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PROPOSAL OF A NEW METHOD FOR ASSESSING THE AMBIENT DOSE EQUIVALENT, WHICH ACCOUNTS FOR THE INFLUENCE OF THE HIGH VOLTAGE IN A MEDICAL X RAY FACILITY

Elton Gomes Pereira

Centro de Desenvolvimento da Tecnologia Nuclear - CDTN, Belo Horizonte, Brazil, egp@cdtn.br

Abstract: Two methods of radiological survey in a medical X ray room are compared. The first method is just the usual one, as done today in Brazil. It is based on the election of a high voltage (HV) value, by legal rule the highest used in the clinic, taken as a standard [1]. This highest HV value is supposed to be constant and representative of all others values, which are simply ignored. This work shows that the results of this approach move away a bit from the actual radiation doses, overestimating the values. A second method is proposed and compared with the first one. It takes the various values of HV into account. One should only assume a quadratic relationship between the dose measurements and HV and change the way of workload data acquirement. This second method presents a modified way to calculate the ambient equivalent dose [*H*(10)*]. It is shown that the spread of values present by the 2nd method is smaller than that of the current one, although in the 2nd method the values are still overestimated, however not too much. Putting both methods side by side, as a conclusion, the second one shows to be better than the first, as it adheres more to the reality.

Keywords: Radiation measurement, radiation protection, radiological survey

1. INTRODUCTION

The electron's voltage of acceleration in an X-ray tube plays an important role in the assessment of the ambient dose equivalent [*H*(10)*]. This is so because the X-ray spectrum depends directly on the HV applied on the tube. This fact is well established. In the daily routine of a clinic one has a manifold spectra of X-rays, as a consequence of the various voltages applied. This fact is currently ignored in the radiological surveys, when the quantity dose equivalent for photons [H_X] is measured, which in turn is used to assess the quantity ambient dose equivalent. This omission is certainly caused by the difficulty to take such a wide set of HV values into account. So, for each distance, as well as behind each shielding barrier, one has a different spectrum reaching the ionization chambers, depending on the HV used in an specific examination. This is true even for the primary spectrum, without any barrier but the air, because it presents a great amount of photons of different energies and intensities. It means the air itself is a kind of barrier, although very weak. For instance, this fact puts another kind of problem, because for sure the spectrum that reaches the chamber, be this spectrum primary or secondary, is completely different from the one that was used in the calibration of that chamber.

This work tries to solve part of the problem, specifically that caused by the influence of the manifold spectra in the H_X measurements. The lack of correspondence between the calibration and de actual spectrum is another problem and it is not approached here.

2. PURPOSE

The radiological surveys are mandatory in determining whether a given area is free or not of special rules, or, as said in radiological protection terminology, whether an area is controlled or not. Controlled areas require special shielding design, special procedures, access control etc. The results of a radiological survey may imply in cost increment and they may also have implications on a tribunal. These are all practical consequences. There is also an argument, philosophical and scientific, to support a tentative to better assess the quantity *H*(10)*, namely, the introduction of a variable which was before ignored. It is now attached to the process of measurement. This paper shows that this variable, the various X-ray spectra present in the examination room, once considered, improves a bit the assessment of *H*(10)*, compared to the current way to assess it today in Brazil.

To hit the goal it is shown that

a) a better data collection in the workload of the room is needed. This requires a little increment of work.

b) a better assessment of *H*(10)* is possible, since a quadratic relationship between H_X and HV be assumed, as shown in [2].

The new approach still carries some abnormalities, because for a given point a difference of 20% between identical measurements still persists. But it is far from the current difference of 110%. This difference would be 0 if the exponents had the truth values, always higher than 2, as shown in [2]. This implies that the proposed method still overestimates the results, but less than does the current one.

A radiological survey was simulated and both models were applied, the current and the proposed one.

3. MATERIALS AND METHODS

The irradiation set consists of a medical X-ray machine fabricated by VMI, model Pulsar 800 Plus, HF generator, operated all the time at 200 mA and 0,1 s. A cubic phantom was used to produce an enhanced scattered radiation. There were no barriers between the source of radiation and the point of measurement, except the air. All measurements were taken with a monitor fabricated by Radcal, model 9015 coupled with a 10X5-180 chamber.

It was established that only twelve values of HV were possible in an hypothetical X-ray room, whose workload was supposed to be 16205 mAs/sem, a value very similar to the current values found in standard clinics. In consequence, twelve radiological surveys were simulated, one for each value of the HV. Some measurements of HV were taken while H_X measurements were running, to guaranty that no HV variation was present. The instrument used was the Unfors Rad/Flu 50 to 150 kV. The results were very satisfactory, presenting differences lower than 1%, not relevant to the scope of this work. High fidelity between set and actual HV is a characteristic of the HF generators.

Seven points of measurements were selected. Six in the secondary beam (scattered radiation) and one in the primary beam (primary radiation). Three measurements of the quantity H_X were integrated for each point, whose mean values are shown in the Table 1. The deviations presented by each set of three measurements were always zero or near zero, all of them smaller than 1%, again a difference not relevant for the purpose of this work. The value "0" in Table 1 means that the measured value was smaller than the chamber threshold of detection.

3.1. The current method

The data shown in Table 2 are derived from those of Table 1, with a correspondence cell by cell. The derivation is obtained just applying the current algorithm to get $H^*(10)$ from H_X, namely,

$$H^*(10)\ [\text{mSv/year}] = H_X\ [\text{nSv}] \times \{W\ [\text{mAs/week}]/\text{load}\ [\text{mAs}]\} \times 50\ [\text{week/y}] \times 10^{-6}\ [\text{mSv/nSv}] \times CF \times T \times U \quad (1)$$

or, rewriting (1) without the units, and considering CF = T = U = 1, what does not disturb the scope of the work:

$$H^*(10) = H_X\ .\ \{W / \text{load}\}\ .\ 5{,}0 \times 10^{-5} \quad (2)$$

Table 2 is the output of (2), fed by the H_X values. Workload (W) and the so called "mAs" (load) are constant, simulated as 16205 mAs/week and 20 mAs, respectively.

Table 2 presents the values of 12 radiological surveys. However it must be stressed that in the current method one chooses the highest HV value used in the room and the radiological surveys is done under that HV value. So, to represent a real radiological survey as done today, Table 2 should have only one column, corresponding to the chosen HV value. It is enough to take a look on the values of $H^*(10)$, for a given point on Table 2, under each value of HV, to see how big is the variation. For instance, the ambient dose equivalent for the point 2 can be 26,2 mSv, if calculated at 60 kV, or 55,4 mSv if calculated at 80 kV. A difference of 110%. And this is not the biggest one. The wider the interval of HV, the bigger the difference!

Table 1 - Dose equivalent for photons - (H_X) [nSv] = Kerma in air [nGy] x 1,14 nSv/nGy

	High voltage (kV_p)											
Point	40	45	50	55	60	65	70	75	80	85	90	95
1	270	422	600	799	1010	1254	1505	1784	2075	2398	2722	3066
2	159	258	370	503	648	800	972	1164	1369	1587	1820	2071
3	106	165	232	305	390	490	583	695	821	940	1086	1225
4	40	53	73	106	132	172	205	251	298	351	390	443
5	13	26	40	53	73	93	119	146	172	199	231	258
6	0	0	7	13	20	26	33	40	53	59	66	73
Pri ($x10^3$)	448	620	800	986	1177	1375	1574	1783	1995	2214	2441	2668

Table 2 - Annual ambient dose equivalent - H*(10) [mSv/ano] - calculated by the current method

	High voltage (kV_p)											
Point	40	45	50	55	60	65	70	75	80	85	90	95
1	10,9	17,1	24,3	32,4	40,9	50,8	61,0	72,3	84,0	97,1	110,2	124,2
2	6,4	10,5	15,0	20,4	26,2	32,4	39,4	47,1	55,4	64,3	73,7	83,9
3	4,3	6,7	9,4	12,4	15,8	19,9	23,6	28,2	33,3	38,1	44,0	49,6
4	1,6	2,2	3,0	4,3	5,4	7,0	8,3	10,2	12,1	14,2	15,8	17,9
5	0,53	1,1	1,6	2,2	3,0	3,8	4,8	5,9	7,0	8,1	9,4	10,5
6	0,00	0,00	0,28	0,53	0,81	1,1	1,3	1,6	2,2	2,4	2,7	3,0
Pri ($x10^4$)	1,8	2,5	3,2	4,0	4,8	5,6	6,3	7,2	8,1	9,0	9,9	11

3.2. The proposed method

It is suggested that the value of the HV applied in each examination be also collected in the workload data acquirement. This is very easy to do, because the hard work is already done in the collection of the other data. The work is normally done by the technician. Tables 3 and 4 show the current and the proposed data collection models, respectively.

Table 3 - Weekly workload data - current method

Load (mAs)	Frequency (incidence / week)	Weekly workload (mAs / week)
5	35	175
10	182	1820
15	133	1995
20	182	3640
25	21	525
30	119	3570
35	0	0
40	112	4480
Total	784	16205

Table 4 - Weekly workload data with HV values

HV (kV_p)	Load (mAs)	Frequency (incidence / week)	Weekly W_T (mAs / week)
45	20	14	280
	20	28	
50	30	35	3290
	40	42	
	10	42	
	15	56	
55	20	21	5075
	25	21	
	30	49	
	40	35	
	15	42	
60	20	28	3640
	30	35	
	40	35	
65	10	77	2170
	20	70	
70	5	35	910
	10	21	
	15	35	
75	10	42	420
80	20	14	280
85	-	0	0
90	20	7	140
95	-	0	0
		Total = 784	16205

According to [2] the dependence between H_X and the HV, from now on, T (tension), may be expressed as

$$H_{X\,\mathrm{T}} / H_{X\,\mathrm{Tref}} = [T/T_{ref}]^2 \qquad (3)$$

This expression is valid for any point and the index T means that the value of H_X is linked to the tension value T. The exponent 2 is an approximation, because the true value is always higher than 2, as demonstrated in [2]. As seen in (3), it is necessary to elect a T value as reference. Of course the obvious chosen value is that used to collect the kerma_{air} and hence, the H_X data in the clinic, which is supposed to be representative of the reality, not the highest one. So, the work necessary to collect the radiological survey data is still the same, nor more neither less than that necessary in the current method.

Now it is possible to account for the wide set of HV values used in the clinic. One should only use the W_T, the workload weighted by the T values, as shown in Table 4.

The equation (2) is now rewritten, without units, as:

$$H^*(10) = \mathrm{k'} \times \sum \{H_{XT} \times W_T\} \qquad (4)$$

The summation is taken under the discrete T values and the constant k' incorporates all those invariable numbers such as load, use and occupancy factors, years to week conversion factor and also units conversion factors. Its numeric value will be calculated in the next page.

Equation (3) can get a little better:

$$H_{X\,\mathrm{T}} = [H_{X\,\mathrm{Tref}} / (T_{ref})^2] \, . \, \mathrm{T}^2 \qquad (5)$$

Now (5) is introduced into (4):

$$H^*(10) = \mathrm{k'} \times [H_{X\,\mathrm{Tref}} / (T_{\mathrm{ref}})^2] \times \sum \{T^2 \times W_T\} \qquad (6)$$

A new improvement is possible noting that the unique variable part in (6) is $[H_{X\,\mathrm{Tref}} / (T_{\mathrm{ref}})^2]$. Then, (6) can be rewritten as:

$$H^*(10) = \mathrm{k} \times [H_{X\,\mathrm{Tref}} / (T_{\mathrm{ref}})^2] \qquad (7)$$

now $\mathrm{k} = \mathrm{k'} \times \sum \{T^2 \times W_T\}$ = constant, because the summation in brackets is constant for a given room.

Implicit in (7) is the fact that it is referred to a given point of measurement, and that the measurement was done under the reference value of HV.

The values of k' and k will be used in the next section. Their values are present now, considering 20 mAs as the load under which all the measurements were taken and CF = T = U = 1.

Table 4 furnishes the value of the summation $\sum \{T^2 \times W_T\}$, on T. The result is 56163625 [kV^2 . mAs / week] = 5,6 x 10^7 [kV^2 . mAs / week]. Note that this value is constant for the room, irrespective the point considered. It should also be noted that for a given radiological survey, once the value of T_{ref} is elected, this value itself, as appears in equation (7), turns out to be a constant too and it must be incorporated to the value of k. Then:

k' = 50[week/year].10^{-6}[mSv/nSv].CF. T. U / 20 [mAs]

k' = 2,5 x 10^{-6} [(week . mSv) / (year . nSv . mAs)]

k = 2,5 x 10^{-6} [(week . mSv) / (year . nSv . mAs)] . 5,6 x x 10^{7} [kV^2 . mAs / week]

k = 1,4 x 10^{2} [(mSv . kV^2) / (year . nSv)]

If one elects the reference HV as 60 kV (T_{ref} = 60 kV), it follows that: $k_{60} = k / (60\ kV)^2$. Then

k_{60} = 3,9 x 10^{-2} [(mSv) / (year . nSv)] and (7) turns

$$H^*(10) = k_{60} \times [H_{X\ 60}] \qquad (8)$$

Table 4 and equation (7) or (8) show that conditions a and b of section 2 are fulfilled.

4. RESULTS

The results of the current method applied in twelve radiological surveys are already shown in Table 2. Each column represents one radiological survey, done as if the correspondent HV value were the highest one used in that room.

The proposed method does not change the way to collect the data in the X-ray room. Then Table 1 still applies. The changes are in the workload data collection and in the algorithm to calculate the value of *H*(10).* In other words, to express the results one has to apply the equation (7) using the workload data shown in Table 4. The results for the twelve chosen values of HV are shown in Table 5. Again, as in Table 2, it is clear that each column represents the results of the assessment of the H*(10) based on the election of the respective HV as the reference. As a matter of comparison with the final part of the third paragraph of section 3.1, let's take the ambient dose equivalent for the point 2, which can be 25,3 mSv, if calculated with 60 kV as the reference HV, or 30,0 mSv if calculated with 80 kV as the reference. A difference of 20% arises, smaller than that prior of 110%, as calculated in the mentioned paragraph.

Table 5 - Annual Ambient dose equivalent - H*(10) [mSv/ano] - calculated by the proposed method

	Reference High Voltage (kV_p)											
Point	40	45	50	55	60	65	70	75	80	85	90	95
1	23,7	29,3	33,7	37,1	39,4	41,7	43,1	44,5	45,5	46,6	47,2	47,7
2	14,0	17,9	20,8	23,3	25,3	26,6	27,9	29,1	30,0	30,8	31,5	32,2
3	9,3	11,4	13,0	14,2	15,2	16,3	16,7	17,3	18,0	18,3	18,8	19,1
4	3,5	3,7	4,1	4,9	5,1	5,7	5,9	6,3	6,5	6,8	6,8	6,9
5	1,1	1,8	2,2	2,5	2,8	3,1	3,4	3,6	3,8	3,9	4,0	4,0
6	0,0	0,0	0,4	0,6	0,8	0,9	0,9	1,0	1,2	1,1	1,1	1,1
Pri (x10^4)	3,9	4,3	4,5	4,6	4,6	4,6	4,5	4,5	4,4	4,3	4,2	4,2

For instance, all the values of the column under the 60 kV as T_{ref} were obtained just multiplying k_{60} = 0,0390025 [(mSv) / (year . nSv)] by the respective value of H_X, shown in Table 1.

5. DISCUSSION

A comparison between Tables 2 and 5 must be made, to allow an appraisal of the methods. It is enough to look at them to see that the proposed method is the best one, because it reduces the dispersion of values. This inquiry can be done just choosing any row of Table 5 and compare the value of its cells with the correspondent cells of the respective row of Table 2.

It can be useful to get a specific point of measurement and make a detailed analysis of its values, obtained by both methods. Be the point 2 the elected one. Should another point be elected, would the conclusions be the same, irrespective the choice.

As a matter of facility, Tables 6 and 7 reproduce, each one, the row referred to the point 2 from both methods, the current and the proposed, extracted from the Tables 2 and 5, respectively.

Now let the 12 x 12 matrixes shown in Tables 8 and 9 be representatives of both methods, respectively. They are referred to the point 2 only. Their elements a_{ij} were constructed taking the division of the H*(10) value got under the tension "j" by the same quantity got under the tension "i". The indices "i" and "j" are referred to the 12 discrete tension values, ranging from 40 kV to 95 kV, growing in steps of 5 kV. The number linked to each element a_{ij} show how big or how small is a value of H*(10) calculated under "j" kV, compared to the same quantity, calculated under "i" kV. Or, what is the same, how big or how small is a value of H_X measured under "j" kV, compared to the same quantity, measured under "i" kV. So, both matrixes are a measure of the spread.

For example, from Table 6:

$a_{50,70}$ = (39,4 mSv/year) / (15,0 mSv/year) = 2,6;

$a_{80,45}$ = (10,5 mSv/year) / (55,4 mSv/year) = 0,2.

And, from Table 7:

$a_{50,70}$ = (27,9 mSv/year) / (20,8 mSv/year) = 1,3;

$a_{80,45}$ = (17,9 mSv/year) / (30,0 mSv/year) = 0,6.

Now it is very easy to see that the wider the HV range, the wider the spread of values for a given point.

A highlighted region ranging from the 60 kV to 80 kV is present in both matrixes. This region was chosen because its HV values are more frequent in a medical X-ray room. Then, focusing the attention on this region is a good way to quantify how big is the spread of values associated to each method.

Table 6 - Annual ambient dose equivalent [mSv/ano] calculated for the point 2 - current method

	High voltage (kV_p)											
Point	40	45	50	55	60	65	70	75	80	85	90	95
2	6,4	10,5	15,0	20,4	26,2	32,4	39,4	47,1	55,4	64,3	73,7	83,9

Table 7 - Annual ambient dose equivalent [mSv/ano] calculated for the point 2 - proposed method

	Reference high voltage (kV_p)											
Point	40	45	50	55	60	65	70	75	80	85	90	95
2	14,0	17,9	20,8	23,3	25,3	26,6	27,9	29,1	30,0	30,8	31,5	32,2

Table 8 - Division of the H*(10) value got under the tension "j" by the same quantity got under the tension "i" - Point 2 - Current method

T	High voltage (kV_p)											
(kV_p)	40	45	50	55	60	65	70	75	80	85	90	95
40	1,0	1,6	2,3	3,2	4,1	5,1	6,2	7,4	8,7	10,0	11,5	13,1
45	0,6	1,0	1,4	1,9	2,5	3,1	3,8	4,5	5,3	6,1	7,0	8,0
50	0,4	0,7	1,0	1,4	1,7	2,2	2,6	3,1	3,7	4,3	4,9	5,6
55	0,3	0,5	0,7	1,0	1,3	1,6	1,9	2,3	2,7	3,2	3,6	4,1
60	0,2	0,4	0,6	0,8	1,0	1,2	1,5	1,8	2,1	2,5	2,8	3,2
65	0,2	0,3	0,5	0,6	0,8	1,0	1,2	1,5	1,7	2,0	2,3	2,6
70	0,2	0,3	0,4	0,5	0,7	0,8	1,0	1,2	1,4	1,6	1,9	2,1
75	0,1	0,2	0,3	0,4	0,6	0,7	0,8	1,0	1,2	1,4	1,6	1,8
80	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,9	1,0	1,2	1,3	1,5
85	0,1	0,2	0,2	0,3	0,4	0,5	0,6	0,7	0,9	1,0	1,1	1,3
90	0,1	0,1	0,2	0,3	0,4	0,4	0,5	0,6	0,8	0,9	1,0	1,1
95	0,1	0,1	0,2	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0

Table 9 - Division of the H*(10) value got under the tension "j" by the same quantity got under the tension "i" - Point 2 - proposed method

T	High voltage (kV_p)											
(kV_p)	40	45	50	55	60	65	70	75	80	85	90	95
40	1,0	1,3	1,5	1,7	1,8	1,9	2,0	2,1	2,1	2,2	2,3	2,3
45	0,8	1,0	1,2	1,3	1,4	1,5	1,6	1,6	1,7	1,7	1,8	1,8
50	0,7	0,9	1,0	1,1	1,2	1,3	1,3	1,4	1,4	1,5	1,5	1,5
55	0,6	0,8	0,9	1,0	1,1	1,1	1,2	1,2	1,3	1,3	1,4	1,4
60	0,6	0,7	0,8	0,9	1,0	1,1	1,1	1,2	1,2	1,2	1,2	1,3
65	0,5	0,7	0,8	0,9	1,0	1,0	1,0	1,1	1,1	1,2	1,2	1,2
70	0,5	0,6	0,7	0,8	0,9	1,0	1,0	1,0	1,1	1,1	1,1	1,2
75	0,5	0,6	0,7	0,8	0,9	0,9	1,0	1,0	1,0	1,1	1,1	1,1
80	0,5	0,6	0,7	0,8	0,8	0,9	0,9	1,0	1,0	1,0	1,1	1,1
85	0,5	0,6	0,7	0,8	0,8	0,9	0,9	0,9	1,0	1,0	1,0	1,0
90	0,4	0,6	0,7	0,7	0,8	0,8	0,9	0,9	1,0	1,0	1,0	1,0
95	0,4	0,6	0,6	0,7	0,8	0,8	0,9	0,9	0,9	1,0	1,0	1,0

Now it is clear why in both matrixes all the elements above the main diagonal are higher than 1, and why those below it are smaller than 1. It is also quite clear that the proposed method presents a narrower spread, what means it is a better approach to the phenomenon of energy deposition in matter.

This fact alone is enough to prove that the proposed method is an improvement compared to the current one, because the growing of the exponent from 0 to 2 and further to its real value - greater than two - points to the same direction of a imaginary arrow that points from a first approximation to the reality of the phenomenon.

It must be stressed that if the exponents used to calculate the data of Table 5 were not 2, but their best values, higher than 2, all the rows of the Table 5 would have presented an even smaller dispersion. The dispersion would not vanish however, because of the energetic dependence of the ionization chamber. But if one tries to include these higher than 2 variable exponents, he would face a bit more complication, due to the variable character of them. The algorithm of the H*(10) calculation would lost its easiness and similarity with the current algorithm, what is of course not desirable. This is why the constant value 2 was chosen to represent the generalized exponent.

The residual dispersion would be small, but not null. Should the X ray spectrum get closer and closer to a unique energy value - and then the spectrum would be a delta function - would the dispersion gets closer and closer to the null value. It means the cells values on Table 9 would get closer and closer to the unity. This trend may already be seen, because some cells outside the main diagonal have the value 1. They are all in the higher HV region and in the neighbor of the main diagonal. This is a trend that can be predicted. It is due to the minimization of both phenomena that follow:

a) the nonlinear relation between the HV and the dose. The higher the HV, the closer to 2 is the exponent, as shown in [2]. And

b) the energetic dependence of the measurement device. The higher the HV, the harder is the beam, and smaller is the energetic dependence.

This paper deals with only the first phenomenon. It suggests a new approach to the problem of measuring the ambient equivalent dose. This approach is only a new step forward a better understanding of what really happens.

The proposed method has an additional advantage in the theme “HV election”. It is not anymore the uncommon highest value; it is the best value, chosen by whom has experience in radiation measurements and by the technician, who knows the frequency of HV values applied in the room.

The proposed method illustrates very well the process of measurement, what in truth is a query of the reality. In this case the arrangements or the improvements are in the mathematical treatment, not in the process of measurement itself, which did not change.

6. CONCLUSION

This paper shows how better is the proposed method compared to the current one.

To ignore the dose dependence on the HV brings deep implications, because there is a law which establishes dose constrains [3]. They should be applied in shield calculations for new rooms or for adequacy verification for older ones. Overestimating the H_X may imply in cost increase, charging the society. It may also demonstrate wrong insecurity ambient, with all the implications derived, legal and psychological. These are all civil implications, which demand a prompt action toward the adoption of the proposed model.

There are also scientific arguments in favor of a better assessment of H*(10). Any process of measuring should always point to a deeper understanding of the reality. To ignore what can be easily considered is a non sense. Of course there is a limit to how deep should we go. But in this case we are far from the limit, because the increment in deepness is so small that it makes no difference in the process of measuring. It changes only the calculation, not the process of measuring itself.

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