Articles

Risk of cancer from diagnostic X-rays: estimates for the UK and 14 other countries

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Summary

Background Diagnostic X-rays are the largest man-made source of radiation exposure to the general population, contributing about 14% of the total annual exposure worldwide from all sources. Although diagnostic X-rays provide great benefits, that their use involves some small risk of developing cancer is generally accepted. Our aim was to estimate the extent of this risk on the basis of the annual number of diagnostic X-rays undertaken in the UK and in 14 other developed countries.

Methods We combined data on the frequency of diagnostic X-ray use, estimated radiation doses from X-rays to individual body organs, and risk models, based mainly on the Japanese atomic bomb survivors, with population-based cancer incidence rates and mortality rates for all causes of death, using life table methods.

Findings Our results indicate that in the UK about 0·6% of the cumulative risk of cancer to age 75 years could be attributable to diagnostic X-rays. This percentage is equivalent to about 700 cases of cancer per year. In 13 other developed countries, estimates of the attributable risk ranged from 0·6% to 1·8%, whereas in Japan, which had the highest estimated annual exposure frequency in the world, it was more than 3%.

Interpretation We provide detailed estimates of the cancer risk from diagnostic X-rays. The calculations involved a number of assumptions and so are inevitably subject to considerable uncertainty. The possibility that we have overestimated the risks cannot be ruled out, but that we have underestimated them substantially seems unlikely.

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Introduction

Diagnostic X-rays are the largest man-made source of radiation exposure to the general population, contributing about 14% of total worldwide exposure from man-made and natural sources.[1] However, although diagnostic X-rays provide great benefits, that their use involves some risk of developing cancer is generally accepted. The risk to an individual is probably small because radiation doses are usually low (typically <10 mGy), but the large number of people exposed annually means that even small individual risks could translate into a considerable number of cancer cases. Small risks are difficult to study directly in epidemiological studies.[2] However, the risk from diagnostic X-rays can be estimated by extrapolating risk estimates from populations exposed to a range of doses, such as the Japanese atomic bomb survivors exposed at 0–4 Gy.[1]

In 1981, Doll and Peto[3] estimated that about 0·5% of cancer deaths in the USA were attributable to diagnostic X-rays. Since then, use of this diagnostic method has increased in most developed countries.[1] There is also wide variation in frequency of use from country to country.[1] Our aim was, therefore, to estimate the risk of cancer on the basis of the annual use of diagnostic X-rays in the UK and in 14 other developed countries for which sufficient data are available.

Methods

We estimated the cumulative risk, to age 75 years, that an individual will develop a cancer caused by diagnostic X-rays,[4] using models for the risk of incident cancer after radiation exposure, estimates of the average annual frequency of exposure for each type of diagnostic X-ray, estimates of the organ-specific radiation doses delivered by each X-ray type, and cancer incidence and all-cause mortality rates for the 15 populations being studied—ie, UK, Australia, Canada, Croatia, Czech Republic, Finland, Germany, Japan, Kuwait, the Netherlands, Norway, Poland, Sweden, Switzerland, and the USA. The source of this information is described below, and details of the calculations are provided in the webappendix (http:// image.thelancet.com/extras/03art4007webappendix.pdf).

Models for risk of cancer from radiation exposure

For cancers of the oesophagus, stomach, colon, liver, lung, bladder, and thyroid, we used linear models in which the extra risk from the X-ray exposure multiplies the population cancer rate by a specific amount—ie, excess relative risk models. These models were based on cancer incidence data from the Japanese atomic bomb survivors and were taken from a review by the United Nations,[1] except the model for lung cancer risk, which was taken from an analysis of smoking and radiation exposure in the atomic bomb survivors.[5] For leukaemia

	Organ								
	Bladder	Breast	Colon	Liver	Lung	Oesophagus*	RBM	Stomach	Thyroid
X-ray type									
Abdomen	1·14	0·05	1·63	1·10	0·27	0·03	0·37	1·64	0·03
Coronary angiography	0·23	0·42	0·51	1·54	37·69	13·79	7·39	0·67	1·08
Cerebral angiography	0·00	0·02	0·00	0·01	1·14	1·98	9·27	0·01	25·06
Barium meal	0·28	0·62	1·82	9·48	1·23	0·54	1·69	8·24	0·22
Barium enema	14·45	0·14	21·51	3·55	0·39	0·06	7·49	4·98	0·01
Cardiac catheterisation	0·23	0·42	0·51	1·54	37·69	13·79	7·39	0·67	1·08
Cervical spine	0·00	0·00	0·00	0·00	0·07	0·12	0·07	0·00	0·84
Chest	0·00	0·01	0·00	0·03	0·07	0·04	0·02	0·02	0·01
Hip	1·16	0·00	0·71	0·01	0·00	0·00	0·12	0·02	0·00
Hysterosalpingography	4·67	0·00	2·82	0·01	0·00	0·00	0·81	0·03	0·00
Intravenous urogram (IVU)	4·42	0·20	5·10	3·49	0·42	0·03	0·83	6·04	0·00
Lumbar myelography	7·90	0·01	10·85	1·30	0·04	0·01	4·06	1·62	0·00
Lumbar spine	2·49	0·03	2·40	2·16	0·15	0·02	0·68	1·51	0·00
Mammography (1-view screen)	0·00	2·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
Pelvis	2·13	0·01	1·85	0·13	0·01	0·00	0·25	0·29	0·00
Skull	0·00	0·00	0·00	0·00	0·01	0·02	0·12	0·00	0·14
Thoracic spine	0·00	0·47	0·00	0·57	2·25	1·15	0·55	0·25	2·97
CT: abdomen	5·07	0·72	6·60	0·05	2·70	0·56	5·58	22·20	0·05
CT: chest	0·02	21·40	0·07	5·64	22·40	28·30	5·94	4·06	2·25
CT: head	0·00	0·03	0·00	0·01	0·09	0·07	2·67	0·00	1·85
CT: internal auditory meatus	0·00	0·02	0·00	0·01	0·08	0·07	0·83	0·00	2·03
CT: orbits	0·00	0·01	0·00	0·00	0·04	0·03	1·05	0·00	0·87
CT: pituitary	0·00	0·01	0·00	0·00	0·04	0·03	0·96	0·00	0·77
CT: pelvis	23·20	0·03	15·10	0·68	0·05	0·01	5·62	1·06	0·00
CT: cervical spine	0·00	0·09	0·00	0·03	0·58	0·51	1·12	0·02	43·90
CT: thoracic spine	0·00	27·70	0·02	1·48	13·40	15·70	2·92	0·98	0·46
CT: lumbar spine	0·67	0·13	3·30	6·88	0·34	0·08	2·52	10·50	0·01

RBM=red bone marrow. *CT scan doses not available and assumed equal to thymus dose.

Table 1: **Estimated organ-specific radiation doses (mGy)[11–13] by type of diagnostic X-ray**

and breast cancer, we used models in which the extra risk from diagnostic X-ray exposure adds to the population rate—ie, excess absolute risk models. For leukaemia, excluding chronic lymphocytic leukaemia, we used a linear-quadratic model based on data from the Japanese atomic bomb survivors.[6] For breast cancer, we used a linear risk model based on a pooled analysis of four selected cohorts, including the Japanese atomic bomb survivors.[7] The lung cancer model included parameters for sex and attained age. All other models included parameters for sex and age at exposure, and for leukaemia and breast cancer attained age was also included.

UK exposure frequency

We based the frequency of exposure of the population to diagnostic X-rays on a worldwide survey of medical radiation use between 1991 and 1996.[1] This survey, which is the most recent that is available, gives the total annual number of exposures per 1000 population for the most common diagnostic X-ray and CT examinations in each country, but does not give the frequency according to age and sex. The most detailed information available on the age and sex distribution of diagnostic X-rays is provided in a British survey undertaken in 1977.[8] Therefore, we estimated the age-specific (0–1, 2–4, 5–9, . . ., 30–39, . . ., and ⩾60 years) and sex-specific annual frequencies by combining the most recent estimate of total annual frequency of each examination type from the worldwide survey[1] with the age-specific and sex-specific frequencies from the British survey (see webappendix).[8]

We estimated the distribution of CT examinations by age and sex in the same way, using age (0–9, . . ., 70–79 years) and sex frequencies from a British survey[9] of CT practice in the UK undertaken in 1989 combined with the most recent total annual frequency data from the worldwide survey.[1] For mammography screening, average annual exposure was based on data from the UK National Health Service (NHS) Breast Screening Programme,[10] which suggest that 70% of women aged 50–64 years attend for breast screening once every 3 years.

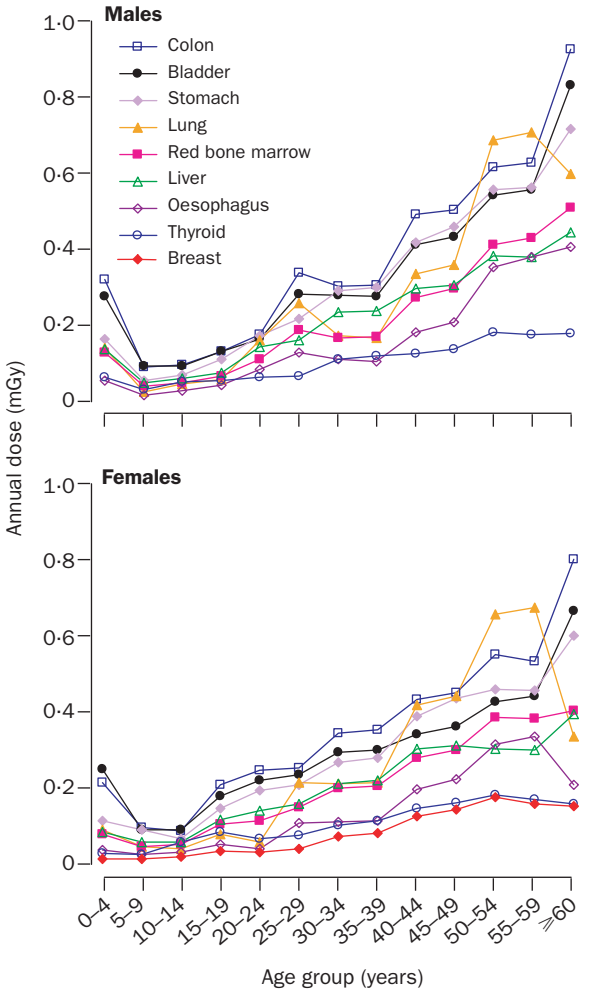

Figure 1: **Estimated average annual radiation dose per person from diagnostic X-rays in UK population for various organs**

	Males					Females				
	Cumulative risk (%)		Attributable risk (%)*	Cancer cases per year†		Cumulative risk (%)		Attributable risk (%)*	Cancer cases per year†	
	Radiation-induced	Population		Radiation-induced	Population	Radiation-induced	Population		Radiation-induced	Population
Cancer type (ICD-9 code)										
Oesophagus (150)	0·002	0·67	0·3	5	1731	0·002	0·33	0·6	6	938
Stomach (151)	0·006	1·33	0·4	15	3370	0·005	0·55	0·9	14	1580
Colon (153)	0·014	1·56	0·9	34	4023	0·026	1·45	1·8	73	4243
Liver (155)	0·001	0·18	0·6	2	477	0·001	0·09	1·3	2	267
Lung (162)	0·007	5·50	0·1	21	13 850	0·013	2·46	0·5	40	7217
Breast (174)	..	..	..	..	..	0·009	6·77	0·1	29	21164
Bladder (188)	0·034	1·70	2·0	85	4328	0·009	0·56	1·7	26	1623
Thyroid (193)	<0·0001	0·06	0·4	1	184	0·001	0·15	0·8	3	495
Leukaemia (204–208, excluding 204.1)	0·008	0·60	1·4	27	1736	0·008	0·42	1·9	26	1322
All cancers listed above	0·072	11·60	0·6	190	29 699	0·074	12·77	0·6	219	38 849
All radiation-inducible cancers‡	0·123	20·40	0·6§	341	53 399	0·126	20·83	0·6§	359	63 856
All cancers	0·123	21·68	0·6	341	57 178	0·126	21·79	0·6	359	66 881

*% of cumulative risk attributable to radiation=radiation-induced cumulative risk*100/population cumulative risk. †estimated number of cases per year based on 1998 UK population. ‡ICD-9 140–239, but excluding 200–203 (lymphomas and multiple myeloma) and 204.1 (chronic lymphocytic leukaemia). §Attributable risk for all radiation-inducible cancers assumed equal to that for all cancers specifically listed.

Table 2: **Estimated cumulative risk of cancer to age 75 years and number of cancer cases per year from diagnostic X-rays in the UK**

UK organ-specific radiation doses

The relevant measure of dose for the risk of a specific type of cancer is the absorbed dose to the appropriate organ of the body, known as the organ-specific radiation dose. We estimated these doses by combining information from a Finnish study (1993–96)[11] with a recent review of doses to patients from medical X-rays in the UK[12] (see webappendix). We took organ dose estimates for CT scans from the British survey of CT practice.[13] Breast doses from mammography screening were taken from a 1997–98 UK survey (assuming a two-view screen at all screening rounds).[14]

Frequency and organ-specific dose information were available for 27 common types of X-ray procedures, comprising 86% of the annual collective effective dose from diagnostic X-rays.[15] Table 1 shows the organ-specific doses for each procedure. We combined these doses with the age-specific and sex-specific annual X-ray frequencies and then multiplied by 100/86, to account for the X-ray procedures for which frequency and dose information were not available, to estimate the average annual radiation dose per person delivered to each main organ in the body, according to age and sex (figure 1).

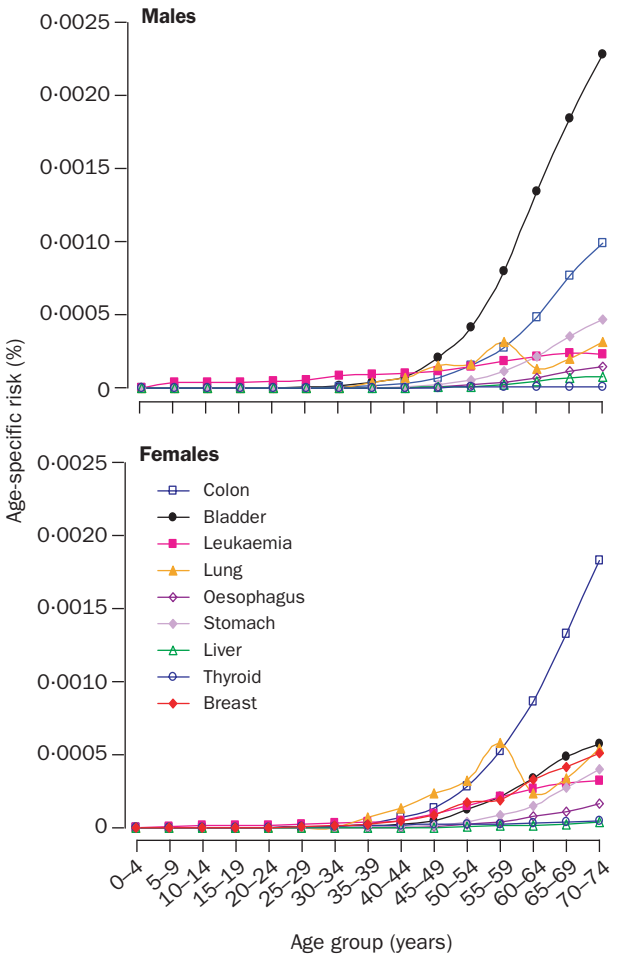

Figure 2: **Estimated annual risk of radiation-induced cancer from diagnostic X-rays in 5-year age groups in UK population**

	Cases of radiation-induced cancer per year*			Cases per million examinations*
	Males	Females	Total	
X-ray type				
Abdomen	16	15	31	30
Barium meal	5	6	11	40
Barium enema	27	28	55	170
Chest	1	3	4	1
Coronary angiography	13	28	41	280
CT scan	31	39	70	60
Cerebral angiography	1	1	2	180
Hip or pelvis	28	24	52	30
Lumbar spine	23	16	39	40
Screening mammography	..	8	8	8
Thoracic spine	2	4	6	20
Each other type	<10	<10	<20	..

*Includes only nine cancer sites listed in Table 2. Detailed estimation of number of radiation-induced cases for all cancers is not possible, since estimates of organ-specific doses are not available for other cancers.

Table 3: **Estimated number of radiation-induced cases of cancer per year in the UK by type of X-ray**

	<1 year		1–14 years		15–34 years		15–54 years		55–74 years		All	
	Males	Females	Males	Females	Males	Females	Males	Females	Males	Females	Males	Females
Cancer type (ICD-9 code)												
Oesophagus (150)	0	0	1	1	1	1	2	2	1	1	5	6
Stomach (151)	0	0	2	2	5	5	6	5	2	2	15	14
Colon (153)	1	2	6	12	11	27	11	24	4	8	34	73
Liver (155)	0	0	0	0	1	0	1	1	0	1	2	2
Lung (162)	0	0	2	7	6	8	9	19	3	6	21	40
Breast (174)	..	0	..	3	..	9	..	13	..	3	..	29
Bladder (188)	6	2	27	8	34	12	16	5	3	1	85	26
Thyroid (193)	0	0	0	1	0	2	0	0	0	0	1	3
Leukaemia (204–208, excluding 204.1)	0	0	2	1	7	4	11	13	6	7	27	26
All cancers listed above†‡	8	5	41	36	65	68	57	81	19	28	190	219
All cancers‡	15	8	74	59	117	112	103	133	35	47	341	359
% of total	4%	2%	22%	16%	34%	31%	30%	37%	10%	13%	100%	100%
% of total—both sexes	3%		19%		33%		34%		11%		100%	

*Estimated number of cancer cases per year based on 1998 UK population. †Number of cancers contributed by CT scans for exposures at ages <1 year, 1–14, 15–34, 35–54, and 55–74 years estimated to be 1, 3, 10, 12, and 5 for males, and 1, 4, 11, 17, and 6 for females. ‡Number of cases in body of table rounded and do not always, therefore, add up to the totals given.

Table 4: **Estimated number of radiation-induced cases of cancer per year* in the UK by age at exposure**

Extension to all cancers

For each of the nine cancer types mentioned, we had all the necessary information to calculate site-specific radiation-induced cancer risks. For other solid cancers, neither detailed risk models nor appropriate organ-specific radiation doses were available. However, when these cancers are considered together as a group, there is strong evidence that they are radiation-inducible with a proportionate increase per Gy close to that for the nine listed cancers combined.[1] In the UK these nine cancer sites account for 56% of total cumulative risk of all solid cancers to age 75 years in men and for 61% in women. Among the remainder, the largest components are prostate (9%) and rectal cancer (6%) in men, and ovarian (6%), cervical (6%), and endometrial cancer (4%) in women. Therefore, to obtain an estimate of the total risk of solid cancers and leukaemia from diagnostic X-rays, we assumed that the percentages of the cumulative risk attributable to radiation from diagnostic X-rays for the sum of the nine listed cancers and for all radiation-inducible cancers were the same. Since there is little evidence that chronic lymphocytic leukaemia, lymphomas, or multiple myeloma are radiation-inducible[1] we excluded them from the estimation of radiation-induced risk.

UK cancer incidence and all-cause mortality rates

We used cancer incidence rates for England and Wales (1988–92) for male and female individuals in 5-year age bands.[16] Lung cancer incidence rates for lifelong non-smokers in a US cancer prevention study[17] were used for the estimation of radiation-induced lung cancer. We calculated all-cause survival probabilities with 1998 UK all-cause mortality rates.[18]

Sensitivity analysis for UK results

We assessed uncertainty in the UK estimated cumulative risks by varying the assumptions in the calculations. First, since individuals who receive diagnostic X-rays are probably less healthy than the general population, we increased all-cause mortality rates by 10% and by 50%. Second, we included a low-dose effectiveness reduction factor of two, halving the risks per unit dose for cancers other than leukaemia.[1] Third, we assumed that the radiation-induced risk lasted for 40 years rather than indefinitely. Fourth, we increased and decreased the estimates of organ dose by 30%. Fifth, we calculated 95% CI for the cumulative risks with the standard errors in the X-ray frequency data from the British survey.[8] Finally, we re-estimated risks with alternative excess relative risk models based on studies of adults in Europe or North America irradiated for medical purposes,[1] rather than the models from the Japanese atomic bomb survivors.

Data for populations other than the UK

We derived cumulative risk estimates for all populations classified as health-care level 1—ie, more than one doctor per 1000 population[1]—for which data on X-ray frequency, cancer incidence, and all-cause mortality rates were available from the same sources as for the UK—namely, Australia, Canada, Croatia, Czech Republic, Finland, Germany, Japan, Kuwait, Netherlands, Norway, Poland, Sweden, Switzerland, and USA. Since population-specific estimates were not available, we used the UK age and sex distributions of diagnostic X-rays and organ-specific radiation dose estimates throughout. For the USA, only the frequencies of CT scans and of all types of X-ray examinations combined were available.[1] Therefore, we estimated USA age-specific and sex-specific frequencies for each X-ray type with the age-specific and sex-specific frequency in the UK[8] multiplied by the ratio of 1991–96 total USA X-ray frequency to 1991–96 UK total frequency. No data were available for the annual frequency of CT examinations in Japan. We therefore used the average frequency for all health-care level 1 countries[1] in the main calculations. We estimated mammography screening

	Radiation-induced lifetime risk*	
	Males	Females
Assumption		
Original assumptions	100	100
All-cause mortality rates increased by 10%	93	95
All-cause mortality rates increased by 50%	80	87
Low-dose effectiveness reduction factor of 2	54	52
Risk persistence of 40 years rather than indefinitely	75	86
Organ dose estimates increased or decreased by 30%	70–130	70–130
X-ray frequency increased or decreased to limits of 95% CI	40–160	60–140
Different risk models (lowest and highest)†	87–269	33–133

*Expressed as a percentage of risks calculated under original assumptions. †Maximum and minimum risks obtained by considering different risk models based on a recent survey.[1]

Table 5: **Effect of varying assumptions on UK radiation-induced cumulative risk estimates**

	Annual X-rays per 1000*	Males		Females		Total	
		Attributable risk (%)	Cases cancer per year	Attributable risk (%)	Cases cancer per year	Attributable risk (%)	Cases cancer per year
Country							
Australia	565	1·2	204	1·5	227	1·3	431
Canada	892	1·1	406	1·0	378	1·1	784
Croatia	903	1·5	66	2·2	103	1·8	169
Czech Republic	883	0·9	67	1·2	105	1·1	172
Finland	704	0·7	20	0·7	30	0·7	50
Germany	1254	1·3	963	1·7	1086	1·5	2049
Japan†	1477	2·9	3724	3·8	3863	3·2	7587
Kuwait	896	0·7	25	0·6	15	0·7	40
Netherlands	600	0·7	100	0·7	108	0·7	208
Norway	708	1·3	28	1·1	49	1·2	77
Poland	641	0·5	99	0·7	192	0·6	291
Sweden	568	1·1	91	0·8	71	0·9	162
Switzerland	750	1·0	93	1·0	80	1·0	173
UK	489	0·6	341	0·6	359	0·6	700
USA	962	0·9	2573	1·0	3122	0·9	5695

*Taken from worldwide survey.[1] †Estimates assume annual frequency of CT examinations in Japan was equal to that for all health-care level 1 countries. However, number of CT scanners per million population in Japan is 3·7 times that for all health-care level 1 countries. If this number is reflected in annual frequency of CT examinations, then for Japan estimated annual number of X-rays per 1000 increases to 1573 and the attributable risk increases to 4·4%, corresponding to 9905 cases of cancer per year.

Table 6: **Frequency of diagnostic X-rays per 1000 population, percentage of cumulative cancer risk to age 75 years attributable to diagnostic X-rays, and number of radiation-induced cases of cancer per year for 15 countries**

exposures for countries with nationwide breast-screening programmes (Australia, Finland, Netherlands, and Sweden) and also for the USA, where mammography is common.[19] For each of these countries, we assumed 70% of women aged 50–69 years were screened biennially. Where appropriate, we combined data from several cancer registries to give an overall estimate for each population. For the USA, we combined data for black and white individuals.

Role of the funding source

The sponsors of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

We estimate that diagnostic X-ray use in the UK causes 0·6% of the cumulative risk of cancer to age 75 years in men and women (table 2), equivalent to 700 cases per year for both sexes combined. Of the nine cancers listed in table 2, bladder cancer accounted for the largest number of radiation-induced cases per year in men, followed by colon cancer and leukaemia. In women, of the nine listed cancers, colon cancer made the greatest contribution to the annual total followed by cancers of the lung and breast. For most cancers, the estimated annual radiation-induced cancer risk started to rise from about age 40 years, and was still rising at age 70 years (figure 2): only 2% of radiation-induced cases arose before age 40 years, and 56% arose between age 65 years and 74 years. The higher colon-cancer cumulative risk in females compared with males was mainly due to the larger parameter in the radiation risk model, whereas the higher cumulative risk of bladder cancer in males compared with females was mainly due to higher rates of bladder cancer in the general population.

The number of cancer cases attributed to each X-ray type depends in part on frequency and radiation dose, but also on the irradiated organs, their radiosensitivity, and the age distribution of those given X-rays. CT scans were responsible for the largest number of cases of the nine listed cancers followed by barium enemas and hip and pelvis X-rays (table 3). CT scans in childhood (before age 15 years) accounted for nine cancers (13% of the total for CT scans; table 4). The estimated average number of cases of cancer per million examinations varied widely with the type of X-ray, from eight or fewer for examinations such as mammography and chest X-rays, which deliver low radiation doses and are predominantly given to older adults, up to 280 for coronary angiography, which delivers higher radiation doses, particularly to the lungs (about 40 mGy per examination). Neonatal exposures (age <1 year) accounted for 3% of radiation-induced cancers, whereas exposures in childhood (1–14 years) accounted for 19% (table 4).

Increasing all-cause mortality rates by 10% and 50% reduced the radiation-induced risks by 7% and 20%, respectively, in men and by 5% and 13% in women (table 5). The introduction of a low-dose effectiveness

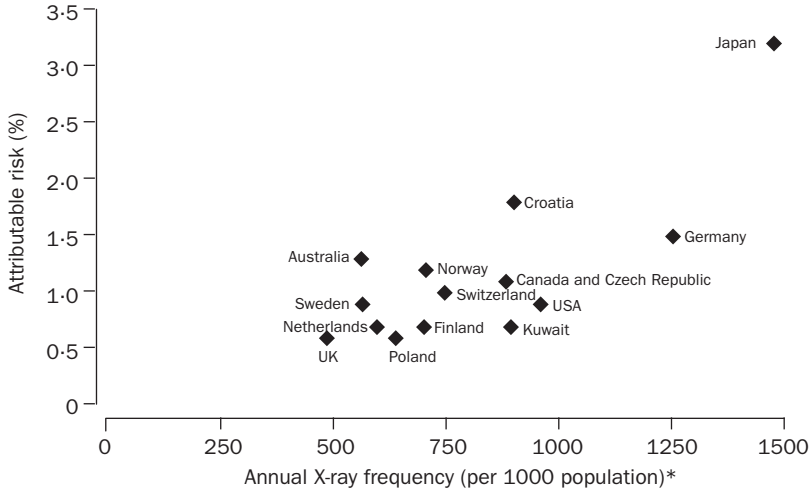

Figure 3: **Risk of cancer attributable to diagnostic X-ray exposures versus annual X-ray frequency**
*Taken from worldwide survey.[1]

reduction factor of 2 for all cancers except leukaemia (for which a linear-quadratic dose-response relation was assumed throughout) approximately halved the risk. The assumption that the radiation-induced risk lasted for 40 years rather than indefinitely reduced risks by 25% in males and 14% in females. Increasing or decreasing organ dose estimates increased or decreased the estimated risks approximately proportionally, as did uncertainty in the X-ray frequencies. Use of different risk models can more than double the risks in males, mainly due to higher lung-cancer coefficients. By contrast, use of different risk models in females increased the risk by no more than 30%, but could reduce it by up to 70%, mainly due to lower colon-cancer coefficients.

Of the 15 countries studied, the UK had the lowest annual frequency of diagnostic X-rays and Japan the highest (table 6 and figure 3).[1] Japan also had the highest attributable risks, with 3·2% of the cumulative risk of cancer attributable to diagnostic X-rays, equivalent to 7587 cases of cancer per year. In all other populations less than 2% of the cumulative cancer risk was attributable to diagnostic X-rays; Croatia and Germany had the highest proportions at 1·8% and 1·5%, respectively, whereas Poland and the UK had the lowest (both 0·6%).

Discussion

Radiation is one of the most extensively researched carcinogens, but the effects of low doses are still somewhat unclear. Our estimates are based on the assumption that small doses of radiation can cause cancer. The weight of evidence from experimental and epidemiological data does not suggest a threshold dose below which radiation exposure does not cause cancer.[20] If there is no threshold then diagnostic X-rays will induce some cancers.

To calculate our estimates, we had to make several other assumptions. We assumed that individuals who receive diagnostic X-rays have mortality rates equal to those of the general population; that low doses of radiation are as harmful per unit dose as doses up to 4 Gy;[20] and that radiation-induced risks persist indefinitely. If any of these assumptions is incorrect, the radiation-induced cumulative risks will be lower than those estimated, possibly by up to 50%. There is also uncertainty in the organ doses associated with each X-ray procedure, in the age-specific frequency of the various procedures, in the appropriate model for radiation-induced risks, and in the extension of risk from the nine specified cancers to all radiation-inducible cancers. If the latter assumptions are incorrect then the risks stated could either increase or decrease.

The only previous estimates for diagnostic X-rays as a whole were for the USA[3] and Germany.[21] Both studies used cruder methods, which did not account for age and sex variation in X-ray exposures or radiation risks. Furthermore, neither study estimated risks for each cancer site separately, using organ-specific radiation doses. Our results for the USA suggest that 0·9% of cancers could be caused by diagnostic X-rays, almost double the 1981 estimate of 0·5% of cancer mortality.[3] This difference might be due to our detailed methods, although our US estimates used cruder data than for other populations. It might also be due to the use of cancer incidence rather than mortality and to the 20% increase in the average annual X-ray frequency between 1980–84[22] and 1991–96.[1] For Germany, our estimated risk of 1·5% was slightly lower than the 1997 estimate of 2%.[21]

Organ-specific radiation doses could vary with age, with doses in paediatric radiology probably being lower than in adults for many common radiographic and fluoroscopic examinations,[23] but possibly higher for CT scans.[24] Brenner and colleagues[25] estimated that the cumulative risk of cancer mortality from CT examinations in the USA is about 800 radiation-induced cancer deaths per million examinations in children aged younger than 15 years. This calculation used age-specific adjustments, resulting in doses for children up to four times higher than those for adults. In a more recent study,[24] a detailed calculation of age-specific adjustments estimated that doses to 0–1 year olds were at most 2·5 times higher than adult doses, and for children aged 2–15 years were at most 1·8 times higher than adult doses. We estimated that childhood CT scans cause nine cases of the nine specified cancers per year in the UK. If we had used the recent estimates of the age-specific radiation doses, this number would have increased to 16 cases. There is concern that radiation doses from CT scans are very variable and could still be unnecessarily high,[26] especially since the frequency of CT examinations is increasing in many countries, in particular for children.[26,27] Furthermore, results of a UK survey[28] noted that most doctors generally underestimate the radiation doses received from commonly requested radiological investigations.

Our cumulative risks were truncated at age 75 years, since cancer incidence and mortality data were not available for older individuals for all the included countries. However, in the UK, about 20% of cancer cases are diagnosed in those aged 75 years and older. Therefore, the total annual number of cases of cancer attributable to diagnostic X-rays at all ages in the UK could be around 20% higher than the number presented here. Reducing either the radiation doses per examination or the frequency of exposure could reduce, approximately proportionally, the annual number of radiation-induced cancer cases per year. However, of the countries studied, the UK had the lowest annual X-ray frequency per 1000 population and the joint lowest estimate of the proportion of cumulative cancer risk attributable to diagnostic X-rays. A survey of UK practice[29] has suggested that the comparatively low frequency of diagnostic X-ray use is due in part to the detailed guidance for doctors on the indicators for X-ray examinations issued by the Royal College of Radiologists.[30]

Although there are clear benefits from the use of diagnostic X-rays, that their use involves some risk of cancer is generally acknowledged. We provide detailed estimates of these risks. Our calculations depended on a number of assumptions, however, and so are inevitably subject to considerable uncertainty. The possibility that we have overestimated the risks cannot be ruled out, but it seems unlikely that we have underestimated them substantially.

Contributors

A Berrington de González had the original idea for this study, acquired the data, did the calculations, and wrote the initial draft of the manuscript. Both authors contributed to design of the study, interpretation of the results, and critical revision of the manuscript. Both authors discussed and approved the final version.

Conflict of interest statement

None declared.

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