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Radiation dose to the lens from CT of the head in young people

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AIM: To determine cumulative scan frequencies and estimate lens dose for paediatric computed tomography (CT) head examinations in the context of potential cataract risk.

MATERIALS AND METHODS: The cumulative number of head-region CT examinations among a cohort of 410,997 children and young adults who underwent CT in the UK between 1985 and 2014 was calculated. Images from a sample of these head examinations (n=668) were reviewed to determine the level of eye inclusion. Lens dose per scan was estimated using the computer program, NCICT V1.0, for different levels of eye inclusion and exposure settings typical of past and present clinical practice.

RESULTS: In total 284,878 patients underwent 448,108 head-region CT examinations. The majority of patients (72%) had a single recorded head-region examination. A small subset (~1%, n=2,494) underwent ≥10 examinations, while 0.1% (n=387) underwent ≥20. The lens was included within the imaged region for 57% of reviewed routine head examinations. In many cases, this appeared to be intentional, i.e. protocol driven. In others, there appeared to have been an attempt to exclude the eyes through gantry angulation. Estimated lens doses were 20–75 mGy (mean: 47 mGy) where the eye was fully included within the examination range and 2–7 mGy (mean: 3.1 mGy) where the lens was fully excluded. Potential cumulative lens doses ranged from ~3 mGy to ~4,700 mGy, with 2,335 patients potentially receiving >500 mGy.

CONCLUSION: The majority of young people will receive cumulative lens doses well below 500 mGy, meaning the risk of cataract induction is likely to be very small.

Abbreviations: SMB, supraorbital-meatal baseline; IMB, infraorbital-meatal baseline; $CTDI_{VOL}$, Volumetric computed tomography dose index.

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Introduction

Radiation exposure to the lens of the eye results in the formation of cataracts.[1–5] For many years it was assumed that the low-dose threshold for cataract induction was around 2,000 mGy, thus well above the normal range of absorbed doses delivered by diagnostic radiography, computed tomography (CT) and diagnostic/interventional fluoroscopy. Recent epidemiological and biological evidence suggests that this threshold may be lower than previously thought, at around 500 mGy.[1,4] A zero-dose threshold, implying cataract induction is a stochastic effect rather than deterministic, is also a possibility.[1] This necessitates a re-evaluation of the potential cataract risk following diagnostic X-ray examinations, especially following multiple exposures. Most recent research investigating eye doses in medical imaging has focused on staff members,[6] particularly those working in interventional fluoroscopy.[7–11] Despite the interest in eye dose in the early days of CT,[12,13] the topic has received limited attention in recent years, e.g. Ref.[14]

Head examinations are the most common CT examination among young people.[15–17] The eyes may or may not be included within the area of primary irradiation depending on gantry angulation, patient position,[13,18] and examination technique. Both infraorbital–meatal baseline (IMB) and supraorbital–meatal baseline (SMB) positioning techniques are used in clinical practice (Fig 1). The eyes are usually fully included within the primary examination region for IMB technique examinations and may be either included or excluded using the SMB technique depending on inferior examination range extent. In some cases, the choice of examination technique may be restricted. Patient position is often fixed (e.g., patient strapped to a spinal board). Helical scan mode usually prevents gantry angulation. Furthermore, the eyes may be directly irradiated despite being outside the imaged region, due to z-overranging effects.[19,20] For these reasons, sequential, non-helical scan mode is often used for head examinations.

It is unclear if the risk of cataract induction is, or ever has been, sufficiently high to influence examination technique. To address this question, it is necessary to (1) determine how many head examinations patients are likely to receive, (2) determine the level of inclusion of the eyes and lens within the imaged region, and (3) estimate the absorbed dose to the lens, per examination, based on different levels of eye inclusion.

Materials and methods

The study was part of a wider research programme investigating the long-term health effects of CT examinations among children and young adults (<22 years).[21,22] The study, based on the core EPI-CT protocol, has involved the establishment of a cohort of 410,997 individuals who underwent at least one CT examination between 1 January 1985 and 1 January 2014, through downloads of examination records held on the radiology information system (RIS) at 90 NHS hospitals in England, Scotland, Wales, and Northern Ireland.

Cumulative examination frequencies

The records of all patients who underwent one or more head-region examination were extracted from the cohort database. These included routine head examinations (those listed as “head”, “cerebrum,” or “brain”, with or without contrast enhancement), and “other” examinations of the head region, including those of the orbits, internal auditory meatus (IAM), pituitary fossa, petrous bones, sinuses, temporomandibular joints, and facial bones. Examinations of multiple regions, e.g. “head and facial bones”, were classed as “other.”

The number of patients undergoing ≥5, 10, 20, 30, 40, and 50 head-region examinations was calculated. Potentially, some patients could have received additional examinations outside the data collection period. A sensitivity analysis was performed by restricting analysis to patients whose first 10, 18, or 22 years of life fell within the data collection period at their respective hospital.

Eye inclusion

The lens is clearly visible on CT images as a region of relatively high attenuation within the globe. To determine technical parameters for examinations, all contributing hospitals were approached and asked to send complete sets of images for examinations performed on cohort members. This was limited by available resources and difficulties in retrieving films from long-term storage. Of the acquired sets

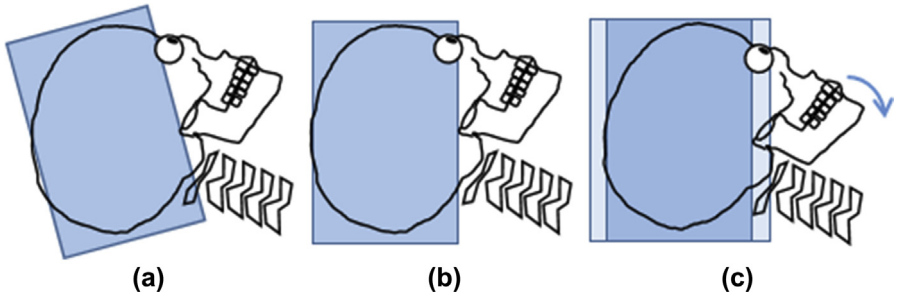

Figure 1 (a) SMB and (b) IMB positioning techniques for CT head examinations. (c) Helical scan with a fixed gantry angle. The head position is adjusted to exclude the eyes, which remain within the z-overranging region (light blue area).

of images, 668 were of the head, performed at 35 hospitals from 1986 to 2013. This sample was representative of the wider cohort, including examinations performed at all hospital types and with wide geographical coverage. These images were used to determine the level of eye inclusion in clinical practice. Only routine head examinations were included in this part of the analysis. Examinations in which some form of unusual patient posture or adaptive technique was evident (e.g. patient was lying on side) were also excluded as were examinations suggesting an uncooperative patient (extensive movement artefacts, head changing orientation between slices).

Each examination was classified according to the level of inclusion of the eyeball and lens: (1) eyes completely included within the examination range: at least one slice inferior to the eyes in which no portion of the eyeball was visible; (2) eyes completely excluded from examination: no portion of eyeballs visible on any slices; (3) partial inclusion of eyes with lens excluded; (4) partial inclusion of eyes with lens included; (5) "skimmed" examinations in which eye inclusion was limited to partial volume effects of the superior aspect of the eyes only.

Dose estimation

Absorbed dose (D) represents the energy deposition per unit mass of material and is measured in gray (Gy, where 1 Gy = 1 J/kg). It can never be directly measured in patients, only estimated. This is typically achieved using an indicator of radiation exposure recorded at the time of examination, such as volumetric CT dose index ($CTDI_{VOL}$). $CTDI_{VOL}$, measured in milligray (mGy), has been automatically recorded for all CT examinations for the last decade or so. It is approximately equivalent to the average absorbed dose per section. Although a useful dose metric in its own right (e.g. for audits), CTDI is more meaningful, in terms of risk indication, when converted to absorbed dose or effective dose.

Absorbed dose to the lens was estimated, for eye inclusion levels 1 to 4, and exposure values typical of past and current clinical practice, using the computer program, NCICT V1.0, developed by Lee *et al.*[23] NCICT is based around section position-specific and patient size/sex-specific conversion factors relating the $CTDI_{VOL}$ to absorbed dose to 33 organs and tissues. If the $CTDI_{VOL}$ is not known, NCICT estimates it based on CT machine manufacturer/model-specific coefficients[24] for given values of tube potential (kV) and tube current–time product (mAs). Conversion factors were determined using the Monte Carlo code MCNPX, incorporating hybrid paediatric phantoms (0, 1, 5, 10, and 15 years)[25] and International Commission on Radiological Protection (ICRP) adult[26] phantoms. These phantoms were constructed using non-uniform rational B-spline (NURBS) surfaces from CT images. Each tissue type, including the eyeball and lens, has a specific composition and density (1.03 and 1.07 g/cm^3, respectively).[25] Monte Carlo simulations were obtained using a model of a reference CT machine (Siemens Sensation 16). Dose estimates take into account energy deposition outside the nominal section width due to scattering, but not z-overranging. Monte Carlo simulation uncertainties were reported to be below 2% for major organs.[23]

Two sources of input data were used for lens dose estimates: (1) the same sample of images reviewed for the eye inclusion analysis, and (2) national surveys completed for the purposes of reference dose establishment.[27–34] The former provided information on older examinations performed between 1985 and 2010, whereas the latter provided information more representative of current practice. For most examinations in the image sample, $CTDI_{VOL}$ was not recorded, thus tube current and voltage were used as the primary input parameters. Values were extracted for a range of manufacturers and models typical of past and current clinical practice, for patients aged 0–10 years and >10 years. The number of examinations for specific scanner types was insufficient to allow more detailed age breakdowns. If tube current modulation was used, the mean value for the base of skull region was used in dose estimates. The 5-year-old male phantom was used to estimate doses for the 0–10 year range and the 15-year-old phantom used for the >10 year range. Differences in lens dose between male and female phantoms are negligible. For dose estimates using national reference data, age ranges were the same as given in the respective report. If separate $CTDI_{VOL}$ figures were given for base of skull and cerebrum regions, the former were used.

Gantry angulation is not possible using NCICT. Different levels of eye inclusion were simulated by varying the inferior examination extent, while the superior extent was fixed (Fig 2). The two levels of partial inclusion were designed to approximate situations 3 and 4 in the scheme described earlier, although the lens itself is not identifiable in the user interface of NCICT.

Research governance

The study received a favourable ethical opinion and Confidentiality Advisory Group (CAG) approval for obtaining patient identifiable data without need for individual consent. All analysis was done using pseudonymised data.

Results

Across the cohort, 284,878 patients underwent 458,108 CT examinations of the head region between 1985 and 2013 (Table 1). Of these, 87% were routine head examinations. The majority of patients received a single examination only (Table 1), whereas around 1% of patients had >10 examinations. Restricting analysis to patients born within the data collection period and reaching 10, 18, or 22 years of age before the close of data collection made little difference to findings (Table 1). The mean number of head region examinations per patient was 1.6 (SD: 1.8, 95th percentile: 4, max: 94). The majority of patients (72%, n=206,029) had a single examination only. The mean patient ages at the time of examination were 11.5 years, 11.2 years and 13.6 years for all head region examinations, routine head examinations and other head examinations, respectively.

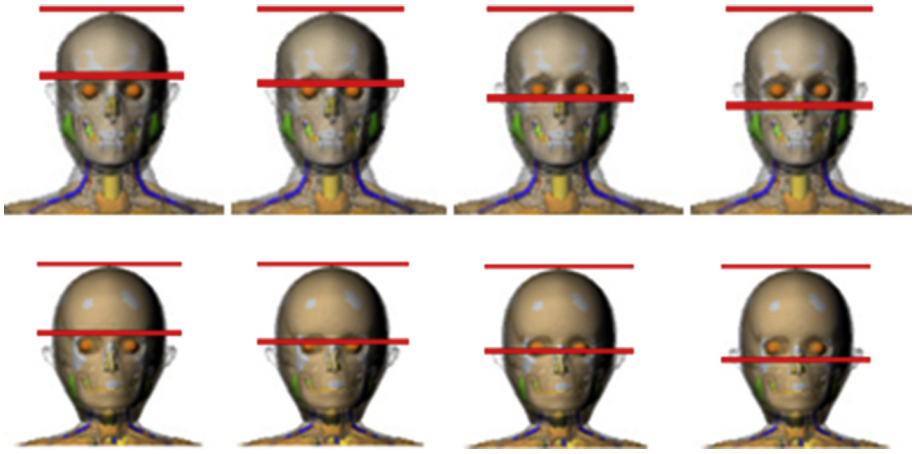

Figure 2 Examination start and finish locations for 15 year (top) and 5 years (bottom) hybrid phantoms in NCICT. From left to right: eyes fully excluded, eyes partially included (lens excluded), eyes partially included (lens included), and eyes fully included.

The percentage of routine head examinations with different levels of eye inclusion is given in Table 2. For hospital-specific figures, only hospitals from which 10 or more image sets were obtained are shown. For all 668 examinations reviewed, 88% included the eyes within the imaged region to some extent, while 57% included the lens. At two hospitals, the lens was included for almost all examinations. There was little suggestion of any impact of patient age on eye inclusion. Likewise, for a given hospital, there was no suggestion of any impact of year of examination on eye inclusion. Other than gantry angulation, no measures to reduce eye dose (e.g. bismuth shields) were noted. Only three helical head examinations were identified. All the remainder were acquired in sequential, non-helical mode.

Estimated lens doses, along with the exposure factor parameters used to derive these figures are given in Table 3 for a range of scanner types. Dose estimates derived from national reference level data are shown in Table 4 (based on mean $CTDI_{VOL}$) and Table 5 (based on 75th percentile $CTDI_{VOL}$). Lens doses varied by a factor of around 15, depending on level of inclusion of the eye within the examination range (Table 3). A seven-to tenfold difference in lens dose was seen for the two levels of partial inclusion. For the position approximating partial eye inclusion with excluded lenses (Situation 3), the lens dose was close to that achieved by complete exclusion, while lens doses were similar for partial inclusion with included lens (Situation 4) and full eye inclusion. An approximately 3–4-fold variation in doses was seen depending on scanner type and tube current/voltage settings.

These estimates assume non-helical examination mode. Z-overranging may extend the exposed range of helical examinations by 1–10 cm depending on model, collimation, section width, and pitch.[19] The diameter of the globe appears to be constant beyond age 1 year, at around 24 mm.[35] If the globe is just excluded from the imaged region, any Z-overranging length greater than around 1.5 cm will result in inclusion of the lens within the primary irradiated field. Thus for helical examinations, lens doses should be assumed to be approximately similar to situations in which the lens is fully included.

For 12 examinations of the orbits, the mean tube current was 308.4 mAs (range: 96–990 mAs), resulting in mean estimated lens dose of 41.3 mGy, assuming full inclusion of the eyes (range: 17.9–127.3 mGy). For eight IAM

Table 1
Number of individuals undergoing a given number of head-region CT examinations among a cohort of 410,997 children and young adults.

Cumulative no. examinations	Frequency of patients				
	Routine head examinations only	All head region examinations	Routine heads first 10 years FU[a]	Routine heads first 18 years FU[a]	Routine heads first 22 years FU[a]
≥1	250,097 (100%)	284,878 (100%)	64,066 (100%)	26,510 (100%)	10,393 (100%)
1	183,074 (73.2%)	203,910 (71.6 %)	44,876 (70.0%)	18,614 (70.2%)	7,241 (69.7%)
≥5	9,162 (3.7 %)	10,460 (3.7%)	3,147 (4.9%)	1,371 (5.2%)	591 (5.7%)
≥10	2,328 (0.9%)	2,568 (0.9%)	881 (1.4%)	387 (1.5%)	169 (1.6%)
≥20	363 (0.1%)	389 (0.1%)	161 (0.3%)	73 (0.3%)	32 (0.3%)
≥30	94 (<0.1%)	99 (<0.1%)	37 (0.1%)	19 (0.1%)	10 (0.1%)
≥40	34 (<0.1%)	36 (<0.1%)	15 (<0.1%)	8 (<0.1%)	6 (0.1%)
≥50	15 (<0.1%)	15 (<0.1%)	7 (<0.1%)	3 (<0.1%)	3 (<0.1%)

Percentage figures refer to the proportion of individuals in each cumulative examination frequency stratum with respect to all patients undergoing at least one head examination, rather than the cohort as a whole.

[a] Figures restricted to patients whose first 10, 18, and 22 years of follow-up (FU) was within the hospital-specific data collection period.

Table 2
Percentage of routine CT head examinations with different levels of eye inclusion.

Hospital ID	No. of examinations reviewed	Eye inclusion level				
		Fully excluded	Skimmed	Partial lens excluded	Partial lens included	Fully included
All hospitals	688	11%	11%	20%	22%	35%
1	21	35%	6%	18%	35%	6%
2	15	27%	27%	40%	0%	7%
3	12	17%	0%	42%	25%	17%
4	20	21%	26%	37%	11%	5%
5	39	0%	0%	0%	10%	90%
6	10	0%	0%	0%	20%	80%
7	89	39%	30%	18%	8%	4%
8	12	8%	0%	58%	25%	8%
9	49	18%	31%	33%	16%	2%
10	16	6%	0%	19%	75%	0%
11	186	0%	0%	1%	18%	81%
12	70	1%	6%	31%	40%	21%
13	20	0%	25%	50%	25%	0%
14	16	13%	6%	63%	19%	0%
15	19	0%	42%	37%	21%	0%

Only centres providing 10 or more examinations are shown for hospital specific figures.

examinations in the axial projection, the mean tube current was 265 mAs (range: 110–830 mAs). Lens inclusion was highly variable, ranging from fully included to fully excluded. The mean estimated lens dose was 14.2 mGy (range: 0.5–72.9 mGy). Doses for coronal projections could not be calculated using NCICT. The tube current values for coronal IAM examinations were generally the same as for axial examinations, with the eyes fully excluded. For 24 sinuses examinations, the majority were in the coronal plane only, fully including the eyes. For six axial examinations, the mean lens dose was 47 mGy (range: 22.2–76.2 mGy). There was no difference in tube current between axial and coronal examinations (mean: 289.4 mAs, range: 50–480 mAs). There were insufficient examinations of the petrous bones or pituitary fossa for meaningful analysis.

Cumulative lens dose scenarios

It was not possible to reliably estimate lens doses for the whole cohort without knowing if the eyes were included within the examination range for each of the >400,000 individual examinations. It was possible, however, to

Table 3
Estimated dose to the lens (mean of left and right) for the four levels of eye inclusion in Fig 2, two patient ages and a range of scanner types typical of current and past practice.

Manufacturer and model	Date range	Age (years)[a]	Tube current (mAs)	Tube voltage (kV)	Estimated lens dose (mGy)			
					Eyes fully excluded	Partial (lens excluded)	Partial (lens included)	Eyes fully included
Toshiba TCT60A	1986–1994	0–10 (5)	480[b]	120[b]	4.6	7.7	55.2	61.6
		>10 (15)			3.6	6.0	59.0	60.9
Siemens Somatom CR	1990–2001	0–10 (5)	402	125	3.2	5.3	38.3	42.7
		>10 (15)	433	125	2.7	4.5	44.1	45.5
Siemens Somatom HiQ	1990–2001	0–10 (5)	431	133	4.8	8.0	57.9	64.6
		>10 (15)	467	133	4.1	6.8	67.1	69.2
Philips Tomoexamination AV	1993–2002	0–10 (5)	298[b]	120[b]	3.0	4.9	35.5	39.6
		>10 (15)			2.3	3.9	37.9	39.2
Philips Tomoexamination CX	1994–2000	0–10 (5)	552[b]	120[b]	5.7	9.4	68.0	75.9
		>10 (15)			4.4	7.4	72.7	75.0
GE LightSpeed	1995–2009	0–10 (5)	229	120	3.3	5.5	39.7	44.3
		>10 (15)	321	129	3.9	6.4	62.9	65.0
Siemens Somatom Plus 4	1996–2002	0–10 (5)	254	122	2.6	4.3	30.6	34.2
		>10 (15)	265	137	2.8	4.7	45.6	47.1
GE HiSpeed	1997–2008	0–10 (5)	225	130	2.5	4.1	29.8	33.2
		>10 (15)	321	132	2.9	4.8	47.2	48.7
Philips Secura	2000–2003	0–10 (5)	207[b]	120[b]	2.1	3.4	24.8	27.7
		>10 (15)			1.6	2.7	26.5	27.4
Siemens Definition AS	2012–2013	0–10 (5)	161	120	1.5	2.4	17.6	19.6
		>10 (15)	337	120	2.4	4.0	39.4	40.6
Toshiba Aquillion 64	2012–2013	0–10 (5)	111	120	2.6	4.3	31.1	34.7
		>10 (15)	161	120	2.0	3.4	33.2	34.3

[a] Figures in parenthesis represent the phantom age used in dose estimations.
[b] Insufficient sample size to allow age stratification of exposure factors.

Table 4
Estimated lens dose based on national survey data.

Source (data collection range)	Age range (years)[a]	Mean $CTDI_{VOL}$ (mGy)	Estimated lens dose (mGy)			
			Eyes fully excluded	Partial (lens excluded)	Partial (lens included)	Eyes fully included
Switzerland (2005)[29]	0–1 (0)	17	1.2	2.1	16.8	17.9
	1–5 (1)	25	1.5	2.3	22.1	23.0
	5–10 (5)	32	2.2	3.6	26.3	29.3
	10–15 (10)	45	2.5	4.0	36.2	38.0
Public Health England (2011)[27]	0–1 (0)	23.9	1.7	2.9	23.7	25.2
	1–5 (1)	34.2	2.0	3.2	30.3	31.4
	>5 (10)	51.0	2.9	4.5	41.0	43.1
Australia (2012)[30]	0–4 (1)	21.2	1.2	2.0	18.8	19.5
	5–14 (10)	29.5	1.7	2.6	23.7	24.9
International (2010-12)[31]	0–1 (0)	25.1	1.7	3.0	24.9	26.4
	1–5 (1)	30.8	1.8	2.8	27.3	28.3
	5–10 (5)	39.9	2.7	4.5	32.7	36.6
	10–15 (10)	45.1	2.5	4.0	36.3	38.1
Health Canada (2013)[b,28]	0–3 (1)	33.1	1.9	3.1	29.3	30.4
	3–7 (5)	44.7	3.1	5.1	36.7	41
	7–13 (10)	51.2	2.9	4.5	41.2	43.2

NCICT inferior section positions for respective eye inclusion categories: 6, 7, 8, and 9 (0 years); 8, 9, 11, and 12 (1 year); 9, 10, 11, and 12 (5 years); 9, 10, 12, and 13 (10 years). $CTDI_{VOL}$ figures based on 16 cm phantom.
[a] Figures in parenthesis represent the phantom age used in dose estimations.
[b] Data represent non-helical examinations only.

Table 5
Lens dose estimates based on diagnostic reference levels or 75th percentiles.

Source (data collection range)	Age range (years)[a]	P75 CTDI (mGy)	Estimated lens dose (mGy)			
			Eyes fully excluded	Partial (lens excluded)	Partial (lens included)	Eyes fully included
Switzerland (2005)[29]	0–1 (0)	20	1.4	2.4	19.8	21.0
	1–5 (1)	30	1.7	2.8	26.6	27.6
	5–10 (5)	40	2.7	4.6	32.8	36.7
	10–15 (10)	60	3.7	5.3	48.2	50.7
France (2004–2008)[32]	1 (1)	30	1.7	2.8	26.6	27.6
	5 (5)	40	2.7	4.6	32.8	36.7
	10 (10)	50	2.2	3.5	32.2	33.8
Public Health England (2011)[b,27]	0–1 (0)	34	2.3	4.1	33.7	35.8
	1–5 (1)	49	2.9	4.5	43.4	45.0
	>5 (10)	65	3.6	5.7	52.2	54.9
Finland (2011-12)[33]	1–5 (1)	25	1.5	2.3	22.1	23.0
	5–10 (5)	29	2.0	3.3	23.8	26.6
	10–15 (10)	35	2.0	3.1	28.1	29.6
Australia (2012)[30]	0–4 (1)	25.5	1.5	2.4	22.6	23.4
	5–14 (10)	32.9	1.8	2.9	26.4	27.8
International (2010-12)[31]	0–1 (0)	29.9	2.1	3.6	29.6	31.5
	1–5 (1)	38.8	2.3	3.6	34.3	35.6
	5–10 (5)	49.7	3.4	5.7	40.8	45.5
	10–15 (10)	54.8	3.1	4.8	44.0	46.3
Health Canada (2013)[c,28]	0–3 (1)	37.4	2.2	3.5	33.1	34.4
	3–7 (5)	48.0	3.3	5.5	39.4	44.0
	7–13 (10)	59.1	3.3	5.2	47.5	49.9
Japan (published 2015)[34]	0–1 (0)	38	2.6	4.6	37.7	40.0
	1–5 (1)	47	2.7	4.3	41.6	43.2
	6–10 (10)	60	3.7	5.3	48.2	50.7

Inferior examination extent positions as in Table 4.
[a] Figures in parenthesis represent the phantom age used in dose estimations.
[b] Figures are for posterior fossa phase of head examination.
[c] Data represent non-helical examinations only.

estimate hypothetical cumulative lens doses for the whole cohort based on different eye-inclusion scenarios. Assuming all routine head examinations fully included the eyes, with each delivering a lens dose of 50 mGy, the mean lens dose for the whole cohort of 410,997 patients would be ~80 mGy (range: 50–4,700 mGy), with 2,335 patients receiving lens doses >500 mGy, 374 receiving >1,000 mGy, and 37 receiving >2,000 mGy. Assuming all examinations

fully excluded the eyes, with each delivering a lens dose of 3 mGy, the mean lens dose would be ~5 mGy (range: 3–282 mGy).

Discussion

The findings from the present study suggest that the risk of cataract induction is likely to be small for the majority of young people undergoing CT examinations of the head. This is primarily on account of the low cumulative frequency of head examinations, and in spite of potentially high single-examination lens doses. Studies published in the late 1970s and early 1980s reported estimated single-examination lens doses of up to 350 mGy.[13,36,37] By the late 1980s and early 1990s, most reported lens dose estimates were below 100 mGy.[38,39] By the mid-1990s, doses as low as 4.4 mGy were being reported for SMB technique routine head examinations.[40] Although the potential for low lens doses was thus achieved relatively early, examination practices potentially resulting in doses of over 50 mGy have continued.

Although single examination doses are unlikely to induce cataracts, the present findings suggest that hundreds, perhaps thousands, of children and young adults have reached cumulative lens doses of several hundred milligray by having undergone multiple head examinations using older-generation equipment, with the eyes included within the primary irradiated field. This does not mean that CT examination has induced cataracts in hundreds or thousands of children, as any threshold represents the dose at which 1% of exposed individuals would be expected to develop a cataract. The true number of cataracts induced by CT examinations is likely to be small, but not zero. This discussion should also be placed in the context of the considerable uncertainty in both dose estimates and the threshold dose for cataract induction (e.g. Ref.[1]), assuming such a threshold indeed exists.

Little has been published on cumulative lens doses for patients undergoing multiple CT examinations. Michel *et al.*[14] estimated a mean cumulative lens dose of 168 mGy from an average of three CT examinations, among 32 patients treated for cholesteatoma in France. Doses were estimated using CT-EXPO,[41] which appears to assume IMB positioning technique, (eyes in primary beam), thus may be overestimates. Bernier *et al.*[42] also used CT-EXPO to estimate a cumulative lens dose of 26 mGy (range: 0–1392 mGy) for a cohort of 27,362 French children who underwent CT examinations of any region before age 5 years.

In the present study, wide variation was found in the level of eye inclusion for routine CT head examinations. It was not possible to retrospectively determine the radiographers' true intentions in this regard, that is, whether they intended to include or exclude the eyes. Gantry angulation is a well-known eye dose reduction technique for CT examinations of the head and neck region (e.g. Ref.[20,43]). If the use of SMB gantry angulation is assumed to represent an attempt to exclude the eyes from the primary field of irradiation, this practice appears to be only partially successful. It must be acknowledged that there are clinical advantages in including the eyes in CT head examinations. The optic nerve is considered to be a part of the brain and visualisation of the eyes may aid in differential diagnosis. Other reasons for unavoidable eye irradiation include the use of immobilisation devices (meaning patient head position is fixed), uncooperative patients, and the inability to angle the gantry. Inclusion of the eyes should not, therefore, be assumed to represent a failure of radiation protection. There are, however, other eye dose reduction techniques, including bismuth shielding and angular tube current modulation, although these may result in decreased image quality.[43]

Four epidemiological studies have been published that have investigated cataract risk following diagnostic X-ray examinations.[44–46] Klein *et al.*[44] reported raised odds ratios for posterior subcapsular (1.45, 95% CI: 1.08, 1.95) and nuclear sclerotic opacities (1.28, 95% CI: 1.02, 1.61) among 4,926 adults who underwent one or more CT head examinations. More recently, Yuan *et al.*[46] reported significantly raised incidence of cataracts among Taiwanese patients aged 10–50 years with head and neck cancer who underwent at least one CT examination, compared to matched controls (adjusted hazard ratio: 1.76, 95% CI: 1.18, 2.63). A third study[45] found no association between CT examination and cortical (0.9, 95% CI: 0.7, 1.1), nuclear (0.8, 95% CI: 0.6, 1.1), or posterior subcapsular opacities (0.9, 95% CI: 0.6, 1.3). None of these studies involved meaningful dose–response analysis. The potential for recall bias may also be considerable. The suggestion of increased cataract incidence after only one CT examination, even at early dose levels, is somewhat dubious,[5] although it could suggest a no-threshold dose response, as previously suggested. A recent study by Chen *et al.*[47] found an increased risk of cataracts among 838 individuals who underwent X-ray guided neuro-interventions, compared to 3,352 controls (hazard ratio: 1.88, 95% CI: 1.08, 3.26). There was a non-significant suggestion of increased cataract risk with increased number of CT examinations, although no formal dose estimation or dose–response analysis was performed.

An epidemiological assessment of cataract incidence among the current CT cohort would be desirable, and theoretically possible. Currently, however, no cataract registry currently exists in the UK and cataracts are not recorded by NHS Digital. Lens dose was found to vary by a factor of 15 depending on the level of eye inclusion. Thus, any future epidemiological assessment of cataracts following CT examinations would involve considerable dosimetric uncertainties unless every single examination could be viewed to determine eye inclusion.

Study limitations and uncertainties

This study has a number of limitations. Firstly, NCICT does not allow simulation of gantry angulation, meaning all sections are orientated as per the IMB technique. SMB positioning, with the eyes excluded, was simulated by shortening examination length. This would irradiate a smaller volume of tissue, thus reducing scatter dose outside

the examination region. Despite this, the present lens dose estimates for the eyes-excluded technique (1.5–5.7 mGy) were reasonably similar to the figures obtained by MacLennan and Hadley[40] (4.4 and 5.1 mGy for two scanner types) using thermoluminescent dosemeters (TLDs) placed on the patient surface for SMB clinical CT head examinations. Doses for coronally orientated examinations (used for sinuses and IAMs) could not be estimated. Some studies have suggested eye doses from coronal examinations are higher than for axial section angulation.[48,49]

Slice thickness in NCICT is restricted to 10 mm, meaning it was not possible to determine lens dose as a continuous function of eye inclusion. It was difficult to maintain the same inferior examination extents for each of the phantom sizes, meaning comparison of lens dose according to age is difficult. Constant X-ray output was assumed during each section acquisition. More modern CT systems can employ angular tube current modulation, reducing output as the tube rotates around anteroposterior-orientated projection angles. Furthermore, the lens cannot be visualised in NCICT; therefore, the "partial inclusion" dose estimates may be less reliable.

Analysis of eye inclusion was based on a review of images printed on film or stored electronically on the PACS network or CDs. These images do not necessarily represent the true exposed region at the time of examination. In addition to Z-overranging effects already discussed, repeated slices, e.g., due to movement, may have been deleted or never printed. In some cases, multiple examinations may have been performed (e.g., pre- and post-contrast) but only entered as a single examination on the RIS system. Finally, there was no information on non-CT head exposures, although doses from general radiography and fluoroscopy are likely to be very low. Skull radiography and fluoroscopic cerebral angiography are now performed in only a small minority of patients.

In conclusion, in the present study, estimated lens doses from head examinations were in the range 20–75 mGy when the eyes are fully included within the examination range, and 2–7 mGy when completely excluded. Although even doses towards the upper limit of this range appear insufficient to induce cataracts, a small subset of patients may undergo sufficiently many scans to exceed the supposed low dose threshold for radiation-induced cataract formation. Although utilising the SMB technique and avoiding the helical mode may reduce cataract risk among children likely to receive multiple examinations, it is acknowledged that clinical requirements must take priority. Further debate on the usefulness of eye inclusion for CT head examinations is encouraged.

Conflict of interest

All authors declare no conflict of interest.

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