Environment International 120 (2018) 1–10

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Subtle excess in lifetime cancer risk related to CT scanning in Spanish young people

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ARTICLE INFO

Handling Editor: Olga-Ioanna Kalantzi

Keywords:
CT scan
Risk
Cancer
Young population
Ionising radiation

ABSTRACT

Background: CT scan is a life-saving medical diagnostic tool, entailing higher levels of ionising radiation exposure than conventional radiography, which may result in an increase in cancer risk, particularly in children. Information about the use and potential health effects of CT scan imaging among young people in Spain is scarce.
Objective: This paper aims to estimate the number of radiation-related cancer cases which can be expected due to the use of CT scanning in Spanish children and young adults in a single year (2013).
Methods: The 2013 distribution of number and types of CT scans performed in young people was obtained for Catalonia and extrapolated to the whole Spain. Organ doses were estimated based on the technical characteristics of 17,406 CT examinations extracted from radiology records. Age and sex-specific data on cancer incidence and life tables were obtained for the Spanish population. Age and sex-specific risk models developed by the Committee on Health Risks of Exposure to Low Levels of Ionizing Radiations (BEIR VII) and Berrington de Gonzalez were used, together, with the dose estimates to derive the lifetime attributable risks of cancer in Spain due to one year of CT scanning and project the number of future cancer cases to be expected.
Results: In 2013, 105,802 CT scans were estimated to have been performed in people younger than age 21. It was estimated that a total of 168.6 cancer cases (95% CrI: 30.1–421.1) will arise over life due to the ionising radiation exposure received during these CTs. Lifetime attributable risks per 100,000 exposed patients were highest for breast and lung cancer. The largest proportion of CTs was to the head and neck and hence the highest numbers of projected cancer cases were of thyroid and oral cavity/pharynx.
Conclusions: Despite the undeniable medical effectiveness of CT scans, this risk assessment suggests a small excess in cancer cases which underlines the need for justification and optimisation in paediatric scanning. Given the intrinsic uncertainties of these risk projection exercises, care should be taken when interpreting the predicted risks.

1. Background

Nowadays, medical radiation has become the largest man-made source of ionising radiation exposure for human beings (UNSCEAR, 2010), and in particular, computed tomography (CT) scanning largely dominates the medical radiation exposures, accounting worldwide for approximately 34% of the annual collective dose (UNSCEAR, 2010). CT scanning is routinely used in patient management from diagnostic and

Abbreviations: AQuAS, Agència de Qualitat i Avaluació Sanitàries de Catalunya (Agency of Quality and Healthcare Evaluation of Catalonia); BEIR VII, Biological Effects of Ionizing Radiation; CT, Computerised Tomography; DICOM, Digital Imaging and Communications in Medicine; LAR, Lifetime attributable risk; LBR, Lifetime baseline risk; LSS, Life Span Study of the atomic bomb survivors in Hiroshima and Nagasaki; NCICT, National Cancer Institute dosimetry system for CT; PerMoS, Performance Monitoring Server for Clinical Data

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https://doi.org/10.1016/j.envint.2018.07.020
Received 23 June 2017; Received in revised form 12 July 2018; Accepted 13 July 2018
Available online 25 July 2018

treatment planning, to disease follow-up. As in most European countries, since its introduction in 1976, Spanish hospitals have progressively adopted this diagnostic technique for its recognised clinical value. Approximately 750 CT scanners are currently in use in Spain (Ministerio de sanidad, servicios sociales e igualdad [Spanish Ministry of Health, social services and equality], 2015), which annually perform > 4.3 million CT scans (90.6% in the public healthcare system (Ministerio de sanidad, servicios sociales e igualdad [Spanish Ministry of health, social services and equality], n.d.)). According to international data, CT imaging in children and adolescents is estimated to account for 3–11% of the total CT activity (UNSCEAR, 2013). In this age group, typical CT organ doses range between tens of mGy for an organ in the scanning field to hundreds of μGy for a distal organ (Lee et al., 2012; Santa-Olalla et al., 2005).

Epidemiological studies have shown that radiation exposure in childhood is linked to a dose-related excess in the rates of tumours, in particular brain tumours, leukaemia, breast and thyroid cancer (Wakeford et al., 2010; Land, 1993; Ron et al., 1995; National Research Council (U.S.), 2006; Monty, 2001; Neglia et al., 2006; Ron et al., 1988), with higher lifetime risk of cancer per unit dose of radiation than for exposure in adulthood (UNSCEAR, 2013). Because little direct evidence is available on risks at doses below 100 mGy, a linear no-threshold (LNT) model is generally used to extrapolate the risk of cancer for doses lower than this (National Research Council (U.S.), 2006) (as in the dose range for most CT imaging). Through this, several studies have projected the risk of incident primary cancers associated with diagnostic CT scan doses in young people (Miglioretti et al., 2013; Journy et al., 2013; Egan et al., 2012; Journy et al., 2017; Li et al., 2011; Su et al., 2014), adults (Richards et al., 2008; Smith-Bindman et al., 2009) or in both (Sodickson et al., 2009; Gibson et al., 2014; Berrington de González and Darby, 2004; Berrington de González, 2009) in different countries applying risk models derived by the BEIR VII committee (National Research Council (U.S.), 2006) and other authoritative agencies (US EPA, 2015; UNSCEAR, 2008; ICRP (International Commission on Radiological Protection), 2007). These studies estimated that a small, but non-negligible, excess in cancer risk can be expected in relation to the widespread use of CT scanning.

In recent years, different studies in the UK (Pearce et al., 2012; Berrington de Gonzalez et al., 2016), Australia (Mathews et al., 2013), and Taiwan (Huang et al., 2014) have attempted to estimate directly the magnitude of radiation-induced cancer risks from paediatric CT scanning. The leukaemia and brain cancer risk estimates resulting from the UK and Australian studies were larger than the estimates obtained using the latest Life Span Study data (Hsu et al., 2013; Preston et al., 2007). At present, methodological limitations such as the inclusion of patients with cancer-prone syndromes, reverse causation, dosimetric flaws, short follow-up and potential residual confounding due to unmeasured factors prevented deriving precise risk estimates from these studies. Although the EPI-CT study, a large scale European study on CT scan risks including over one million exposed children, will produce results soon (Bosch de Basea et al., 2015), extrapolation from higher dose studies remains the most solid basis for predicting risk from CT scanning in young people.

For the first time, we estimated the use of CT imaging in Spanish young population and subsequently assessed the potential impact of the current practices of paediatric and young adult CT scanning on the cancer burden of Spain.

2. Methods

2.1. Study population and related data

The Spanish National health care system reported that the annual number of CT scans in Spain increased from 3,830,238 CT scans in 2010 to 4,307,391 in 2013 (Ministerio de Sanidad, Servicios Sociales e Igualdad [Ministry of Health, Social Services and Equality], 2013), according to the latest data at the time of this analysis. The distribution of CT scans by age, sex and body part scanned was not available at the country level. However, the Agency of Quality and Healthcare Evaluation of Catalonia (Agència de Qualitat i Avaluació Sanitàries de Catalunya; AQuAS) of the Catalan Department of Health, made it accessible for the year 2015 for Catalonia, the 2nd most populated Autonomous Community of Spain were 15.9% of its population reside. A total of 374,270 CT scans were performed in the general population aged 0 to 100 years. Approximately 3% of these were performed in the population below 21 years of age. The Catalan relative distribution was applied to the 2013 country-level figures in order to estimate the age, sex and anatomical area-specific distribution of CT scans performed in Spain, assuming stable (over the years) and similar CT distributions between Catalonia and Spain.

In order to estimate the number of cancer cases that could be induced by CT scan radiation, we used the most up-to-date age and sex-specific Spanish cancer incidence rates available in the *Cancer Incidence in Five Continents* (*CIV*) (Forman et al., 2007) series to infer the background rates of cancer among children and young adults. Due to the lack of a national population-based registry, the incidence data are based on the 2007 CIV rates provided by the 7 population-based Spanish cancer registries. In the absence of more recent data we had to assume the rates were similar to the 2013 rates and will continue to be stable in the future (Forman et al., 2007). Spanish age and sex-specific survival data (latest available data) was obtained for the year 2013 at the National Statistics Institute (Instituto Nacional de Estadística) (2013). Using data from the Spanish branch of the EPI-CT cohort study we estimated that 6.64% CTs were performed in young people who would not survive long enough (at least 5 years) to develop a potentially radiation-induced cancer. These CTs were removed (by age bands, sex and body area scanned) from the population at risk as was done in Berrington's risk projections (2009). An important indication for CT scanning is suspicion of and follow-up for cancer. These CT examinations have to be excluded from our risk prediction analyses because their related CT scan radiation would not be responsible for the onset of the cancer they were used to diagnose/monitor. Therefore, we used the data from the only Spanish EPI-CT participating hospital that provided complete reason for the scan and estimated that, in 2013, out of the 2624 CT scans performed in patients aged 0 to 20 years, 8.8% were related to a cancer code (suspicion, diagnosis or follow-up of the condition). Therefore, this proportion of CT scans with similar age-sex-anatomical area distribution was excluded.

2.2. Dosimetry at the organ level

For the estimation of absorbed doses to the organ, protocol parameters (kVp, mAs and pitch), machine specifications (model and manufacturer), anonymous patient characteristics (age and sex), and the descriptions of the anatomical areas scanned were extracted from the DICOM headers of 33,947 CT performed on patients below 21 years old between 2010 and 2013. This information was collected using the software PerMoS (Luxembourg Institute of Science and Technology, Luxembourg) in 9 EPI-CT participating Spanish hospitals. For each type of CT examination, the start and end of the exposed body region were defined on computational anthropometric phantoms by a radiologist and validated by an independent paediatric radiologist. The gender-specific phantoms used were compliant with the International Commission on Radiological Protection references (ICRP 89) and represented newborns, children at ages 1, 5, 10, and 15 and adults (ICRP, 2002). Due to the lack of registered information on the use of a bowtie filter as the x-ray beam shaping attenuator, we used expert opinion to impute the use of a head filter in newborns as by 50%:50% chance irrespective of the scanned area. In older patients, head and body filters were imputed in head/neck and thorax/abdomen + pelvis/extremities scans, respectively. After discarding 16,541 examinations due to missing parameters, absorbed organ-doses (mGy) were estimated for

17,406 CTs using the NCICT version 1.0 software (Lee et al., 2015). The minimum and maximum number of CT scans used to estimate doses for a specific combination of age band and anatomical area scanned were 1 and 3876, respectively.

Finally, a look up table of median and interquartile range of organ doses were compiled by 5-year age bands and examination type, and assigned to each of the 2013 examinations.

2.3. Lifetime attributable risk models for several cancer sites

Given the site-specific irradiation and resulting heterogeneous organ doses in each type of scan, we estimated the number of radiation-induced cancer cases by applying the lifetime attributable risks (LAR); the cumulative age-specific excess lifetime risks of cancer as a function of organ-doses. The radiation-induced risk of cancer incidence was calculated for the following 17 different cancer-sites: oral cavity and pharynx, brain, colon, lung, urinary bladder, breast, stomach, thyroid, liver, pancreas, kidney, prostate, esophagus, ovaries, rectum, uterus and leukaemia by applying the risk models developed by the BEIR VII committee (National Research Council (U.S.), 2006) and Berrington de Gonzalez et al. (2009, 2012). They have been described elsewhere (National Research Council (U.S.), 2006; Berrington de González, 2009; Berrington de Gonzalez et al., 2012) and are explained in detail in the supplementary web material. A dose and dose-rate effectiveness factor (DDREF), modelled by a lognormal distribution with a geometric mean of 1.5 and a geometric standard deviation equal to 1.35 was applied to extrapolate the expected risk to the low and sparsely ionising radiation doses delivered in a CT scan (National Research Council (U.S.), 2006), reducing the ERR per unit dose accordingly. The risk models were estimated using risk-free latent periods of 5 years for solid cancers and of 2 years for leukaemia. The sex-averaged cumulative risks were calculated per 100,000 children and young adults undergoing 1 CT scan by examination type (anatomical area) and patient characteristics (age). The lifetime baseline risk (LBR) is the risk of developing cancer from birth to the end of life, considered as 110 years of age, in the absence of CT-scan radiation exposure. The LBR was estimated as well for 100,000 unexposed children and young adults. Then, the LAR by exposure age, examination type and cancer-site was multiplied by the estimated number of patients that received a CT scan in 2013, in order to estimate the predicted number of cancer cases. We also calculated the attributable fraction (AF) or proportion of cases which occur due to exposure using the following formula:

$$AF = \frac{CI_e - CI_u}{CI_e}$$

where CI_e was the cumulative incidence among the exposed population and CI_u is the cumulative incidence in nonexposed only.

2.4. Uncertainties in cancer risk estimation

Several uncertainties that could have influenced the estimation of the excess of radiation-induced cancer risk were considered statistically independent and were taken into account in computing the combined uncertainty. Treatment of uncertainty included the statistical uncertainty in the estimates of risk parameters, in the DDREF value, in the risk transport between populations and in the estimation of organ-doses. Following the BEIR VII (National Research Council (U.S.), 2006) and NCI methods (Berrington de González, 2009; Berrington de Gonzalez et al., 2012), we drew lognormal probability distributions for all the model parameters that provided confidence intervals in the original BEIR VII cancer-sites and for the new NCI models (brain and central nervous system) (Berrington de González, 2009; Berrington de Gonzalez et al., 2012). Furthermore, normal and cumulative distributions were drawn respectively for two additional new NCI models: prostate and uterus. The DDREF uncertainty was expressed as a probability distribution of possible values, following a lognormal distribution with a geometric mean of 1.5 and geometric standard deviation equal to 1.35 guided by the methods developed by the BEIR VII based on the LSS and experimental data (National Research Council (U.S.), 2006). Uncertainty in dose estimates was included by drawing a normal probability distribution for each CT scan type and age group and sampling from them. Finally, the transport of risk estimates between populations was performed by assigning discrete weights equal to 0.3 and 0.7 when appropriate to the EAR and ERR LAR (as the Bernoulli probability that the relative and the additive risk transport, independently, are correct) and calculating a weighted arithmetic mean on a linear scale.

Uncertainties overall were combined and incorporated in the risk estimates by applying Monte Carlo simulations to sample 10,000 times from the probability distribution of each uncertain factor. The risk analyses were performed with R version 3.1.1 and STATA 14.0 (StataCorp LP, Tx USA). Additionally to the mean LAR estimates, the LAR obtained using the 2.5th and 97.5th percentile of the resulting distribution (without previous assumptions on its possible symmetry) were reported as credibility intervals (CrI).

3. Results

The extrapolation of the Catalan CT scan distribution to the entire Spanish population resulted in an estimated 105,802 CT scans performed in Spain in 2013 among those aged 20 years or less in a population of 9.7 million people. Taking into account the 2013 0–20 years old Spanish population, this represents a crude rate of 10.9 scans per 1000 Spanish children and young adults. Of this, 11,195 CT scans of the spine, lumbar spine, sacrum, whole body, arms and 'unknown anatomical area' were not included in this risk projection exercise due to the paucity of PACS-recorded CT technical parameters in these anatomical locations to be used for dose estimation.

The estimated distribution of the remaining 94,607 CTs by age group, sex and type of scan is displayed in Table 1. 52,283 scans (55.3%) and 42,324 (44.7%) were undergone by male and female patients, respectively, with a male: female CT scan ratio of 1.45: 1 among those below 10 years old, which decreased to 1.1: 1 among those in the 15–20 age group. Approximately 57% of all the 2013 CTs in young people were performed in the 15–20 years age group. The proportion of CT scans across age groups was generally similar for males and females, though it was somewhat higher in females aged 15–20 years old (59.97% of all CTs in females) than in males (54.68% CTs of all male CT imaging). In both sexes, overall, the three more prevalent anatomical areas scanned were: head (62.6%), abdomen (13.3%) and thorax (10.32%).

The median organ doses for the brain, oral cavity and pharynx, lung, stomach, pancreas and liver were consistently higher among the oldest patients for those CT scan types that included these organs in the scan field (Table 2). Brain-doses progressively increased with age, with head examinations providing a range of median doses from 23.6 mGy in 0 to 4 years old children to 37.9 mGy among those that were 20 years of age. The active bone marrow doses received during thoracic spine, abdomen, pelvis and chest-to-pelvis CT also increased with age, whereas the bone marrow doses received during head and face CT examinations showed the opposite pattern. Wide variability of organ-doses was identified among those combinations of age, sex and scan type for which fewer examinations were available for dose estimation, such as chest-to-pelvis CT and thoracic spine CT (data not shown). With respect to the organ doses received from different CT types, median brain doses due to a face CT were half of those delivered in a head CT, in the different age groups. Similarly, the thyroid gland in the youngest age group received 22.8 mGy (average of median doses of males and females) during a cervical spine CT, slightly below 13 mGy from a neck and thoracic spine CT, and 8.1 mGy from a thorax CT. In the oldest age group, a cervical spine CT delivered an averaged median thyroid dose of 16.7 mGy, while neck, thoracic spine and thorax CT delivered 13.0,

Table 1
Estimated distribution of CT scans by sex and age groups in Spain, in 2013.

CT scan type	< 1		1–4		5–9		10–14		15–20		Total	
	N	%	N	%	N	%	N	%	N	%	N	%
Male												
Head	2191	(66.3%)	3820	(75.3%)	4256	(66.9%)	6012	(67.1%)	16,938	(59.3%)	33,217	(63.5%)
Abdomen	377	(11.4%)	101	(2.0%)	373	(5.9%)	746	(8.3%)	4954	(17.3%)	6551	(12.5%)
Thorax	566	(17.1%)	755	(14.9%)	1051	(16.5%)	1051	(11.7%)	2060	(7.2%)	5483	(10.5%)
Leg	12	(0.4%)	15	(0.3%)	128	(2.0%)	412	(4.6%)	1520	(5.3%)	2087	(4.0%)
Face	12	(0.4%)	37	(0.7%)	175	(2.8%)	223	(2.5%)	927	(3.2%)	1374	(2.6%)
Cervical spine	35	(1.1%)	110	(2.2%)	110	(1.7%)	204	(2.3%)	726	(2.5%)	1185	(2.3%)
Neck	21	(0.6%)	195	(3.8%)	176	(2.8%)	100	(1.1%)	652	(2.3%)	1144	(2.2%)
Trunk[a]	23	(0.7%)	13	(0.3%)	21	(0.3%)	83	(0.9%)	404	(1.4%)	544	(1.0%)
Pelvis	58	(1.8%)	13	(0.3%)	40	(0.6%)	90	(1.0%)	185	(0.6%)	386	(0.7%)
Thoracic spine	12	(0.4%)	15	(0.3%)	27	(0.4%)	38	(0.4%)	220	(0.8%)	312	(0.6%)
									Total		52,283	(100%)
Female												
Head	1494	(66.2%)	2564	(71.0%)	2802	(65.2%)	3683	(54.4%)	15,479	(61.0%)	26,022	(61.5%)
Abdomen	253	(11.2%)	96	(2.7%)	233	(5.4%)	816	(12.0%)	4629	(18.2%)	6027	(14.2%)
Thorax	346	(15.3%)	746	(20.7%)	709	(16.5%)	848	(12.5%)	1636	(6.4%)	4285	(10.1%)
Leg	12	(0.5%)	4	(0.1%)	117	(2.7%)	692	(10.2%)	1233	(4.9%)	2058	(4.9%)
Face	1	(0.0%)	4	(0.1%)	131	(3.0%)	276	(4.1%)	654	(2.6%)	1066	(2.5%)
Neck	35	(1.6%)	71	(2.0%)	116	(2.7%)	231	(3.4%)	437	(1.7%)	890	(2.1%)
Cervical spine	12	(0.5%)	70	(1.9%)	84	(2.0%)	99	(1.5%)	487	(1.9%)	752	(1.8%)
Trunk[a]	35	(1.6%)	15	(0.4%)	5	(0.1%)	38	(0.6%)	406	(1.6%)	499	(1.2%)
Pelvis	58	(2.6%)	26	(0.7%)	61	(1.4%)	44	(0.6%)	243	(1.0%)	432	(1.0%)
Thoracic spine	12	(0.5%)	15	(0.4%)	38	(0.9%)	49	(0.7%)	179	(0.7%)	293	(0.7%)
									Total		42,324	(100%)

[a] Combined CT scan of chest, abdomen and pelvis.

60.5 and 20.7 mGy to the thyroid, respectively.

In Table 3, the lifetime accumulated baseline (LBR) and the additional radiation-related probability of cancer incidence (LAR) are displayed for a number of cancer sites selected for being in or proximal to the scanning field. For each cancer type, a single LBR value is provided due to the cumulative nature of the risk from birth to the end of life (considered as 110 years).

Lifetime attributable risks per 100,000 exposed patients were highest for breast cancer in women who received one thorax, thoracic spine or chest-to-pelvis CT, closely followed by lung cancer from one thoracic spine or chest CT and thyroid cancer from one chest or cervical spine CT scan. Considering all cancer sites together, the examinations that conferred the highest LAR were: chest-to-pelvis, thorax, thoracic spine and abdomen CT with total LAR values such as 23,674.2, 20,995.8, 18,654.8, and 17,047.2 per 100,000 exposed, respectively. The examination type that conferred the lowest LAR was neck CT, with a total LAR of 3998.8 per 100,000 exposed.

The lifetime attributable risks did not show a consistent dependence on age at exposure, with risk patterns in different directions among those exposed at older ages (15–20 year olds) compared with lower ages (< 1 year) depending on the area scanned. The risks for brain cancer consistently decreased with increasing age at the time of the exposure for virtually all CT scan types whereas leukaemia risks presented a decreasing pattern with increasing age for head, face, neck and thorax CT and an unclear pattern for the remaining CT scan types. Among the oldest age group (15–20 year olds) the highest predicted risks (LAR × 10^5) were observed for breast cancer among women following a thoracic spine CT (LAR = 209.3). In the youngest group (< 1 year olds) the highest risks per 100,000 exposed individuals were observed for breast cancer following a CT scan of the thorax (LAR = 458.8). LAR showed a wide variability according to the scan type.

Applying the LAR (95% CrI) to the estimated age-sex and body part scanned distribution of the CT examinations in 2013 among those aged 0 to 20 in Spain, we predicted that 168.6 (30.1–421.1) additional cancer cases may occur over the life course of this population due to the doses received during CT scanning (Table 4). This is in comparison to the approximately 39,028 cancers expected over life due to other causes, hence an attributable risk percent (AR%) of about 0.43% (0.08%–1.1%).

The CT scans that contributed most to the projected cancer cases are shown in Table 4. The predicted incident cancer cases were, in order of frequency, cancers of the thyroid (31.8 (2.8–101.8) cases; 18.9% of all excess cases), oral cavity and pharynx cancer (22.7 (4.7–48.8) cases; 13.5% of all excess cases), lung cancer (18.4 (3.0–48.6) cases; 10.9% of all excess cases), colon cancer (17.7 (3.8–38.9) cases; 10.5%) closely followed by breast cancer (14.8 (2.3–41.3) cases; 8.8%). The majority of the projected cancer cases were found among those in the highest age group at the time of the exposure, accounting for 43.8% of all the incident cases (n = 74 (17.2–151.4)). Overall, 38.6% (n = 65.1 (9.5–171.4)) and 25.8% (n = 43.5 (9.3–95.5)) of all the predicted cancer cases are estimated to result from head and abdomen CT imaging, respectively. Although the total LAR of a single head CT (summing all the cancer site specific LAR) was inferior to that of an abdomen examination (6317.8 *vs.* 17,047.3 per × 10^5 exposed), the elevated head scan frequency (62.6% of all procedures) translated into a higher number of predicted cancer cases (n = 65.1 (9.5–171.4)), in particular, 91.5% of all the brain cancer cases and 88.5% of the oral cavity and pharynx cancers. Thorax, chest-to-pelvis and leg CTs accounted for most of the remaining expected cancer cases (24.3 (5.5–118.2), 3 (1.3–10.2) and 2.6 (1.6–7.6), respectively) while the rest of the CT scans contributed minimally to the predicted future cancer cases. Head CTs were the main contributor (70.1%) to the leukaemia cases too (n = 6 (1.6–21.0) due to the extremely high frequency of this examination.

4. Discussion

According to our estimations, 105,000 CT scans were performed in 2013 in the young population in Spain, dominated by far by head CTs, followed by abdomen CTs as a result of a distribution largely driven by the 15–20 age group. The unprecedented use of the examination settings of approximately 17,400 real CT scans warranted the estimation of robust and realistic organ-doses currently used in clinical practice.

Table 2
Median, 25th and 75th percentile organ-doses (mGy) across age groups for the relevant organs included in the scanned area by type of CT scan.

CT type/organ dose	< 1 year			1–4 years			5–9 years			10–14 years			15–20 years		
	Med	25thp	75thp	Med	25thp	75thp	Med	25thp	75thp	Med	25thp	75thp	Med	25thp	75thp
Head CT															
Brain	23.6	13.2	32.7	27.0	17.2	33.1	27.9	17.8	38.4	33.4	23.3	43.5	37.9	17.3	43.1
Oral cavity	6.4	1.9	22.5	26.7	13.5	33.2	25.8	16.4	34.7	26.8	16.7	33.3	26.8	15.4	31.9
Active bone marrow	8.2	4.4	11.8	6.9	3.5	9.3	4.6	2.6	6.2	3.1	1.9	4.1	2.3	1.3	2.7
Face CT															
Brain	12.5	7.6	20.0	15.5	8.2	24.0	18.0	9.5	23.0	17.0	9.2	17.5	15.3	5.9	17.1
Oral cavity	28.7	17.3	41.6	26.4	14.7	39.0	36.3	19.0	37.6	29.3	16.7	34.2	26.3	11.4	32.7
Active bone marrow	6.0	3.9	8.7	3.7	2.1	5.5	3.4	1.7	4.0	2.2	1.3	2.6	1.4	0.5	1.7
Cervical spine CT															
Thyroid	22.8	13.5	43.8	31.8	20.2	51.6	37.6	23.1	49.1	35.2	15.1	48.8	16.6	15.8	18.3
Active bone marrow	2.6	1.7	5.1	2.2	1.3	3.7	2.6	1.6	3.0	2.4	1.6	3.0	2.2	2.0	2.4
Neck CT															
Thyroid	12.8	5.0	17.3	22.5	10.2	33.1	23.5	16.8	29.4	15.8	8.0	31.6	13.0	7.6	33.0
Active bone marrow	1.8	1.5	2.5	2.0	1.0	2.4	1.5	1.2	1.9	1.4	0.6	2.3	1.5	0.7	2.7
Esophagus	4.6	2.0	5.7	4.9	2.1	7.2	4.7	3.3	5.8	4.7	1.9	8.3	5.3	2.8	9.5
Thoracic spine CT															
Thyroid	12.8	10.4	15.9	22.6	17.7	27.6	24.8	11.8	33.0	21.6	13.3	25.9	60.5	60.5	60.5
Active b. marrow	4.5	4.0	5.8	4.5	3.8	5.7	6.3	5.0	7.3	6.3	4.5	10.7	12.1	12.1	12.1
Breast[a]	11.8	11.2	18.5	16.6	12.6	19.8	19.1	14.9	22.9	20.8	15.0	31.6	38.7	38.7	38.7
Lungs	14.5	14.2	22.2	20.2	15.4	23.7	22.5	17.5	27.5	23.4	16.9	38.3	42.1	42.1	42.1
Esophagus	12.8	11.5	17.3	16.6	12.7	19.5	19.1	15.6	22.8	19.1	13.8	29.9	35.0	35.0	35.0
Thorax CT															
Thyroid	8.1	4.7	11.8	10.8	8.0	18.6	13.4	8.7	24.3	23.9	7.7	37.5	20.7	4.9	34.7
Active bone marrow	2.7	2.0	4.3	2.2	1.6	3.9	3.3	1.8	5.8	5.8	1.7	9.0	5.0	1.0	9.9
Breast[a]	2.7	2.0	4.3	2.2	1.6	3.9	3.3	1.8	5.8	5.8	1.7	9.0	5.0	1.0	9.9
Lungs	8.5	6.2	14.2	9.2	6.9	15.7	11.4	6.3	20.3	18.8	5.8	28.8	15.5	3.2	30.3
Esophagus	7.2	5.4	11.4	7.7	5.9	13.4	10.1	5.5	18.2	16.6	4.9	25.0	13.9	2.9	24.8
Abdomen CT															
Stomach	6.6	5.5	11.7	13.2	7.0	25.8	19.7	13.8	28.1	25.3	17.3	32.9	22.3	11.7	27.4
Colon	7.1	6.0	14.1	14.5	8.3	29.4	22.8	16.8	32.7	30.4	20.4	39.0	27.2	14.0	33.5
Rectum	5.6	3.9	9.3	9.4	5.4	17.8	12.4	8.0	18.0	16.8	11.0	23.6	19.5	9.9	24.0
Pancreas	6.7	5.8	12.9	12.9	7.3	26.4	19.1	13.6	27.7	25.8	17.5	33.1	24.4	11.2	29.7
Liver	6.5	5.2	11.2	12.2	6.7	24.1	17.9	12.3	25.4	22.7	15.4	30.1	19.2	10.9	23.7
Kidney	6.9	5.8	12.9	13.6	7.4	26.9	20.0	14.4	29.2	27.3	18.6	34.5	25.1	12.7	30.9
Trunk CT															
Thyroid	5.6	2.4	7.9	7.6	4.2	11.7	10.1	4.7	19.7	24.9	8.4	47.1	12.6	8.6	38.9
Active bone marrow	3.1	2.6	5.6	5.8	3.2	9.6	11.0	8.9	19.0	15.4	8.1	23.6	8.3	5.7	25.5
Breast[a]	5.8	5.0	9.8	10.1	6.5	17.0	18.8	12.8	27.4	21.2	11.2	33.6	11.9	8.1	36.7
Stomach	7.2	6.1	11.8	13.0	8.4	22.0	24.6	17.5	35.7	25.6	13.7	40.6	13.7	9.4	42.3
Colon	7.6	6.3	11.9	14.4	9.3	24.1	27.2	19.4	39.1	27.5	14.8	43.6	13.4	9.1	41.1
Rectum	6.2	4.4	9.0	11.3	7.4	19.8	17.0	14.7	29.3	21.3	11.9	33.7	10.7	7.3	32.9
Pancreas	7.1	6.1	11.7	12.7	8.3	21.5	22.8	16.5	33.0	23.2	12.5	36.8	13.2	9.0	40.5
Liver	7.1	6.1	11.7	12.5	8.1	21.2	23.5	16.6	34.1	24.7	13.2	39.2	13.8	9.4	42.6
Kidney	7.2	6.2	11.8	13.0	8.5	22.0	23.8	17.4	34.2	25.4	13.4	40.1	13.3	9.1	40.9
Pelvis CT															
Urinary bladder	15.2	8.1	28.1	25.3	11.0	34.2	24.1	13.0	37.7	32.9	20.0	41.8	39.8	3.7	40.8
Prostate[b]	10.7	3.1	23.3	11.5	5.2	27.1	9.9	5.8	27.2	21.0	9.6	32.7	28.3	2.8	30.9
Ovaries[a]	14.6	4.7	27.1	24.2	16.6	34.1	24.1	13.5	32.2	24.7	18.5	30.3	24.7	18.5	30.3
Uterus[a]	13.7	4.3	26.6	23.1	16.0	32.8	23.1	12.6	30.7	22.7	17.3	28.4	22.7	17.3	28.4
Leg CT															
Active bone marrow	8.4	8.4	8.4	5.8	5.3	7.5	8.1	7.5	8.8	3.0	1.4	3.1	2.1	1.1	3.0
Prostate[b]	12.8	12.8	15.8	12.8	12.8	15.8	47.5	47.0	47.5	21.6	20.8	27.1	21.5	21.5	21.5
Ovaries[a]	10.4	10.4	10.4	8.9	7.5	11.7	8.9	8.9	16.1	6.9	4.7	8.4	5.0	3.4	5.4
Uterus[a]	11.0	11.0	11.0	10.2	8.6	13.8	10.2	10.2	18.8	8.8	4.5	10.3	4.5	3.1	4.9

[a] Only in females.
[b] Only in males.

This is an alternative approach to other dosimetric strategies observed in similar studies based on surveys (Berrington de González, 2009), scanner protocols (Journy et al., 2013; Egan et al., 2012), on both (Journy et al., 2017) or derived from smaller samples of clinical data (Miglioretti et al., 2013). Our estimated doses were similar to previously published for CT imaging, showing the robustness of the different dosimetric approaches (Miglioretti et al., 2013; Journy et al., 2013; Su et al., 2014; Pearce et al., 2012). For example, our estimation of brain doses in a head CT for the 0 to 4 years age group was 23.6 mGy, and 28.8 mGy in Miglioretti et al. (2013) and 28.0 in Pearce et al. (2012) in the 1–4 year olds. We also estimated red bone marrow doses of 2.2 mGy for a thorax CT in 5 to 9 years of age, whereas Journy et al. (2013), Miglioretti et al. (2013)) and Pearce et al. (2012) reported red bone marrow doses of 1, 3.9 and 3.0 mGy for the same procedure and age group, respectively. Thyroid doses for a thorax CT were similar to those estimated by Journy et al. (2013) and slightly larger than those by

Table 3
Estimated sex-averaged lifetime background risks (LBR) and lifetime attributable risks per 100,000 exposed subjects (LAR) of the tissues and organs exposed by CT scan type by age group of exposure.

CT type/cancer site	LBR × 10^{-5}[a]	LAR × 10^{-5} from age (in groups) at the time of the CT scan to age 110				
		< 1 year	1–4 years	5–9 years	10–14 years	15–20 year
Head CT						
Brain	790.7	34.22	28.30	22.22	18.78	16.65
Oral cavity and pharynx	1435.7	25.73	23.44	34.02	47.94	35.37
Leukaemia	1281.4	43.27	33.61	15.10	6.32	2.80
Face CT						
Brain	790.7	13.75	11.35	11.62	9.85	6.57
Oral cavity and pharynx	1435.7	71.72	65.58	52.80	29.83	39.28
Leukaemia	1281.4	22.73	17.73	5.14	5.15	1.95
Cervical spine CT						
Thyroid	532.7	131.02	107.06	170.71	82.95	74.38
Leukaemia	1281.4	16.41	12.65	3.27	1.27	3.40
Neck CT						
Thyroid	532.7	57.35	46.90	33.38	25.32	46.07
Leukaemia	1281.4	7.32	5.64	3.11	3.16	2.30
Esophagus	477.7	4.06	3.75	3.38	2.32	3.06
Thoracic spine CT						
Thyroid	532.7	101.93	83.30	117.94	69.75	26.27
Leukaemia	1281.4	9.70	7.66	6.14	7.70	8.64
Breast[c]	9416.5	318.60	282.27	280.99	207.00	209.25
Lungs	5226.8	129.71	118.05	185.77	153.72	113.93
Esophagus	477.7	11.59	10.67	13.42	9.24	8.35
Thorax CT						
Thyroid	532.7	252.14	206.01	41.10	70.26	25.40
Leukaemia	1281.4	40.20	31.10	7.47	6.36	5.22
Breast[c]	9416.5	458.75	406.49	250.29	163.54	159.07
Lungs	5226.8	238.07	216.58	111.39	97.70	96.84
Esophagus	477.7	23.17	21.34	10.07	10.52	7.15
Abdomen CT						
Stomach	1888.0	62.80	57.19	53.20	56.50	54.66
Colon	5571.0	83.61	77.31	93.27	81.35	121.12
Rectosigmoid	2404.5	6.24	5.75	12.41	9.17	8.26
Gallbladder	–	–	–	–	–	–
Pancreas	1379.5	14.68	13.61	18.44	14.44	18.09
Liver	1105.4	30.87	28.23	27.81	26.29	19.60
Kidney	1087.4	13.61	12.28	15.96	15.61	14.43
Trunk CT						
Thyroid	532.7	18.36	15.05	34.35	37.47	51.95
Leukaemia	1281.4	13.69	10.76	6.67	14.13	7.46
Breast[c]	9416.5	158.67	140.59	219.59	204.83	180.79
Stomach	1888.0	36.05	32.82	55.37	55.55	45.29
Colon	5571.0	69.53	64.36	100.66	111.06	74.23
Rectosigmoid	2404.5	7.45	6.87	9.22	11.49	7.67
Pancreas	1379.5	9.48	8.79	16.45	20.59	13.89
Liver	1105.4	16.67	15.20	32.26	32.67	21.72
Kidney	1087.4	10.68	9.65	15.36	14.61	11.79
Pelvis CT						
Urinary bladder	4561.3	105.36	97.53	91.61	106.17	96.81
Prostate[b]	13,534.7	39.68	36.88	41.44	33.64	38.02
Ovaries[c]	1290.7	10.05	9.23	23.23	33.94	13.94
Uterus[c]	239.5	21.71	19.87	25.69	20.97	12.89
Leg CT						
Leukaemia	1281.4	28.21	21.82	4.99	15.27	2.47
Prostate[b]	13,534.7	41.70	38.76	42.64	81.90	38.35
Ovaries[c]	1290.7	16.12	14.93	9.17	8.05	4.55
Uterus[c]	239.5	11.07	10.11	9.07	10.55	4.00

[a] Calculated from birth to age 110.
[b] Only in male patients.
[c] Only in female patients.

Su et al. (2014). Our reconstruction of doses for a given examination type is based on an assessment of the typically exposed organs and tissues provided by expert judgment, and does not allow variability among patients. Therefore, the absorbed doses of those organs partially included or in the periphery of the scan volumes may be overestimated, as could be the case of the thyroid in thorax CTs or underestimated, if the landmarks over the computational phantom excluded a truly irradiated organ. Consequently, they have to be taken with caution, as it is suggested that the comparison of the estimated doses among studies is made only for the organs entirely included in the scanning field (Hall and Giaccia, 2006). Although historical data suggests that greater attenuation of the incident radiation (and therefore lower organ-doses)

Table 4
Predicted cancer cases by cancer site and age group.

Cancer site/CT type	Total expected cancers from all 2013 CT scans (95% CrI)	Expected number of cancers by age group and selected CT scans				
		< 1 year	1–4 years	5–9 years	10–14 years	15–20 years
Thyroid cancer	31.8 (2.8–101.8)					
Head CT		7.99	11.36	0.55	0.55	1.74
Thorax CT		1.60	2.53	0.59	1.11	0.81
Oral cavity cancer	22.7 (4.7–48.8)					
Head CT		0.88	1.40	2.47	4.29	11.06
Face CT		0.01	0.03	0.16	0.14	0.63
Lung cancer	18.4 (3.0–48.6)					
Thorax CT		1.69	2.73	1.70	1.61	3.27
Abdomen CT		0.30	0.09	0.12	0.51	1.67
Colon cancer	17.7 (3.8–38.9)					
Abdomen CT		0.49	0.13	0.57	1.18	11.12
Thorax CT		0.39	0.56	0.36	0.54	0.71
Chest-to-pelvis		0.03	0.02	0.03	0.13	0.55
Breast cancer[a]	14.8 (2.3–41.3)					
Thorax CT		1.35	2.56	1.57	1.25	2.46
Abdomen CT		0.43	0.14	0.22	0.78	1.77
Brain cancer	12.4 (2.7–25.8)					
Head CT		1.31	1.88	1.66	1.96	5.32
Stomach cancer	11.8 (2.4–27.2)					
Abdomen CT		0.34	0.10	0.28	0.85	5.02
Thorax CT		0.55	0.83	0.62	0.79	1.45
Bladder cancer	10.6 (2.5–22.9)					
Abdomen CT		0.30	0.08	0.60	0.53	4.64
Leg CT		0.03	0.02	0.21	1.04	1.15
Leukaemia	8.9 (1.6–21.0)					
Head CT		1.55	2.09	1.10	0.60	0.85
Thorax CT		0.33	0.39	0.11	0.11	0.18
Abdomen CT		0.13	0.03	0.02	0.11	0.54
Remaining sites						
Liver cancer	5.2 (1.0–12.4)	0.50	0.52	0.57	0.82	2.80
Pancreas cancer	3.4 (0.7–7.9)	0.23	0.24	0.33	0.42	2.18
Kidney cancer	2.8 (0.6–6.6)	0.22	0.21	0.27	0.41	1.73
Esophagus cancer	2.1 (0.3–5.6)	0.32	0.45	0.28	0.33	0.70
Prostate cancer[b]	2.0 (0.6–4.1)	0.14	0.08	0.13	0.44	1.17
Rectum cancer	1.5 (0.3–3.2)	0.08	0.04	0.12	0.24	1.02
Ovaries cancer[a]	1.5 (0.4–2.9)	0.05	0.04	0.08	0.32	0.97
Uterus cancer[a]	1.0 (0.3–2.0)	0.05	0.03	0.06	0.18	0.70
Total by age groups	168.6 (30.1–421.1)	23.14	31.10	16.70	23.83	73.84
	%	13.7%	18.4%	9.9%	14.1%	43.8%

[a] Only in female patients.
[b] Only in male patients.

would be expected in the oldest patients, the pattern of age-specific doses in this study is different, with higher median doses on average, for the same procedures, among older patients. This likely reflects the fact that, by 2013, most of the hospitals used paediatric specific protocols adapted (1) to patient height and weight, (2) to clinical indication and (3) optimised to minimise doses in younger patients, compared to the use of adult protocols in the oldest patients.

The fact that LAR for site-specific cancers showed no clear dependence on age at exposure may seem paradoxical when data from the LSS and other studies show clearly an age at exposure dependence of risk. In particular, it is observed that exposure in childhood tends to result in higher risks than exposure later in life, particularly for leukaemia, thyroid cancer and breast cancer (UNSCEAR, 2013). The absence of clear pattern here is, in fact, related to the higher median doses received in general by the older patients, offsetting the higher risk coefficients in younger patients. The predicted gender-averaged LBR of brain cancer and leukaemia were slightly higher for the Spanish compared to the French population (Journy et al., 2013), whereas the opposite was observed for thyroid and breast cancer, although in general terms the LBR for the cancer sites assessed in both studies were similar in order of magnitude, reflecting similar cancer incidence and survival rates.

In our study, the highest LAR following CT scan radiation exposure were found for breast, lung, and thyroid cancer. For the three neoplasms, radiation exposure during childhood is a well-documented risk factor (UNSCEAR, 2013; National Research Council (U.S.), 2006; Hall and Giaccia, 2006; Howe and McLaughlin, 1996; Ronckers et al., 2005; Ozasa et al., 2012; Nikiforov and Gnepp, 1994). In the French study, higher breast cancer risks were reported (Journy et al., 2013) whereas similar lifetime risks of brain cancer after a head CT (per 100,000 exposed) were presented for the those groups of children aged 5 years and older (Journy et al., 2013). Chest-to-pelvis CTs conferred the highest lifetime risks when taking into account all the cancer sites (LAR per 100,000 exposed patients). This was related to a combination of high specific organ-doses and higher radiosensitivity of the breast and colon. We estimated that the organ-doses received by the young population who underwent a CT scan during 2013 would produce approximately 168.6 additional cancers over life (mainly thyroid, oral cavity and pharynx, lung and colon cancer). This estimation might be conservative given the fact that over 11,000 CT scans (10%) were discarded due to unavailable parameters for dose estimation. Furthermore, the present estimation might underestimate the actual number of cancer cases if within the discarded scans conducted due to cancer suspicion there is an elevated fraction of cancer-free results.

In a wider age range population (0 to > 85 years), Berrington de González (2009) projected primarily lung and colon cancer cases resulting from one year of CT imaging (Berrington de González, 2009). Similar attributable fractions of radiogenic cancer cases were observed

in comparable studies (Web Table 1).

It is important to bear in mind that our organ-dose estimates might be affected by some degree of uncertainty, given the fact that we did not take into account the patient body shape and orientation due to unavailability of height, weight and patient position information. Also, the definition of the prototypical scan landmarks by a paediatric radiologist might not describe the potential variability in clinical practice when scanning a patient. We estimated that a variation of ± 10% on the landmarks of the head and abdomen CT would result in a variation of 0.1–0.8% on the brain and of 0.5–31.5% colon doses, respectively when keeping the rest of parameters the same. Additionally, although the use of the bowtie filter in newborns was imputed based on expert opinion and common paediatric CT protocols we would not expect that this would introduce a substantial error in the dose estimations given the fact that newborn CT scans represented 8.4% of all the CTs used for dose estimation. Despite of this, we acknowledge the contributing effect of these factors to the existing difficulty and variability in organ-dose estimation. Furthermore, despite of the substantial number of CT scan parameters for dose estimation, these may differ from those used in other Spanish hospitals in terms of total number of detectors, number of slices per scan or slice width. Additionally, tissues such as the bone marrow will present substantial absorbed dose heterogeneity due to their own physical distribution throughout the body and partial irradiation of the CTs.

The risk models used in this paper, which are mainly based on cancer incidence within the LSS cohort, implicitly carry some uncertainties given the fact that 1) the BEIR VII report used constant values as risk-free latent periods between exposure and onset of disease despite the lack of precise knowledge on the aetiology of cancer among young people (National Research Council (U.S.), 2006) 2) the DDREF distribution centered around 1.5 was based on experimental data and the latest LSS data, and reflects the inherent uncertainty in this parameter 3) the DDREF may not perfectly fit all cancer sites, 4) the transport of risk estimates between the Japanese and any population implied combining the EAR and ERR LAR in an imperfect way that approximates their relationship with baseline cancer rates (National Research Council (U.S.), 2006) and 5) the BEIR VII assumed an underlying linear no threshold dose-response (LNT) model modified by the age of exposure, attained age and gender although the mechanisms of radiogenic cancer at low doses are not fully understood.

The use of alternative minimal latent periods was assessed by the BEIR VII committee resulting in no different risk estimates, thus, confirming the adequacy of using 5 years for solid cancer and 2 years for leukaemia in the risk calculations. Based on observations in various epidemiologic data sets, alternative DDREF values (2, 2 and ≤3) were proposed by the US EPA (2015), International Commission on Radiological Protection (ICRP) 103 report (2007) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2006) (2008), respectively, resulting in substantially different risk estimates. In particular, it was described that moving from a risk reduction factor of 2 to 1.5 increased solid cancer risk estimates by 33% (Cucinotta and Kim, 2012). The different BEIR VII committee, UNSCEAR, ICRP and EPA use of ERR and EAR mixtures for risk transport between populations suggest a lack of consensus about the appropriateness of one combination over the other. In general though, the BEIR VII committee considered that given the wide confidence intervals that the ERR and EAR presented for the risk estimates in most populations both models fitted reasonably well the data (National Research Council (U.S.), 2006). Also, the UNSCEAR 2006 report (2008) used both the additive and multiplicative models to estimate risks with no inclination for one over the other, as did the ICRP 103 (2007), arithmetically averaging both values. The US EPA (2015) used similar weights for the ERR and EAR models than the ones used here but combined the models using a weighted arithmetic mean in a linear scale instead of a geometric mean in a log scale, resulting in LAR projections 6 to 12% higher than the ones derived by the BEIR VII (US EPA, 2015). Finally, the adopted LNT model controversy is still unsettled, especially in the low-dose range, where the expected small radiogenic health effects are difficult to detect against the normal fluctuations in the baseline cancer incidence rates. Despite this, the increasingly large body of epidemiological and experimental evidence currently supports the use of this model and justifies that the US EPA (2015), UNSCEAR 2006 (2008) and ICRP 103 (2007) report have adopted it as well. Regarding the risk models used, the ERR and EAR models proposed by the ICRP 103 (2007) present a slightly smoother decrease in risk with age-at-exposure per decade than the ones used here and the decrease continues even beyond age 30. This would result in proportionally larger number of projected cancer cases. On the other hand, the UNSCEAR 2006 ERR and EAR models are cancer specific and in most cases they only allow to be modified by attained age (UNSCEAR, 2008). The BEIR VII (National Research Council (U.S.), 2006) approach did not account for the uncertainties associated to the definition of the relative biological effectiveness (RBE) per unit absorbed doses used to evaluate the radiogenic cancer risks on the LSS cohort. According to this, the estimation of risks from low-dose x-ray exposure may be underestimated by a factor of 2 or 3 (National Research Council (U.S.), 2006). Additionally, the BEIR VII analyses failed to address other sources of uncertainty such as the fact that the LSS population exposed at younger ages is still at risk of developing radiation-induced malignancies, assuming that the observed risk patterns were stable for the youngest survivors (National Research Council (U.S.), 2006). Also, the BEIR VII report assumed that although the LSS cohort registered solid cancer incidence after 1958 most probably missing some early childhood cancers, the risks might be similar to those observed in the initial years of follow-up. An increased number of cancer cases within the LSS cohort would translate in different risk coefficients and values for the parameters that express the relationship of risk with attained age and age at exposure. All in all, it is important to regard the obtained cancer estimates as the result of statistical and subjective uncertainties, derived from the BEIR VII committee and NIH adoption of risk models, parameters, risk-reduction factors, model mixtures and latency periods based on specific datasets and underlying assumptions. The effect of these unaccounted sources of uncertainty may result in an influential contribution to the overall uncertainty of the present risk estimates.

One limitation of our study is that we extrapolated data from Catalonia to the rest of the country. To our knowledge there is no *a priori* reason to expect different CT scanning practices between Catalonia and Spain. This does, however, introduce further uncertainty in our cancer estimates. Additionally, cancer incidence was assumed stable from 2007 to 2013, although some variability was observed in the previous years. Due to the annual fluctuation of rates of rare cancer types, we did not extrapolate the site-specific cancer incidence of 2007 onwards. Therefore, if 2013 cancer incidence differed from 2007, a slightly different LAR would be expected given that the ERR model contributes substantially in the risks for most cancer sites. However, no major changes would be expected for breast cancer due to the fact that it relies entirely on the EAR model. The assumption of stability over time of the life table data is another source of uncertainty. Finally, we estimated the independent risks attributable to one CT scan, which is aligned with the fact that most population in this age-range will receive a single CT, as observed in a previous study (Bosch de Basea et al., 2016). Although the previously mentioned factors enlarge the margins of uncertainty of this assessment exercise, the statistical, dosimetric and modelling methodology used is consistent with the published literature (National Research Council (U.S.), 2006). Despite the medical effectiveness of CT scan, the results of this risk analyses provide some information regarding the small but undeniable CT-related excess in cancer, the second leading cause of disease-related death in the Spanish population (Instituto Nacional de Estadística. (National Statistics Institute), 2014). While the relative excess risk of cancer over life is estimated to be small (0.43%) compared to the baseline cancer risk in the population, it should be noted that our estimates are based only on

one year of scanning. It is not uncommon for patients to receive more scans in childhood and adolescence, as well as over life, with some patients receiving tens of scans in a few years for the follow-up of some conditions. Consequently, cancer risks in those patients will be greater and care must be taken to ensure they receive appropriate radiological protection.

Risk estimates in this study were based on recent CT scanning practices in Spanish young people. Studies indicate that, within the radiological and radiation protection communities, the increased consciousness of the potential health consequences of CT scanning have impacted both the scanning frequency in young people and the radiation dose levels used (Singh et al., 2009). Hence, a similar exercise conducted on CT scanning in earlier years would most likely have resulted in a higher lifetime excess of cancer. In the absence of accurate direct estimates of risks from CT exposed patients followed up for long time periods, risk projection studies provide important information to: a) enforce the CT indication guidelines to minimise CT scans without a clear medical benefit, b) promote dose-reduction practices and the optimization of CT acquisition parameters within staff radiologists and technologists, and c) favour the steady renewal of scanners in Spain by those equipped with new dose reduction features such as the iterative model reconstruction technology. Also, the identification of higher cancer risk age groups and types of CT scans is a useful approach to patient protection safety. Additionally, this paper provides some scientifically based evidence for complex medical decisions regarding the use of ionising radiation in young population.

5. Conclusion

The first estimation of the CT scan use in the 0–20 year old Spanish population indicated that in 2013, 105,802 CT scans were performed, representing a crude rate of 10.9 scans per 1000 Spanish young people. The sizeable amount of contemporary clinical data allowed the reconstruction of the doses used and the assertion that they were relatable to those reported in similar studies in other countries. Using the estimated parameters from the risk models proposed by the BEIR VII report and Berrington de González it was estimated that 168.6 (30.1–421.1) additional cancer cases may occur over the life course of this exposed population, mainly of the thyroid, oral cavity and pharynx, lung and colon. This represented an attributable risk percent of about 0.43% (0.08%–1.1%), which provides an important piece of information when assessing the risk-benefit of a CT scan in a paediatric patient. Although the minimisation of the radiation exposure of the patient must guide the clinical practice, the estimated infinitesimal increase in risk may help easing the concerns regarding well justified CT examinations.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.07.020.

Funding

This work was partly supported by the European Community's Seventh Framework Programme (FP7/2007-2013) [grant number 269912 - EPI-CT: Epidemiological study to quantify risks for paediatric computerised tomography and to optimise doses]. Complementary funding was received from a grant from the Spanish Nuclear Safety Council (Consejo de Seguridad Nuclear) (SRO/3347/2015/227.06). M. Bosch de Basea was the recipient of a fellowship of the Centro de Investigación Biomédica en Red de Epidemiología y Salud Pública (CIBERESP) for a short stay abroad at Newcastle University. David Moriña was partially supported by grants from the Instituto de Salud Carlos III-ISCIII (Spanish Government) cofunded by FEDER funds/European Regional Development Fund (ERDF) - a way to build Europe (References: RD12/0036/0056, PI11/02090 and PI16/01254) and from the Agència de Gestió d'Ajuts Universitaris i de Recerca (2014SGR756) and RecerCaixa 2015 (MD088652).

Acknowledgements

The authors gratefully acknowledge scientific and technical assistance provided by Ana Espinosa (ISGlobal) and Tomàs Salas (AQuAS). ISGlobal is a member of the CERCA Programme, Generalitat de Catalunya.

Disclosure of interests

The authors declare that they have no competing financial interests.

Human participant protection

The Ethics Committee of the International Agency for Research on Cancer approved the EPI-CT study protocol (IARC IEC 12-35). In Spain the protocol was approved by the Ethics committee of the Parc Salut Mar in Barcelona (the ethics committee of CREAL -1SGlobal) as well as by all appropriate hospital ethics committees, prior to commencing the epidemiological study.

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