Hospital radiological protection: Linear accelerator bunker shielding

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Abstract: Ionizing radiations and radioactive isotopes are frequently used in medicine for either diagnosis or treatment purposes. In both cases it is highly relevant to be aware of the dose that can be received by the patients as well as for the public and the workers who carry out such labors and how to protect them as much as possible following the corresponding legislation. To make the hospital become a risk-free place involving such radiation, protection measures must be applied: from individual protection protocols to shielding of the facilities using ionizing radiation. In this TFG, radiological protection concepts and protocols will be used to design the shielding of the bunker of a linear accelerator located at the Hospital Clínic de Barcelona.

I. INTRODUCTION

Ionizing radiations are electromagnetic radiations or particle beams energetic that are enough to ionize electrons of the target material in which the radiation is directed. Such radiation must have an energy of 10 eV or higher to be considered ionizing. The emission of radiation is always due to the interaction of a charged particle with an atom, ion, electron or another charged particle, so if the ionizing radiation is caused by photons or neutrons - non charged particles - it is referred as indirect ionizing radiation for the ionization is produced by the charged particles generated from the interaction of the before mentioned non-charged particle with the material. On the other hand, if the ionization is produced by charged particles it is called directly-ionizing radiation. These types of radiation are found to be a great resource in different field and types of work, such as medical physics, industry and energy related work, research, . . .

In medical physics the use of ionizing radiation has become more relevant during the last decades and it is used both for therapy and diagnosis. Ionizing radiation in the medical environment is used in: diagnostic radiology, nuclear medicine and radiotherapy.

In nuclear medicine, a radioactive isotope is introduced in the patient with either diagnostic or therapeutic purposes. The radioactive substance must be attached to a drug so when it is administrated the radiopharmaceutical is located in the area to treat. When used for diagnose, the γ-rays emitted by the radionuclide are detected from the exterior. Usually the detection of such radiation is complemented by a computed tomography scan, so the anatomical image and the radionuclide emission complement one another. If the purpose is therapy, the aim is for the emitted radiation (β or γ) to deposit absorbed dose in the area of interest.

Radiotherapy is an extended discipline to treat tumors in oncological patients. External beam radiotherapy uses high-energy x-rays or electrons from an accelerator to irradiate the volume affected by the tumour. Another treatment modality is brachytherapy; the source used in these treatments is an encapsulated source, unlike the sources used in nuclear medicine, introduced in the patient to irradiate the area that must be treated during a controlled period of time. The source can either be introduced by surgery and left for days or in the hospital using an applicator and leaving the source much less time. The most common brachytherapy sources are ^{137}Cs, ^{192}Ir, ^{125}I, ^{103}Pd and ^{106}Ru.

For diagnostic radiology, x-rays are used to acquire images of the human body. Different energies and equipment are employed depending on the part of the body which must be examined. For instance, the x-ray spectra involved in breast imaging (mammography) (up to 40 kV) are significantly softer than those used for general x-ray diagnosis (70–150 kV) because the area explored can be considered as a soft tissue and the contrast between the different parts of it is very low. To examine parts that contain bone structures the required energies are much larger, for the different tissues have more significant different electronic density which is what is detected.

Using ionizing radiation for medical purposes is one of the most important applications of this type of radiation and can imply a great exposure to high-energy ionizing radiation, so this use must be regulated in order to protect as much as possible the exposed people.

II. HOSPITAL RADIOLOGICAL PROTECTION

Nowadays, the use of ionizing radiation has become more important to treat certain diseases. However, being exposed to ionizing radiations must be avoided unless required for therapy or diagnosis since they can be harmful when the exposure is uncontrolled; in case of radiation interacting with biological matter, which is basically composed by liquid water, the water molecules can be ionized releasing great amounts of chemical energy. When exposed to ionizing direct and indirect radiation during an extended time some alteration may be induced in tissue molecules and in extreme cases even the DNA can suffer modification or DNA damage. Therefore the existence of a radiological protection is fundamental to protect the patients and hospital workers against unwanted —not justified— radiation and its harmful effects.

Radiological protection is based on three principles: justification, optimization and annual dose limit. Being exposed to ionizing radiation is considered to be justified if the benefits are greater than the detriment produced by it. Moreover, the dose rate allowed to receive is different depending on who is exposed to the radiation (patients, hospital workers or public).

The main criteria for optimisation is the ALARA principle (As Low As Reasonably Achievable).Ionizing radiation has to affect the minimum number of people as possible and with the lowest absorbed dose. This criteria also takes into account economical factors.

In a hospital, the radiological service is in charge of implementig radiological protection standards in all radioactive facilities. This standards are linked to the legal regulations dictated by the CSN (Consejo de Seguridad Nacional) and other regulatiory organizations.

The main tasks performed by the radiological protection service in a hospital are: implementation and verification of the current legislation, designing and checking the shieldings for radiotherapy, nuclear medicine and diagnostic radiology facilities.

A. Specific magnitudes and units

To understand some of the requirements needed to shield a facility where ionizing radiation is used, specific magnitudes and units related to the impact of this radiation in the human body must be known (radiological units).

- Absorbed dose (D): It is the energy absorbed per unit mass, in other words, is the energy that *stays* in the mass studied after the irradiation. It is defined as

$$D = \frac{\mathrm{d}\epsilon}{\mathrm{d}m}.$$

  Absorbed dose is measured in grays [1 Gy = 1 J/kg].

- Equivalent dose (H_W) and effective dose (E): These magnitudes are derived from the absorbed dose and take into account the effect of different type of radiation: photons, electrons, ... (equivalent dose) and the effect it has in different tissues (effective dose). The weight factor for photons is 1 and for neutrons it depends on the energy, the value of the factor taken into account is also 1 in this case since the energy that the neutrons have at the door is low.

  To obtain the equivalent and effective dose, the absorbed dose must be weighted by the weight factor of each radiation or tissue, respectively.

$$H_W = \sum_R w_R \, D_R,$$

  where the sum over R is for all the types of radiation.

$$E = \sum_T w_T \, H_{W,T}$$

  where the sum over T makes reference to the different tissues where the radiation is absorbed.

  The equivalent and effective dose is measured in sievert [1 Sv]

  Dose limits for exposed workers and members of the public must be taken into account when shielding a facility: 6 mSv/year for exposed workers and 1 mSv/year for public in general.

- Workload (W): The workload takes into account the absorbed dose at the isocenter of the accelerator ($d = 1$ m). It is usually expressed in Gy/week and its value depends on the number of treatments and the absorbed dose delivered in each treatment. The value used by the DIN-6847 norm is $W = 10^3$ Gy/week.

- Direction factor (U): It corresponds to the fraction of the time (or workload) which the main beam is directed towards the area which we have to shield. In the practical case of the linac in the Hospital Clínic, it has been used $U = 1$ for all areas to be protected to obtain a more conservative shielding.

- Occupation factor (T): The occupation factor refers to the time that the people behind a wall will be present over the time where the accelerator will be used. $T = 1$ is used when the adjacent room is occupied by workers who are present at all time. $T = 0.1$ is used for areas which are occupied one-tenth or less than the total irradiation time (toilets, waiting rooms, ...).

III. LINEAR ACCELERATOR (LINAC) USED IN RADIOTHERAPY

Radiological protection protocols must be applied to shield a linear acceleration bunker from a radiotherapy facility at the Hospital Clínic de Barcelona. Two guidelines exist to carry out the shielding of this type of facilities: the Norm DIN-6847 and the NCRP Report Nº151. In the practical case developed here, the Norm DIN-6847 is the one used because it has a more conservative perspective and it is the one used by the Radiological Protection department at the Hospital Clínic de Barcelona.

The main difference between the said protocols is that for the NCRP the Tenth Value Layers(TVL) (the thickness required to reduce the intensity of the radiation to $\frac{1}{10}$) have a dependence with the incidence angle. In consequence, some areas affected by the photon beam at a small scattering angle need a thicker shielding than the one required using the DIN regulation. On the other hand, when using the DIN the TVL only depends on the material and the type of radiation (direct, leakage, neutrons, . . .)

A. Theoretical basis

In radiotherapy, high-energy photon beams are used to irradiate the patient and kill the carcinogenic cells. Nowadays, linacs are the most used equipment in external beam radiotherapy having replaced the old ^{60}Co units. The x-ray beam emitted by the accelerator comes from bremsstrahlung radiation produced by accelerated electrons directed to a tungsten (W) target.

The electrons are generated in the electron gun, when the inside tungsten filament is heated and electrons are ejected into a tube (waveguide) where they are accelerated. The electron gun emits bunches of electrons; it is not an homogeneous flux. This tube where the electrons are injected to is separated in sections so the electron can be accelerated when it is located in the gap between the separated sections. The different cavities of the tube are submitted to an alternating current so the electric field generated pushes the electron bunches, accelerating them. Once the electrons have reached the desired energy and before the impact with the tungsten target, the electrons are bent with a magnetic field so all the different energy electrons converge into a smaller and more located section of the target.

Once the photon beam has been emitted by the accelerator head, the fluence of the beam is not the same in all the beam area; it has a pointy center and therefore the dose deposition has an irregular distribution. In most cases, the beam must be *flat* to achieve this objective, a flattening filter is used so the fluence of the photon beam is the same in all the beam. This device is not always used, in some cases the treatment is carried out without such flattening filter. The linac used in this practical case, the one in the Hospital Clínic de Barcelona, is a VARIAN TrueBeam accelerator of 18 MeV.

B. Types of radiation and barriers

The main objective when designing and calculating the structural shielding of a Linac bunker is to reduce as much as possible the dose to the adjoining rooms of the facility. To do so, it is important to distinguish between the direct beam emitted by the accelerator, the scattered radiation, the leakage radiation and the neutron radiation produced by photonuclear reactions and

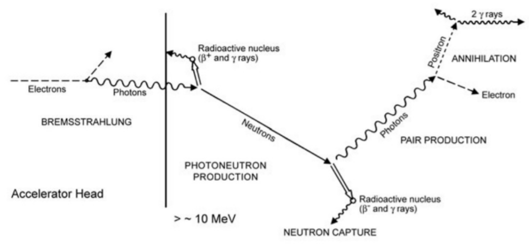

FIG. 1: Different radiation production reaction in an accelerator.

neutron capture γ-rays.

The radiation emitted directly from the accelerator towards the patient it is referred as direct radiation. This radiation beam comes from the bremsstrahlung produced by the accelerated electrons. Even though the beam is directed to the patient, when shielding the bunker the maximum field of radiation must be contemplated so at least two walls and the roof area above the accelerator have to be shielded against this radiation component. From the accelerator head, leakage radiation must be considered. Although the acceleration head is shielded to prevent photons to get out in any other direction but the main radiation directed towards the patient there is always leakage in other directions. The scattered radiation taken into account it is mostly scattered by the patient when being irradiated by the direct beam. Unlike the radiation emitted by the acceleration which is bremsstrahlung, the scattered radiation is produced by the Compton effect, photoelectric effect or pair production for the projectile particle is now a photon. In most of the walls and areas to be shielded the scattered radiation taken into account has only been scattered once, by the patient. But when calculating the shielding of the door, terciary bremsstrahlung radiation becomes relevant due to the presence of the maze, the photons have been scattered at least twice.

When talking about an accelerator which produces a photon beam with energy above 10 MeV neutron production must be taken into account when shielding the facility. Only if the energy of the photons is greater than 10 MeV, the neutron production becomes relevant for the energy must be larger than the binding energy of the neutron. The nuclear reactions that take place by the neutron interaction are β decays and neutron capture as it is shown in fig 1. Some of the emitted bremsstrahlung when interacting with some nucleus in the accelerator head, the patient or the shielding itself can excite said target nucleus which decays by a neutron emission. This reactions which produce neutrons through (γ, n) reactions take place when the photons collide with nucleous of high atomic number - for example, W or lead(Pb) - mostly in the accelerator head. A photodisintegration reaction can also be: $\gamma +_Z^A X \rightarrow_Z^{A-1} X + n$.

The materials used for shielding a bunker are usually: concrete ($\rho_c = 2.3 \text{ g cm}^{-3}$) for the walls and roof, lead

($\rho_{\rm Pb} = 11.34\,{\rm g\,cm^{-3}}$) for the door as well as paraffin($\rho_{\rm p} = 0.8\ {\rm g\,cm^{-3}}$) to shield against the neutron radiation. In this particular case heavy concrete ($\rho_{\rm hc} = 3.2\ {\rm g\,cm^{-3}}$) will be used in all walls in order to optimize the space. To shield against neutron radiation it is required a material with low mass number. Since neutron moderation is the direct consequence of elastic collisions between neutrons and the nuclei of the shielding material, materials with a high hydrogen content are the best moderators. In linac bunkers the material employed to shield against neutron radiation is paraffin.

C. Shielding design

When designing the structural shielding of a radiotherapy bunker it is needed the map of the facility and those adjoining rooms; to determine the different occupation and use factors needed for the calculations of the shielding thickness.

The main expression used to determine the thickness of the construction material used in each wall or area of the room is

$$s_i = z_i \, \log F_i, \tag{1}$$

where s_i is the required thickness, z_i is the TVL thickness, it depends on the material and the type of radiation taken into account and $\log F_i$ is the number of TVL necessary to attenuate enough the beam so it accomplishes the maximum legal dose beyond the barrier. The value of z_i needs to be approximated from the Figure 3, Table 2 and Table 3 of the Norm DIN 6847-2 depending on the maximum energy of the photon beam, in this case 18 MeV. The subscript i denotes the radiation component which has to be included (direct, leakage, secondary, neutron radiation, scattered and direct and tertiary radiation) and the DIN standard notation is the one adopted. F_i is the attenuation factor:

$$F_i = \frac{T\,W\,U\,R_i}{H_w}.$$

Here, R_i refers to the reduction factor, it varies for each radiation component, and H_w is the maximum permitted effective dose rate (Sv/week), depending on the person receiving the radiation (public or exposed workers).

Direct radiation. Direct radiation has to be taken into account in those points of the map where the photon beam can be directed against (Points 1, 2 and 3). The reduction factor for direct radiation is

$$R_{Xn} = \frac{a_0^2}{a_n^2}$$

$a_0 = 1$ m is the distance to the isocenter and a_n is the distance from the emitting source (accelerator head) to the point that must be protected.

In the areas where direct radiation affects, the other components of the radiation (neutron, leakage and secondary) can be neglected for the shielding against direct radiation will always be enough to protect against the others.

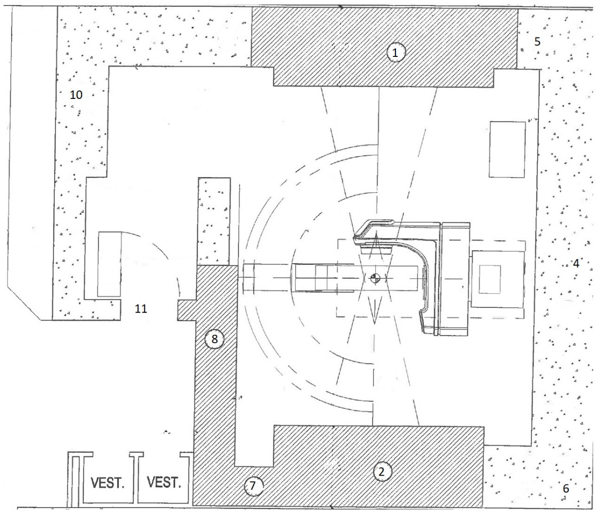

FIG. 2: Map of the accelerator bunker. The points 3 and 9 belong to the ceiling of the bunker.

Leakage radiation. Leakage radiation has to be considered in the points 4, 5, 6, 7, 8, 9 and 10. The reduction factor for leakage radiation is

$$R_{Xd} = \frac{\dot{D}_{Xd}}{\dot{D}_{Xn}} \frac{a_0^2}{a_n^2}\,\alpha.$$

$\dot{D}_{Xd}/\dot{D}_{Xn}$ is the proportion of radiation that can be scaped from the accelerator head and must be provided by the manufacturer of the accelerator. In this case, $\dot{D}_{Xd}/\dot{D}_{Xn} = 0.001$. α is the IMRT factor. This factor takes into account the intensity of bremsstrahlung radiation in the accelerator head required to deposit the same absorbed dose when using a smaller field of radiation (Intensity Modulated Radiation Therapy procedures). Since this increase of the amount of radiation is only relevant in the accelerator head, the IMRT factor only needs to be specified for the radiation emitted by the radiation head (leakage and neutrons). $\alpha = 2.5$ for all kinds of radiation if not specified otherwise by the person responsible for radiological protection

Secondary radiation. Secondary radiation has to be taken into account in the points 4, 5, 6, 7, 8, 9 and 10. The reduction factor for this component of the radiation is

$$R_{Xd} = 10^{-2}\,k\,\frac{A_{Xn}}{a_{Xs}^2}.$$

$k = 1$ in the case of bremsstrahlung photons. Other values of k would apply in the case of electrons. a_{Xs} is the distance from the patient (first scattering point of the direct radiation) to the point that has to be protected. A_{Xn} is the maximum radiation field size at the isocenter (1 m). Usually the maximum field size for accelerators of these characteristics is 40 cm × 40 cm, so $A_{Xn} = 0.16$ m^2.

Direct neutron radiation. Direct neutron radiation has to be contemplated in the points 4, 5, 6, 7, 8, 9 and 10. The reduction factor is

$$R_{Nn} = \frac{\dot{D}_N}{\dot{D}_{Xn}} \frac{a_0^2}{a_n^2} \alpha\, 10$$

$\dot{D}_N/\dot{D}_{Xn}$ must be provided by the manufacturer of the accelerator. In this case, $\dot{D}_{Xd}/\dot{D}_{Xn} = 0.002$.

Tertiary radiation. Tertiary radiation has to be taken into account only in the door (point 11). The reduction factor for is:

$$R_{Xt} = 10^{-2} \left[\frac{\dot{D}_{Xd}}{\dot{D}_{Xn}} \frac{a_0^2}{a_n^2} + 10^{-6} \right] \frac{A_{Xt}}{a_{Xt}^2} \alpha$$

A_{Xt} is the area in the direction of the area to be protected affected by tertiary radiation, and a_{Xt} is the distance from the center of this area to the point to be protected.

Scattered neutron radiation. Scattered neutron radiation is only important close to the door. The reduction factor is

$$R_{Ns} = \frac{\dot{D}_N}{\dot{D}_{Xn}} \cdot \frac{a_0}{a_n} \cdot \frac{b}{l} \cdot \alpha$$

b/l is the width-to-length ratio of the bunker maze.

When two or more components of the radiation field affect the studied area, it must be verified whether the thickest shielding is enough or if an increment is needed. It is usually required greater shielding for the scattered radiation and direct neutron radiation alike so it has to be compared this two components. The calculus of the increment, if necessary, is described in the Norm DIN 6847-2.

IV. RESULTS AND CONCLUSIONS

Once all the calculations have been made, it has been obtained a range for 90 to 165 cm of heavy concrete in each of the walls and roof and 1.25 cm of lead and 26.30cm of paraffin in the door, as shown in Table I. The floor does not need any shielding because the bunker is located just above the foundations of the hospital.

It also has to be taken into account that the radiological protection of a radiotherapy facility does not only include the shielding of the bunker; the area must be marked as an area with irradiation risk and emergency stopping buttons must be available inside the bunker and in the control area. Moreover, the bunker door must have a security system which does not allow to proceed with the therapy if it is open and a light sign must be present at the entrance to alert if the accelerator is on.

TABLE I: Shielding results

Point	Material	Thickness s_i (cm)
1	Heavy concrete	145
2	Heavy concrete	155
3	Heavy concrete	165
4	Heavy concrete	95
5	Heavy concrete	90
6	Heavy concrete	90
7	Heavy concrete	110
8	Heavy concrete	100
9	Heavy concrete	95
10	Heavy concrete	140
11	Lead	1.25
11	Paraffin	26.30

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