Radiation Risks from Medical X-ray Examinations as a Function of the Age and Sex of the Patient

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ABSTRACT

The radiation risks from medical x-ray examinations have been evaluated as a function of the age and sex of the patient in terms, separately, of the lifetime risk of radiation-induced cancer to the patient and the risk of deleterious heritable effects appearing in the progeny of the patient. These risks have been estimated on the basis of the risk models described in *ICRP Publication 103,* together with typical organ doses for a range of common x-ray examinations derived by Monte Carlo calculation from patient dose data obtained in recent national surveys of UK radiology practice.

The radiation-induced cancer risk was found to vary with patient age and sex in a different manner for different types of x-ray examination, depending on which organs were being irradiated. The effective dose (E) for each examination was also calculated and used to derive age/sex/examination-specific risk coefficients (risk per unit E). The risk coefficient for a particular age band, sex and examination can differ from ICRP's nominal risk coefficient for detriment-adjusted cancer (5.5% per Sv), which is averaged over all ages and both sexes, by up to a factor of ten. For most types of x-ray examination, a single set of age and sex dependent risk coefficients (based on that for uniform whole body exposure) provides an estimate of risk that is mostly within ± 50% of the specific risk for the particular examination. However, grouping examinations within four anatomical regions (head, neck, chest and abdomen & pelvis) led to a further four sets of averaged age and sex dependent risk coefficients that allow improved assessment of risk within ± 30% of the specific risk. Typical levels of cancer risk range from less than about 1 in a billion ($<10^{-9}$) for any patient having an x-ray examination of the knee or foot, to just over 1 in a 1,000 (10^{-3}) for a young girl having a CT scan of the whole trunk.

The risk of deleterious heritable effects appearing in the progeny (including the second generation) of patients undergoing x-ray examinations with a significant gonad dose was found typically to range from less than 1 in a million to 1 in 15,000 for a female patient having a CT scan of the abdomen and pelvis. These risks are assumed to be independent of patient age and gender up until the age for each sex when reproduction becomes unlikely, when the risk obviously falls to zero.

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1 INTRODUCTION

In its system of protection for the control of sources of exposure to ionising radiation, the International Commission on Radiological Protection has developed the concept of effective dose (E) to allow the summation of radiation exposures, whether whole or partial-body, from internal or external sources (ICRP, 2007). Effective dose (E) provides a single measure of the dose to a reference person (of average age and gender) that is roughly proportional to the total 'radiation detriment' from stochastic effects associated with the exposure. As defined by ICRP, the 'radiation detriment' takes account of the life lost from fatal cancers and heritable effects, and the reduced quality of life associated with non-fatal cancers and heritable effects. E is calculated as a weighted sum of the mean absorbed doses (or strictly the mean equivalent doses) to those tissues and organs in the body that are prone to radiation-induced cancer or heritable effects, using the detriment-related tissue weighting factors specified by ICRP. For planned public and occupational exposures to radiation, ICRP specifies dose limits, constraints and reference levels in terms of effective dose. Whereas the concepts of limitation do not apply in the same way to medical exposures, they are subject to the fundamental principles of justification and optimisation. Justification requires that the medical benefits should outweigh the radiation risks (ICRP, 2007). ICRP has not made any specific recommendations on how to derive radiation risks from medical exposures but it has become common practice to convert estimates of E for particular x-ray examinations to radiation risks using the nominal probability coefficients for fatal cancer or aggregated detriment (with or without the risk of severe hereditary disorders), as published by ICRP.

There are a number of important limitations in using E in this way to express the risks from medical exposures (Martin, 2007; Brenner, 2008), a purpose for which it was not intended. In particular:

- the nominal risk coefficients and the tissue weighting factors are averaged over all ages and both sexes in the general population or the working population, and consequently are not applicable to individual patients of particular age and sex;
- it combines the risks of cancer induction, cancer mortality and heritable effects into a single measure of 'detriment' using subjective judgements;
- the tissue weighting factors used to calculate E are based on the contribution from each tissue or organ to aggregated detriment (including the risk of severe hereditary disorders), and consequently it is not strictly correct to multiply E by the nominal probability coefficients for only fatal cancers to predict the fatal cancer risk, as is often done;
- simplifying assumptions are made in the choice of a limited number of rounded tissue weighting factors that are regarded as adequate for protection purposes, but not for the calculation of risk;
- the risk models are based on the life tables and baseline cancer rates for a composite population derived from 7 populations with long-running cancer registries (4 Asian populations – Shanghai, Osaka, Hiroshima and

Nagasaki; and 3 Euro-American populations – Sweden, UK and USA), and consequently are not strictly applicable to UK patients;

- the tissue weighting factors and the list of remainder organs change periodically as improved data on radiation risks are obtained and when new ICRP recommendations are published (ICRP, 1991; ICRP, 2007). Consequently, estimates of E made under different sets of recommendations will not be directly comparable.

Effective dose (and ICRP's nominal probability coefficients for radiation-induced cancer and heritable effects) should not be used to assess risks to individual patients of specific age, sex and nationality, an application for which it was not intended. It can, however, be a valuable tool for comparing the doses (and risks of aggregated detriment) to a reference person (of 'average' age, gender and nationality) from different medical diagnostic procedures and from other sources of radiation exposure. In this way the radiation doses and risks associated with different types of x-ray or nuclear medicine examination can be usefully compared with each other and can be put into a wider perspective by comparing them with, for example, natural background radiation or the additional cosmic radiation associated with high-altitude airline flights (see for example the publication "X-rays – how safe are they?" (NRPB et al, 2001)). Effective dose can also be used to compare the levels of patient protection afforded by different hospitals or different countries when carrying out the same diagnostic procedures on essentially the same reference patient (Hart and Wall, 2002, 2004; European Commission, 2008). Nonetheless, there are situations in medical radiology when it is not sufficient to consider only a reference patient and a more individual approach to risk assessment is required.

The UK *Ionising Radiation (Medical Exposure) Regulations* (IR(ME)R, 2000) require that the 'practitioner' shall be responsible for the justification of every medical exposure, taking into account the characteristics of the individual patient involved. In diagnostic radiology the process of justification requires the assessment of the clinical benefits and the health risks to each individual patient from any proposed x-ray examination and demonstration that the benefits outweigh the risks. Both the clinical benefits and the health risks from the radiation exposure will be dependent, inter alia, on the age and sex of the patient, and so to help the clinician balance one against the other for each patient, information on how the radiation risks for a particular type of x-ray examination vary with age and sex would be useful. This is particularly true in view of the fact that most x-ray examinations that involve significant amounts of radiation are performed on elderly patients to diagnose the diseases that occur later in life. The risks of radiation-induced cancer will be reduced for these elderly patients compared to the risks estimated from ICRP's nominal probability coefficients that are averaged over all ages in the population, and the risks of heritable effects are of no concern for patients who are beyond their reproductive years. Conversely, the risks to young children will be higher than those averaged over the whole population and radiologists need to know how much higher, particularly when justifying the relatively high dose CT examinations that are increasingly being carried out on children.

A number of national and international bodies have developed radiation risk models in recent years from which it is possible to calculate the lifetime risks of radiation-induced cancer as a function of the age and sex of the exposed person (BEIR VII, 2006; UNSCEAR, 2006; ICRP, 2007). All three of these models are primarily based on the same epidemiological data from the Japanese atomic bomb survivors' lifespan study (LSS) but with some significant differences in the risk projection and transfer models used by the three bodies (see Appendix 1). The dependence of the radiation-induced cancer risk on sex and age at exposure varies with cancer site in all three models. In this report we have used the ICRP risk models described in *ICRP Publication 103* (ICRP, 2007) to calculate the lifetime risks of radiation-induced cancer per unit dose as a function of organ, sex and age at exposure. We have chosen the ICRP models because they are the most recently published of the three, are from the recognised international authority on radiation protection and are those used in the calculation of effective dose with which we make extensive comparisons in this report. No attempt has been made to assess the severity or detriment associated with these radiation-induced cancers in this report (apart from omitting bone and skin cancer for the reasons given in Section 2), on the assumption that patients are primarily concerned about the risks of getting cancer irrespective of how successfully it can be treated. The same approach was adopted in our recent assessment of the childhood cancer risks following foetal exposures in diagnostic radiology (HPA et al, 2009).

To take account of radiation-induced heritable effects, we have also separately estimated the probability of passing on severe hereditary disorders for those x-ray examinations that involve significant exposure of the gonads when performed on patients with reproductive potential.

We have estimated the typical organ doses (and effective doses using both *ICRP Publication 60* (ICRP, 1991*)* and *ICRP Publication 103* (ICRP, 2007) tissue weighting factors) for a range of common x-ray examinations involving radiography, fluoroscopy and computed tomography (CT), using Monte Carlo calculations and patient dose data from recent national surveys of UK radiology practice. These organ doses have been combined with the corresponding organ-specific risk coefficients to estimate the typical risks of radiation-induced cancer for these common x-ray examinations as a function of the age and sex of the patient. Then we have divided these age and sex specific risks by the effective dose for each of the selected x-ray examinations to derive risk coefficients (risk per E) to compare with ICRP's nominal risk coefficients that are averaged over all ages and both sexes and apply to uniform whole-body irradiation. The extent to which these age and sex dependent risk coefficients vary between different types of x-ray examination that expose different organs is discussed, to determine whether a limited set of coefficients would adequately cover all or most types of x-ray examination.

2 *ICRP PUBLICATION 103* RISK MODELS FOR RADIATION-INDUCED CANCER

The radiation risk models developed by ICRP for use in its 2007 recommendations are described in Annex A of *ICRP Publication 103* (ICRP, 2007). In general, the risk models are based on incidence data from the life span study (LSS) of the Japanese atomic bomb survivors, with follow up from 1958 to 1998 and with DS02 dosimetry. Excess relative risk (ERR) and/ or excess absolute risk (EAR) models were developed for cancer incidence and mortality as a function of age at exposure and sex, for the following 10 specific organs: breast, lung, stomach, colon, red bone marrow (RBM), bladder, liver, thyroid, oesophagus and ovary; and also for the remainder (all other organs together).

For solid cancers, these models involve a linear dose response allowing for the modifying effects of sex, age at exposure and attained age;

e.g. $ERR = \beta_s D \cdot \exp[\gamma (e-30) + \eta \log(a/70)]$

where $\beta_s = \beta_{Male}$ or β_{Female} = sex specific estimates of ERR per Sv

and D = mean organ dose (Sv)
e = age at exposure (years)
a = attained age (years)

or $EAR = \beta_s D \cdot \exp[\gamma (e-30) + \eta \log(a/70)]$

where $\beta_s = \beta_{Male}$ or β_{Female} = sex specific estimates of EAR per 10^4 persons per year per Sv.

The coefficients β_{Male} , β_{Female} , γ and η are given in Tables A.4.6 to A.4.9 of *ICRP Publication 103* (ICRP, 2007) for ERR and EAR in terms of cancer incidence and mortality for the 9 solid cancer sites. In the EAR models for breast cancer, the magnitude of the age effect is different below and above 50 years.

For leukaemia (following irradiation of the red bone marrow), however, ICRP (2007) uses a linear-quadratic dose response that allows for the modifying effects of sex, age at exposure and time following exposure, as described by Preston et al (1994). The equations expressing this risk and the coefficients that provide the best fit to the LSS data are not specifically included in *ICRP Publication 103* (ICRP, 2007), although we have assumed the EAR modelling data given in Appendix 2 of Preston et al (1994).

While multiplicative (ERR) or additive (EAR) models lead to virtually identical descriptions of the excess risk in the population used to derive the risk estimates, they can lead to markedly different excess risk estimates when applied to other populations with different baseline cancer rates. In *ICRP Publication 103* (ICRP, 2007), composite baseline cancer rates averaged across four Asian (Shanghai, Osaka, Hiroshima and Nagasaki) and three Euro-American (Sweden, UK and USA) populations were used when calculating the

nominal risk coefficients. For this composite population, the relative weights (%) given to ERR and EAR were varied by ICRP for the different cancer sites (organs) based on judgements concerning their relative applicability, as follows:

ERR:EAR = 0:100% for breast and RBM
= 100:0% for thyroid and skin
= 30:70% for lung
= 50:50% for all other cancer sites.

There were insufficient data in the LSS on excess bone cancers to derive age and sex specific risks, so only the nominal risk coefficient averaged over all ages and both sexes taken from *ICRP Publication 60* (ICRP, 1991) (based on patients receiving therapeutic injections of radium-224) was used in *ICRP Publication 103* (ICRP, 2007) for bone cancer. It is noted that this risk estimate for bone cancer is based on average bone dose from radium-224, whereas current dosimetric models estimate doses to bone surfaces. Being an alpha-emitter of short half-life (3.6 d), radium-224 deposits most of its energy near the bone surface so that the endosteal dose is about 9 times higher than the average bone dose (Puskin et al, 1992). The already very low risk for radiation-induced bone cancer quoted in *ICRP Publications 60* and *103* (0.07% per Gy) would be a factor of 9 lower still if calculated on the basis of dose to the bone surface. For these reasons, bone cancer risks are ignored in the following calculations of the total cancer risk (as indeed they are in the BEIR VII risk models).

There was also little information on excess skin cancers in the LSS (and problems related to differences in risk due to skin pigmentation in the Japanese population). Consequently *ICRP Publication 103* (ICRP, 2007) used the nominal skin cancer risk (averaged over all ages and both sexes) of 0.1 per Gy from *ICRP Publication 59* (ICRP, 1992) (based mainly on medical exposures) but with an estimated lethality of only 0.2%, which was chosen to be conservative (i.e. to overestimate the risk). In addition, there is little evidence for radiation-induced skin cancer at doses below 1 Gy, so the assumption of a linear non-threshold (LNT) response model for the skin may be less justified than for other cancer sites. For these reasons, skin cancer risks are ignored in the following calculations of the total cancer risk (as they are in the BEIR VII risk models).

For solid cancers, risks are divided by a dose and dose rate effectiveness factor (DDREF) of 2 when estimating risks for the relatively low doses involved in medical exposures. For the purposes of applying DDREF, low doses can be considered as being less than 100 mGy (Muirhead et al (NRPB, 1993); Wakeford and Tawn, 2010). None of the x-ray examinations discussed in this report involve acute doses to any organ that exceed 50 mGy (see Table 17). For leukaemia, dose and dose rate effectiveness is represented by a linear-quadratic dose-effect model rather than the use of a DDREF. Although not specifically stated in *ICRP Publication 103* (ICRP, 2007), latency periods of 2 years for leukaemia and 5 years for solid cancers were used in ICRP's calculations (Dale Preston, personal communication, 2010) and we have used the same assumptions in the following calculations.

A brief comparison of the main features of the *ICRP Publication 103* (ICRP, 2007) risk model and those developed by the US National Research Council of the National Academies (BEIR VII, 2006) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2006) is given in Appendix A.

3 RADIATION-INDUCED CANCER RISK COEFFICIENTS BY ORGAN, AGE AND SEX, ACCORDING TO ICRP PUBLICATION 103

Computer programs have been developed at HPA to calculate the lifetime risks of cancer incidence or mortality per unit dose as a function of organ, age and sex according to the *ICRP Publication 103* (ICRP, 2007) risk models described in the previous section.

To check whether the models used in this report conformed to the methodology adopted by ICRP, the lifetime risk of cancer incidence was first calculated for each organ, averaged over all ages and both sexes in the whole population, for comparison with the nominal risk coefficients shown in the 2nd column of Table A.4.1 of *ICRP Publication 103* (ICRP, 2007). The same composite population (4 Asian and 3 Euro-American components) was used in these calculations as in *ICRP Publication 103* and the results are shown in Table 1 for each organ.

TABLE 1 Comparison of HPA and ICRP risk calculations

Organ or Tissue	Lifetime risk of cancer incidence HPA calculations (% per Sv)	Nominal risk coefficients Table A.4.1 of ICRP 103 (% per Sv)	HPA / ICRP
Lung	1.08	1.14	0.95
Stomach	0.79	0.79	1.00
Breast	0.97	1.12	0.87
Colon	0.66	0.65	1.02
RBM (Leukaemia)	0.63	0.42	1.50
Bladder	0.41	0.43	0.95
Liver	0.31	0.30	1.03
Thyroid	0.19	0.33	0.58
Oesophagus	0.16	0.15	1.07
Ovary	0.11	0.11	1.00
Other	1.34	1.44	0.93
All Cancers*	**6.65**	**6.88**	**0.97**

*Excluding bone and skin cancer

There is very good agreement between the risk estimates derived here and the ICRP values in Table 1 for cancers of the lung, stomach, colon, bladder, liver, oesophagus, and ovary. Agreement is also reasonable in relation to breast and ‘other’ cancers, which suggests that we are faithfully following the risks models

advocated by ICRP for most cancers. However, the agreement is not so good for cancers of the red bone marrow (leukaemia) and thyroid. Small discrepancies of a few percent are to be expected in the two sets of calculations due to differences, for example, in the way that the demographic and cancer baseline data were applied (e.g. on an annual or 5 yearly basis), different approaches to extrapolating risks beyond 85 years and rounding errors. The relatively large discrepancies (~50%) between the two sets of calculated risks for the thyroid and red bone marrow (leukaemia) have been thoroughly investigated, but remain difficult to explain.

Although they are expressed as '% per Sv', the risk coefficients shown in Table 1 were all calculated by us for a dose of 10 mSv (being the rough order of magnitude for the organ doses expected from the higher-dose x-ray examinations) and multiplied by 100 to give the risk per Sv. This will make no difference for solid cancers where the dose-response model is linear, but would potentially make a difference for leukaemia where a linear-quadratic dose-response model is used. However, when the risk coefficients for leukaemia were calculated for red bone marrow doses ranging from 1 μSv to 1 Sv, there was no significant change from the 0.63% per Sv value shown in Table 1 for doses up to 100 mSv, after which it increased to about 1.1% per Sv for a dose of 1 Sv. Consequently the discrepancy between values calculated here and the ICRP risk coefficient for leukaemia cannot be a result of calculating the risks at different dose levels. We have also carefully checked our implementation of the models for leukaemia and thyroid cancer against those described by ICRP (Dale Preston, personal communication, 2010) and we have been unable to find any explanation for the discrepancies observed.

Nonetheless, when all cancers are added together the total cancer risk predicted by the HPA calculations (6.65% per Sv) is within 3% of the ICRP figure (6.88% per Sv). Overall, therefore, our models are sufficiently robust for the purposes of assessing risks from medical x-ray examinations.

Lifetime risks of cancer incidence per unit dose were calculated for each organ and each gender divided into 10 year age bands. The small numbers of excess cancers observed in each group of the LSS when the data are divided up by organ, age and sex, lead to large inherent uncertainties in any mathematical model developed to express the risk for each organ as a function of age at exposure and sex. It was consequently thought inappropriate to resolve the estimated risks into anything smaller than 10 year age bands. Since it was intended to use these primarily to assess radiation risks to patients in the UK (and possibly in Europe and the USA), they were calculated using the *ICRP Publication 103* Euro-American population only (i.e. utilising data from UK, Sweden and the USA). The results are shown in Table 2 for each organ separately and for all cancers together.

Figures 1 and 2 present the same data graphically, with Figure 1 illustrating the lifetime risk of all cancers as a function of age at exposure and sex, assuming uniform whole-body irradiation, and Figures 2a and 2b showing the lifetime risk per unit dose for each cancer site (organ) separately (Figure 2a: lung, colon, breast, stomach, red bone marrow and 'other organs'; and Figure 2b: bladder, thyroid, ovary, liver and oesophagus).

TABLE 2 Lifetime risks of cancer incidence by organ, age and sex for a composite Euro-American population (% per Gy)

Organ	Age at exposure (y)									
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
Males										
Lung	0.65	0.69	0.73	0.78	0.80	0.76	0.61	0.38	0.15	0.00
Stomach	0.93	0.73	0.57	0.43	0.31	0.20	0.12	0.06	0.02	0.00
Colon	1.49	1.22	0.98	0.79	0.60	0.43	0.25	0.12	0.03	0.00
RBM	1.06	1.05	0.77	0.76	0.78	0.65	0.49	0.33	0.17	0.03
Bladder	0.89	0.76	0.65	0.55	0.46	0.35	0.23	0.12	0.04	0.00
Liver	0.56	0.44	0.34	0.26	0.18	0.12	0.07	0.03	0.01	0.00
Thyroid	0.18	0.10	0.05	0.03	0.01	0.01	0.00	0.00	0.00	0.00
Oesophagus	0.12	0.11	0.11	0.11	0.12	0.14	0.15	0.15	0.10	0.00
Other	4.11	2.89	2.02	1.42	0.96	0.60	0.31	0.12	0.03	0.00
All cancers	**9.98**	**8.00**	**6.22**	**5.12**	**4.22**	**3.27**	**2.23**	**1.32**	**0.55**	**0.04**
Females										
Breast	4.92	3.34	2.21	1.44	0.84	0.45	0.21	0.08	0.02	0.00
Lung	1.36	1.46	1.58	1.70	1.78	1.72	1.39	0.82	0.29	0.01
Stomach	1.45	1.14	0.88	0.67	0.48	0.33	0.20	0.10	0.03	0.00
Colon	0.73	0.59	0.48	0.38	0.29	0.21	0.14	0.07	0.02	0.00
RBM	0.48	0.48	0.50	0.45	0.77	0.49	0.29	0.15	0.06	0.01
Bladder	0.70	0.61	0.52	0.45	0.39	0.32	0.24	0.14	0.05	0.00
Liver	0.24	0.19	0.15	0.11	0.08	0.06	0.03	0.02	0.00	0.00
Thyroid	0.92	0.52	0.26	0.13	0.06	0.02	0.01	0.00	0.00	0.00
Oesophagus	0.10	0.09	0.10	0.12	0.15	0.21	0.28	0.30	0.19	0.01
Ovary	0.51	0.40	0.31	0.24	0.17	0.11	0.06	0.02	0.01	0.00
Other	2.99	2.17	1.56	1.11	0.75	0.48	0.27	0.13	0.04	0.00
All cancers	**14.4**	**11.0**	**8.54**	**6.78**	**5.76**	**4.41**	**3.10**	**1.83**	**0.70**	**0.02**

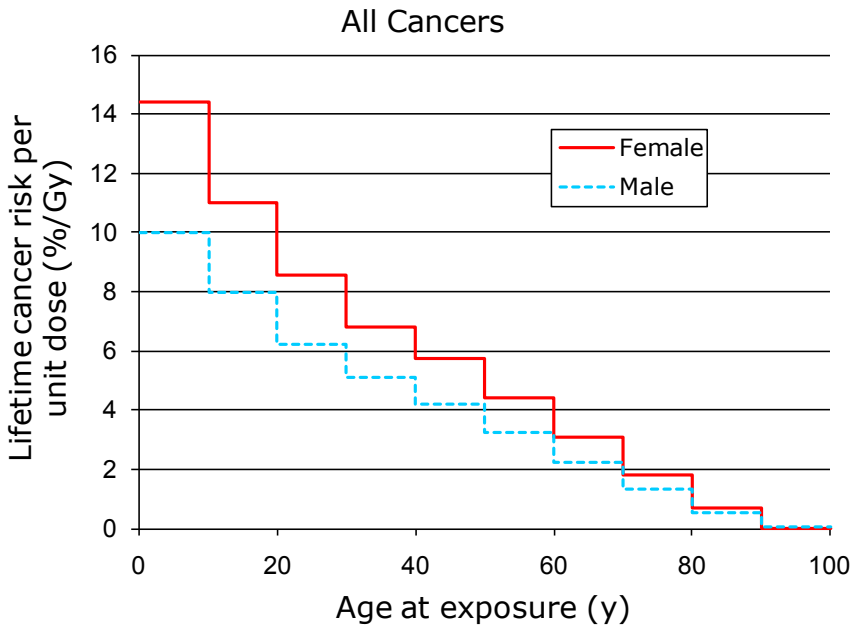

FIGURE 1 Lifetime risk of cancer incidence by age and sex for all cancers, following uniform whole-body irradiation

Figure 1 clearly demonstrates the steady fall in the total radiation-induced cancer risk with age at exposure (assuming all organs receive the same dose) and that females are at higher risk than males (by 27 - 44%) at all ages except above 90 years. Young children (0-9 years old) are at about twice the risk of adults in their thirties and approaching 5 times the risk of adults in their sixties, for both sexes. This steady rate of decrease in risk with age (approximately a factor of two for every 30 years) when all radiation-induced cancers are taken into account will be used as a yardstick for comparison with the variations of risk with age seen for different x-ray examinations later in this report (Section 7).

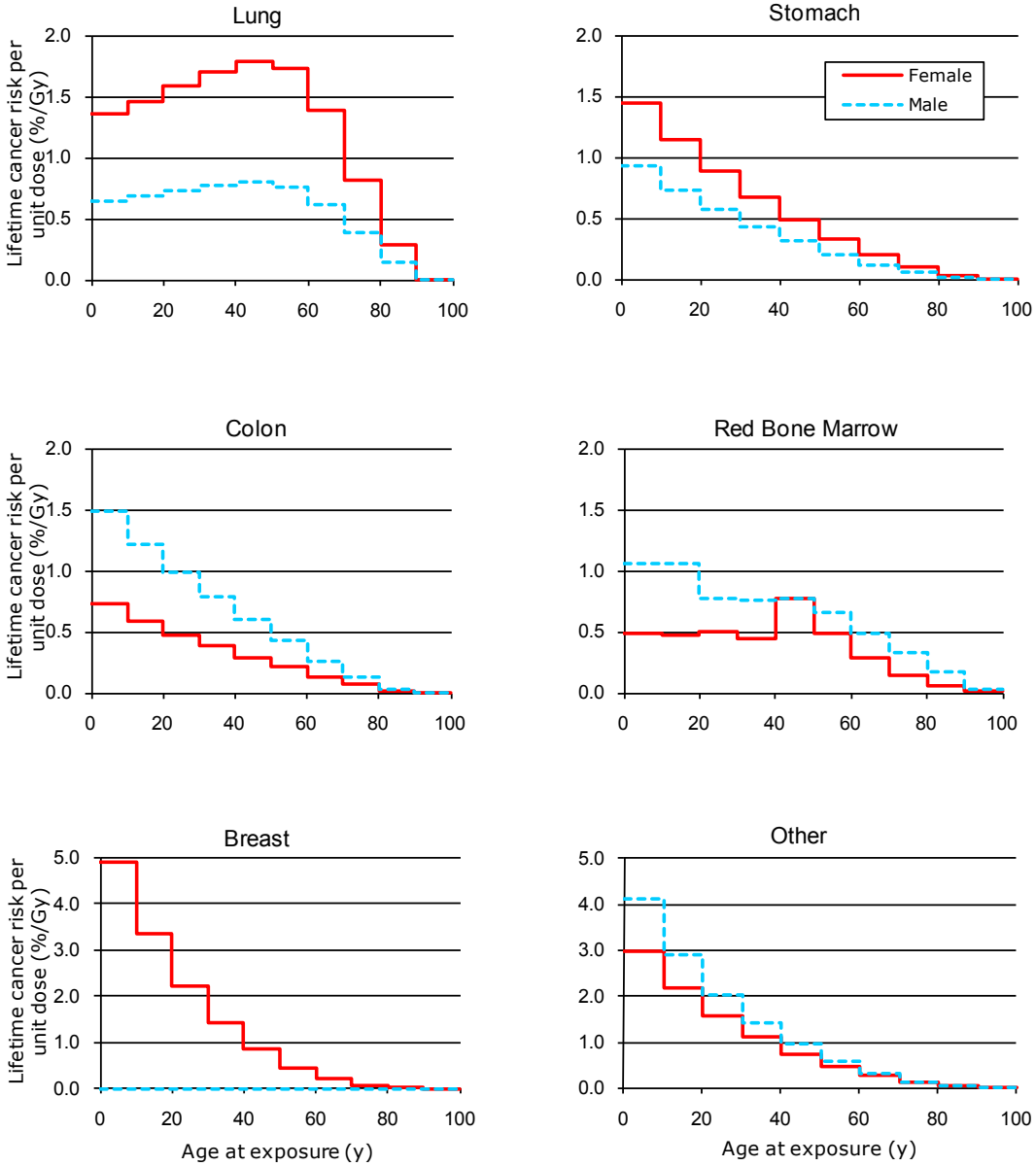

FIGURE 2a Lifetime risk of cancer incidence by age and sex for the 5 most radiosensitive organs and 'Other' organs

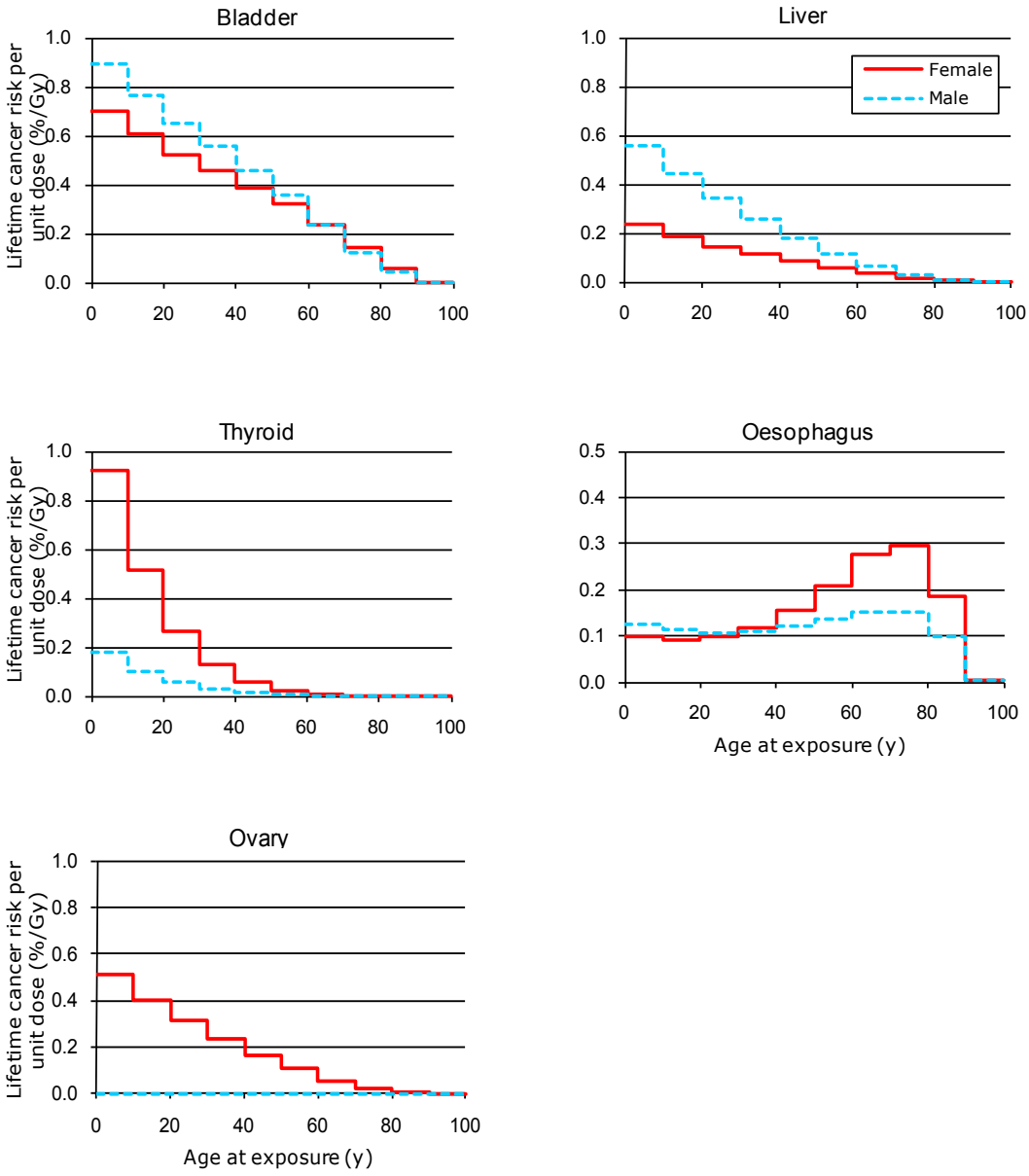

FIGURE 2b Lifetime risk of cancer incidence by age and sex for the other 5 radiosensitive organs

Notwithstanding the large uncertainties associated with the models for each cancer site, Figures 2a and 2b suggest a steady decrease in risk with age at exposure for some of the cancer sites but not for others. Cancers of the stomach, colon, breast, 'other organs', bladder, liver, thyroid and ovary all show a steady decrease in risk with age for both sexes. However, the rates of decrease vary between the different organs and the risks are higher (at all ages) for males when considering colon, liver and 'other' cancers, but higher for females in the case of stomach, thyroid and, of course, ovary and breast cancer. The rates of the decrease with age over the first 4 or 5 age bands (up to age 60 years) are particularly high for breast cancer (females) and thyroid cancer (females). However, a steady decrease in risk with age at exposure is not seen for either sex for cancers of the lung, red bone marrow and oesophagus, where the risk actually increases or remains relatively constant up to age 50 years for the first two of these cancers and up to age 80 years for the last.

It is therefore apparent that the way in which the total radiation–induced cancer risk varies with age and sex depends critically on which organs are irradiated and could be quite different for different types of x-ray examination, since they usually involve very non-uniform exposures of the body. To determine the extent of these differences, we have estimated typical organ doses for a range of common x-ray examinations and combined them with the corresponding organ-specific risk coefficients from Table 2 to estimate the total risk of radiation-induced cancer as a function of the age and sex of the patient for each examination. The methods we have used to calculate organ (and effective) doses for about 40 common types of x-ray examination involving radiography, fluoroscopy and computed tomography (CT) are described in Section 5 of this report, after a brief discussion in Section 4 of the risks of radiation-induced heritable effects.

4 RISK OF RADIATION-INDUCED HERITABLE EFFECTS ACCORDING TO *ICRP PUBLICATION 103*

The derivation of risk estimates for radiation-induced heritable effects is discussed in Annex A, Section A.6 of *ICRP Publication 103* (ICRP, 2007). In the absence of direct evidence of hereditary risk in humans, ICRP has used animal data to derive a nominal risk coefficient for human protection. Moreover, ICRP concluded that expressing the heritable risks of radiation for the first two generations adequately reflects the current state of knowledge. Table A.6.6 of *ICRP Publication 103* gives a risk coefficient of 0.54% per Gy for the reproductive population, which is reduced to 40% of the original value (ie to 0.22% per Gy) for the whole population, for the total of three classes of heritable effects (Mendelian diseases, chronic diseases and congenital abnormalities) expressed over two generations. The risk coefficient for the whole population is rounded to 0.2% per Gy in Table A.4.1 of *ICRP Publication 103,* when it is combined with the nominal risk coefficients for radiation-induced

cancers (and adjusted for lethality, severity and years of life lost) to derive the tissue weighting factors.

As an indication of the risk of heritable effects in the progeny of patients undergoing medical exposures as a function of their age and sex, we shall assume a similarly rounded risk coefficient of 0.5% per Gy of gonadal dose for all male or female patients of reproductive capacity (i.e. independent of gender or age until reproduction can be considered to cease). For patients beyond their reproductive years (or for those with medical conditions that make them unable to conceive), the risk of heritable effects is obviously zero. No account will be taken of the severity or lethality of these heritable effects (it is noted that when adjusted for lethality and quality of life in Table A.4.1 of *ICRP Publication 103* (ICRP, 2007), the nominal risk coefficient for heritable effects remains substantially unchanged).

5 ORGAN AND EFFECTIVE DOSES FOR COMMON X-RAY EXAMINATIONS ON ADULT PATIENTS IN THE UK

It is apparent from Sections 3 and 4 that the way in which the radiation–induced risk of cancer and heritable disease varies with the age and sex of the patient depends on which organs receive significant radiation doses in a particular x-ray examination. To determine the extent of these differences, typical organ doses have been estimated for a range of common x-ray examinations. Typical effective doses (according to both *ICRP Publication 60* and *ICRP Publication 103*) have also been estimated for each examination, for use in the calculation of risks per unit effective dose (see Section 7) for comparison with ICRP's nominal risk coefficients. The methods we have used to calculate the organ and effective doses for about 40 common types of x-ray examination involving radiography, fluoroscopy and computed tomography (CT) are described in detail and the results are given in terms of the highest three organ doses, gonad doses and effective doses, for each x-ray examination.

5.1 Individual radiographs

Organ doses and effective doses have been calculated for 24 types of individual radiograph using the Monte Carlo program PCXMC developed by the Finnish Centre for Radiation and Nuclear Safety (Tapiovaara et al, 2008). PCXMC uses a mathematical (stylized) hermaphrodite phantom to model the patient, which contains all of the 31 organs or tissues (listed in Table 3) necessary for calculating effective dose with both the current tissue weighting factors of *ICRP Publication 103* (ICRP, 2007) and the previous tissue weighting factors of *ICRP Publication 60* (ICRP, 1991).

TABLE 3 Organs and tissues modelled in the PCXMC phantom

Adrenals	Heart	Ovaries	Spleen
Brain	Kidneys	Pancreas	Stomach
Breasts	Liver	Prostate	Testes
Colon (large intestine)	Lungs	Red bone marrow	Thymus
Upper large intestine	Lymph nodes	Salivary glands	Thyroid
Lower large intestine	Muscle	Skeleton (bone)	Urinary bladder
Extrathoracic airways	Oesophagus	Skin	Uterus
Gall bladder	Oral Mucosa	Small intestine	

The phantom size can be adjusted to mimic patients of any height and weight, but the standard size for an adult averaged over both sexes (height 178.6 cm, weight 73.2 kg) was used in all these calculations. Reasons for not specifically modelling doses to children are discussed in Sections 8 and 9. The x-ray beam projection, size and position are freely adjustable, as is the x-ray spectrum through appropriate selection of the x-ray tube voltage, filtration and anode angle. The organ doses are calculated by PCXMC relative to the incident air kerma (IAK = the air kerma at the point where the central axis of the x-ray beam enters the patient, free-in-air, without backscatter). This must be provided by the user in mGy or alternatively in terms of the dose-area product (DAP) in mGy cm^2.

Typical IAK or DAP values representative of current radiography practice on adult patients in the UK for the 24 types of radiograph were taken from the most recent (2005) review of the UK National Patient Dose Database (NPDD) (Hart et al, 2007). The typical IAK was derived from the mean entrance surface dose (ESD) by dividing by the appropriate backscatter factor (BSF) for each type of radiograph. Appropriate BSF values were obtained from the tables in the Appendix to report NRPB-R186 (Jones and Wall, 1985). Typical DAP values were based on the mean DAP values seen in the 2005 review of the NPDD (Hart et al, 2007).

The mean absorbed doses to the 31 organs listed in Table 3 and effective doses as defined in *ICRP Publication 60* (E-60) and in *ICRP Publication 103* (E-103) were calculated using PCXMC for each type of radiograph. Where both mean ESD and mean DAP values were available, the calculations were performed for each input dose quantity separately, using the respective mean tube voltage and mean tube filtration values from the 2005 review of the NPDD (Hart et al, 2007) to define the x-ray spectrum, and the results were then averaged. For lateral projections, organ and effective doses were calculated for both left and right lateral views and again the results were averaged.

The highest three organ doses for each of the 24 types of individual radiograph listed in anatomical order from head to foot are shown in Table 4. Organ doses from single radiographs can typically reach about 2 mGy for superficial organs in the direct beam, such as the testes in AP projections of the pelvis and hips. Levels of dose fall to just a few microgray when only a small fraction of the tissue is in the direct beam and a limited section of the patient is being

examined, as can be seen for skin, bone and muscle in radiographs of the knee and foot.

TABLE 4 Highest three organ doses for each type of individual radiograph (mGy)

Radiograph	Highest organ dose (mGy)		2nd highest organ dose (mGy)		3rd highest organ dose (mGy)	
Head AP	Oral mucosa	0.52	Salivary glands	0.37	ET airways	0.36
Head PA	Salivary glands	0.51	Brain	0.24	Oral mucosa	0.16
Head Lat	Salivary glands	0.39	Oral mucosa	0.27	Brain	0.24
Cervical spine AP	Thyroid	0.33	ET airways	0.12	Oral mucosa	0.077
Cervical spine Lat	Thyroid	0.20	Salivary glands	0.011	ET airways	0.093
Shoulder AP	Thyroid	0.035	Lungs	0.024	Thymus	0.022
Shoulder (axial)	Thymus	0.071	Bone	0.014	Lungs	0.011
Chest PA	Adrenals	0.052	Lungs	0.046	Spleen	0.043
Chest Lat	Breasts	0.11	Lungs	0.072	Heart /Liver	0.055
Thoracic spine AP	Thymus	1.6	Heart	0.91	Breasts	0.57
Thoracic spine Lat	Lungs	0.53	Spleen	0.40	Bone	0.35
Lumbar spine AP	Stomach	1.3	Gall bladder	1.1	Small intestine	0.80
Lumbar spine Lat	Spleen	1.4	Kidneys	0.81	Pancreas	0.48
LSJ Lat	Ovaries	0.73	Small intestine	0.71	Colon	0.48
Abdomen AP	Bladder	1.4	Stomach	1.2	Gall bladder	1.0
Pelvis AP	Testes	2.1	Bladder	1.3	Prostate	0.87
Single Hip AP	Testes	0.76	Bladder	0.50	Prostate	0.42
Both Hips AP	Testes	2.3	Bladder	1.3	Prostate	0.98
Femur AP	Testes	0.20	Prostate	0.069	Skin	0.040
Femur Lat	Skin	0.032	Bone	0.026	Muscle	0.018
Knee AP	Skin	0.005	Bone	0.004	Muscle	0.002
Knee Lat	Skin	0.003	Bone	0.003	Muscle	0.002
Foot (dorsi-plantar)	Skin	0.003	Bone	0.003	Muscle	0.001
Foot (oblique)	Skin	0.003	Bone	0.003	Muscle	0.001

AP = Antero-posterior
PA = Postero-anterior
Lat = Lateral (average of Left and Right Lateral)
ET = Extrathoracic
LSJ = Lumbo-sacral joint

The typical gonadal doses for each of the 24 types of individual radiograph are shown in Table 5. These will be used to estimate the risks of heritable effects for male or female patients of reproductive capacity by multiplying the relevant gonadal dose by the risk coefficient of 0.5% per Gy (see Section 4).

TABLE 5 Typical gonadal doses for each type of individual radiograph

Radiograph	Ovary dose (mGy)	Testes dose (mGy)
Head AP	0	0
Head PA	0	0
Head Lat	0	0
Cervical spine AP	0	0
Cervical spine Lat	0	0
Shoulder AP	0	0
Shoulder (axial)	0	0
Chest PA	0	0
Chest Lat	0	0
Thoracic spine AP	0	0
Thoracic spine Lat	0	0
Lumbar spine AP	0.057	0.014
Lumbar spine Lat	0.42	0.004
LSJ Lat	0.73	0.006
Abdomen AP	0.63	0.15
Pelvis AP	0.52	2.1
Single Hip AP	0.18	0.76
Both Hips AP	0.15	2.3
Femur AP	0.002	0.20
Femur Lat	0	0.004
Knee AP	0	0
Knee Lat	0	0
Foot (dorsi-plantar)	0	0

AP = Antero-posterior PA = Postero-anterior

Lat = Lateral (average of Left and Right Lateral)

LSJ = Lumbo-sacral joint

Typical effective doses (E-60 and E-103) for each radiograph are shown in Table 6. They range from about 0.5 mSv for radiographs of the abdomen, down to 0.0001 mSv (0.1 μSv) for radiographs of the foot. The ratio E-103/E-60, shown in the last column, ranges from 1.5 for AP radiographs of the head to 0.47 for AP radiographs of the femur. The high ratio for head AP is due to the relatively high doses to the oral mucosa, salivary glands and extrathoracic airways from this projection (see Table 3) and to the allocation of tissue weighting factors to these organs in the definition of E-103 but not E-60. Also for a head AP radiograph, the thyroid dose (~0.3 mGy) exceeds the brain dose (~0.2 mGy) so the ICRP “remainder rule” does not come into play when calculating E-60, as it does for a CT head scan (see Section 5.4). Conversely, the low ratio for femur AP is due to the relatively high dose to the testes from this projection (see Tables 3 and 4) and the reduction in the tissue weighting factor for the gonads from 0.2 in E-60 to 0.08 in E-103.

TABLE 6 Typical effective doses for adult patients based on average of DAP & ESD measurements from 2005 review of NPDD (and average of L & R laterals)

Radiograph	E- 60 (mSv)	E- 103 (mSv)	E-103 / E-60
Head AP	0.022	0.033	1.50
Head PA	0.016	0.020	1.23
Head Lat	0.012	0.016	1.33
Cervical spine AP	0.018	0.018	0.97
Cervical spine Lat	0.012	0.012	1.04
Shoulder AP	0.007	0.007	1.01
Shoulder (axial)	0.005	0.004	0.83
Chest PA	0.014	0.014	1.04
Chest Lat	0.031	0.038	1.22
Thoracic spine AP	0.22	0.24	1.09
Thoracic spine Lat	0.15	0.14	0.97
Lumbar spine AP	0.41	0.39	0.95
Lumbar spine Lat	0.25	0.21	0.84
Lumbo-sacral joint Lat	0.21	0.17	0.81
Abdomen AP	0.47	0.43	0.91
Pelvis AP	0.45	0.28	0.63
Single Hip AP	0.15	0.087	0.59
Both Hips AP	0.35	0.19	0.54
Femur AP	0.02	0.011	0.47
Femur Lat	0.002	0.001	0.52
Knee AP	0.0002	0.0001	0.56
Knee Lat	0.0002	0.0001	0.66
Foot (dorsi-plantar)	0.0001	0.0001	1.00
Foot (oblique)	0.0001	0.0001	1.00

AP = Antero-posterior

PA = Postero-anterior

Lat = Lateral (average of Left and Right Lateral)

The conversion coefficients relating effective dose to DAP (E-60/DAP and E-103/DAP) are shown in Table 7 for the 24 types of radiograph. They range from about 0.2 mSv/Gy cm^2 for AP projections of the thoracic spine, lumbar spine and abdomen (for both E-60 and E-103) to 0.003 mSv/Gy cm^2 for radiographs of the foot, depending critically on which radiosensitive organs are included in the x-ray field. These conversion coefficients provide useful information for deriving effective dose estimates for adult patients from DAP measurements for any x-ray examination when the x-ray field size, position and projection (and strictly the x-ray spectrum) are similar to those used for the radiographs listed in Table 7.

TABLE 7 Effective dose per unit DAP for 24 types of radiograph

Radiograph	E- 60/DAP (mSv/Gy cm^2)	E- 103/DAP (mSv/Gy cm^2)
Head AP	0.039	0.058
Head PA	0.028	0.034
Head Lat	0.028	0.037
Cervical spine AP	0.19	0.19
Cervical spine Lat	0.11	0.12
Shoulder AP	0.063	0.064
Shoulder (axial)	0.056	0.046
Chest PA	0.15	0.16
Chest Lat	0.12	0.13
Thoracic spine AP	0.22	0.24
Thoracic spine Lat	0.093	0.091
Lumbar spine AP	0.24	0.22
Lumbar spine Lat	0.11	0.092
Lumbo-sacral joint Lat	0.097	0.078
Abdomen AP	0.20	0.18
Pelvis AP	0.22	0.14
Single Hip AP	0.23	0.13
Both Hips AP	0.23	0.13
Femur AP	0.077	0.036
Femur Lat	0.0064	0.0034
Knee AP	0.0061	0.0034
Knee Lat	0.0055	0.0030
Foot (dorsi-plantar)	0.0046	0.0032
Foot (oblique)	0.0046	0.0032

AP = Antero-posterior

PA = Postero-anterior

Lat = Lateral (average of Left and Right Lateral)

5.2 Complete radiographic examinations

Some types of complete x-ray examination usually involve taking only one radiograph while others involve taking a number of individual radiographs with different projections or covering different parts of the body, and do not use any fluoroscopy. The typical numbers of each radiograph by projection for 14 common radiographic examinations are shown in Table 8. The first 13 examinations simply involve one or more of the individual radiographs listed in Tables 4-7 and the highest three organ doses, the gonadal doses and effective doses for these complete examinations have been derived by summing the appropriate doses from Tables 4-6 and are shown in Tables 9-11. The last complete examination in Table 8, intravenous urography (IVU), involves a series of additional radiographic views not yet considered.

TABLE 8 Typical projections for complete radiographic examinations on adult patients

	Projection		
Examination	AP	PA	LAT
Head (Skull)	1	1	1
Cervical spine	1	-	1
Shoulder	1	-	1 (axial)
Chest	-	1	-
Thoracic spine	1	-	1
Lumbar spine	1	-	1
Abdomen	1	-	-
Pelvis	1	-	-
Single Hip	1	-	-
Both Hips	1	-	-
Femur	1	-	1
Knee	1	-	1
Foot	1 (DP)	-	1(oblique)
IVU	5 (3 KUB, 2 kidney)		

DP = dorsi-plantar

IVU = Intravenous urography

KUB = Kidneys, ureters and bladder

Whereas radiographic IVU examinations are increasingly being replaced by computed tomography (CT), it was considered worthwhile to conduct a small survey of ten hospitals at the end of 2009 to determine the typical protocol currently used for radiographic IVU examinations in the UK. Between 4 and 6 radiographs were taken for routine IVU examinations, with all ten hospitals including a pre-contrast radiograph of the kidneys, ureters and bladder (KUB), a radiograph of the kidneys 5 minutes post-injection, a KUB radiograph 15-20 minutes post-injection and either a KUB or bladder radiograph post-micturition. Some hospitals included in addition a radiograph of the kidneys immediately after contrast injection and/or another one 10 minutes later to bring the total number of radiographs for 3 of the hospitals up to 5 and for 2 of the hospitals up to 6. All these radiographs are taken with an AP projection. When calculating the organ and effective doses, we assumed that a typical IVU examination consists of 5 radiographs - 3 full length views of the KUB and 2 of just the kidneys. PCXMC was used to calculate the effective doses per unit DAP for both types of radiograph (KUB and kidney) and the mean DAP value for complete IVU examinations (11.6 Gy cm^2) from the 2005 review of the NPDD (Hart et al, 2007) was used to derive the typical effective doses, with the total DAP value divided between the two types of radiograph according to the relative number of radiographs taken and the relative x-ray field area. Thus with typically 3 KUB radiographs and 2 kidney radiographs, and the KUB field area being approximately twice the kidney field area, the total DAP was divided 3:1 between KUB and kidney components to derive the typical organ and effective doses for the complete IVU examination shown in Tables 9-11.

TABLE 9 Highest three organ doses for each complete radiographic examination

Examination	Highest organ dose (mGy)		2nd highest organ dose (mGy)		3rd highest organ dose (mGy)	
Head (AP+PA+Lat)	Salivary glands	1.3	Oral mucosa	0.95	Brain	0.68
Cervical spine	Thyroid	0.92	ET airways	0.22	Salivary glands	0.18
Shoulder	Thymus	0.093	Thyroid	0.043	Bone	0.035
Chest	Adrenals	0.052	Lung	0.046	Spleen	0.043
Thoracic spine	Thymus	1.7	Heart	1.1	Lung	0.95
Lumbar spine	Spleen	1.6	Stomach	1.5	Liver	1.5
Abdomen	Bladder	1.4	Stomach	1.2	Gall bladder	1.0
Pelvis	Testes	2.1	Bladder	1.3	Prostate	0.87
Single Hip	Testes	0.76	Bladder	0.50	Prostate	0.42
Both Hips	Testes	2.3	Bladder	1.3	Prostate	0.98
Femur	Testes	0.21	Skin	0.072	Prostate	0.070
Knee	Skin	0.009	Bone	0.007	Muscle	0.004
Foot	Skin	0.007	Bone	0.006	Muscle	0.002
IVU	Stomach	6.9	Gall bladder	6.2	Colon	4.0

TABLE 10 Typical gonadal doses for each complete radiographic examination

Examination	Ovary dose (mGy)	Testes dose (mGy)
Head (AP+PA+Lat)	0	0
Cervical spine	0	0
Shoulder	0	0
Chest	0	0
Thoracic spine	0.001	0
Lumbar spine	0.99	0.018
Abdomen	0.63	0.15
Pelvis	0.52	2.1
Single Hip	0.18	0.76
Both Hips	0.15	2.3
Femur	0.002	0.21
Knee	0	0
Foot	0	0
IVU	2.3	0.50

TABLE 11 Typical effective doses for complete radiographic examinations

Examination	E-60 (mGy)	E-103 (mGy)	E-103 / E-60
Head (Skull)	0.05	0.068	1.36
Cervical spine	0.03	0.03	1.00
Shoulder	0.012	0.011	0.92
Chest	0.014	0.014	1.00
Thoracic spine	0.37	0.38	1.03
Lumbar spine	0.66	0.60	0.91
Abdomen	0.47	0.43	0.91
Pelvis	0.45	0.28	0.62
Single Hip	0.15	0.087	0.58
Both Hips	0.35	0.19	0.54
Femur	0.022	0.012	0.55
Knee	0.0004	0.0002	0.5
Foot	0.0002	0.0002	1.00
IVU	2.3	2.1	0.91

For complete examinations of the foot and knee, effective doses still remain well below 1 μSv, whereas for lumbar spine examinations involving an AP and a lateral projection the effective doses reach about 0.6 mSv and for IVU examinations they are just over 2 mSv.

5.3 Complete examinations involving fluoroscopy and radiography

Common x-ray examinations that involve fluoroscopy and radiography include those of the alimentary canal and the blood vessels, which require the use of a contrast medium to visualize soft tissues that would otherwise be transparent to x-rays. Fluoroscopy is used to follow the passage of the contrast medium and radiography, fluorography or digital spot imaging is used to take images of interesting features for diagnosis. Examinations of the alimentary canal from the oesophagus to the rectum usually involve solutions of barium sulphate as the contrast medium, taken as a drink to examine the oesophagus (barium swallow), stomach (barium meal) and small intestine (barium follow), or as an enema to examine the colon and rectum (barium enema). The frequency of barium meals has dropped significantly in the UK over the past few years (being largely replaced by endoscopy) (Hart et al, 2010) and so only barium swallows, follows and enemas are considered further in this study. Iodinated contrast media are used to examine blood flow through arteries or veins and two of the most common examinations are those of the coronary arteries (coronary angiography) and of the femoral arteries and the aorta (femoral angiography).

A small survey of 10 hospitals was conducted at the end of 2009 to determine the typical protocols currently used for barium swallow, follow and enema examinations in the UK. For barium swallow examinations, the typical protocol involved the following imaging: fluoroscopy to track the passage of barium through the throat and oesophagus; several digital spot images of the throat

using lateral (left and right) and AP projections; followed by several images of the oesophagus mostly using AP, right posterior oblique (RPO) and right anterior oblique (RAO) projections; and finally an image of the stomach (AP) to check for any blockage. The average number of spot images taken was about 25 with the intervening periods of fluoroscopy totalling on average about 1.5 minutes for the whole examination. When calculating the organ and effective doses, we assumed that a typical barium swallow examination involves taking 5 images at each of the five projections through the throat and oesophagus, and one at the AP projection of the stomach, with equal periods of fluoroscopy spent at each projection. PCXMC (Tapiovaara et al, 2008) was used to calculate the effective doses per unit DAP for each projection. The mean DAP value for complete barium swallow examinations on adult patients (6.4 Gy cm^2) from the 2005 review of the NPDD (Hart et al, 2007) was used to derive the typical effective doses, with the total DAP value divided between each projection according to the relative number of images taken and the relative x-ray field area. The resulting highest three organ doses for a complete barium swallow examination are shown in Table 12, gonadal doses in Table 13 and the typical effective doses are shown in Table 14. The mean number of spot images for over 14,000 adult patients having barium swallow examinations at 60 hospitals in the 2005 review of the NPDD (Hart et al, 2007) was 26 and the mean fluoroscopy time was 113 seconds, both of which are reasonably close to the values seen in the 10 hospitals recently surveyed.

TABLE 12 Highest three organ doses for complete x-ray examinations involving radiography and fluoroscopy (mGy)

Examination	Highest organ dose (mGy)		2nd highest organ dose (mGy)		3rd highest organ dose (mGy)	
Barium swallow	Thyroid	7.6	Thymus	5.4	Heart	3.4
Barium follow	Kidneys	6.1	Bladder	2.8	Spleen	2.8
Barium enema	Bladder	7.0	Uterus	6.1	Ovaries	5.7
Coronary angiography	Lungs	15.3	Adrenals	13.9	Heart	12.7
Femoral angiography	Kidneys	10.2	Bone	6.0	Ovary	5.9

TABLE 13 Typical gonadal doses for complete x-ray examinations involving radiography and fluoroscopy

Radiograph	Ovary dose (mGy)	Testes dose (mGy)
Barium swallow	0.02	0
Barium follow	2.6	0.21
Barium enema	5.7	7.0
Coronary angiography	0.02	0
Femoral angiography	5.9	0.98

TABLE 14 Typical effective doses for adult patients from complete x-ray examinations involving radiography and fluoroscopy

Examination	E-60 (mSv)	E-103 (mSv)	E-103 / E-60
Barium swallow	1.4	1.5	1.07
Barium follow	1.5	1.3	0.87
Barium enema	3.0	2.2	0.73
Coronary angiography	3.9	3.9	1.00
Femoral angiography	2.8	2.3	0.82

For barium follow examinations, between 2 and 6 spot images (average = 5) were taken, mostly of the whole abdomen, with duration of fluoroscopy ranging from 0 to 150 seconds (average = 60s) at the ten hospitals in the survey. All of the spot images were taken with either a PA projection (in 7 hospitals) or with an AP projection (in 3 hospitals). The mean DAP value for complete barium follow examinations on adult patients (10.0 Gy cm^2) from the 2005 review of the NPDD (Hart et al, 2007) was used to derive the typical effective doses, assuming a 70:30 percentage split between the use of PA or AP projections. The resulting highest three organ doses for a complete barium follow examination are shown in Table 12, gonadal dose in Table 13 and the typical effective doses are shown in Table 14. The mean number of spot images for over 4,500 adult patients having barium follow examinations at 43 hospitals in the 2005 review of the NPDD (Hart et al, 2007) was 6 and the mean fluoroscopy time was 106 seconds – not too dissimilar from the values seen in the small survey of practice at ten hospitals.

For barium enemas, between 10 and 18 (average = 12) radiographic spot images were taken at the 10 hospitals in the survey, with intervening periods of fluoroscopy totalling on average about 2 minutes (118 sec) for the whole examination. The radiographic projections commonly used at all the hospitals (with only slight variations) were:

- 1 lateral rectum
- 3 views of sigmoid colon (left posterior oblique (LPO), RAO, left anterior oblique (LAO))
- 4 views of whole colon (2AP, 2PA)
- 1 LAO of splenic flexure
- 1 RAO of hepatic flexure
- 2 views of caecum (AP, PA)

When calculating the organ and effective doses, we assumed that a typical barium enema examination consists of the above 12 types of radiographic image together with 12 equal periods of fluoroscopy using the same x-ray field sizes and projections as the 12 radiographs. PCXMC (Tapiovaara et al, 2008) was used to calculate the effective doses per unit DAP for each type of radiograph (and the associated period of fluoroscopy). The mean DAP value for complete barium enema examinations on adult patients (17.8 Gy cm^2) from the 2005 review of the NPDD (Hart et al, 2007) was used to derive the typical effective doses, with the total DAP value divided between each type of radiograph according to the relative number of radiographs taken and the

relative x-ray field area. The resulting highest three organ doses for a complete barium enema examination are shown in Table 12, gonadal doses in Table 13 and the typical effective doses are shown in Table 14. The mean number of spot images for over 44,000 adult patients having barium enema examinations at 108 hospitals in the 2005 review of the NPDD (Hart et al, 2007) was also 12 and the mean fluoroscopy time of 122 seconds was very close to that seen in the 10 hospitals recently surveyed (118 sec).

For coronary angiography examinations, information was obtained on the typical protocol currently used at a major London hospital (Sarah Peters, personal communication, 2010). The left coronary artery is typically imaged with the following five projections:

- PA (initially to guide catheter into position)
- 45° LAO with 30° caudal tilt
- 30° RAO with 30° caudal tilt
- 30° RAO with 30° cranial tilt
- 45° LAO with 30° cranial tilt

The right coronary artery is typically imaged with the following three projections:

- 45° LAO
- 45° LAO with 30° cranial tilt
- 30° RAO

This protocol is similar to the 'standard' diagnostic procedure for coronary angiography observed at the Western Infirmary, Glasgow in 1998 (Clark et al, 2000). In current practice, the left ventricle is usually imaged with ultrasound and is no longer routinely included in a coronary angiography x-ray examination. PCXMC (Tapiovaara et al, 2008) was used to calculate the effective doses per unit DAP for each of the 7 different projections listed above with the x-ray beam area adjusted so that it just covered the heart in each case. The weight of the phantom was increased to 79 kg to correspond with the mean patient weight seen for this examination in the 2005 review of the NPDD (Hart et al, 2007). The mean DAP value for complete coronary angiography examinations on adult patients (25.7 Gy cm^2) from the 2005 review of the NPDD (Hart et al, 2007) was used to derive the typical effective doses, with the total DAP value divided between each of the above projections according to the number of times the projection was used (i.e. twice for '45° LAO with 30° cranial tilt' and once for all the others) and the relative x-ray beam area. The resulting highest three organ doses for a complete coronary angiography examination are shown in Table 12, gonadal doses in Table 13 and the typical effective doses are shown in Table 14.

The E/DAP values derived for each projection through the heart are shown in Table 15. Values range from 0.12 to 0.19 mSv/ mGy cm^2, with the oblique projections giving higher values than the PA and being reduced slightly by a cranial tilt and more so by a caudal tilt. Not surprisingly, the oblique views through the heart with cranial tilt give very similar E/DAP values as for the PA Chest radiograph shown in Table 7.

TABLE 15 Effective dose per unit DAP for 7 projections through the heart used in coronary angiography

Projection	E-60 / DAP (mSv/Gy cm^2)	E-103/DAP (mSv/Gy cm^2)
PA	0.12	0.12
45° LAO with 30° caudal tilt	0.13	0.13
30° RAO with 30° caudal tilt	0.13	0.14
30° RAO with 30° cranial tilt	0.16	0.16
45° LAO with 30° cranial tilt	0.16	0.15
45° LAO	0.18	0.19
30° RAO	0.17	0.18
Complete coronary angiography exam	**0.16**	**0.16**

LAO = Left anterior oblique

RAO = Right anterior oblique

For femoral angiography examinations, the typical protocol observed at the Royal Infirmary, Edinburgh, when using a newly installed Philips Integris 3000 vascular x-ray system (Hoskins et al, 1996), was used as the basis for the present dose calculations. According to this study, a typical femoral angiography examination consists of the 7 projections shown in Table 16 and the corresponding number of digital spot images, together with the typical tube voltage used for taking them. The total DAP for the examination was estimated to be split 75%:25% between the first 3 projections in the trunk and the last 4 projections in the legs.

TABLE 16 Projections used in a typical femoral angiography examination

Projection	No. of digital spot images	Tube voltage (kV)	% of total DAP
Aorta PA	18	70	25
Pelvis PA	18	72	25
Pelvis 30° LAO	18	75	25
Upper leg PA	11	60	6.25
Middle leg PA	11	60	6.25
Lower leg PA	11	55	6.25
Foot	11	50	6.25

PA = Postero-anterior

LAO = Left anterior oblique

PCXMC (Tapiovaara et al, 2008) was used to calculate the effective doses per unit DAP for each of the 7 different projections in Table 16. The mean DAP value for complete femoral angiography examinations on adult patients (34.3 Gy cm^2) from the 2005 review of the NPDD (Hart et al, 2007) was used to derive the typical effective doses, with 75% of the total DAP value divided equally between the first 3 projections and 25% divided equally between the last 4 projections, since the x-ray beam area remained the same for all projections. The resulting highest three organ doses for a complete femoral angiography examination are shown in Table 12, gonadal dose in Table 13 and the typical effective doses are shown in Table 14.

For these five complete x-ray examinations involving fluoroscopy and radiography, the highest organ and effective doses are for coronary

angiography, where the lungs receive about 15 mGy, the ovaries about 6 mGy and both the effective doses (E-60 and E-103) are about 4 mSv.

5.4 Computed tomography (CT) examinations

Organ doses and effective doses have been calculated for 5 types of CT examination using the general–purpose Monte Carlo radiation transport code, MCNPX (Pelowitz, 2008), and a mathematical (stylized) hermaphrodite adult phantom developed at the HPA (HPA 18+) to model an adult patient (Jansen et al, 2009). The HPA 18+ phantom contains all of the 31 organs or tissues necessary for calculating effective dose with both the current tissue weighting factors of *ICRP Publication 103* (ICRP, 2007) and the previous tissue weighting factors of *ICRP Publication 60* (ICRP, 1991). It is very similar to the standard adult phantom used in PCXMC (Tapiovaara et al, 2008) for conventional x-ray examinations. Simulations were performed in relation to exposure conditions for the Philips LX (Philips Healthcare, Best, The Netherlands) since dose coefficients for this CT scanner were shown in a previous study broadly to represent the middle of the range observed for 27 scanner models from 5 CT manufacturers (Shrimpton and Edyvean, 1998).

The organ doses were calculated relative to the weighted CT dose index ($CTDI_W$) or the volume weighted CT dose index ($CTDI_{vol}$) for every 1 cm thick transverse slice of the phantom. Typical $CTDI_W$ or $CTDI_{vol}$ values and the extent of the scanned volume representative of current radiography practice on adult patients in the UK for the 5 types of CT examination were taken from the most recent (2003) HPA review of doses from CT in the UK (Shrimpton et al, 2005).

The highest three organ doses for each of the 5 types of CT examination are shown in Table 17 and the gonadal doses are shown in Table 18. The brain receives a dose as high as 45 mGy from a CT head scan, while CT scans through the trunk result in maximum doses of about 15 mGy to organs that are completely covered by the scan, with those close to the surface of the body receiving slightly higher doses than those at depth.

TABLE 17 Highest three organ doses for each type of CT examination (mGy)

CT examination	Highest organ dose (mGy)		2nd highest organ dose (mGy)		3rd highest organ dose (mGy)	
CT Head	Brain	45	Oral mucosa	10.2	ET airways	10
CT Chest	Thymus	14.6	Lung	13.8	Heart	13.5
CT Abdomen	Kidneys	16.3	Stomach	14.3	Spleen	13.8
CT Abdomen + Pelvis	Kidneys	15	Bladder	14.2	ULI	13.3
CT CAP	Thymus	14.6	Kidneys	14.1	Lung	13.9

CAP = Chest + Abdomen + Pelvis

ET = Extrathoracic

ULI = Upper large intestine

TABLE 18 Typical gonadal doses for each type of CT examination

CT examination	Ovary dose (mGy)	Testes dose (mGy)
CT Head	0	0
CT Chest	0.16	0.004
CT Abdomen	7.9	0.12
CT Abdomen + Pelvis	13	1.4
CT Chest + Abdomen + Pelvis	11	0.55

Typical effective doses (E-60 and E-103) for each CT examination are shown in Table 19. They range from about 10 mSv for CT examinations of the entire trunk (chest + abdomen + pelvis) down to about 1.5 mSv for CT head scans. The ratio E-103/E-60, shown in the last column, ranges from 0.84 for CT head to 1.14 for CT chest. The low ratio for CT head (compared to a high ratio for radiography of the head) is due to the very high brain dose from CT head scans and the old ICRP “remainder rule” that is applied for E-60 but not for E-103. Under this rule, if a remainder organ receives a higher dose than any of the organs with a specified tissue weighting factor (such as the brain in a CT head scan), it is given a tissue weighting factor for E-60 of half that for all the remainder organs (0.5 x 0.05 = 0.025). In contrast, for E-103, where the brain is no longer a ‘remainder’ organ, it is given a specific tissue weighting factor of 0.01. The high E-103/E-60 ratio of 1.14 for CT chest examinations is due to the relatively high breast dose (10.6 mSv) and the higher tissue weighting factor for the breast in E-103 (0.12) compared to E-60 (0.05).

TABLE 19 Typical Effective doses for CT examinations on adult patients from the 2003 review of CT practice in the UK

CT examination	E-60 (mSv)	E-103 (mSv)	$\frac{\text{E-103}}{\text{E-60}}$
CT Head	1.6	1.4	0.84
CT Chest	5.8	6.6	1.14
CT Abdomen	5.1	5.6	1.09
CT Abdomen + Pelvis	6.8	6.7	0.98
CT Chest + Abdomen + Pelvis	9.2	10	1.09

6 RADIATION RISKS AS A FUNCTION OF AGE AND SEX FOR COMMON X-RAY EXAMINATIONS IN THE UK

In Section 5, estimates were made of the typical organ doses for a range of common x-ray examinations involving radiography, fluoroscopy and CT, using Monte Carlo calculations and patient dose data from recent national surveys of UK radiology practice. In this Section, these organ doses are combined with the corresponding organ-specific risk coefficients from Sections 3 and 4 to estimate the risks of radiation-induced cancer and heritable effects for a selection of common x-ray examinations as a function of the age and sex of the patient.

A fundamental limitation of these calculations is that the organ doses have been estimated for adult patients and are assumed to remain unchanged for young children. At this stage, no account has been taken of the fact that, if full optimisation of the exposure conditions to the size of the patient is practiced, the organ and effective doses might be lower for young children than for adults. This possibility is discussed in more detail in Sections 8 and 9, but in this Section it is only the impact of the variation in the risk per unit dose with age that is being assessed.

6.1 Risks of radiation-induced cancer

The organ, age and sex specific risk coefficients from Table 2 have been multiplied by the corresponding organ doses for a selection of the x-ray examinations described in Section 5 and summed over all organs to provide the typical total lifetime cancer risks for each examination as a function of the age and sex of the patient.

The dose corresponding to the risk coefficients for “other” organs in Table 2 is calculated as the weighted average of the doses to the brain, salivary glands and the 14 ‘remainder tissues’ specified in *ICRP Publication 103* (ICRP, 2007), with the sum of the weighting factors for each of these organs (i.e. 0.14) re-normalised to unity. This procedure is similar to that recommended by ICRP for averaging the dose to ‘remainder tissues’ (ICRP, 2007).

The results are shown in Table 20 for 20 types of complete x-ray examination. Figure 3 presents the data in Table 20 graphically for the 20 x-ray examinations.

TABLE 20 Typical total lifetime cancer risk as function of age at exposure and sex for 20 x-ray examinations (per million, 10^{-6})

		Age at exposure (y)									
Examination	Sex	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
Head	M	12	8.5	5.9	4.4	3.2	2.2	1.3	0.6	0.3	0.0
(AP+PA+Lat)	F	11	7.7	5.3	3.7	2.9	1.8	1.0	0.5	0.2	0.0
Cervical spine	M	2.7	1.9	1.2	0.9	0.6	0.4	0.2	0.1	0.1	0.0
(AP+Lat)	F	6.2	3.7	2.2	1.3	0.8	0.5	0.3	0.2	0.1	0.0
Chest	M	1.3	1.1	0.9	0.8	0.7	0.6	0.5	0.3	0.1	0.0
(PA)	F	1.9	1.6	1.4	1.3	1.2	1.1	0.8	0.5	0.2	0.0
Thoracic spine	M	30	24	20	17	16	13	9.7	6.1	2.6	0.1
(AP+Lat)	F	65	50	40	34	30	25	18	11	4.2	0.1
Abdomen	M	55	44	35	27	21	15	9.3	4.8	1.7	0.1
(AP)	F	49	39	31	25	20	14	9.4	5.2	1.8	0.0
Pelvis	M	31	25	20	16	13	9.4	5.9	3.0	1.0	0.0
(AP)	F	24	19	16	13	10	7.8	5.2	2.9	1.0	0.0
Lumbar spine	M	72	56	43	34	26	19	12	6.1	2.3	0.1
(AP+Lat)	F	65	51	41	32	26	19	12	6.8	2.4	0.1
Knee	M	0.011	0.008	0.005	0.004	0.003	0.002	0.001	0.000	0.000	0.000
(AP+Lat)	F	0.008	0.006	0.004	0.003	0.002	0.001	0.001	0.000	0.000	0.000
Foot	M	0.0049	0.0035	0.0024	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000	0.0000
(AP+Lat)	F	0.0036	0.0026	0.0019	0.0013	0.0009	0.0006	0.0003	0.0002	0.0000	0.0000
IVU	M	260	210	160	130	97	69	42	21	7.4	0.3
	F	240	190	150	120	92	67	44	24	8.3	0.2
Ba swallow	M	130	96	73	58	46	36	25	15	6.3	0.3
	F	290	200	140	110	83	62	43	25	9.8	0.3
Ba follow	M	170	140	100	84	66	48	30	16	6.4	0.5
	F	140	110	91	72	61	43	28	15	5.4	0.2
Ba enema	M	260	210	160	130	110	79	51	27	11	0.9
	F	200	160	130	110	92	66	42	23	8.1	0.3
Coronary	M	330	290	250	230	210	190	150	94	41	2.1
angiography	F	430	390	370	360	370	330	270	170	66	1.7
Femoral	M	280	220	170	140	110	85	56	32	14	1.6
angiography	F	210	170	140	110	110	73	45	24	8.8	0.5
CT head	M	250	190	130	100	80	57	36	20	9.0	1.2
	F	190	140	100	77	71	46	27	13	4.8	0.3
CT chest	M	530	440	350	300	260	220	160	99	42	2.2
	F	1100	860	680	560	490	390	290	180	68	1.7
CT abdomen	M	670	530	400	310	240	170	110	56	21	1.5
	F	610	480	380	300	240	170	110	59	20	0.6
CT abdomen +	M	850	670	520	410	320	230	150	78	29	1.9
pelvis	F	740	590	470	370	310	230	150	80	28	0.8
CT chest +	M	960	780	630	520	440	340	240	140	58	3.3
abdo + pelvis	F	1500	1100	910	740	640	500	360	210	80	2.1

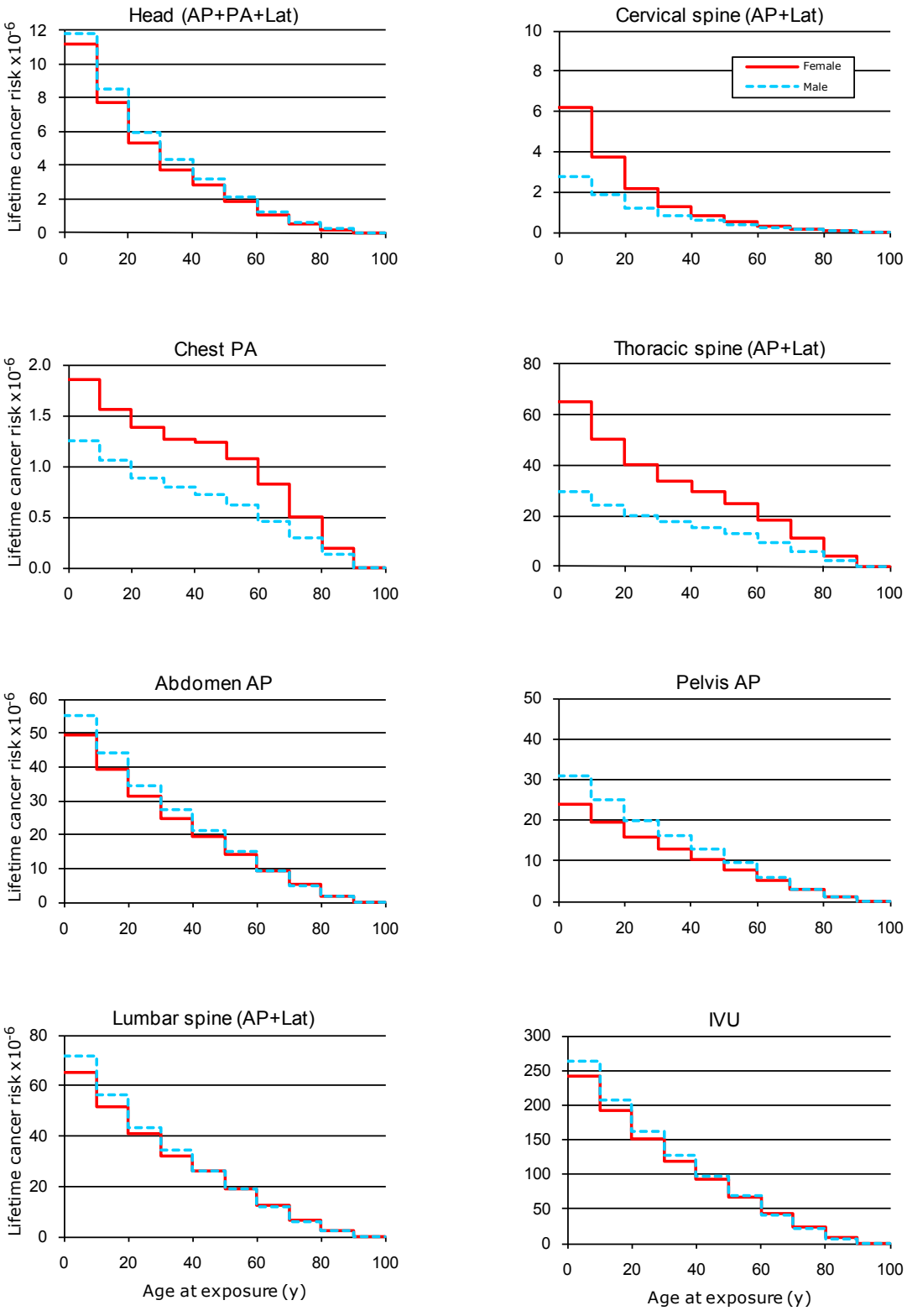

FIGURE 3a Typical total lifetime cancer risk as function of age at exposure and sex for 8 radiographic x-ray examinations

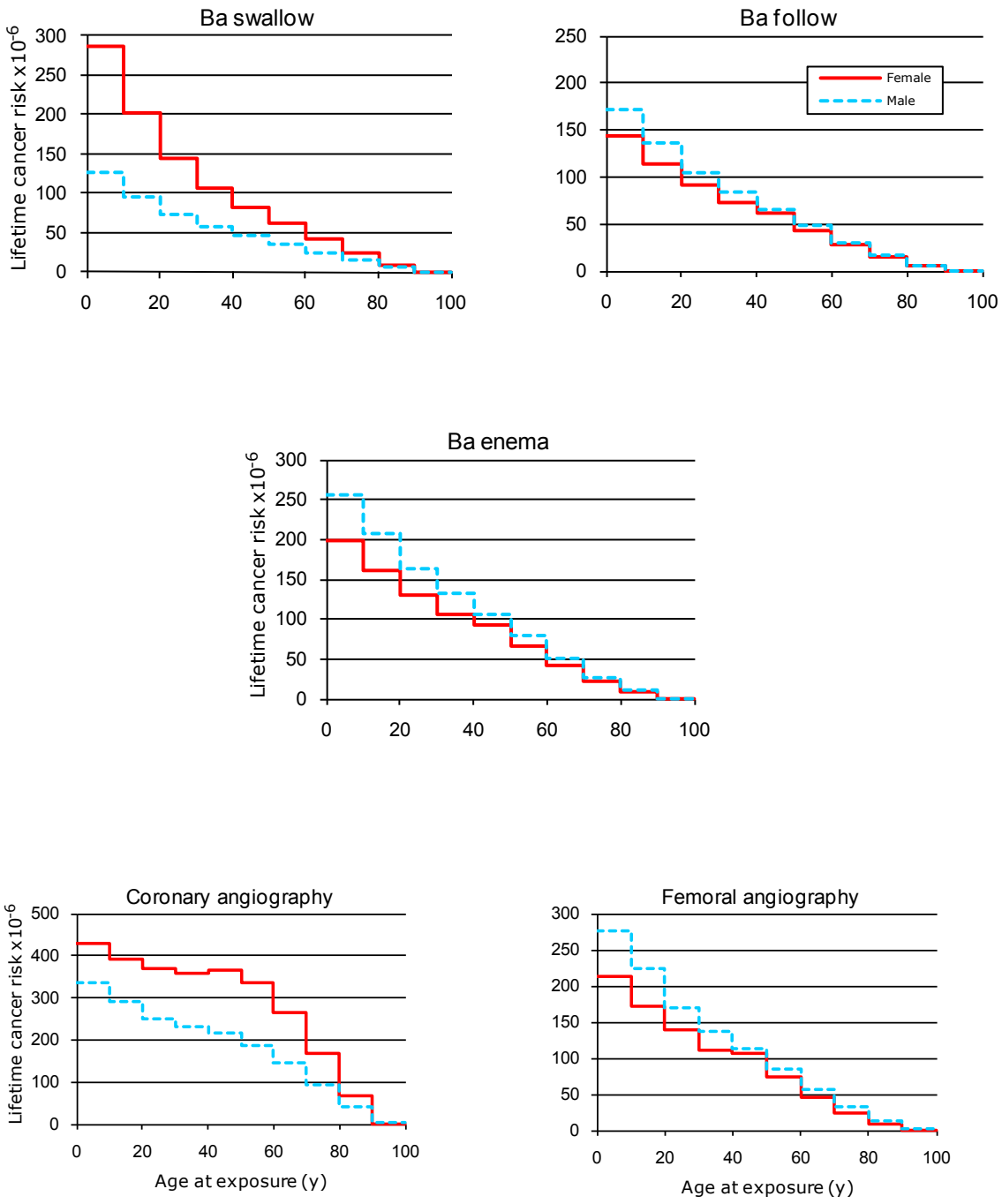

FIGURE 3b Typical total lifetime cancer risk as function of age at exposure and sex for 5 x-ray examinations involving radiography and fluoroscopy

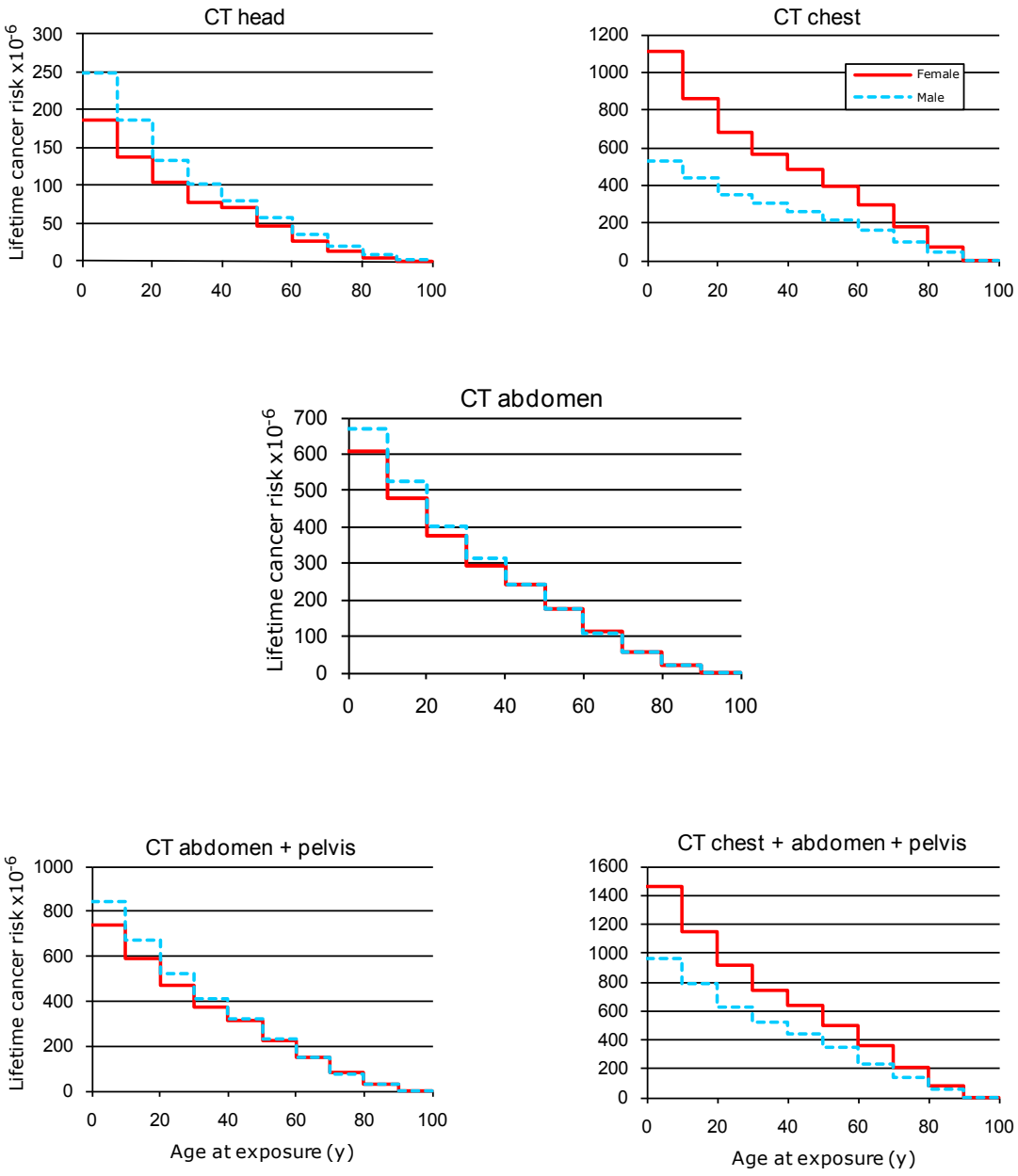

FIGURE 3c Typical total lifetime cancer risk as function of age at exposure and sex for 5 CT examinations

It can be seen that the typical levels of risk range from less than 1 in 100 million ($<10^{-8}$) for any patient having an x-ray examination of the knee or foot, to over 1 in a 1,000 ($1.5\ 10^{-3}$) for a young girl having a CT scan of the whole trunk (chest + abdomen + pelvis). However, it should be appreciated that the risks for children shown in Table 20 and Figure 3 have been estimated on the assumption that the organ doses they receive from a particular type of x-ray examination are the same as for adults (see Sections 8 and 9 for further discussion).

The general trend for the total lifetime cancer risk to fall steadily with increasing age at exposure is seen for all types of examination, except for coronary angiography on female patients. Coronary angiography involves relatively high doses to the lung and oesophagus, and these two organs are exceptional in that the risk increases with age up to at least 60 years, particularly for female patients (see Figures 2a and 2b). The Chest PA examination also shows a much less steep fall in risk with age than other examinations (apart from coronary angiography) due to the relatively high lung and oesophageal doses, but this effect is not so apparent for other examinations that predominantly irradiate the chest, such as CT Chest and Thoracic spine (AP+Lat). However, for all these examinations of the chest region, the risks for female patients are considerably higher than those for male patients at all ages, reflecting the shape of the risk curves for lung and breast cancer shown in Figure 2a.

Those examinations that predominantly involve irradiation of the abdomen and pelvis (i.e. Abdomen AP, Pelvis AP, Lumbar spine AP + Lat, IVU, Ba follow, Ba enema, Femoral angiography, CT abdomen and CT abdomen + pelvis) all show a steady decrease in risk with age for both sexes. For males, however, the risk is slightly higher than for females in the younger age groups and falls more rapidly with age.

Those examinations that involve irradiation of the neck region where the thyroid receives substantially higher doses than any other radiosensitive organ (i.e. Cervical spine and Ba Swallow), place young females at much higher risk than young males, in line with the variation in risk per unit dose with age and sex for thyroid cancer shown in Figure 2b. For Head (AP+PA+Lat) and CT head examinations, the thyroid dose is considerably lower than that to some of the “other” organs that lie in the head (e.g. brain, salivary glands, oral mucosa and extrathoracic airways) (see Tables 9 and 17). Consequently, the relationship between risk, age and sex for these two examinations, as shown in Figures 3a and 3c, closely resembles that for ‘other’ organs shown in Figure 2a, where young males are at higher risk than young females.

6.2 Risks of radiation-induced heritable effects

The risk coefficient for heritable effects of 0.5% per Gy from Section 4 has been multiplied by the typical gonadal doses from Tables 10, 13 and 18 to provide the risks of heritable effects for male and female patients of reproductive potential, for those complete x-ray examinations that involve significant gonadal doses. The results are shown in Table 21 for 12 such examinations. The risks are assumed to be independent of patient age for those of reproductive capacity and naturally fall to zero for patients beyond their reproductive years.

TABLE 21 Typical risk of radiation-induced heritable effects for patients of reproductive potential for complete x-ray examinations involving significant gonad doses

	Risk of heritable effects (per million, 10^{-6})	
Examination	Female	Male
Lumbar spine	5.0	0.09
Abdomen	3.2	0.75
Pelvis	2.6	11
Single Hip	0.90	3.8
Both Hips	0.75	11.5
Barium follow	13	1.1
Barium enema	29	35
Femoral angiography	30	4.9
CT Chest	0.8	0.02
CT Abdomen	39	0.6
CT Abdomen + Pelvis	62	7
CT Chest + Abdomen + Pelvis	54	2.7

For female patients the risks are highest for CT examinations of the abdomen and pelvis, followed by femoral angiography and barium enemas. For male patients the highest risk arises from barium enemas. However for none of these relatively high gonad dose examinations does the typical risk exceed 1 in 15,000 for males or females. In contrast, the natural incidence of significant congenital defects in the UK population is about 1% - 3% (NRPB, 1993).

7 RELATIONSHIP BETWEEN LIFETIME CANCER RISK AND EFFECTIVE DOSE FOR COMMON X-RAY EXAMINATIONS

As stated in the Introduction (Section 1), it is common practice to use the ICRP concept of effective dose when assessing the radiation risks associated with medical x-ray examinations. Such estimates of E for a particular medical x-ray examination have been frequently converted to radiation risks using the nominal probability coefficients for fatal cancer or aggregated detriment (with or without the risk of severe hereditary disorders), as given in *ICRP Publication 60* (ICRP, 1991) or *ICRP Publication 103* (ICRP, 2007). The serious limitations of this approach to risk assessment for medical exposures are discussed in Section 1. However, it remains the case that considerable effort is being devoted on a worldwide scale to calculating effective doses for medical x-ray procedures and in recent years these will have been increasingly in terms of E-103 (the *ICRP Publication 103* definition of effective dose). Therefore we have divided the age and sex specific radiation-induced cancer risks for each of the x-ray examinations shown in Table 20 by the corresponding effective dose (E-103) for the examination, to derive new age and sex specific risk coefficients expressing the total lifetime cancer risk per unit effective dose for each examination. The results are shown in Table 22 for all

the examinations in Table 20 (except those of the knee and foot for which the cancer risks are insignificant).

TABLE 22 Total lifetime cancer risk per unit effective dose as function of age at exposure and sex for 18 types of x-ray examination (% per Sv)

		Age at exposure (y)									
Examination	Sex	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
Head	M	17	12	8.7	6.4	4.7	3.2	1.8	0.9	0.4	0.0
(AP+PA+Lat)	F	16	11	7.8	5.4	4.2	2.7	1.5	0.7	0.3	0.0
Cervical spine	M	9.1	6.2	4.1	2.8	2.0	1.3	0.8	0.4	0.2	0.0
(AP+Lat)	F	20	12	7.2	4.2	2.6	1.6	1.0	0.5	0.2	0.0
Chest	M	8.7	7.4	6.2	5.5	5.0	4.3	3.2	2.0	0.9	0.1
(PA)	F	13	11	9.6	8.8	8.6	7.5	5.7	3.5	1.3	0.0
Thoracic spine	M	7.8	6.4	5.2	4.6	4.1	3.4	2.5	1.6	0.7	0.0
(AP+Lat)	F	17	13	11	8.8	7.8	6.5	4.8	2.9	1.1	0.0
Abdomen	M	13	10	8.1	6.4	4.9	3.5	2.2	1.1	0.4	0.0
(AP)	F	12	9.2	7.3	5.8	4.5	3.3	2.2	1.2	0.4	0.0
Pelvis	M	11	8.8	7.0	5.7	4.5	3.3	2.1	1.1	0.4	0.0
(AP)	F	8.4	6.8	5.5	4.5	3.6	2.7	1.8	1.0	0.4	0.0
Lumbar spine	M	12	9.4	7.2	5.7	4.4	3.1	1.9	1.0	0.4	0.0
(AP+Lat)	F	11	8.6	6.8	5.3	4.3	3.1	2.0	1.1	0.4	0.0
IVU	M	12	9.8	7.6	6.0	4.5	3.2	2.0	1.0	0.3	0.0
	F	11	9.0	7.1	5.6	4.3	3.1	2.0	1.1	0.4	0.0
Ba swallow	M	8.3	6.3	4.8	3.8	3.0	2.3	1.6	1.0	0.4	0.0
	F	19	13	9.5	7.0	5.4	4.0	2.8	1.7	0.6	0.0
Ba follow	M	13	10	8.0	6.3	5.0	3.6	2.3	1.2	0.5	0.0
	F	11	8.7	6.9	5.5	4.7	3.3	2.1	1.1	0.4	0.0
Ba enema	M	12	9.6	7.5	6.1	4.9	3.7	2.3	1.3	0.5	0.0
	F	9.2	7.4	6.0	4.8	4.3	3.0	2.0	1.1	0.4	0.0
Coronary	M	8.6	7.5	6.4	5.9	5.5	4.8	3.7	2.4	1.0	0.1
angiography	F	11	10	9.5	9.2	9.4	8.6	6.8	4.3	1.7	0.0
Femoral	M	12	9.9	7.4	6.1	5.0	3.8	2.5	1.4	0.6	0.1
angiography	F	9.4	7.5	6.1	4.9	4.7	3.2	2.0	1.1	0.4	0.0
CT head	M	18	14	9.5	7.3	5.7	4.1	2.6	1.4	0.6	0.1
	F	13	9.9	7.5	5.5	5.1	3.3	1.9	1.0	0.3	0.0
CT chest	M	8.0	6.6	5.3	4.6	4.0	3.3	2.4	1.5	0.6	0.0
	F	17	13	10	8.5	7.3	6.0	4.4	2.6	1.0	0.0
CT abdomen	M	12	9.4	7.2	5.6	4.3	3.1	1.9	1.0	0.4	0.0
	F	11	8.5	6.7	5.3	4.3	3.1	2.0	1.1	0.4	0.0
CT abdomen +	M	13	10	7.8	6.2	4.9	3.5	2.2	1.2	0.4	0.0
pelvis	F	11	8.9	7.1	5.6	4.7	3.4	2.2	1.2	0.4	0.0
CT chest +	M	9.6	7.8	6.2	5.2	4.3	3.4	2.4	1.4	0.6	0.0
abdo + pelvis	F	15	11	9.1	7.4	6.3	5.0	3.6	2.1	0.8	0.0

It should be noted that our previous assumption that children receive the same organ doses as adults when calculating absolute levels of risk in Section 6, will have no influence on the risk coefficients (risk per unit E) calculated in this Section, since the same doses appear in the numerator and the denominator.

These new age and sex specific risk coefficients for cancer incidence for different x-ray examinations can be compared with ICRP's nominal risk coefficients for aggregated detriment that are averaged over all ages and both sexes and apply to uniform whole-body irradiation. For example, Table 23 shows a comparison between the range in risk per E (over both sexes and all examinations) for 3 particular age bands and ICRP's nominal risk coefficients for detriment-adjusted cancer (ICRP, 2007).

TABLE 23 Comparison between age and sex specific risk coefficients for cancer incidence for x-ray examinations (present work) and ICRP nominal risk coefficients for detriment-adjusted cancer (ICRP, 2007)

Source of data	Scope of data	Population	Risk/E
Present work (Table 22)	Range in risk/E for both sexes and all examinations	0 – 9 y	7.8 – 20 % per Sv
		30 - 39 y	2.8 – 9.2 % per Sv
		60 – 69 y	0.8 – 6.8 % per Sv
ICRP Publication 103 (ICRP, 2007)	Nominal risk coefficient for detriment-adjusted cancer	Whole	5.5 % per Sv
		Adult	4.0 % per Sv

The average age of men in the Euro-American population that was used to derive the present risk coefficients is 35.6 years and the average age of women is 38.7 years, so the risk coefficients shown for the 30-39 year age band are most appropriate for comparison with the ICRP nominal risk coefficients for the whole population. Despite the fact that ICRP's nominal risk coefficient is for detriment-adjusted cancer, it lies in the middle of the range seen for the risk of cancer incidence (with no modification for severity or years of life lost) in the 30-39 age band for both sexes and all examinations. However, for a particular age band, sex and examination, the risk coefficient can vary from this 'nominal' value by up to a factor of ten.

The data in Table 22 are illustrated graphically in Figure 4, where risk coefficient versus age at exposure curves are plotted for male and female patients, separately, for all 18 examinations. We have also included, for comparison, the data from Figure 1 showing the variation in risk per unit dose with sex and age at exposure for all radiation-induced cancers following uniform whole body irradiation. Since 19 curves are shown in Figure 4, the stepped graphs of Figures 1-3 have been replaced by smooth curves linking the centre point of each age band, to improve clarity.

It can be seen from Figure 4 that, although the shapes of the risk coefficient versus age at exposure curves for each gender do vary between the different x-ray examinations, they are fairly symmetrically distributed around the corresponding curve for uniform whole body exposure.

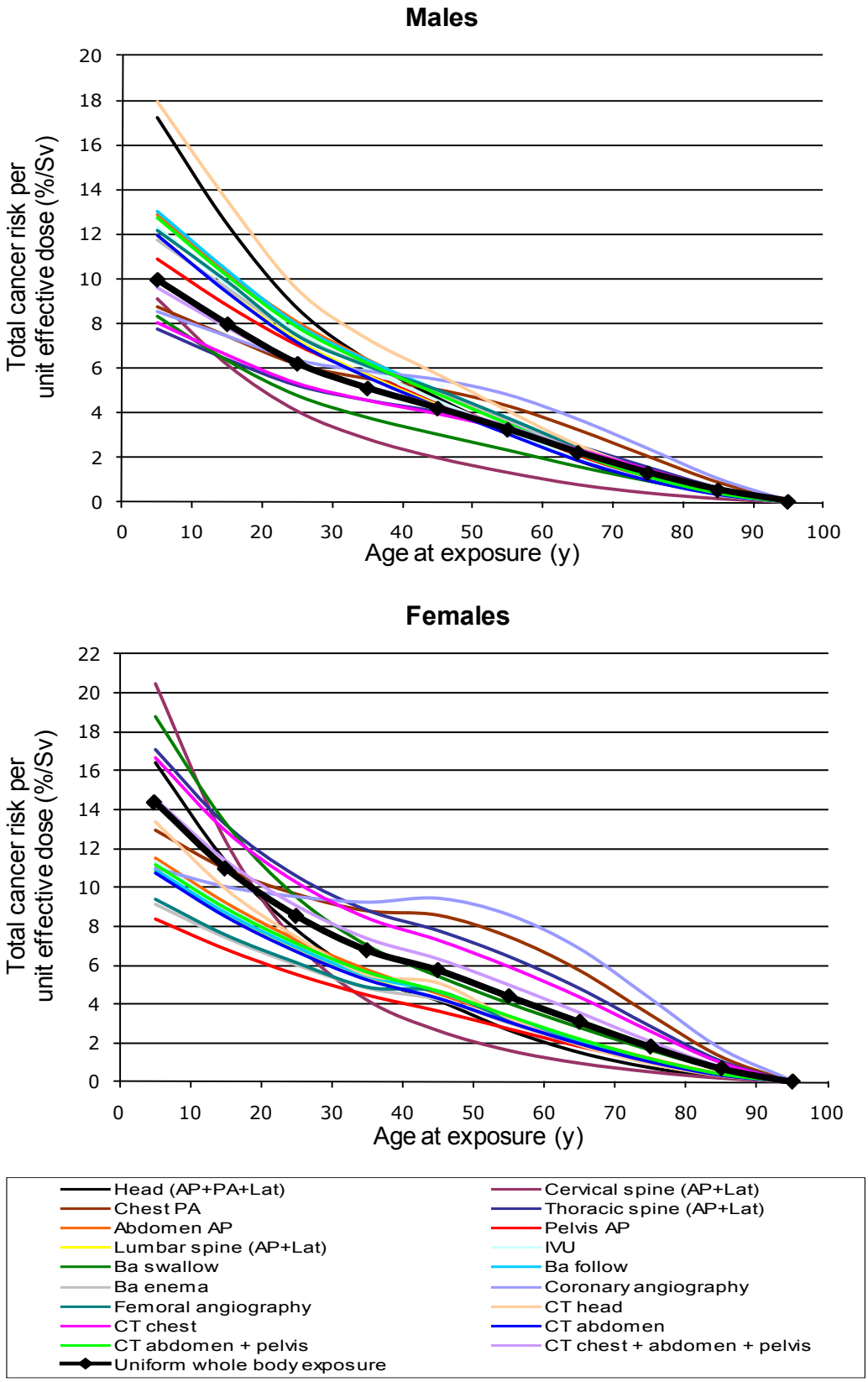

FIGURE 4 Total lifetime cancer risk per unit effective dose as a function of age at exposure and sex for 18 x-ray examinations and for uniform whole body exposure

For male patients, there are two examinations where the risk coefficient versus age curves lie appreciably above the uniform whole-body exposure curve at low ages (<25 years): Head (AP+PA+Lat) and CT Head. There are two more where it lies appreciably higher at ages above 55 years: Coronary angiography and Chest PA. There is also one examination where the curve lies appreciably below that for uniform whole-body exposure at ages above 40 years: Cervical spine (AP+Lat). For all other examinations on male patients, the risk coefficients lie within ±50% of those for uniform whole-body exposure at all ages, as can be seen from Figure 5, where the percentage difference between the risk coefficients for each examination and that for uniform whole-body exposure are plotted as a function of age for male patients. Differences larger than 50% in the last age band (90-100 years) can be ignored as there are large uncertainties in the risk models above 90 years of age (due primarily to a paucity of baseline cancer rate data after 90 years) and the actual risk coefficients are very low for this age band.

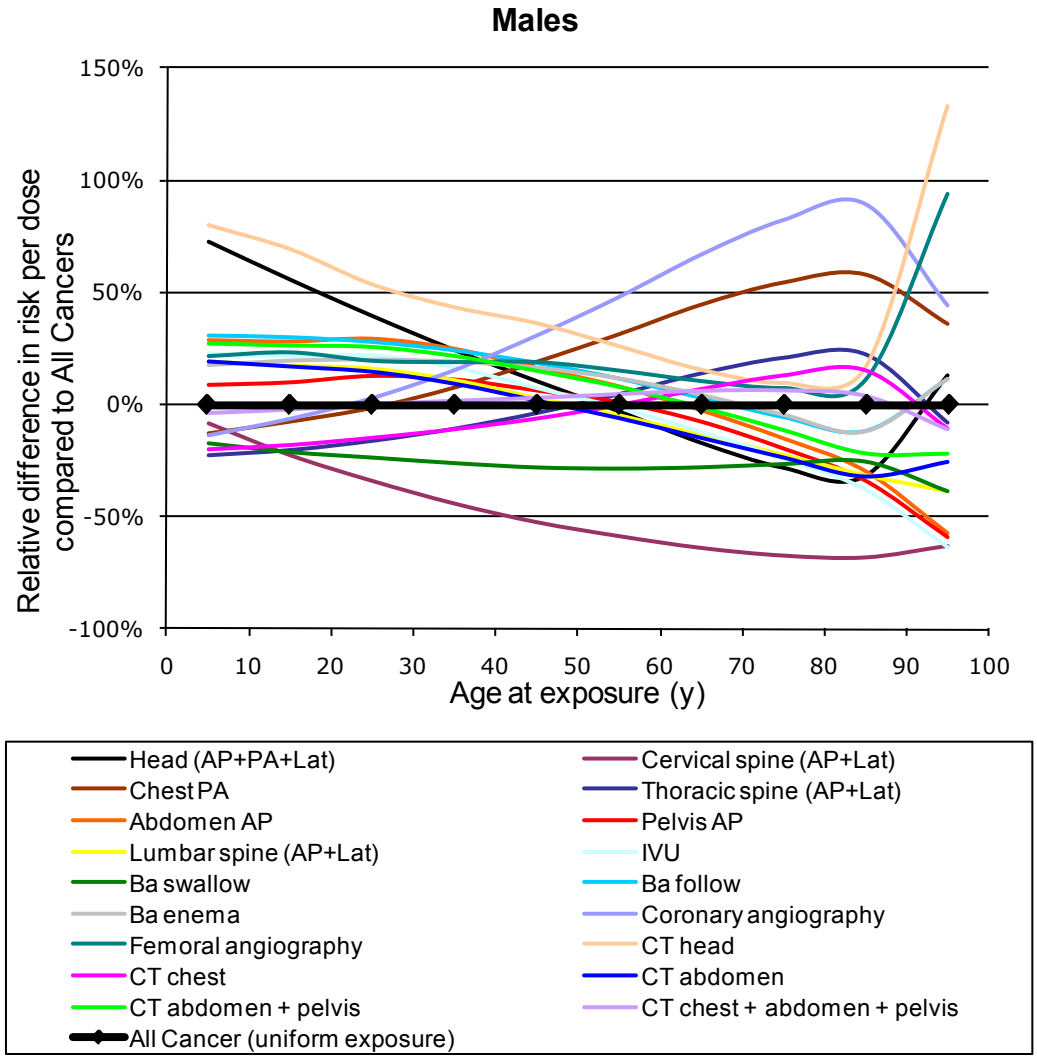

FIGURE 5 Percentage difference in risk coefficient for each examination and uniform whole-body exposure as function of age for male patients

For female patients, there are two examinations where the risk coefficient versus age curves lie appreciably above the uniform whole-body exposure curve for ages above 40 years: Coronary angiography and Chest PA. There is one that lies appreciably below for all ages above 40 years: Cervical spine (AP+Lat). Differences of slightly larger than 50% also occur for the Head (AP+PA+Lat), CT Head and Thoracic spine (AP+Lat) examinations between 60 and 90 years of age. For all other examinations on female patients, the risk coefficients lie within ±50% of those for uniform whole-body exposure at all ages, as can be seen from Figure 6, where the percentage difference between the risk coefficients for each examination and that for uniform whole-body exposure are plotted as a function of age for female patients.

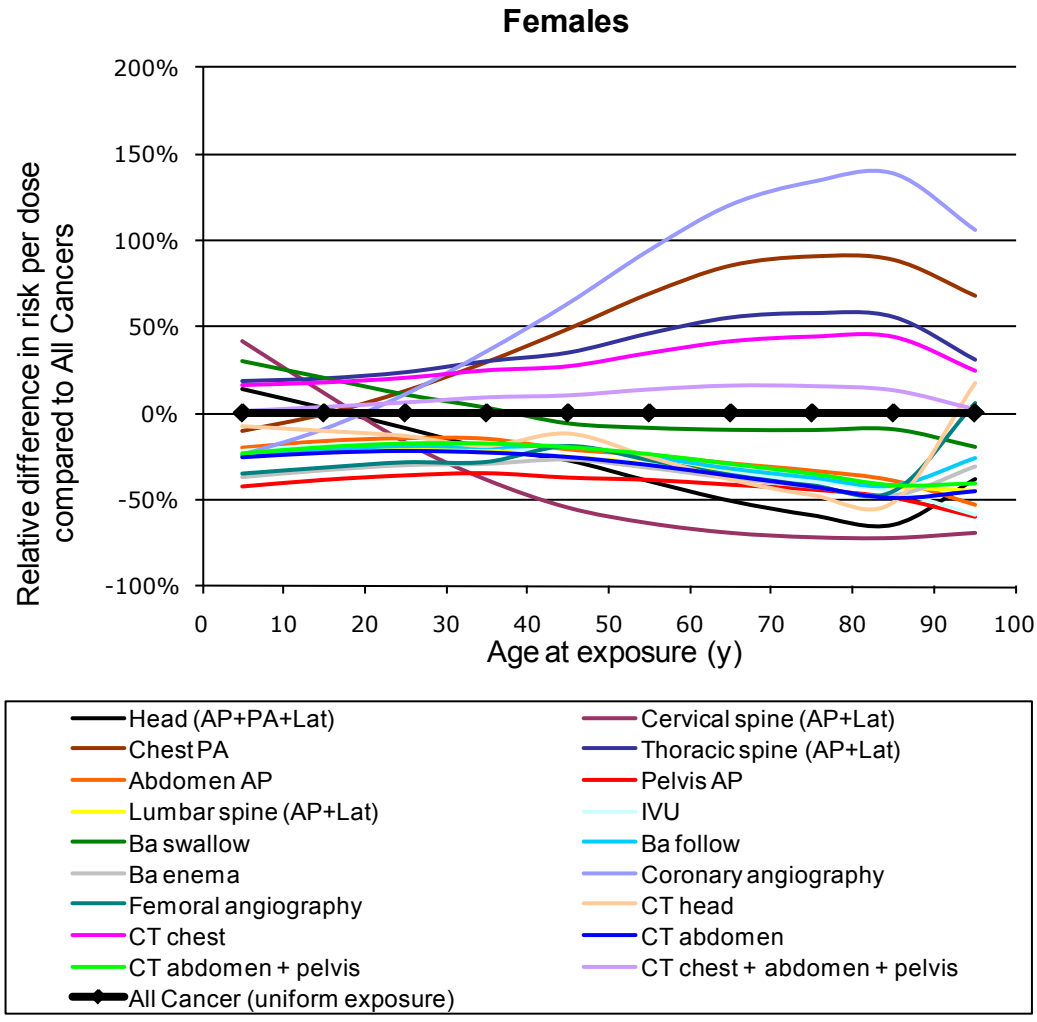

FIGURE 6 Percentage difference in risk coefficient for each examination and uniform whole-body exposure as function of age for female patients

A system is described in Section 9.3 of the Discussion that allows for these apparent differences in the trends with age and sex of the risk coefficients for examinations that take place in the head, neck or chest regions compared to other examinations that are mainly in the abdominal/ pelvic region.

8 RELATIONSHIP BETWEEN ADULT AND PAEDIATRIC DOSES FOR COMMON X-RAY EXAMINATIONS

The levels of radiation-induced cancer risk for children from different types of x-ray examination presented in Section 6 are based on the assumption that children receive the same organ doses as adults. It might be expected that if full optimisation of the exposure conditions to the size of the patient is practiced, the organ and effective doses would be lower for young children than for adults. To a first approximation (without considering, for example, whether higher spatial resolution in the images might be necessary to visualise the smaller anatomical details in children, and also differences in tissue contrast), the optimum exposure conditions for children would be those that result in the same level of radiation dose to the image receptor as for adults. With less attenuation of the x-ray beam through their smaller bodies, lower entrance doses can be used for babies and young children than for adults, while still maintaining the same exit dose and hence the same dose to the image receptor. However the organ doses will not be reduced to the same extent as the entrance doses, depending on their depth in the body, with those near the exit surface being less reduced than those near the entrance surface. So although significantly lower ESD and DAP values can be used for young children while maintaining similar image quality as for adults, the organ and effective doses will not be reduced to the same extent.

The extent to which optimisation of patient protection is practised in paediatric radiology appears to be very variable around the UK, with specialised paediatric hospitals often achieving far lower patient doses for the children in their care than general hospitals. For example, a recent review of the DAP values used for three common fluoroscopic examinations on children at Great Ormond Street Hospital, London (Hiorns et al, 2006) showed substantially lower doses (by factors of between 5 and 25) than those reported for children of similar ages in the 2000 review of the NPDD (Hart et al, 2002), which included data for children from about 20 hospitals, less than half of which were specialised paediatric hospitals. There also appears to be considerable variation between different imaging modalities in the extent to which paediatric doses have been reduced below adult doses, with CT notably failing in this regard compared to more conventional imaging systems, at least up until a few years ago.

In an attempt to get some feel of the likely differences in doses received by children and adults, we have looked at some available UK data on doses to children of different ages and to adults for three types of x-ray examination: simple radiographic examinations, more complex examinations involving radiography and fluoroscopy, and CT examinations.

For three simple radiographic examinations of the chest, abdomen and pelvis/hips, we have used the paediatric patient dose data published in '*Guidelines on Best Practice in the X-ray Imaging of Children'* (Cook et al, 1998). Patient doses (in term of ESD and DAP) were measured on children in five age groups from newborn to 15 years old, undergoing these examinations at Queen Mary's Hospital for Children, Carshalton, following the best practice guidelines advocated in the document. These doses are consequently representative of the lowest doses that were being delivered to children from these examinations in the UK in the late 1990s. The DAP values (and tube voltage values) quoted in the guidelines document for the five age groups have been interpolated to match five discrete ages (0, 1, 5, 10 and 15 years) and are shown in Table 24. The relationship between DAP values that are measured in the x-ray beam as it enters the patient and organ doses inside the patient will depend on the position of the organ and the amount of attenuation of the x-ray beam as it passes through the child. The attenuation is a function of the size of the child and the x-ray spectrum (mainly determined by the tube voltage), and we have used the effective dose to provide an indication of the average effect of organ position. E-60/DAP coefficients are available in report NRPB-R279 (Hart et al, 1996) for children of typical size corresponding to each of the 5 ages, as a function of tube voltage, total filtration (which we shall assume to be equivalent to 3 mm Al in all cases) and type of x-ray examination. The appropriate coefficients from NRPB-R279 for each age and examination are also shown in Table 24, followed by the calculated effective doses and the ratio of the effective dose at each paediatric age to that for adult patients for the same examination, which is shown in the last column of the Table (using data on adult doses from this report).

Table 24 Doses to children and adults for three simple radiographic examinations

Examination	Age (y)					
	0	1	5	10	15	Adult
Chest AP/PA	(AP)	(PA)	(PA)	(PA)	PA)	(PA)
Tube voltage (kV)	70	73	75	80	80	86
DAP (Gy cm^2)	0.003	0.005	0.01	0.02	0.04	0.09
E-60/DAP (mSv/Gy cm^2)	2.2	0.58	0.41	0.28	0.16	0.15
E-60 (mSv)	0.007	0.003	0.004	0.006	0.006	0.014
E-60(age)/E-60(adult)	**0.5**	**0.2**	**0.3**	**0.4**	**0.4**	**1.00**
Abdomen AP						
Tube voltage (kV)	60	60	80	80	85	75
DAP (Gy cm^2)	0.005	0.02	0.05	0.2	0.6	2.2
E-60/DAP (mSv/Gy cm^2)	2.0	0.91	0.64	0.40	0.28	0.20
E-60 (mSv)	0.01	0.02	0.03	0.08	0.17	0.44
E-60(age)/E-60(adult)	**0.02**	**0.05**	**0.07**	**0.18**	**0.39**	**1.00**
Pelvis/hips AP						
Tube voltage (kV)	60	60	70	75	80	71
DAP (Gy cm^2)	0.003	0.01	0.10	0.3	0.5	1.9
E-60/DAP (mSv/Gy cm^2)	2.2	1.1	0.60	0.28	0.21	0.22
E-60 (mSv)	0.007	0.01	0.06	0.08	0.11	0.42
E-60(age)/E-60(adult)	**0.02**	**0.02**	**0.14**	**0.19**	**0.26**	**1.00**

E-60/DAP data from report NRPB-R279 (Hart et al, 1996)

It is interesting to note that for all three examinations in Table 24 the effective dose for a 15 year old ‘child’ is less than half that shown for an adult, despite them being of similar stature. This probably reflects the greater attention given to patient protection for even older children in a specialised paediatric hospital following best practice guidelines, compared to that given to adults in general hospitals. For chest examinations, the ratio of child to adult doses ranges from 0.4 to 0.2 in moving from a 15 year old to a 1 year old child, and increases to 0.5 for a newborn baby because the projection changes from PA to AP for these very young patients. On average, doses to children aged 0-9 years old (the first age band in our risk calculations) are about 35% of those for adults. Doses to 10-19 year olds (the second age band in our risk calculations) are about 40% of those for adults for a simple radiographic chest examination. For the abdomen and pelvis/hip examinations, doses for 0-9 year olds are about 5% of those for adults, whereas doses for 10-19 year olds are about 25% of adult values.

For three more complex examinations involving radiography and fluoroscopy, we have used paediatric patient dose data for micturating cystourethrography (MCU), barium meal and barium swallow examinations from the 2005 review of the NPDD (Hart et al, 2007). About 40 hospitals contributed paediatric dose data for these examinations and only about 15% of them were specialised paediatric hospitals, so the doses will be more representative of general practice in the UK in the early 2000s. The mean DAP values for these three examinations as a function of patient age are shown in Table 25. Approximate E-60/DAP coefficients have been taken from report NRPB-R279 (Hart et

al, 1996) under the following assumptions: coefficients for PA urinary bladder radiographs are appropriate for MCUs; PA abdomen radiographs for barium meals; and AP chest radiographs for barium swallows. The same tube voltages as a function of patient age for Pelvis/hips AP, Abdomen AP and Chest AP/PA as shown in Table 24 were used for MCUs, barium meals and barium swallows, respectively. The appropriate E-60/DAP coefficients are also shown in Table 25, followed by the calculated effective doses and the ratio of the effective dose at each paediatric age to that for adult patients for the same examination, which is shown in the last column of the Table (using data from this report).

TABLE 25 Doses to children and adults for three examinations involving radiography and fluoroscopy

Examination	Age (y)					
	0	1	5	10	15	Adult
MCU						
DAP (Gy cm^2)	0.27	0.48	0.74	1.2	1.9	9.3
E-60/DAP (mSv/Gy cm^2) (as for PA urinary bladder)	1.28	0.64	0.46	0.32	0.20	0.20
E-60 (mSv)	0.35	0.31	0.34	0.38	0.38	1.9
E-60(age)/E-60(adult)	**0.18**	**0.16**	**0.18**	**0.20**	**0.20**	**1.00**
Barium meal						
DAP (Gy cm^2)	0.38	0.77	0.85	2.0	3.5	10
E-60/DAP (mSv/Gy cm^2) (as for PA abdomen)	1.37	0.54	0.41	0.26	0.17	0.15
E-60 (mSv)	0.52	0.42	0.35	0.52	0.60	1.5
E-60(age)/E-60(adult)	**0.35**	**0.28**	**0.23**	**0.35**	**0.40**	**1.00**
Barium swallow						
DAP (Gy cm^2)	0.53	0.86	0.86	2.3	2.5	6.4
E-60/DAP (mSv/Gy cm^2) (as for AP chest)	2.20	0.98	0.57	0.40	0.27	0.25
E-60 (mSv)	1.2	0.84	0.49	0.92	0.68	1.6
E-60(age)/E-60(adult)	**0.75**	**0.53**	**0.31**	**0.58**	**0.43**	**1.00**

E-60/DAP data from report NRPB-R279 (Hart et al, 1996)

Again, it is interesting to note that for all three examinations in Table 25, the effective dose for a 15 year old ‘child’ is less than half that shown for an adult, despite them being of similar stature and despite the sample of hospitals supplying the data containing few that were specialised in paediatrics. The ratio of child to adult doses ranges from about 0.2 to 0.8 for all three examinations. On average, doses to children in both our younger age bands (0-9 and 10-19 years old) are about 20% of those for adults for MCU examinations, 35% for barium meal examinations and 50% for barium swallow examinations.

For two common CT examinations that are carried out on children and adults (CT chest and CT head), we have used patient dose data from the most recent (2003) HPA review of doses from CT in the UK, published in report NRPB-W67 (Shrimpton et al, 2005). The equivalent patient dose quantity to DAP for CT examinations is the dose-length product (DLP) and the values given for 0-1, 5 and 10 year old patients undergoing CT chest and CT head examinations in NRPB-W67 are shown in Table 26. E-60/DLP

coefficients for these examinations as a function of patient age are also given in NRPB-W67 (Shrimpton et al, 2005), and the appropriate coefficients for each CT examination and age are also shown in Table 26, followed by the calculated effective doses and the ratio of the effective dose at each paediatric age to that for adult patients for the same examination, which is shown in the last column of the Table (using data from this report).

TABLE 26 Doses to children and adults from two common CT examinations

	Age (y)					
CT examination	0	1	5	10	15	Adult
CT Chest						
DLP (mGy cm)	160[a]	160[a]	200[a]	300[a]	-	400[b]
E-60/DLP[c] (mSv/mGy cm)	0.033[a]	0.033[a]	0.018[a]	0.013[a]	-	0.014[b]
E-60	5.3	5.3	3.6	3.9	-	5.6
E-60(age)/E-60(adult)	**0.95**	**0.95**	**0.64**	**0.70**	**-**	**1.00**
CT Head						
DLP (mGy cm)	230[a]	230[a]	380[a]	510[a]	-	690[a]
E-60/DLP[c] (mSv/mGy cm)	0.0088[a]	0.0088[a]	0.0040[a]	0.0032[a]	-	0.0021[a]
E-60	2.0	2.0	1.5	1.6	-	1.5
E-60(age)/E-60(adult)	**1.3**	**1.3**	**1.0**	**1.1**	**-**	**1.00**

[a] Referred to measurements in the 16 cm diameter CT dosimetry phantom.
[b] Referred to measurements in the 32 cm diameter CT dosimetry phantom.
[c] E-60/DLP data from report NRPB-W67 (Shrimpton et al, 2005).

For these two CT examinations, there is little indication of a reduction in effective doses to children compared to adults, indeed doses for CT head scans on neonates appear to be higher. These doses are based on a review of CT practice in the UK conducted in 2003, at a time when the world was slowly becoming aware of the radiation protection problems associated with paediatric CT (although the UK has for many years been at the forefront of developments in patient protection (NRPB, 1990; Shrimpton and Wall, 2000)). In the USA prior to 2000, the vast majority of CT examinations on children were conducted using similar techniques and exposure factors to those used for adults, resulting in effective doses to the smallest children that could be as much as three times higher than the adult doses. By 2011, a number of national and international initiatives have evolved aimed at optimising the protection of children having CT scans. In particular, the *Image Gently* campaign in the USA [www.imagegently.org] now provides extensive guidance on how to reduce paediatric CT doses, including recommended CT examination protocols for children that are designed to result in similar image quality and patient doses as for adults. So it is likely that the situation in the USA is now similar to that seen in the UK in 2003, with CT doses to young children being of a comparable size to those for adults. With the intense interest and resources being devoted to patient dose reduction in CT over the past few years, it is likely that the relationship between paediatric and adult CT doses will become more in line with that seen for the longer established conventional imaging modalities in the near future.

DISCUSSION

In this report we have evaluated the radiation risks from medical x-ray examinations as a function of the age and sex of the patient in terms of the lifetime risk of radiation-induced cancer to the patient and the risk of deleterious heritable effects appearing in the progeny of the patient, separately. We have used the risk models described in *ICRP Publication 103* (ICRP, 2007) to calculate the probability of these effects occurring, but have not taken account of their lethality or severity. Such considerations have been omitted in view of the unavoidably subjective judgements involved and the limited relevance of 'radiation detriment' (as developed by ICRP for the control of occupational and public exposures) when assessing risks to patients.

9.1 Risk of radiation-induced cancer

Radiation-induced bone and skin cancer were omitted from our calculations (primarily due to lack of suitable data from the LSS of atomic bomb survivors) but this will not have a significant impact on our estimates of the total cancer risk; the same approach was adopted by the BEIR VII committee (BEIR VII, 2006). We obtained very good agreement between our calculations and those of ICRP for the risk averaged over all ages and both sexes for 9 of the 11 cancer sites considered. The reasons for the present disagreement by up to 50% for the other 2 cancer sites (red bone marrow and thyroid) still remain unresolved, even after thorough investigation. However, these discrepancies are unlikely to have a significant impact on our estimates of the total cancer risk and the way it varies with the age and sex of the patient.

When all organs receive the same dose (uniform whole-body exposure), our calculations predicted a total cancer risk of about 12% per Gy in the 0-9 year age group, with a steady rate of decrease with age (approximately a factor of two for every 30 years) and with females at higher risk than males (by 27 - 44%) at all ages (as shown in Figure 1). It is interesting to compare these HPA (ICRP) predictions of the total cancer risks following uniform exposure with those predicted by the BEIR VII risk model (BEIR VII, 2006). Both are plotted in Figure 7 as a function of age and sex, with the risks averaged over the same age groups as in Figure 1. It can be seen that the risks are lower for our calculations using the ICRP risk model and baseline cancer rates for a Euro-American population, with the differences between the sexes less and the rate of decrease in risk with age less pronounced over the lower age bands than predicted by the BEIR VII risk model in relation to an American population. In particular, the risk coefficients predicted by the BEIR VII model for the 0-9 year age band are higher by a factor 1.8 than the ICRP estimates for male patients and higher by a factor 2.4 for female patients; for the 30-39 year age band, the corresponding factors are 1.3 and 1.4. The BEIR VII risks are expected to be generally about 33% higher than the HPA (ICRP) risks owing to differences in DDREF, with assumed values of 1.5 and 2, respectively, for these models. There will also be some influence from the different assumed reference populations and baseline cancer rates (American for BEIR VII and Euro-American for HPA models). The larger differences seen over the lower age bands are

presumably due to differences in the models chosen to fit what are essentially the same epidemiological data from the Japanese LSS and their projection to an American or Euro-American population. The BEIR VII model includes cancer of the prostate and uterus, and omits oesophageal cancer (see Appendix A), but these are all relatively low risk organs for radiation-induced cancer and are unlikely to have a significant impact on the shape of the total cancer risk curves shown in Figure 7. These substantial differences seen between the HPA (ICRP) and BEIR VII risk estimates, particularly for low ages at exposure, serve to highlight the large uncertainties associated with the different assumptions that are made when trying to describe sparse epidemiological data by mathematical equations. We have adopted the ICRP model as being the most appropriate one to use in the context of this report since it is the one that has been used to develop the concept of effective dose, which we use to derive practical risk coefficients for x-ray examinations.

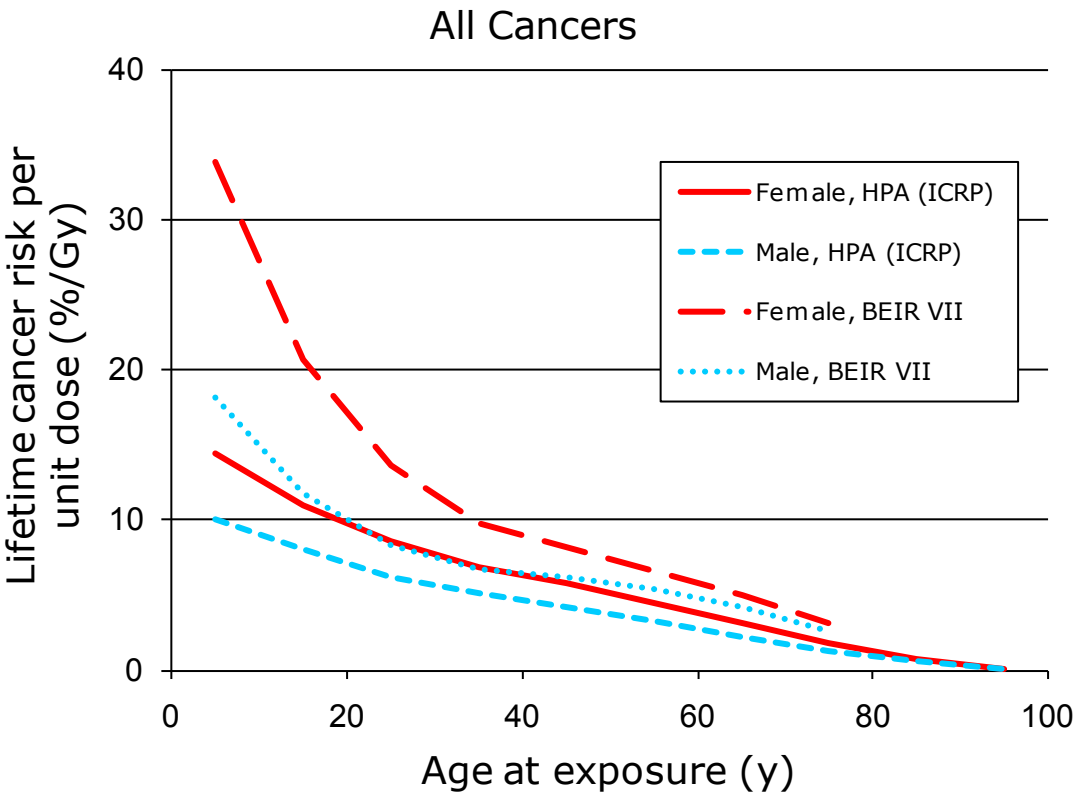

FIGURE 7 Lifetime risk of cancer incidence by age and sex for all cancers following uniform whole-body irradiation according to HPA (ICRP 103) and BEIR VII risk models

Considering the variation in risk as a function of age and sex for individual cancer sites, our calculations show a steady decrease in risk with age at exposure for most of the cancer sites. The rates of the decrease with age over the first 4 or 5 age bands (up to

age 60) were seen to be particularly high for breast cancer and thyroid cancer in females.

The steep decrease with age for breast cancer could have important implications for mammography used in breast cancer screening. Previous predictions of the radiation risks involved in the UK breast screening programme (NHSBSP, 2003) were based on the risk models described by NRPB (1993). The risks predicted for young girls in this 1993 NRPB model were similar to those obtained using the *ICRP Publication 103* model (4.3 % per Gy compared to 4.9 % per Gy in this report) but the risks for the two age groups (50-59 and 60-69 years) that include the ages when women are invited into the breast screening programme were 3 and 4 times higher than those that the current *ICRP Publication 103* model predicts. The 1993 NRPB risk model for breast cancer was based on epidemiological data for North American women who had high medical exposures, rather than the Japanese LSS because, at the time, it was considered more appropriate to transfer risks across populations with similar baseline cancer rates. As described in Section 2, the Japanese LSS data for breast cancer has been transferred to the Euro-American population in the *ICRP Publication 103* risk model solely in terms of the EAR to mitigate the problem of the lower baseline breast cancer rates in Japan. The resulting much lower risks predicted for women between 50 and 70 years of age could, if considered reliable, have a major positive impact on the justification of the Breast Screening Programme in the UK, which has traditionally been quantified in terms of the number of cancers induced and detected (NHSBSP, 2003).

The very steep decrease in the risk of thyroid cancer with age for girls (but not for boys) has meant that we have proposed two specific sets of risk coefficients for female and male patients undergoing x-ray examinations of the neck (e.g. cervical spine) in which the dose to the thyroid is likely to exceed the dose to any other radiosensitive organ (see Figure 8 and Table 29 later in Section 9.3 of this Discussion).

A steady decrease in risk with age at exposure was not seen for either sex for cancers of the lung, red bone marrow and oesophagus; the risk actually increases or remains relatively constant up to age 50 years for the first two of these cancers and up to age 80 years for the last. In contrast, the BEIR VII risk model does show a decrease in risk with age for the first two cancers (the oesophagus was not included in the BEIR VII risk model). However, in the context of this report, we shall assume that the *ICRP Publication 103* risk model currently provides the most appropriate fit to the epidemiological data.

Since the total radiation–induced cancer risk varies with age and sex in a way that depends on which organs are irradiated, typical organ doses have been calculated for about 40 types of x-ray examination, as currently carried out on adult patients in the UK. Typical effective doses have also been calculated (according to both *ICRP Publication 60* and *ICRP Publication 103*) for each examination, so that the risks per unit effective dose can be derived for comparison with ICRP's nominal risk coefficients. These calculations are based on patient dose measurements seen in recent large-scale national surveys of radiology practice in the UK, and extensive Monte Carlo modelling of these x-ray examinations on a highly-detailed geometric phantom representing a typical adult patient with 31 separate organs and tissues. The results consequently provide a reliable update of typical organ and effective doses received by patients from

common x-ray examinations in the UK to replace those previously published by NRPB (e.g. Wall and Hart, 1997).

Organ doses were seen to range typically from 1 µGy to muscle for simple radiographs of the foot to 45 mGy to the brain for a CT head scan (see Tables 4, 9, 12 & 17). CT scans through the trunk resulted in maximum doses of about 15 mGy to organs that are completely covered by the scan and some complex fluoroscopic examinations, such as coronary angiography, could also result in organ doses of a similar magnitude. Typical gonadal doses (of interest for the risk of heritable effects) exceeded 1 mGy in only a few types of fluoroscopic examination that involve irradiation of the pelvic area and just exceeded 10 mGy in those CT examinations that include scans through the pelvis (see Tables 5, 10, 13 & 18).

Typical effective doses were found to range from well below 1 µSv for radiographic examinations of the foot or knee, to about 10 mSv for CT examinations of the entire trunk (i.e. chest, abdomen and pelvis) (see Tables 6, 11, 14 & 19). The ratio E-103/E-60 ranged from about 0.5 for radiographic examinations of the pelvis, hips and femur (due to the relatively high gonad doses and the reduced weighting factor for heritable effects in E-103 compared to E-60) to 1.5 for an AP radiograph of the head (due to the inclusion of the highly-irradiated salivary glands, oral mucosa and extrathoracic airways in E-103). For most other types of x-ray examination studied in this report, E-103 values were within 20% of E-60 values and for about half of them the difference was less than ±10%. The change to E-103 from E-60 will consequently have a significant impact for only a few types of x-ray examination and it did not lead to a substantial difference when recently estimating the collective effective dose from all x-ray examinations in the UK (Hart et al, 2010).

When organ doses for particular x-ray examinations are combined with age and sex specific risk coefficients, the lifetime risks of radiation-induced cancer are seen to fall with patient age for all examinations. However, the slope varies markedly between examinations, as does the magnitude of the risk and the relative risk between men and women. The level of risk typically ranges from less than about 1 in a billion ($<10^{-9}$) for any patient having an x-ray examination of the knee or foot, to over 1 in a 1,000 (10^{-3}) for a young girl having a CT scan of the whole trunk (i.e. chest + abdomen + pelvis) (see Table 20 and Figure 3).

However, the risks for children have been estimated on the assumption that the organ doses they receive from a particular type of x-ray examination are the same as for adults. The relationship between effective doses received by paediatric and adult patients from the same type of x-ray examination was studied and, although little difference could be seen for CT examinations (at least in 2003), there was evidence that for conventional x-ray examinations the effective doses were significantly lower for children compared to adults. When simple radiographic examinations of the abdomen and pelvis were conducted in a specialised paediatric hospital following best practice guidelines, the effective doses to children in the 0-9 year age group were only about 5% of the adult doses and in the 10-19 year age group they were about 25% of the adult doses. Not surprisingly, such large reductions for children were not seen in a sample of about 40 mostly-general hospitals where the mean effective doses for three fluoroscopic examinations were studied. In this situation, doses in both the 0-9 and 10-

19 year age bands were between 20% and 50% of those typically received by adult patients. However, even these more modest reductions in doses to children will be sufficient to offset the increase in cancer risk per unit dose seen for the youngest age band (on average about a factor of 2 higher compared to 30-39 year old adults) for most conventional (non-CT) examinations. For CT examinations, a similar reduction in paediatric doses has not yet been widely reported in the UK, although the intense interest and resources being currently devoted to this problem on a worldwide scale will undoubtedly lead to significant reductions in the doses to children undergoing CT examinations in the near future.

In a previously published information leaflet for patients ("X-rays – how safe are they?" (NRPB et al, 2001)), x-ray examinations were divided into four broad risk bands according to a scheme proposed by the Chief Medical Officer of the Department of Health in 1995 (Department of Health, 1995; Calman,1996):

- Negligible < 1 in a million risk ($<10^{-6}$)
- Minimal 1 in a million – 1 in 100,000 risk ($10^{-6} – 10^{-5}$)
- Very low 1 in 100,000 – 1 in 10,000 risk ($10^{-5} – 10^{-4}$)
- Low 1 in 10,000 – 1 in 1,000 risk ($10^{-4} – 10^{-3}$)

Risks below 1 in a million as a consequence of a health care intervention were considered to be "of little concern for ordinary living", being on a par with the annual chance of being struck by lightning. Radiographic x-ray examinations of the knee and foot are seen typically to involve such 'negligible' risks for patients of all ages and both sexes and the same is likely to be true for all examinations of the distal parts of the arms and legs. Radiographic examinations of the chest and cervical spine also involve 'negligible' risks for patients over about 30 years of age, but just creep into the 'minimal' risk band for younger patients of either sex (see Table 20), if no account is taken of the fact that the actual doses given to children are likely to be lower than those to adults. When this is taken into account, chest examinations remain in the 'negligible' risk band for patients of all ages and both sexes, and cervical spine examinations remain in this band for male patients of all ages but could move into the 'minimal' risk band for young girls.

For all other purely radiographic examinations (apart from IVUs), Table 20 indicates that the risks lie in the 'Very Low' risk band (1 in 100,000 – 1 in 10,000 risk) for all patients below about 70 years of age, and fall into the 'Minimal' or 'Negligible' risk band at higher ages. These examinations could also fall into the 'Minimal' risk band for children (0-19 years old) if doses to children are up to 5 times lower than doses to adults. For IVUs, examinations involving radiography and fluoroscopy, and CT head scans, the typical risks lie in the lower half of the 'Low' risk band (1 in 10,000 – 1 in 1,000 risk) for all patients up to between 20 and 50 years old, depending on the examination and gender, apart from coronary angiography where this level of risk persists to age 70 years for males and 80 years for females. Risks drop into the 'Very Low', 'Minimal' and 'Negligible' risk bands as the patient age increases, and into the 'Very Low' band for children if they receive lower doses than adults, as predicted for all these examinations except CT Head scans. For the other CT examinations, the typical risks lie in the upper half of the 'Low' risk band for younger patients and could exceed a 1 in 1,000 risk for girls having a CT Chest + Abdomen + Pelvis scan, putting them into the next higher risk

band, labelled ‘Moderate’ according to the scheme proposed by the CMO in 1995 (Department of Health, 1995):

- Moderate 1 in 1,000 – 1 in 100 risk (10^{-3} – 10^{-2})

We can update and extend the Table in our previously published leaflet “X-rays – How safe are they?” (NRPB et al, 2001) by placing the x-ray examinations in Table 20 in the appropriate broad risk band according to the total lifetime cancer risk for patients of average age (i.e. in the 30-39 year age band), differentiating when necessary between males and females (i.e. when the risks for male and female patients do not fall into the same risk band). This has been done in Table 27.

TABLE 27 X-ray examinations divided into four broad risk bands for the typical total lifetime cancer risk for patients of average age (30-39 years old)

Examination	Sex	Total lifetime cancer risk (30-39 year age band)
		NEGLIGIBLE RISK
Cervical spine	M	
Chest	M	Less than
Knee	B	1 in a million
Foot	B	
		MINIMAL RISK
Head	B	1 in a million
Cervical spine	F	to
Chest	F	1 in 100,000
		VERY LOW RISK
Thoracic spine	B	
Abdomen	B	
Pelvis	B	1 in 100,000
Lumbar spine	B	to
Ba swallow	M	1 in 10,000
Ba follow	B	
CT head	F	
		LOW RISK
IVU	B	
Ba swallow	F	
Ba enema	B	
Coronary angiography	B	
Femoral angiography	B	1 in 10,000
CT head	M	to
CT chest	B	1 in 1,000
CT abdomen	B	
CT abdomen + pelvis	B	
CT chest + abdomen + pelvis	B	

M = Male, F = female, B = Both (Male and Female)

For younger and older patients (relative to 30-39 years old), the risks might fall into higher or lower risk bands, respectively, as discussed above. These typical risk levels can be compared with the natural baseline lifetime risk of getting cancer in the UK, which currently stands at about 1 in 3.

9.2 Risk of radiation-induced heritable effects

We have taken a rounded value of the risk coefficient in *ICRP Publication 103* (ICRP, 2007) for heritable effects of radiation in the reproductive population (0.5% per Gy of gonadal dose) to indicate the probability of deleterious genetic effects occurring in the progeny of patients undergoing medical exposures. The risks are assumed to be independent of gender or age up until the age for each sex when reproduction becomes unlikely, when the risks obviously fall to zero. No account is taken of the severity or lethality of these heritable effects, but when *ICRP Publication 103* does so the nominal risk coefficient remains substantially unchanged.

Combining this risk coefficient with the typical gonadal doses given in Tables 5, 10, 13 and 18, we found that for no examination did the risk of heritable effects exceed 1 in 15,000 for males or females (see Table 21). Consequently x-ray examinations can be divided into just three broad risk bands for heritable effects, following the same scheme as for lifetime cancer risks above: ‘Negligible’, ‘Minimal’ and ‘Very Low’. This analysis is shown in Table 28. These risk levels can be compared with the natural incidence of significant congenital defects in the UK population of about 1 - 3% (NRPB, 1993; HPA et al, 2009).

TABLE 28 X-ray examinations divided into three broad risk bands for the typical risk of heritable effects for patients of reproductive potential

Examination	Sex	Risk of heritable effects (patients of reproductive potential)
		NEGLIGIBLE RISK
Head (AP+PA+Lat)	B	
Cervical spine	B	
Shoulder	B	
Chest	B	
Thoracic spine	B	
Lumbar spine	M	Less than
Abdomen	M	1 in a million
Single/Both Hips	F	
Femur	B	
Knee	B	
Foot	B	
CT Chest	B	
CT Abdomen	M	
		MINIMAL RISK
Lumbar spine	F	
Abdomen	F	
Pelvis	F	1 in a million
Single/Both Hips	M	to
Ba follow	M	1 in 100,000
Femoral angiography	M	
CT Abdomen + Pelvis	M	
CT Chest + Abdomen + Pelvis	M	
		VERY LOW RISK
Pelvis	M	
Both Hips	M	
Ba follow	F	1 in 100,000
Ba enema	B	to
Femoral angiography	F	1 in 10,000
CT Abdomen	F	
CT Abdomen + Pelvis	F	
CT Chest + Abdomen + Pelvis	F	

M = Male, F = Female, B = Both (Male and Female)

9.3 Relationship between cancer risk and effective dose

As discussed in the Introduction (Section 1), there are serious limitations in using ICRP's nominal probability coefficients for aggregated detriment to convert effective doses into lifetime cancer risks for patients undergoing x-ray examinations. Effective dose was not intended for use to determine risk in this way. However, to enable estimates of effective doses for x-ray examinations to be converted into cancer risk estimates, we have derived specific risk coefficients expressing the total lifetime cancer risk per unit effective dose (E-103) for 18 types of x-ray examination as a function of the age and sex of the patient (see Table 22 and Figure 4). For 13 of the examinations, the curves in Figure 4, showing the risk coefficient versus age at exposure for each gender, lie reasonably close to the corresponding curve for uniform whole body exposure. For the other 5 examinations that irradiate the head, neck or chest regions, the risk coefficients differ by more than 50% from those for uniform whole body exposure over significant parts of the age range for one or both sexes.

It could be argued that in view of the large uncertainties involved in both the estimates of the cancer risk per unit dose and the estimates of the organ and effective doses, differences of less than 50% in the risk coefficients are relatively insignificant. Consequently the age and sex specific risk coefficients for uniform whole body exposure could be taken as a good enough approximation for all x-ray examinations, apart from the five which differ from it by more than 50% (CT Head (male), Head (AP+PA+Lat) (male), Cervical spine (both), Coronary angiography (both) and Chest PA (both)).

However, an alternative approach is to group types of x-ray examination by broad region of anatomy under investigation and derive a set of age- and sex-dependent risk coefficients per unit effective dose for each region based on the average for the appropriate examinations. The results discussed in the previous two paragraphs indicate that in order to reduce differences to <50%, a minimum of four regions would be required, on the basis of the following scheme for grouping examinations:

- Head region (CT Head and Head (AP+PA+Lat));
- Neck region (Cervical spine (AP+Lat));
- Chest region (Chest PA, Thoracic spine (AP+Lat), Coronary angiography and CT chest);
- Abdomen & Pelvis region (Abdomen (AP), Pelvis (AP), Lumbar spine (AP+Lat), IVU, Ba follow, Ba enema, Femoral angiography, CT Abdomen and CT Abdomen + pelvis).

Two of the examinations in Table 22 (Ba swallow and CT chest + abdomen + pelvis) have not been included in any of the above regions because the investigation covers more than one region. For these and other similarly extensive x-ray examinations, it is proposed that the risk coefficients for uniform whole body exposure can be used. The resulting mean risk-coefficient versus age curves for these four anatomical regions and for uniform whole body exposure are shown separately for male and female patients in Figure 8. Numerical values for these ten proposed sets of age- and sex-specific risk coefficients are shown in Table 29.

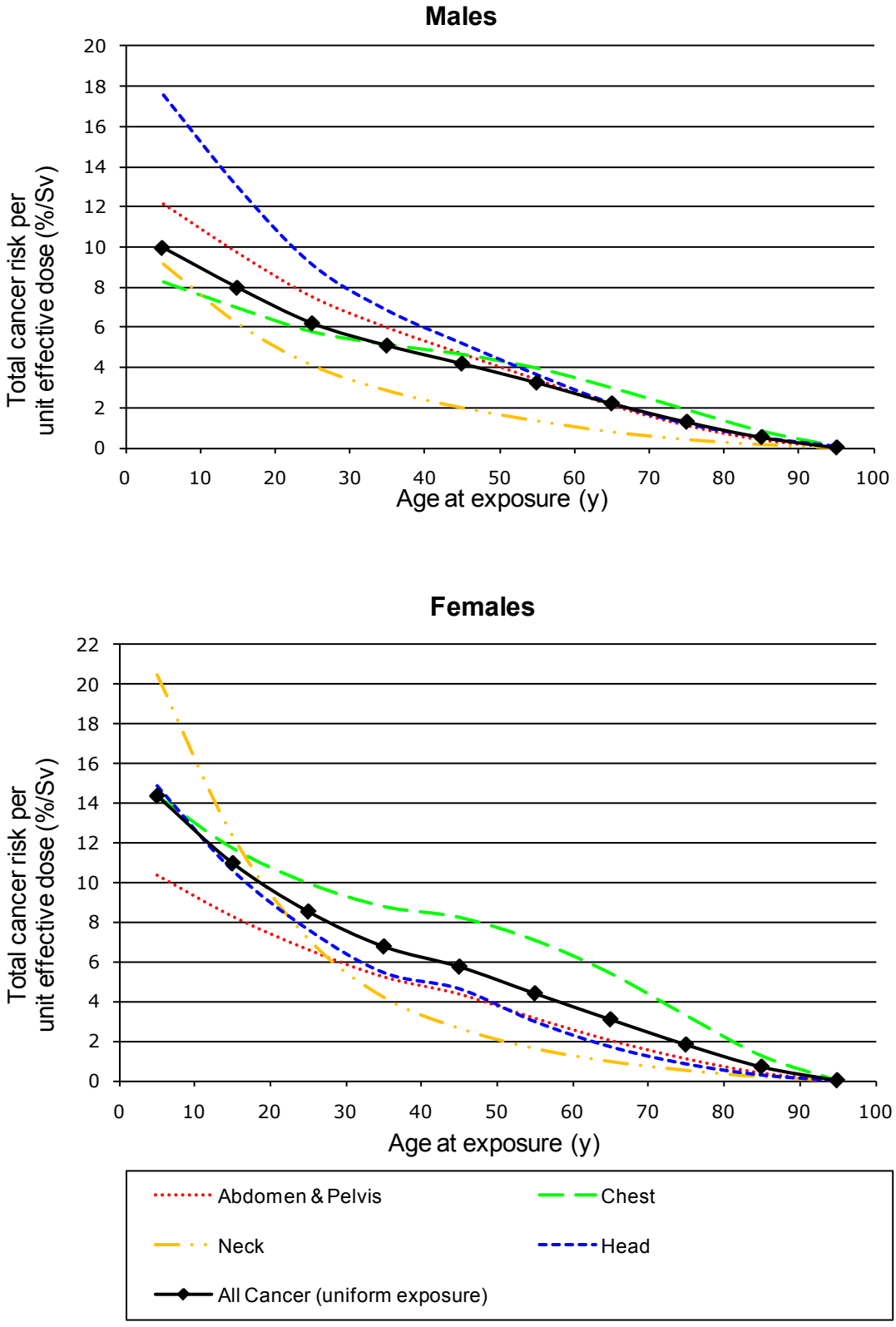

FIGURE 8 Mean total lifetime cancer risk per unit effective dose as a function of age at exposure, sex and anatomical region of examination, in relation to the trend for uniform whole body exposure

TABLE 29 Proposed total lifetime cancer risk per unit effective dose (% per Sv) as a function of age at exposure and sex for x-ray examinations conducted in different of regions of anatomy

Anatomical region	Age group (years)									
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
MALE										
Head	18	13	9.1	6.8	5.2	3.6	2.2	1.2	0.5	0.1
Neck	9.1	6.2	4.1	2.8	2.0	1.3	0.8	0.4	0.2	0.0
Chest	8.3	7.0	5.8	5.1	4.6	4.0	3.0	1.9	0.8	0.0
Abdomen & pelvis	12	9.7	7.5	6.0	4.7	3.4	2.2	1.1	0.4	0.0
Whole body (uniform)	**10**	**8.0**	**6.2**	**5.1**	**4.2**	**3.3**	**2.2**	**1.3**	**0.6**	**0.04**
FEMALE										
Head	15	11	7.6	5.5	4.6	3.0	1.7	0.9	0.3	0.0
Neck	20	12	7.2	4.2	2.6	1.6	1.0	0.5	0.2	0.0
Chest	14	12	10	8.8	8.3	7.1	5.4	3.3	1.3	0.0
Abdomen & pelvis	10	8.3	6.6	5.2	4.4	3.2	2.0	1.1	0.4	0.0
Whole body (uniform)	**14**	**11**	**8.5**	**6.8**	**5.8**	**4.4**	**3.1**	**1.8**	**0.7**	**0.02**

By grouping examinations in this way, specific coefficients for the individual types of x-ray examination now lie within ±30% of the corresponding mean coefficients for the appropriate anatomical region (except for patient ages above 90 years where the numerical values are in any case very low).

It is proposed that these ten sets of risk coefficients listed in Table 29 will be sufficient to cover all types of x-ray examination that expose the head, neck, abdomen and pelvis. There will, of course, be other types of x-ray imaging procedure that we have not considered in this study but which may use very similar x-ray fields and projections to those examinations modelled. For example, coronary angioplasty can involve similar fields of view and projections to coronary angiography (categorised here as 'chest region'), and examinations of the larynx and pharynx can be very similar to cervical spine examinations in this regard ('neck region'). It would be appropriate to use one of these region-specific sets of risk coefficients for any other type of examination where the anatomical area under x-ray investigation was roughly constrained to that particular region of the body. For the more extensive types of x-ray examination that encompass more than one region of the body, it would be more appropriate to use the risk coefficients for uniform whole body exposure. As a first approximation, all other x-ray examinations can also be covered by the sets of age- and sex-dependent risk coefficients for uniform whole body exposure.

For examinations of the distal portions of the limbs, the risks of radiation-induced cancer are generally so low (see Table 20) that the use of age- and sex-specific risk coefficients is irrelevant. For examinations of the proximal portions of the limbs (i.e. hips, upper femur, shoulder and upper humerus), the risk coefficients for uniform whole body exposure can be assumed to be sufficiently appropriate.

These proposed sets of age and sex dependent risk coefficients are considered to provide a practical means for estimating the lifetime cancer risks associated with medical

x-ray examinations, a purpose for which ICRP's nominal risk coefficient for detriment-adjusted cancer (5.5 % per Sv) was not intended. For most x-ray examinations, the risk coefficients for young patients are about twice ICRP's nominal risk coefficient, and for a few specific examinations they can be about three times higher (range in factor: 1.3 to 3.8). Conversely, for patients in their sixties, the risk coefficients for most examinations are about one half of ICRP's nominal risk coefficient (range in factor: 0.15 to 1.2), whereas for patients in their seventies they are less than one third (range in factor: 0.1 to 0.8) and for patients in their eighties they are down to one tenth (range in factor: 0.04 to 0.3).

10 CONCLUSIONS

We have evaluated the radiation risks from medical x-ray examinations as a function of the age and sex of the patient in terms of the lifetime risk of radiation-induced cancer to the patient. We have also separately evaluated the risk of deleterious heritable effects appearing in the progeny of patients who subsequently procreate. The risk models described in *ICRP Publication 103* and recent surveys of patient doses in the UK were used in these evaluations.

The radiation-induced cancer risk was found to vary with patient age and sex in a different manner for different types of x-ray examination, depending on which organs were being irradiated. By dividing the relevant age/sex-specific risks by the effective dose (E-103) for each examination, age/sex/examination-specific risk coefficients were generated and compared. It was found that the risk coefficient for a particular age band, sex and examination could differ from ICRP's nominal risk coefficient for detriment-adjusted cancer that is averaged over all ages and both sexes (5.5% per Sv), by up to a factor of ten. For most, but not all, types of x-ray examination, a single set of age and sex dependent risk coefficients (based on uniform whole body exposure) can provide an adequate approximation (mostly within ±50% of the detailed risk). However, four further general sets of age and sex dependent risk coefficients, relating to examinations conducted in four separate anatomical regions (head, neck, chest and abdomen & pelvis), are proposed to enable pragmatic estimates of risk for such examinations that are more closely matched to the detailed calculations of risk (within ± 30%).

The appropriate selection of one of these proposed risk coefficients for multiplication with an estimate of the effective dose (E-103) for any examination can provide a more reliable estimate of the total lifetime cancer risk for a patient of particular age and sex than has been possible in the past, when only ICRP's nominal risk coefficient has been available. The typical levels of risk were found to range from less than about 1 in a billion ($<10^{-9}$) for any patient having an x-ray examination of the knee or foot, to over 1 in a 1,000 (10^{-3}) for a young girl having a CT scan of the whole trunk. These absolute levels of risk have been calculated assuming that children receive the same organ doses as adults. In practice, children may well receive substantially lower doses for radiographic and fluoroscopic x-ray examinations, and hence lower risks, but this may not yet be the case for CT examinations. However any differences between adult and paediatric doses will have no influence on the risk coefficients (risk per unit E) that we

have calculated, since the same doses appear in the numerator and the denominator. Consequently adequate estimates of risk for children can be calculated using the appropriate age and sex specific risk coefficient and an appropriate level of effective dose for the child.

It is also proposed that the risk of deleterious heritable effects appearing in the progeny of patients undergoing x-ray examinations can be estimated separately by multiplying the gonadal dose by a rounded value of *ICRP Publication 103's* risk coefficient for heritable effects of radiation in the reproductive population (0.50% per Gy). The risks are assumed to be independent of gender or age until reproductive activity ceases, when the risks obviously fall to zero. For examinations with a significant gonad dose, the typical levels of risk were found to range from less than 1 in a million to 1 in 15,000 for a female patient having a CT scan of the abdomen and pelvis.

11 REFERENCES

BEIR VII (2006). Health Risks from Exposure to Low Levels of Ionizing Radiation. Biological Effects of Ionizing Radiation VII Phase 2. National Research Council of the National Academies. The National Academies Press, Washington D.C. (www.nap.edu).

Brenner DJ (2008). Effective dose: a flawed concept that could and should be replaced. *Br J Radiol,* **81**, 521-523.

Calman K (1996). Cancer: science and society and the communication of risk. *BMJ*, **313**, 799-802.

Clark AL, Brennan AG, Robertson LJ and McArthur JD (2000). Factors affecting patient radiation exposure during routine coronary angiography in a tertiary referral centre. *Br J Radiol,* **73**, 184-189.

Cook JV, Shah K, Pablot S, Kyriou J, Pettett A, and Fitzgerald M (1998). Guidelines on Best Practice in the X-ray Imaging of Children. Queen Mary's Hospital for Children, Carshalton, Surrey and The Radiological Protection Centre, St Georges Healthcare NHS Trust, London.

Department of Health (1995). On the State of the Public Health 1995. *In* Introduction to the Annual Report of the Chief Medical Officer of the Department of Health for the year 1995. London, HMSO.

European Commission (2008). Radiation Protection No. 154. European Guidance on Estimating Population Dose from Medical X-ray Procedures (http://ec.europa.eu/energy/nuclear/radiation_protection/publications_en.htm).

Hart D, Hillier MC and Wall BF (2002). Doses to patients from medical x-ray examinations in the UK – 2000 review. Report NRPB-W14 (www.hpa.org.uk).

Hart D, Hillier MC and Wall BF (2007). Doses to patients from radiographic and fluoroscopic x-ray imaging procedures in the UK – 2005 review. Report HPA-RPD-029 (www.hpa.org.uk).

Hart D, Jones DG and Wall BF (1996). Coefficients for estimating effective doses from paediatric x-ray examinations. Report NRPB-R279 (www.hpa.org.uk).

Hart D and Wall BF (2002). Radiation exposure of the UK population from medical and dental x-ray examinations. Report NRPB-W4 (www.hpa.org.uk).

Hart D and Wall BF (2004). UK population dose from medical x-ray examinations. *Eur J Radiol*, **50**, 285-291.

Hart D, Wall BF, Hillier MC and Shrimpton PC (2010). Frequency and collective dose for medical and dental x-ray examinations in the UK, 2008. Report HPA-CRCE-012 (www.hpa.org.uk).

Hiorns MP, Saini A and Marsden PJ (2006). A review of current local dose-area product levels for paediatric fluoroscopy in a tertiary referral centre compared with national standards. Why are they so different? *Br J Radiol,* **79**, 326-330.

Hoskins PR, Gillespie I and Ireland HM (1996). Patient dose measurements from femoral angiography. *Br J Radiol,* **69**, 1159-1164.

HPA, RCR and CoR (2009). Protection of pregnant patients during diagnostic medical exposures to ionising radiation. Advice from the Health Protection Agency, the Royal College of Radiologists and the College of Radiographers. *Doc of HPA*, RCE-9 (www.hpa.org.uk).

ICRP (1991). The 1990 Recommendations of the International Commission on Radiological Protection. Publication 60. *Ann ICRP*, **21**, Nos 1-3.

ICRP (1992). The biological basis for dose limitation in the skin. Publication 59. *Ann ICRP*, **22**, No 2.

ICRP (2007). The 2007 Recommendations of the International Commission on Radiological Protection. Publication 103. *Ann ICRP*, **37**, Nos 2-4.

IR(ME)R (2000). The Ionising Radiation (Medical Exposure) Regulations 2000. SI (2000) No. 1059. TSO, London.

Jansen JTM, Shrimpton PC and Zankl M (2009). Development of PC-based Monte Carlo simulations for the calculation of scanner-specific normalised doses from CT. International Conference on Mathematics, Computational Methods and Reactor Physics, Saratoga Springs, NY, 3-7 May 2009. (On CD-ROM, American Nuclear Society, La Grange Park, IL, USA).

Jones DG and Wall BF (1985). Organ doses from medical x-ray examinations calculated using Monte Carlo techniques. Report NRPB-R186 (www.hpa.org.uk).

Martin CJ (2007). Effective dose: how should it be applied to medical exposures? *Br J Radiol,* **80**, 639-647.

NHSBSP (2003). Review of radiation risk in breast screening. NHSBSP Publication No. 54. NHS Cancer Screening Programmes, Sheffield (www.cancerscreening.nhs.uk).

NRPB (1990). Patient dose reduction in diagnostic radiology. Report by the Royal College of Radiologists and the National Radiological Protection Board. *Doc of NRPB*, **1** (3) (www.hpa.org.uk).

NRPB (1993). Estimates of late radiation risks to the UK population. Prepared by Muirhead CR, Cox R, Stather JW, MacGibbon BH, Edwards AA and Haylock RGE. *Doc of NRPB*, **4** (4) (www.hpa.org.uk).

NRPB, CoR, RCR and RCGP (2001). X-rays – how safe are they? An information leaflet for patients prepared by the National Radiological Protection Board, College of Radiographers, Royal College of Radiologists and Royal College of General Practitioners (www.hpa.org.uk).

Pelowitz DB (Editor) (2008). MCNPX User's Manual, Version 2.6.0. Report LA-CP-07-1473. Los Alamos National Laboratory, NM, USA.

Preston DL, Kusumi S, Tomonaga M, Izumi,S, Ron,E, Kuramoto A, Kamada N, Dohy, H, Matsui T, Nonaka H, Thompson DE, Soda M and Mabuchi K (1994). Cancer incidence in atomic bomb survivors. Part III: Leukemia, lymphoma and multiple myeloma, 1950-1987. *Radiat Res*, **137**, S68-S97.

Puskin JS, Nelson NS and Nelson CB (1992). Bone cancer risk estimates. *Health Phys*, **63** (5), 579-580.

Shrimpton PC and Edyvean S (1998). CT scanner dosimetry. *Br J Radiol*, **71**, 1-3.

Shrimpton PC, Hillier MC, Lewis MA and Dunn M (2005). Doses from computed tomography (CT) examinations in the UK – 2003 review. Report NRPB-W67 (www.hpa.org.uk).

Shrimpton PC and Wall BF (2000). Reference doses for paediatric computed tomography. *Radiat Prot Dosim*, **90**, No 1-2, 249-252.

Tapiovaara M, Lakkisto M and Servomaa A (2008). PCXMC: A PC-based Monte Carlo program for calculating patient doses in medical x-ray examinations. Report STUK-A139, 2nd Edition. Helsinki, Finnish Centre for Radiation and Nuclear Safety.

UNSCEAR (2006). United Nations Scientific Committee on the Effects of Atomic Radiation 2006 Report: Effects of ionizing radiation - Volume 1. United Nations, New York (www.unscear.org).

Wakeford R and Tawn EJ (2010). The meaning of low dose and low dose-rate (Editorial). *J Radiol Prot*, **30**, 1-3.

Wall B F and Hart D (1997). Revised radiation doses for typical x-ray examinations. *Br J Radiol*, **70**, 437-439.

APPENDIX A
Comparison of the latest ICRP, BEIR and UNSCEAR risk models

Brief summaries of the main features of the risk models developed by ICRP, BEIR and UNSCEAR are given on the following pages.

ICRP Publication 103, 2007

ICRP (2007). The 2007 Recommendations of the International Commission on Radiological Protection. Publication 103. Annals of the ICRP 37, 2-4.
(Main author - Dale Preston)

Lifetime Attributable Risks (LAR) for cancer incidence and mortality developed using excess relative risk (ERR) and excess absolute risk (EAR) models for 10 organs - oesophagus, stomach, colon, liver, lung, breast, ovary, bladder, thyroid, red bone marrow (RBM) + 'remainder' ('other solid'), where:

> "Remainder" (other solid) = Salivary glands, brain, adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus (16 in all).

ICRP Publication 60 (ICRP, 1991) nominal risks (averaged over the whole population) were used for bone and skin cancers, because of poor data from the Japanese lifespan study, LSS (skin cancer data for Japanese not appropriate for general population due to differences in skin pigmentation and LSS provides no data for bone cancer). ICRP nominal risk for bone cancer is based on average bone dose, not dose to bone surfaces and could be factor of 9 times too high (Paragraph A 113; ICRP, 2007). [N.B. risks for bone and skin cancer were not considered in this HPA report].

DDREF = 2 (except for leukaemia where linear-quadratic dose-effect model used)

In general, parameters in risk models were based on incidence data from Japanese LSS with follow up from 1958 to 1998 with DS02 dosimetry.

ERR & EAR models developed for the above 10 organs (apart from bone and skin for which ICRP 60 models were used) and for 'remainder' (= 'other solid').

For solid cancers, these models involved a linear dose response allowing for modifying effects of sex, age at exposure (i.e. risks remain constant after exposure) and attained age (i.e. risks decline as survivors get older).

For leukaemia, an EAR model was used with a linear-quadratic dose response allowing for modifying effects of sex, age at exposure and time following exposure.

Relative weights (%) given to ERR and EAR varied for different cancer sites (organs) according to available data:

ERR:EAR	= 0:100% breast and RBM
	= 100:0% thyroid and skin
	= 30:70% lung
	= 50:50% all others

Baseline cancer rates averaged over 7 populations (4 Asian and 3 Euro-American) by using an unweighted average of the Asian & Euro-American data.

> Asian populations: Shanghai, China; Osaka, Hiroshima and Nagasaki, Japan;

Euro-American populations: Sweden, UK, USA (SEER).

LAR for incidence for all cancers = 17% per Sv (averaged over both sexes and all ages in 7 populations) [NB skin contributes 10% per Sv to total LAR for incidence]

LAR for mortality for all cancers = 4.0% per Sv (averaged over both sexes and all ages in 7 populations) [NB skin contributes 0.04% per Sv to total LAR for mortality]

BEIR VII, 2006

BEIR VII (2006). Health Risks from Exposure to Low Levels of Ionizing Radiation. Biological Effects of Ionizing Radiation VII Phase 2. National Research Council of the National Academies. The National Academies Press, Washington D.C. [www.nap.edu].
(Main author - Dale Preston)

Lifetime Attributable Risks (LAR) for cancer incidence and mortality given for 11 organs - stomach, colon, liver, lung, breast, uterus, ovary, prostate, bladder, thyroid, RBM + 'others'

Risks for oesophagus, bone and skin cancers not considered by BEIR VII (but uterus and prostate are)

DDREF = 1.5 (except for leukaemia where linear-quadratic dose-effect model used)

In general, parameters in risk models were based on incidence data from Japanese LSS with follow up from 1958 to 1998 with DS02 dosimetry.

ERR & EAR models developed for the above 11 organs and for 'other' 'all solid and 'all cancers'.

For solid cancers these models involved a linear dose response allowing for modifying effects of sex, age at exposure and attained age.

e.g. $ERR = \beta_s D \cdot \exp(\gamma e) \cdot a^{\eta}$

where $\beta_s = \beta_M$ or β_F = sex specific estimates of ERR per Sv
e = age at exposure (years)
a = attained age (years)

ERR & EAR decline with increasing age at exposure.

ERR declines while EAR increases (strongly), with increasing attained age.

For leukaemia a 70%:30% ERR:EAR model was used, with a linear-quadratic dose response allowing for modifying effects of sex, age at exposure and time following exposure.

Relative weights (%) given to ERR and EAR varied for different cancer sites (organs):

ERR:EAR = 0:100% breast
= 100:0% thyroid
= 30:70% lung
= 70:30% all others

Baseline cancer rates from USA SEER Registries (1995-1999)

LAR for incidence for all cancers = 11.5% per Gy (averaged over both sexes and all ages in USA population)

LAR for mortality for all cancers = 5.7% per Gy (averaged over both sexes and all ages in USA population)

UNSCEAR, 2006

UNSCEAR (2006). United Nations Scientific Committee on the Effects of Atomic Radiation 2006 Report: Effects of Ionizing Radiation. Volume 1. United Nations, New York.
www.unscear.org
(Main author - Mark Little)

Risks for 20 organs - oesophagus, stomach, colon, liver, lung, bone, skin, breast, ovary, bladder, thyroid, RBM, salivary glands, small intestine (incl. duodenum), rectum, pancreas, uterus, prostate, kidney, brain & CNS.

(However, only 19 excess cases of bone cancer in LSS, so bone risks very approximate)

DDREF = 1 (linear-quadratic and linear-quadratic-exponential models implicitly adjust for extrapolation to low doses)

In general, parameters in risk models were based on incidence data from Japanese LSS with follow up from 1950 to 2000 with DS02 dosimetry.

Longer follow-up in LSS shows that neither of the previous projection models (in UNSCEAR 2000), based on age-at-exposure or attained-age, fit well.

5 models developed based on ERR or EAR and allowing for modifying effects of age-at-exposure and attained age:-

ERR, D, sex, age, years since exposure	[ERR decreases with time since exposure]
ERR, D, sex, age at exposure	[Old model - ERR constant over time]
ERR, D + D^2, sex, age, years since exposure	[ERR decreases with time since exposure]
EAR, D, age, years since exposure	[EAR decreases with time since exposure]
EAR, D + D^2, age, years since exposure	[EAR decreases with time since exposure]

For 5 populations separately (China, Japan, Peurto Rico, UK, USA)

Generally - EAR risks < ERR risks

UNSCEAR 2006 lifetime risks slightly lower than UNSCEAR 2000 risks

due to: new dosimetry (10%)
increased follow-up (3-7%)
different risk projection and transfer models (34-40%)