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PAPER

On methods for radiometric surveying in radiotherapy bunkers

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Abstract

Radiometric surveys in radiotherapy bunkers have been carried out in Brazil for many years, both by the same radiotherapy facility for verification of shielding as by the regulatory agency for licensing and control purposes. In recent years, the Intensity Modulated Radiation Therapy (IMRT) technique has been gradually incorporated into many facilities. Therefore, it has been necessary to consider the increased leakage component that has an important impact on the secondary walls. For that, a radiometric survey method has been used that considers an increased 'time of beam—on' for the secondary walls. In this work we discuss two methods of doing this: the first considers that this 'time of beam—on' affects the sum of the two components, leakage and scattered. In another method it is considered that only the leakage component is affected by this extended 'time of beam—on'. We compare the methods and show that for secondary walls with $U = 1$ the first method overestimates dose rates by important percentages and for secondary walls with $U < 1$ it can both overestimate or underestimate the dose rates, depending on the parameters of the project. An optimized procedure is proposed, according to the use factor (U) of the secondary wall to be measured.

1. Introduction

The licensing process of a linear accelerator (LINAC) radiotherapy facility involves, in the final part of it, a crucial step that consists of a regulatory inspection during which, among many other checks, a radiometric survey is performed on the surroundings of the treatment bunker with the aim of verifying whether radiation levels are adequate. In Brazil this has been carried out since several decades by Brazilian Nuclear Regulatory Authority (CNEN). The methodology used in this radiometric survey is to measure the instantaneous dose-equivalent rate in Sv/h at strategic points and calculate the weekly rate through a simple equation that involves the weekly workload W (equation (5) below, see for example [1]).

With the emergence of IMRT technology, the secondary walls began to have to oversee a larger leakage-radiation workload, due to the largest number of monitor units required [2, 3]. This new leakage-radiation workload was generally called W_L. So that the radiometric surveys in services that have an IMRT technique began to be performed using, for the secondary walls, the same formula but with the new W_L leakage-radiation workload instead of W (i.e. Equation (6)).

In this work we show that this formula is not completely suitable to determine the weekly dose-equivalent rate R for a secondary wall. We propose a new method through a new formula obtained from the equations used in the calculation of shielding, which should replace the historically used. We show that the old formula overestimates dose rates always in cases where the secondary wall has a unit use factor ($U = 1$). In cases where the use factor is not equal to 1 we show that the old method can both overestimate and underestimate.

We experimentally verified these results through varied radiometric surveys that we performed in various radiotherapy services. From these verifications we propose a simple protocol to optimize the radiometric surveys that must be performed as the final stage of the licensing process of the radiotherapy service[3].

This article is organized as follows: after this introduction, in section 2 we recall the old method then we deduce the correct equation which defines the new method and compare them. In section 3 we use real results obtained for several bunkers to verify the equations obtained. Section 4 is for discussion of our results and proposal of a protocol and section 5 is for our conclusions.

2. Method

We consider a secondary barrier of a LINAC bunker, in a radiotherapy facility that uses IMRT technique. The total instantaneous dose-equivalent rate $I_T\left[\frac{Sv}{h}\right]$, with the machine operating at the absorbed-dose output rate $\dot{D}_o$ at 1 m in $\left[\frac{Gy}{h}\right]$, measured 30 cm beyond the secondary barrier, is composed both by leakage $I_L\left[\frac{Sv}{h}\right]$ and patient-scattered radiation $I_{ps}\left[\frac{Sv}{h}\right]$:

$$I_T = I_L + I_{ps} \tag{1}$$

It is possible to measure I_T using a phantom and keeping completely open the collimator and completely open the multileafs. The leakage component I_L is measured without phantom and with completely closed collimator and completely closed multileafs ([2]).

Then I_{ps} will be given by:

$$I_{ps} = I_T - I_L \tag{2}$$

Each measure will be given by a reading (L (leakage) and L_T (total)) and the Natural Background (L_{BG}) as:

$$I_T = L_T - L_{BG} \tag{3}$$

$$I_L = L - L_{BG}. \tag{4}$$

2.1. Method 1 (historical old method)

Radiometric surveys in radiotherapy bunkers have been doing for a long time by measuring only I_T, both before the advent of the IMRT technique and after the incorporation of this technique, so that the total weekly dose-equivalent rate, call it R' $[\frac{Sv}{week}]$, for a weekly workload W $[\frac{Gy}{week}]$, leakage-radiation workload W_L $[\frac{Gy}{week}]$, occupation factor T and $\dot{D}_o \equiv$ absorbed-dose output rate at 1 m in $[\frac{Gy}{h}]$, is calculated by ([4–6])

[3] Our conclusions are valid for the IMRT technique and also for the other modulated techniques, such as for example VMAT. It is important to highlight that in Brazil, due to the Nuclear Regulations, it is mandatory to perform the Radiometric surveys using the greatest potential that the LINAC can provide, as the shielding walls must be projected in this way. That is why for dual energy LINACs, the surveys are always performed using the highest potential, in those cases of the present paper, the 10 MV.

(a) Before IMRT- In this case $W = W_L$ i.e. there is an unique weekly workload, using (3), we have:

$$R' = (L_T - L_{BG})\frac{W}{\dot{D}_o}\,UT. \tag{5}$$

(b) With IMRT: W is substituted by W_L and we have:

$$R' = (L_T - L_{BG})\frac{W_L}{\dot{D}_o}\,UT. \tag{6}$$

We remark that this last equation comes from the equation (5) used historically in which the weekly primary load W has been replaced by W_L.

2.2. Method 2 (new or NCRP151 method [2])

Taking into account equation (1), the total weekly dose-equivalent rate, R $[\frac{Sv}{week}]$, for a weekly workload W $[\frac{Gy}{week}]$, leakage-radiation workload W_L $[\frac{Gy}{week}]$, occupation factor T, use factor U and $\dot{D}_o \equiv$ absorbed-dose output rate at 1 m in $[\frac{Gy}{h}]$, is given by ([7])

$$R = \left\{I_L\frac{W_L}{\dot{D}_o} + (I_T - I_L)\frac{W\ U}{\dot{D}_o}\right\}T, \tag{7}$$

Again, each measure will be given by a reading (L (leakage) and L_T (total)) and the Natural Background (L_{BG}), so that, using (3) and (4), the equation (7) can be written as

$$R = \left\{(L - L_{BG})\frac{W_L}{\dot{D}_o} + (L_T - L)\frac{W\ U}{\dot{D}_o}\right\}T. \tag{8}$$

Note that

$$\frac{W}{\dot{D}_o} \equiv t_{beam\ on}\quad in\ [\frac{h}{week}]\ and\ we\ call\ it\ t_{bo} \tag{9}$$

and

$$\frac{W_L}{\dot{D}_o} \equiv t_{beam\ on-IMRT}\quad in\ [\frac{h}{week}]\ and\ we\ call\ it\ t_L; \tag{10}$$

so we can write equation (8) as

$$R = \{(L - L_{BG})\,t_L + (L_T - L)\,U\,t_{bo}\}\,T. \tag{11}$$

The equation (11) is the heart of the new methodology proposed by the authors.

2.3. Comparison between the two methods

Using definition (10) we can write for the old method, equation (6)

$$R' = (L_T - L_{BG})\ U\ T\ t_L \tag{12}$$

and using that:

$$L_T = L + L_T - L \tag{13}$$

we have

$$R' = \{(L - L_{BG})\ U\ t_L + (L_T - L)\ U\ t_L\}\,T \tag{14}$$

In order to compare we write again the two equations (14) (old method) and (11) (new method) together

$$R = \{(L - L_{BG})\, t_L + (L_T - L)\, U\, t_{bo}\}\, T \quad \text{“new”} \tag{15}$$

$$R' = \{(L - L_{BG})\, U\, t_L + (L_T - L)\, U\, t_L\}\, T \quad \text{“old”} \tag{16}$$

The proposed equation is (15) and it is deducted from the theory of shield calculation for IMRT technique ([2]). We can notice in equation (16) two problems: i) the scattered component (the second term of the RHS) is multiplied by t_L instead of the correct value t_{bo} (we know that the weekly scattered component does not undergo modification by the use of the IMRT technique) and ii) the leakage component (the first term of the RHS) is affected by the use factor U even if it is different from 1 (we know that the leakage radiation is always present for any Gantry orientation: U = 1). We emphasize that this ‘old method’ is still widely used in our country. Then there will be differences in measuring dose rates according to one method or another. To analyze these differences we are going to consider two situations: the first is when the use factor of the secondary wall is the unit $U = 1$ (call it “*pure*”) and the second when $U < 1$ (call it “*not pure*”).

(A) **Situation** $U = 1$ (secondary wall pure).

From equations (15) and (16), making $U = 1$, we have

$$R' - R = (L_T - L)(t_L - t_{bo})T \tag{17}$$

Since on the Right Side of this equation each factor is positive, we have $R' - R$ is always positive

$$R' - R = (L_T - L)(t_L - t_{bo})T > 0 \tag{18}$$

This already is an indication that the old method, in this situation, overestimates the dose rates.

Let’s calculate the relative excess $\frac{R' - R}{R}$. From equations (17) and (15) we obtain:

$$\frac{R' - R}{R} = \frac{t_L - t_{bo}}{\frac{L - L_{BG}}{L_T - L}\, t_L + t_{bo}}, \quad valid\ if\ \ L_T - L \neq 0. \tag{19}$$

(B) **Situation** $U < 1$ (secondary wall not pure).

From equations (15) and (16) we obtain

$$R' - R = \{(L - L_{BG})(U - 1)t_L + (L_T - L)U\,(t_L - t_{bo})\}\; T \tag{20}$$

Investigating the sign of $R' - R$ we have found two cases:

Case B1) ‘overestimated’

$$R' - R \geqslant 0 \Longleftrightarrow \tag{21}$$

$$\frac{L_T - L}{L - L_{BG}} \geqslant \frac{1 - U}{U}.\frac{t_L}{t_L - t_{bo}},\quad valid\ if\ L - L_{BG} \neq 0\ \ and\ \ t_L - t_{bo} \neq 0 \tag{22}$$

or

$$\frac{Scattered}{Leakage - BG} \geqslant \frac{1 - U}{U}.\frac{t_L}{t_L - t_{bo}},\quad valid\ if\ Leakage - BG \neq 0\ \ and\ \ t_L - t_{bo} \neq 0. \tag{23}$$

Defining the quantity

$$S(U,\, t_{bo},\, t_L) \equiv \frac{1 - U}{U}.\frac{t_L}{t_L - t_{bo}}, \tag{24}$$

Equation (23) can be written as

$$\frac{Scattered}{Leakage - BG} \geqslant S(U,\, t_{bo},\, t_L),\quad valid\ if\ Leakage - BG \neq 0\ \ and\ \ t_L - t_{bo} \neq 0. \tag{25}$$

Case B2) ‘subestimated’

$$R' - R < 0 \Longleftrightarrow \tag{26}$$

$$\frac{L_T - L}{L - L_{BG}} < \frac{1 - U}{U}.\frac{t_L}{t_L - t_{bo}},\quad valid\ if\ L - L_{BG} \neq 0\ \ and\ \ t_L - t_{bo} \neq 0 \tag{27}$$

or

$$\frac{Scattered}{Leakage - BG} < \frac{1 - U}{U}.\frac{t_L}{t_L - t_{bo}},\quad valid\ if\ Leakage - BG \neq 0\ \ and\ \ t_L - t_{bo} \neq 0. \tag{28}$$

or using the quantity S

$$\frac{Scattered}{Leakage - BG} < S(U,\, t_{bo},\, t_L),\quad valid\ if\ Leakage - BG \neq 0\ \ and\ \ t_L - t_{bo} \neq 0. \tag{29}$$

Equation (22) or (25) gives the conditions for $R' - R \geqslant 0$ i.e. R' overestimate dose rates. Equation (27) or (29) gives the conditions for $R' - R < 0$ i.e. R' under-estimate dose rates.

For the relative difference we obtain:

$$\frac{R' - R}{R} = \frac{\left(U - 1\right)t_L + \frac{L_T - L}{L - L_{BG}}U(t_L - t_{bo})}{t_L + \frac{L_T - L}{L - L_{BG}}Ut_{bo}},\quad valid\ if\ L - L_{BG} \neq 0. \tag{30}$$

3. Results

In this section we particularize the situations and cases found in the last section, for concrete real examples with real values of parameters and verify them experimentally.

We have made measures for several radiotherapy bunkers that show results that verify our statements. Here we present, not to occupy so much space, only two bunkers of them: one in which we study the secondary walls with $U = 1$ and another where we study

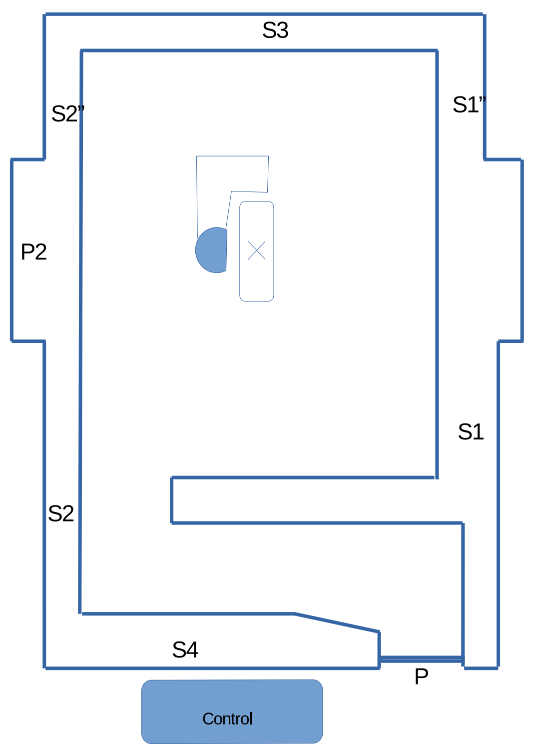

Figure 1. Bunker A. The neighborhoods of each wall are indicated in the table 1.

those that have $U < 1$. However, all the studied bunkers are in our preprint [8]. The measures are made in each case for the photon beam of the greatest potential, as explained in footnote 1.

(A) **Situation** $U = 1$.

BUNKER (A) This bunker (figure 1) houses a LINAC manufactured by Elekta, model Versa HD, with photon beam of 6 and 10 MV, electron beam of 6, 9, 12 and 15 MeV, with primary workload $W = 1100\frac{Gy}{week}$ and secondary IMRT leakage load $W_L = 3300\frac{Gy}{week}$ and in a nominal absorbed-dose output rate $\dot{D}_o = 360\frac{Gy}{h}$.

From equations (9) and (10) we obtain:

$$t_{bo} = 3, 06\frac{h}{week}, \tag{31}$$

$$t_L = 9, 17\frac{h}{week}. \tag{32}$$

We have made the measures for the secondary walls of the bunker with a Ionization chamber manufactured by Ludlum, model 9DP, pressurized, serial number 25009346.

Next we show the values obtained for each of four walls and we comment on the results obtained:

-S1: Treatment room. Occupancy factor $T = \frac{1}{2}$. Uncontrolled area with contribution from another source. Then limit: $P = 10\frac{\mu Sv}{week}$.

$L_T = 5, 01\frac{\mu Sv}{h}$

$L = 0, 19\frac{\mu Sv}{h}$

$L_{BG} = 0, 09\frac{\mu Sv}{h}$

Then from equations (17) and (19) we have

$$R' - R = 14, 725\frac{\mu Sv}{week} \tag{33}$$

$$\frac{R' - R}{R} \cong 1, 88 \tag{34}$$

It means

$$R' \cong 2, 88R \tag{35}$$

Or equivalently $R' = 22, 55\frac{\mu Sv}{week}$

$R = 7, 822\frac{\mu Sv}{week}$,

and then the old method is giving ≅188 % excess for this wall. In this example, very interesting, the old method indicates a dose rate that exceeds in ≅125% the allowed limit for an uncontrolled area where contributes two sources (i.e $P = 10\frac{\mu Sv}{week}$), while the new method indicates a lower dose rate than this allowed limit. In other words, the old method is incorrectly condemning this wall. Then the old method must be discarded for this wall.

Following the same procedure that for the previous wall we finally have for the next walls:

-S2: Rest area. Uncontrolled area with $T = 1$. $P = 20\frac{\mu Sv}{week}$.

$L_T = 5, 49\frac{\mu Sv}{h}$

$L = 0, 24\frac{\mu Sv}{h}$

$L_{BG} = 0, 09\frac{\mu Sv}{h}$

$$R' - R = 32, 078\frac{\mu Sv}{week} \tag{36}$$

$$\frac{R' - R}{R} = \cong 1, 84 \tag{37}$$

$R' = 49, 50\frac{\mu Sv}{week}$

$R = 17, 42\frac{\mu Sv}{week}$.

The old method is giving ≅184 % excess for this wall. This means a dose rate that exceeds in ≅148% the allowed limit for an uncontrolled area ($P = 20\frac{\mu Sv}{week}$), while the new method indicates a lower dose rate than this allowed limit. In other words, the old method again is incorrectly condemning a wall. Then the old method must be discarded for this wall.

-S1': Treatment room. Occupancy factor $T = \frac{1}{2}$. Uncontrolled area with contribution from another source. Then limit: $P = 10\frac{\mu Sv}{week}$.

$L_T = 15, 10\frac{\mu Sv}{h}$

$L = 0, 21\frac{\mu Sv}{h}$

$L_{BG} = 0, 09\frac{\mu Sv}{h}$

$$R' - R = 32, 078\frac{\mu Sv}{week} \tag{38}$$

$$\frac{R' - R}{R} = \cong 1, 95 \tag{39}$$

$R' = 68, 82\frac{\mu Sv}{week}$

$R = 23, 33\frac{\mu Sv}{week}$.

The old method is giving ≅195 % excess for this wall. So the old method indicates a dose rate that

Table 1. Bunker A. Measurements for Secondaries Walls with Ionization Pressurized Chamber Ludlum 9DP Serial Number 25 009 346. This bunker houses a LINAC manufactured by Elekta, model Versa HD, with photon beam of 6 and 10 MV, electron beam of 6, 9, 12 and 15 MeV, with primary workload $W = 1100\frac{Gy}{week}$ and secondary IMRT leakage load $W_L = 3300\frac{Gy}{week}$ and in a nominal absorbed-dose output rate $\dot{D}_o = 360\frac{Gy}{h}$. The Old method says that 3 walls are not safe (S1, S1' and S2). But the new method says that only S1' is not good from the point of view of radiological protection. Several walls (S2', P and Ts) were safe according to the old method, which as we know, over-sizes in this situation ($U = 1$), then it is not necessary to apply the new method that is, the leakage component L need not be measured (NM). We did this in the case of wall P. In other words, for the situation $U = 1$, we can leave the new method only to be applied to the hot points of the old method.

Wall	Destination	T	U	Area/Limit	$L_T[\frac{\mu Sv}{h}]$	$L[\frac{\mu Sv}{h}]$	$L_{BG}[\frac{\mu Sv}{h}]$	$R'\frac{\mu Sv}{week}$	$R\frac{\mu Sv}{week}$	$\frac{R'-R}{R}\times 100$
S1	Treatment Room	$\frac{1}{2}$	1	Uncontrolled/ $P = 10\frac{\mu Sv}{week}$	5.01	0.19	0.09	22.55	7.82	188 %
S1'	Treatment Room	$\frac{1}{2}$	1	Uncontrolled/ $P = 10\frac{\mu Sv}{week}$	15.1	0.21	0.09	68.80	23.30	190 %
S2	Rest area	1	1	Uncontrolled/ $P = 20\frac{\mu Sv}{week}$	5.49	0.24	0.09	49.50	17.42	184 %
S2'	Rest area	1	1	Uncontrolled/ $P = 20\frac{\mu Sv}{week}$	2.30	0.12	0.09	20.26	6.94	192 %
P	Door	$\frac{1}{8}$	1	Uncontrolled/ $P = 20\frac{\mu Sv}{week}$	8.0	*NM*	0.09	9.064	–	–%
Ts	Reception	1	1	Uncontrolled/ $P = 20\frac{\mu Sv}{week}$	0.31	0.21	0.09	2.017	1.406	43 %

exceeds in ≅588% the allowed limit for an uncontrolled area where contributes two sources (i.e $P = 10\frac{\mu Sv}{week}$), while the new method indicates a dose rate exceeding ≅133% this allowed limit. In other words, both methods are condemning this wall and it will have to be reformulated. Even so, the new method requires increasing the thickness of the wall by only approximately 1.2 HVL when the old method asks approximately 2.8 HVL.

-S2': Rest area. Uncontrolled area with $T = 1$. Allowed Limit $P = 20\frac{\mu Sv}{week}$

$L_T = 2,\ 30\frac{\mu Sv}{h}$

$L = 0,\ 12\frac{\mu Sv}{h}$

$L_{BG} = 0,\ 09\frac{\mu Sv}{h}$

$$R' - R = 13,\ 32\frac{\mu Sv}{week} \tag{40}$$

$$\frac{R' - R}{R} = \cong 1,\ 92 \tag{41}$$

$R' = 20,\ 26\frac{\mu Sv}{week}$

$R = 6,\ 94\frac{\mu Sv}{week}$.

We see that the old method is giving ≅192 % excess for this wall. Furthermore the old method indicates a dose rate that exceeds in only ≅1, 3% the allowed limit for an uncontrolled area ($P = 20\frac{\mu Sv}{week}$) which is acceptable within the margin of error (we accept up to 20 %), while the new method indicates a lower dose rate than this allowed limit. In other words, both methods indicates an acceptable dose rate for this wall. The results for all secondary walls of this bunker (figure 1) are summarized in table 1.

Following the same above methodology we have analyzed several other bunkers for which we have also verified our results. For details and calculations we remit the reader to our extended preprint [8] .

(B) **Situation** $U < 1$.

BUNKER (B) This bunker (figure 2) houses a LINAC, manufactured by Varian, model Clinac CX, with photon beam of 6 and 10 MV, electron beam of 6, 9, 12, 15 and 18 MeV, with primary workload $W = 1200\frac{Gy}{week}$ and secondary IMRT leakage load $W_L = 3600\frac{Gy}{week}$ and in a nominal absorbed-dose output rate $\dot{D}_o = 360\frac{Gy}{h}$.

-Wall C: Control console, defined as controlled area, $P = 400\frac{\mu Sv}{week}$, with $T = 1$ and $U = \frac{1}{5}$ for scattered component ([2]).

From equation (24) we have:

$$S(U,\ t_{bo},\ t_L) = 6. \tag{42}$$

Measures with Ionization chamber manufactured by Ludlum, model 9DP, pressurized, serial number 25 018 216, we obtained for this wall :

$L_T = 6,\ 30\frac{\mu Sv}{h}$

$L = 4,\ 30\frac{\mu Sv}{h}$

$L_{BG} = 1,\ 20\frac{\mu Sv}{h}$

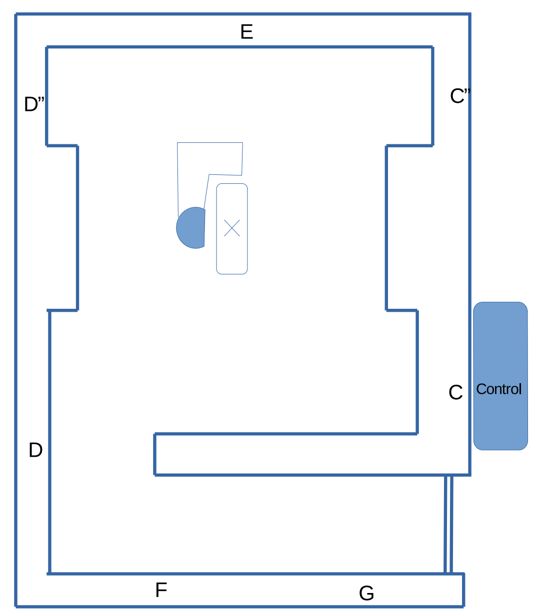

Figure 2. Bunker B. The neighborhoods of each wall are indicated in the table 2.

We need to verify which is valid equation (25)) or equation (29)). We have

$$\frac{Scattered}{Leakage - BG} = \frac{L_T - L}{L - L_{BG}} = 0,\ 645, \tag{43}$$

so, because $0,\ 645 < 6 = S(U,\ t_{bo},\ t_L)$, it is verified equation (29), i.e:.

$$\frac{Scattered}{Leakage - BG} < S(U,\ t_{bo},\ t_L) \tag{44}$$

Then, we are in the **Case B2**) which means $R' - R < 0$ i.e. R' is underestimating doses.

From equation (30) it is obtained:

$$\frac{R' - R}{R} = -0,\ 68 \tag{45}$$

so

$$R' = R - 0,\ 68\ R = 0,\ 32\ R \tag{46}$$

or equivalently $R' = 10,\ 20\frac{\mu Sv}{week}$

$R = 32,\ 33\frac{\mu Sv}{week}$

The old method underestimates in ≅68 % for de dose rate at the Control Console (wall C) . It is important to note that in this 'underestimated' case it is not possible to know in advance how much the method underestimates without measuring the leakage component, that is, without applying the new method. Therefore, in the case $U < 1$ and underestimated (case B2), it will always be necessary to use the new method because, with the old method, we could be underestimating a dose rate that actually exceeds the allowed limit. This is not the case for this wall because both methods indicates an adequate dose rate, i.e. , less than the allowed limit for controlled area ($400\frac{\mu Sv}{week}$). Note that if this region had been hypothetically considered as uncontrolled area, that is, with allowed limit

Table 2. Bunker B. Measurements for Secondaries Walls with Ionization Pressurized Chamber Ludlum 9DP Serial Number 25 018 216. This bunker houses a LINAC manufactured by Varian, model Clinac CX, with photon beam of 6 and 10 MV, electron beam of 6, 9, 12, 15 and 18 MeV, with primary workload $W = 1200\frac{Gy}{week}$ and secondary IMRT leakage load $W_L = 3600\frac{Gy}{week}$ and in a nominal absorbed-dose output rate $\dot{D}_o = 360\frac{Gy}{h}$. On two walls with $U = 1$ (the door P and TS) the old method, as we already know, gives overestimated values (situation (A) or 'pure'), but in this case acceptable (less than the allowed limit) and therefore it is enough to measure with the old method. On the other hand, for the walls C, D, D' and C' (all with $U < 1$, situation (B) or not 'pure') the old method gives underestimated values (case B2) and, since we do not know in advance how much, it is necessary to use the new method to verify if the dose rate is acceptable. We see that, in particular, the old method underestimates in $\cong$68 % for de dose rate at the Control Console, wall *C*.

Wall	Destination	T	U	Area / Limit	$L_T[\frac{\mu Sv}{h}]$	$L[\frac{\mu Sv}{h}]$	$L_{BG}[\frac{\mu Sv}{h}]$	$R'\frac{\mu Sv}{week}$	$R\frac{\mu Sv}{week}$	$Difference = \frac{R'-R}{R} \times 100$
P	Door	$\frac{1}{8}$	1	Controlled / $P = 400\frac{\mu Sv}{week}$	7.00	3.30	1.20	7.25	4.17	74 %
C	Control console	1	$\frac{1}{5}$	Controlled / $P = 400\frac{\mu Sv}{week}$	6.30	4.30	1.20	10.2	32.33	−68 %
D	External area	$\frac{1}{8}$	$\frac{1}{5}$	Uncontrolled / $P = 20\frac{\mu Sv}{week}$	2.90	1.50	1.20	0.17	0.49	−65 %
D'	External area	$\frac{1}{8}$	$\frac{1}{5}$	Uncontrolled / $P = 20\frac{\mu Sv}{week}$	2.20	1.40	1.20	0.10	0.32	−69 %
Ts1	Technical area	$\frac{1}{8}$	1	Uncontrolled / $P = 20\frac{\mu Sv}{week}$	3.21	1.50	1.20	2.51	1.09	130 %
C'	Stabilizer	$\frac{1}{2}$	$\frac{1}{5}$	Uncontrolled / $P = 20\frac{\mu Sv}{week}$	5.90	1.36	1.20	1.18	2.31	−49 %

$P = 20\frac{\mu Sv}{week}$, then the old method would be completely wrong and should be discarded because it would be accepting a shielding that is not really sufficient (the real dose rate being $R = 32,\ 33\frac{\mu Sv}{week}$).

For the other secondary walls, measurements and calculations are presented in table 2. We see that on two walls with $U = 1$ (the door and TS) the old method, as we already know, gives overestimated values (situation (A) or 'pure'), but in this case acceptable (less than the allowed limit) and therefore it is enough to measure with the old method. On the other hand, for the walls C, D, D' and C' (all with $U < 1$, situation (B) or not 'pure') the old method gives underestimated values (case **B2**), and since we do not know in advance how much, it is necessary to use the new method to verify if the dose rate is acceptable.

Again, following the same above methodology we have analyzed another bunker and verified our results. The details, for the interested reader, are shown in [8].

4. Discussion

We can say that, from the theoretical point of view, the old method for measuring secondary walls is not strictly correct. Based on the analysis and the examples we have presented, we may notice that when $U = 1$ the old method overestimates the dose rates but it can still be used to provide an upper bound for dose rates, as long as it does not exceed the allowed limits (legal and project goal). For the situation $U < 1$, the new method must be used. This makes it possible to decide if the dose rate is adequate, that is, if the shielding is sufficient. The old method does not prove reliable in this case because it is not known if it overestimates or underestimates the dose rates and by how much. To know this, it is necessary to measure the leakage component separately (closing the collimator and the multi-leafs, as we saw in section II) and apply the new method. One way to work would be the following: situation $U = 1$: the 'hot' points obtained with the old method must be verified with the new method. Situation $U < 1$: apply the new method.

5. Conclusions

We have compared two methods to perform radiometric surveys for the secondary walls in LINAC radiotherapy services that use IMRT technique. One, the 'old' method, employs an adapted formula of the period prior to IMRT technique and is widely used in all radiotherapy services with LINAC. The 'new' method uses a formula that is deducted from the theory of structural shielding for IMRT. We found that for secondary walls there are differences: if the secondary wall is 'pure' ($U = 1$) the old method always super-estimate the dose rates. If the secondary wall is 'not pure' ($U < 1$) the old method can both overestimate or underestimate the dose rates. We have carried out a series of measurements that verify these conclusions. An optimized procedure is proposed: in the case of 'pure' secondary walls ($U = 1$) measure first with the old method and, at hot points, discard it and use the new method; in the case of secondary walls with $U < 1$ only the new method must be used.

6. Ethical statement

Our research work has not included humans or animals in our measurements.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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