An estimation of cost of concrete shielding in a radiotherapy room housing a clinical linear accelerator that produces high-energy photons – Part II

Uma estimativa do custo da blindagem de concreto em uma sala de radioterapia que abriga um acelerador linear clínico que produz fótons de alta energia – Parte II

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ABSTRACT
High-energy photons produced by large medical linear accelerators are widely used in medicine for the treatment of various types of malignant tumors. In the last decades the use of photon beams in radiation therapy was improved due to the arising of advanced technologies and techniques of treatment such as IMRT (intensity modulated radiation therapy), VMAT (volumetric modulated arc therapy), IGRT (image guided radiotherapy) and SBRT (stereotactic body radiation therapy). However, we should guarantee that the use of these procedures does not increase the radiation doses in the vicinities of the radiotherapy room above the permissible level. In this work we carry out an estimation of cost of concrete shielding for a standard radiotherapy room and for photon energies ranging from 4 to 30 MeV (megaelectron volts), and always considering the constraint of the allowed level of radiation in the vicinity of the room. Results have indicated that total cost of concrete increases about 22-25% when photon energies increase from the minimum to the maximum values analyzed. Results also indicated an overall linear increasing of cost with the area of the treatment room and may support some of the guidelines of radiation protection.

Keywords: radiotherapy, radiation protection, linear accelerator, shielding.

RESUMO
Fótons de alta energia produzidos por grandes aceleradores lineares médicos são amplamente utilizados na medicina para o tratamento de vários tipos de tumores malignos. Nas últimas décadas o uso de feixes de fótons em radioterapia foi aprimorado devido ao surgimento de tecnologias e técnicas avançadas de tratamento como IMRT (radioterapia de intensidade modulada), VMAT (terapia de arco modulado volumétrico), IGRT (radioterapia guiada por imagem) e SBRT (radioterapia estereotáxica corporal). No entanto, devemos garantir que o uso
desses procedimentos não aumente as doses de radiação nas proximidades da sala de radioterapia acima do nível permitido. Neste trabalho realizamos uma estimativa de custo de blindagem de concreto para uma sala de radioterapia padrão e para energias de fótons que variam de 4 a 30 MeV (megaelettron volts), e sempre considerando a restrição do nível de radiação permitido nas proximidades da sala. Os resultados indicaram que o custo total do concreto aumenta cerca de 22-25% quando as energias dos fótons aumentam dos valores mínimos para os valores máximos analisados. Os resultados também indicaram um aumento linear geral do custo com a área da sala de tratamento e podem apoiar algumas das diretrizes de proteção radiológica.

**Palavras-chave:** radioterapia, proteção radiológica, acelerador linear, blindagem.

1 INTRODUCTION

Photon beams produced by large clinical particle linear accelerators are widely used for the treatment of various kind of cancer [SCARINGI, 2018; TSENG, 2020]. In the last decades external beam radiation therapy has significantly evolved due to the appearing of new technologies and advanced techniques of treatment, such as IMRT (intensity modulated radiation therapy), VMAT (volumetric modulated arc therapy), IGRT (image guided radiotherapy) and SBRT (stereotactic body radiation therapy) [KOKA, 2022]. All these modern treatment procedures used in external beam radiotherapy have the capability to deliver a high and conformal radiation dose distribution to the tumor. These procedures have the advantage of deliver a high dose to the planning target volume while preserving the surrounding healthy structures. However, the use of these advanced tools may require an especial attention in protecting the areas surrounding the facility room.

In this study we performed a shielding calculation of the walls of a standard radiotherapy facility room housing a linear accelerator that produces photons of 4, 6, 8, 10, 12, 15, 18, 20, 25 and 30 MeV\(^1\), and to different scenarios of treatment. First considering that all patients are treated with conventional radiotherapy; second considering that a part of patients are treated with IMRT and VMAT in different proportions. Considerations about which energy is more suitable for each type of treatment are not being considered [KRY, 2009; HUANG, 2020] and an

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\(^1\) 1 megaelectron-volt (MeV) refers to the maximum energy of a photon produced by the process of bremsstrahlung when an electron accelerated to a voltage of 1 mega-volt (MV) hits a heavy metallic target. Along text we may use indistinctly MeV or MV.
overall estimation of the cost of concrete shielding (in US$) as a function of photon beam energies and area available to build the room is discussed.

2 METHODS

A standard radiotherapy facility room is depicted in Figures 1 and 2. It should be noticed that this room design is different from the room shown in a previous work [DE PAIVA, 2022]; now the primary photon beam falls on walls C and F instead of walls A and E. These two rooms represent the most common radiotherapy room layout found everywhere.

When a photon beam traverses the primary barrier the transmission factor is written as [NCRP, 2005; DE PAIVA, 2018; DE PAIVA, 2022]

\[ B_{\text{prim}} = \frac{P d_{\text{prim}}^2}{WUT}, \quad (1) \]

where \( d_{\text{prim}} \) is the distance from the source to the point of interest; \( P \) is the shielding design goal, \( W \) is the workload, and \( T \) and \( U \) are the dimensionless occupancy and use factors. Let us assume that walls C, F and T are primary barriers; all the others are secondary barriers. Locations behind walls A (garden), B, C, D (parking lot), G (waiting room) and T, T1, T2 (offices) are uncontrolled type areas and region behind wall E (control room) is a controlled type area. The shielding design goals for uncontrolled and controlled areas are, respectively, 0.02 and 0.1 mSv/week [NCRP, 2005]; the use factors for primary barriers are 1/4 (C, F and T) and 1 for the others; the occupancy factors are 1/16 for A, B, C, D; 1 for E, and 1/2 for G, T1, T2 and T.

For the leakage radiation (radiation that escapes from the accelerator head) the transmission factor is similarly given by

\[ B_L = \frac{P d_L^2}{(0.1\% W)UT}, \quad (2) \]
Figure 1. The scheme of the standard radiotherapy facility room used throughout calculations.

Figure 2. A schematic lateral view of the treatment room used in this short note.

Here $d_L$ is the distance from the isocenter (a point about which the source
can rotate up to 360 degrees) to the point of interest and is assumed that 0.1% of radiation doses escape from the accelerator head [NCRP, 2005]. Thus, when advanced procedures are included in the routine treatment the workload for leakage radiation can increase due to the large amount of monitor units per dose of radiation and is given by [NCRP, 2005]

\[
W_L = W_{conv} + C_i W_{conv} + C_V W_{conv},
\]

(3)

where \( C_i \) and \( C_V \) are the IMRT and VMAT modulation factors.

For radiation scattered at patient the transmission factor is written as

\[
B_{scat} = \frac{1}{\text{coef}} \frac{P d_{scat}^2 d_{sec}^2}{WUT} \frac{400}{F},
\]

(4)

where \( d_{scat} \) and \( d_{sec} \) are, respectively, the distances from the photon source to the scattering point (located at the isocenter) and from the scattering point to the point of interest; \( F \) is the field area at the isocenter, and \( \text{coef} \) is the fraction of the primary beam that scatters from the patient which depends on the incidence angle.

Finally, the thickness \( t \) for primary or leakage barriers are

\[
t = TVL_1 + (n - 1)TVL_e,
\]

(5)

where \( TVL_1 \) and \( TVL_e \) are the first and the equilibrium \( TVL \)'s (tenth-value layers), and \( n \) is the number of \( TVL \)'s given by \( n = -\log (B) \). For scattered radiation the thickness is given by

\[
t_{scat} = n TVL_{scat}.
\]

(6)

Along this study a set of assumptions and approaches are adopted:

i. Only single photon beam energies are considered.

ii. A standard radiation treatment room is considered.

iii. The maximum area available to build the room is \( a \times b \).
iv. Parameters $e$, $f$, $h$ and $h_0$ are constants for all photon energies and have the values (in meters): $e = f = 2.7$, $h = 5.7$ and $h_0 = 0.4$. Details on these parameters are shown in Figures 1 and 2.

v. The isocenter is a point located at $(c/2, b/2)$.

vi. The absorbed-dose output rate is assumed to be constant for all photon energies.

vii. Wall F is calculated as a primary barrier but is assumed to have the thickness of 1 TVL of the primary radiation for each photon energy. Wall G has the thickness of the primary barrier thickness of F minus 1 TVL.

viii. Scattered radiation incident on walls A and E comes from 90 degrees scattering of the primary beam at patient.

ix. Scattered radiation incident on walls B and D comes from scattering of the primary beam at an angle defined when the beam incidence is horizontal.

x. The values of TVL’s for primary and leakage radiation are obtained by linear interpolation at energies whenever they are not available.

xi. The values of TVL’s and scatter fractions for scattered radiation are obtained by linear interpolation at energies whenever they are not available.

xii. Radiation doses from particles produced in the accelerator head are not considered.

xiii. In this study the price of one cubic meter of concrete was arbitrary chosen as US$ 100. This approach allows anyone to obtain the total costs for any value of cubic meter of concrete.

To perform all calculations of barrier thicknesses, widths and volumes a computational calculation routine based on the Fortran programming language was implemented [DE PAIVA, 2018; DE PAIVA, 2022].

3 RESULTS

In this study we consider photon energies ranging from 4 to 30 MeV; three conventional workloads, 800, 1.000 and 1.200 Gy/week; and the three following scenarios of treatment.

i. 100% of patients treated with conventional radiotherapy.

ii. 50% of patients treated with conventional radiotherapy, 30% with IMRT and 20% with VMAT [DE PAIVA, 2022].
iii. 10% of patients treated with conventional radiotherapy, 50% with IMRT and
40% with VMAT.

The modulation factors for IMRT and VMAT are $C_I = 5$ and $C_V = 3$ [NCRP, 2005; SALEH, 2017]. According to equation (3) the leak workloads for case ii above are respectively 2.080, 2.600 and 3.120 Gy/week; for case iii the leak workloads are 3.040, 3.800 and 4.560 Gy/week.

In Figure 3 are shown results of calculations of the total cost of concrete as a function of the photon beams, with constants $a = 15$ and $b = 11$ meters. In lower part of Figure 3 100% conventional radiotherapy treatment is considered. Results indicate that total cost of the room varies from US$ 39,506 at 4 MV to US$ 50,984 at 30 MV for the 800 Gy/week workload (circles); US$ 40,335 at 4 MV to US$ 52,052 at 30 MV for the 1,000 Gy/week workload (triangles), and US$ 41,029 at 4 MV to US$ 52,600 at 30 MV for the 1,200 Gy/week workload (squares). A difference in cost about 22% between the minimum and maximum energy to each workload and an overall difference in total cost among workloads of less than 2% can be observed.

Results presented on middle part of Figure 3 include 30% IMRT and 20% VMAT techniques. The total cost of concrete now changes from US$ 39,696 at 4 MV to US$ 53,280 at 30 MV for the 800 Gy/week conventional workload (2,080 Gy/week leakage workload); US$ 40,524 at 4 MV to US$ 54,329 at 30 MV for the 1,000 Gy/week workload (2,600 Gy/week leakage workload), and US$ 41,237 at 4 MV to US$ 55,257 at 30 MV for the 1,200 Gy/week workload (3,120 Gy/week leakage workload). A difference in cost about 25% between the minimum and maximum energy to each workload can be observed, and results also indicate an overall difference in total cost among workloads about 2%.

Results presented on upper part of Figure 3 include 50% IMRT and 40% VMAT techniques. The total cost of concrete now changes from US$ 40,494 at 4 MV to US$ 54,237 at 30 MV for the 800 Gy/week conventional workload (3,040 Gy/week leakage workload); US$ 41,341 at 4 MV to US$ 55,277 at 30 MV for the 1,000 Gy/week workload (3,800 Gy/week leakage workload), and US$ 42,049 at 4 MV to US$ 56,193 at 30 MV for the 1,200 Gy/week workload (4,560 Gy/week leakage workload). A difference in cost about 25% between the minimum and maximum energy to each workload can be observed, and results also indicate an
overall difference in total cost among workloads of less than 2%. Figure 3 also shows that the inclusion of IMRT and VMAT advanced techniques increases the total cost of concrete up to 6.8% at 30 MV as compared to the 100% conventional technique.

Figure 3. Total cost of concrete as a function of the photon beam energies. Bottom: 100% conventional radiotherapy treatment at the workloads 800 (circles), 1,000 (triangles) and 1,200 (squares) Gy/week. Middle: results after the inclusion of IMRT and VMAT techniques (30% IMRT, 20% VMAT). Top: inclusion of IMRT and VMAT (50% IMRT, 40% VMAT).

In Figures 4 and 5 the total cost of concrete is plotted against the total area of the room (11 ≤ a ≤ 20 and 7 ≤ b ≤ 14 meters but limiting the maximum area to
247 m$^2$). Results are presented for photon energies of 4, 6 and 10 MV (Figure 4) and 15, 18 and 30 MV (Figure 5) at 1,000 Gy/week conventional workload, considering 100% conventional (circles), 30% IMRT plus 20% VMAT (triangles, 2,600 Gy/week leakage workload), and 50% IMRT plus 40% VMAT (squares, 3,800 Gy/week leakage workload). Solid lines are linear fits to the data. Results have indicated that the minimum area (imposed by geometric considerations) varies from 81 m$^2$ at 4 MV up to 99 m$^2$ at 30 MV, and again the expected increasing of total cost with energies is observed. When only conventional procedure is considered, the costs vary from US$ 24,180 at 81 m$^2$ to US$ 53,639 at 247 m$^2$ for 4 MV and US$ 36,160 at 99 m$^2$ to US$ 69,194 at 247 m$^2$ for 30 MV. After the inclusion of 30% IMRT and 20% VMAT the costs vary from US$ 24,332 at 81 m$^2$ to US$ 54,139 at 247 m$^2$ for 4 MV and US$ 37,542 at 99 m$^2$ to US$ 72,439 at 247 m$^2$ for 30 MV; after the inclusion of 50% IMRT and 40% VMAT the costs vary from US$ 24,774 at 81 m$^2$ to US$ 55,383 at 247 m$^2$ for 4 MV and US$ 38,141 at 99 m$^2$ to US$ 73,912 at 247 m$^2$ for 30 MV. The differences in costs for the three procedures increase with energy and area varying from 2.5% (81 m$^2$) to 3.2% (247 m$^2$) for 4 MV up to 5.5% (99 m$^2$) to 6.8% (247 m$^2$) for 30 MV. The set of data can be fitted by the following linear equations ($0.940 \leq R^2 \leq 0.995$).

$$\text{Total Cost} = 10^3[a_i \times \text{Area} + b_i], (7)$$

where index $i = 1$ stands for 100% conventional treatment; $i = 2$ stands for 30% IMRT plus 20% VMAT treatment; and $i = 3$ stands for 50% IMRT plus 40% VMAT treatment.
Figure 4. Total cost as a function of the area of the facility room for the 4, 6 and 10 MV photon beams at the constant 1,000 Gy/week conventional workload. Circles are results obtained for 100% conventional treatment; triangles are results obtained after the inclusion of IMRT and VMAT techniques (30% IMRT, 20% VMAT), and squares are results obtained after the inclusion of IMRT and VMAT techniques (50% IMRT, 40% VMAT). Solid lines are linear fits to the data.
Figure 5. Total cost as a function of the area of the facility room for the 15, 18 and 30 MV photon beams at the constant 1,000 Gy/week conventional workload. Circles are results obtained for 100% conventional treatment; triangles are results obtained after the inclusion of IMRT and VMAT techniques (30% IMRT, 20% VMAT), and squares are results obtained after the inclusion of IMRT and VMAT techniques (50% IMRT, 40% VMAT). Solid lines are linear fits to the data.

Coefficients $a_i, b_i$ are:

i. 4 MV: $a_1 = 0.1739983, b_1 = 10.662365; a_2 = 0.1791573, b_2 = 10.943739; a_3 = 0.1811085, b_3 = 11.253192$

ii. 6 MV: $a_1 = 0.1802041, b_1 = 11.645556; a_2 = 0.1916346, b_2 = 11.130555; a_3 = 0.1929486, b_3 = 11.600161$
iii. 10 MV: $a_1 = 0.1943201, b_1 = 12.365312; a_2 = 0.1850145, b_2 = 14.746881$

$v_3 a_3 = 0.1880735, b_3 = 15.031708$

iv. 15 MV: $a_1 = 0.2034303, b_1 = 12.840483; a_2 = 0.1974965, b_2 = 15.656982$

$v_3 a_3 = 0.2019331, b_3 = 15.814594$

v. 18 MV: $a_1 = 0.2059838, b_1 = 13.404099; a_2 = 0.2111783, b_2 = 14.893685$

$v_3 a_3 = 0.2158775, b_3 = 15.041875$

vi. 30 MV: $a_1 = 0.2216901, b_1 = 14.772696; a_2 = 0.2120231, b_2 = 18.600498$

$v_3 a_3 = 0.2173678, b_3 = 18.646863$

4 CONCLUSIONS

In this simple work a general description of cost of concrete shielding is performed to a standard external photon beam radiation treatment room and results may support the guidelines of radiation protection and may also serve as a guide to estimate the total cost by occasion of an upgrade for a higher photon energy or by occasion of the building of a new facility room. The layout of the standard room presented in this study, when the photon beam is pointed to the maze, implies in an increase of cost up to 5% for higher energies in relation to the case reported in a previous work where the beam does not point to the maze. A set of linear equations describing the total cost of concrete shielding was also found for three scenarios of external photon beam radiotherapy.
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