Cost-Benefit Analysis and Radiation Protection*

by J.U. Ahmed and H.T. Daw

Cost-benefit analysis is a tool to find the best way of allocating resources. The International Commission on Radiological Protection (ICRP), in its publication No. 26, recommends this method in justifying radiation exposure practices and in keeping exposures as low as is reasonably achievable, economic and social considerations being taken into account

1. BASIC PHILOSOPHY

A proposed practice involving radiation exposure can be justified by considering its benefits and its costs The aim is to ensure a net benefit. This can be expressed as:

$$B = V - (P + X + Y)$$

where: B is the net benefit; V is the gross benefit; P is the basic production cost, excluding protection; X is the cost of achieving the selected level of protection; and Y is the cost assigned to the detriment involved in the practice.

If B is negative, the practice cannot be justified. The practice becomes increasingly justifiable at increasing positive values of B However, some of the benefits and detriments are intangible or subjective and not easily quantified. While P and X costs can be readily expressed in monetary terms, V may contain components difficult to quantify. The quantification of Y is the most problematic and probably the most controversial issue.

Thus value judgements have to be introduced into the cost-benefit analysis. Such judgements should reflect the interests of society and therefore require the participation of competent authorities and governmental bodies as well as representative views of various sectors of the public.

Once a practice has been justified by a cost-benefit analysis, the radiation exposure of individuals and populations resulting from that practice should be kept as low as reasonably achievable, economic and social factors being taken into account (i.e. application of the ALARA principle).

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To justify introducing a new, or modifying an existing, practice involves many considerations other than radiation protection. The only part radiation consideration plays in the cost-benefit analysis is the cost of radiation protection and the cost of the health detriment resulting from exposure of individuals and populations to radiation

Cost-benefit analysis helps to ensure that the total benefit outweighs the total detriment resulting from a particular practice. The total detriment includes all costs and negative aspects of the proposed practice such as capital and operating costs, radiation protection costs, cost of health detriments resulting from exposure of individuals and public to radiation and other risks, land use, etc. The total benefit includes the value of the product, increased employment, availability of energy, raising standard of living, etc.

2. ELEMENTS CONSIDERED IN JUSTIFICATION

From the viewpoint of radiation protection, it is just not enough to justify a practice by demonstrating a net benefit. Although analysis may show a net benefit, there may be instances where radiation exposure risks for some individuals may be unacceptably high Therefore an overriding requirement is that the individual dose limits, as set by the international bodies or authorized by the national competent authorities should not be exceeded; otherwise the practice is unjustifiable.

To judge the cost of the health detriment to a population or to gauge the acceptability of risk to individuals resulting from exposure to radiation, it is important to clarify certain concepts, namely the individual dose limits and the collective dose.

Dose Limits

These are set by the ICRP and are expressed in dose equivalent limits. The objective is to prevent the occurrence of harmful non-stochastic effects and to reduce the frequencies of stochastic effects to a level low enough to be deemed acceptable.

The non-stochastic effects are characterized by a causality relationship between dose and effect. The effects will always occur when the dose received reaches or exceeds a certain value — the threshold value. For doses above the threshold, the severity of the damage will be related to the dose; the higher the dose, the more serious the effect.

Stochastic effects follow a probabilistic dose-effect relationship. The effects considered here are the induction of malignancy and genetic effects. These are late effects, time being required for the manifestation either of the genetic effects or malignant diseases. It should be noted that for stochastic effects the dose received does not affect the severity of the effect. In addition, it is not possible to distinguish a radiation-induced case from that of a spontaneous one.

Although it is possible to prevent non-stochastic effects by setting the limits below the threshold dose, the dose limits for stochastic effects are set with a view to limit the risk to an acceptable level. Further, although the shape of the dose-effect relationship curve is known for fairly high doses, it is not well known for low doses because of the statistical uncertainties related to the spontaneous occurrence of the effects. Therefore, in setting the dose limits for stochastic effects, a cautious approach has been followed by assuming a direct proportionality between the dose and effect (i.e. with no threshold). This means that any exposure to radiation may involve some degree of risk.

Table I — Weighting Factors for Deriving a Weighted Dose Equivalent Relevant for Total Detriment Assessments

Organ	ICRP Risk Factor R_T (Sv^{-1})		W_T	Total Risk Factor R_i (Sv^{-1})		W_i
Gonads	0.4	10^{-2}	0.25	0 8	10^{-2}	0.50
Breast	0 25	10^{-2}	0.15	0.24	10^{-2}	0.15
Red bone marrow	0.2	10^{-2}	0.12	0.2	10^{-2}	0.12
Lung	0.2	10^{-2}	0.12	0.2	10^{-2}	0.12
Thyroid	0.05	10^{-2}	0.03	0.10	10^{-2}	0.06
Bone	0.05	10^{-2}	0.03	0.04	10^{-4}	0.02
Remainder	0.5	10^{-2}	0.30	0.4	10^{-2}	0.24
Skin				0.02	10^{-2}	0.02
TOTAL	1.65	10^{-2}	1.00	2	10^{-2}	1.23

The basic principle for setting dose limits for stochastic effects is that the acceptable health detriment should be equal whether the whole body is irradiated uniformly, or whether there is non-uniform irradiation. For that purpose, the concept of the effective dose equivalent, H_E, is used for setting individual dose limits. The effective dose equivalent, H_E, is defined as:

$$H_E = \sum_T W_T H_T$$

where: W_T is a weighting factor representing, the ratio of the lethal stochastic detriment in the irradiated tissue T to the total stochastic detriment when the body is irradiated uniformly; H_T is the mean dose equivalent in organ or tissue T

The values of W_T are shown in Table 1, column 3

Apart from the organs listed in Table 1, a weighting factor of 0.6 each should be given to the five remainder organs receiving the highest dose equivalents; exposure of all other tissues can be neglected. ICRP, in its 1978 statement (ICRP Report No. 28), pointed out that the hands, forearms, feet, ankles, skin and the lens of the eye should not be included among the remainder organs. These tissues therefore are to be excluded from the computation $\sum_T W_T H_T$. In the assessment of detriment from exposure of population groups, a small risk of fatal cancers resulting from exposure to the skin may need to be taken into account and for that purpose a value of $W_T = 0.01$ is to be used.

Risk Factors

Cost-benefit analysis in radiation protection operates in a region of low individual doses, lower than the dose limits. Using the direct proportionality between dose and effect, it follows that the detriment to health is proportional to the effective dose-equivalent resulting from the practice being examined. The proportionality factor is called the risk factor[1] ICRP and UNSCEAR[2], after scrutinizing a mass of biological data obtained both from human experience and animal research, suggested risk factors for stochastic effects resulting from exposure to ionizing radiations. These risk factors are considered by the ICRP in setting the ICRP dose limits For occupational exposure ICRP (Report No 26) believed "that the calculated rate at which fatal malignancies might be induced by occupational exposure to radiation should in any case not exceed the occupational fatality rate of industries recognized as having a high standard of safety". These safe industries are generally recognized to be those in which the average annual mortality due to occupational hazards does not exceed 10^{-4}. For members of the public the ICRP (Report No.26) indicates that from a review of available information related to risk regularly accepted in everyday life, it can be concluded that the level of acceptability for fatal risks to the general public is an order of magnitude lower than for occupational risks. On this basis a risk in the range of $10^{-6} - 10^{-5}$ per annum would likely be acceptable to any individual member of the public.

In radiation protection, it is not enough that the individuals' risk is set at a sufficiently low level. In addition, the total detriment to society resulting from a practice involving exposure to radiation should be kept as low as is reasonably achievable, economic and social factors being considered. The collective detriment to health for a group of individuals is the sum of detriments to the individuals making up the group. Therefore, with the assumption of direct proportionality between stochastic biological effects and dose equivalent, the collective detriment to health is directly proportional to the collective effective dose equivalent The collective effective dose equivalent, S_E, in a population consisting of N individuals is:

$$S_E = \bar{H}_E N$$

where: $\bar{H}_E$ is the per caput effective dose equivalent received by individuals.

The total number of health detriments, G_{total}, in a population of N individuals, is therefore.

$$G_{total} = kS_E$$

The constant of proportionality k = R g,
where: R is the risk factor for the occurrence of the detriment; and g the severity factor.

The risk factors for various organs, as set by the ICRP, are given in Table 1, column 2. These risk factors are to be used in estimating the fatal radiation-induced cancers and severe hereditary effects in the first two generations. The total risk factor is 1.65×10^{-2} Sv^{-1}, of which 1.25×10^{-2} Sv^{-1} is for the fatal radiation induced cancers and 0.4×10^{-2} Sv^{-1} for the severe hereditary effects for the first two generations.

The risk factor of 0.4×10^{-2} Sv^{-1} for severe hereditary effects in the first two generations has been derived by considering the age structure of the general public and workers. ICRP Report No.26 gave a risk factor of 10^{-2} Sv^{-1} for serious hereditary ill health within the first two generations following irradiation of either parent. However, in the general public not all those irradiated are fully reproductive Hence, only a fraction of the

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[1] Strictly speaking the proportionality constant is composed of 2 constants, i e. the risk factor and g, the severity factor (see later). For lethal effects, g is considered to be unity.

[2] United Nations Scientific Committee on the Effects of Atomic Radiation

total collective gonadal dose is genetically significant and so a risk factor lower than 10^{-2} per man-sievert should apply to the total collective dose. In the case of the general public, a correction factor of 30/70 = 0.43 would be appropriate by assuming 30 years as the mean age of child bearing and 70 years as the mean life-span. This corrected risk factor ($0.4 \times 10^{-2}\ Sv^{-1}$) is shown in Table 1, column 2, against gonads.

The working population has a different age structure which includes age groups between 18 and 65, a span of 47 years. The number of years of exposure before the age of 30 is 12 so it may be necessary to introduce an appropriate correction factor of 12/47 = 0.26

The difference in the risk factors for the general public and workers is not large enough to warrant the use of separate risk factors in the two cases. Therefore, the ICRP in its Report No.26 suggests the use of a unified risk factor of about $0.4 \times 10^{-2}\ Sv^{-2}$.

In assessing the health detriment, additional considerations arise when applying the risk factors.

(i) For the general public a small risk of fatal cancer resulting from exposure of the skin may need to be taken into account, for example, when the whole skin is exposed to soft β radiation. In this case ICRP Report No. 28 suggests that a risk factor of about $10^{-4}\ Sy^{-1}$ may be used for the mean dose over the entire surface of the skin and a weighting factor of 0 01 is to be applied for the assessment of skin fatal cancers.

(ii) For organs like the thyroid and skin, the radiation exposure may, in addition to the lethal effect, induce a large number of non-lethal effects, the latter being as significant as the former. In the case of the thyroid and skin, there is a dominating incidence of non-lethal cancers and the total risk factors are considered to be twice those for fatal cancers, as explained later.

(iii) The risk of hereditary damage that may be expressed in all subsequent generations per unit dose is considered to be about twice that used for the first two generations only. (ICRP Report No.26).

Risk factors for non-lethal cancers are assumed to be equal to those for lethal cancers under the following considerations:

Let m denote the mortality factor (the ratio of the mortality to the morbidity rate), the per caput risk of a lethal effect will be mR if R is the total risk factor ($R_{lethal} + R_{non\text{-}lethal}$) per unit dose equivalent The risk of a non-lethal effect will therefore be $(1 - m)R$. If the lethal risk is given a severity weighting factor of unity, however, the risk of non-lethal effects should be given considerably less weight, probably less than expressed by the fraction m. If we simplify the assessment by using m also as the weighting factor for severity of the non-lethal effects (a rather arbitrary assumption) the total health detriment for unit collective dose equivalent commitment will be:

$$m.R + (1 - m).R.m = mR\,(2 - m) \xrightarrow[\text{for } m \ll 1]{} 2\,mR = 2\,R_{lethal}$$

It may therefore be appropriate to multiply the risk of lethal effects by two in the case where there is a dominating incidence of non-lethal effects (skin and thyroid).

∴ The total detriment per unit collective dose resulting from uniform whole-body irradiation would be:

$$1.65 \times 10^{-2}_{(w.b.)} + 0.4 \times 10^{-2}_{(gonad)} + 0.02 \times 10^{-2} + 0.05 \times 10^{-2}_{(thyroid)} = 2.12 \times 10^{-2}$$

This could be rounded off to 2×10^{-2} (Table 1, column 4) by reducing somewhat the detriment from exposure of the remainder organs.

In cost-benefit analysis, there is a practical problem in the use of the above total health detriment, since it is usually the collective effective dose equivalent in man-sievert and not the expected weighted number of harmful effects that is entered in the calculation.

As mentioned earlier, this matter is currently being considered by an Advisory Group convened by the IAEA. The Group's provisional report suggests that the total detriment mentioned above be transformed into an "expanded" collective effective dose equivalent commitment. For this purpose, a new set of weighting factor (W_i) should be derived to calculate a weighted dose equivalent which can be used in assessing total detriment (Table 1, column 5).

From Table 1, it may be noted that to cause one case of lethal cancer or severe hereditary effect in the first two generations after uniform whole-body irradiation, the dose equivalent, $\bar{H}$, needed is on the average 60 Sv, derived from the formula:

$$\bar{H} = \frac{W_T}{R_T} = 60 \text{ Sv}$$

In this case the weighting factor for the whole body is 1, which is the sum of all organ weighting factors.

The derivation of the new weighting factor W_i which is to be considered in assessing all severe health detriment can be based either on

– taking $\bar{H} = 60$ which is the value for the **lethal effect** and in this case the sum of the weighting factors to account for all the **severe health detriment** should be greater than unity, as sbown in the last column, i.e. 1 23, or

– the weighting factor W_i should be related to the average dose equivalent which would produce a lethal or non lethal cancer and severe hereditary effects in all generations. This dose would be $60/1.23 \cong 50$ Sv.

Then in that case the W_i should be adjusted to add up to unity.

Using the first method it follows that the weighted dose equivalent which is relevant in cost-benefit analysis assessment is a factor f greater than the effective dose equivalent. The factor f is given by:

$$f = \Sigma \frac{W_i H_i}{H_E} = \frac{\Sigma_i W_i H_i}{\sum_T W_T H_T}$$

If only the gonads or the thyroid gland is exposed, then f = 2. As before, the skin is excluded from the computation of $\sum_T W_T H_T$. However:

$$f. H_E = \Sigma W_i H_i = H_{skin}$$

which means that the weighted dose equivalent becomes skin dose equivalent

These conclusions are in conformity with ICRP's statement following the 1980 Brighton meeting:

> "The Commission has reached the following conclusions with regard to the use of the effective dose equivalent in optimization assessments. The addition of the future genetic harm in the case of uniform whole-body exposure would add a further risk of 0 4 X 10^{-2} Sv^{-1} in the case of the public, or rather less in the case of the average worker, to the total assumed risk of 1.65 X 10^{-2} Sv^{-1}, i.e. it would increase the total detriment by at most 24 per cent. In the less likely case that the gonads would receive the dominating dose, the genetic harm would be twice that implied by the effective dose equivalent alone.

> "The weight of the additional detriment attributed to non-lethal cancer would depend upon the weight to be attached to a given length of time lost from normal health (during illness prior to cure) relative to an equal period of life lost as a result of death from fatal cancer. If that relative weight (K) is taken to be 0.1 (as in ICRP Publication No. 27), the addition of the detriment due to non-lethal cancer and the induction of benign tumours would only increase the total non-genetic detriment by 2 per cent, in the case of uniform whole-body exposure. If organs such as thyroid and skin, for which cancers have a low fatality rate, are irradiated alone and K is taken to be as high as 0.5, the total detriment will approach about twice that implied by the use of the effective dose equivalent alone. In most cases of external exposure or exposure to mixtures of radionuclides, however, the use of the effective dose equivalent alone would not significantly underestimate the total detriment".

The additional detriment due to non-lethal cancer would increase the total non-genetic detriment by about 2 per cent, as given in the ICRP statement and by about 5 per cent using the weighting factors W_i (Table 1, column 5). This is due to the different methods of estimating the severity factor g. The ICRP statement gives g as proportional to the man-years lost as a result of the harmful effects but the second alternative, mentioned in this article, considers g proportional to the mortality/morbidity ratio.

3. COST OF DETRIMENT

As mentioned earlier the collective effective dose equivalent usually enters into the calculation in cost-benefit analysis. It could be argued that the relationship between the cost of the health detriment and collective dose equivalent is directly proportional:

$$Y = \alpha S_E$$

where Y = cost of health detriment: α = constant, referring to the cost of unit collective dose equivalent; and S_E = collective effective dose equivalent

Ideally, if it were possible to arrive at a universal monetary value for the cost of radiation's deleterious stochastic health effects, then α would have a unique value. In practice this is not possible.

In assessing the cost of the total detriment it may be desirable to use the correction factor, f:

$$Y = f \alpha S_E$$

However, as explained above the inclusion of f will, in most practical situations, not substantially alter the result.

$$\therefore Y = \alpha S_E$$

The cost of the health detriment resulting from a practice in a given year should be a constant and therefore α has to be constant if the risk to the individual is sufficiently small This should be guaranteed by the basic dose limits. However, other socio-economic considerations may come into play. These may vary greatly from country to country and also may be vary with time. National authorities may wish to spend extra money and effort to meet socio-economic and political ends not necessarily required by consideration of radiation protection alone. Recognizing these factors a practical approach would be to add another term to the above equation. Thus:

$Y = \alpha S_E + \beta \Sigma N_i F(\bar{H}_i)$ *(This formula is based on the current considerations of the ICRP and other international organizations including the IAEA.)*

where $\bar{H}_i$ is the mean per caput dose equivalent to the individual in the group i containing N individual (N_i).

The second term would take care of the social factors which are dictated by national circumstances such as the perception of risk, and the distribution of dose equivalents within the exposed group

At the international level it would be appropriate to give information on the first part of the equation. The second term should be left to national authorities.

4. OPTIMIZATION OF RADIATION PROTECTION

To optimize radiation protection for a given practice, the incremental costs involved in reducing the collective dose (S), from a given level to a range of lower levels, are compared with the incremental health benefits that result. The ALARA value is that level of collective dose below which the cost of any additional radiation protection measures would exceed the worth of the reduction of health detriment. This assessment may be facilitated by the assignment of a monetary value to unit of collective dose (the value of α mentioned previously). However, a precise α value is not always needed in practice, since significant reductions in dose may be achieved at low costs and in such cases, no formal analysis or value of α is needed. Conversely, it is sometimes apparent without a formal analysis that a possible improvement will be exceedingly costly but results in trivial dose reduction. In both these cases an order of magnitude in the value of α could be used instead of a precise value.

Optimization of radiation protection should generally be carried out separately for the publ.c and workers, although some judgement is required in deciding the relative fractions of the available resources to be devoted to each group. If trade-offs between workers' exposure and public exposure are considered, it should be remembered that 1 man-sievert reduction in workers' exposure is not necessarily equivalent to a 1 man-sievert reduction in public exposure.

Optimization of protection has been carried out in the past mostly by qualitative, rather than quantitative methods. Quantitative optimization is now gradually being

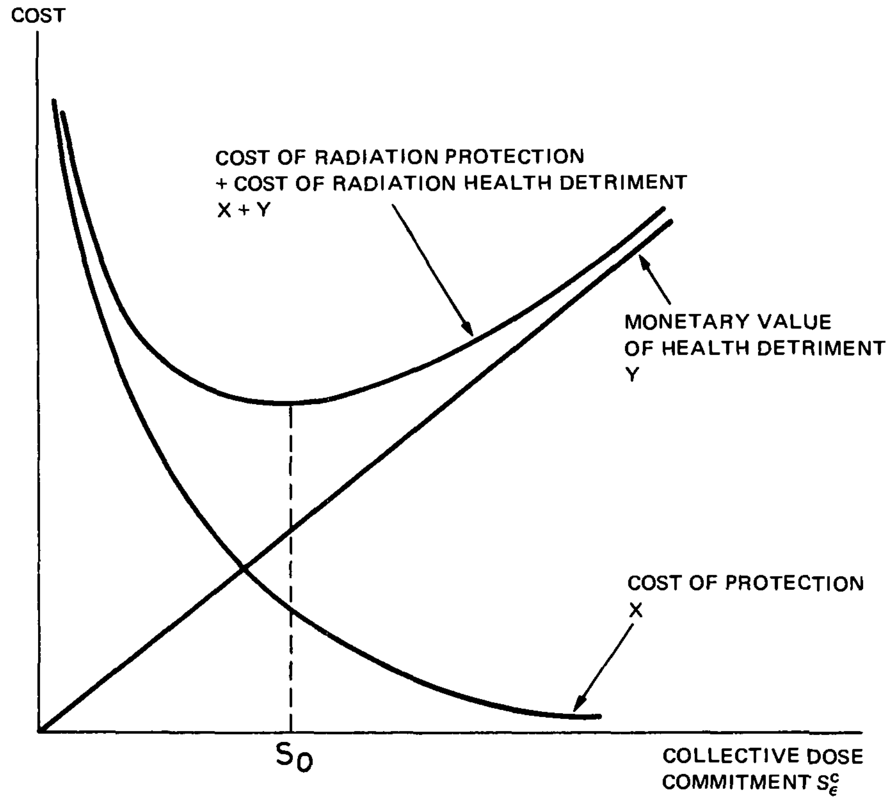

Figure 1. Optimization of radiation protection.

implemented. The method involves a differential cost-benefit analysis. Thus, if the general cost-benefit equation is differentiated with respect to S, the optimum net benefit shall be considered as attained at a value S_0 such that:

$$\frac{dV}{dS} - \left(\frac{dP}{dS} + \frac{dX}{dS} + \frac{dY}{dS}\right) = 0$$

If V and P are considered constants, the optimization condition is reduced to:

$$\frac{dX}{dS} = -\frac{dY}{dS}$$

Theoretically therefore, $dX/dS = -\alpha$ is the optimal condition for radiation protection (Fig.1).

If the change from one protection level to another is not described by a smooth function but rather by some step function, then the decision to go from a level of protection A to a more expensive level of protection B should be taken if:

$$\frac{X_B - X_A}{S_A - S_B} < \alpha$$

Except in medical exposures of patients for diagnostic or therapeutic purposes, a constraint on optimization is required as the distribution of benefit and detriment are rarely related to the same individuals For this reason, optimization of protection is only appropriate if each individual is guaranteed a sufficient degree of protection. This is assured if the dose limits to individuals are respected These dose limits therefore are a necessary boundary condition for optimization procedures.

In practice, optimization of radiation protection is often difficult and complex, with several sub-systems to be optimized The process would be less difficult if the sub-systems to be optimized are independent and not inter-related. In the latter cases, some judgement may be required whether further reductions of the collective dose will be worth the additional effort.

5. REMARKS

The value of α in monetary terms (adjusted for inflation) should in theory be constant However, in practice the situation is far from this. A literature survey shows a wide range for the value of α ranging from 1000 – 100 000 US dollars per man-sievert. This range for α reflects the different methods used to value the detriment. The most common methods of evaluating α are by arbitrary assignments, life valuation methodologies and direct surveys.

Several approaches have been used by economists to evaluate how society assigns values to human life and these may be used to derive a value of α by multiplying with the risk factor. The values calculated are not meant to imply an actual monetary value of life Instead, they are intended to provide measures by which fair and consistent resource allocation to radiation protection are made. These measures will vary from country to country and from time to time and so will the value of α.

In conclusion, cost-benefit analysis can be used in radiation protection to justify a practice involving exposure to ionizing radiation and in applying the principle of ALARA. It must be recognized that the data base for such analysis ranges from well-identified and quantifiable information, to information which is subjective in character and is intangible. In considering cost-benefit analysis, ethical problems are involved in trying to assign a monetary value to human life.

Cost-benefit analysis may raise issues ranging from local to global problems as well as problems extending in time from the present to the distant future. Nevertheless, cost-benefit analysis as applied to radiation protection is of assistance to the decision-making authorities and it helps public acceptance and understanding of practices which involve exposure to radiation.