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Potential risks of cardiovascular and cerebrovascular disease and cancer due to cumulative doses received from diagnostic CT scans?

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Abstract

Potential risks from radiation exposure on the development of cardiovascular and cerebrovascular disease are indicated by epidemiological studies. Medical exposures give the largest dose to the population from artificial sources, with cumulative doses from multiple CT scans being significant. Data on doses from scans performed on 12 CT scanners in three hospitals over a period of 5½ years, derived using Radimetrics™ software, have been reviewed for 105 757 patients. Data have been downloaded for heart, brain, thyroid, and effective doses, and cumulative doses analysed using Excel™ spreadsheets. 2.4% of patients having body CT scans received cumulative doses to the heart over 100 mSv, 9% of whom were under 50 years. 9.6% of patients having head CT scans received cumulative doses to the brain over 100 mSv with 0.08% over 500 mSv from whom 41% were under 50 years, but only 1.3% of patients scanned had thyroid/carotid artery doses over 100 mSv. An approximate evaluation of potential risks from exposures of the heart above 100 mSv and brain over 500 mSv for patients under 60 years would suggest that at most only one patient would demonstrate any excess risk from vascular disease resulting from the exposures. 0.67% of patients scanned received effective doses over

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100 mSv, in line with results from European studies, with 8.4% being under 50 years. The application of age and sex specific risk coefficients relating to excess cancer incidence suggests that two or three patients with effective doses over 100 mSv and five patients with effective doses between 50 and 100 mSv, from those examined, might develop cancer as a result of exposure. However, this will be an overestimate, since it does not take patients' health into account. Exposure management software can aid in evaluating cumulative doses and identifying individual patients receiving substantial doses from repetitive imaging.

Keywords: heart dose, brain dose, cumulative effective dose, computed tomography, cardiovascular effects, cerebrovascular effects

(Some figures may appear in colour only in the online journal)

1. Introduction

Heart and circulatory diseases account for just over 25% of deaths in the UK each year. Coronary artery and cerebrovascular diseases are linked to atherosclerotic changes in the arteries, and represent the principal causes of vascular disease mortality and morbidity. These diseases are strongly influenced by smoking, diet, and other lifestyle and individual factors, but radiation exposure can contribute through microvascular damage to the myocardium, leading to tissue degeneration and fibrosis, that accelerate the development of atherosclerosis. An increased risk of cardiovascular and cerebrovascular disease from radiation exposure was observed in data from the Life Span Study cohort of the Japanese atomic bomb survivors (1950–2003), who exhibit excess relative risks for both heart disease and stroke that increase with dose [1–3]. Approximately 60% of radiation-related excess non-cancer deaths among this group have been from circulatory disease [4].

Risks of cardiovascular disease can be increased by several fold in patients treated with radiotherapy for cancers in the thorax [2]. Examples from recent studies include increases in ischaemic heart disease in women treated for breast cancer [5], in coronary heart disease for patients receiving treatment for Hodgkins lymphoma [6], in cardiac mortality among patients receiving radiotherapy for treatment of the oesophagus [7], and in the incidence of grade 3 cardiac events, namely acute coronary syndrome events or congestive heart failure, among patients receiving radiotherapy for lung cancer [8]. These studies also report that risks are significantly higher among individuals with pre-existing cardiac disease. Based on the evidence available, ICRP 118 concluded that there are excess risks of heart disease for patients given radiotherapy that results in acute heart doses of 1 to 2 Gy with the excess risks becoming apparent 10–20 years after exposure, but there may not be a dose threshold below which no effect occurs [2].

Patients treated with radiotherapy for head and neck cancer (50–70 Gy) have significantly increased risks of carotid artery stenosis [9] and stroke [10, 11]. Meta-analyses of data from around the world have shown a doubling in the risk of stroke among patients receiving radiotherapy of the head and neck [12–14] reported that the increase in ischaemic cerebrovascular events in head and neck patients was linked to the volume of the carotid arteries receiving doses of 10 Gy. ICRP 118 concluded that the risks of cerebrovascular effects from radiation exposure are similar to those for cardiovascular disease, but with a possible threshold dose of 0.5 Gy [2].

Following on from the concern raised, cohort studies have been carried out on other populations irradiated through accidental or occupational total-body exposures [15]. Raised

incidences of cerebrovascular and cardiovascular disease have been reported among Chernobyl liquidators who received doses in the range 150–250 mGy [16, 17], and workers at the Mayak nuclear plant who received whole body doses up to 2 Gy [18, 19]. Relationships between risk of circulatory disease and radiation dose extending down to 100 mGy have also been observed among workers in nuclear establishments in the UK, USA and France [20, 21], and the UK national registry for radiation workers shows a link between cumulative dose and mortality from ischaemic heart disease [22]. However, there is substantial heterogeneity in the association between radiation exposure and circulatory disease. Based on the available evidence ICRP 118 proposed that a threshold acute dose of about 0.5 Gy for both cardiovascular and cerebrovascular disease may lead to approximately 1% of exposed individuals developing the diseases starting about 10 years after exposure [2].

Medical exposures make up the largest source of radiation dose to the general population from artificial sources. Repeated radiological diagnostic or interventional procedures can lead to significant radiation exposure of individual patients. The largest contributor to doses from medical imaging is computed tomography (CT) scanning. There have recently been a number of studies demonstrating that substantial numbers of patients receive effective doses over 100 mSv from CT scans in the USA [23, 24] and Europe [25]. The proportion of patients receiving effective doses at this level in European hospitals was 0.65% on average and varied between about 0.02% and 5% at individual hospitals [25], while the numbers of patients aged under 50 years in these studies were not insignificant [23]. Doses to individual organs within the scanned field may be much larger than the effective dose, so it is likely that organs with an associated risk of cardiovascular or cerebrovascular disease for some patients may receive doses in the range that could increase risks of vascular disease. A single chest CT scan will typically give can a dose of 6–16 mGy to the heart, while a head CT scan can give doses of 20–60 mGy to the brain. A study has therefore been carried out to evaluate cumulative doses to the heart, brain and carotid arteries that are linked to cardiovascular or cerebrovascular disease for CT scans performed in a UK hospital trust.

Concern about cumulative doses from medical imaging has been the subject of recent technical meetings organised by the International Atomic Energy Agency (IAEA). Following these, a position statement calling for action in strengthening radiation protection of patients undergoing recurrent imaging procedures has been issued [26] endorsed by the European Federation of Organisations for Medical Physics, European Society of Radiology, Global Diagnostic Imaging, Healthcare IT and Radiation Therapy Trade Association, Heads of European Radiological Competent Authorities, Image Gently Alliance, International Organisation for Medical Physics, International Society of Radiology, International Society of Radiographers and Radiological Technologists, in collaboration with the World Health Organisation. This encourages actions to:

- Assess the level of recurrent radiological imaging and associated radiation doses.
- Undertake research to understand the distribution, frequency, and magnitude of recurrent imaging.
- Develop strategies for radiological imaging in clinical conditions that require recurrent imaging.
- Monitor radiation exposure history of patients.

In this study, cumulative effective doses have also been evaluated in order to determine whether the numbers and proportions of patients receiving effective doses over 100 mSv is similar to results reported in the USA and Europe [23–25].

2. Methods

The Radimetrics^{TM} dose management software (version 3.0 A; Bayer AG Berlin, GDR) is installed on a virtual machine hosted at the Oxford University Hospitals NHS Foundation Trust (OUH). Images, including dose sheets from all the CT scanners within the trust, are sent to the picture archiving and communication system (PACS) and then forwarded on to the Radimetrics platform for processing. A query/retrieve connection to the PACS from the Radimetrics platform is also enabled to ensure that the Radimetrics database is kept up to date. Dose information such as dose length product and the volume averaged CT dose index ($CTDI_{vol}$) as well as scan parameters for the examination and individual acquisitions are extracted from the digital imaging communications in medicine (DICOM) fields of the images or from the dose sheet by automatic character recognition. The OUH as of June 2021 has had 12 CT scanners at three sites since late 2015, five of which have been replaced. The CTs consist of four GE Lightspeed VCTs, one Canon Aquilion 64, three GE Revolution HDs, one GE Revolution CT (256 slice), and three Siemens Somatom Drives.

The Radimetrics Platform uses a Monte Carlo simulator including x-ray source spectra and patient phantoms for modelling the x-ray interactions with patient tissues. The patients are represented by a set of stylised phantoms with organs depicted as simple geometric shapes [27, 28], with seven phantoms representing newborn, 1, 5, 10, and 15 years old children and male, female and pregnant female adults. In addition, bariatric phantoms are constructed by adding layers of adipose tissue to the torso. The phantom selected for each patient for the organ and tissue dose calculations is based on age, gender and mid-scan diameter or weight. Values for an effective dose are calculated by combining theses doses using tissue weighting factors [29] There are a total of 54 different phantoms that are listed in the Radimetrics platform.

The software contains simulations run for different scan protocols for each phantom and data on the energy deposited in every organ within each slice are obtained from a look-up table, based on the scan parameters and patient information, and the organ doses for individual scans scaled based on $CTDI_{vol}$. The $CTDI_{vol}$ is an important parameter for calculation of patient dose and therefore the $CTDI_{vol}$ calibration of each CT scanner at the OUH is checked at acceptance of the unit and also biennially during the CT scanner's lifetime. The Radimetrics platform allows exporting of patient and examination data through the summary pages of the user interface. Records can be listed in three levels, patient, examination, and acquisition. Once the record level is chosen, filters can be applied to the data. Protocols for a clinical indication can be named differently on each CT scanner and therefore these device protocols can be linked to one master protocol within the Radimetrics platform. Identification and filtering are more effective when using the master protocols rather than attempting to include every device protocol that is on the database.

The unit of analysis for the study was the examination event, which included summed data from all acquisitions during a single visit to the CT scanner and so may represent more than a single scan. The exporting of acquisition events removed detailed series descriptions, but collected all the dose data and reduced the size of the dataset to be manipulated. The examination events were filtered by date, modality, device and master protocol. All head and body master protocols were included in the filter, so that only extremity and interventional procedures were excluded. Only the relevant fields from the records for the analysis were selected during the export, this included protocol name, series description, date performed, device, patient medical record number (MRN), gender, age at exam and finally organ doses and effective dose. Data on patient doses have been accumulated over a period of $5\frac{1}{2}$ years from CT scans performed between 26 October 2015 and 6 May 2021. In order to evaluate cumulative doses, data were downloaded into an Excel^{TM} (Microsoft Corp, Redmond, WA, USA) spreadsheet for 215 194

Table 1. Example of results of further processing that was performed in Excel™.

Scan	Gender	Age	ID	No. of Exams	Sum of brain CT (mGy)	Sum of thyroid CT (mGy)	Sum of heart CT (mGy)	Sum of E (mSv)
Head (6)	M	64	1	6	276.081	103.889	4.508	19.1

E indicates effective dose.

CT examinations performed on 105 757 patients receiving CT scans over the period, for the heart, thyroid and effective dose, 65 394 of whom had body scans and 58 430 head scans, with over 18 000 having both (18 067). The thyroid was used as a surrogate for the carotid arteries since these doses are not evaluated by the software. Patient MRNs were removed and replaced with a nonidentifiable key. This was completed by removing MRN duplicates, assigning a unique key to each unique MRN and then using a lookup table to link the key to each MRN in the main data export. Once checked and the accuracy confirmed of the assigning of keys to the correct MRN, all patient MRN data was removed.

Further processing was completed to provide a table which consisted of one row and nine columns for each patient (table 1). Protocol names in the original export from Radimetrics were edited manually to be characterised as either body or head examinations using the Excel filter. If a patient had received both head and body examinations during the analysis period, these were listed as 'head/body' and included the number of those examinations, for example one body and one head exam is listed as 'body (1)/head (1)'. The doses from Radimetrics software are all recorded in mSv, but it is more appropriate for doses to organs and tissues to be given as mean absorbed doses in mGy [30], so this approach will be adopted here.

$CTDI_{vol}$ calculations are calibrated on a 16 cm phantom for head and some paediatric scans and a 32 cm phantom for body scans. The choice of phantom for calculation of $CTDI_{vol}$ from a particular protocol is selected when the protocol is first created and could introduce a source of error for the reported $CTDI_{vol}$ and subsequently the organ doses calculated within the Radimetrics platform. Review of the data extracted revealed that the head phantom had been selected for spine examinations on one CT scanner used during the 1st 4 years of the study. This would approximately double the organ doses calculated for the spine examination, but only affected 205 or 0.2% of the patients within the dataset.

3. Results

3.1. Distribution of organ doses among patient cohort

Doses to the relevant organs from all scans performed were summed for each patient, and separate sets for each organ were ordered according to dose levels so that numbers of patients receiving doses within given ranges could be identified for each organ. 5609 patients received cumulative doses to the brain of over 100 mGy from CT head scans, 1545 received cumulative heart doses over 100 mGy from body scans, and 1426 received thyroid doses over 100 mGy. Since cardiovascular and cerebrovascular effects are only manifest 10–20 years after exposure, the proportions of patients within different age ranges receiving higher doses were assessed, and percentages in different dose ranges are given in table 2. The cumulative effective doses received by patients were analysed to allow comparison with studies performed in other parts of the world. A total of 713 patients received effective doses over 100 mSv and a further

Table 2. Proportions of CT patients who received doses to organs considered to present a risk for vascular effects within different dose ranges. The percentages relate to all patients having scans. For the brain the proportions are also given as a function of the number having head scans.

Organ/tissues	20–50 (mGy)	50–100 (mGy)	100–150 (mGy)	150–200 (mGy)	200–300 (mGy)	300–400 (mGy)	400–500 (mGy)	>500 (mGy)
Heart	31.3%	3.8%	1.6%	0.44%	0.23%	0.044%	0.011%	0.007%
Thyroid	13.5%	4.8%	0.85%	0.33%	0.14%	0.024%	0.004%	—
Brain (all CT)	24.2%	10.7%	3.2%	1.1%	0.71%	0.17%	0.052%	0.044%
Brain (CT head)	43.8%	19.5%	5.7%	2.07%	1.29%	0.315%	0.10%	0.080%
Effective dose (mSv)	13.8%	2.8%	0.49%	0.12%	0.051%	0.004%	—	—

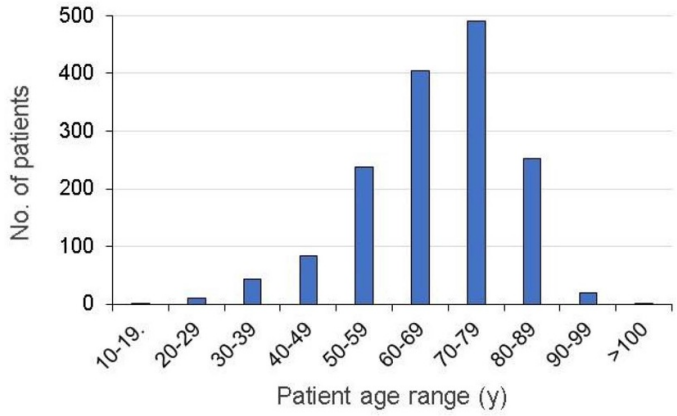

Figure 1. Bar chart showing the numbers of patients in different age ranges receiving doses to the heart over 100 mGy from body CT scans.

2913 received doses between 50 and 100 mSv, and age and sex specific risk coefficients were applied to the data to evaluate the potential excess incidence of cancer resulting from the exposures [30].

3.2. Cardiovascular effects and heart doses

The main organ at risk for cardiovascular effects was considered to be the heart which included the coronary arteries. 2.4% of patients received a dose to the heart of over 100 mGy with one patient receiving over 600 mGy. The distribution of heart dose among patients in different age groups is shown in figure 1 with 139 patients under 50 years, making up 9% of patients receiving a dose to the heart over 100 mGy and 0.2% of all patients having body CT scans. Ten times fewer patients received doses over 200 mGy, than 100 mGy, and the patient age distributions were similar for both groups. Patients who received doses over 500 mGy ranged in age from 57 to 76 years. An assessment of whether doses from CT examinations of the trunk might increase the risk of cardiovascular disease was made by applying the ICRP risk coefficient of 1% for a dose of 500 mGy pro rata to all patients under 60 years who received a dose to the heart of over 100 mGy, as there may be no threshold dose for cardiovascular effects [2] and this suggested that one patient might be affected, but the numbers of patients even approaching the 500 mGy level was minimal (table 2), so if this were the threshold, the actual risk would appear to be extremely small.

3.3. Cerebrovascular effects and doses to the brain and carotid arteries

Individual patients received doses to the brain of up to one gray from head CT scans. 5609 patients making up 9.6% of the total received doses to the brain over 100 mGy, with 47 patients receiving over 500 mGy (table 2) of which 41% were under 50 years. The age distribution for patients receiving brain doses over 200 mGy and 500 mGy were rather different (figure 2), with a greater proportion of younger patients among the group receiving the higher dose. In order to obtain an approximate assessment of whether doses from CT examinations might produce a risk of cerebrovascular disease, the ICRP risk coefficient of 1% for a dose of 500 mGy was applied pro rata to all patients under 60 years who received a dose to the brain of over 500 mGy,

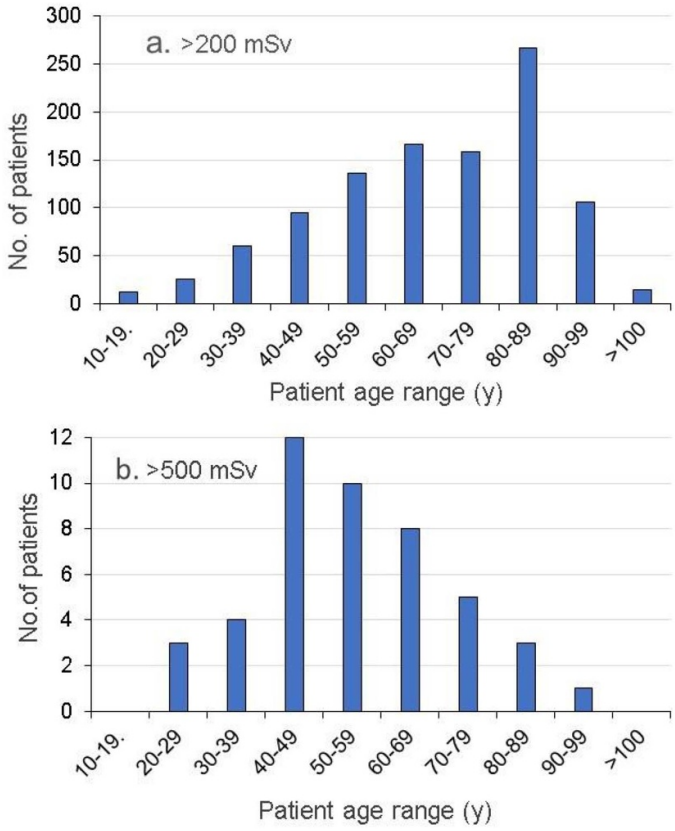

Figure 2. Bar chart showing the numbers of patients in different age ranges receiving doses to the brain from head CT scans: (a) over 200 mGy and (b) 500 mGy.

which is the threshold dose suggested for cerebrovascular effects [2], this gave a 40% risk that one patient might be affected.

Irradiation of the carotid artery as well as the brain can potentially contribute to cerebrovascular effects, so an attempt was made to assess carotid doses by using the thyroid gland as a surrogate. Since the thyroid is on the periphery of head and body scans, both may make contributions to the dose, so all CT scan patients were included in the assessment. Although 1426 patients (1.35%) had thyroid doses over 100 mGy, none received over 500 mGy (table 2) and the distribution of patient ages was similar to that for body scans (figure 3).

3.4. Cumulative effective dose

In order to allow a comparison with studies of cumulative doses from CT scans in other parts of the world, the proportion of patients with cumulative effective doses over 100 mSv was assessed. 713 patients had cumulative doses over 100 mSv, which represents 0.67% of the total number having CT scans (table 1). The age distribution for patients receiving doses over 100 mSv (figure 4(a)) followed similar patterns to the distribution for all patients, and 60 patients, making up 8.4% of this group, were under 50 years, representing 0.06% of all patients undergoing CT scans. The effective doses with an associated 1% risk of cancer induction

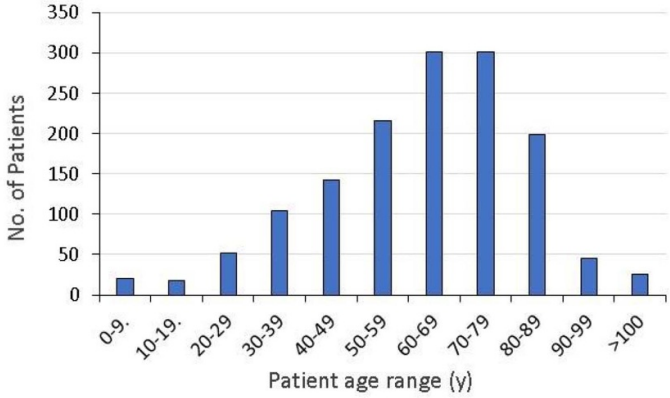

Figure 3. Bar chart showing the numbers of patients in different age ranges receiving doses to the thyroid over 100 mGy from body or head CT scans.

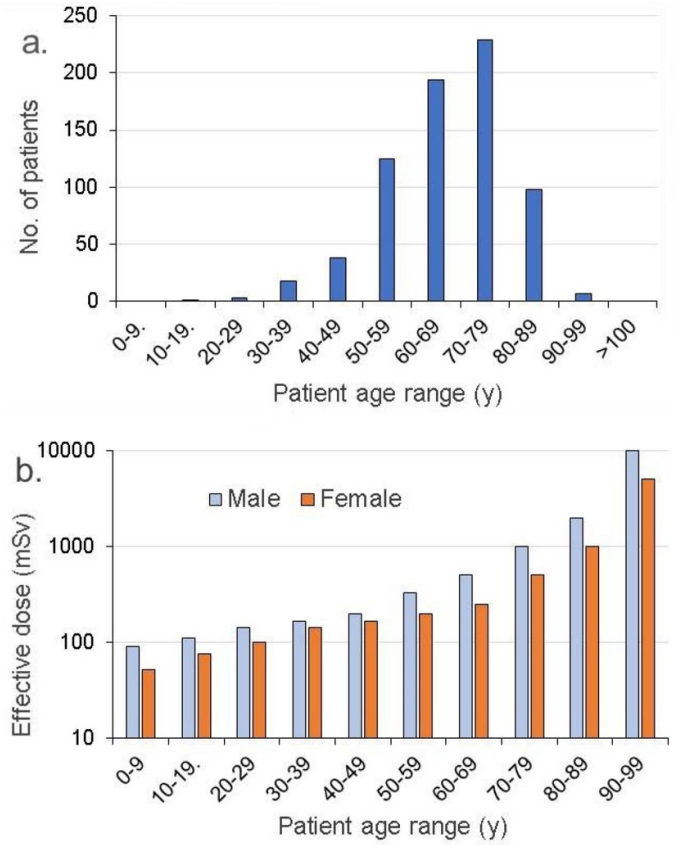

Figure 4. Bar charts showing (a) the numbers of patients in different age ranges receiving effective doses over 100 mSv, and (b) the cumulative effective doses from chest abdomen pelvis CT scans with a 1% excess risk of inducing cancer for different sexes and age ranges.

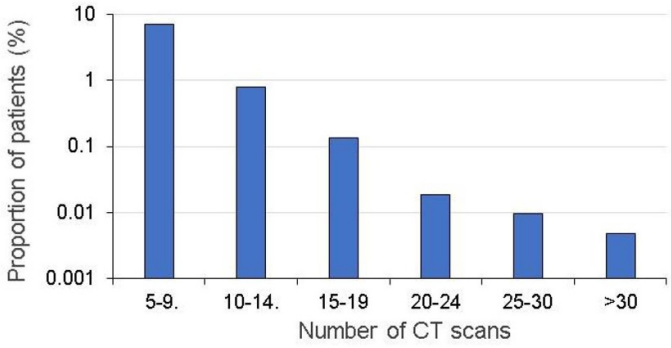

Figure 5. Proportions of patients receiving different numbers of CT examinations.

for a chest abdomen pelvis CT scan were calculated from the data in ICRP Publication 147 [30] and are given in figure 4(b) for comparison. It can be seen that the effective dose with an associated 1% risk for CT scans is 100 mSv at the age of about 30 years, 200 mSv at 50 years, and 500 mSv at 70 years. Age and sex specific risk coefficients relating to cancer incidence for chest abdomen pelvis CT examinations [30] were applied to the effective doses for all patients receiving effective doses over 100 mSv and those receiving doses between 50 and 100 mSv. The results indicated that between two and three of the 713 patients receiving effective doses over 100 mSv might be expected to develop cancer as a result of the radiation exposure, while five patients from the 2916 receiving effective doses between 50 and 100 mSv might develop cancer as a result, and these represent less than 0.01% of all patients scanned. When considering these numbers, it must be remembered that the health reasons for which patients are having CT scans may shorten the lives of many, so the actual risks are likely to be substantially lower. There were 29 patients with a greater than 1% excess risk of cancer incidence whose ages varied between 3 and 68 years with an average age of 46 years. Again, highlighting the need for an emphasis on a robust system of justification for patients who receive multiple scans. Figure 5 plots the numbers of CT scans that individual patients received which went up to over 30, with 8% receiving five or more scans, but less than 1% received more than ten scans. The average age of patients receiving ten or more CT scans was 66 years, with a range of 23 to 93 years.

4. Discussion

ICRP report 118 [2] suggests that an acute dose of 500 mGy can be taken as representing a threshold dose for the induction of changes in vascular systems that might lead to a 1% excess risk of cardiovascular or cerebrovascular disease after 10–20 years. Since most people will from time to time have medical imaging investigations, many of which could involve CT scans, these could potentially contribute to the development of vascular disease. The availability of organ dose data from dose management software systems provides an opportunity to evaluate potential exposures to organs at risk from CT scans and may help in the assessment of potential risks. In this study doses to the heart, brain and thyroid, used as a surrogate for the carotid artery, have been evaluated for 105 757 patients. The proportions of patients having body scans, who receive significant doses to the heart, and patients having head scans, who receive high doses to the brain, have been evaluated.

The radiation doses to the heart and brain reported here each represent a series of exposures, usually tens of mGy, that have been accumulated over the study period of 5½ years. They differ from acute doses received by the Japanese atomic bomb survivors [1–3] or by radiotherapy patients [5, 7, 8, 10, 11] on which much of the epidemiological evidence of cardiovascular and cerebrovascular effects are based. However, since there is now accumulating evidence that these effects may occur among workers at nuclear establishments [20–23], who receive organ doses similar to or lower than those received by many patients from imaging, there is a need to evaluate the potential risk from such effects. The mechanism of damage and how this might vary between chronic and acute exposures in not fully understood. If cells are damaged by radiation and the body is unable to repair the damage, the cells enter a senescent state. They will never again divide, but start to synthesise and secrete inflammatory molecules, and it is changes of this type in endothelial cells lining the coronary artery that underly atherosclerosis and cardiovascular disease. Senescent cells giving similar responses are present in the body naturally and the numbers increase with age. The effects of radiation will be more severe with higher exposures, but the form of the dose effect relationship is unknown or how this might vary with the age of the exposed individual. Therefore, a pro rata application of the approximate risk at an organ dose of 500 mGy, proposed by the ICRP, has been used to give an indication of potential numbers of patients that might be affected [2]. Cancer induction, on the other hand, occurs through DNA damage induced in cells that continue to divide taking forward genetic changes. The linear-no-threshold dose-effect model is used as the best alternative to describe cancer risk, but the form of the relationship below 100 mGy is uncertain, and risks from radiation exposure are known to be higher among younger persons [29].

Few patients received a dose over 500 mGy to the heart, suggesting that risks are relatively low. However, the assessments have only been made for CT scans carried out during a period of 5½ years, and patients, particularly those with heart problems, may receive additional exposures from interventional cardiology and other imaging procedures [31, 32]. Since studies of radiotherapy patients have shown that individuals with underlying heart conditions are the ones at a higher risk of developing further cardiovascular disease following radiation exposure [5, 8], this group is likely to be at particular risk. Studies of heart doses from interventional procedures are limited. A study in a UK paediatric hospital reported typical doses to the heart of 20–40 mGy per procedure with doses for some procedures of several 100 mGy [33]. The same authors reported heart doses of several 100 mGy for paediatric cardiology procedures based on analysis of dose measurements for the upper 90th percentile of cases in data published by the National Council on Radiation Protection and Measurement with heart doses over 1 Gy for some patients in the 70–85 kg weight range [34]. Reports of high doses from interventional procedures on adults include endovascular aortic aneurysm repair (EVAR), a life-saving procedure. Doses reported for EVAR include median cumulative doses to organs in the trunk of 190–270 mGy [35], and median heart doses of 84 mGy with some cases reaching several 100 mGy [36]. The body CT scans received by a proportion of patients in this study are likely to either precede or be ancillary to interventional procedures and the summation of doses from the two types of procedure could result in some patients receiving doses above 500 mGy. Therefore, cumulative doses to the heart received from both CT and interventional procedures have the potential to increase the risk of cardiovascular disease, especially in paediatric patients.

Doses to the brain from CT head scans are more significant with 0.1% of patients receiving doses above 500 mGy, of which 41% were under 50 years. The age distribution for patients receiving cumulative doses to the brain over 500 mGy differed from that for other procedures (figure 2(b)), which may be linked to the severity and more rapid evolution of disease, and

requirements for monitoring disease progression and effectiveness of treatment, although the numbers in the group analysed are limited. When the risk coefficient of 1% for a dose of 500 mGy [2] was applied pro rata to all patients under 60 years who received a dose to the brain of over 500 mGy, this suggested that there was a 40% risk that one patient might develop cerebrovascular disease as a result. Doses to the carotid artery based on the thyroid dose did not exceed 500 mGy over the period of the study. Thus, exposure of the brain from CT imaging presents the main risk of contributing to cerebrovascular disease, and this is lower than the potential risk of brain cancer identified in other studies [37, 38]. The approximate evaluation of risks for both cerebrovascular and cardiovascular disease suggests that it would be unlikely that more than one patient, from all those scanned over the period of the study, would be affected.

The study of cumulative effective doses showed that 0.67% of patients received over 100 mSv during the 5 years period, which is similar to the average for European countries [25], and 8.4% of patients in this group were under 50 years. Application of the risk coefficients relating to age and sex in figure 4(b) shows that there is a 1% excess risk of cancer incidence relating to radiation exposure from a cumulative effective dose due to CT scans of the trunk amounting to 100 mSv at an age of 30 years and 200 mSv at an age of 50 years. This emphasises the greater importance of proper justification and optimisation of CT scans for younger age groups. The application of age and sex specific risk coefficients relating to excess cancer incidence, based on the LNT model, indicated that the radiation exposure from the CT scans might lead to between two and three patients with effective doses over 100 mSv developing cancer and five patients with effective doses between 50 and 100 mSv. However, the risk coefficients relate to healthy individuals, and since the patients' health conditions will in many cases shorten their lives, the actual number is likely to be substantially lower. The results provide supporting evidence for the call for action in terms of strengthening radiation protection of patients undergoing recurrent imaging procedures, through monitoring of frequencies and magnitudes of recurrent imaging, and developing strategies for clinical conditions for which it is required [26].

5. Limitations of the study

The study summed doses to organs considered to be associated with a risk of cardiovascular or cerebrovascular disease from CT scans derived from a Radimetrics dose management system. The software calculated organ doses based on standard phantoms, with limited adjustment for patient size. There may therefore be significant differences in organ doses for some patients from actual values [39, 40].

Doses for spine CT examinations on one CT scanner were based on a 16 cm phantom instead of the 32 cm one. This affected 205 or 0.2% of the patients within the dataset and would double the calculated organ doses for those scans. Doses have only been evaluated for a period of $5^1/_2$ years and the organs of the same patients could have received other similar doses previously or may in the future.

The assessments of risk for cardiovascular and cerebrovascular disease for body and head scans are crude because of the limited information available and are only intended as approximate indicators of possible levels of risk. Calculations of risk for cancer incidence from effective dose simply use age and sex factors based on the LNT model and all body CT examinations are assumed to have risk coefficients similar to those for chest abdomen pelvis CT scans. None of the calculations take account of the health of individual patients, which may shorten their lives, and so are likely to overestimate risks.

6. Conclusions

Assessments of doses to their heart, brain and carotid arteries relating to the risks from cardiovascular and cerebrovascular disease have been made for patients undergoing CT scans over a $5^1/_2$ years period for 12 CT scanners at three hospitals. 2.4% of patients having body CT scans received cumulative doses to the heart of over 100 mGy, and 9% of these were under 50 years with one patient receiving a heart dose over 600 mGy. There may be a small risk of contributing to cardiovascular disease, especially for patients who might also be exposed during interventional cardiology procedures.

9.6% of patients having head CT scans received cumulative doses to the brain over 100 mGy with 0.08% over 500 mGy and one patient over 1 Gy. 41% of those receiving a dose over 500 mGy were under 50 years. However, only 1.3% of patients scanned had carotid artery doses over 100 mGy and none over 500 mGy. Thus, irradiation of the brain from head CT scans could potentially contribute to cerebrovascular disease, but risks are likely to be limited.

Taking all CT scans together 0.67% of the patients received cumulative effective doses over 100 mSv, which represents a similar proportion to that found in other European studies. 8.4% of these patients were under 50 years, representing 0.06% of all patients undergoing CT scans. The application of age and sex specific risk coefficients relating to excess cancer incidence suggests that between two and three patients with effective doses over 100 mSv, but this is likely to be an overestimate, since it does not take the patients' health into account. The use of exposure management software, such as that provided by Radimetrics, could aid in evaluating doses from recurrent imaging and identifying individual patients who receive substantial doses, as proposed by the IAEA statement [26], as well as aid in optimisation of CT scan protocols.

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