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ON THE USE OF AGE-SPECIFIC EFFECTIVE DOSE COEFFICIENTS IN RADIATION PROTECTION OF THE PUBLIC*

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Abstract

Current radiation protection standards for the public include a limit on effective dose in any year for individuals in critical groups. This paper considers the question of how the annual dose limit should be applied in controlling routine exposures of populations consisting of individuals of all ages. We assume that the fundamental objective of radiation protection is limitation of lifetime risk and, therefore, that standards for controlling routine exposures of the public should provide a reasonable correspondence with lifetime risk, taking into account the age dependence of intakes and doses and the variety of radionuclides and exposure pathways of concern. Using new calculations of the *per capita* (population-averaged) risk of cancer mortality per unit activity inhaled or ingested in the U.S. Environmental Protection Agency's Federal Guidance Report No. 13, we show that applying a limit on annual effective dose only to adults, which was the usual practice in radiation protection of the public before the development of age-specific effective dose coefficients, provides a considerably better correspondence with lifetime risk than applying the annual dose limit to the critical group of any age.

1. INTRODUCTION

Current radiation protection standards for the public include a limit on effective dose in any year for individuals in critical groups (e.g., see ref. [1]). The annual dose limit, which currently is 1 mSv, is applied to control of routine exposures which, for purposes of radiation protection, usually are assumed to occur continuously over a lifetime.

This paper considers the question of how a limit on annual effective dose should be applied in controlling routine exposures of the public when the population consists of individuals of all ages and radionuclide intakes or exposures, dose, and risk all depend on age. Specifically, to what age group in the population should a limit on annual effective dose be applied? The same question applies to annual dose constraints for specific sources or practices at a fraction of the annual dose limit [1].

In addressing this question, we assume that the fundamental objective of radiation protection standards for the public is limitation of lifetime risk, essentially without regard for how risk is apportioned with age. Thus, in our view, when radiation protection standards are expressed in terms of a limit on annual dose, the dose limit should be applied in a way that provides a reasonable correspondence with lifetime risk from chronic exposure for any radionuclide and intake pathway of concern. We also assume, consistent with current practice, that the annual dose from internal exposure would be represented by the committed dose from all intakes of radionuclides during the year.

A limit on dose in any year for individual members of the public could be applied either to the critical group of any age or only to adults. This paper investigates whether applying a limit on annual effective dose to the critical age group or to adults provides the better correspondence with lifetime risk from chronic exposure of the public, taking into account the age dependence of intakes and doses and the variety of radionuclides and intake pathways of concern.

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2. BACKGROUND

Until recently, compliance with an annual dose limit for the public generally was based on estimates of dose only to adults, primarily because information on the age dependence of doses from radionuclide intakes, obtained from age-specific dosimetric and biokinetic models, had not been developed for the large number of radionuclides of concern. Applying an annual dose limit for the public to adults involved an implicit assumption that annual doses to younger age groups, although they might be higher than those to adults, would be relatively unimportant in determining lifetime risks, because most of the intakes and dose from chronic exposure would be experienced during adult years.

Over the last decade, however, the International Commission on Radiological Protection (ICRP) developed an extensive compilation of age-specific effective dose coefficients for inhalation and ingestion of radionuclides by members of the public, based on age-specific dosimetric and biokinetic models [2]. These data were developed largely in response to the Chernobyl accident, and the intent was to provide a set of dose coefficients for use in establishing guidelines for responses to radiation accidents, especially guidelines for interdiction of foodstuffs. For accidents, doses and risks from short-term exposures of particularly radiosensitive subgroups of the population are the primary concern, rather than doses and risks from chronic lifetime exposure.

The ICRP has not issued a formal statement on how its age-specific effective dose coefficients should be used in complying with the annual dose limit for routine exposures of the public. Absent any such statement, it would be natural to assume that the annual dose limit should be applied to the critical group of any age, taking into account the age dependence of radionuclide intakes and effective dose coefficients, rather than only to adults as in the past. Indeed, the Basic Safety Standards recently issued by the International Atomic Energy Agency [3], which are based on current ICRP recommendations [1], include a statement that compliance with the annual dose limit is to be based on the annual effective dose for the critical group of any age.

In a previous paper [4], we suggested, based on the limited information on the age dependence of doses from radionuclide intakes available at the time, that applying a limit on annual dose for the public to the critical group of any age could be questioned on the grounds that this approach provides a relatively poor correspondence with lifetime risk compared with the usual practice at that time of applying the annual dose limit only to adults. This paper provides a further investigation into this issue using the ICRP's age-specific effective dose coefficients [2], new calculations of the cancer risk per unit activity inhaled or ingested for various exposure pathways given in Federal Guidance Report No. 13 [5] issued by the U.S. Environmental Protection Agency (EPA) and described in the following section, and data on the age dependence of intakes for various environmental media of concern.

3. CANCER RISKS FROM ENVIRONMENTAL EXPOSURE TO RADIONUCLIDES

The EPA's Federal Guidance Report No. 13 [5] presents new calculations of risk coefficients in the form of *per capita* (population-averaged) cancer risks in the U.S. population per unit activity intake of radionuclides in the environment and, for external exposure, per unit activity concentration in the environment. Risk coefficients for cancer mortality and morbidity are calculated, but only the values for cancer mortality are used in this paper. For constant concentrations of radionuclides in the environment, as would result, for example, from long-term, essentially uniform releases, the risk coefficients can be used to assess risk from chronic lifetime exposure. For internal exposure, which is the only mode of exposure considered in this paper, risk coefficients are calculated for inhalation, ingestion of tap water, ingestion of food, and ingestion of radioiodine in cow's milk.

The risk coefficients for cancer mortality from radionuclide intakes by each exposure pathway were calculated based on (1) estimates of the lifetime risk per unit absorbed dose received at each age for each gender, taking into account recent vital statistics and cancer mortality data for the U.S., (2) the absorbed dose rate as a function of time following a unit activity intake at each age, calculated using the

ICRP's current age-specific dosimetric and biokinetic models (see ref. [2] and references therein), (3) the assumption of constant activity concentrations of radionuclides in environmental media (air, tap water, food, or cow's milk), (4) and age- and gender-specific intake rates for each environmental medium in the U.S. population. In addition, the EPA's estimate of the risk per unit absorbed dose for bone surfaces is about a factor of five less than the value used by the ICRP, and the EPA's estimates of the relative biological effectiveness for alpha particles for leukemia and breast cancer are less than the radiation weighting factor of 20 used by the ICRP in calculating the effective dose [5]. Thus, the risk coefficients for internal exposure in the Federal Guidance Report are not based on calculations of committed effective doses and a nominal probability coefficient for cancer fatalities of 0.05 Sv^{-1} [1].

The risk coefficients for cancer mortality for intakes of selected radionuclides in air, tap water, foods, and cow's milk from Federal Guidance Report No. 13 [5] are given in Table 1. Again, these results can be used to assess *per capita* lifetime risks for the U.S. population from chronic exposure to constant concentrations of radionuclides in the environment, using estimates of average lifetime intakes of each medium [5]. The differences in the risk coefficients for intakes in tap water, foods, and cow's milk reflect differences in the age dependence of the intake rates of these environmental media [5].

TABLE 1. U.S. CANCER MORTALITY RISK COEFFICIENTS (Bq^{-1}) FOR INTAKES OF SELECTED RADIONUCLIDES IN VARIOUS ENVIRONMENTAL MEDIA[a]

Radionuclide	Environmental medium			
	Air[b]	Tap water	Foods	Cow's milk[c]
^{3}H	1.04E-12	9.44E-13	1.20E-12	
^{14}C	3.68E-13	2.89E-11	3.68E-11	
^{60}Co	2.32E-09	2.75E-10	3.88E-10	
^{89}Sr	7.60E-11	2.10E-10	2.97E-10	
^{90}Sr	1.08E-09	1.34E-09	1.62E-09	
^{99}Tc	1.86E-11	4.28E-11	6.17E-11	
^{129}I	4.42E-10	4.07E-10	5.31E-10	8.86E-10
^{131}I	1.48E-10	1.31E-10	1.85E-10	3.78E-10
^{134}Cs	3.05E-10	7.91E-10	9.57E-10	
^{137}Cs	2.19E-10	5.66E-10	6.88E-10	
^{226}Ra	2.93E-07	5.32E-09	7.15E-09	
^{232}Th	1.10E-06	1.87E-09	2.45E-09	
^{238}U	6.07E-07	1.13E-09	1.51E-09	
^{239}Pu	8.45E-07	2.85E-09	3.63E-09	

[a] Values from EPA's Federal Guidance Report No. 13 [5] are *per capita* (population-averaged) risks per unit activity intake and can be used to assess lifetime risks averaged over both genders and all ages in U.S. population for constant concentrations of radionuclides in the environmental media.

[b] For inhalation exposure, ^{3}H is assumed to be HTO, ^{14}C is CO_2, ^{89}Sr, ^{90}Sr, ^{99}Tc, ^{134}Cs, and ^{137}Cs are compounds of Type F, ^{226}Ra is Type M, ^{60}Co, ^{232}Th, ^{238}U, and ^{239}Pu are Type S, and ^{129}I and ^{131}I are in elemental form.

[c] Intakes of cow's milk are considered separately from intakes of all foods only for isotopes of iodine.

4. ANALYSIS AND RESULTS

As indicated in Section 1, this paper is based on an assumption that the fundamental objective of radiation protection standards for the public is limitation of lifetime risk, and the particular question we investigate is whether applying a limit on annual effective dose to the critical group of any age or only to adults provides the better correspondence with lifetime risk from chronic exposure, taking into account the age dependence of intakes and doses and the variety of radionuclides and intake pathways of concern.

To investigate this question, we assume that air, tap water, foods, and cow's milk contain constant concentrations of the radionuclides listed in Table 1. For each radionuclide and environmental medium, we assume that the EPA's risk coefficient for cancer mortality in Table 1 provides the proper estimate of risk from chronic lifetime exposure. In order to compare these results with the risks that would result from use of the ICRP's age-specific effective dose coefficients [2] in determining limits on allowable concentrations in the environment, the ICRP's effective dose coefficients for adults and the critical group other than adults are converted to corresponding risk coefficients by multiplying by the risk per unit dose from uniform whole-body irradiation for the U.S. population of 0.0575 Sv^{-1} [5]. Thus, for example, the risk coefficient corresponding to the ICRP's effective dose coefficient for ingestion of ^{90}Sr by adults is taken to be (2.8E-08 Sv Bq^{-1}) × (5.75E-02 Sv^{-1}) = 1.6E-09 Bq^{-1}.

In Table 2, the EPA's risk coefficients for cancer mortality for intakes of radionuclides in the different environmental media listed in Table 1 are compared with the risk coefficients corresponding to the ICRP's effective dose coefficients for adults and the critical group other than adults calculated as described above. For each radionuclide and intake pathway, the critical group is the population group for which the product of the ICRP's age-specific effective dose coefficient for inhalation or ingestion [2] and the average age-specific intake rate in the U.S. population [5] attains its highest value.

Table 2 gives the EPA's risk coefficient for cancer mortality relative to the risk coefficient corresponding to the ICRP's effective dose coefficient for adults or the critical group of any age, except no entry is given for a younger age group when the critical group is adults. For intakes of ^{129}I and ^{131}I by any pathway, the substantial differences between the two risk coefficients mainly reflect the difference between the EPA's calculation of cancer mortality [5] and the ICRP's use of total detriment, which includes a contribution from weighted non-fatal cancer incidence, in calculating the effective dose [1]. For intakes of ^{226}Ra, ^{232}Th, and ^{239}Pu in tap water and foods, the substantial differences between the two risk coefficients mainly reflect, first, the difference between the EPA's calculation of the dose received as the integral of the survival function for the population and the dose rate as a function of time after intake [5] and the ICRP's use of committed doses and, second, the lower relative biological effectiveness for alpha particles for leukemia adopted by the EPA [5].

The results in Table 2 may be interpreted as follows. In nearly all cases where the critical group is not adults (e.g., for intakes of ^{90}Sr in foods), the risk coefficient corresponding to the ICRP's effective dose coefficient for adults is closer to the EPA's risk coefficient than the risk coefficient corresponding to the ICRP's effective dose coefficient for the critical group. Therefore, recalling that the EPA's risk coefficient is proportional to the risk of cancer mortality from chronic lifetime exposure to constant concentrations of radionuclides in the environment, we conclude that, in nearly all cases, applying a limit on annual effective dose only to adults would provide a considerably better correspondence with lifetime risk than applying the annual dose limit to the critical group of any age. The one exception in Table 2 is inhalation of ^{226}Ra, for which applying the annual dose limit to the critical group (15-year olds) would provide a slightly better correspondence with lifetime risk. In this case, however, the ICRP's effective dose coefficients for adults and the critical group differ by only about 30% and, thus, the choice of the age group to which the annual dose limit would be applied does not have a significant effect on the lifetime risk. We also note that whenever the EPA's risk coefficient is higher than the corresponding ICRP value (i.e., the ratio in Table 2 is greater than unity), which occurs only for adults, the risk coefficients differ by no more than a factor of two. Thus, applying a limit on annual effective dose only to adults would not result in lifetime risks that greatly exceed any assumed limit on risk.

TABLE 2. RATIO OF U.S. CANCER MORTALITY RISK COEFFICIENT TO RISK COEFFICIENT CORRESPONDING TO ICRP'S EFFECTIVE DOSE COEFFICIENT FOR ADULTS OR CRITICAL GROUP OF ANY AGE FOR SELECTED RADIONUCLIDES IN ENVIRONMENTAL MEDIA[a]

Radionuclide – Age group	Environmental medium			
	Air[b]	Tap water	Foods	Cow's milk[c]
^{3}H – Adult	1.0	0.9	1.2	
Other (age)[d]	–	–	0.7 (5 y)	
^{14}C – Adult	1.0	0.9	1.1	
Other (age)	0.7 (10 y)	–	0.6 (5 y)	
^{60}Co – Adult	1.3	1.4	2.0	
Other (age)	–	0.09 (Infant)	0.12 (Infant)	
^{89}Sr – Adult	1.3	1.4	2.0	
Other (age)	0.09 (Infant)	0.10 (Infant)	0.14 (Infant)	
^{90}Sr – Adult	0.8	0.8	1.0	
Other (age)	0.15 (15 y)	0.3 (15 y)	0.4 (15 y)	
^{99}Tc – Adult	1.1	1.2	1.7	
Other (age)	0.13 (1 y)	0.07 (Infant)	0.11 (Infant)	
^{129}I – Adult	0.08	0.06	0.08	0.14
Other (age)	0.05 (10 y)	–	0.05 (10 y)	0.08 (10 y)
^{131}I – Adult	0.13	0.10	0.15	0.3
Other (age)	0.016 (1 y)	0.023 (5 y)	0.03 (5 y)	0.04 (1 y)
^{134}Cs – Adult	0.8	0.7	0.9	
Other (age)	–	–	–	
^{137}Cs – Adult	0.8	0.8	0.9	
Other (age)	–	–	–	
^{226}Ra – Adult	1.5	0.3	0.4	
Other (age)	1.1 (15 y)	0.06 (15 y)	0.08 (15 y)	
^{232}Th – Adult	0.8	0.14	0.19	
Other (age)	–	0.007 (Infant)	0.009 (Infant)	
^{238}U – Adult	1.4	0.4	0.6	
Other (age)	–	0.06 (Infant)	0.08 (Infant)	
^{239}Pu – Adult	0.9	0.20	0.25	
Other (age)	–	0.012 (Infant)	0.015 (Infant)	

[a] Risk coefficient for cancer mortality in U.S. population is value given in Table 1; risk coefficient corresponding to ICRP's effective dose coefficient for adults or critical group is age-specific dose coefficient for inhalation or ingestion given in ref. [2] multiplied by risk per unit dose from uniform whole-body irradiation for U.S. population of 0.0575 Sv^{-1} [5].

[b] See footnote *b* in Table 1.

[c] See footnote *c* in Table 1.

[d] No entry is given for "Other (age)" when critical group is adults. When critical group is not adults, entry in parentheses gives age for critical group.

Another perspective on the difference between the two options for applying an annual dose limit can be obtained by comparing the annual effective dose to the critical group of any age other than adults with the annual effective dose to adults for the same concentrations of radionuclides in the environment, using the ICRP's age-specific dose coefficients [2] and the age-specific intake rates of the different media in the U.S. population [5]. In the worst case (^{131}I in cow's milk), the limit on allowable concentration in the environment based on a limit on annual effective dose to the critical group would be nearly an order of magnitude more restrictive than the concentration limit based on the same annual dose limit to adults. In several other cases (^{131}I in foods, ^{226}Ra and ^{232}Th in tap water and foods, and ^{239}Pu in foods), regulating on the basis of the annual dose to the critical group other than adults would result in limits on allowable concentrations in the environment which are more restrictive by a factor of 3-5.

5. CONCLUSIONS

Based on new calculations of the *per capita* risk of cancer mortality from inhalation or ingestion of radionuclides [5], we have shown that applying a limit on annual effective dose for the public only to adults provides a considerably better correspondence with lifetime risk from chronic exposure than applying the annual dose limit to the critical group of any age. Thus, based on an assumption that the annual dose limit should be applied in a way that provides a reasonable correspondence with lifetime risk from chronic exposure for any radionuclide and intake pathway of concern, we believe that the annual dose limit should be applied only to adults, which was the usual practice in radiation protection of the public before the development of age-specific effective dose coefficients by the ICRP.

We recognize that there are arguments in favor of applying the annual dose limit for the public to the critical group of any age, in spite of the rather poor correspondence with lifetime risk from chronic exposure that results. Radiation protection generally is concerned with control of exposures, without undue concern for the magnitude and variability of actual doses and risks in exposed populations. In addition, applying the annual dose limit to the critical group of any age, rather than to adults, provides a greater margin of safety in reducing risks below an assumed limit on acceptable risk, which can be viewed as more important for radiation protection than the objective we have emphasized of achieving a greater consistency in controlling lifetime risks. Finally, applying the annual dose limit to the critical group of any age can be viewed as appropriate if the resulting limits on allowable concentrations of radionuclides in the environment are reasonably achievable.

However, we also believe that there are certain counterarguments in favor of applying the annual dose limit for the public only to adults, rather than to the critical group of any age. First, radiation protection of the public is increasingly being affected by laws and regulations concerned primarily with health protection of the public for other hazardous substances [6]. Therefore, since risk is the only measure of impact that can be used in comparing approaches to control of exposures for radionuclides and other carcinogens, standards for limiting radiation exposure should correspond reasonably well with an assumed limit on risk. In addition, the ICRP has recommended that certain types of radiation exposure should be controlled based on risk rather than dose [7,8]. If a recommendation to control potential exposures based on risk is to be taken seriously, then we believe that all aspects of risk should be considered in implementing such a recommendation and, furthermore, that control of lifetime risk, rather than annual risk, should be the primary concern.

Second, while annual doses below the limit of 1 mSv for all controlled sources combined may be reasonably achievable for the critical group of any age, this may not be the case for dose constraints for individual sources or practices at a fraction of the dose limit [1]. Dose constraints as low as a few percent of the annual dose limit have been established for certain sources, e.g., airborne releases of radioiodine [9]. Given the substantial differences between the effective dose coefficients for adults and other age groups in some cases [2], such low dose constraints may not be reasonably achievable when applied to age groups other than adults. Furthermore, the resulting annual doses to adults may be at exempt levels where efforts to control exposures at any costs would be unwarranted [10].

Finally, if the annual dose limit of 1 mSv is applied to the critical group of any age, rather than only to adults, based in part on an argument that the limit is reasonably achievable for any age group, this argument could have the undesirable effect of blurring the careful distinction between the principles of optimization and dose limitation in radiation protection [1]. We believe that these two principles should be separate and distinct and, furthermore, that implementation of the principle of dose limitation should be based solely on considerations of acceptable risk but all considerations of doses that are reasonably achievable should be applied only in implementing the principle of optimization.

In conclusion, we have shown that applying an annual dose limit or dose constraint for the public to the critical group of any age, rather than only to adults, has potentially important ramifications for the control of lifetime risks, the feasibility of implementing standards for specific sources or practices, and the principles of radiation protection. Thus, we would welcome further consideration of this matter by the ICRP with the objective of formulating a recommendation on how age-specific effective dose coefficients should be used in complying with an annual dose limit for the public and annual dose constraints for specific sources or practices.

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