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ECONOMICS OF RADIATION PROTECTION: EQUITY CONSIDERATIONS

ABSTRACT. In order to implement cost-benefit analysis of protective actions to reduce radiological exposures, one needs to attribute a monetary value to the avoided exposure. Recently, the International Commission on Radiological Protection has stressed the need to take into consideration not only the collective exposure to ionising radiation but also its dispersion in the population. In this paper, by using some well known and some recent results in the economics of uncertainty, we discuss how to integrate these recommendations in the valuation of the benefit of protection.

KEY WORDS: Radiation protection, equity, economics of uncertainty, optimisation

1. INTRODUCTION

Because of the uncertainty related to the existence of potential health effects induced by radiation exposure at low doses, the International Commission on Radiological Protection (ICRP) has adopted the reasonable assumption that there is some additional risk of cancer from any increment of dose. As a consequence, the proper attitude in radiological protection is to take any reasonable step to reduce all exposures as low as reasonably achievable, economic and social factors being taken into account. This attitude is known as the ALARA principle[1] or optimisation of protection principle and constitutes (with the justification of practice and the limitation of individual doses) the basis of the system of radiological protection recommended by ICRP.

ICRP proposes guidelines to value investments in the field of radiological protection (see ICRP, 1973, 1983, 1985 and 1991). One of the purposes of any radiological protection investment is to reduce

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the doses to which workers and the population are exposed. In order to evaluate these investments, one needs to compare their costs with the reduction in individual and collective doses they induce (see Stokell *et al*., 1991). To proceed to the computations, it is necessary to attach a monetary value to the detriment associated with each dose level.

The purpose of the present paper is to analyse the constraints imposed by the ICRP recommendations on the parameters of a widely used model of detriment valuation (the so-called value of the man-sievert) (see Berthet *et al*., 1992 and Lefaure *et al*., 1993). In the first section, we briefly present this model and its notation, as well as the three goals assigned by the ICRP recommendations to any investment in the field. In the following three sections, by using some results in the economics of uncertainty, we derive the implications of these goals in order to narrow the range of values admissible for one of the key parameters in the model.

2. THE MODEL AND THE ICRP RECOMMENDATIONS

In order to value the detriment associated with a dose level x, it is customary to define the average cost of this detriment ($\alpha_{\text{Ref}}(x)$) by a piecewise function:

$$\alpha_{\text{Ref}}(x) = \alpha_{\text{base}} \qquad \text{for} \quad x \leqslant x_0$$
$$\alpha_{\text{Ref}}(x) = \alpha_{\text{base}} \left(\frac{x}{x_0}\right)^a \qquad \text{for} \quad x \geqslant x_0$$

This function[2] implies, in accordance with economic intuition, that the average cost is constant (and equal to α_{base}) below a dose level (x_0) and becomes a function of x for values of the dose that exceed the level x_0.

The value of α_{base} reflects the basic monetary valuation of health effects associated with exposure and will not be discussed here. Similarly, the value x_0, which can vary according to categories of exposure (i.e. different categories of workers, or the public, as well as normal or accidental situations), will not receive our attention. Our main concern will be to determine some range of values for the exponent 'a' in accordance with the ICRP recommendations.

Quite naturally, the first goal in the optimisation procedure defined by the ICRP is to reduce collective dose (i.e., reduce individual doses as well as the number of people exposed). However, the recommendations have also progressively stressed the need to introduce equity considerations in addition to the efficiency one. This is the reason why the following two goals have been added:

– reduce the dispersion of the individual exposure levels within the exposed population, and
– give priority in the reduction of dispersion at the highest individual exposure levels.

In practice, the application of the cost-benefit analysis leads to calculate the cost of the collective exposure according to the distribution of individual doses. Assuming a continuous distribution of individual exposures $(f(x))$, this cost is given by:

$$CT = \alpha_{\text{base}} \int_0^{x_0} x \cdot f(x)\,\mathrm{d}x + \frac{\alpha_{\text{base}}}{(x_0)^a} \int_{x_0}^{x_{\max}} x^{a+1} \cdot f(x)\,\mathrm{d}x$$

where:

$x =$ level of individual exposure,
$f(x) =$ frequency,
$x_{\max} =$ limit value of individual exposure.

The cumulative distribution function of doses is expressed by $F(x)$, with $F'(x) = f(x)$.

The combination of the three objectives (i.e. reduction of collective exposure, reduction of the dispersion, priority in the reduction of dispersion at the highest individual levels of exposure) is discussed in the following paragraphs by analysing the costs associated with various distributions of individual exposures, $F(x)$ being considered as the initial situation. The discussion focuses on the value of the exponent 'a'.

3. INCENTIVE TO REDUCE THE COLLECTIVE EXPOSURE

Starting from the initial situation, we assume an increase in the exposure level for a part of the exposed population. By assumption, this modification does not concern the population exposed below

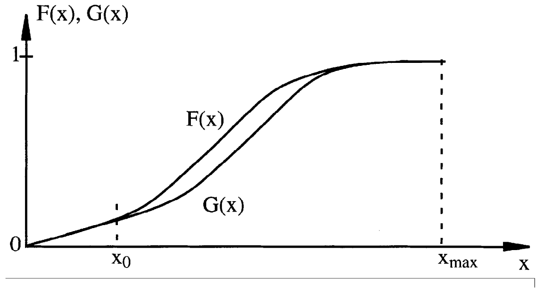

Figure 1. Cumulative distribution functions.

x_0. The density of dose, $g(x)$, associated with this new situation leads to a higher collective dose and corresponds to a 'first order stochastically deteriorating shift' of the dose, so that $G(x)$ is lower or at most equal to $F(x)$, as described in Figure 1.

For the sake of simplification, because $F(x) = G(x)$ for $x \leqslant x_0$, the cost of the situations will be calculated only for the levels of individual exposure greater than x_0. Moreover, the term $[\alpha_{\text{base}}/(x_0)^a]$, being constant and positive, is omitted in the following equations. The simplified cost of the new situation is given by:

$$\widehat{CT} = \int_{x_0}^{x_{\max}} x^{a+1} \cdot g(x)\,\mathrm{d}x$$

The first objective of the reference monetary value system deals with the incentive to reduce collective exposure. Consequently, the cost of the new situation has to be greater than the initial one (i.e. $\widehat{CT} > CT$):

$$\begin{aligned}
\widehat{CT} &= \int_{x_0}^{x_{\max}} x^{a+1} g(x)\,\mathrm{d}x \\
&= x_{\max}^{a+1} - x_0^{a+1} \cdot G(x_0) - (a+1) \int_{x_0}^{x_{\max}} x^a G(x)\,\mathrm{d}x \\
CT &= \int_{x_0}^{x_{\max}} x^{a+1} f(x)\,\mathrm{d}x \\
&= x_{\max}^{a+1} - x_0^{a+1} \cdot F(x_0) - (a+1) \int_{x_0}^{x_{\max}} x^a F(x)\,\mathrm{d}x \\
\widehat{CT} - CT &= -(a+1) \cdot \int_{x_0}^{x_{\max}} (G(x) - F(x)) \cdot x^a \cdot \mathrm{d}x
\end{aligned}$$

Since $(G(x) - F(x))$ is not greater than zero, and since x^a is strictly positive, $\widehat{CT}$ will be greater than CT if and only if 'a'

is greater than (-1). This condition warrants that an increase in individual exposure level leads to an increase in the associated cost of the exposure.

4. INCENTIVE TO REDUCE THE DISPERSION

Recently, the ICRP has stressed the need to reduce the dispersion of the individual exposure levels for a given collective dose. This additional recommendation will in fact narrow the range of possible values for the exponent 'a'. Since the collective dose (and hence also the average one) is kept constant while its dispersion in the population is reduced, it is natural to model the situation by using the notion of a 'mean preserving spread' (or contraction), first proposed by Rothschild and Stiglitz (1970 and 1971) (see Figure 2). In order to obtain an incentive to reduce the dispersion at a constant collective dose, a less dispersed distribution should induce a lower total cost.

To model the situation, let us denote by $h(x)$ a new distribution function derived from the initial one $f(x)$ by reducing the dispersion of individual exposures in an interval $[r, t]$. For the sake of notation, we also refer to $s(x)$ where:

$$h(x) = f(x) + s(x)$$

Furthermore, we will also have: $s(x) = S'(x)$ and $T'(x) = S(x)$.

To obtain a mean preserving contraction of the individual doses, the function $s(x)$ has to satisfy:

$$\int_r^t s(x)\,\mathrm{d}x = 0$$

and:

$$T(\lambda) = \int_r^\lambda S(x)\,\mathrm{d}x \leqslant 0 \quad \text{for:} \quad r \leqslant \lambda < t,$$
$$\text{with:} \quad T(\lambda) = 0 \quad \text{at} \quad \lambda = t.$$

A mean preserving contraction is depicted in Figure 2. To comply with the second ICRP recommendation, the total cost associated with the distribution $h(x)$, which will be denoted CT_1, has to be lower than the initial cost CT. Using the definition of the total cost, we have:

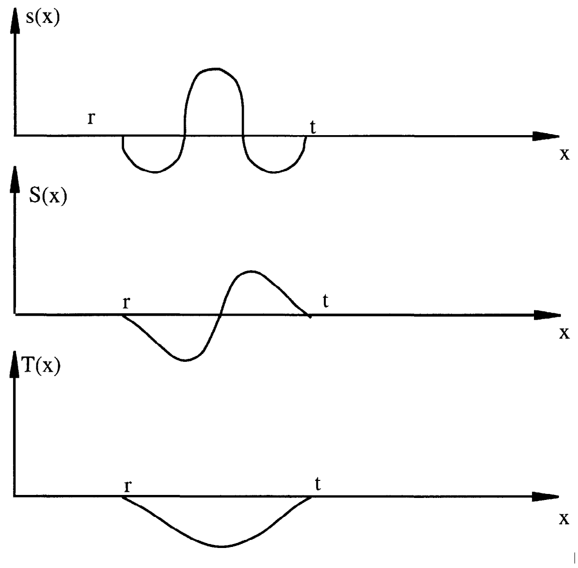

Figure 2. Characteristics of the 'mean preserving spread'.

$$CT_1 = \int_{x_0}^{x_{\max}} x^{a+1}(f(x) + s(x))\,\mathrm{d}x$$

and:

$$\begin{aligned} CT_1 - CT &= \int_r^t x^{a+1} \cdot s(x) \cdot \mathrm{d}x \\ &= [x^{a+1} \cdot S(x)]_r^t - (a+1) \int_r^t S(x) \cdot x^a \cdot \mathrm{d}x \\ &= -(a+1) \int_r^t S(x) \cdot x^a \cdot \mathrm{d}x \\ &= -(a+1) \cdot \Big\{ [x^a \cdot T(x)]_r^t \\ &\quad -a \cdot \int_r^t x^{a-1} \cdot T(x) \cdot \mathrm{d}x \Big\} \\ &= (a+1) \cdot a \cdot \int_r^t x^{a-1} \cdot T(x) \cdot \mathrm{d}x \end{aligned}$$

The condition $CT_1 - CT < 0$ will be satisfied, as soon as 'a' is greater than 0. It should be noted that $a = 0$ implies an indifference between the two distributions.

5. INCENTIVE TO REDUCE DISPERSION AT HIGHEST INDIVIDUAL EXPOSURE LEVELS

As indicated in Section 2, ICRP favours a reduction in dispersion that takes place at an initially high level of exposure relative to an identical reduction at a lower level of exposure. To formalise this preference, we consider a translation to the right of the mean preserving contraction that takes place in the interval $[r, t]$[3]. As shown in Figure 3, the function $s(x)$ is moved from the interval $[r, t]$ to the interval $[r', t'] = [r + b, t + b]$. In line with ICRP, such a shift, which changes neither the collective dose nor its total dispersion, should reduce the total cost of the detriment.

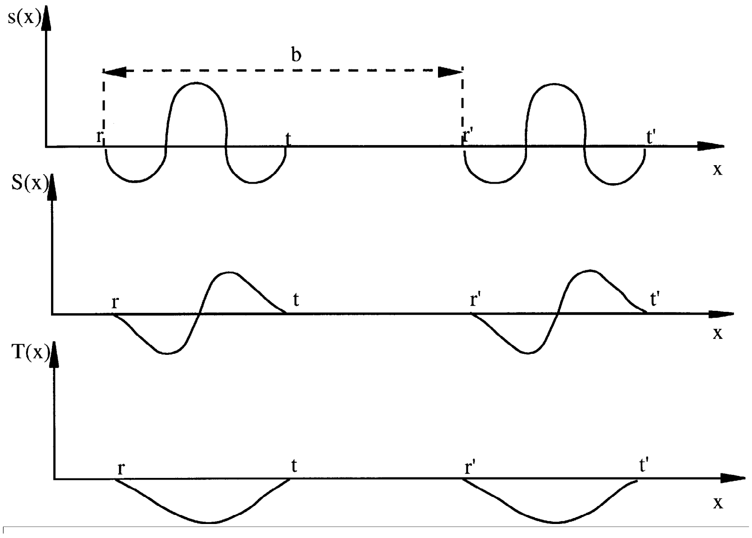

Figure 3. Characteristics of the two reductions of dispersion.

Remembering that $CT_1 - CT$, the impact of the initial mean preserving contraction corresponds to:

$$CT_1 - CT = \int_r^t x^{a+1} \cdot s(x) \cdot \mathrm{d}x$$
$$= a \cdot (a+1) \cdot \int_r^t x^{a-1} \cdot T(x) \cdot \mathrm{d}x$$

we also have:

$$CT_2 - CT = \int_{r'}^{t'} y^{a+1} \cdot s(y) \cdot \mathrm{d}y$$

$$= a \cdot (a+1) \cdot \int_{r'}^{t'} y^{a-1} \cdot T(y) \cdot \mathrm{d}y$$
$$= a \cdot (a+1) \cdot \int_{r}^{t} (x+b)^{a-1} \cdot T(x) \cdot \mathrm{d}x$$

where CT_2 is the cost of the detriment applying to $s(x)$ in the interval $[r', t']$. Consequently:

$$CT_2 - CT_1 = a \cdot (a+1) \cdot \int_{r}^{t} ((x+b)^{a-1} - x^{a-1}) \cdot T(x) \cdot \mathrm{d}x$$

Three cases have to be distinguished then:

– If $a > 1$, and since b is strictly positive, the total cost CT_2 *(i.e. reduction of dispersion at the highest levels of individual exposures)* is lower than the total cost CT_1 *(i.e. reduction of dispersion at the lowest levels of individual exposures)*. In this case, the model provides an incentive to reduce the dispersion at the highest levels of individual exposures.

– If $a = 1$, the two total costs are equal. Even if this condition provides an incentive to reduce the dispersion of individual exposures, there is no difference according to which levels of individual exposures are concerned with the reduction.

– If $a < 1$, the total cost CT_1 *(i.e. reduction of dispersion at the lowest levels of individual exposures)* is lower than the cost CT_2 *(i.e. reduction of dispersion at the highest levels of individual exposures)*. In this case, the model provides an incentive to reduce the dispersion at the lowest levels of individual exposures.

In order to satisfy the third objective *(i.e. to give priority in the reduction of dispersion at the highest individual exposure levels)*, the exponent 'a' has to be greater than 1. As a consequence, the three objectives of the ICRP put successively stronger restrictions on the admissible values of 'a'. If one wants to simultaneously satisfy the three objectives, the exponent 'a' should exceed unity, and the average cost curve of the detriment[4] is shown in Figure 4.

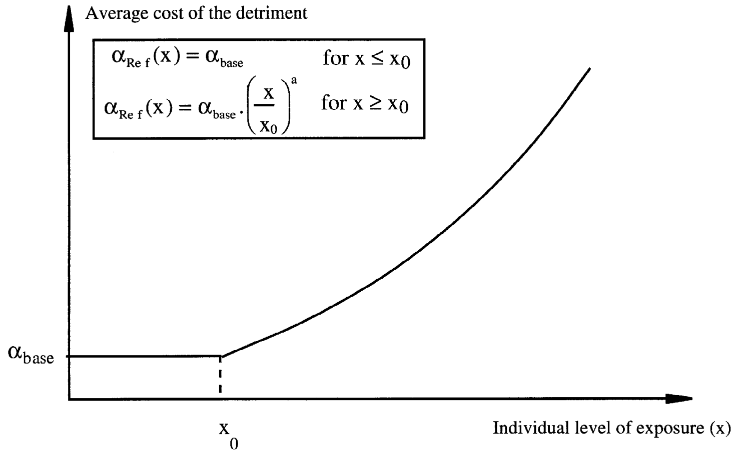

Figure 4. Average cost curve of the detriment.

6. CONCLUSION

In order to evaluate preventive investments that are taken to manage the radiological risks, it is necessary to attribute a monetary value to the unit of exposure. In recent years, the ICRP has issued general guidelines specifying the objectives to be achieved by the preventive investments. While the ICRP initially expressed concern about the level of individual and collective doses, it has recently paid more attention to equity considerations. In line with a standard approach, this is expressed by a preference for a less dispersed distribution of exposures, preferably at the highest levels of exposure.

By using concepts and techniques that are more or less familiar in the economic analysis of risk, we have translated the ICRP objectives into constraints on the shape of the curve linking the average cost of the detriment to a given level of exposure.

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NOTES

[1] The acronym ALARA, which is familiar for practitioners of radiation protection, stands for 'As Low As Reasonably Achievable'.

[2] We refer here to the type of function currently used in the field of radiation protection. Our analysis could easily be extended to any everywhere differentiable functional form. For this extension, the interested reader may refer to Eeckhoudt *et al*. (1995).

[3] For an analysis of the relationship between such a shift in distribution and properties of a utility function see Eeckhoudt *et al*. (1995). While the preference for a mean preserving contraction corresponds to 'risk aversion', the third ICRP recommendation reminds us of the notion of 'prudence'.

[4] We present Figure 4 with cost of detriment as a function of the individual level of exposure as is usual in the radiation protection literature. Such a figure might be turned upside down to obtain a relationship between a utility axis and a non-exposure one, which is the kind of relationship more familiar to risk theorist.

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