}\right)}$	10.81×10^{-6} Sv Gy^{-1}	method of Kersey (1979)
$H_{n,D}$	4.65×10^{-6} Sv Gy^{-1}	method by Wu and McGinely (2003) [14]

The alternative method is expected to give a more accurate estimate than the Kersey method. A conservatively safe approach would use the larger value for the neutron dose equivalent at the maze door.

H_n	1740 µSv week^{-1}	Neutron Dose Equivalent
$H_w = H_{tot} + H_{cg} + H_n$	2.02 mSv week^{-1}	The total dose equivalent at the door

4.8. Shielding Barrier for the Maze Door

The maze entrance is located in a controlled area and the shielding design goal is:

P = 0.1 mSv week^{-1}. For this work the total dose equivalent at the door is 2.02 mSv week^{-1}, of which ≈ 86 % is from neutrons, 6 % from low-energy and scattered and transmitted leakage photons and 8 % from neutron capture gamma rays. Each component is considered separately. The TVL for scattered and leakage photons (H_{Tot}) varies between 3 and 6 mm of lead depending on the maze length (McGinely, 2002), whereas the TVL for neutron capture gamma rays (H_{cg}) can be as much as 61 mm of lead (NCRP,1984) depending on maze length. For this work, the shielding for neutron capture gamma rays will suffice for scattered and leakage-radiations (H_{Tot}) components if it is assumed that the photon spectrum at the door is dominated by neutron capture gamma rays. Therefore, it is not necessary to calculate separately the shielding for the (H_{Tot}) contribution at the door. In a situation like this where the lead used to attenuate the neutron capture gamma rays is nearly transparent to the neutrons and the thickness of BPE needed for the neutron weakly attenuates the neutron capture gamma rays, the following approach is straightforward and conservatively safe. Independently determine the material thickness for each radiation needed to achieve one-half of the shielding design goal.

The weekly dose equivalent at the maze entrance was found to be:

H_n = 1740 µSv week^{-1}

To reduce this neutron dose equivalent to P/2 = 50 µ Sv week^{-1}, the number of TVLs required is:

n= $\log(\frac{1740}{50})$ = 1.54

Using a TVL of 45 mm for BPE [3], the required thickness for neutron shielding (with the additional HVL) is (1.54) (45 mm) ≈ 70.2 mm of BPE.

The weekly contribution from the neutron capture gamma-ray dose equivalent, H_{cg} = 159 μSv week^{-1}, is attenuated to a level of 50 μSv week^{-1} with n= $\log(\frac{159}{50})$ = 0.5, using the TVL of 61 mm of lead the thickness is found to be 30.64 mm of lead.

The total shielding for the maze door is 3 cm of lead and 7 cm of BPE. The borated polyethylene should be sandwiched between two layers of lead, each 1.5 cm thick.

SUMMARY OF RESULTS

Table 4.20: Summary of the calculated values for the thicknesses of the barriers

Locations	Barriers	Existing Thickness	Calculated .Thickness	Additional. Shielding Required
A	Primary	305 cm	168 cm	NO
B	Secondary	170 cm	82 cm	NO
C	Secondary	170 cm	62cm	NO
D	Primary	270 cm	157 cm	NO
E	Secondary	130 cm	76 cm	NO

Table 4.21: Calculated dose equivalent at the maze door

Low energy leakage and scattered radiations	**Wall-scattered radiation (D_{WH})**	**Head leakage wall-scattered radiation (D_{LH})**	**Patient scattered radiations (D_{PH})**	**Head leakage radiations through maze wall (DTH)**	**H_{tot}**
	2.95 µSv week^{-1}	9.04 µSv week^{-1}	36.14 µSv week^{-1}	0.92 µSv week^{-1}	124.35 µSv week^{-1}
High Energy Capture Gamma and neutrons	Capture Gamma dose Equivalent at the door (H_{cg})			Neutrons dose Equivalent at the door (H_n)	
	159 µSv week^{-1}			1740 µSv week^{-1}	

Table 4.22: Doses rate measured at the facility

Locations	**Measured dose equivalent (µSv/h)**	**Measured dose equivalent (mSv/week)**	**Design goal (mSv/week)**
A	Background	Background	0.02
B	≈	≈	0.02
C	≈	≈	0.02
D	≈	≈	0.1
E	≈	≈	0.1
Door	3.3	**0.132**	0.1
Control room	0.1	0.004	0.02
Patient's waiting room	0.04	0.001	0.02

Note that the measurement has been done under the most severe conditions where the dose is higher, about 5Gy, large field size 30 cm × 30 cm , high energy 18 MV and the gantry angle is oriented where the measurement was made.

The dose equivalent measured outside the door was slightly higher than the shielding design goal, meaning an additional shielding might be needed to protect occupationally exposed workers and patients exist near to the door. Section 4.8 gives the shielding of the door needed to protect workers and members of public.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

This study was designed to assess the structural shielding for the LINAC facility at Nouakchott Oncology Center and verify the adequacy of the shielding and design to protect occupationally exposed workers and the public. The methodology proposed in NCRP report 151 was used.

The average weekly load estimated for the 6MV photon beam, W (6 MV) = 183 Gy/week corresponding to 19 patients per day approximately.

The average weekly load estimated for the 18MV photon beam, W (18MV) = 161 Gy/week corresponding to 16 patients per day approximately.

The thickness of the primary barrier was calculated to be 168 cm and that of secondary barrier was 82 cm. the existing thickness were 305 cm and 165 cm for the primary barrier and secondary barrier respectively. The existing thickness (primary and secondary) provide adequate protection for the occupationally exposed workers and the public.

For this work the total dose equivalent at the door is 2.02 mSv week^{-1}, of which ≈ 86 % is from neutrons, 6 % from low-energy scattered and transmitted leakage photons, and 8 % from neutron capture gamma rays.

The dose rate measurement show that the shielding provided by the entrance door is not adequate so an additional shielding is required for the door or the workload should be constrained to a value that will enable compliance with the designed goal.

5.2. RECOMMENDATION

The followings are some recommendations from the study done:

Hospital Management

a. Re-evaluation of shielding adequacy should be done by a Radiation Protection Officer or qualified experts when the factors that affect the shielding integrity changes;

b. The licensee should comply with the guidance given by the Regulatory Authority;

c. The Licensee should acquire a neutron detector to monitor the neutron fluence rate to verify that the levels are acceptable.

Regulatory Authority

d. The Regulatory Authority should provide guidance to the licensee not to exceed the workload that will enable the entrance door to provide acceptable shielding;

e. Regulatory Authority should acquire a neutron detector to monitor the neutron fluence rate to verify compliance with regulatory requirements.

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APPENDIX A

H: High Voltage L: Low Voltage W_L: Low Voltage Workload W_H: High Voltage Workload

Table A1: Data collected at the facility for March 2016

		3/1/2016		
Nbr of patients	**Localization**	**6 MV**	**18 MV**	**Doses**
	12 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Carcinom		H	2 Gy
19 L	1 × Larynx		H	2 Gy
	1 × Lympharynx		H	2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
13 H	1 × Glioblastoma			2 Gy
	1 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
		3/2/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	13 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Carcinom		H	2 Gy
19 L	1 × Larynx		H	2 Gy
	1 × Lympharynx		H	2 Gy
	1 × Sarcome			2 Gy
	1 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
12 H	1 × Retinoblastoma		H	2 Gy
	1 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
	1 × anal Canal			2 Gy
		3/3/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	14 × Breast	L		2 Gy

21 L	8 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Carcinom		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Lympharynx		H	2 Gy
	1 × Sarcome		H	2 Gy
17 H	1 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Glioblastoma			2 Gy
	1 × Retinoblastoma		H	2 Gy
	1 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
	1 × anal Canal		H	2 Gy
	1 × Metastatic		H	4 Gy
		3/4/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
20 L **22 H**	14 × Breast	L		2 Gy
	11 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Carcinom		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Lympharynx		H	2 Gy
	1 × Sarcome		H	2 Gy
	1 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Glioblastoma			2 Gy
	1 × Retinoblastoma		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Cerebral	L		2 Gy
	2 × anal Canal		H	2 Gy
	2 × Metastatic		H	4 Gy
		3/7/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
18 L	13 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Carcinom		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Lympharynx		H	2 Gy

	1 × Sarcome			2 Gy
18 H	1 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Glioblastoma			2 Gy
	1 × Retinoblastoma		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Cerebral	L		2 Gy
	1 × anal Canal		H	2 Gy
	2 × Metastatic		H	4 Gy
		WOKLOADS		
		WL=194 Gy/WK	**WH=164Gy/WK**	
		3/24/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
15 L	5 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Leg	L		2 Gy
	1 × Larynx		H	2 Gy
12 H	1 × Cavum	L		2 Gy
	3 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
	2 × anal Canal		H	2 Gy
	1 × Glioblastoma		H	2 Gy
		3/25/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
14 L	6 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Leg			2 Gy
	1 × Larynx		H	2 Gy
13 H	1 × Cavum	L		2 Gy
	1 × Retinoblastoma		H	2 Gy
	3 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
	2 × anal Canal		H	2 Gy
		3/29/2016		

	Localization	**6 MV**	**18 MV**	**Doses**
16 L	6 × Breast	L		2 Gy
	13 × Col		H	2 Gy
	1 × ORL	L		2 Gy
	1 × Leg	L		2 Gy
16 H	2 × Cavum	L		2 Gy
	1 × Retinoblastoma		H	2 Gy
	3 × Esophagus	L		2 Gy
	3 × Cerebral	L		2 Gy
	2 × anal Canal		H	2 Gy
		3/30/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
15 L	6 × Breast	L		2 Gy
	14 × Col		H	2 Gy
	1 × ORL	L		2 Gy
	1 × Leg			2 Gy
	1 × Larynx		H	2 Gy
19 H	2 × Cavum	L		2 Gy
	1 × Retinoblastoma		H	2 Gy
	3 × Esophagus	L		2 Gy
	3 × Cerebral	L		2 Gy
	1 × Lung		H	2 Gy
	2 × anal Canal		H	2 Gy
		3/31/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
16 L	6 × Breast	L		2 Gy
	14 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Leg	L		2 Gy
	2 × Larynx		H	2 Gy
20 H	2 × Cavum	L		2 Gy
	1 × Retinoblastoma		H	2 Gy
	3 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
	1 × Lung		H	2 Gy
	1 × anal Canal		H	2 Gy
	1 × Bladder		H	2 Gy
		WOKLOADS		
		WL=152 Gy/WK	**WH=160 Gy/WK**	
	March Workoads	**WL=194 Gy/WK**	**WH=164Gy/WK”**	

Table A2: Data collected at the facility for April 2016

		4/4/2016		
Nbr of patients/day	**Localization**	**6 MV**	**18 MV**	**Doses**
13 L **21 H**	6 × Breast	L		2 Gy
	12 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	2 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	1 × Cavum	L		2 Gy
	1 × Rectum		H	2 Gy
	2 × Lung		H	2 Gy
	1 × Retinoblastoma		H	2 Gy
	1 × Bladder		H	2 Gy
	2 × Esophagus	L		2 Gy
	1 × Cerebral	L		2 Gy
	1 × Metastatic		H	4 Gy
		4/7/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
15 L	5 × Breast	L		2 Gy
	15 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	2 × Anal		H	2 Gy
	2 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Rectum		H	2 Gy
24 H	1 × Lung		H	2 Gy
	1 × Retinoblastoma		H	2 Gy
	1 × Bladder		H	2 Gy
	3 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
	1 × Metastatic		H	4 Gy
		4/8/2016		

	Localization	6 MV	18 MV	Doses
16 L	5 × Breast	L		2 Gy
	14 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	2 × Anal		H	2 Gy
	2 × Larynx		H	2 Gy
23 H	1 × Leg	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Poumon		H	2 Gy
	1 × Retinoblastoma		H	2 Gy
	1 × Bladder		H	2 Gy
	3 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
	1 × Metastatic		H	4 Gy

4/12/2016

	Localization	6 MV	18 MV	Doses
17 L	6 × Breast	L		2 Gy
	13 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	2 × Anal		H	2 Gy
	2 × Larynx		H	2 Gy
20 H	1 × Leg	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Retinoblastoma		H	2 Gy
	1 × Bladder		H	2 Gy
	3 × Esophagus	L		2 Gy
	1 × Cerebral	L		2 Gy

4/13/2016

	Localization	6 MV	18 MV	Doses
18 L	6 × Breast	L		2 Gy
	15 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	2 × Anal		H	2 Gy
	2 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Rectum		H	2 Gy

23 H	1 × Retinoblastoma		H	2 Gy
	1 × Bladder		H	2 Gy
	3 × Esophagus	L		2 Gy
	2 × Cerebral	L		2 Gy
	1 × Metastatic		H	4 Gy

WORKLOADS

WL=158 Gy/WK **WH=222 Gy/WK**

4/25/2016

	Localization	6 MV	18 MV	Doses
19 L	9 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	5 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	1 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Bladder		H	2 Gy
	2 × Esophagus	L		2 Gy
22 H	1 × Cerebral	L		2 Gy
	1 × Metastatic		H	2 Gy
	1 × Vulva		H	2 Gy

4/26/2016

	Localization	6 MV	18 MV	Doses
16 L	6 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	5 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Leg	L		2 Gy
	1 × Larynx		H	2 Gy
	2 × Rectum		H	2 Gy
25 H	1 × Bladder		H	2 Gy
	2 × Esophagus	L		2 Gy
	1 × Cerebral	L		2 Gy
	1 × Metastatic		H	2 Gy
	1 × Vulva		H	2 Gy
	1 × Maxi		H	2 Gy

4/27/2016

	Localization	6 MV	18 MV	Doses
17 L	5 × Breast	L		2 Gy
	3 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
24 H	1 × Bladder		H	2 Gy
	2 × Esophagus	L		2 Gy
	1 × Cerebral	L		2 Gy
	1 × Vulva		H	2 Gy
	1 × Maxi	L		2 Gy
	1 × Lung		H	2 Gy

4/28/2016

	Localization	6 MV	18 MV	Doses
18 L	4 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	1 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
21 H	1 × Bladder		H	2 Gy
	2 × Esophagus	L		2 Gy
	1 × Cerebral	L		2 Gy
	1 × Vulva		H	2 Gy
	1 × Maxi	L		2 Gy
	1 × Lung		H	
	1 × Sinus	L		2 Gy
	1 × Hypopharynx	L		2 Gy

4/29/2016

	Localization	6 MV	18 MV	Doses
	6 × Breast	L		2 Gy

	6 × Col		H	2 Gy
	5 × ORL	L		2 Gy
19 L	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	2 × Cavum	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Bladder		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Cerebral	L		2 Gy
24 H	1 × Vulva		H	2 Gy
	1 × Maxi	L		2 Gy
	1 × Lung		H	2 Gy
	1 × Sinus	L		2 Gy
	1 × Hypopharynx	L		2 Gy
	WL=166 Gy/WK		**WH=130 Gy/WK**	
	April Workloads		**WL=166 Gy/WK**	**WH=222 Gy/WK**

Table A3: Data collected at the facility for May 2016

		5/2/2016		
Nbr of patients/day	**Localization**	**6 MV**	**18 MV**	**Doses**
	8 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	5 × ORL	L		2 Gy
20 L	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	2 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
12 H	1 × Bladder		H	2 Gy
	3 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
		5/3/2016		
	Localization	**6 MV**	**18 MV**	**Doses**

17 L	5 × Breast	L		2 Gy
	5 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	1 × Cavum	L		2 Gy
11 H	2 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
		5/4/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
18 L	6 × Breast	L		2 Gy
	5 × Col		H	2 Gy
	5 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	1 × Cavum	L		2 Gy
12 H	3 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Bladder		H	2 Gy
	2 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
		5/5/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
20 L	6 × Breast	L		2 Gy
	5 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy

	1 × Cavum	L		2 Gy
12 H	3 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Bladder		H	2 Gy
	2 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
	2 × Hypopharynx	L		2 Gy
		5/6/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
19 L	7 × Breast	L		2 Gy
	4 × Col		H	2 Gy
	5 × ORL	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Leg	L		2 Gy
	1 × Cavum	L		2 Gy
11 H	3 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
	2 × Hypopharynx	L		2 Gy
		WORKLOADS		
		WL=188 Gy/WK	**WH=116 Gy/WK**	
		5/20/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
20 L	7 × Breast	L		2 Gy
	4 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	2 × Cavum	L		2 Gy
	4 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Bladder		H	2 Gy

	2 × Esophagus	L		2 Gy
12 H	1 × Vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Vagina		H	2 Gy
		5/23/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	5 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
18 L	2 × Cavum	L		2 Gy
	3 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	2 × Bladder		H	2 Gy
14 H	2 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Vagina		H	2 Gy
		5/24/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	7 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	5 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
19 L	2 × Cavum	L		2 Gy
	3 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
	2 × Sinus	L		2 Gy
	2 × Bladder		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
16 H	1 × Hypopharynx	L		2 Gy
	1 × Vagina		H	2 Gy
	2 × Metastatic		H	4 Gy
		5/26/2016		
	Localization	**6 MV**	**18 MV**	**Doses**

20 L	6 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	2 × Cavum	L		2 Gy
	3 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
18 H	2 × Sinus	L		2 Gy
	2 × Bladder		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Vagina		H	2 Gy
	2 × Metastatic		H	2 Gy
		5/27/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
18 L	6 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	1 × Cavum	L		2 Gy
	3 × Rectum		H	2 Gy
	1× Maxi	L		2 Gy
18 H	2 × Sinus	L		2 Gy
	2 × Bladder		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Vagina		H	2 Gy
	2 × Metastatic		H	2 Gy
		WORKLOADS		
		WL=190 Gy/WK	**WH=156 Gy/WK**	
	May Workloads	**WL=190 Gy/WK**	**WH=156 Gy/WK**	

Table A4: Data collected at the facility for June 2016

		6/1/2016		

Nbr of patients/day	Localization	6 MV	18 MV	Doses
19 L	7 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	4 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
17 H	4 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Bladder		H	2 Gy
	2 × Basin		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Hypopharynx		H	2 Gy
		6/6/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
16 L	6 × Breast	L		2 Gy
	5 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	3 × Rectum		H	2 Gy
	2 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
16 H	2 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Bladder		H	2 Gy
	2 × Basin		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Hypopharynx		H	2 Gy
	1 × Lung		H	2 Gy
	1 × Esophagus	L		2 Gy
		6/7/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
18 L	6 × Breast	L		2 Gy
	4 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	4 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy

14 H	3 × Sinus	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Basin		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Hypopharynx		H	2 Gy
	1 × Lung		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Vagina		H	2 Gy
		6/7/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
15 L	5 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	5 × ORL	L		2 Gy
	4 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	2 × Sinus	L		2 Gy
	2 × Bladder		H	2 Gy
17 H	1 × Basin		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Hypopharynx		H	2 Gy
	1 × Lung		H	2 Gy
	1 × Esophagus	L		2 Gy
	1 × Vagina		H	2 Gy
		6/8/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
15 L	4 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	2 × Sinus	L		2 Gy
	2 × Bladder		H	2 Gy
16 H	1 × Basin		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Hypopharynx		H	2 Gy
	1 × Lung		H	2 Gy
	1 × Prostate		H	2 Gy

	1 × Vagina		H	2 Gy
		WORKLOADS		
		WL=166 Gy/WK	**WH=160 Gy/WK**	
		6/24/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
19 L	9 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	3 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
16 H	1 × Bladder		H	2 Gy
	1 × Epaul		H	2 Gy
	1 × Oropharynx		H	2 Gy
	1 × Lymphoma		H	2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Metastatic		H	4 Gy
		6/27/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
19 L	8 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	3 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
16 H	1 × Bladder		H	2 Gy
	1 × Epaul		H	2 Gy
	1 × Oropharynx		H	2 Gy
	1 × Lymphoma		H	2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Porostate		H	2 Gy
		6/28/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	8 × Breast	L		2 Gy

	9 × Col		H	2 Gy
	8 × ORL	L		2 Gy
	3 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
19 L	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Oropharynx		H	2 Gy
18 H	1 × Lymphoma		H	2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Porostate		H	2 Gy
		6/29/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	8 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	3 × Rectum		H	2 Gy
18 L	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Oropharynx		H	2 Gy
17 H	1 × Lymphoma		H	2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Porostate		H	2 Gy
		6/30/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	8 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	9 × ORL	L		2 Gy
20 L	3 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Vagina		H	2 Gy
	1 × Oropharynx		H	2 Gy
	1 × Lymphoma		H	2 Gy

16 H	1 × Sarcoma		H	2 Gy
	1 × Porostate		H	2 Gy
		WORKLOADS		
		WL=190 Gy/WK	**WH=166 Gy/WK**	
	Jun Workloads	**WL=190 Gy/WK**	**WH=166 Gy/WK**	

Table A5: Data collected at the facility for July 2016

		7/1/2016		
Nbr of patients/day	**Localization**	**6 MV**	**18 MV**	**Doses**
	8 × Breast	L		2 Gy
	11 × Col		H	2 Gy
	9 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
24 L	4 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	1 × Oropharynx	L		2 Gy
	2 × Sinus	L		2 Gy
20 H	1 × Vagina		H	2 Gy
	1 × Pelvis	L		2 Gy
	1 × lymphoma	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Bladder		H	2 Gy
		7/4/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	7 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	8 × ORL	L		2 Gy
22 L	1 × Prostate		H	2 Gy
	4 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	1 × Oropharynx	L		2 Gy

18 H	2 × Sinus	L		2 Gy
	1 × Vagina		H	2 Gy
	1 × Pelvis	L		2 Gy
	1 × lymphoma	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Bladder		H	2 Gy
		7/5/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
18 L	7 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	8 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	4 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
17 H	1 × Vagina		H	2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Bladder		H	2 Gy
		7/8/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
12 L	6 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	2 × Rectum		H	2 Gy
13 H	1 × Sarcoma		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Bladder		H	2 Gy
		7/11/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
15 L	7 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy

16 H	4 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1× Maxi	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Bladder		H	2 Gy
		WORKLOADS		
		WL=182 Gy/wk	**WH=168 Gy/wk**	
		7/12/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
19 L	7 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	8 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	3 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
16 H	2 × Sinus	L		2 Gy
	2 × Vagina		H	2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Bladder		H	2 Gy
		7/13/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
20 L	8 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	8 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	3 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
14 H	2 × Sinus	L		2 Gy
	1 × Vagina		H	2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Stomach		H	2 Gy

		7/14/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
19 L	7 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	8 × ORL	L		2 Gy
	1 × Prostate		H	2 Gy
	3 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
15 H	2 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Bladder		H	2 Gy
		7/18/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
16 L	6 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
11 H	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
		7/19/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
18 L	8 × Breast	L		2 Gy
	5 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
10 H	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Stomach		H	2 Gy
		WORKLOADS		

		WL=184 Gy/wk	WH=132 Gy/wk	
		7/20/2016		
	Localization	6 MV	18 MV	Doses
21 L 13 H	8 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	9 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	2 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Bladder		H	2 Gy
		7/22/2016		
	Localization	6 MV	18 MV	Doses
16 L 12 H	6 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Stomach		H	2 Gy
		7/25/2016		
	Localization	6 MV	18 MV	Doses
14 L	6 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	2 × Sinus	L		2 Gy
	1 × Sarcoma		H	2 Gy

12 H	1 × Vagina		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Metastatic		H	4 Gy

7/26/2016

	Localization	**6 MV**	**18 MV**	**Dose**
15 L	6 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
14 H	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy

7/28/2016

	Localization	**6 MV**	**18 MV**	**Doses**
16 L	7 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	6 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
16 H	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Anal		H	2 Gy
	3 × Metastatic		H	4 Gy

7/29/2016

	Localization	**6 MV**	**18 MV**	**Dose**
	6 × Breast	L		2 Gy

16 L	6 × Col		H	2 Gy
	7 × ORL	L		2 Gy
	2 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
15 H	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Anal		H	2 Gy
	2 × Metastatic		H	4 Gy
		WORKLOADS		
		WL=164 Gy/wk	**WH=140 Gy/wk**	
	July Workloads	**WL=184 Gy/WK**	**WH=168 Gy/WK**	

Table A6: Data collected at the facility for August 2016

		8/1/2016		
Nbr of patients/day	**Localization**	**6 MV**	**18 MV**	**Doses**
14 L	7 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
14 H	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
	1 × Lung		H	2 Gy
		8/2/2016		

	Localization	6 MV	18 MV	Doses
13 L	6 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Sinus	L		2 Gy
14 H	1 × Sarcoma		H	2 Gy
	1 × Vagina		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Rachis		H	2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
	1 × Lung		H	2 Gy
		8/3/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
13 L	7 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
15 H	1 × Sarcoma		H	2 Gy
	1 × Bladder		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Anal		H	2 Gy
	4 × Metastatic		H	4 Gy
	1 × Esophagus	L		2 Gy
		8/4/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
13 L	7 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Stomach		H	2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy

13 H	1 × Sinus	L		2 Gy
	1 × Lung		H	2 Gy
	1 × vulva		H	2 Gy
		8/5/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
14 L	7 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
15 H	1 × Bladder		H	2 Gy
	2 × Stomach		H	2 Gy
	1 × Anal		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Sinus	L		2 Gy
	1 × Lung		H	2 Gy
	1 × vulva		H	2 Gy
		WORKLOADS		
		WL=132 Gy/wk	**WH=140 Gy/wk**	
		8/8/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
11 L	6 × Breast	L		2 Gy
	10 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
16 H	2 × Stomach		H	2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
	1 × Lung		H	2 Gy
	1 × vulva		H	2 Gy
		8/9/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	7 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	2 × ORL	L		2 Gy

11 L	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
16 H	2 × Stomach		H	2 Gy
	1 × Anal		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Lung		H	2 Gy
	1 × vulva		H	2 Gy
	1 × Esophagus	L		2 Gy
		8/11/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
10 L	6 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
14 H	1 × Anal		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Lung		H	2 Gy
	1 × vulva		H	2 Gy
	1 × Esophagus	L		2 Gy
		8/12/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
10 L	6 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
13 H	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
	1 × Lung		H	2 Gy
	1 × vulva		H	2 Gy
	1 × Esophagus	L		2 Gy
		8/17/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
11 L	7 × Breast	L		2 Gy
	10 × Col		H	2 Gy
	1 × ORL	L		2 Gy

	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
14 H	1 × Lung		H	2 Gy
	1 × vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
		WORKLOADS		
		WL=106 Gy/wk	**WH=146 Gy/wk**	
		8/18/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	7 × Breast	L		2 Gy
	10 × Col		H	2 Gy
11 L	1 × ORL	L		2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
12 H	1 × Metastatic		H	4 Gy
	1 × vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
		8/19/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	7 × Breast	L		2 Gy
	8 × Col		H	2 Gy
	1 × ORL	L		2 Gy
9 L	1 × Cavum	L		2 Gy
	1 × Metastatic		H	4 Gy
	1 × vulva		H	2 Gy
12 H	1 × Hypopharynx			2 Gy
	1 × Rectum		H	2 Gy
	1 × Bladder		H	2 Gy
		8/22/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	10 × Breast	L		2 Gy
	10 × Col		H	2 Gy
13 L	1 × ORL	L		2 Gy

14 H	1 × Cavum	L		2 Gy
	2 × Metastatic		H	4 Gy
	1 × vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Rectum		H	2 Gy
		8/23/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
	12 × Breast	L		2 Gy
	7 × Col		H	2 Gy
	3 × ORL	L		2 Gy
18 L	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
13 H	2 × Metastatic		H	4 Gy
	1 × vulva		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
		8/24/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
16 L	11 × Breast	L		2 Gy
	13 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
18 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × LARYNX			2 Gy
		WORKLOADS		
		WL=134 Gy/wk	**WH=138 Gy/wk**	
		8/25/2016		

	Localization	**6 MV**	**18 MV**	**Doses**
14 L	9 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
14 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
		8/26/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
15 L	10 × Breast	L		2 Gy
	10 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
14 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
	1 × Hypopharynx			2 Gy
	1 × Bladder		H	2 Gy
		8/29/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
16 L	10 × Breast	L		2 Gy
	10 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
14 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
		8/30/2016		
	Localization	**6 MV**	**18 MV**	**Doses**

15 L	9 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
15 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Thorax		H	2 Gy
		8/31/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
16 L	10 × Breast	L		2 Gy
	10 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
15 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Thorax		H	2 Gy
		WORKLOADS		
		WL=152 Gy/wk	**WH=144 Gy/wk**	
	August Workloads	**WL=152 Gy/WK**	**WH=146 Gy/WK**	

Table A7: Data collected at the facility for September 2016

		9/5/2016		
Nbr of patients/day	**Localization**	**6 MV**	**18 MV**	**Doses**

16 L	10 × Breast	L		2 Gy
	9 × Col		H	2 Gy
	2 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
14 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Metastatic		H	4 Gy
	2 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Thorax		H	2 Gy
		9/6/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
20 L	13 × Breast	L		2 Gy
	12 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
16 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	2 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
		9/7/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
21 L	13 × Breast	L		2 Gy
	10 × Col		H	2 Gy
	5 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
15 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
		9/8/2016		

	Localization	**6 MV**	**18 MV**	**Doses**
19 L	13 × Breast	L		2 Gy
	10 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
15 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
		9/9/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
19 L	12 × Breast	L		2 Gy
	10 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
15 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
		WORKLOADS		
		WL=190 Gy/wk	**WH=150 Gy/wk**	
	September Workloads	**WL=190 Gy/WK**	**WH=150 Gy/WK**	

Table A8: Data collected at the facility for October 2016

		10/4/2016		
Nbr of patients/day	**Localization**	**6 MV**	**18 MV**	**Doses**
	10 × Breast	L		2 Gy

17 L	7 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	1 × Cavum	L		2 Gy
13 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	2 × Hypopharynx	L		2 Gy
	1 × Bladder		H	2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
	2 × Metastatic		H	4 Gy
		10/6/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
23 L	12 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	4 × ORL	L		2 Gy
	1 × Rectum		H	2 Gy
	2 × Cavum	L		2 Gy
12 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	3 × Hypopharynx	L		2 Gy
	1 × Nephro	L		2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
	2 × Metastatic		H	4 Gy
		10/7/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
20 L	10 × Breast	L		2 Gy
	6 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	2 × Cavum	L		2 Gy
10 H	1 × Oropharynx	L		2 Gy
	1 × Anal		H	2 Gy
	3 × Hypopharynx	L		2 Gy
	1 × Nephro	L		2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Metastatic		H	4 Gy

		10/10/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
18 L	7 × Breast	L		2 Gy
	4 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	3 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
8 H	1 × Anal		H	2 Gy
	3 × Hypopharynx	L		2 Gy
	1 × Nephro	L		2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Metastatic		H	4 Gy
		10/10/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
19 L	8 × Breast	L		2 Gy
	4 × Col		H	2 Gy
	3 × ORL	L		2 Gy
	3 × Cavum	L		2 Gy
	1 × Oropharynx	L		2 Gy
8 H	1 × Anal		H	2 Gy
	3 × Hypopharynx	L		2 Gy
	1 × Nephro	L		2 Gy
	1 × Thorax		H	2 Gy
	1 × Larynx		H	2 Gy
	1 × Metastatic		H	4 Gy
		WORKLOADS		
		WL=194 Gy/wk	**WH=102 Gy/wk**	
		10/24/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
18 L	8 × Breast	L		2 Gy
	5 × Col		H	2 Gy
	1 × ORL	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Prostate		H	2 Gy
	1 × Hypopharynx	L		2 Gy
	1 × Orbit	L		2 Gy

11 H	1 × Lung		H	2 Gy
	2 × Larynx		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Esophagus	L		2 Gy
		10/25/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
17 L	12 × Breast	L		2 Gy
	5 × Col		H	2 Gy
	1 × ORL	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Prostate		H	2 Gy
11 H	1 × Hypopharynx	L		2 Gy
	1 × Orbit	L		2 Gy
	2 × Lung		H	2 Gy
	2 × Larynx		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Esophagus	L		2 Gy
		10/26/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
16 L	11 × Breast	L		2 Gy
	4 × Col		H	2 Gy
	1 × ORL	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Prostate		H	2 Gy
11 H	1 × Orbit	L		2 Gy
	2 × Lung		H	2 Gy
	2 × Larynx		H	2 Gy
	2 × Metastatic		H	4 Gy
	1 × Esophagus	L		2 Gy
		10/27/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
16 L	11 × Breast	L		2 Gy
	4 × Col		H	2 Gy
	1 × ORL	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Prostate		H	2 Gy
	1 × Orbit	L		2 Gy

12 H	2 × Lung		H	2 Gy
	2 × Larynx		H	2 Gy
	3 × Metastatic		H	4 Gy
	1 × Esophagus	L		2 Gy
		10/28/2016		
	Localization	**6 MV**	**18 MV**	**Doses**
14 L	9 × Breast	L		2 Gy
	4 × Col		H	2 Gy
	1 × ORL	L		2 Gy
	2 × Cavum	L		2 Gy
	1 × Prostate		H	2 Gy
12 H	1 × Orbit	L		2 Gy
	2 × Lung		H	2 Gy
	2 × Larynx		H	2 Gy
	3 × Metastatic		H	4 Gy
	1 × Esophagus	L		2 Gy
		WORKLOADS		
		WL=162 Gy/wk	**WH=114 Gy/wk**	
	October Workloads	**WL=194 Gy/wk**	**WH=114 Gy/wk**	

APPENDIX B

Table B.1-- Primary barrier TVLs for ordinary concrete (2.35 g cm^{-3}), steel (7.87 g cm^{-3}) and lead (11.35 g cm^{-3}).Values in centimeter. [3]

Energy (MV)	Materials	TVL$_1$ (cm)	TVL$_e$ (cm)
6 (MV)	Concrete	37	33
	Steel	10	10
	Lead	5.7	5.7
18 (MV)	Concrete	45	43
	Steel	11	11
	Lead	5.7	5.7

Table B.2-- Scatter fraction (a) at 1 m from a human size phantom, target- to- phantom distance of 1 m, and field size of 400 cm^2 (McGinley,2002; Taylor et al, 1999. [3]

	Scatter fraction (a)	
Angle (degrees)	6 (MV)	18 (MV)
10	1.04×10^{-2}	1.42×10^{-2}
30	2.77×10^{-3}	2.53×10^{-3}
45	1.39×10^{-3}	8.64×10^{-4}
90	4.26×10^{-4}	1.89×10^{-4}

Table B.3-- TVLs in Concrete (centimeters) for patient-scattered radiation at various scatter angles, values are valid for shielding design purpose and are conservatively safe in nature. [3]

	TVL (cm)	
Scatter angle (degrees)	6 (MV)	18 (MV)
15	34	44
30	26	32
90	17	19

Table B.4—TVLs for leakage radiation in ordinary concrete (in centimeter) [3]

Energy (MV)	TVL_1 (cm)	TVL_e (cm)
6 (MV)	34	29
18 (MV)	36	34

Table B.5— Differential dose albedo (wall-reflection coefficient). Multiply each table entry by 10^{-3} (e.g., the entry 3.4 means 3.4×10^{-3}). Normal incidence in ordinary concrete, for bremsstrahlung and monoenergetic photons. [3]

0 Degree concrete Incidence	Angle of Reflection or Scatter (degrees) from (measured from the normal)				
Source	0	30	45	60	75
6 MV	5.3	5.2	4.7	4.0	2.7
18 MV	3.4	3.4	3.0	2.5	1.6
0.5 MeV	19.0	17.0	15.0	13.0	8.0

Table B.6— Differential dose albedo (wall-reflection coefficient). Multiply each table entry by 10^{-3} (e.g., the entry 4.8 means 4.8 × 10^{-3}). 45 degree of incidence, ordinary concrete, for bremsstrahlung and monoenergetic photons. [3]

45 Degree concrete Incidence	Angle of Reflection or Scatter (degrees) from (measured from the normal)				
Source	0	30	45	60	75
6 MV	6.4	7.1	7.3	7.7	8.0
18 MV	4.5	4.6	4.6	4.3	4.0
0.5 MeV	22.0	22.5	22.0	20.0	18.0

Table B.7— Suggested transmission factors (percentage depth dose for a 10 cm × 10 cm field, 100 cm SSD at a depth of 30 cm) [9]

Energy	CO-60	6 MV	10 MV	15 MV	18 MV
Transmission, f	0.15	0.23	0.28	0.34	0.38