

OPTIMIZATION AND DECISION-MAKING RADIATION PROTECTION IN OPEN MOVABLE GAMMAGRAPHY FACILITIES

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ABSTRACT

To determine optimized dose limits for workers, a study of radiation protection optimization was undertaken in gammagraphy facilities, using the Multi-Attribute Utility Analysis technique. A total of 25 protection options, distributed in 12 irradiation configurations in an open movable type installation, were analyzed. In the determination of the optimized dose limit, the following attributes were considered: cost of the protection, costs of the detriment for different alpha values, individual equivalent doses and collective doses. The variables studied in the evaluation included: effective workload, and type and activity of the radiation sources, source-operator distance, type and thickness of the materials used in the protection shielding. Other parameters analyzed included the quality of the radiographic image and the technical procedures employed. The optimal analytic solutions that resulted in the optimized dose limit were determined by means of a sensitivity analysis and by direct and logical evaluations. Thus, independent of the values of the monetary coefficient attributed to the detriment, of the annual interests applied to the protection cost, and of the type of installation studied, it was concluded that the primary limit of the annual dose for workers, 50 mSv, can be easily reduced to an optimized annual dose limit of 5 mSv.

Key Words: optimization, dose limits, protection options, gammagraphy.

I. INTRODUCTION

The International Commission on Radiological Protection-ICRP has established since the early 1970s, an ionizing radiation Protection System based on the following general principles ^[1]: a) The justification of a practice; b) Protection optimization; c) Individual dose limits. The principle of protection optimization intends to decrease the individual dose until it reaches a value that is considered as an acceptable risk. This value is 1/10 of the values of the annual limits. Therefore, the optimization principle deals with the dose range between 1/10 and 1 value of the dose limits. This range is considered as a region of tolerable risk. The basic concept of protection optimization ^[2, 3] aims at generating a state of mind in all those who are responsible for the irradiation control, so that they continually ask themselves: Did I do every reasonable thing I could have done in order to reduce those radiation doses? This question needs to be repeated and answered until it reaches the dose value range of acceptable risks. To reduce the dose values from a practical stand point, it is possible to formalize several protection options with different prices and different

reductions in the dose value. Assuming that the more expensive protection options are those that produce a greater decrease in the dose values and the less expensive ones produce less decrease in the dose values, the problem is to define which option should be selected to be used.

Among the different available techniques ^[3, 4], selecting the option to be put in practice stands out the multi-attribute utility analysis because it accepts any number of protection attributes in monetary terms. This technique is based on the score (utility) for the relevant attributes of a certain option so that, if the score U_i of an option i , is greater than the score U_n of an option n , the option i will override option n . In cases in which the score is the same for two options, there is no preference for either of them. The practical implementation of this analysis only became possible in 1973^[5], when it was used to evaluate the radiological impact between the economic gain and the social gain, starting with the introduction of the collective equivalent dose, $S_{i,k}$, as a function of the concepts of objective and subjective detriment to health, G_k . The objective of this paper aims at radioprotection

optimization in gammagraphy facilities with the purpose of defining constraint dose limits, taking into account the radiographic quality and meeting the annual dose limits.

II. METHODOLOGY

Among the three types of radiographic facilities shielded enclosures, open fixed and open movable used in gammagraphy^[6], this paper deals with open movable facilities, illustrations shown on Fig. 1. The protection barrier was built with several materials, thicknesses and geometries, as described in the protection option shown on Table 1 and Fig. 2, respectively, where a total of 25 protection options, distributed in 12 irradiation

configuration were studied (Tables 1 and 2). In order to determine the optimized dose limits, the following attributes were considered: cost of the protection, costs of the detriment for different alpha values, individual equivalent doses and collective doses.

The variables studied in the evaluation included: effective workload and type and activity of the radiation sources (Table 2). Other parameters analyzed included the quality of the radiographic image and the technical procedures employed. The optimal analytic solutions that resulted in the optimized dose limits were determined by means of a sensitivity analysis and by direct and logical evaluations.

TABLE 1. Characteristics of Protection Shielding Materials Used in Open Movable Radiography Facilities.

Attributes of Protection		Materials Thickness Used in the Protection Shielding													
Option	Annual Cost US\$	Protection Shielding	Protection Shielding two												
		Lead (mm) "d"	1,5	3,0	4,8	6,3	7,8	9,5	12,7	15,9	19,0				
1	1217	14,28													
2	1616	19,00													
3	1283	14,28			² B										
4	1305	14,28				² B									
5	38	¹ W	¹ B												
6	815	9,52													
7	857	9,52		² B											
8	903	9,52				² B									
9	945	9,52								² B					
10	988	9,52									² B				
12	373	3,00						² B							
13	395	3,00								² B					
14	438	3,00									² B				
15	481	3,00												² B	
16	1259	14,28		² B											
17	837	9,52	² B												
18	523	3,00													² B
19	1347	14,28								² B					
20	1390	14,28									² B				
21	1083	12,27													
22	1126	12,27		² B											
23	1171	12,27					² B								
24	1214	12,27								² B					
25	352	3,00					² B								
26	924	9,52						² B							

¹W – Tungsten Collimator; ²B - Protection shielding in the operator's opposite hand; ¹B- Protection shielding placed in the semicircle in the operator's opposite hand; B - Represents the use of the screen (two plates); d - Represents the protection barrier.

TABLE 2 - Characteristics of the Irradiation Scenarios in the Open Movable Facilities.

Configuration	Source	⁽¹⁾ A	⁽²⁾ W _e	⁽³⁾ NPO	⁽⁴⁾ Materials	⁽⁵⁾ PJR(%)
Ia; Ib; Ic	¹⁹² Ir	1,85	150	5/6/5	Soil ; Pb; W ⁽⁶⁾	50;30 e 10
IIa; IIb; IIc	¹⁹² Ir	1,11	260	5/6/6	Soil ; Pb; W ⁽⁶⁾	50;30 e 10
IIIa; IIIb; IIIc	¹⁹² Ir	0,74	400	5/5/5	Soil ; Pb; W ⁽⁶⁾	50;30 e 10
IVa; IVb; IVc	¹⁹² Ir	0,37	700	5/6/6	Soil ; Pb; W ⁽⁶⁾	50;30 e 10

1 - Activity (Terabecquerel); 2 - Annual effective workload (h); 3 - Number of the protection option; 4 - Material used in the shielding 5 - % of radiography assembly; 6 - Tungsten Collimator (19 mm);

Evaluation of the individual annual effective dose

The whole body annual effective dose, H, for individuals occupationally exposed was calculated from the exposure rate ^[7], defined by Equation 1 from the effective workload. The “build-up” factors for air, Pb, Fe, used in the exposure rate were determined by Taylor's method^[8]. For conversion purposes, exposure to the absorbed dose was considered as 1 R in the air, equal to 0.01 Gy (1 rad) in the tissue. To convert the absorbed dose to an effective dose, w_R = 1 was used.

$$\dot{X} = \phi \times E \times \delta \tag{1}$$

where \dot{X} is the exposure rate in mR.h⁻¹; ϕ is the flow density, that is, the photons or number of particles per square centimeter per second (photons.cm⁻². s⁻¹); $\phi \times E$ is the radiant energy rate MeV cm⁻² s⁻¹; E is the photonic energy in MeV; δ is the conversion factor from a radiant energy rate to an exposure rate;

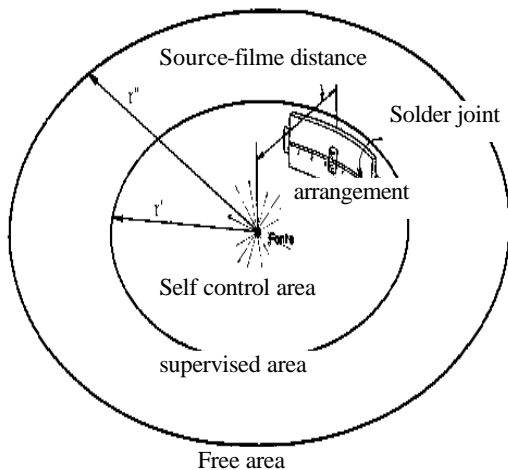


Figure 1. Illustration of the Work Area in the Open Movable Facility.

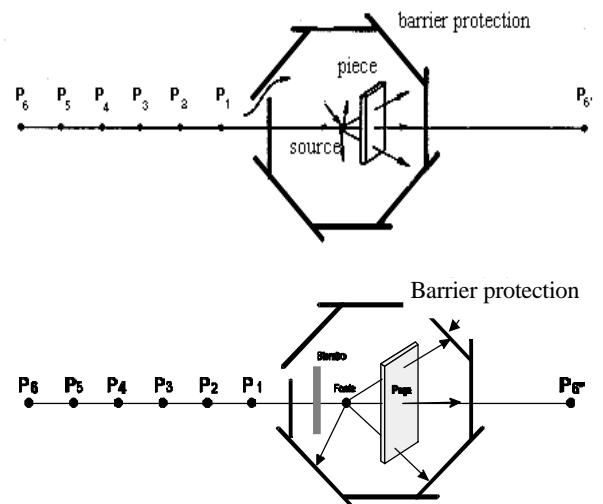
Annual collective dose

The annual collective equivalent dose for the workers was calculated considering the number of persons involved in the job^[9], (CNEN-6.04, 1986), that is, the

person in charge for the radiography facility; the operator; the operator assistant and the dark camera technician. The equation used in the collective equivalent dose calculation^[5], (ICRP-22 1973) was:

$$S_c = \sum_i N_i \times \bar{H}_{trab} \tag{2}$$

where, N_i is the number of workers and \bar{H}_{trab} is the average individual annual effective dose affecting the workers. The collective dose for public individuals was not calculated, because it is difficult to evaluate several factors, such as: the uncertainty in the number of persons in the houses and inside the company, the uncertainty in the facilities position relative to the houses, etc. For this reason, it was assumed that the collective dose during one year, was 1 sievert-person, as established⁽¹⁾ in the Brazilian regulations, in order to prevent the protection optimization calculation. Actually, the real collective dose will be lower.



P₁, P₂, P₃ e P₄ - Source-operator distance equal to 8.1; 8.8; 10.8 and 15 m, respectively; P₅ - source-operator distance for h ≤ 15 mSv/year; P₆ and P_{6'} - source-public personal distance of the operator's hand and opposite operator's hand respectively.

Figure 2. Illustration of the Irradiation Geometry Used in an Open Movable Facility.

Protection shielding cost

The term protection cost refers to the monetary cost of the materials used in the protection shielding (barrier protection) adding 3% to the annual shielding cost, such as maintenance cost, and the area isolation cost. The value of the protection shielding cost was determined as a function of the type and the thickness of the materials used and annualized considering that the life-time of the protection shielding will be twenty years. The price of the materials used in the protection barriers was obtained by an arithmetic average of the values obtained in three shops (one in São Paulo and two in Recife) - Lead sheet - US\$ 6.45 kg⁻¹ and density of the 11.3 g/cm³, Steel sheet - US\$ 0.85 kg⁻¹ and density of the 7.8 g/cm³, Tungsten Collimator - US\$: 320.00 and density of the 17.8 g/cm³, Plywood board - US\$: 8.50.

The Radioprotection Optimization

The analytical solution that optimizes the protection was obtained by using the aid technique for decision making in radiological protection known as multi-attribute utility analysis. The equation used in the analytical solution that optimizes the protection option^[3, 4], is:

$$U_i = \sum_{j=1}^n k_j \times u_{j,i} \quad \text{with} \quad \sum_j k_j = 1 \quad (3)$$

where k_j is a scaling constant that expresses the relative importance, or weight, assigned to each factor j , u_j is a single utility function, that expresses the various utilities of the factors n associated with each protection option i , and U_i is the total utility function of each option i . The higher the figure of merit, U_i , the better the overall ranking of the option, so the analytical solution will be the option which maximizes U_i . Having specified the relevant radiological protection attributes, it is necessary to incorporate the criteria for the relative importance of the attribute and this is carried out through a utility function u_j that yields the relative desirability of the possible outcomes for attribute j . At the best outcome, or lowest adverse consequence for each attribute (e.g. lowest cost, minimum collective dose), a utility u_j of 1 is assigned, and for the worst consequence, a utility of 0 is used. The major advantage of this technique is that these utility functions need not necessarily be linear. In this paper, the protection cost $u(X)$, the collective equivalent dose $u(S)$, and the individual equivalent dose $u(h_2)$, in the range of $5 \text{ mSv} < h_2 < 15 \text{ mSv}$ were considered as being a linear function type $u(z) = a + b.z$, where the constants a e b are obtained assuming that $u(X) = u(S) = 0$, and $u(h_2) = 0.9$ when X, S, a and h_2 assume the maximum values and $u(X) = u(S) = u(h_2) = 1$ when X, S and h_2 , assume the minimum values. For values of the individual annual equivalent doses " h_3 " in the range of $15 \text{ mSv} \leq h_3 \leq 50 \text{ mSv}$, the utility function was defined by

$$u(h_3) = a + b \times e^{c \times [h_3(\text{Sv}) - 0.015]} \quad (4)$$

where $u(h_3) = 0.9$ for $h_3 = 15 \text{ mSv}$ and $u(h_3) = 0$ for $h_3 = 50 \text{ mSv}$. A risk of *adverse attitude* was assumed in this equation. In the cases where the individual annual equivalent doses are lower than 5 mSv, the utility function assume the unitary value, that is, $u(h_1) = 1$.

Scaling constant

The assessment of the various k_j , expressing the relative importance of attribute j , can be performed in two possible ways. The *direct evaluation*^[3], takes into account the range of values associated with each attribute, in order to classify the attribute as either important or not. In this case, the scaling constants $k(X)$, $k(S)$, $k(h_1)$, $k(h_2)$ and $k(h_3)$ of their respective attributes, j , were obtained by means of these relationships:

$$\frac{k(S)}{k(X)} = \frac{R(h_1)}{R(X)} = \frac{R(h_2)}{R(X)} = \frac{R(h_3)}{R(X)} \quad (5)$$

where R represents the attribute range value specified between parenthesis; k represents the scaling constant of the attribute between parenthesis. The *substitution rates*^[3] first order the attributes from the most important to the least important. Then, the importance of each attribute is assigned relative to the most important one. In this case, the value of the scaling constant $k(X)$, $k(S)$, $k(h_1)$, $k(h_2)$ and $k(h_3)$ assume the value

$$k(X) = k(S_C) = k \quad \text{and} \quad k(h_1) \neq k(h_2) \neq k(h_3) \quad \text{with} \quad (3)$$

$$k = 1 / [2 + (R(h_1) + R(h_2) + R(h_3)) / R(X)] \quad (6)$$

$$k(h_1) = \frac{R(h_1)}{R(X)} \times k(X) \quad (7)$$

$$k(h_2) = \frac{R(h_2)}{R(X)} \times k(X) \quad (8)$$

$$k(h_3) = \frac{R(h_3)}{R(X)} \times k(X) \quad (9)$$

Because these values were not assumed, they were called *logical evaluation* in a formal manner, rather than *substitution rates*.

Sensitivity Analysis

The use of quantitative decision-support techniques involve the use of data and models, which contain uncertainties of various types, such as uncertainties associated with an imperfect knowledge of the performance of the options under different circumstances, or the parameters and data used in the assessment, e.g. dose estimates, technical specification of the option etc. A basically different type of variability is associated with the criteria used in the optimization study, such as the value of the unit collective dose. Even though these criteria should be externally imposed, it is legitimate, as part of the sensitivity, to investigate which would have been the result, had

different criteria been imposed. Investigation of some of the above uncertainties through a sensitivity analysis provides important insights into the stability of the results with regard to variation in the data, assumption and judgements of the analytical procedure. In particular, the sensitivity analysis highlights the aspects that have the greatest influence on the results. In this paper four different sensitivity analysis were conducted aiming to obtain insights about the analytical solution stability. In the first sensitivity analysis the relevance of the attributes was analyzed, changing the scaling constants values. In the second one, the variation in the value of the unit collective dose was added to the sensitivity analysis I, and a new set of scaling constants. In the third one, the variation in the annual interest applied to the option protection cost X was added to the sensitivity analysis II. In the last one, the annual interests applied to the option protection cost was introduced in the logic and in the direct evaluation of scaling constants cases.

Sensitivity analysis I

In this type of analysis a maximum utility was imposed to each one of the scaling constants k_j , and a minimum for the remainder scaling constants forming the sequence:

$$\begin{aligned} k_1(X) = 0.8 \text{ and } k_1(S) = k_1(h_1) = k_1(h_2) = k_1(h_3) = 0.05; \\ k_2(S) = 0.8 \text{ and } k_2(X) = k_2(h_1) = k_2(h_2) = k_2(h_3) = 0.05; \\ k_4(h_1) = 0.8 \text{ and } k_4(S) = k_4(X) = k_4(h_2) = k_4(h_3) = 0.05; \\ k_5(h_2) = 0.8 \text{ and } k_5(h_1) = k_5(S) = k_5(X) = k_5(h_3) = 0.05; \\ k_6(h_3) = 0.8 \text{ and } k_6(h_2) = k_6(h_1) = k_6(S) = k_6(X) = 0.05 \end{aligned}$$

Sensitivity Analysis II

The sensitivity analysis II, is similar to the sensitivity analysis I, just differing in the scaling constants values of the attributes, as in this analysis the values will depend on the associated monetary coefficient of the unitary collective dose α , that assumes different values: US\$ 3,000 /person-sievert, current value in Brazil^[10]; US\$ 10,000 /person-sievert, official value adopted in Brazil^[11]; US\$ 20,000 /person-sievert, value adopted in the European Community and in the United State^[4] and US\$ 25,000 /person-sievert, value adopted in Japan^[4].

Thus, the scaling constants in the case of $j = 1$ assume the value given by the following equation:

$$\begin{aligned} k_1(X) = 0.8 \text{ with } k_1(S) \neq k_1(h_1) = k_1(h_2) = k_1(h_3) \text{ and} \\ k_1(S) = \alpha \times [R(S) k_1(X) / R(X)] \text{ and } k_1(h_1) = k_1(h_2) = k_1(h_3) = \{1 - \\ k_1(X) \times [1 + R(S) / R(X)]\} / 3. \text{ Similarly, the equation for } j=2 \text{ will be:} \end{aligned}$$

$$k_2(h_1) = 0,8 \text{ and}$$

$$k_2(X) = k_2(h_2) = k_2(h_3) = 0.20 / \{3 + \alpha \times [R(S) / R(X)]\}$$

and so on for the remainder values of j .

Sensitivity Analysis III

On sensitivity analysis III, the annual interests of 3%, 6%, 9% and 12% were added to the protection “costs X”, according to the “price” table, using the same approaches of sensitivity analysis II, with respect to the scaling constants of the attributes and the associated monetary coefficients of the unitary collective dose.

Sensitivity Analysis IV

On sensitivity analysis IV, the annual interests of 3%, 6%, 9% and 12% applied to the protection option costs were introduced in the logic evaluations (equation 6, 7, 8 and 9) and in the direct evaluations (equation 5) of the scaling constant.

III. RESULTS AND DISCUSSION

Among the twenty five protection options studied in the radiography open fixed facilities, just thirteen options were considered as an optima analytic solution (Tables 3 and 4), and the best options being 32 (Table 5). From Table 5, it can be realized that 30.8% of the optima options present annual individual equivalent dose in the range $h \leq 5$ mSv, 38.5% in the range $5\text{mSv} < h \leq 15$ mSv, and 30.8% in the range between $15 \text{ mSv} < h < 50$ mSv. On the other hand, it can be seen that the adaptation of a facility in operation, the protection shielding characteristics of which are similar to one of the protection options, considered in this paper, can be achieved in a simple, easy, fast way and at a low operational cost, offering an optimized option that meets the requirements of the ALARA principle.

IV. CONCLUSIONS

The following conclusions can be drawn from this paper:

- The annual individual equivalent dose limit for workers, in the area of the radiography facility – open fixed can be easily reduced below 5 mSv;
- In order to reach the annual dose value below 5 mSv-year, protection options should be used with either the same or similar characteristics of those of the optimized options in their respective dose ranges;
- The optimized protection options in terms of the individual and collective equivalent doses, are not altered when different values of the monetary coefficient for the detriment and of the annual interest applied to the protection shielding cost are used.

TABLE 3 – Relative values of the frequency and preference of the attributes of optimized protection options in the open movable facilities for range individual equivalent annual dose.

dh	Opção	X _P	X _P +X _Y	h	S _C	%F ₁	%P(X _P)	%P(X _P +X _Y)	%P(h)	%P(S _C)	E ₁	E ₂	
h < 5 mSv	5	38	92	0,0045	0,018	92	100	100	100	100	392	392	
	2	1616	1760	0,0120	0,048	4	0	0	93	74	171	171	
	10	988	1075	0,0073	0,029	4	40	41	98	90	232	233	
	5 mSv < h < 15 mSv	15	481	634	0,0130	0,051	1	72	68	92	71	236	232
		18	523	607	0,0070	0,028	4	69	69	98	91	262	262
		19	1347	1419	0,0060	0,024	4	17	20	99	95	215	218
		20	1390	1464	0,0062	0,025	4	14	18	99	94	211	215
24	1214	1295	0,0068	0,027	4	25	28	98	92	220	222		
h > 15 mSv	1	1217	1501	0,0237	0,095	3	25	16	87	33	148	138	
	7	857	1256	0,0330	0,133	2	48	30	77	0	127	109	
	8	903	1134	0,0192	0,077	4	45	38	89	49	186	179	
	14	438	684	0,0210	0,082	4	75	65	88	44	211	201	
	16	1259	1445	0,0155	0,062	4	23	19	90	62	178	175	
	22	1126	1338	0,0177	0,071	4	31	25	87	54	176	171	

Relative preference for the attribute protection total cost; %P(h) - Relative preference for the attribute equivalent dose; %P(a) - Relative preference for the attribute isolation area; %P(S_C) - Relative preference for the attribute collective dose; %F₁ - Relative frequency of appearance of the protection option excellent analytic solution; E₁, E₂; E₃ - Total score of preference of the attributes, E₁ = %P(X_P) + %P(h) + %P(S_C) + %P(a) + %F₁; E₂ = %P(X_P+X_Y) + %P(h) + %P(S_C) + %P(a) + %F₁; E₃ = %P(X_P+X_Y+X_a) + %P(h) + %P(S_C) + %P(a) + %F₁

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