DESIGN OF A TREATMENT ROOM FOR AN 18-MV LINAC

ACCELERATORS

KEYWORDS: *Monte Carlo methods, shielding design, linear accelerator*

LUIS HERNANDEZ-ADAME,[a]* HECTOR CONTRERAS-SANDOVAL,[a] HECTOR RENE VEGA-CARRILLO,[a] and LEONEL HUMBERTO PEREZ LANDEROS[b]

[a]*Universidad Autonoma de Zacatecas, Unidad Academica de Estudios Nucleares Apartado Postal 336, Zacatecas, 98000, Mexico*
[b]*Instituto Zacatecano del Tumor, Apartado Postal 294, Zacatecas, 98000, México*

Received April 19, 2010
Accepted for Publication December 2, 2010

This work studies the design of the treatment room for an 18-MV linac to ensure radiation protection and safety of hospital staff and patients. The walls' thickness, the door, and the maze were designed according to the National Council on Radiation Protection and Measurements Report 151 recommendations. The results of this work are contrasted with the Monte Carlo calculations performed with the MCNP5 code where dose equivalents due to neutrons and neutron spectra estimated at different points inside and outside the radiotherapy room verify that the shielding thicknesses obtained are enough to reduce the dose level permitted by Mexican regulation.

I. INTRODUCTION

For the more than 200 cancer types that have been identified, radiotherapy with a linac is one of the most frequently used techniques for the control and treatment of those cancers.[1,2] In radiotherapy, beams of electrons or bremsstrahlung photons are used to deliver a lethal dose to the tumor while avoiding the healthy cells.[3,4] Superficial tumors are treated with electrons while deep-seated tumors are treated with X-rays.[5] Linacs working above 8 MV produce neutrons during photon interaction with nuclei in the linac's head, patient, and bunker walls; these neutrons induce activation of air and surrounding materials.[6] Photoneutrons deliver an undesirable dose to the patient and are not considered in the planning routine; however, they could induce new tumors.[2,7] Radiotherapy using linacs is the most common procedure used worldwide; it has been estimated there will be a need for 10 000 linacs by 2015 (Ref. 7). Photons and neutrons are the radiation problem considered during the design of a linac bunker. Design guidelines have been addressed in National Council on Radiation Protection and Measurements (NCRP) publications.[8–10] In recent years an increment of cancer incidence has been reported in the state of Zacatecas in Mexico. Therefore, health authorities have decided to purchase an 18-MV linac; for this, a bunker must be designed to protect hospital staff and patients.

The aim of this work is to review the NCRP Report No. 151 (NCRP 151) procedure to evaluate the shielding of an 18-MV linac and to estimate the neutron spectra inside and outside the linac bunker using Monte Carlo methods.

II. DEFINITIONS AND CONSIDERATIONS OF NCRP 151

Limit dose (P): The maximum level of dose equivalent H that can be measured behind the barrier.

Controlled area: A restricted area for radiation workers or authorized personnel. The dose equivalent H for this area is 0.1 mSv/week (5 mSv/yr).

Uncontrolled area: Any area with free access. The dose equivalent is 0.02 mSv/week (1 mSv/yr). In the design of barriers to protect uncontrolled areas, it must be considered that the maximum value of the radiation in any-one-hour R_h must be <0.02 mSv/h.

Workload (W): The absorbed dose in 1 week of work at 1 m from the target (Gy/week). Considering the intensity-modulated radiation therapy (IMRT) technique, the workload is expressed as the quotient of the

*E-mail: dameluis@hotmail.com

needed monitor units MU to apply 1 Gy in the isocenter of a planification with IMRT MU_{IMRT} and the monitor units that are necessary for a conventional treatment MU_{conv}, as shown in Eq. (1):

$$C_1 = \frac{MU_{\mathrm{IMRT}}}{MU_{conv}} \quad . \tag{1}$$

Use factor (U): The fraction of the workload that the primary beam is directed through the place to protect. The use factor for primary barriers is taken from Table 3.1 of NCRP 151.

Occupancy factor (T): The fraction of the accelerator operating time that an individual is likely to be in an area outside but next to a shielded room.

Tenth-value layer (TVL): The material thickness that attenuates the radiation intensity at 10% of its initial value.

Primary barriers are those that receive the X-ray beam directly; they must be capable of reducing the radiation to the limit dose levels P. The linac's highest energy is taken to calculate the thickness barrier.

Secondary barriers attenuate radiation leaking out from the head and radiation scattered by the patient and by items inside the treatment room. The dose contribution due to the scattered radiation increases with the intensity and area of the radiation beam, the scattering angle that crosses the patient, in such way that NCRP 151 proposes in Table B.4 of Appendix B the fraction of the beam that is scattered for different scattering angles α in a human-sized phantom.

The maze in a radiotherapy room is designed to attenuate photons and neutrons produced by the primary beam interacting with the surfaces and patient inside the room. In the door the dose due to photons transported in the maze depends upon the following components:

1. H_S is the dose equivalent per week due to scatter of the primary beam from the room surfaces, as shown in Fig. 1, and is calculated with Eq. (2):

$$H_S = \frac{W \cdot U_G \cdot \alpha_0 \cdot A_0 \cdot \alpha_Z \cdot A_Z}{(d_{pp} \cdot d_r \cdot d)^2} \quad , \tag{2}$$

where

W = workload (Gy/week)

U_G = use factor

α_0 = reflection coefficient at the first scattering surface A_0

α_Z = reflection coefficient for second reflection from the maze surface A_z

A_0 = beam area at the first scattering surface (m^2)

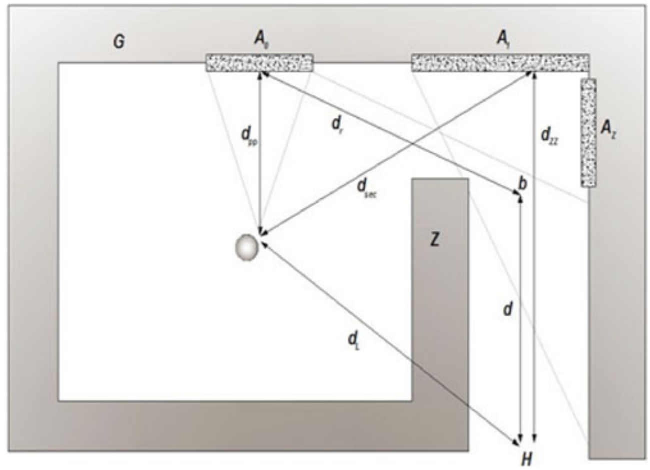

Fig. 1. Layout and parameters used for dose due to the photons at the door.

A_Z = cross-sectional area of maze inner entry projected onto the maze wall

d_{pp} = distance from the isocenter at primary barrier (m)

d_r = distance from beam center at the first reflection, past the edge of the inner maze wall, to point b on the midline of the maze (m)

d = centerline distance along the maze from point b to the maze door (m).

2. H_{LS} is the dose equivalent per week due to head-leakage photons scattered by the room surfaces and is calculated with Eq. (3):

$$H_{LS} = \frac{L_f \cdot W_L \cdot U_G \cdot \alpha_1 \cdot A_1}{(d_{sec} \cdot d_{zz})^2} \quad , \tag{3}$$

where

L_f = head-leakage radiation ratio at 1 m from the target taken from NCRP 151

W_L = workload for leakage radiation (Gy/week)

α_1 = reflection coefficient for scatter of leakage radiation

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

d_{sec} = distance from the target to the maze centerline (m)

d_{zz} = centerline distance along the maze (m).

3. H_{ps} is the dose equivalent per week at the maze door due to patient-scattered radiation and is calculated with Eq. (4):

$$H_{ps} = \frac{a(\theta)\cdot W\cdot U_G\cdot\left(\dfrac{F}{400}\right)\cdot\alpha_1\cdot A_1}{(d_{sca}\cdot d_{sec}\cdot d_{zz})^2} \quad , \tag{4}$$

where

$a(\theta)$ = scatter fraction for patient-scattered radiation at angle θ (from Table B.4 in Appendix B of NCRP 151)

F = field area at mid-depth of the patient at 1 m (cm^2)

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

4. H_{LT} is the dose equivalent per week at the maze door due to leakage radiation that is transmitted through the inner maze wall and is calculated with Eq. (5):

$$H_{LT} = \frac{L_f\cdot W_L\cdot U_G\cdot B}{d_L^2} \quad , \tag{5}$$

where

B = transmission factor for wall Z along the oblique path traced by d_L

d_L = distance from the target to the center of the maze door through the inner maze wall (m).

The total dose due to the photons in the door is calculated with Eq. (6) and the sum of all the components. However, McGinley[8] suggests the use of a factor of 2.64 as well as a factor f that estimates the fraction of the primary beam that is transmitted through the patient (f = 0.34 for energy >11 MeV):

$$HH_{Tot} = 2.64\cdot(fH_S + H_{LS} + H_{ps} + H_{LT}) \quad . \tag{6}$$

II.A. Photon Dose Due to Neutron Capture

Bunker doors are designed with lead thick enough to stop leakage and scattered photons. Equation (7) is used to estimate the photon dose per unit dose delivered at the isocenter due to neutron capture h_φ:

$$h_\varphi = K\cdot\varphi_A \times 10^{-(d_2/TVD)} \quad , \tag{7}$$

where

K = neutron capture gamma-ray dose equivalent to the total neutron fluence ratio at location A in Fig. 2

φ_A = total neutron fluence (m^{-2}) per unit absorbed dose (Gy) of X-rays at the isocenter at location A

d_2 = distance from location A to the door (m)

TVD = tenth-value distance.

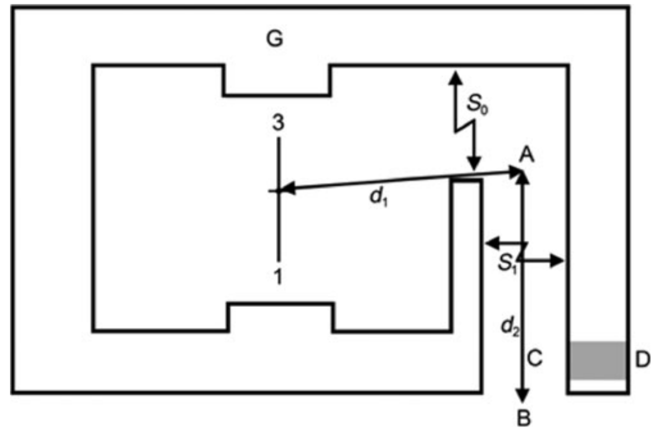

Fig. 2. Parameters used for the neutron fluence.

II.B. Dose Due to Photoneutrons

At any point in the room the total neutron fluence φ_A, shown in Eq. (8), is due to direct neutrons φ_{dir} coming from the head, scattered neutrons φ_{sc}, and a thermal component φ_{th} due to room-return[11]:

$$\varphi_A = \frac{\beta\cdot Q_n}{4\cdot\pi\cdot d_1^2} + \frac{5.4\cdot\beta\cdot Q_n}{2\cdot\pi\cdot s} + \frac{1.3\cdot Q_n}{2\cdot\pi\cdot s} \quad , \tag{8}$$

where

β = transmission factor for neutrons that pass through the head (β is 1 and 0.85 for the lead and tungsten heads, respectively)

d_1 = distance from the isocenter to location A (m) in Fig. 2

Q_n = neutron source strength per gray applied at the isocenter (n/Gy) given in Table B.9 of Appendix B of NCRP 151 (Ref. 9)

S = total surface area of the treatment room (m^2).

To calculate the neutron dose $H_{n,D}$ at the maze entrance, NCRP 151 proposes two methods: the Kersey method, shown in Eq. (9), and the McGinley method, shown in Eq. (10):

$$H_{n,D} = H_0\cdot\left(\frac{S_0}{S_1}\right)\cdot\left(\frac{d_0}{d_1}\right)^2 \times 10^{-(d_2/5)} \tag{9}$$

and

$$H_{n,D} = 2.4\times 10^{-15}\cdot\varphi_A\cdot\sqrt{\frac{S_0}{S_1}} \times [1.64\times 10^{-(d_2/1.9)} + 10^{-(d_2/TVD)}] \quad , \tag{10}$$

where

H_0 = total neutron dose equivalent (mSv/ Gy) applied to the isocenter, at a distance d_0, which is 1.41 m, according to Kersey's method

S_0/S_1 = ratio of the inner maze entrance cross-sectional area to the cross-sectional area along the maze, as shown in Fig. 2.

The coefficient in Eq. (10) is in Sv n^{-1} m^2, where n stands for "per neutron emitted."

III. MATERIALS AND METHODS

The bunker design was for a Varian 2100 linac under the following working conditions: 40 patients will be treated in 8 h (5 patients/h); workload $W = 500$ Gy/week recommended by NCRP 151, according to IMRT; workload for leakage radiation $W_L = 900$ Gy/week; and the limit dose is 0.02 mSv/week for the general public and 0.1 mSv/week for radiation workers. The walls are made of ordinary 2.35 g/cm^3 concrete, whose elemental composition is Portland-type concrete.[12]

Figure 3 shows a layout from the distribution of the barriers in the radiotherapy room. Walls exposed to the primary radiation are 1, 2, floor, and ceiling. Those exposed to secondary radiation are 1S, 2S, 3, 4, and 5.

III.A. Shielding Calculations

III.A.1. Primary Barriers

Calculate the transmission factor B_x for the barrier with Eq. (11):

$$B_x = \frac{P \cdot d^2}{W \cdot U \cdot T} \ , \tag{11}$$

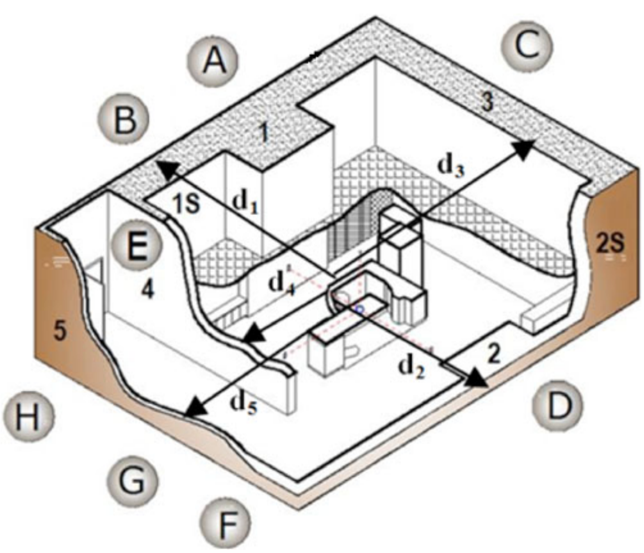

Fig. 3. Distribution for primary and secondary barriers.

where

P = limit dose (Sv/wk)

W = workload (Gy/wk)

d = distance from the target to the target to point to be protected (m)

U = use factor

T = occupancy factor.

The TVL number n is calculated with Eq. (12), and the thickness of the barrier is obtained with Eq. (13):

$$n = \log_{10}\left[\frac{1}{B_x}\right] \tag{12}$$

and

$$t_{barrier} = \mathrm{TVL}_1 + (n-1)\mathrm{TVL}_e \ , \tag{13}$$

where

TVL_1 = first tenth-value layer

TVL_e = equilibrium tenth-value layer that accounts for the spectral changes in the radiation as it penetrates the barrier.

As a general rule, the primary barrier's width W_p is determined using the diagonal length of the beam's largest area, 40×40 cm^2, adding 30.5 cm to each side, as shown in Eq. (14), where d_w is the distance from the target to the adjacent secondary barrier (m):

$$W_p = 0.566 d_W + 0.61 \ . \tag{14}$$

In these calculations for uncontrolled areas, the dose limit in any hour R_h must be <0.02 mSv. This is calculated with Eq. (15):

$$R_h = \frac{N_{\max}}{t \cdot \bar{N}_h}\left[\frac{B_{pri} \cdot W_{pri} \cdot U_{pri}}{d_{pri}^2}\right] \ , \tag{15}$$

where

$N_{\max}$ = maximum number of patients that will be treated in 1 h

$\bar{N}_h$ = half-number of patients treated in 1 h during the week

t = number of treatment hours during the week

B_{pri} = transmission factor of the primary barrier

W_{pri} = workload of the primary barrier (Sv/week)

U_{pri} = use factor for the primary barrier

d_{pri} = distance from the target to the primary barrier (m).

III.A.2. Secondary Barriers

This shielding is calculated with the double source criteria, including the scattered and leakage radiation; the necessary thickness is calculated to independently obtain the limit dose P behind the barrier for each contribution (scattering and leakage radiation). With Eq. (16) the barrier transmission factor B_{ps} for scattered radiation can be calculated:

$$B_{ps} = \frac{P}{aWT} d_{sca}^2 d_{sec}^2 \frac{400}{F} \ , \tag{16}$$

where

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

d_{sec} = distance from the patient to the point to be protected (m)

F = area of the maximum field at 1 m (cm^2)

α = coefficient of the scattering radiation fraction scattered by the patient.

This calculation is obtained from Appendix B of NCRP 151. With Eq. (17) the transmission factor B_L for leakage radiation is calculated:

$$B_L = \frac{P \cdot d_L^2}{10^{-3} \cdot W_L \cdot T} \ , \tag{17}$$

where

d_L = distance from the isocenter to the secondary barrier (m)

W_L = workload for leakage radiation (Sv/week)

P = limit dose (Sv/week)

T = occupancy factor.

Equations (12) and (13) calculate the TVLs and barrier thickness. To define the final thickness, the thickness required to deal with the scattered radiation is compared with the thickness barrier that holds the leakage radiation. If the lowest thickness is different from the highest in more than one TVL, definitive thickness is the highest; otherwise, another half-value layer will be added to the highest calculated thicknesses. It must be verified that in uncontrolled areas, the dose limit at any time R_h, calculated with Eq. (18), should not be $>$0.02 mSv:

$$R_h = \frac{N_{\max}}{t \cdot \bar{N}_h} \left[\left(\frac{C_F \cdot B_L \cdot W_L}{d_L^2} \right) + \left(\frac{a \cdot F \cdot B_{ps} \cdot W_{ps} \cdot U_{ps}}{400 \cdot d_{sec}^2} \right) \right] \ , \tag{18}$$

where

C_F = head leakage factor (10^{-3})

d_L = distance from the isocenter to the secondary barrier (m)

TABLE I

Parameters Used to Calculate the Shield Features of the Door

$d_h = 3.3$ $d_r = 6.4$ $d_1 = 7.4$	$d = 7.4$ $d_0 = 1.41$ $S_0 = 2.4$ m^2	$\alpha_0 = 30$ deg $\alpha_1 = 30$ deg $S_1 = 2.5$ m^2	$d_z = 7.8$ $d_{sec} = 7.7$ $\alpha_z = 45$ deg	$d_{zz} = 10.3$ $d_L = 8.8$

a = fraction of scattered radiation in the patient at 1 m for a 400-cm^2 field at a given angle

F = maximum field area at 1 m (cm^2)

d_{sec} = distance from the patient to the secondary barrier (m)

B_L = attenuation factor of the given barrier for leakage radiation

W_L = workload for leakage radiation (Sv/week)

B_{PS} = barrier attenuation factor to the scattered radiation in the patient

W_{PS} = workload of scattered radiation by the patient (Sv/week)

U_{PS} = barrier use factor.

The NCRP 151 procedure to calculate the barriers is based on the type or area and the limit dose, and then several simple closed-form equations are applied, making the designing task fast and insightful. However, in this procedure the underlying physical interactions are not considered, and results tend to be conservative, producing overshielded areas. Also, the presence of steel beams, conduits, or ventilation ducts is not considered, leaving no room to apply optimization procedures.

III.A.3. Door Shield Design

To calculate the door, the dose at the end of the maze must be estimated. With Fig. 1, the equivalent dose due to scattered and leakage radiation in the door is calculated using Eq. (6) and data in Table I.

Using Eq. (19) the dose contribution due to neutron capture H_{cg} is calculated:

$$H_{cg} = W_L \cdot h_{\varphi} \ . \tag{19}$$

III.B. Monte Carlo Calculation

To analyze the neutron spectra around the linac and outside the bunker, Monte Carlo calculations were carried out using the MCNP 5 code.[13]

The photoneutron source term for the MCNP calculations was obtained using the Tosi et al.[14] function shown in Eq. (20) that contains the expression for evaporation neutrons and for direct-reaction or knock-on neutrons:

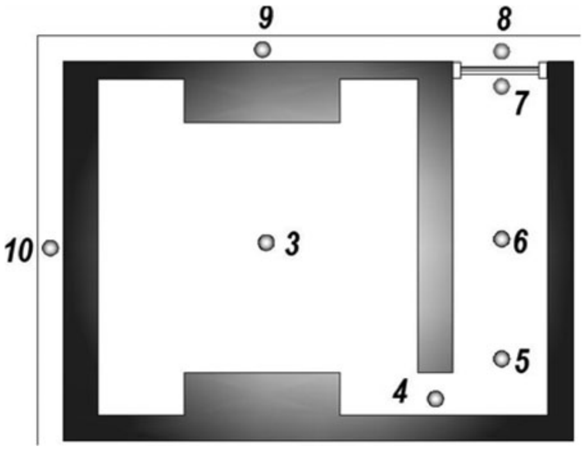

Fig. 4. Detector distribution.

$$n(E_n) = X\frac{E_n}{T^2}\exp\left[-\frac{E_n}{T}\right] + Y\frac{\ln\left[\dfrac{E_{\max}}{E_n+B}\right]}{\displaystyle\int_0^{E_{\max}-B}\ln\left[\frac{E_{\max}}{E_n+B}\right]dE_n}\ , \tag{20}$$

where

$X = 0.8929$ and $Y = 0.1071$ for tungsten heads

$T = 0.5$ MeV

$B = 7.34$ MeV

$E_{\max} = 18$ MeV

E_n = neutron energy

$n(E_n)$ = amount of photoneutrons with energy between E_n and $E_n + dE_n$.

The source was located at the center of a 10-cm-radius sphere made of tungsten[15] with a conic aperture to produce an irradiation area of 10×10 cm^2 at the isocenter located 10 cm deep in a water-made head phantom ($15 \times 15 \times 15$ cm^3). With MCNP5, a detailed model of the treatment room was made, modeling the walls as Portland concrete[12] and the door with a 5% borated-polyethylene sheet sandwiched between two lead sheets. Neutron spectra and the dose equivalent H, in points 1 to 10 shown in Figs. 4 and 5, were estimated; H was obtained using the fluence-to-dose equivalent conversion factors from NCRP Report No. 38 (Ref. 16). In the calculations, cross sections from the ENDF/B-VI.8 libraries were utilized; the histories used in the calculations were large enough to obtain a Monte Carlo uncertainty <5%.

IV. RESULTS

IV.A. NCRP 151 Procedure

In Table II, the primary and secondary barriers' thicknesses obtained with NCRP 151 are shown. The width of the primary barriers is 4 m, and the thickness variations depend upon the area to be protected, the use factor, the occupancy factor, and the dose level limit per hour for uncontrolled areas. The door is a 6.2-cm-thick plate of 5% borated polyethylene sandwiched between two 3-cm-thick sheets of lead.

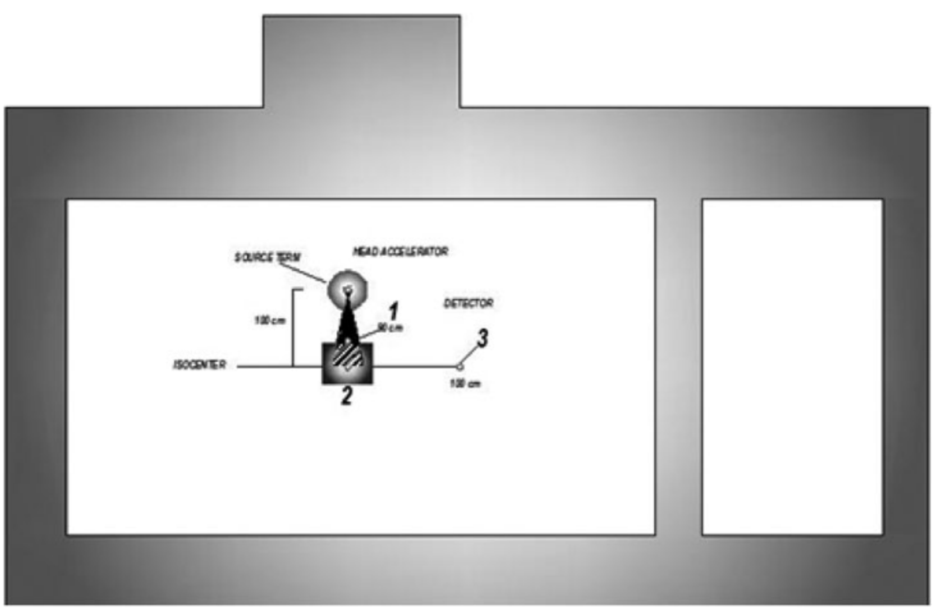

Fig. 5. View of the treatment room on the Z-axis.

TABLE II

Thickness for Primary and Secondary Barriers

Site in Fig. 3	Wall	Near	Thickness (cm)	
			Primary	Secondary
A	1	Simulator hall	200	
B	1S	Control room		80
C	3	Garden		100
D	2	Garden		100
E	4	Maze	230	80
F	5	Brachytherapy hall		80
G	5	Brachytherapy control room		80
H	5	Office		80
I	Ceiling	Unoccupied	215	100

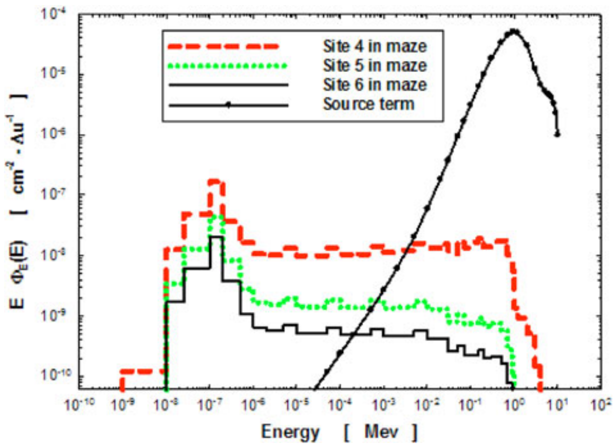

Fig. 7. Neutron spectra at the maze.

IV.B. MCNP Simulation

Figure 6 shows the spectra on the phantom surface, in the isocenter, and 100 cm from the isocenter. For comparison the source term was also included. Spectra above the phantom surface and at 100 cm from isocenter are alike. Both have thermal neutrons due to room-return and neutron interaction with the water phantom; these spectra have a maximum near 1 MeV due to evaporation neutrons.

The dose equivalent H per gray of X-ray is 2.04 mSv/Gy above the phantom and 6.9×10^{-3} mSv/Gy at 100 cm; the difference is due to the distance with respect to the source term and to the neutron interaction with the phantom. The spectrum at the isocenter shows an increase in the thermal neutrons and a decrease in neutrons produced by evaporation and knock-on reactions due to moderation and neutron thermalization in the phantom. Here, H is 0.012 mSv/Gy.

Neutron spectra in the maze (points 4, 5, and 6 of Fig. 4) are shown in Fig. 7, where the spectrum decreases as the distance increases. Evaporation neutrons are strongly reduced, enhancing the thermal neutrons due to distance and interactions with air and walls inside the hall. The dose equivalent H is 1.3×10^{-3} mSv/Gy (site 4), 2.2×10^{-4} mSv/Gy (site 5), and 9.5×10^{-5} mSv/Gy (site 6).

Figure 8 evaluates the shielding obtained at the door. The spectra are shown inside and outside, where the shielding effect of the door can be noticed. Outside, the spectra decrease in all components, but in the fast neutron zone the spectrum is negligible. In these locations H is 5×10^{-5} mSv/Gy (inside) and 2×10^{-6} mSv/Gy (outside).

Figure 9 shows the neutron spectra behind the primary and secondary barriers (points 9 and 10 in Fig. 4). We can observe that neutrons are strongly reduced and are mostly in the thermal region.

Outside the primary barrier H is 8×10^{-9} mSv/Gy, and outside the secondary barriers H is 6.3×10^{-8} mSv/Gy. The spectrum has been practically attenuated by the wall thickness calculated because the neutrons are attenuated by the air, hydrogen, and other elements contained in the concrete.

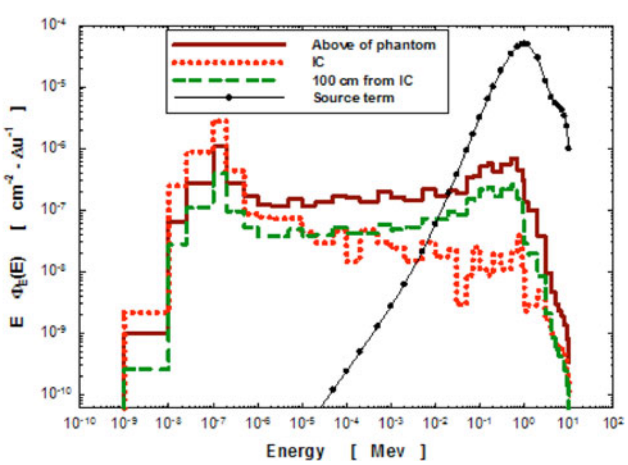

Fig. 6. Neutron spectra around the phantom (IC = isocenter).

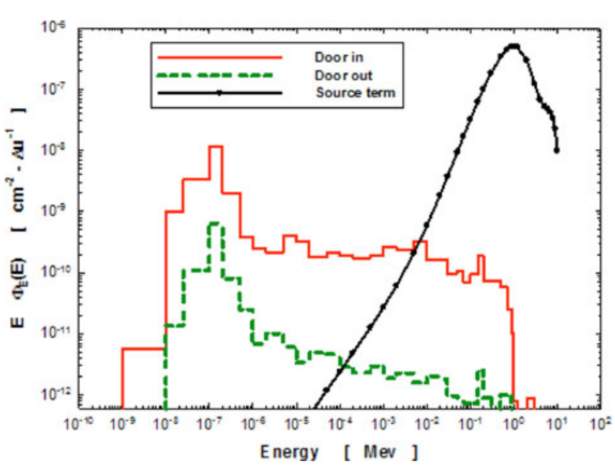

Fig. 8. Neutron spectra by the door.

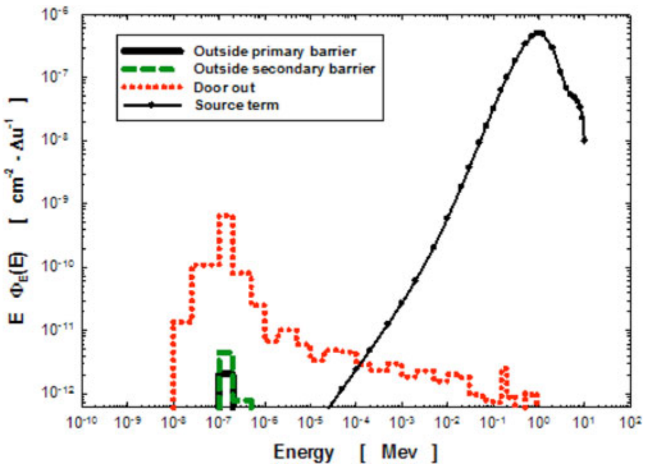

Fig. 9. Neutron spectra outside the door and behind primary and secondary barriers.

V. CONCLUSIONS

The thicknesses for the wall and door obtained with the NCRP 151 procedures and the results obtained through the Monte Carlo calculations show that the shielding is enough to reduce the dose equivalent H level due to neutrons produced by the accelerator head to acceptable values according Mexican regulations (0.4 mSv/week to controlled areas and 0.02 mSv/week to uncontrolled areas). The shielding design has been made for a neutron source strength Q of 0.96×10^{12} n/Gy of X-rays at the isocenter, dose equivalent H of 0.1 mSv/week for controlled areas, and 0.02 mSv/week for uncontrolled areas as well as their respective values of occupancy, use, and workload factors. Monte Carlo calculations show H of 7.2×10^{-6} mSv/week outside the primary barrier, H of 5.6×10^{-5} mSv/week outside the secondary barrier, and H of 0.002 mSv/week outside the door. The dose behind the primary and secondary barriers can be considered negligible. The flux in these areas has decreased almost completely in the fast (near 1 MeV) and epithermal neutron zone where the neutrons are the most dangerous. Outside the door is considered a controlled area, and the H is lower than reference value given by NCRP 151 and Mexican regulations. Therefore, the shielding designs are enough to attenuate the dose due to neutrons where the dose equivalent will be depreciated and the work areas will be safe.

ACKNOWLEDGMENTS

This work has been partially supported by Consejo Zacatecano de Ciencia, Tecnologia e Innovacion and Consejo Nacional de Ciencia y Tecnologia.

REFERENCES

1. C. ONGARO, A. ZANINI, U. NASTASI, J. RODENAS, and G. OTTAVIANO, "Analysis of Photoneutron Spectra Produced in Medical Accelerators," *Phys. Med. Biol.*, **45**, L55 (2000).

2. M. ZABIHZADEH, M. REZA, M. ALLAHVERDI, A. MESBAHI, and S. RABEE, "Monte Carlo Estimation of Photoneutrons Contamination from High-Energy X-Ray Medical Accelerators in Treatment Room and Maze: A Simplified Model," *Radiat. Prot. Dosim.*, **135**, 21 (2009).

3. A. J. LENOX, "Accelerators for Cancer Therapy," *Radiat. Phys. Chem.*, **61**, 223 (2001).

4. H. R. VEGA-CARRILLO, B. HERNANDEZ, V. M. HERNANDEZ, and A. ORTIZ, "Neutron Spectrum and Doses in a 18 MV LINAC," *J. Radioanal. Nucl. Chem.*, **283**, 261 (2010).

5. R. BARQUERO, R. MENDEZ, H. R. VEGA-CARRILLO, M. P. IÑIGUEZ, and T. M. EDWARDS, "Neutron Spectra and Dosimetric Features Around a 18 MV Medical Linear Accelerator," *Health Phys.*, **88**, 49 (2005).

6. H. R. VEGA-CARRILLO, A. ORTIZ, V. M. HERNANDEZ, B. HERNANDEZ, and T. RIVERA, "H*(10) and Neutron Spectra Around LINACs," *J. Radioanal. Nucl. Chem.*, **283**, 537 (2010).

7. "Radiation Protection in the Design of Radiotherapy Facilities," IAEA Safety Report Series No. 47, International Atomic Energy Agency (2006).

8. P. H. McGINLEY, *Shielding Techniques for Radiation Oncology Facilities*, Medical Physics Publishing, Madison, Wisconsin (1998).

9. "Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities," Report No. 151, National Council on Radiation Protection and Measurements (2005).

10. "Radiation Protection Design Guidelines for 0.1–100 MeV Particle Accelerator Facilities," Report No. 51, National Council on Radiation Protection and Measurements (1977).

11. H. R. VEGA-CARRILLO, E. MANZANARES, M. P. IÑIGUEZ, E. GALLEGO, and A. LORENTE, "Study of Room-Return Neutrons," *Radiat. Meas.*, **42**, 413 (2007).

12. S. M. SELTZER and M. J. BERGER, "Evaluation of the Collision Stopping Power of Elements and Compounds for Electrons and Positrons," *Int. J. Appl. Radiat. Isot.*, **33**, 1189 (1982).

13. X-5 MONTE CARLO TEAM, "MCNP-A General Monte Carlo N-Particle Transport Code," Version 5, LA-UR-03-1987, Los Alamos National Laboratory (2003).

14. G. TOSI, A. TORRESIN, S. AGOSTEO, A. FOGLIO, V. SANGIUST, L. ZENI, and M. SILARI, "Neutron Measurements Around Medical Electron Accelerators by Active and Passive Detection Techniques," *Med. Phys.*, **18**, 54 (1991).

15. R. C. FALCAO, A. FACURE, and X. SILVA, "Neutron Dose Calculation at the Maze Entrance of Medical Linear Accelerator Rooms," *Radiat. Prot. Dosim.*, **283**, 123 (2006).

16. "Protection Against Neutron Radiation," NCRP Report No. 38, National Council on Radiation Protection and Measurements (1971).