Radiation Protection Dosimetry (2010), Vol. 138, No. 3, pp. 245–250
Advance Access publication 13 November 2009
doi:10.1093/rpd/ncp259

IMPACT OF THE NEW NUCLEAR DECAY DATA OF ICRP PUBLICATION 107 ON INHALATION DOSE COEFFICIENTS FOR WORKERS

K. Manabe[1,*], A. Endo[1] and K. F. Eckerman[2]
[1]Japan Atomic Energy Agency, 2-4 Shirakata-Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan
[2]Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831, USA

Received July 29 2009, revised October 6 2009, accepted October 15 2009

The impact a revision of nuclear decay data had on dose coefficients was studied using data newly published in ICRP Publication 107 (ICRP 107) and existing data from ICRP Publication 38 (ICRP 38). Committed effective dose coefficients for occupational inhalation of radionuclides were calculated using two sets of decay data with the dose and risk calculation software DCAL for 90 elements, 774 nuclides and 1572 cases. The dose coefficients based on ICRP 107 increased by over 10 % compared with those based on ICRP 38 in 98 cases, and decreased by over 10 % in 54 cases. It was found that the differences in dose coefficients mainly originated from changes in the radiation energy emitted per nuclear transformation. In addition, revisions of the half-lives, radiation types and decay modes also resulted in changes in the dose coefficients.

INTRODUCTION

The International Commission on Radiological Protection (ICRP) issued its latest Recommendations for a system of radiation protection in ICRP Publication 103(1) in 2007. The new Recommendations retained the protection quantities, equivalent and effective doses that were defined in ICRP Publication 60(2) (ICRP60) for the purpose of radiological protection. However, the dosimetric parameters, which included the radiation weighting factors, w_R, and tissue weighting factors, w_T, were revised by taking into account new scientific information on the biology and physics of radiation exposure. In the new Recommendations, ICRP also decided to use reference computational phantoms of adult male and female and to update the nuclear decay data on radionuclides. In addition to those revisions, ICRP has been developing biokinetic models for internal exposures including a new human alimentary tract model(3) and element-specific systemic models, and will publish new dose coefficients in due course.

As part of this development, a new nuclear decay database was published in ICRP Publication 107(4) (ICRP 107) to replace the existing nuclear decay database provided in ICRP Publication 38(5) (ICRP 38), which was used to calculate dose coefficients in past ICRP publications(6–19). The new database was assembled using the latest information on nuclear structure and decay properties, and contains a set of the energies and yields of emitted radiations, half-lives, decay modes, decay chains and beta particle spectra for 1252 radionuclides. The database will be used in future dose coefficient calculations by ICRP(1,4).

Revision of nuclear decay data is likely to cause corresponding changes in internal doses because any radionuclides incorporated into the body irradiate its tissues with their specific energies over time periods that are determined by their specific physical and biological half-lives. The purpose of the present study is to clarify the impact that the revision of nuclear decay data had on dose coefficients. Committed effective dose per unit acute inhalation for workers, $e_{inh}(50)$ (Sv Bq^{-1}), were calculated using the two databases provided by ICRP 107 and ICRP 38, and changes of $e_{inh}(50)$ due to the update of nuclear decay data and the reasons were analysed.

MATERIALS AND METHODS

Computer program used in the calculations

The dose and risk calculation software, DCAL(20), developed at Oak Ridge National Laboratory was used to calculate the dose coefficients. DCAL has been used in calculations in several ICRP Publications(10–15). The latest version of DCAL, DCAL09, used in the present calculations employs ICRP 107 as a data set for dose calculations.

DCAL consists of a series of computational modules and data libraries. Biokinetic and dosimetric calculations can be performed for acute intake per unit activity of a radionuclide through inhalation, ingestion and injection into the blood at user-specified ages at intake. The data libraries used in DCAL can be replaced by arbitrary libraries with

---

*Corresponding author: manabe.kentaro@jaea.go.jp

the provision that their format conform to that of the default data(20). This flexibility enabled the doses to be calculated using the two data sets of ICRP 107 and ICRP 38.

The dose coefficients was computed using the three DCAL modules: the activity calculation module (ACTACAL), the specific effective energy calculation module (SEECAL) and the dose rate calculation module (EPACAL), all three of which were used in batch mode in the present calculations.

Preparation of nuclear decay data

DCAL09 uses the nuclear decay data library of ICRP 107, which consists of five data files to identify the characteristics of radionuclides: ICRP-07.NDX, ICRP-07.RAD, ICRP-07.BET, ICRP-07.ACK and ICRP-07.NSF files. The files used in DCAL09 are three of them, ICRP-07.NDX, ICRP-07.RAD and ICRP-07.BET. The ICRP-07.NDX file contains pointers to the initial record of the ICRP-07.RAD and ICRP-07.BET files, a half-life, branching fractions of decay chains, and so on, for each nuclide. The ICRP-07.RAD file contains data on the energy and yield of each radiation emitted in the nuclear transformations of radionuclides. The ICRP-07.BET file contains beta particle spectrum data of beta emitters.

The data format of ICRP 38 data files provided by the older version of DCAL containing the ICRP38.NDX, ICRP38.RAD and ICRP38.BET files partially differed from that of the ICRP-07.NDX, ICRP-07.RAD and ICRP-07.BET files, and hence was converted to a format compatible with DCAL09.

It should be noted that the ICRP38.RAD file does not contain any data on alpha recoil nuclei and that the older version of DCAL calculates the energies and yields of alpha recoil nuclei from those of alpha particles. However, the ICRP-07.RAD file does contain data on both alpha-particles and alpha recoil nuclei for the alpha particle emitters, and therefore the radiation data on alpha recoil nuclei was added in converting the format of the ICRP38.RAD file. The data and format of the ICRP38.BET and ICRP38.NDX files were converted to that required by DCAL09.

Calculation condition

Committed effective dose coefficients were calculated under the exposure conditions given in Table 1. The values of w_R and w_T of ICRP 60(2), the human respiratory tract model of ICRP Publication 66(21) and the biokinetic models of ICRP Publications 30(6–9), 56(10), 67(11) and 69(13) were used, because DCAL09 is compatible with the dosimetric models of ICRP Publication 60.

Table 1. Calculation conditions.

Number of nuclides	744
Exposure type	Occupational
Intake route	Inhalation
AMAD[a]	5 µm
Absorption type	ICRP 68(12)

[a]AMAD is activity median thermodynamic diameter.

Calculation of dose coefficients for spontaneously fissioning nuclides was not performed, since the SAF values as a function of neutron energy are not available in DCAL09 and organ doses for neutrons are not calculated by the same manner as used for photons. The SAF data for neutrons will be included in a future version of DCAL.

The absorption types of F (Fast), M (Moderate), S (Slow) and V (Vapour) were adopted in accordance with ICRP Publication 68(12). The total number of calculated cases was 1572 in consideration of the variation of the absorption types of nuclides.

The two dose coefficients of $e_{\mathrm{inh}}(50)_{38}$ and $e_{\mathrm{inh}}(50)_{107}$, which were based on ICRP 38 and ICRP 107, respectively, were then calculated and compared with each other.

RESULTS AND DISCUSSIONS

Correlation between changes in $e_{\mathrm{inh}}(50)$ and total radiation energy

The following two indices, $D_{E_{\mathrm{tot}}}$ (%) and D_e (%), were defined to indicate the difference in total energy of the emitted radiations and dose coefficients:

$$D_{E_{\mathrm{tot}}} = \left(\frac{E_{\mathrm{tot107}}}{E_{\mathrm{tot38}}} - 1\right) \times 100, \tag{1}$$

$$D_e = \left[\frac{e_{\mathrm{inh}}(50)_{107}}{e_{\mathrm{inh}}(50)_{38}} - 1\right] \times 100, \tag{2}$$

where E_{tot107} and E_{tot38} are the total energies of parent nuclide radiations taken from the ICRP-07.NDX and ICRP38.NDX files, respectively, and $e_{\mathrm{inh}}(50)_{107}$ and $e_{\mathrm{inh}}(50)_{38}$ are the dose coefficients calculated using the corresponding nuclear decay data.

Figure 1 gives the correlation between $D_{E_{\mathrm{tot}}}$ and D_e. The data was plotted using the following two categories: the open circles indicate nuclides that directly decay into stable nuclides, while the crosses indicate nuclides that have decay chains. Figure 1 reveals that although $D_{E_{\mathrm{tot}}}$ and D_e nearly correlate

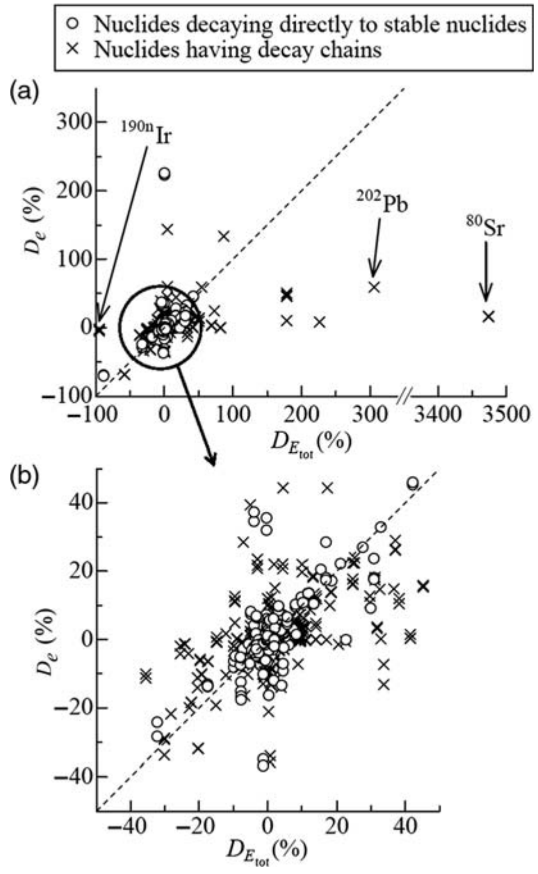

Figure 1. (**a**) Correlation between $D_{E_{\text{tot}}}$ and D_e for all cases. The dashed line indicates the line with a slope of 1. (**b**) An expansion of the circled area of (**a**).

with the nuclides that directly decay into stable nuclides, some deviations from the line with a slope of 1 can be observed. The results indicate that the increase in radiation energy is not completely proportional to that of $e_{\text{inh}}(50)$. The reason for that is because absorbed fractions of electrons in the lung region and photons are not proportional to their energies and the energy dependence of electrons and photons differ from each other. Therefore, the values of $e_{\text{inh}}(50)$ are not completely correlated with the increments of radiation energy.

With nuclides that have decay chains, the deviation in the relationship between $D_{E_{\text{tot}}}$ and D_e from the line is, in many cases, quite marked. This tendency indicates that doses from decay products can affect the $e_{\text{inh}}(50)$ of their parent nuclides, and that the changes in the radiation energy of the parent nuclides do not correlate with the values of $e_{\text{inh}}(50)$.

Tables 2 and 3 give the nuclides that had large absolute D_e values along with the causes of the

Table 2. Nuclides with significantly large positive D_e values.

Nuclide	Absorption type	$D_{E_{\text{tot}}}$ (%)	D_e (%)	Cause of D_e
^{114}In	M	+0.284	+226	d
^{194}Tl	F	+86.7	+134	a, c
^{189}Pt	F	+54.4	+59.3	a
^{202}Pb	F	+306	+59.3	a, c
^{193}Hg (Organic)	F	+178	+50.6	a, c
^{173}Lu	S	+42.2	+46.0	a
^{192m}Ir	M	+4.53	+44.4	c
^{236}Np	M	+17.2	+44.4	a, c
^{114m}In	M	−5.05	+39.4	d[a]
^{99}Rh	S	−3.96	+37.3	c
^{80}Br	M	−0.299	+35.6	d
^{135}Cs	F	+32.8	+32.9	a
^{185}Ir	F	+37.1	+29.0	a
^{121}I	F	−0.701	+28.5	c
^{186m}Ir	F	+16.9	+28.5	a, b
^{155}Tb	M	+27.6	+27.0	a
^{162}Yb	M	+73.0	+24.6	a
^{124m}Sb	F	+25.2	+23.9	a
^{188}Ir	F	+30.8	+23.7	a
^{149}Gd	F	+24.6	+22.4	a

Causes are a: change in E_{tot}, b: change in half-life, c: change in radiation type and decay mode and d: change in shape of beta particle spectrum.

[a] D_e of ^{114m}In was caused by the change in the shape of the beta particle spectrum data of its daughter nuclide: ^{114}In.

Table 3. Nuclides with significantly large negative D_e values.

Nuclide	Absorption type	$D_{E_{\text{tot}}}$ (%)	D_e (%)	Cause of D_e
^{123}Te	M	−88.5	−70.3	a
^{135}Ce	S	−57.8	−68.5	a
^{190}Ir	S	−13.4	−36.8	a, c
^{190m}Ir	S	−7.63	−35.8	b
^{195m}Ir	F	−30.2	−33.8	a
^{173}Ta	M	−20.3	−31.9	a, b
^{120m}I	F	−32.2	−28.3	a
^{199}Pb	F	−28.2	−21.8	a
^{205}Po	M	−0.303	−21.1	b
^{234}Np	M	−22.8	−20.0	a
^{240}Np	M	−15.1	−19.2	a, b
^{234}Pa	M	−22.3	−18.5	a
^{178m}Hf	M	−7.72	−17.6	a
^{189}Re	F	−6.70	−16.4	a
^{189m}Os	F	+3.26	−16.3	b
^{120}I	V	−7.78	−15.1	a
^{170}Hf	M	−20.5	−14.1	a
^{179}Ta	M	−17.5	−13.8	a
^{207}At	M	+33.7	−13.2	c
^{81}Sr	S	−1.01	−11.0	b

Causes are a: change in E_{tot}, b: change in half-life and c: change in radiation type and decay mode.

changes in $e_{\mathrm{inh}}(50)$. Of all the 1572 calculated cases, the D_e was 10 % larger in 98 cases and less than -10 % in 54 cases. It was found that in many cases the change in E_{tot} was mainly the origin of a large D_e, with some $e_{\mathrm{inh}}(50)_{107}$ being a multiple or a fraction of $e_{\mathrm{inh}}(50)_{38}$.

In the following sections, the reasons for the changes in $e_{\mathrm{inh}}(50)$ will be further discussed.

Radioactive equilibrium

The significant deviations from the line of ^{80}Sr and $^{190\mathrm{n}}$Ir indicated by arrows in Figure 1 can be explained by the radioactive equilibrium effect. For ^{80}Sr, the D_{e} was 17.3 % while the $D_{E_{\mathrm{tot}}}$ was 3470 %, thus indicating that the difference of the $e_{\mathrm{inh}}(50)$ was small, in spite of the large difference of the E_{tot} of ^{80}Sr in ICRP 107 and ICRP 38. A radioactive equilibrium exists between ^{80}Sr (half-life = 1.77 h) and its daughter, ^{80}Rb (half-life = 33.4 s), and the total number of nuclear transformations of ^{80}Rb is nearly equal to that of ^{80}Sr. Furthermore, because the E_{tot} of ^{80}Rb is about seven times larger than that of ^{80}Sr, the $e_{\mathrm{inh}}(50)$ of ^{80}Sr is dominated by the emissions of ^{80}Rb, which are almost the same for ICRP 107 and ICRP 38.

With $^{190\mathrm{n}}$Ir, the E_{tot} drastically decreased as the $D_{E_{\mathrm{tot}}}$ was -94.8 %, while its D_e was only -5.06 %. Similar to the case of ^{80}Sr, this was caused by the radioactive equilibrium between $^{190\mathrm{n}}$Ir and $^{190\mathrm{m}}$Os.

Change in half-life

With ^{81}Sr, the $D_{E_{\mathrm{tot}}}$ and D_e were -1.01 and -11.0 %, respectively, as indicated in Table 3. The half-life of ^{81}Sr changes from 25.5 to 22.3 m, resulting in a decrement of the number of nuclear transformations over the integration period of 50 y. This decreased the value of the $e_{\mathrm{inh}}(50)$ of ^{81}Sr, and the same reason can be applied to ^{173}Ta, $^{186\mathrm{m}}$Ir, $^{190\mathrm{m}}$Ir and others.

Change in radiation type and decay mode

The D_{e} of $^{192\mathrm{m}}$Ir was as large as 44.4 % in spite of its small $D_{E_{\mathrm{tot}}}$ of 4.53 %, which can be explained by the revision of the type of the radiations emitted by $^{192\mathrm{m}}$Ir. $^{192\mathrm{m}}$Ir transforms to ^{192}Ir by an isometric transition. In the transformation, only one gamma ray is emitted in ICRP 38, while most of the energy is emitted as Auger electrons in ICRP 107. The self-absorbed fractions of electrons are much larger than those of photons, and hence the value of $e_{\mathrm{inh}}(50)$ increases.

Another example is ^{202}Pb. The $D_{E_{\mathrm{tot}}}$ of ^{202}Pb was 306 % while the D_e was 59.3 %. ^{202}Pb is in a radioactive equilibrium with ^{202}Tl, and the D_e of ^{202}Pb was expected to be around 20 % because the E_{tot} of ^{202}Tl is about 15 times as large as that of ^{202}Pb and the $D_{E_{\mathrm{tot}}}$ of ^{202}Tl was only -0.306 %. However, the calculated D_e was 59.3 %, which was caused by the addition of alpha decay to the decay modes of ^{202}Pb. The value of w_{R} for alpha particles is 20, and therefore the value of $e_{\mathrm{inh}}(50)$ was significantly increased by the addition of the alpha decay.

As with these two nuclides, the changes in the type of radiation and decay modes caused deviations from the line in Figure 1 that were also seen with ^{190}Ir, ^{193}Hg, ^{194}Tl, ^{207}At, etc.

In addition, large D_e values were found in ^{80}Br and ^{114}In due to changes in the shape of beta particle spectra.

Analysis considering contribution of decay products, half-lives and w_{R}

The above analyses revealed that the difference of dose coefficients originated from the revisions of radiation energies of parent nuclides and their decay products, half-lives, decay modes and branching fractions. Then, an index, E_{eff}, was introduced to consider the contribution of decay products, change in half-lives and difference of w_{R} as follows:

$$E_{\mathrm{eff}} = \sum_{i=1}^{n} nt_{50}(i) \times [20 \times E_{\alpha}(i) + E_{\mathrm{e}}(i) + E_{\mathrm{p}}(i)], \tag{3}$$

where the summation is over all members of the decay chain included in the dose calculation; $nt_{50}(i)$ is the total number of nuclear transformations of member i occurring in 50 y; and $E_{\alpha}(i)$, $E_{\mathrm{e}}(i)$ and $E_{\mathrm{p}}(i)$ are the emitted energy of alpha particles, electrons and photons, respectively, per nuclear transformation of member i. In the square brackets, $E_{\alpha}(i)$, $E_{\mathrm{e}}(i)$ and $E_{\mathrm{p}}(i)$ are weighted by the respective w_{R} values: 20 for alpha particle and 1 for electron and photon. The value of $\mathrm{nt}_{50}(i)$ was computed using DCAL, and $D_{E_{\mathrm{eff}}}$ was defined as follows:

$$D_{E_{\mathrm{eff}}} = \left(\frac{E_{\mathrm{eff107}}}{E_{\mathrm{eff38}}} - 1 \right) \times 100, \tag{4}$$

where E_{eff107} and E_{eff38} are E_{eff} calculated using the data of ICRP 107 and ICRP 38, respectively.

Figure 2 shows the correlation between $D_{E_{\mathrm{eff}}}$ and D_e. The data were plotted using the same two categories as those of Figure 1. It is shown in Figure 1 that some plots, such as ^{80}Sr, $^{190\mathrm{n}}$Ir and ^{202}Pb, largely deviated from the dashed line due to the contribution of E_{tot} from the decay products or the addition of alpha decay. In Figure 2, the plots of the nuclides are close to the line by considering these factors using $D_{E_{\mathrm{eff}}}$. Therefore, it is concluded that dispersion of the plotted data around the line in

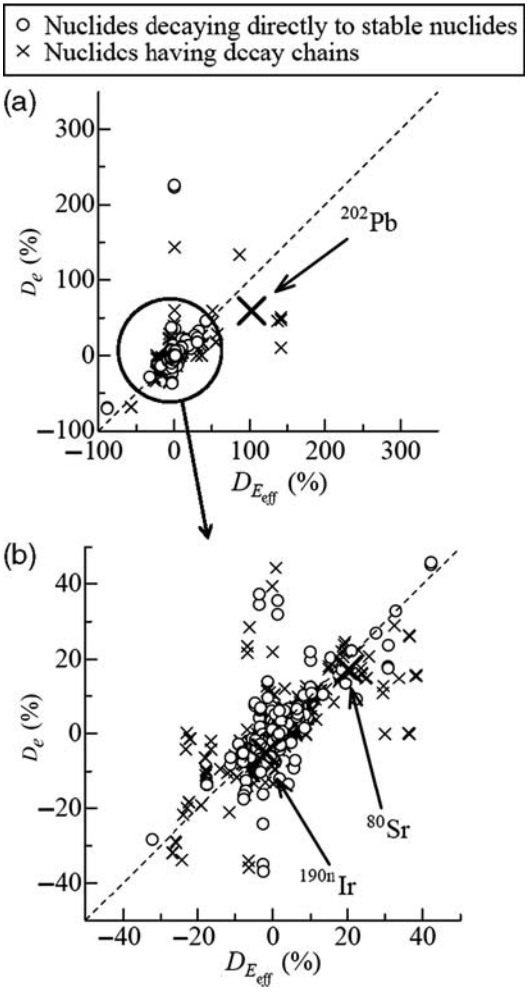

Figure 2. (**a**) Correlation between $D_{E_{eff}}$ and D_e for all cases. The dashed line indicates the line with a slope of 1. (**b**) An expansion of the circled area of (**a**).

Figure 2 mainly originated from the changes in the types and energy spectra of radiations emitted from radionuclides of ICRP 107 and ICRP 38.

CONCLUSIONS

The impact that the revision of the radionuclide decay data had on dose coefficients for inhalation was studied by calculating the dose coefficients using the new nuclear decay data provided by ICRP 107. This revealed that for some nuclides the dose coefficients increased or decreased several fold. The changes in the dose coefficients were mainly caused by the updated radiation energy data. In addition, revisions of the half-lives, decay modes and energy spectra also had an effect on the changes in the dose coefficients. The overall conclusion was that the adoption of the latest nuclear decay data provided by ICRP 107 has improved the reliability of the dose coefficients.

The latest version of DCAL software, DCAL09, is available by contacting K. F. Eckerman (eckermankf@ornl.gov).

ACKNOWLEDGEMENT

The authors wish to thank Dr F. Takahashi of Japan Atomic Energy Agency for his helpful advice on this work.

REFERENCES

1. International Commission on Radiological Protection. *The 2007 Recommendation of the International Commission on Radiological Protection*. ICRP Publication 103. Ann. ICRP **37** (2–4) (2007).
2. International Commission on Radiological Protection. *1990 Recommendations of the International Commission on Radiological Protection*. ICRP Publication 60. Ann. ICRP **21** (1–3) (1991).
3. International Commission on Radiological Protection. *Human alimentary tract model for radiological protection*. ICRP Publication 100. Ann. ICRP **36** (1–2) (2006).
4. International Commission on Radiological Protection. *Nuclear decay data for dosimetric calculations.* ICRP Publication 107. Ann. ICRP **38**(3) (2009).
5. International Commission on Radiological Protection. *Radionuclide transformations: energy and intensity of emissions.* ICRP Publication 38. Ann. ICRP **11–13** (1983).
6. International Commission on Radiological Protection. *Limits for intakes of radionuclides by workers.* Part 1. ICRP Publication 30. Ann. ICRP **2**(3–4) (1979).
7. International Commission on Radiological Protection. *Limits for intakes of radionuclides by workers.* Part 2. ICRP Publication 30. Ann. ICRP **4**(3–4) (1980).
8. International Commission on Radiological Protection. *Limits for intakes of radionuclides by workers.* Part 3. ICRP Publication 30. Ann. ICRP **6**(2–3) (1981).
9. International Commission on Radiological Protection. *Limits for intakes of radionuclides by workers.* Part 4. ICRP Publication 30. Ann. ICRP **19**(4) (1988).
10. International Commission on Radiological Protection. *Age-dependent doses to members of the public from intakes of radionuclides.* Part 1. ICRP Publication 56. Ann. ICRP **20**(2) (1989).
11. International Commission on Radiological Protection. *Age-dependent doses to members of the public from intake of radionuclides.* Part 2. ICRP Publication 67. Ann. ICRP **23**(3–4) (1993).
12. International Commission on Radiological Protection. *Dose coefficients for intakes of radionuclides by workers.* ICRP Publication 68. Ann. ICRP **24**(4) (1994).

13. International Commission on Radiological Protection. *Age-dependent doses to members of the public from intake of radionuclides*. Part 3. ICRP Publication 69. Ann. ICRP **25**(1) (1995).
14. International Commission on Radiological Protection. *Age-dependent doses to members of the public from intakes of radionuclides*. Part 4. ICRP Publication 71. Ann. ICRP **25**(3–4) (1995).
15. International Commission on Radiological Protection. *Age-dependent doses to members of the public from intakes of radionuclides*. Part 5. ICRP Publication 72. Ann. ICRP **26**(1) (1996).
16. International Commission on Radiological Protection. *Individual monitoring for internal exposure of workers*. ICRP Publication 78. Ann. ICRP **27**(3–4) (1997).
17. International Commission on Radiological Protection. *Radiation dose to patients from radiopharmaceuticals*. ICRP Publication 80. Ann. ICRP **28**(3) (1998).
18. International Commission on Radiological Protection. *Doses to infants from ingestion of radionuclides in mother's milk*. ICRP Publication 95. Ann. ICRP **34**(3–4) (2004).
19. International Commission on Radiological Protection. *Radiation dose to patients from radiopharmaceuticals*. ICRP Publication 106. Ann. ICRP **38**(1–2) (2008).
20. Eckerman, K. F., Leggett, R. W., Cristy, M., Nelson, C. B., Ryman, J. C., Sjoreen, A. L. and Ward, R. C. *User's guide to the DCAL system*. ORNL/TM-2001/190 (2006).
21. International Commission on Radiological Protection. *Human respiratory tract model for radiological protection*. ICRP Publication 66. Ann. ICRP **24**(1–3) (1994).