



Strahlenschutzkommission

Geschäftsstelle der
Strahlenschutzkommission
Postfach 12 06 29
D-53048 Bonn
<http://www.ssk.de>

Paediatric CT exposure and cancer

Recommendation by the Commission on Radiological Protection

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CT-Expositionen im Kindesalter und Krebserkrankungen

Empfehlung der Strahlenschutzkommission

This translation is for informational purposes only, and is not a substitute for the official statement. The original version of the statement, published on www.ssk.de, is the only definitive and official version.

Preface

In recent years, results of large-scale studies have been published in relation to the link between exposure to diagnostic CT scans in childhood and the development of cancer later in life. These studies include the European Epidemiological Study to Quantify Risks for Paediatric Computerized Tomography (EPI-CT study) and the Risk of Pediatric and Adolescent Cancer Associated with Medical Imaging (RIC) Study from the USA and Canada. Accordingly, the Federal Ministry for the Environment instructed the German Commission on Radiological Protection (SSK) to assess the current scientific evidence. In particular, the aim was to examine the evidence for a causal relationship between CT exposure in childhood and subsequent development of cancer in relation to the level of exposure, to analyse trends in the use of CT scans on children in Germany, and to identify potential high-risk groups.

In order to assess the current scientific evidence and examine the issues outlined above, the “Cancer and childhood CT exposure” working group of the SSK’s “Radiation Risk” committee was set up, comprising the following members:

- Prof. Dr. Mentzel
- Dr. Deng
- Ms Gill, M. Sc.
- Prof. Dr. Klein
- Prof. Dr. Renz
- Prof. Dr. Dr. Sorantin
- Dr. Stamm
- Prof. Dr. Wollschläger

The working group was also supported by Professor Hauptmann (Brandenburg Medical School Theodor Fontane, an expert advisor to the working group). The SSK thanks the Federal Office for Radiation Protection (BfS) for providing extensive technical information and professional support.

Chair of the working group
on “Cancer and childhood
CT exposure”

Chair of the
“Radiation Risk”
Committee

Chair of the
German Commission on
Radiological Protection

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1 Introduction

On 21 June 2023, the Federal Ministry for the Environment (BMUV, now BMUKN) commissioned the German Commission on Radiological Protection (SSK) to investigate the association between diagnostic radiation exposure from computed tomography (CT) examinations in childhood and cancer (malignant tumours). The aim was to evaluate “recent studies on cancer and leukaemia following low-dose medical radiation exposure in childhood, such as the EPI-CT study (European Epidemiological Study to Quantify Risks for Paediatric Computerized Tomography)” (Hauptmann et al. 2023, Bosch de Basea Gomez et al. 2023) and to answer the following questions:

- How strong is the evidence for a causal relationship between radiation exposure and subsequent disease as a function of the level of exposure?
- Can a trend be observed in the use of CT scans on children in Germany?
- Do the available studies provide any evidence of particularly high-risk groups or areas of application?
- According to SSK, do these findings indicate a need for action by the BMUV (now the BMUKN) and, if so, in what form?

In Germany, the lifetime excess absolute risk of developing a malignant tumour is approximately 45% for women and 52% for men (RKI und GEKID 2023). The risk of malignant diseases rises slightly with age from around the age of 10, before increasing more rapidly from around the age of 40 to 50. Less than 1% of new malignancies in Germany occur in people under the age of 18. In Germany, there are approximately 2,290 incident cases per year among children and adolescents in this age range. With approximately 17 cases per 100,000 children and adolescents each year, malignant tumours are relatively rare diseases in this age group (Ronckers et al. 2025).

The risk of malignant diseases, which rises sharply with age, generally corresponds to the fact that, over the course of a human life, the number of genetic mutations increases while the capacity for tumour defense simultaneously declines. In general, there are many different causes of cancer in adults. A combination of individual genetics, environmental exposures and lifestyle factors contribute to the risk of developing cancer (Cooper 2000, Jassim et al. 2023). These factors can influence the development of malignant cell populations and uncontrolled growth. The causes of cancer in children are generally unclear, with known risk factors (genetic factors and environmental exposures) only able to account for around 10% of incident cases (Erdmann et al. 2019, Schüz und Erdmann 2016).

The risk factors classified as carcinogenic to humans by the WHO’s International Agency for Research on Cancer (IARC) include ionising radiation (IARC 2000). The regulations governing radiation protection, which are based primarily on International Commission on Radiological Protection (ICRP) Publication 103, are underpinned by the linear no-threshold (LNT) model, which is used to assess the relationship between cancer risk and radiation dose. With regard to human radiation exposure *in vivo*, there is internationally accepted evidence of a proportional relationship between dose and risk in the range of approximately 100 mGy to 1 Gy (IAEA 2023). For the purposes of radiation protection, the LNT model assumes that this relationship can be extrapolated linearly to lower dose levels, and that no threshold level exists.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) assesses the overall risk of developing cancer following exposure during childhood and adolescence as being higher compared to exposed adults, with potentially radiation-induced tumours developing within a period of a few years to many decades after exposure. However,

this increased sensitivity to radiation is only observed for certain types of cancer, including leukaemia and cancers of the thyroid, breast, skin and brain (UNSCEAR 2013).

Both diagnostic imaging and interventional medical procedures often rely on the use of ionising radiation, including in children and adolescents, with the organ dose for individual examinations generally remaining well below 100 mGy. X-ray diagnostics include conventional X-ray imaging and CT scans. The extent to which the radiation from these diagnostic procedures in children and adolescents actually increases their cancer risk later in life is a matter of debate. The epidemiological evidence available so far does not allow for a reliable characterisation of the form of the dose–response relationship between radiation doses of less than approximately 50 mGy and the risk of cancer. At present, such relationships are therefore extrapolated linearly downwards from the range of doses for which empirical evidence exists. This extrapolation is of limited value when it comes to assessing the actual additional cancer risk to patients undergoing X-ray diagnostic procedures.

Dose–response relationships derived from other studies are used to estimate the number of cancer cases caused by diagnostic radiation exposure from CT examinations. For example, Berrington de Gonzalez et al. (2009) and Smith-Bindman et al. (2025b) used the model developed by the National Research Council’s committee on “Biological Effects of Ionizing Radiation VII” (Council 2006). This model is largely based on the findings of the Life Span Study (LSS)¹ of survivors of the atomic bombs of Hiroshima and Nagasaki. Smith-Bindman et al. (2025b) estimate, based on data on the frequency and dose of CT scans from a Californian CT dose registry (University of California San Francisco International CT Dose Registry), that radiation from 93,000,000 CT scans performed on 61,510,000 patients (children and adults) in the US in 2023 will cause approximately 103,000 cases of cancer by the time of their death. Based on 3,069,000 CT scans performed on children in 2023, the team of authors estimate that this will result in approximately 9,700 cases of cancer later in life. The authors conclude that around 5% of all new cancer cases diagnosed each year in the US could be caused by CT examinations. From a methodological perspective, the registry study has limitations due to the risk models used and existing uncertainties. CT scans are carried out particularly on older and seriously ill patients, but the estimate was made for the entire population. The frequency of CT scans per capita is substantially higher in the US than in Germany. Furthermore, the study’s estimates cannot be applied to children in Germany, as the criteria for treatment in Germany are very strict due to radiation protection legislation. For example, the proportion of CT scans performed on children is 4.2% in the US, compared with less than 1% in Germany. For further details, please refer to the statement issued by the Federal Office for Radiation Protection (BfS) (BfS 2025).

With regard to CT methodology, it should be noted that, due to the relative sizes of the skull and the trunk, cranial CT (cCT) is particularly relevant for newborns, infants and young children, as a large area of blood-forming – and thus radiation-sensitive – bone marrow is exposed. In X-ray diagnostics involving the trunk, account must also be taken of the higher radiation sensitivity compared with the peripheral skeleton, given the higher proportion of haematopoietic (blood-forming) bone marrow. Compared with adults, children also have a higher proportion of haematopoietic bone marrow even in the peripheral skeleton.

It is difficult to reliably estimate the cancer risk following diagnostic radiation exposure from CT scans in children and adolescents using epidemiological studies. The reasons include the

¹ The Life Span Study is a research programme operated by the Radiation Effects Research Foundation (RERF); see https://www.rerf.or.jp/en/programs/research_activities_e/outline_e/proglss-en/

low incidence of malignant tumours up to middle adulthood, the relatively infrequent use of CT scans in childhood, and the need for long follow-up periods due to the latency of several years before cancer develops, particularly in the case of solid tumours. One particular methodological challenge in these studies stems from the possibility of systematic bias, as CT scans are part of the initial diagnostic process when solid tumours are suspected. Cancers diagnosed following a CT scan may therefore have already developed before the scan. An increased incidence of disease following CT scans does therefore not, in itself, prove that the diagnostic radiation exposure caused the disease. In the mid-2010s, a critical view was taken of some epidemiological studies conducted in relation to this issue due to potential biases (Boice 2015, Walsh et al. 2014).

Since then, the available epidemiological evidence regarding the extent of the cancer risk in later life due to diagnostic CT exposure during childhood and adolescence has evolved, primarily due to the publication of findings from the European EPI-CT study and the US–Canadian RIC Study (Smith-Bindman et al. 2025a). One aim of these studies was to allow accurate estimation of the radiation risk without bias due to methodological factors.

In parallel to the publication of radiation-epidemiological evidence, technical advances in radiology in recent years have enabled a substantial reduction in the dose received during an examination. Furthermore, developments in radiological diagnostics using non-ionising radiation have led to changes in the indications for CT scans. This topic is addressed in the SSK recommendation on “Diagnostic Imaging in Children” (SSK 2022).

Taken together, the changing scientific landscape in epidemiology and developments in radiological diagnostics highlight the need to reassess the radiation risk associated with CT scans in children and adolescents.

2 Recommendations

Current epidemiological studies on CT scans show that there is a consistent dose–response relationship between CT scans in childhood and the risk of malignant brain tumours and haematological malignancies later in life. For malignant brain tumours, this relationship was shown to be statistically significant at brain doses of approximately 50 mGy or higher and at bone marrow doses of approximately 25 mGy or higher for leukaemia and lymphoma.

Based on the findings of these studies and the approximately 150,000 CT scans performed on children in Germany each year, it can be estimated that a number in the low to mid-double digits of these children could develop cancer later in life as a result of the radiation exposure from the CT scans. The medical benefit of the CT examinations, which must be weighed against this estimated risk, was not quantified in the studies examined.

The SSK's recommendations are as follows:

- The use of computed tomography (CT) in children and adolescents requires a strict indication and the consideration of alternative procedures that do not involve ionising radiation, taking into account of the current “Recommendations for medical imaging procedures” from the SSK. In the case of highly vulnerable groups (e.g., those with cancer predisposition syndromes, CPSs), the increased risk must be taken into account.
- Radiological facilities that examine children and adolescents should maintain and apply regularly updated standard operating procedures (SOPs) for CT scans in children and adolescents, accounting for various parameters (age, weight, sagittal diameter).
- The financial planning of healthcare facilities should take account of the additional demand for alternative diagnostic procedures (e.g. magnetic resonance imaging, MRI) in children and adolescents, which is necessary for radiation safety reasons, as well as the associated personal costs and longer time requirements.
- Given the risks involved and children's higher sensitivity to ionising radiation, as well as the often specific clinical questions involved, planned CT scans should be carried out in specialist centres for paediatric and adolescent diagnostic radiology.
- All medical applications of ionising radiation should be recorded, including dose-relevant parameters – for example as part of the electronic patient record or in a separate national dose registry (see the ACR Dose Index Registry (<https://www.acr.org/Practice-Management-Quality-Informatics/Registries/Dose-Index-Registry>)).
- Equipment manufacturers should in the future be required to include information on the size-specific dose estimate (SSDE) in dose reports, to provide operators of CT scanners with appropriate, tailored protocols for CT scans frequently performed on children and adolescents, and ensure that technical staff receive training.

3 Scientific justification

The request for advice was made to the SSK at a time when new findings from large-scale epidemiological studies on the association between CT scans in childhood and the risk of cancer were being published. Prior to this, the first major studies on the predicted or observed cancer risk associated with CT scans had already been published at the start of the 21st century (Brenner et al. 2001, Pearce et al. 2012b). At the same time, paediatric radiology now has access to innovative technological developments that can help to reduce the radiation exposure of children undergoing scans. These developments include photon-counting CT, additional filters, iterative reconstruction algorithms and the use of artificial intelligence (Mese et al. 2024). However, the availability of CT scanners is also expanding, which is likely to result in variations in radiation dose levels in paediatric CT. For example, CT radiation exposure is significantly lower in specialist paediatric and adolescent radiology centres than in general radiology departments (Strauss et al. 2019). In addition to strict indications, key factors in reducing radiation doses include tailored examination protocols that are suitable for children and can be implemented quickly and in a cost-neutral manner, as well as the use of alternative imaging techniques that do not involve ionising radiation. These aspects are generally taken into account in the SSK's recommendations (SSK 2022).

The key point of this recommendation is the association between CT scans in childhood and the development of cancer later in life. The cancer risk associated with ionising radiation is cumulative and depends on the age at which exposure occurs. It is generally accepted that children are more strongly affected by the consequences of radiation exposure than adults. Firstly, children have a higher radiation risk than adults for a number of cancer types (UNSCEAR 2013). Furthermore, children have a longer remaining life expectancy than adults, which means there is a longer period of time during which cancer can develop. Children may also be exposed to a higher radiation dose than necessary if the CT settings are not adjusted for their smaller body size compared to the adult reference body.

Childhood cancer is rare (Steliarova-Foucher et al. 2017). The data for the years 2012 to 2021 show that an average of 2,290 new cases of cancer were diagnosed annually among children and adolescents under the age of 18 in Germany, which corresponds to approximately 0.5% of the total incident cancer cases. The most common cancers were leukaemias (29.2%), followed by tumours of the central nervous system (24%), lymphomas (15.8%), soft tissue sarcomas (5.4%), peripheral nerve cell tumours (5.4%) and bone tumours (5%). According to the German Childhood Cancer Registry, other types of cancer account for a total of approximately 15% of malignant tumours (Ronckers et al. 2025).

Causal links with genetic factors and environmental exposures are increasingly being identified. It is estimated that around 8% of cancers in children and adolescents are caused by genetic alterations (Gröbner et al. 2018, Zhang et al. 2015). Cancer predisposition syndromes (CPS) not only have an inherent ability to increase the risk of developing malignant diseases, but can also increase the susceptibility of young people to developing cancer following exposure to ionising radiation. This means that children and adolescents with malignant diseases may also be predisposed to radiation-induced secondary malignancies (Porter 2016, Bochtler et al. 2018). This increased risk of developing a malignant disease persists for years or decades after the initial radiation exposure. For children and adolescents with cancer resulting from CPS, diagnostic imaging examinations are unavoidable (Lindor et al. 2008, Glutig et al. 2021). It is therefore essential to take their increased radiation sensitivity into account when selecting imaging techniques for patients with CPS.

The following scientific findings regarding CT applications in children and adolescents are based on a structured and pre-planned literature review following the PECO framework (P –

Population, E – Exposure, C – Comparator, O – Outcome) (Morgan et al. 2018) and on data collected by the Federal Statistical Office (e.g. hospital statistics based on case rates) and the BfS. With regard to the indications for CT scans in childhood and adolescence, relevant national and international guidelines were analysed using corresponding keyword searches and are presented here as examples. The considered list of guidelines does not claim to be an exhaustive consideration of all guidelines that include CT scans in children. The literature from 2000 onwards was reviewed in order to assess groups of children and adolescents classified as having varying risks of developing malignancies (e.g., those with CPS). Using search engines (PubMed, Cochrane Library, Scopus), searches were conducted with keywords such as “computed tomography, low dose, ionising radiation, preterm, newborn, infants, children, adolescents”; in the case of “cancer predisposition syndrome, cancer susceptibility syndrome”, such conditions were also considered individually (e.g. “ataxia–telangiectasia, Nijmegen breakage syndrome, hereditary retinoblastoma, neurofibromatosis type I”). There was a beneficial reciprocal exchange of information and collaboration with the “CT & Dose” task force of the European Society of Paediatric Radiology (ESPR) (<https://www.espr.org/taskforces/ct-dose/>).

3.1 Causal link between radiation exposure and brain tumours and haematological malignancies

3.1.1 Research question

This chapter describes previously published studies that analyse the link between diagnostic radiation exposure during CT scans in childhood and adolescence and the subsequent risk of developing cancer. It examines the extent to which the evidence suggests a causal association, for example by demonstrating a dose–response relationship (Hill 1965). As most studies focus on brain tumours and/or haematological malignancies, other endpoints are not presented here.

3.1.2 Literature search

Relevant literature was identified in two ways. A search was first carried out in PubMed in July 2024 and repeated in December 2025. The same search terms were used as in the systematic review published by Cao et al. (2022) on the link between CT exposure and cancer risk:

((Paediatric[Title/Abstract]) OR (Child[Title/Abstract]) OR (Adolescent[Title/Abstract]) OR (Adolescent[MeSH]) OR (Child[MeSH]) OR (Infant[MeSH]) OR ("Young Adult"[MeSH])) AND (("Tomography, X-Ray Computed"[MeSH]) OR (CT[Title/Abstract]) OR ("Computed Tomography"[Title/Abstract]) OR ("Computerized Tomography"[Title/Abstract]) OR ("Computerised Tomography"[Title/Abstract]) OR ("Radiation Exposure"[MeSH])) AND ("Neoplasms, Radiation-Induced"[MeSH]) AND (2012/1/1:3000/12[patd] NOTat[Anmali]"[Hum]"[MeSH])

In addition, snowballing (also known as “reference tracking”) (Badampudi et al. 2015) was carried out using the following tools: <https://tera-tools.com/> and <https://estech.shinyapps.io/citationchaser/>. In snowballing, a pre-selected list of index publications is used to identify all further articles that are cited by, or that cite, the index articles.

The following index publications were used:

- Abalo KD, et al. Early life ionizing radiation exposure and cancer risks: systematic review and meta-analysis. *Pediatr Radiol*. 2021 Jan;51(1):45-56. Epub 2020 Sep 10th <https://doi.org/10.1007/s00247-020-04803-0>
- (Erratum in: *Pediatr Radiol*. 2020 Oct 22; PMID: 32910229.)
- Berrington de Gonzales A, et al. Epidemiological studies of CT scans and cancer risk: The state of the science. *Br J Radiol* 2021; 95(1135): 20210471. <https://doi.org/10.1259/bjr.20210471>
- Bosch de Basea M, et al. Risk of haematological malignancies from CT radiation exposure in children, adolescents and young adults. *Nature Medicine* 2023; 29: 3111-3119. <https://doi.org/10.1038/s41591-023-02620-0>
- Daniels RD, et al. Strengths and Weaknesses of Dosimetry Used in Studies of Low-Dose Radiation Exposure and Cancer. *JNCI Monographs* 2020; 2020(56): <https://doi.org/10.1093/jncimonographs/lgaa004>
- Foucault A, et al. Childhood cancer risks estimates following CT scans: an update of the French CT cohort study. *Eur Radiol* 2022; 32, 5491–5498. <https://doi.org/10.1007/s00330-022-08602-z>
- Captain M, et al. Epidemiological studies of low-dose ionizing radiation and cancer: Summary bias assessment and meta-analysis. *JNCI Monographs* 2020; 2020(56): 188-200. <https://doi.org/10.1093/jncimonographs/lgaa010>
- Captain M, et al. Brain cancer after radiation exposure from CT examinations of children and young adults: Results from the EPI-CT cohort study. *Lancet Oncol* 2022. 24: 45-53. [https://doi.org/10.1016/S1470-2045\(22\)00655-6](https://doi.org/10.1016/S1470-2045(22)00655-6)
- NCRP. Implications of Recent Epidemiologic Studies for the Linear Nonthreshold Model and Radiation Protection, Commentary No. 27. 2018. Bethesda, MD: National Council on Radiation Protection and Measurements.
- Shao YH, et al. Exposure to Tomographic Scans and Cancer Risks. *JNCI Cancer Spectr* 2020; 4(1): pkz072. <https://doi.org/10.1093/jncics/pkz072> (Adults)
- Thierry-Chef I, et al. Dose estimation for the European Epidemiological Study on Paediatric Computed Tomography (EPI-CT). *Radiat Res* 2021; 196: 74-99. <https://doi.org/10.1667/RADE-20-00231.1>
- Smoll NR, et al. Computed tomography scan radiation and brain cancer incidence. *Neuro-Oncology* 2023; 25(7): 1368-1376. <https://doi.org/10.1093/neuonc/noad012>

3.1.3 Studies

The following overview includes longitudinal epidemiological studies in which the focus was on exposure to ionising radiation from CT scans during childhood and adolescence, in which an organ dose for the respective endpoint was assigned to each study participant for each CT scan and in which risks were observed empirically and dose-dependent risk estimates were presented.

3.1.3.1 Excluded studies

Studies were excluded when they did not use individual organ doses or only carried out external comparisons with the general population (e.g. Huang et al. 2014, Kojimahara et al. 2020 and Wang et al. 2023).

Likewise, a retrospective Korean cohort study (Han et al. 2025) involving 1.38 million children who had undergone CT scans was not taken into account in detail. Although individual dosimetry was carried out and an internal dose–response analysis was made for various types of cancer, a direct association between organ dose and estimated relative risks cannot be derived

from this study. Firstly, relative risks were only reported in relation to one standard deviation of the dose distribution, but not per unit dose. Furthermore, the tables only listed CTDI_{vol} values for a reference phantom, rather than organ doses estimated for the individual patient's anatomy.

“Projection studies” were also not included. These investigations do not conduct a study of their own to determine whether there is an association between radiation exposure from CT scans and the cancer risk observed later in life. Rather, they apply risk models derived from earlier studies to the measured radiation exposure from CT scans in a population group in order to predict the number of additional cancer cases expected to result for that group. Two examples are the studies by Berrington de Gonzalez et al. (2009) and Smith-Bindman et al. (2025b), both of which use the cancer risk model developed by the National Research Council's committee on “Biological Effects of Ionizing Radiation VII”. This model is based largely on risk estimates derived from the survivors of the atomic bombings of Hiroshima and Nagasaki (LSS).

3.1.3.2 Overview of the studies that were considered in detail

Five key studies are described in detail below. 1) The EPI-CT study (Hauptmann et al. 2023, Bosch de Basea Gomez et al. 2023) is a pooled analysis of several European cohort studies on malignant brain tumours and haematological malignancies. 2) The Australian study (Smoll et al. 2023) is a retrospective cohort study of malignant brain tumours using Medicare data. 3)+4) The two Finnish studies (Nikkilä et al. 2018, Abuhamed et al. 2025) are register-based case-control studies on childhood leukaemia and (malignant and non-malignant) brain tumours, both following the same design. 5) The retrospective RIC Study (Smith-Bindman et al. 2025a, Kwan et al. 2022) examines a cohort of children followed from birth to the age of 21 in the USA and Ontario (Canada) and has so far reported risks of haematological and oncological diseases.

1) *EPI-CT*

The EPI-CT study is based on individual studies with a similar design conducted in nine European countries (Bosch de Basea et al. 2015). The results of the individual studies were published separately in some cases, but are not taken into account here for the sake of the pooled analysis.

Hospitals were contacted in order to identify cohorts comprising a total of 948,174 patients who had undergone at least one CT scan in the period from 1977 to 2014, before reaching the age of 18. The resulting data was cross-referenced with the relevant cancer registries in order to obtain information on the subsequent occurrence of cancer.

For the brain tumour endpoint, participants were excluded from the study if the follow-up period was less than 5 years or if a malignant brain tumour developed during that period. For the purposes of the risk analysis, therefore, account was only taken of brain tumours that developed at least 5 years after the first CT scan. These measures, which are explained in greater detail in sections 3.1.5.5 and 3.1.5.6, were taken to prevent biased radiation risk estimates from cancer cases that could not have been caused by the CT exposure.

For the endpoints relating to haematological malignancies, individuals with a follow-up period of less than 2 years or who had been diagnosed with cancer during that period were excluded. The “time at risk” taken into account began 2 years after the participants' first CT scan.

A new dosimetry system was used to estimate the exposure of the individuals undergoing treatment (Thierry-Chef et al. 2021). To this end, all the details collected in the individual studies from examinations stored in the picture archiving and communication system (PACS) were first combined. The National Cancer Institute dosimetry system for Computed Tomography (NCICT) (<https://dceg.cancer.gov/tools/radiation-dosimetry-tools/computed-tomography>, Lee et al. 2022) was used to calculate organ doses for approximately 30 different organs

for each one of the examinations identified from the PACS data. The scans documented in the PACS represented only a subset of all CT scans and were predominantly from recent years. Each CT scan was then matched with the most appropriate scan from the subgroup of PACS data, and the organ doses from that scan were used. For the endpoint “brain tumours”, the cumulative dose was taken into account with a 5-year time lag; for haematological malignancies, the time lag was 2 years as it is assumed that, for biological reasons, exposure cannot lead to clinically apparent cancer before this time.

2) Australia

The Australian study (Smoll et al. 2023) is a cohort of 10,524,842 Australian Medicare participants aged between 0 and 19 years, covering the period from 1985 to 2005. Of the participants, 611,544 had undergone at least one CT scan before the age of 20. The cohort was cross-referenced with the national cancer registry and mortality registry up to 2012. Organ doses were calculated using NCICT, drawing on data relating to typical technical conditions for specific CT scans. To this end, data was collected from surveys, study protocols, databases used for regulatory purposes, and the literature. This recommendation only took account of the updated analysis (Smoll et al. 2023); an earlier publication with a shorter follow-up period was not included (Mathews et al. 2013).

Only cancer diagnoses made more than 2 years after the first CT scan were included. Furthermore, the “period at risk” began 2 years after the first CT scan. In the dose–response analysis, the cumulative dose was applied with a 2-year time lag.

3)+4) Finland

The Finnish study on leukaemia (Nikkilä et al. 2018) identified 1,093 cases of childhood leukaemia (under the age of 15) from the Finnish cancer registry between 1990 and 2011, and for each case, three matching controls in terms of gender and year of birth. For these individuals, data was collected on all CT scans carried out at the country’s 10 largest hospitals. Between 1975 and 2011, an estimated 87% of all CT scans performed on children in Finland were carried out at the participating hospitals. Expert advice was sought to ensure plausible values for the technical configurations of the CT scanners, taking account of the device manufacturer and, where it was known, the model. Based on these assumptions, the individual cumulative bone marrow doses were calculated using NCICT. In the dose–response analysis, the cumulative doses were applied with a 2-year time lag. Children and adolescents with the following CPS were excluded from the study to avoid biasing the radiation risk estimate: neurofibromatosis type 1 and type 2, tuberous sclerosis, Li-Fraumeni syndrome, naevoid basal cell carcinoma syndrome, Turcot syndrome, Cowden syndrome, retinoblastoma predisposition, Rubinstein-Taybi syndrome.

The Finnish study on malignant and non-malignant brain tumours (Abuhamed et al. 2025) identified 967 cases (under the age of 15) between 1990 and 2016. The cumulative dose was taken into account in the dose–response analysis with a 5-year time lag. Otherwise, the study followed the design of the childhood leukaemia study (Nikkilä et al. 2018).

5) RIC Study

The RIC Study adopted a birth cohort methodology, encompassing over 3.7 million newborns from the years 1996 to 2016 (Smith-Bindman et al. 2025a). These individuals were either registered at one of a total of six US healthcare facilities affiliated with the Kaiser Permanente healthcare network or were members of the public health insurance scheme for the Canadian province of Ontario. Children with a follow-up period of less than 6 months, as well as those diagnosed with cancer within the first 6 months of life, were excluded. The members of the cohort were followed up until they reached the age of 21, until a cancer diagnosis was made, or

until the end of December 2017 at the latest. On average, the follow-up period was approximately 10 years per person and totalled approximately 35.7 million person-years.

The clinical records made it possible to record all radiological examinations. These included conventional X-ray examinations, CT scans, fluoroscopies, angiographies and nuclear medicine procedures. However, the birth cohort also included children who had not been exposed, i.e. those who had not undergone a radiological examination. For all radiological examinations performed, the individual bone marrow dose was estimated using a prediction model (Stewart et al. 2025). The cumulative radiation dose was taken into account in the dose–response analysis with a lag time of 6 months (see section 3.1.5.6), whilst a sensitivity analysis extended this period to 2 years. It was also possible to assess the indications for radiological examinations for children within the Kaiser Permanente healthcare network, as well as for inpatient and emergency examinations in Ontario. In Ontario, this covered 60% of all radiological examinations.

To identify haematological malignancies, the RIC Study used the clinical records of the included participants as well as record linkage with cancer registries. On the basis of clinical records, individuals diagnosed with Down’s syndrome were also identified, as they are at higher risk of developing leukaemia.

3.1.4 Results

Haematological malignancies

The results of the EPI-CT study show a clear and strong association between cumulative bone marrow dose and risk of both myeloid and lymphoid malignancies. The excess relative risk (ERR) per 100 mGy for myeloid malignancies was 2.01 (95% confidence interval (CI): 1.02–3.42) with 578 cases. For lymphatic malignancies, the ERR was 1.96 (95% CI: 1.10–3.12) with 790 cases. The results proved robust in a series of sensitivity analyses, including analyses using longer exclusion periods than the 2 years used in the main analysis, or excluding individuals who received the highest doses. In the analysis stratified by age group (< 5 years, 5 to < 10 years, ≥ 10 years), it was observed that, for both endpoints, the ERR per 100 mGy rose with the age group. This finding is unexpected (see below), particularly given the higher radiation sensitivity of children compared with adults demonstrated in the LSS.

The case-control study from Finland also found a positive association between cumulative bone marrow dose and the incidence of childhood leukaemia. However, the excess odds ratio (EOR) was 13 per 100 mGy (95% CI: 2–26) and therefore six times higher than in the EPI-CT study. This high figure was attributed to the influence of random fluctuations, a plausible explanation given the small number of exposed cases of only eight.

In a linear dose–response analysis in the cohort with 2,961 diagnosed haematological malignancies, the RIC Study estimated an excess relative risk per 100 mGy of 2.54 (95% CI: 1.70–3.51). Based on this estimate, the proportion of all haematological malignancies attributable to diagnostic radiation exposure was 10.1% (95% CI: 5.8–14.2). At a bone marrow dose of at least 30 mGy (average 57 mGy), the additional cumulative incidence of haematological malignancies in individuals without Down’s syndrome up to the age of 21 was estimated at 25.6 per 10,000 children. A bone marrow dose of 30 mGy was equivalent to approximately two cranial CT scans, for which the average bone marrow dose was estimated at 13.7 mGy. In the sensitivity analysis using a lag time of 2 years for the cumulative dose, the ERR per 100 mGy was 2.16 (95% CI: 1.30–3.16). Further sensitivity analyses, such as those excluding observations with bone marrow doses of over 50 or 100 mGy, or those excluding children with Down’s syndrome, yielded estimates of the ERR per 100 mGy that were consistent with the main result.

In an analysis of the RIC Study based on separate dose categories, the respective relative risks for the dose categories 15–20 mGy, 20–30 mGy, 30–50 mGy, 50–100 mGy and ≥ 100 mGy increased with dose and, including their confidence interval (CI) boundaries, exceeded 1. In this analysis, 89 out of 2,961 haematological malignancies were observed in individuals with an estimated cumulative bone marrow dose of at least 20 mGy.

A linear dose–response relationship was observed in the RIC Study both for lymphoid malignancies – including acute lymphoblastic leukaemia (ALL) – with an ERR per 100 mGy of 1.95 (95% CI: 1.09–2.97) and for myeloproliferative malignancies and myelodysplastic syndrome (ERR per 100 mGy 10.19; 95% CI: 3.61–20.82). This association is particularly evident in the case of non-Hodgkin’s lymphoma (ERR per 100 mGy: 2.56; 95% CI: 1.52–3.81). Unlike in the EPI-CT study, no associations were found for Hodgkin’s lymphoma (ERR per 100 mGy 0.00; 95% CI: 0.00–1.10) or AML (ERR per 100 mGy 0.00; 95% CI: 0.00–1.49).

Brain tumours

For risk of malignant brain tumours, the EPI-CT study shows a significant association with the cumulative brain dose from CT scans of the skull, with an ERR per 100 mGy of 1.27 (95% CI: 0.51–2.69) and 165 exposed cases. The results were also similar for the glioma subgroup. An expected increase in risk per unit dose at younger age at time of exposure was not observed. A wide range of sensitivity analyses rule out methodological biases as the sole cause of the observed association.

The Australian study showed consistent results for malignant brain tumours, with an ERR of 0.80 per 100 mGy (95% CI: 0.54–1.06) and 4,472 cases, of which 237 were exposed. For gliomas, the results were similar and showed little variation across different sensitivity analyses.

The Finnish study encompassed both malignant and non-malignant brain tumours. The EOR per 100 mGy of cumulative brain dose was 5.50 (95% CI: 0.31–10.95) based on nine exposed cases. The EOR was 3.48 per 100 mGy (95% CI: -2.33–9.64; four exposed cases) for malignant brain tumours and 1.06 (95% CI: -6.55–9.30; three exposed cases) for gliomas (high- and low-grade gliomas). Due to the very low number of exposed cases, the accuracy of these estimates is severely limited. The estimated risk coefficient for malignant brain tumours was three to four times higher than in the EPI-CT study and the Australian study; however, it was not statistically significantly different from zero.

Age at time of exposure

The EPI-CT study also examined how the radiation-associated risk varies with age at the time of exposure. For haematological malignancies, the ERR per 100 mGy increased significantly with increasing age at time of exposure ($p=0.001$): 0.78 for < 5 years, 1.81 for 5 to < 10 years and 4.02 for ≥ 10 years (Bosch de Basea Gomez et al. 2023). In keeping with this, for a fixed dose and a fixed time from exposure, the RIC Study observed an increase in the relative risk of haematological malignancies from the < 1 year age group (2.18 at 30 mGy vs. no exposure) to those of 1 to 4 years (2.81) and 5 to 10 years (6.09), with the risk dropping off again to 3.54 in the age group from 10 to 20 years. The Finnish study on childhood leukaemia did not confirm these findings, given the small number of cases.

In the EPI-CT study, Hauptmann et al. 2023 observed no significant difference in ERR per 100 mGy for malignant brain tumours between different age groups at time of exposure ($p = 0.16$): 0.40 for $0 < 6$ years, 1.98 for 6 to < 12 years and 1.62 for ≥ 12 years. The Finnish study on brain tumours did not report an estimated cancer risk per unit dose stratified by age group. The estimated cancer risk for the categorical comparison of individuals who had ever been exposed to CT scans versus those who had never been exposed showed no statistically

significant difference between age groups at the time of diagnosis. The Australian study did not report results of age-stratified analyses. However, no statistically significant improvement in the model of the dose–response analysis was observed when age at exposure was taken into account.

Details of the methods and results of these key studies are set out in Table 1.

Table 1: Methods and results of the studies considered (author: Prof. Michael Hauptmann, Brandenburg Medical School Theodor Fontane)

	Australia (Smoll et al. 2023)	EPI-CT Europe (Bosch de Basea Gomez et al. 2023, Bosch de Basea et al. 2015,Hauptmann et al. 2023)		RIC California, USA & Ontario, Canada (Smith-Bindman et al. 2025a)	Finland (Abuhamed et al. 2025, Nikkilä et al. 2018)	
Year of publication	2023	2024		2025	2025	2018
Design	Cohort	Cohort of exposed cases (≥ 1 CT scan)		Cohort	Case control	
Endpoints	Malignant intracranial brain tumours	Malignant intracranial brain tumours	Haematotological malignancies	Haematological malignancies	Malignant and non-malignant brain tumours 0-15 years	Leukaemia 0-15 years
Scope of study						
Persons	10,524,842	658,752	876,771	3,724,623		
Person-years	235,643,748	4,536,716	6,863,833	35,715,325		
Medium follow-up (in years)	22.4	6.9	7.8	10.1		
Cases				2,961	604	911
Controls					1,809	2,730
Exposed cases	237	141	790 lymphatic, 578 myeloid neoplasias	1,700 (of which 272 with cumulative bone mark dose ≥ 1 mGy)	9	8
Exposure period	1985 – 2005	1977 – 2014		1996 – 2017	1978 – 2011	
Age at exposure (years)	0 – 19	0 – 22		0 – 21	0 – 14	
Diagnosis period	1985 – 2012	1977 – 2014		1996 – 2017	1990 – 2016	1990 – 2011
Dosimetry	Assignment of CT protocols by body, year and age based on technical parameters for external CT examinations from surveys, clinical protocols and literature, dose calculation with NCICT	Derivation of CT protocols by body part, gender, age and CT scanner type based on technical parameters for subset of 378 000 CT scans, dose calculation with NCICT		Dose calculation for 27 595 CTs based on technical parameters, height, weight, sex, body part. Imputation for all other CTs with this data based on height, weight, gender, date, Setup, body part, number of phases.	Technical parameters partly collected, partly estimated, dose calculation with NCICT	
Dose metrics	cumulative brain dose (mGy)	cumulative brain dose (mGy)	cumulative bone marrow dose (mGy)	cumulative bone marrow dose (mGy)	cumulative brain dose (mGy)	cumulative bone marrow dose (mGy)

Lag interval (years)*	2	5	2	0.5	5	2
Cumulative dose (mGy)	44 (mean) 32 (median)	47.4 (mean) 44.0 (median)	15.6 (mean)	14.0 (mean) by all imaging modalities among persons with cumulative bone marrow dose ≥ 0.1 mGy	22.0 (mean)	9.71 (median cases) 7.14 (Median controls)
Exclusion period (years)**		5	2	0.5	None	None
Statistical Risk model	RR = EXP(b*dose), ERR = RR-1	RR= 1+ b* dose with b = ERR		RR= 1+ b* dose with b = ERR	OR = EXP(b* dose), EOR = OR-1	OR = EXP (b* dose), EOR = OR-1
Main results	ERR/100 mGy = 0.80 (95% CI: 0.54-1.06), (4,472 cases)	ERR/100 mGy = 1.27 (95% CI: 0.51-2.69), (165 cases)	All haematological malignancies ERR/100 mGy = 1.96 (95% CI: 1.10- 3.12), (790 cases) Lymphatic malignancies ERR/100 mGy = 2.01 (95% CI: 1.02-3.42), (578 cases) Myeloid malignancies ERR/100 mGy = 2.02 (95% CI: 0.47-4.77), (203 cases)	All haematological malignancies ERR/100 mGy = 2.54 (95% CI: 1.70-3.51), (2961 cases) Lymphatic malignancies ERR/100 mGy = 1.95 (95% CI: 1.09-2.97), (2,349 cases) Myeloid malignancies ERR/100 mGy= 1.82 (95% CI: >0-4.02), (460 cases)	EOR/100 mGy = 5.50 (95% CI: 0.31, 10.95), (9 exposed cases) Malignant brain tumours EOR/100 mGy = 3.48 (95% CI: - 2.33, 9.64), (4 exposed cases)	EOR/100 mGy = 13 (95% CI: 2-26), (8 exposed cases)

RR: Relative risk, ERR: Excess RR, CI: Confidence interval, EOR: Excess odds ratio

*Assumed minimum possible time interval in which exposure can cause a diagnosis of the endpoint.

**Interval at which individuals must have remained tumour-free after the first CT scan to be included in analysis.

3.1.1 Methodological evaluation of the included CT studies

When assessing the validity of radiation epidemiological studies, various methodological aspects must be taken into account. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2017) provides a general overview of relevant methodological criteria, the most important of which are explained in greater detail in the context of the studies considered here.

3.1.1.1 Study design

The included studies are epidemiological observational studies in which information on radiation exposure and health outcomes was recorded at an individual level, i.e., separately for each person in the study population. In observational studies, it is not possible to actively intervene in the study population or to control for confounding factors. In principle, the level of evidence that can be achieved is therefore lower than that which can be achieved in randomised controlled trials. In particular, epidemiological studies alone do not allow for definitive causal conclusions to be drawn about the association between radiation exposure and a medical endpoint.

However, epidemiological studies conducted to a high methodological standard can provide strong evidence when combined with the current understanding of the physical, biological and physiological effects of radiation, as established through controlled studies.

3.1.1.2 Dosimetry

Systematically biased dose estimations can distort the estimated dose–response relationship. Furthermore, random errors in dosimetry can also influence statistical estimates of parameters (section 3.1.5.8). The reliability of the dosimetry is therefore a key criterion when it comes to evaluating an epidemiological study. In order to assess the quality of the dosimetry in the studies under consideration, it is necessary to consider the source of the dose–relevant information, the level of detail and accuracy of the information used, and the dose estimation method itself.

The exposure estimates in the considered studies are based on lists of CT scans compiled by either hospitals or health insurance funds for the purposes of booking appointments or billing. These lists contain basic information (e.g. date, examined body part, sex, age) and may also document examinations that were planned but were not carried out or were carried out differently. The list entries often do not indicate how many CT scans were performed as part of an examination. Consequently, some scans may be missing from the lists because they were deemed unsatisfactory during quality control and subsequently deleted and repeated. Reasons for poor image quality in CT scans include motion artefacts, which can occur particularly during longer scans and when patient adherence is low (e.g. in young children). This suggests that the likelihood of undocumented, discarded runs depends on the child’s age at the time of the CT scan. At the same time, CT scans in the past led to higher organ doses than they do today, as less use was made of protocols optimised for children and adolescents.

In all studies, detailed information on dose-relevant technical parameters (e.g. scanner type, manufacturer, model, CTDI_{vol}, pitch, tube current, tube voltage) was available only for either a subset of the CT scans performed or for CT scans carried out on individuals who were similar to the study population but were not included in the study. This available information was used to derive plausible sets of parameters for categories of CT examinations (protocols) in all studies. Categories were established based on factors including examined body part, sex, age group and calendar year. For each of these groups, the various relevant organ doses were estimated using NCICT (Lee et al. 2015) or a proprietary prediction model for all types of radiological examinations (RIC Study, Stewart et al. 2025).

Knowledge of the details of the scan protocols is important because the radiation dose associated with a CT scan has fallen substantially over time. This is due to improvements in scanner technology and the increasingly widespread optimisation of protocols for examining children and adolescents. The uncertainty in the dosimetry was modelled in detail for the EPI-CT study (Thierry-Chef et al. 2021, Simon et al. 2014a), but these results were not incorporated into the methodology of the dose–response analysis. No quantitative analyses of dosimetric uncertainty are available for the Australian study or the Finnish studies. Full details of the dosimetry for the RIC Study, including the associated uncertainties, can be found in Stewart et al. (2025). The dose–response analysis did not apply any methods to account for uncertainties in the bone marrow dose.

The question of the information source is also relevant when it comes to personal characteristics. For example, body height and weight are relevant factors for determining the organ dose. However, unlike the individuals' respective ages, this information was not documented (EPI-CT, Australian study, Finnish studies) or was only partially documented (RIC). There is considerable variation in height and weight among children and adolescents of the same age, meaning that standard values derived from age are not perfect surrogate markers. The exception to this is the skull, which on average reaches adult size by around age 10 in girls and 14 in boys (Farkas et al. 1992).

Regardless of the exact dosimetry procedure, there are difficulties when it comes to fully recording all CT scans performed on individuals in the study population. For most of the children in the EPI-CT study, all paediatric CT scans performed on them were recorded. Nevertheless, it cannot be ruled out that some individual CT scans may have been carried out which were not included in the study. For example, children and adolescents may have undergone other CT scans prior to their first CT scan that was included in the study, and it may not have been possible to record these prior scans for reasons including that they were carried out at other facilities. This would result in an underestimation of radiation exposure and, consequently, an overestimation of the radiation risk per unit dose. In the Finnish studies, the hospitals included in the survey of CT scans accounted for approximately 87% of all CT scans carried out in the country. Given the structure of the healthcare systems in Australia, the USA and Canada, it can be assumed that the Australian study and the RIC Study provide an almost complete record of all CT scans (Australia) and all radiological examinations (RIC).

One difference between the considered studies lies in the proportion of exposed individuals within the study population. Whilst the EPI-CT study only includes individuals who had undergone at least one CT scan before reaching adulthood, the Australian study, the Finnish studies and the RIC Study relate to the general population, of whom only a small proportion had undergone CT scans. As a result, the studies from Australia, Finland and the USA/Canada include a large number of unexposed individuals, who are not very informative for assessing the dose-dependent radiation risk. However, given the large cohort of approximately 3.7 million people, the RIC Study encompassed over 270,000 CT scans. In addition, there were around 267,000 fluoroscopies, 11,000 angiograms, 66,000 nuclear medicine examinations and 6.7 million conventional X-ray examinations.

3.1.1.3 Definition and ascertainment of health endpoints

The definition of the recorded health endpoints is relevant when it comes to comparing and evaluating the considered epidemiological studies. All of the studies included in the review consider new, i.e. incident, cases of cancer as the endpoint, rather than mortality. Another common feature of the studies was that the endpoints were ascertained by cross-referencing patient data with national (paediatric) cancer registries.

The collection of cancer incidence data via cancer registries presents specific methodological challenges and therefore requires a reliable cancer registration system. The quality of cancer registries can vary considerably depending on the region and time period in terms of the exhaustiveness and completeness of the data. In Europe, it can be assumed that both have been very high since at least the 1990s.

However, in the absence of national cancer registries, it is difficult to record all incident cases of cancer in the study population. For example, this is the case for adults in Germany. Separating cancer registration for children and adolescents from that for adults can also make it difficult to ensure that cases are recorded exhaustively. In the EPI-CT study, for example, the use of childhood cancer registries in France and Germany meant that only cancer cases diagnosed up to the age of 15 could be included.

Another important question is whether the incidence among individuals with varying degrees of exposure could be recorded with the same level of exhaustiveness in follow-up. If the intensity of follow-up varied depending on exposure status and was, for example, indirectly influenced by the indication for the CT scan, this could lead to bias, known as confounding.

Even where high-quality cancer registries exist, difficulties may arise when it comes to correctly identifying individuals within a study population in the cancer registry. For data protection reasons, data matching (record linkage) is often carried out not using real names, dates of birth and addresses, but rather using accession numbers. These are strings of characters resulting from the cryptographic encoding of the real data. The subsequent comparison is stochastic due to uncertainties in the spelling. As a result, the details of individuals who are actually registered in a study population may sometimes not be identified at all in registers, or may be identified incorrectly. This may lead to an under-reporting of cancer incidence; however, this is likely to affect both exposed and unexposed individuals equally and should therefore not cause any bias. While stochastic record linkage was required in the EPI-CT study, the Australian study and the RIC Study, the Finnish studies used the unique national identification number.

Incidence rates can be calculated in cohort studies such as the EPI-CT study, the Australian study and the RIC Study. To do this, the number of incident cases recorded in the cancer registries must be put into context by considering the entire period over which cases were counted. This period is calculated as the total person-years, i.e. the sum of the individual follow-up periods. An accurate calculation of person-years requires that the end of the follow-up period be known for all members of a cohort; for those who have died, this means the date of death, and for those still alive, it means the date on which they left the cohort – for example, as a result of moving house. In the EPI-CT study, there was a lack of information on vital status and date of death for France and Germany. Consequently, mortality tables for the general population were consulted in order to instead obtain representative data on remaining life expectancy for calculating person years. This gives rise to uncertainties, particularly as mortality rates are likely to be higher among people who underwent CT scans during childhood and adolescence than in the general population. In the Australian study, it was possible to record mortality rates completely via the national mortality registry. The RIC Study used data from the healthcare network and, in Ontario, health insurance data to ascertain mortality rates.

The coding of cancers according to statistical classifications of clinical conditions such as the International Classification of Diseases (ICD), International Classification of Diseases for Oncology (ICD-O) or International Classification of Childhood Cancer (ICCC) is subject to changes that reflect evolving medical knowledge about these diseases. In recent years, this has mainly concerned leukaemias and lymphomas and their classification into subgroups. Consequently, studies conducted in different regions or in different time periods may differ in terms of their definition of cancer groups, which can, to some extent, limit their comparability.

Changes in the diagnosis of cancers – for example, due to new imaging technologies or the introduction of screening programmes – can result in a trend in the recorded incidence of cancer over time. Risk factors for cancer development that vary over the years – such as chemical pollutants or environmental exposures – can also give rise to trends over time. If organ doses from CT scans decrease parallel in time but not causally related, this temporal correlation may lead to a spurious statistical association between organ dose and the incidence of cancer. One way to avoid the distortion of study results due to non-causal associations of this kind is to adjust for or stratify by the calendar year period in which a diagnosis was made. This method was used in the Australian study and the EPI-CT study. In the Finnish studies, however, participants were matched only by age and not by year of birth. In the RIC Study, the dose–response analysis was adjusted for the calendar year of birth.

In the case of brain tumours, the heterogeneity of the studies stems from the decision as to whether account is taken only of malignant tumours or also of benign tumours as a health endpoint. The Finnish studies included benign brain tumours, whereas EPI-CT and the Australian study did not. Differences in the definition of endpoints make it difficult to compare and combine the results of individual studies.

3.1.1.4 Confounding

In the context of the research question at hand, a confounder is a variable that is systematically associated with both the level of radiation exposure from CT scans and the risk of developing cancer. If a confounder has a causal effect on cancer risk, a statistical association between CT exposure and cancer may arise even if the CT exposure itself has no causal influence on cancer risk. A prerequisite for this is that the strength of the association between the confounder and CT exposure is high, and that the confounder is also a strong risk factor for cancer. Furthermore, for a confounder to be responsible for an association between CT exposure and cancer risk in the study population, the confounder must also be highly prevalent.

Reverse causation

Distortions due to reverse causation (see Explanation of terms) may arise if CT exposure is the result of early symptoms of a cancer that has not yet been diagnosed – for example, because CT imaging is used for cancer diagnosis after the emergence of clinical symptoms. Analogous examples from the literature include the association between radiation exposure from ^{131}I – which was previously used for thyroid imaging – and the incidence of thyroid cancer (Boice 2015, Dickman et al. 2003). A similar situation applies to the question of the association between exposure to Thorotrast, a contrast agent formerly used in cerebral angiography, and the occurrence of brain tumours (Boice 2015, Travis et al. 2003).

One way to prevent reverse causation is to collect information on why the radiation exposure was administered. For example, information on the clinical indication can be used to exclude individuals who have undergone CT diagnostics to investigate a suspected brain tumour in the presence of relevant symptoms. This was not, however, possible in the brain tumour studies under consideration. Instead, these studies used exclusion periods (section 3.1.5.5) to ensure that tumours arising during the follow-up period were not already present prior to the CT scan and were therefore not the actual reason for performing the examination.

As CT imaging is rarely used in children to diagnose suspected leukaemia or lymphoma, it can be assumed from the outset that reverse causation plays a minor role in relation to these health endpoints when investigating the role diagnostic radiation exposure. Furthermore, the RIC Study was able to evaluate the indications for almost all radiological examinations. The study was thus able to exclude radiological examinations carried out due to a possible suspicion of cancer.

Confounding by indication

In the context of this recommendation, confounding by indication (see Explanation of terms) refers to a situation in which a disease, acting as a causally responsible third variable, both makes CT examinations more likely and constitutes an independent causal risk factor for cancer (Meulepas et al. 2016, Journy et al. 2016a). An overview of this topic in the context of exposure to low doses of radiation is provided by Little et al. (2022b). Of particular relevance here are organ transplants and CPS such as Fanconi anaemia or Down syndrome (see section 3.3.3). For example, people with Down syndrome have an increased risk of developing leukaemia (Hasle et al. 2000). A discussion of the available evidence regarding the frequency of CT scans in people with Down syndrome and the prevalence of this condition is provided by Meulepas et al. (2016) and Schubauer-Berigan et al. (2020).

Confounding by indication may, in principle, compromise the accurate estimation of the actual association between CT exposure and the risk of solid tumours, as well as the risk of leukaemia or lymphoma. To control for confounding by indication, it is necessary to collect reliable data on cancer predisposition; however, this is difficult in large cohorts.

In the Finnish studies, data was collected on the CPS listed in section 3.1.3, allowing individuals to be excluded. Only a small proportion of the cohorts included in the EPI-CT study had information on CPS. Consequently, the potential influence of confounding by indication was examined here through an in-depth analysis of well-documented subgroups from several cohorts (France, Germany, UK) (Journy et al. 2016a, Journy et al. 2016b, Berrington de Gonzalez et al. 2016, Krille et al. 2015). In the examined sub-cohorts, the exclusion of individuals for whom CPS or a history of cancer was found in their medical records resulted in a lower risk coefficient per unit dose. However, there were no changes to the conclusions of the studies regarding whether there is a dose-dependent increase in risk. The studies show that a lack of clinical information in purely register-based studies can lead to bias in the estimated dose–response relationship.

The Australian study did not provide any information on CPS.

In the RIC Study, it was possible to estimate the proportion of children with Down syndrome directly; at 4,124 out of just over 3.7 million children, this proportion was approximately 0.1%. Furthermore, the RIC Study also stratified the analyses according to Down's syndrome diagnosis. In addition, a sensitivity analysis was conducted excluding children with Down's syndrome, yielding results consistent with those of the primary analysis.

One alternative is to estimate the effects of confounding by indication based on statistical considerations that take account of the respective strengths of the association between the confounder and CT exposure and cancer, as well as the prevalence of the confounder (Meulepas et al. 2016, Meulepas et al. 2018, Journy et al. 2016a, Hauptmann et al. 2020). The analyses showed that the influence of CPS can ultimately be disregarded, primarily due to their rarity.

3.1.1.5 Exclusion period

The purpose of applying an exclusion period is to prevent reverse causation. To this end, a time window is established immediately following the CT scan, within which any cases of cancer that arise are not counted as a health event, as they were likely already present at the time of the scan. Members of the study population who were diagnosed with cancer prior to the CT scan or who develop cancer during the exclusion period are typically excluded from the analysis. Studies can differ in terms of whether they also apply this approach to systemic diseases or benign tumours, such as meningiomas.

Certain conventions have become established regarding the specific choice of time period to be excluded. These conventions are based on an understanding of the earliest possible time at which a radiation-induced disease could have developed, up to the point of clinical detectability using diagnostic methods available at the time of the study. For example, it is known that diseases of the haematopoietic system can develop more rapidly than solid tumours. In principle, it is possible that cancers that develop after the end of the exclusion period originated prior to the CT exposure if this period was not chosen appropriately. At the same time, the period should be chosen so as to avoid under-reporting of radiation-induced cancers. Based on purely empirical studies as well as mechanistic modelling, it can be assumed that the time taken to progress from tumour initiation to clinical manifestation ranges from a few months to a few years for haematological malignancies and several years for solid tumours (Little et al. 2024b, Richardson und Ashmore 2005). However, there is considerable uncertainty surrounding these models, and estimates for different types of cancer can vary by over 10 years in some cases.

The exclusion period for haematological malignancies was 2 years in the EPI-CT and the Finnish study and 6 months in the RIC study. In the investigation of brain tumours, the exclusion period was 5 years in the EPI-CT study and the Finnish study and 2 years in the Australian study. Methods to support the selection of a time period for exclusion include sensitivity analyses, which was implemented in the EPI-CT study, the Australian study and the RIC Study.

3.1.1.6 Latency period

When estimating the dose–response relationship, the use of a latency period is one way of accounting for the slow development of radiation-induced cancers during calculation of the cumulative radiation dose. The assumption here is that the current risk of experiencing a health event depends on the cumulative radiation dose received at the onset of the disease. At time of diagnosis, the cumulative radiation dose may be higher than at time of disease onset. The cumulative radiation dose at the time of the cancer diagnosis is considered irrelevant because it relates to a period after the onset of the disease.

The latency period need not necessarily coincide with the exclusion period (section 3.1.5.5), although this was the case in the primary analyses of the considered studies.

The specific choice of latency period follows the same conventions as those outlined for the exclusion period in section 3.1.5.5. Sensitivity analyses can also be used to examine the extent to which the study results depend on the arbitrary choice of a specific latency period. This was implemented in the Australian study, the EPI-CT study and the RIC Study. Compared with the primary analysis, the results of these analyses did not yield different conclusions as to whether a dose–response relationship exists at all.

3.1.1.7 Statistical analysis

The regression models used in the considered studies are subject to uncertainties because the risk models require assumptions to be made as to the form of the dose–response relationship. The Australian (Smoll et al. 2023) and Finnish studies (Abuhamed et al. 2025, Nikkilä et al. 2018) assumed a log-linear relationship as the standard parametric form in Poisson regression (Australia) and conditional logistic regression (Finland), respectively. In contrast, the EPI-CT study and the RIC Study used a model with a linear relationship between the excess relative risk and the dose. The different models limit the comparability of the ERR estimates per unit dose, but the difference between the log-linear and linear trends in the lower dose range is small. With regard to a classification into dose categories, the results of the studies show that – within the existing margins of uncertainty – the data is consistent with a linear dose–response

relationship in the range of organ doses starting at approximately 50 mGy for brain tumours and 25 mGy for leukaemias and lymphomas.

3.1.1.8 Measurement uncertainty

Conventional regression models that predict the occurrence of health events following radiation exposure are based on the assumption that the information used to predict the health event – such as dose measurements – has been recorded without measurement uncertainty or methodological errors. Given the complexity of this topic, it can only be outlined briefly here. A more detailed account is provided by, for example, Carroll et al. (2006) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2012).

Work is currently underway on developing statistical methods and their application to complex dose calculation programmes, such as those used in cohort studies involving repeated or daily exposure (Bellamy et al. 2024, Little et al. 2024a, Zhang et al. 2017, Kwon et al. 2016). In the studies considered for this recommendation, the number of CT scans performed per participant is based entirely on electronically recorded data. Self-reports provided retrospectively by study participants, which are prone to error, were not used. This means that the measurement error is limited to the exact level of exposure for each scan.

There are various ways of dealing with measurement errors that may distort the risk estimates or estimates of uncertainty in the recorded exposure. This potential source of bias is ignored in the Australian study, the Finnish studies and the RIC Study. In the EPI-CT study, a specific method was developed to account for various measurement errors (Simon et al. 2014b) but was not used in the dose–response analysis. A detailed analysis of the potential impact on risk estimates is therefore still pending.

3.1.2 Summary

The large cohort studies from Europe – EPI-CT (Hauptmann et al. 2023, Bosch de Basea Gomez et al. 2023) – and Australia (Smoll et al. 2023) – demonstrate consistent and convincing dose–response relationships for malignant brain tumours and haematological malignancies. For haematological malignancies, the results of the RIC Study, which is based on a birth cohort, are very similar to those of the EPI-CT study. It would be implausible to suggest that these results are entirely due to systematic biases and spurious associations arising from methodological limitations. This conclusion is supported by having converging evidence from studies with different methodological approaches, e.g., with respect to their study designs. Nevertheless, there remains no explanation for why the EPI-CT study and the RIC Study did not identify an expected higher risk per unit dose associated with exposure in early childhood compared with later childhood and adolescence. The EPI-CT study and the RIC Study showed conflicting results for Hodgkin’s lymphoma (dose-dependent risk in EPI-CT but not in RIC) and non-Hodgkin’s lymphoma (dose-dependent risk in RIC but not in EPI-CT). When analysing these differences further, it is important to bear in mind that the follow-up period for the RIC Study ended at the age of 21, whereas participants in the EPI-CT study were followed up into their adulthood, in some cases, until the age of 41.

The Finnish studies (Abuhamed et al. 2025, Nikkilä et al. 2018) are of limited informative value due to the very small number of exposed cases, with extremely wide confidence intervals for the estimated risks, including negative estimates.

The EPI-CT study and the Australian study discounted diagnosed endpoints during an exclusion period of several years following the first CT scan in order to avoid bias due to reverse causation. Similarly, both studies disregarded CT scans carried out in the last years of the individual follow-up, as it was assumed that these could not impact the risk that quickly. In all

cases, the results were robust to variations in the exclusion period (section 3.1.5.5) and latency period (section 3.1.5.6). This also applies to the RIC Study. As the studies had a relatively short follow-up period (median < 15 years or follow-up only until the age of 21 in the RIC Study), it remains unclear – for the time being – how long the risks remain elevated following exposure.

Compared with the findings of the study of survivors of the atomic bombs in Hiroshima and Nagasaki (LSS), the estimated radiation risks per unit dose are higher in the CT studies from Australia, Finland, Europe and the USA/Canada that are considered here. For the LSS, the publication by Bosch de Basea Gomez et al. (2023) for leukaemia without chronic lymphocytic leukaemia (CLL) reports an ERR per 100 mGy of 0.77 (95% CI: 0.31–1.20), calculated specifically using the LSS data for an exposure before the age of 20. It is worth noting that the mortality follow-up for the LSS began in 1950. Cancer-related deaths occurring at an earlier stage are therefore not included in the LSS. Incidences of leukaemia were also first recorded from 1950 onwards. As leukaemia, in particular, can develop just a few years after radiation exposure, it is reasonable to assume that leukaemia is under-reported in the LSS. For brain tumours, Pearce et al. (2012b) used the LSS data to calculate an ERR per 100 mGy of 0.61 (95% CI: 0.01–6.39) for those who were exposed before the age of 20 and with a follow-up period of less than 20 years. However, when the wide CI is taken into account, the estimates are consistent with the CT studies.

Based on the empirical evidence, it can be assumed that for every 10,000 CT scans of the head performed on children and adolescents, approximately one additional malignant brain tumour will be caused by radiation exposure over the subsequent 5 to 15 years (Hauptmann et al. 2023). For every 10,000 CT scans involving a bone marrow dose of approximately 15 mGy, 1 to 10 cases of haematological malignancies are also expected to occur within approximately 10 years of the scan due to the radiation exposure (Bosch de Basea Gomez et al. 2023, Smith-Bindman et al. 2025a). For leukaemia, a 2022 survey covering 185 countries reported an age-standardised incidence rate (ASR) of 5.3 per 100,000, with a total of 487,294 cases, while the ASR for children aged 0 to 19 was 3.1 (77 681 cases) (Daltveit et al. 2025). The global age-standardised rate (ASR) for brain tumour incidence for 2019 is reported as 4.8 per 100,000 for men compared with 3.6 per 100,000 for women (347 992 cases in total), with the ASR for those aged 0 to 14 standing at 2.2 (boys) and 1.9 (girls) (Ilic und Ilic 2023).

3.2 Trend in CT application in relation to age and gender

3.2.1 Indications for CT scans

Paediatric CT examinations require consideration of the specific characteristics of children in terms of anatomy, circulation, metabolism and the degree of organ maturation, including age-related changes in radiation sensitivity. The consideration of these aspects is supported by all leading scientific societies – and an overview can be found in Frush (2011). In general, it should be noted that technical advances are causing the range of indications to shift across the various imaging modalities. CT scans therefore need to be considered alongside MRI and ultrasound, which do not use ionising radiation. Ultimately, however, the decision to perform a CT scan is a matter of individual assessment and must take account of diagnostic certainty, availability and the condition of the patient. One exception to this is mild traumatic brain injury (TBI), which leads to frequent cranial CT scans with no clinically relevant findings, procedures that relevant guidelines and diagnostic pathways advise against (see below).

The literature includes practical recommendations on the use of CT scans in children, including those from the American College of Radiology (ACR) and ESPR, as well as in the “Recommendations for Radiology” published by the Austrian Society for Radiology and Nuclear Medicine (<https://www.oerg.at>), which provides an interactive online portal

(<https://www.orientierungshilfe.at>), and in the “Recommendations for medical imaging procedures”, which can be found on the SSK website (<https://www.ssk.de>).

Recommendations and “clinical decision rules” have been developed for various indications. Particularly worthy of mention here are the Pediatric Emergency Care Applied Research Network (PECARN; pecarn.org) and the National Institute for Health and Care Excellence (NICE; <https://www.nice.org.uk/>).

- Trauma, particularly polytrauma and traumatic brain injury:
Recommendations can be found in Ryan et al. (2020), Osmond et al. (2010), NICE (2023) and Radiopaedia (2020). The criteria for ordering a cranial CT scan in cases of child abuse are strict. Here, the ACR has issued a recommendation that takes account of both the child’s age and their clinical condition (Wootton-Gorges et al. 2017). According to the S2k guideline on traumatic brain injury in childhood and adolescence issued by the Association of the Scientific Medical Societies in Germany (AWMF 2022), mandatory indications for a CT scan include coma/loss of consciousness, persistent impaired consciousness, focal neurological deficits resulting from the trauma, (suspected) depressed fracture, skull base fracture and open head injury, with the examination to be carried out in accordance with the ALARA principle using protocols adapted to the patient’s age and weight.
- Thorax:
Airway abnormalities (Kulkarni et al. 2016), interstitial lung diseases, postoperative complications, oncological conditions (pulmonary nodules, thoracic wall and mediastinal tumours), cardiac CT, CT angiography (CTA) of the major mediastinal vessels, including visualisation of coronary artery origins or coronary fistulas (Raimondi und Warin-Fresse 2016), postoperative complications following cardiac/vascular surgery (Francone et al. 2022).
- Abdomen:
Trauma (injuries to parenchymal or hollow organs in cases of severe abdominal trauma), in the following clinical pictures if ultrasound, conventional radiography or MRI are inconclusive: e.g., acute abdomen, suspected perforation, haematuria, investigation of abdominal and pelvic tumours.
- Musculoskeletal system:
Trauma (fractures near or involving joints, where clinically relevant), inflammatory conditions where ultrasound and MRI are inconclusive or contraindicated, and the planning of orthopaedic surgery for malformations (ACR 2019).

The European Diagnostic Reference Levels for Paediatric Imaging (PiDRL) working group, which is coordinated by the European Society of Radiology (ESR), has conducted a Europe-wide survey on the clinical applications of CT scans in children and adolescents (European Commission 2018). Of 33 paediatric radiology centres, 17 responded (representing a response rate of 51.5%). The survey revealed the frequencies shown in Figure 1 in relation to the use of CT scans in children.

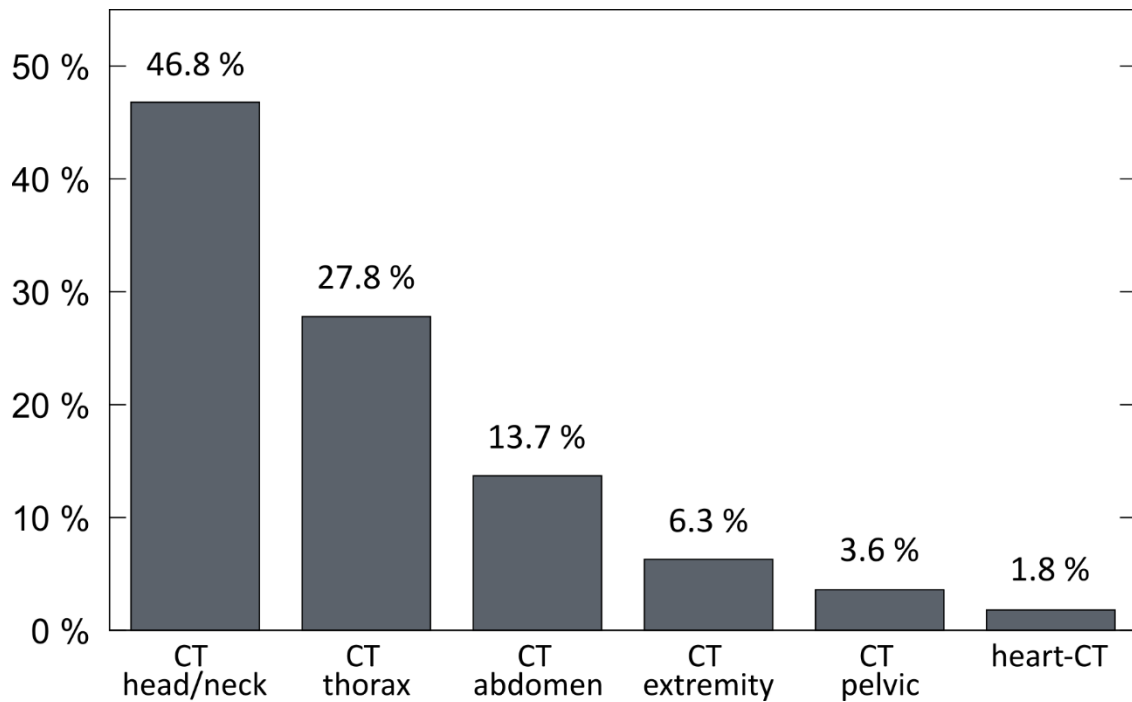


Figure 1: Frequency of CT scans in children (author: Professor Erich Sorantin, Clinical Department of Paediatric Radiology, Graz (Austria), with data from the European Commission 2018)

In Germany, guidelines issued by the AWMF frequently address indications for CT scans. The guideline on TBI in children and adolescents is a good example of how the importance of various imaging modalities has changed over time. The 2004 AWMF guideline on “Vorgehen bei leichtem Schädel-Hirntrauma” (“Management of mild traumatic brain injury”) recommends that the need for imaging should be determined by the presence of neurological symptoms and/or external injuries. The guideline recommends first an ultrasound scan, followed by an X-ray examination (of the skull in three planes) or a CT scan of the head (AWMF Guideline Register No. 064/015, 2004). In the 2011 update “Das Schädel-Hirn-Trauma im Kindesalter” (“Traumatic brain injury in children”) (AMWF Guideline Register No. 024/018, S2k, 2011), cCT is the gold standard for children and adolescents with traumatic brain injury if specific symptoms are present, a fracture is suspected or specific comorbidities are identified, e.g. alcohol or drug intoxication, or in the event of a coagulation disorder. X-ray is no longer relevant, and MRI is not recommended as an alternative. According to the current 2022 guideline “Das Schädel-Hirn-Trauma im Kindes- und Jugendalter” (“Traumatic brain injury in children and adolescents”) (AWMF 2022), a CT scan of the head is mandatory in the event of the following indications: coma/loss of consciousness, persistent impaired consciousness, focal neurological deficits resulting from the trauma, (suspected) depressed fracture, skull base fracture and open head injury. In addition, the guideline lists numerous optional indications for which MRI is the preferred alternative, provided that this does not result in a significant delay (strong consensus within the guideline). The update to this guideline has led to a significant reduction in the number of CT scans for traumatic brain injury in children and adolescents in favour of MRI (see 3.2.2).

Outlined below are a number of other key German guidelines in which CT plays a relevant role.

The S2k guideline on “Polytraumaversorgung im Kindesalter” (“Management of Paediatric Polytrauma”) (AWMF 2020) states that a suspected diagnosis of polytrauma is a prerequisite for diagnostic imaging with CT, provided that this suspicion is still upheld following the initial

examination. In children with polytrauma, the indication for CT should be determined by the team, and scans should be carried out in a timely manner in accordance with age-specific examination protocols.

The S1 guideline “Trauma des muskuloskelettalen Systems im Kindes- und Jugendalter – Bildgebende Diagnostik” (“Trauma to the musculoskeletal system in children and adolescents – Diagnostic imaging”) (AWMF 2019) recommends the use of CT – in conjunction with protocols adapted to the patient’s age and weight – for complex injuries to the extremities, pelvis and spine and, where appropriate, preoperatively. The examination protocols should be established in consultation with specialist staff with expertise in administration and medical physics, taking account of the specific circumstances in the radiological departments, and set out in standard operating procedures (SOPs).

The guidelines of the Society for Paediatric Oncology and Haematology (GPOH) recommend CT as the imaging method of choice for the initial staging of tumours and for monitoring disease progression in certain oncological conditions. Given that CT scans are more sensitive than chest X-rays when it comes to detecting pulmonary nodules (Peuchot und Libshitz 1987), CT lung scans are generally recommended as the gold standard for detecting pulmonary metastases (e.g. AWMF 2016b, AWMF 2021c, AWMF 2021b, AWMF 2023, AWMF 2016a). Given that even lung MRI does not match the sensitivity of lung CT, CT cannot be (fully) replaced for the detection of pulmonary metastases. However, due to technical improvements, MRI lung imaging is becoming increasingly sensitive to pulmonary nodules (Renz et al. 2022; Yang et al. 2022). Follow-up assessments are carried out using chest X-rays and CT scans, sometimes alternately, in accordance with the guidelines mentioned above. In future, guidelines should increasingly recognise thoracic MRI as an alternative method for follow-up examinations that does not involve ionising radiation.

According to current consensus recommendations and guidelines, echocardiography remains the standard diagnostic method for people with congenital heart defects; however, in cases where the condition cannot be fully assessed, MRI is a useful complementary method (Achenbach et al. 2012; Gohmann et al. 2022). Cardiac CT scans using current technology (low radiation exposure and short scan times) can be used as a substitute for invasive cardiac catheterisation and as an alternative to MRI, for example in cases where MRI is contraindicated – such as with pacemakers that are not necessarily MRI-compatible – or where the longer MRI scan could otherwise only be performed under anaesthesia. The benefits of a CT scan must be weighed against the risks of radiation exposure (Achenbach et al. 2012; Gohmann et al. 2022; Francone et al. 2022).

3.2.2 Frequency of CT scans

In the National Cohort (NAKO) study, data on radiological imaging was collected retrospectively. This data is available in the form of self-reported information for approximately 8,000 people and only for adults (aged 20 and over) (Zeeb et al. 2024). Other studies published to date on the frequency of CT scans in children and the associated radiation exposure also provide data either solely on the frequency of CT scans (Galanski et al. 2006) or on dose distribution (Wollschläger et al. 2023).

Accordingly, the corresponding trends over time were illustrated by collecting and analysing data from the hospital statistics based on case rates (Diagnostic-Related Groups (DRG) Statistics) and from the Federal Statistical Office’s basic hospital data for the period 2005 to 2021. The following trends can be observed in inpatient CT scans in Germany for children aged between 1 and 20 years, based on the Operation and Procedure Codes (OPS codes):

- The absolute number of (both native and contrast-enhanced) CT scans performed on children and adults has risen from around 3 million in 2005 to 6.8 million in 2021. The number of CT scans performed on children has levelled off at around 70,000 per year (OPS codes 3-20, 3-22, 3-24).
- Whilst the number of CT scans per 1,000 people in the population rose from 36 in 2005 to 81.6 in 2021, the number of CT scans per 1,000 children remained relatively constant at 5.26 to 5.64.
- In the case of “native CT scans of the skull” in particular, the number of scans performed on children fell from 32,000 (2005) to 20,500 (2021) (approx. -40%) (OPS code 3-200).
- In contrast, the number of contrast-enhanced CT scans performed on children during the same period rose from just under 18,000 in 2005 to just under 27,000 in 2021 (an increase of approximately 50%) (OPS code 3-22). There is no definitive explanation for this increase.
- In particular, there has been a sharp rise in the percentage of cardiac CT scans performed on children and adolescents, even though the absolute figures – at 350 scans per year – remain relatively low. It was not possible to confirm a suspected reduction in the number of cardiac catheterisation procedures in this context. The indications for cardiac CT scans are primarily for the planning of interventional and surgical procedures.
- The number of single photon emission CT/positron emission tomography CT (SPECT/PET-CT) scans (OPS codes 3-72 and 3-73) performed on children, which are rarely indicated, shows a slight increase in absolute terms from 765 in 2010 to 1,074 in 2021. However, the percentage is falling (from 3.1% to 1.9%).

If we include the figures from the statutory health insurance outpatient sector in Germany for the period from 2018 to 2022, the figures also remain relatively stable in terms of the total number of CT scans performed on children and adolescents – at around 40,000 per year – and the relative proportion of less than 1%. The total number of CT scans in this sector rose from 4.75 million (2018) to 5.6 million (2022), while the number of CT scans performed on children aged 0 to 19 varied slightly over the observation period (2018 [41,800], 2019 [41,200], 2020 [37,500], 2021 [38,000] and 2022 [40,800], source: BfS personal communication). The downward trend, particularly in terms of cranial CT scans, was also observed in the USA between 1997 and 2014 (Seifi et al. 2022). With 181,000 cranial CT scans carried out in 2014, this represented a fall to 30% of the 1997 figure (527000).

In the KiCT study, Pokora et al. (2016) already showed a similar trend for the period from 2006 to 2012. Based on extrapolated billing data from the AOK health insurance fund, a decline of approximately 30% in the number of CT scans was observed. Comparing the number of examinations per 1,000 children from this publication (as shown in Figure 1 of the publication), this corresponds to a decrease from 8.15 per 1,000 children in 2006 to 6.15 per 1,000 children in 2012. This is broadly in line with the analyses performed here, which shows an average of 5.35 examinations per 1,000 children between 2010 and 2015 (see Figure 2).

In contrast, a similar study in the Netherlands (Meulepas et al. 2017) found that the number of CT scans performed on children rose from 7,700 in 1990 to 13,300 in 2000 and 26,000 in 2012. However, this trend has slowed substantially since 2007, and by 2012 the rate stood at 6.7 CT scans per 1,000 children, which was similar to the rate in Germany (5.2 in 2013). In an Italian study, the number of CT scans performed on children also rose from 9,000 (2004) to 14,400 (2014), with the number of scans per 1,000 children increasing from 6.3 to 8.5 (Pola et al. 2018). In the UK, Pearce et al. (2012a) found an almost doubling of the number of scans performed from 24,900 (1993) to 48,300 (2002). However, the highest rates of increase were seen among

those aged 15 and over. The annual rate of CT scans per 1,000 children rose during this period from 2.24 (1993) to 3.54 (2002). All the publications mentioned relate to periods that, for the most part, predate 2010.

A sub-study of the EPI-CT study in Spain (Bosch de Basea et al. 2016) reports a statistically insignificant change in the number of CT scans per 1,000 children, from 15.2 (2005) to 18 (2013).

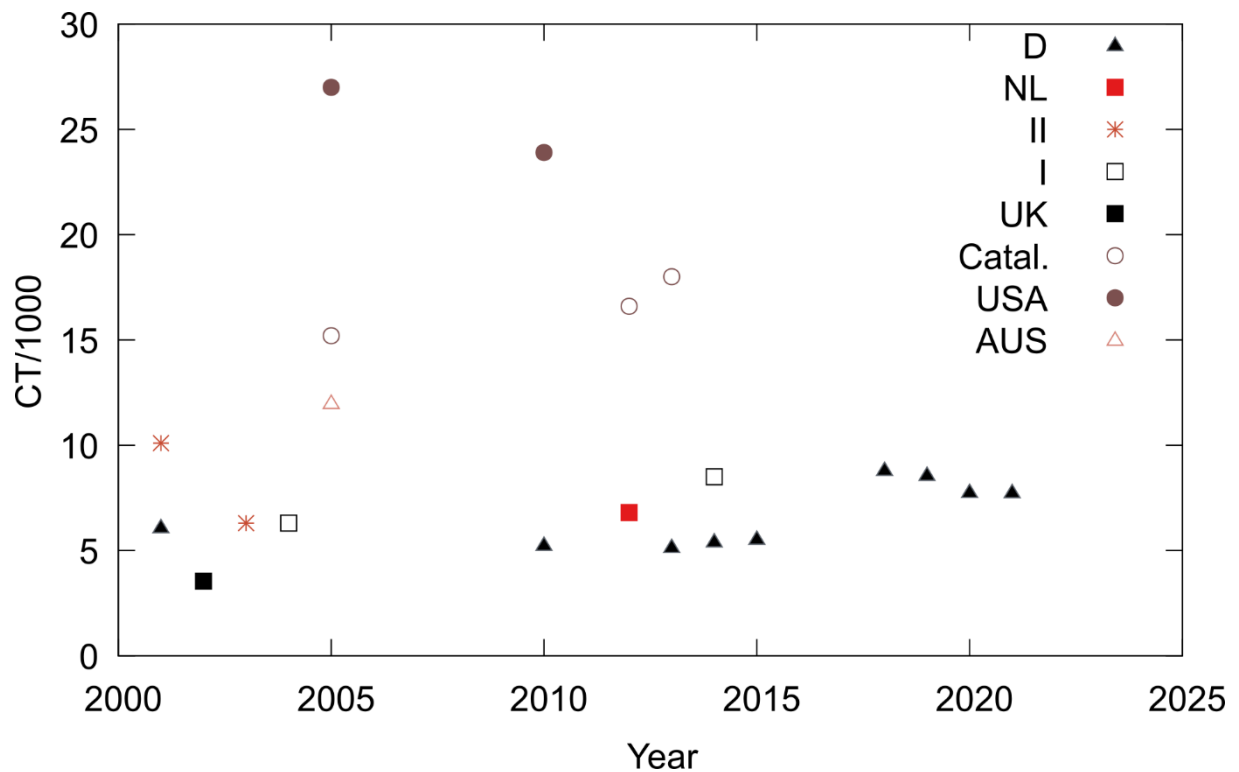


Figure 2: The graph shows the number of CT scans per 1,000 children, based on data from various international publications (see below), for the years 2001 to 2021, compared with the analysis for Germany (D). The overall annual rate of CT scans in Germany per 1,000 inhabitants has more than doubled, rising from 36.1 in 2005 to 81.6 in 2021.

The jump in the figures for Germany between 2015 and 2018 is due to the fact that figures for the outpatient sector were also available for the years 2018 to 2021. This is not the case for the years 2005 to 2015.

The publications from which the data for the figure was taken are as follows: Netherlands (NL): Meulepas et al. 2017, Israel (II): Chodick et al. 2006, Italy (I): Pola et al. 2018, United Kingdom (UK): Pearce et al. 2012a, Catalonia (Catal.): Bosch de Basea et al. 2016, USA: Miglioretti et al. 2013, Australia (AUS): Brady et al. 2016.

When interpreting the figures from the DRG statistics (covering the period 2005 to 2021), which are based on Operation and Procedure Codes (OPS codes), the following methodological limitations must be taken into account. It is impossible to rule out the presence of a bias resulting in an overestimation or underestimation of the number of CT scans (Dreger et al. 2015, Icks et al. 2017), as multiple OPS codes may be assigned to a single examination (e.g. without contrast medium (native) and contrast-enhanced) or to several successive areas of the body (e.g. thorax plus abdomen plus pelvis). Converting billing codes into measurable, empirically verifiable

variables may affect the data structure (Konrad et al. 2019), such that the number of CT scans may be higher or lower depending on how the billing codes are interpreted. Reducing bias in the estimation of CT frequencies relies on knowing the specific date of the billed examination for each individual. For example, this makes it possible to record a CT scan of the thorax – which may have two assigned billing codes, such as “CT thorax” and “CT abdomen”, on the same date – as a single CT scan rather than incorrectly as two separate scans. In this analysis, only the individual billing codes were used to illustrate frequency, as the DRG statistics do not provide daily or monthly data for the individual CT scans performed.

Nevertheless, DRG statistics and health insurance fund data generally provide a starting point for describing trends in the number of performed CT scans. The BfS also uses health insurance fund data for adults to monitor medical radiation exposure over time (Nekolla et al. 2017). Furthermore, the advantage of health insurance fund data is that “recall bias” (a distortion in the estimated exposure – in this case, CT scans caused by variations in individuals’ recall when providing self-reported information) is less pronounced in comparison with self-reported data from a questionnaire survey (Dreger et al. 2015; Garcia et al. 2023).

The DRG statistics only cover CT scans performed on inpatients but not those carried out in outpatient settings, whether in private medical practices or within hospitals. This may explain the lower number of CT scans performed on children in Germany compared to other countries. However, the BfS also provides data from the statutory health insurance outpatient sector, which shows a virtually constant number of examinations for children aged between 0 and 19 years, ranging from approximately 41,800 (2018) to 40,800 (2022). The number of CT scanners in hospitals can also be obtained from the Federal Statistical Office. This figure has risen from 1,241 in 2005 to approximately 1,600 in 2022 (source: Federal Statistical Office, basic hospital data, special series 12/6/1/1 (Destatis) and Federal Health Monitoring System (GBE)). If we also take into account the figures from the Organisation for Economic Co-operation and Development (OECD), we can estimate that there were approximately 2,560 CT scanners in 2008 and 3,050 in 2021. These figures are broadly in line with those provided by the equipment manufacturers organized under the European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry (COCIR), which put the total number of CT scanners installed in Germany at 3,150 in 2023 (COCIR 2023).

3.2.3 Dose in applications of CT

Various dose metrics can be used to estimate patient exposure, collective dose and risk:

- CTDI_{vol}: The computed tomography dose index (CTDI), defined as the average dose within the scanned volume, is a metric used in dosimetry and forms the basis for calculating radiation exposure, determined using two Plexiglas phantoms of different sizes; it allows for dose comparisons between different protocols and enables the operator to monitor radiation exposure directly at the scanner.
- SSDE: Scales the CTDI_{vol} to the actual size of the patient; useful for comparing dose values across different patient groups (age/weight). Any differences are then determined solely by the examination technique.
- Dose–length product (DLP): A dose measure that can be calculated from the CTDI_{vol} and the scan length L ($DLP = CTDI_{vol} * L$) and which represents a measure of the total exposure over a series of scans.
- Organ equivalent dose: This reflects the risk to the specific organ exposed to the radiation; for example, in CT scans, the organ dose to the brain (cranial CT) and the red bone marrow (spinal CT) may be critical. In the case of X-rays, the organ equivalent dose is equal to the absorbed organ dose, which is most commonly used in epidemiology.

- Effective dose: An estimate is usually made using age-dependent conversion factors (k-factors) to convert the DLP into an effective dose ($E = k \cdot DLP$).

Unfortunately, there is currently no way to display the last two dose parameters, organ dose and effective dose, which are directly linked to the risk of radiation exposure, on CT scanners. In the future, it is conceivable that these parameters could be displayed directly on the operator console and included in the radiation dose structured report (RDSR) thanks to AI-based automatic contouring and fast algorithms for personalised dose estimation.

The publication by Romanyukha et al. (2016) discusses the concept of effective dose and the criticism levelled at its (simplistic) use as a means of comparing risks. There are no specific tissue weighting factors available for children, which makes it difficult to perform a risk assessment in comparison with adults, given the increased radiation risk for certain types of tumours. A study by Kopp et al. (2020) also recognises the need to minimise uncertainties regarding lifetime attributable risk (LAR) and ERR in relation to age and sex by using automated, individualized dose estimation for organ equivalent dose and effective dose in future.

The use of age-specific conversion factors (k-factors) to convert the DLP into an effective dose leads to uncertainties in determining the effective dose for underweight to normal-weight individuals and for children (in these cases, the effective dose tends to be underestimated by up to a factor of three). Conversely, in overweight individuals, the effective dose determined using age-specific k-factors tends to be overestimated. As the use of age-specific k-factors leads to significant uncertainties in determining the effective dose for underweight to normal-weight individuals, a large multicentre study based on dose registry data was conducted to determine k-factors stratified by age, body diameter and equipment manufacturer (Chu et al. 2023). One finding of this study, conducted at the universities of California and Florida, was that the k-factor values derived from data on over 120,000 patients were generally higher than those reported in previous studies.

The EPI-CT study and the study by Wollschläger et al. (2023) provide sufficient data for assessing radiation exposure. The two publications describe a decline in organ doses (EPI-CT: in the periods prior to 1991, between 1991 and 2001, and after 2001) and technical dose parameters (Wollschläger et al. 2023; depending on the age group, $CTDI_{vol}$ between 5% and 40% and DLP between 4% and 47% when comparing the period from 1980 to 2010 with the period from 2016 to 2018). It can therefore be concluded that there is a downward trend in the mean/median dose for paediatric CT scans over time, and that scanner technology has become increasingly efficient over time. This is also supported by the study by Hauptmann et al. (2023), which shows a decrease in the average brain dose from 52 mGy in 1992 to 3 mGy in 2011. The importance of organ doses in assessing risk in children and adolescents is clearly demonstrated in the publications by Bosch de Basea Gomez et al. (2023) regarding the dose to the red bone marrow (8 mGy for a typical CT scan) and by Little et al. (2023).

A reduction in (organ) dose values for CT scans of the head and lungs was also found in the two publications by Lee et al. (Lee et al. 2019, Lee et al. 2024). When limited to lung examinations, a decrease in radiation exposure (as a median, 12% per year) was also observed between 2007 and 2014 by Esser et al. (2018).

The trends mentioned above are also reflected in the development of diagnostic reference levels (DRLs). The $CTDI_{vol}$ values were reduced by up to 50% between the first publication year of 2010 and the current publication in 2022 (see Table 2). The same applies to the calculated effective dose.

Table 2: Development of diagnostic reference levels (DRL) for CT scans in children and adolescents (compiled from BfS 2022). In order to remain compliant with ICRP guidelines, the median was used in 2022, whereas the mean had been used in the past. This to some extent limits the direct comparability of trends over time.

investigation (CT)	age (years)	DRW (CTDI _{vol} in mGy)		
		2010	2016	2022
cerebral skull	1 year	33	30	25
	1 - < 5	40	35	35
	5 - < 10	50	50	40
	10 - < 15	60	55	45
thorax	newborns	1.5	1.0	1.0
	< 1	2.0	1.7	1.5
	1 - < 5	3.5	2.6	2.0
	5 - < 10	5.0	4.0	3.0
	10 - < 15	8.0	6.5	5.0
abdomen	6 - < 10	8.0	5.0	4.0
	10 - < 15	13.0	7.0	7.0

The number of available DRL for children and adolescents is very limited, meaning that a large number of potential CT scans cannot be included or assessed, and there is also very little data available on radiation exposure from these scans. Consequently, the SSK working group collected dose values at two paediatric radiology centres (Graz University Hospital, Austria; Hannover Medical School, Germany) for all CT scans (Graz) and highly specialised CT scans (Hannover) and analysed this data over time.

The Graz analysis (Sorantin et al., in preparation), covering the period from 2008 to 2020, shows that a significant reduction in DLP can be achieved thanks to technological advances (iterative image reconstruction, new convolution kernels). Effective doses were calculated using conversion factors. Over the years, these have been significantly reduced for examinations involving higher radiation doses (multi-organ examinations such as polytrauma CT scans and CT angiography) across all age groups, with a particularly marked reduction among infants and adolescents.

The analysis carried out in Hannover particularly serves to highlight the rapid technological advances in CT scanner engineering and the associated potential reduction in radiation exposure, especially among newborns (Renz et al. 2025). Consecutive CT scans of the heart in 59 children aged ≤ 1 year were analysed using a modern photon-counting CT scanner. Using this new technology, it was possible to achieve dose values (CTDI_{vol}: mean 0.14 mGy, standard deviation 0.05 mGy, median 0.14 mGy, range 0.07–0.33 mGy) significantly below the DRLs of thoracic CT scans in newborns (CTDI_{vol} 1 mGy from 0 to <3 months, 1.5 mGy from 3 to 12 months). In this age group, the thyroid gland, the spine/ribs and the mammary glands are radiation-sensitive organs within the examination field.

These two studies show that specialist paediatric and adolescent radiology departments can achieve a substantial reduction in dose thanks to innovations in scanner technology, paired with individually tailored examination techniques for children.

In order to ensure continuous monitoring of dose values in the future and to enable the BfS to easily adapt the DRL to evolving scanner technology, the following measures are desirable:

- Implementation of a national dose registry (similar to the Dose Index Registry in the USA (NRDR)). The BfS has already commissioned a feasibility study on this matter. The results are expected by the end of 2027. Until then, it makes sense to use dose data from dose management systems to draw up and adjust DRL.
- Indication-based DRL based on age and weight (see Paulo et al. 2020, Tsapaki et al. 2021, SSK 2025b).
- List of indications for CT scans in children (see SSK 2022, Table 1a and Table 1b).
- National protocol recommendations (also based on indications) for CT scans in children. A similar initiative was launched in the US under the name “Image Gently” (<http://www.imagegently.org/>) and was heavily promoted. However, no further updates have been made since 2014, meaning that there is a significant need for action in this area, for example by professional associations.
- Standardisation of naming conventions for examination protocols (e.g. based on RadLex, LOINC) or the mapping of protocol classes or body regions, particularly in view of the increasing number of combined examination regions such as Neck Thorax, Thorax Abdomen Pelvis, etc.

3.3 Assessment of vulnerable groups

3.3.1 Children and adolescents in comparison with adults

Due to rapid cell division, growth processes and hormonal changes during puberty, children and adolescents differ significantly from adults in terms of the cancer risk caused by ionising radiation. Key evidence that allows a direct comparison of radiation-related cancer risk between children and adults comes from the Life Span Study of the atomic bomb survivors of Hiroshima and Nagasaki (UNSCEAR 2013, Little et al. 2022a). Given the simultaneous acute exposure of the population, age at exposure and birth cohort are inseparably connected in this study.

For the group of leukaemias excluding chronic lymphocytic leukaemia (CLL) and adult T-cell leukaemia (ATL), the LSS indicated an excess relative risk of incidence of approximately 50 about 5 years after exposure to a bone marrow dose of 1 Gy, assuming an age at exposure of 10 years (Hsu et al. 2013). For an age at exposure of 30, the excess relative risk was approximately 20. The excess absolute risk also decreased with increasing age at exposure up to approximately 10 years after exposure. For subgroups of leukaemia and for lymphomas, the pattern of results was more complex (Little et al. 2022a, Hsu et al. 2013).

When considered as an overall group, there is clear evidence – for both cancer incidence and mortality – that the excess relative risk for a given dose decreases by approximately 20–30% per decade with increasing age at exposure (Little et al. 2022a, UNSCEAR 2013). The pattern of results is similar for the excess absolute risk. However, analyses of individual types of cancer show that a more differentiated approach is necessary. There is evidence of the age-related pattern described for thyroid cancer, salivary gland cancer, female breast cancer, uterine cancer (endometrial carcinoma), non-melanoma skin cancer and brain tumours. In this context, the period of puberty proves to be a phase during which the body is particularly susceptible to radiation-induced breast and uterine cancer. In contrast, the radiation-related risk of lung cancer or colorectal cancer in the LSS does not show such an association with age at exposure (Little et al. 2022a).

Other studies have also shown that, regarding the risk of breast cancer in women following radiation exposure, puberty is a developmental stage associated with higher radiation risk (Ronckers et al. 2005, Cooke et al. 2013). For other types of cancer, however, there is as yet insufficient evidence to suggest that puberty represents a particularly vulnerable phase in terms of sensitivity to radiation. Nevertheless, given the increased cell division and hormonal changes during this stage of development, it is prudent to assume that sensitivity is elevated.

Several epidemiological studies show that exposure to CT scans during childhood can increase the risk of haematological malignancies and brain tumours. Section 3.1 provides details of these studies. It is therefore still essential to scrutinise the use of CT scans, particularly in children, and to thoroughly explore alternatives. The principles of dose reduction apply to all age groups, albeit with age-appropriate adjustments. Whilst particular care must be taken to minimise the radiation dose for each individual CT scan in young children, the focus for adolescents is also on reducing unnecessary radiation exposure caused by repeated CT scans (Kalra et al. 2004). Technical improvements to CT scanners, the adjustment of scan parameters to the children's height and weight, and the restriction of the body regions being scanned allow relevant dose reductions while maintaining the same diagnostic quality (Kalra et al. 2011). In line with the recommendations of the SSK (SSK 2022), techniques not involving ionising radiation – such as MRI and ultrasound – should be preferred where viable given the clinical indication, particularly in children for whom ionising radiation is frequently used for diagnostic purposes (e.g. in cancer patients).

In addition to the effects of higher excess relative or absolute radiation risk during childhood for a range of cancers, children have more time after radiation exposure to develop potential adverse effects such as radiation-induced cancers due to their longer life expectancy.

Long-term studies and cancer registries are crucial for determining the long-term cancer risk following CT exposure in children more accurately and for further improving the relevant preventive measures (Brenner et al. 2007). Children and adolescents who were exposed to high levels of radiation exposure at a young age should undergo long-term monitoring to enable the early detection of potential radiation-induced cancers (kinderkrebsinfo 2016).

Finally, it is essential to provide parents, caregivers and healthcare professionals with comprehensive information about the potential risks of ionising radiation and the available imaging alternatives in order to avoid unnecessary CT scans. The diagnostic benefits should always be carefully weighed against the risk and communicated in an understandable manner.

The following section discusses various groups that are considered particularly susceptible to the adverse effects of ionising radiation due to their age, metabolic activity or genetically determined radiation sensitivity. There is very little reliable data available on this subject. For example, cancer registries do not record whether a registered person has a history of premature birth. Furthermore, the survival rate of extremely premature infants has only increased significantly in recent decades, meaning that no long-term follow-up studies are yet available. Knowledge regarding the exact sensitivity in cases of CPS remain very limited; this is compounded by the very small number of cases of these rare diseases.

3.3.2 Foetuses, newborns and infants in relation to weight and week of pregnancy

Although the analyses in section 3.1.4 did not indicate any increased risks for younger children compared to older children, it is widely assumed that foetuses and very young children are more sensitive to radiation regarding cancer induction. In addition to a generally longer remaining life expectancy and consequently a higher likelihood of developing a tumour, one reason is that, due to their young age, their body exhibits active cell proliferation and a high number of undifferentiated cells. These categories are therefore examined in more detail below.

3.3.2.1 Foetuses

Human prenatal development is characterised by increased rates of cell division and cell specialisation (differentiation), as well as cell migration processes. These processes can be disrupted by ionising radiation, leading to the assumption that the embryo or foetus is relatively sensitive to radiation throughout the entire intrauterine development (Fiebich et al. 2021). The likelihood and nature of the consequences of radiation exposure vary depending on the type and intensity of the radiation, as well as the stage of prenatal development at the time of exposure. Foetal development in the womb is commonly divided into three main stages: the pre-implantation phase (first to second week post-conception (p.c.)), the organogenesis phase (third to eighth week p.c.) and foetal phase (from the ninth week p.c.).

Detailed descriptions of the effects of in utero radiation exposure have already been provided in the past by the German Commission on Radiological Protection, the ICRP and UNSCEAR (UNSCEAR 1986, SSK 1989, ICRP 2000, ICRP 2003, Streffer et al. 2003, SSK 2025a).

The quantitative assessment of the risk of malignant disease following in utero exposure has so far been derived from two cohorts: individuals who were exposed in utero as a result of the atomic bomb explosions at Hiroshima and Nagasaki, and those whose mothers underwent X-ray examinations of the abdomen or pelvis during pregnancy (Oxford Survey of Childhood Cancers (OSCC) study). For an up-to-date summary of this data, please refer to the SSK's recommendation on "Effects after prenatal radiation exposure" (SSK 2025a). Accordingly, different analyses and assumptions regarding the doses associated with X-rays in OSCC lead to estimates of the ERR per dose for cancers up to age 15 ranging from 13 Gy^{-1} to 61 Gy^{-1} , with the EAR standing at 1% to 6% per Gy for mortality and approximately half that for incidence. For individuals exposed in utero as a result of the atomic bomb detonations, the estimated ERR values are substantially lower, which may be explained by the delayed start of the analysis of cancer mortality among the atomic bomb survivors. In its 2025 recommendation, the SSK noted that the risk estimates from the OSCC study are comparable with risk projections for ERR following CT scans in childhood and adolescence, and concludes that the cancer risk remains constant from late pregnancy through birth and into early childhood and only then decreases with increasing age at exposure (SSK 2025a). The risk estimates for cancer induction following CT scans in childhood, as presented in Chapter 3.1.4 (1 to 2 children per 10,000 undergoing a CT scan), are also comparable in magnitude to the OSCC data, assuming a linear dose–response relationship..

Both the OSCC and the study of atomic bomb survivors exposed in utero have limitations that make it desirable to expand the body of evidence. A relatively recent search for studies on cancer risks resulting from early diagnostic exposure to ionising radiation in the databases PubMed, Scopus, Web of Science, Global Health and EMBASE between 2000 and 2019, based on eight studies (seven case-control studies and one cohort study), concluded that prenatal exposure during an X-ray or CT scan does not result in a statistically significant increased risk of any type of cancer, leukaemia or brain tumours (Abalo et al. 2021), particularly not in the two included CT studies (Bailey et al. 2010, Tettamanti et al. 2017). Here, it should be noted that the mother's exposure status was determined using questionnaires or interviews. As doses to the foetus were not estimated, it was not possible to carry out dose–response analyses in either of the two studies. The discrepancy between the non-increased cancer risk associated with prenatal radiation exposure (yes/no) estimated in the meta-analysis by Abalo et al. 2021 and the dose-dependent risk estimated in earlier studies can be explained by the small number of cases with substantial exposure on which the meta-analysis was based. This, in turn, is due to the decline in the frequency of X-ray examinations during pregnancy, resulting from the switch to techniques without ionising radiation such as ultrasound or MRI, as well as the

reduction in the dose per scan following the establishment and improvement of radiation protection regulations for patients.

3.3.2.2 Dose in the foetus

In one of the first retrospective studies involving 50 pregnant women, the doses to the foetus were determined following radiological examination of the pelvis or lower abdomen (Osei und Faulkner 1999). The results varied considerably depending on the type of examination, ranging from less than 0.01 mGy to 117 mGy (gestational age: 2–24 weeks). The highest mean foetal dose, 89 mGy, was determined following a CT scan of the pelvis. The majority of the unborn babies (around 68%) were at a stage of pregnancy of less than 8 weeks, while 18% were between 8 and 15 weeks.

In 2003, Osei et al. described the FetDose software for estimating the radiation dose to the foetus, which calculates the absorbed dose and the risk to the foetus from conventional X-ray and fluoroscopy procedures performed on pregnant patients. This can also be used to determine the dose to the foetus resulting from occupational exposure of pregnant workers in radiology (Osei et al. 2003). The normalised uterine doses used to calculate the foetal dose are taken from NRPB-SR262 (Hart et al. 1991) and NRPB-SR250 (Jones und Shrimpton 1993). This software was used to determine the exposure data for 367 fetuses and 414 examinations (from five institutions in five countries) (Osei et al. 2003, Osei und Darko 2013). The radiation doses to which the 367 fetuses were exposed ranged from less than 0.001 mGy during an X-ray examination of the pregnant mother's chest to 21.9 mGy during a CT scan of the lumbar spine. Some of the women underwent multiple examinations (two to four different examinations on the same patient), whilst others underwent repeated examinations (two to three repeated examinations on the same patient), which contributed to increased foetal doses. Around 78% (285) of the fetuses studied were exposed to doses of less than 1 mGy, and around 4% (16) of them were exposed to radiation doses of more than 10 mGy.

A further assessment of foetal radiation doses and radiation doses to the pregnant woman during CT scans was provided by studies on radiation doses during CT pelvimetry (Mokubangele et al. 2022). This study from Cameroon (2017 to 2019) included 194 pregnant women. The average effective dose for pregnant women was 0.78 mSv, and the mean individual dose for the unborn child was 1.5 mGy (range: 0.76 mGy to 1.87 mGy).

A relatively recent study based on CT data from 44 pregnant women (gestational age 8 to 35 weeks) confirmed absorbed radiation doses for the foetus in the range of 0.97 to 2.24 mGy, with an average of 1.63 ± 0.33 mGy (Qu et al. 2023). The normalised foetal organ dose showed a significant association with gestational age, the pregnant individual's abdominal circumference and the position of the foetus. Analysis of the CT radiation dose, taking into account the size of the person being examined (SSDE), based on CT-scan and ^{18}F -FDG standardised uptake value (SUV) image doses from respective images of nine pregnant women, yielded a foetal dose (foetal self-dose) from ^{18}F -FDG PET for the first trimester of 2.18 mGy (single data point), for the second trimester ranging from 0.74 mGy to 1.82 mGy, and for the third trimester ranging from 0.017 mGy to 0.0017 mGy. This ultimately results in a combined SSDE and foetal dose of 1.2 mGy to 8.2mGy (Burton et al. 2023).

Although the mentioned studies are not directly comparable, they suggest a strong reduction in the dose to the foetus over the last few decades.

3.3.2.3 Premature and newborn infants in relation to weight and week of pregnancy

The effects of radiation exposure should not be underestimated in newborns in general, and especially not in premature infants. Because of the small size of their bodies, generally all of

their organs are located within the radiation field, resulting in a higher effective dose than in children and adults.

X-ray examinations have become indispensable for diagnosis, treatment and monitoring of a patient's condition, particularly in neonatal intensive care units. CT scans can also lead to potentially life-saving treatment and an improved quality of life for this age group, thanks to more accurate diagnosis. There is no comprehensive data available on dose measurement during CT scans of newborns, so any conclusions regarding radiation exposure in this age group can only be based on X-ray examinations (particularly of the chest).

A normal pregnancy lasts between 38 and 42 weeks, with births at less than 37 weeks' gestational age being described as preterm and those at < 28 weeks as extremely preterm. A baby born on the due date weighing less than 2,500 g is referred to as a low-birth-weight (LBW) infant or newborn; a baby weighing less than 1,000 g is referred to as a very-low-birth-weight (VLBW) newborn. Assuming that foetuses may be at higher risk of radiation-induced cancer than children, extremely premature infants and newborns weighing less than 1,000 g may be more sensitive to radiation than full-term infants due to the immaturity of foetal tissue. As explained in section 3.3.2.2, this assumption is not necessarily supported by the available data. Despite the uncertainty regarding the exact level of risk, however, there is a consensus that every possible measure should be taken to minimise radiation exposure during medical imaging for these newborns, provided that this does not compromise diagnostic accuracy or procedural safety (Toscan et al. 2024).

In 2020, an estimated 13.4 million infants worldwide were born prematurely (i.e., before reaching 37 weeks of pregnancy) (Ohuma et al. 2023). Premature infants are more susceptible to immediate and long-term morbidity and mortality than full-term newborns, with complications arising from prematurity being the leading cause of death among children under the age of 5 (Perin et al. 2022). The shorter the duration of pregnancy and the lower the birth weight, the closer the clinical monitoring that is required. X-ray examinations are of crucial importance for the diagnosis and assessment of these unwell newborns (Gislason-Lee 2021). This applies in particular to chest X-rays, and less commonly to abdominal X-rays, as well as contrast-enhanced examinations of the gastrointestinal or urogenital tract. In cases where complications arise, a CT scan may also be used.

A retrospective cohort study examined the medical radiation exposure of preterm and full-term infants between 2008 and 2015 to determine whether the effective dose exceeded 1 mSv (Hogan et al. 2018). It was shown that the likelihood of exceeding the 1 mSv was significantly higher for very preterm and extremely preterm infants (OR 1.85 [95% CI: 1.03–3.32] or 2.53 [95% CI: 1.53–4.21]), whereas this was not the case for late preterm infants (OR 1.14 [95% CI: 0.73–1.78]). In 69% of full-term and 55% of preterm infants, the fact that this value was exceeded could be attributed to a single CT scan ($p < 0.001$). The proportion of preterm infants who underwent at least one X-ray of the chest, abdomen or neck was roughly twice that of full-term babies. In the first year after discharge from the neonatal unit, significantly more preterm infants were also exposed to a dose of >1 mSv (3.7% vs. 1.7%; $p < 0.001$) (Hogan et al. 2018). It should be noted that, rather than adding up the actual measured doses from individual X-ray examinations, published average values (Osei und Faulkner 1999) were multiplied by the number of individual images per patient. This may lead to uncertainty regarding the actual organ doses. Similar observations were made for 206 preterm infants with very low birth weight, with the effective dose calculated using a voxel-based model based on the dimensions of an 8-week-old infant (height 57 cm, weight 4.2 kg) (Ebenebe et al. 2019). The median cumulative effective dose in the birth-weight groups < 750 g and > 750 g for X-ray examinations were 210.6 μ Sv (68.4 μ Sv to 882.6 μ Sv) and 43.5 μ Sv (3.6 μ Sv to 537.6 μ Sv) respectively ($p < 0.001$). The mean effective dose per image was 10.4 μ Sv (range: 1.7 μ Sv to

48.5 μSv) for chest X-rays, 12.5 μSv (range: 2.8 μSv to 38.7 μSv) for abdominal X-rays and 18.6 μSv (range: 3.8 μSv to 48.0 μSv) for combined chest and abdominal imaging. In infants with a birth weight of ≤ 750 g, the median cumulative effective dose was 3.5 times higher than in infants with a birth weight of 751 g to 1,000 g, and as much as 7 times higher than in infants with a birth weight of 1,251 g to 1,500 g (Ebenebe et al. 2019). Overall, this highlights the need for effective dose monitoring protocols for very premature infants, as a very low birth weight – and consequently the presence of comorbidities – is associated with significantly increased radiation exposure (Su et al. 2023, Ebenebe et al. 2019, Park et al. 2018).

A more recent (retrospective) study examined radiation exposure and the associated predicted risk of radiation-induced cancer mortality in samples of full-term and preterm infants (Weiß et al. 2025). Of the 3,843 newborns (age 241.1 ± 35.45 days), 1,307 (34%) underwent at least one X-ray examination, with an average of 3.19 X-ray examinations per infant (cumulative effective dose of 23.7 μSv). The effective dose was estimated from the dose–area product using Elbakri’s method (Elbakri 2014), applying conversion factors determined by voltage, weight class (500–6,000 g), filter (3 mm Al, 0.1 mm Cu) and type of exposure (anterior-posterior, chest/abdomen). The number of X-ray examinations showed a negative correlation with birth weight. A correlation was found between the prematurity of the infant, the number of X-ray examinations and radiation exposure. The greatest radiation exposure occurred in combined examinations of the chest/abdomen, particularly in newborns < 500 g (Weiß et al. 2025).

To date, there have been no further observations in order to assess the potential risk of radiation-induced cancer in premature infants. Cancer registries have so far not recorded data on obstetric history. Data on the duration of pregnancy is only collected in the study protocol for the therapy optimisation studies for acute lymphoblastic leukaemia. The study for the international cooperative treatment protocol for children and adolescents with acute lymphoblastic leukaemia (AIEOP-BFM ALL 2009) from 2010 to 2015 included a total of 284 former preterm infants (< 37 weeks’ gestational age). Of the 2,217 people with ALL from Germany included in this study, 185 (8.5%) were former preterm infants. Extremely preterm infants (< 32 weeks’ gestational age) accounted for 1.2% ($n = 26$). According to data from the Federal Institute for Quality Assurance and Transparency in Healthcare (IQTIQ), the proportion of preterm infants in Germany was 7.9% in this period, and 1.0% in the case of preterm infants < 32 weeks. A clear link between preterm birth or extremely preterm birth and the incidence of childhood ALL cannot therefore be confirmed (personal communication from Professor Martin Schrappe, Kiel, principal investigator of the AIEOP-BFM-ALL 2017 treatment optimisation study, according to EudraCT coding: AIEOP-BFM 2017 2016-001935-12). Information regarding examinations involving ionising radiation carried out prior to the onset of a malignancy is not recorded in the GPOH study protocols.

3.3.3 Children with germline mutations/CPS

People with various germline mutations/CPS can be expected to have increased sensitivities to radiation. Early diagnostic examinations for people with CPS should be carried out at suitably equipped centres with expertise in the imaging of children and adolescents, and, where possible, without the use of ionising radiation.

Cancer is relatively rare in children and adolescents (Ronckers et al. 2025). The presence of a genetic tumour disorder is suggested by certain patterns of tumour clustering within families or multiple tumours in a single individual (bilateral involvement, multifocality, multiple types) or by specific clinical signs (e.g. café-au-lait spots in neurofibromatosis type I or macroglossia in Beckwith–Wiedemann syndrome), as well as by specific entities (e.g. pleuropulmonary blastoma in DICER1 syndrome, adrenal carcinoma in Li-Fraumeni syndrome) or an early age of onset for a particular tumour type (Jongmans et al. 2016). In recent years, an increasing

number of genetic risk factors for cancer in children and adolescents have been identified, and these can be utilised for early detection, general diagnosis and treatment (Ronckers et al. 2025). Over 50 different rare diseases have been described as CPS. These have been categorised into nine main groups by the American Association for Cancer Research (AACR) (Brodeur et al. 2017, Table 3).

Table 3: The nine main groups of CPS (according to the American Association for Cancer Research (AACR))

Tumour predisposition group	Specific syndromes/hereditary disease
Li-Fraumeni syndrome	Li-Fraumeni syndrome
Neurofibromatoses	Neurofibromatosis type I and II, swan nomatosis
High-growth syndromes and Wilms tumour	Beckwith-Wiedemann syndrome/hemihypertrophy, WAGR syndrome (Wilms tumour, aniridia, anomalies of the genitourinary system, mental retardation), Denys-Drash and Frasier syndrome, Perlman syndrome, Bohring-Opitz syndrome, Mulibrey-Nanism, Simpson-Golabi-Behmel syndrome
Neural tumour syndromes	Hereditary retinoblastoma and neuroblastoma, Gorlin syndrome, rhabdoid TPS
Gastrointestinal cancer syndromes	Familial adenomatous polyposis, familial juvenile polyposis, Peutz-Jeghers syndrome, Lynch syndrome
Neuroendocrine syndromes	Multiple endocrine neoplasia syndromes, from Hippel-Lindau disease, hereditary paraganglioma pheochromocytoma syndrome, familial medullary thyroid carcinoma, parathyroid carcinoma syndrome
Leukaemia predisposition syndromes	GATA2 deficiency, Familial platelet disease with predisposition to acute myeloid leukaemia, trisomies 21
DNA instability syndromes	Bloom syndrome, Rothmund-Thomson syndrome, Ataxia teleangiectatica, Fanconi anemia
Other syndromes	DICER1 syndrome, Costello syndrome, Weaver syndrome, Sotos syndrome, Rubinstein-Taybi syndrome, Schinzel-Giedion syndrome, Noonan syndrome, Tuberous sclerosis complex (TSC)

The following section takes a closer look at leukaemia predisposition syndromes as examples. (Hereditary) leukaemia predisposition syndromes can be classified into different categories based on clinical features, biological functions and the signaling pathways involved, although individual syndromes may also be assigned to other CPS groups (Saida 2017):

- genetic instability/DNA repair syndromes (such as Li-Fraumeni syndrome (LFS), caused by a p53 tumour suppressor gene mutation; constitutional mismatch repair deficiency syndrome (CMMRD), caused by biallelic (homozygous) alterations in the mismatch repair genes; WRN-mutated Werner syndrome; and the “chromosome breakage syndromes” (Bloom syndrome, Fanconi anaemia, ataxia–telangiectasia/Louis-Bar syndrome, Nijmegen breakage syndrome)

- RAS signaling pathway dysfunction (e.g., Noonan syndrome, caused by alterations in the PTPN11 gene; the similar Casitas B-lineage lymphoma syndrome (CBL); and neurofibromatosis type I (NF1, also known as Recklinghausen's disease))
- bone marrow failure (e.g., familial aplastic anaemia with an SRP72 mutation, Kostman syndrome caused by an HAX1 mutation, and thrombocytopenia with an ANKRD26 mutation)
- telomeropathies and immunodeficiency syndromes (e.g., dyskeratosis congenita (Zinsser-Engman-Cole syndrome) caused by mutations in the DKC1, TERT or TERC genes, or mutations in the Wiskott-Aldrich syndrome gene (WAS))
- abnormalities in (haematopoietic) transcription factors (e.g., mutations in the RUNX1, GATA2, PAX5, SH2B3 or ETV6 gene)
- purely familial leukaemias (e.g. germline mutations in the GATA2, CEBPA, DDX41 or RUNX1 gene)
- aneuploidies (e.g., trisomy 21).

One of the most common genetic syndromes and one of the most well-established risk factors for (acute) leukaemia in childhood is Down's syndrome, which is caused by partial or complete trisomy of chromosome 21 (Shimada 2021). The incidence of Down's syndrome is estimated at 1 in 800 births, with the number of people living with trisomy 21 estimated at around 50,000 in Germany and around 200,000 in the USA (Avet-Loiseau et al. 1995, Bull 2020, Hoppen 2021). The development of transient abnormal myelopoiesis (TAM) that is considered as a putative precursor of myeloid leukaemia associated with Down syndrome, requires a specific genetic mutation in the GATA1 transcription factor in addition to trisomy.; This mutation results in an exclusive expression of the shorter isoform GATA1s in the foetal stem and/or progenitor cells (Wechsler et al. 2002). Approximately 10% of newborns with Down syndrome present with a transient myeloproliferative disorder and, of them, around 20% to 30% develop (acute myeloid) leukaemia after regression of TAM (Shimada 2021). People with Down syndrome are estimated to be 10 to 20 times more likely to develop acute leukaemia; the cumulative risk of developing leukaemia in people with Down's syndrome has been estimated at 2.1% by the age of 5 and 2.7% by the age of 30 (Roizen und Patterson 2003). Due to comorbidities (e.g. congenital heart defects, abnormalities of the nervous system or the musculoskeletal system), it can be assumed that imaging techniques are used more frequently (AWMF 2025). An analysis of data from over 4 million children's medical records across six US healthcare systems (1996 to 2016, a sub-cohort of the RIC Study described in section 3.1), of whom 3,095 had been diagnosed with Down's syndrome, revealed that children with Down's syndrome underwent almost 10 times as many medical imaging examinations as other children (Marlow et al. 2023, AWMF 2025). Imaging procedures involving ionising radiation were performed 9.5 times more frequently (95% CI: 8.2–10.9) in children with Down's syndrome under the age of 1 and 2.3 times more frequently among those aged between 1 and 18 (95% CI: 2.0–2.5). However, the mean cumulative bone marrow dose calculated from imaging (over an average period of 4.2 years) was twice as high in children with Down syndrome as in other children (4.7 mGy vs. 1.9 mGy) (Marlow et al. 2023). The use of imaging involving ionising radiation in these children should therefore be subject to scrutiny, and the justifying indication must be established with particular strictness.

It is generally accepted that early detection of a tumour can lead to improved clinical outcomes, which in children often results in cure. For this reason, clinical early detection protocols incorporating clinical, biochemical and imaging methods have been implemented and evaluated for CPS. It has been shown that, for Li-Fraumeni syndrome, participation in these screening

programmes resulted in a 5-year survival rate of 89%, compared to 60% in the unscreened group (Villani et al. 2011). In general, 4% of people with Li-Fraumeni syndrome have developed a tumour within their first year of life. This figure rises to 22% by the age of 5 and 41% by the age of 18. It can be assumed that this risk is likely to be further increased by adverse environmental factors, as well as by ionising radiation. In some cases, CPS are known to be associated with a particularly high level of radiation-induced carcinogenicity. In 30% of cases, people with Li-Fraumeni syndrome develop a malignancy in the previously irradiated region following radiotherapy (Bougeard et al. 2015). Similar findings have been reported in children with hereditary retinoblastoma and neurofibromatosis (Kleinerman 2009). Overall, data on secondary malignant neoplasms – for example, in individuals with Li-Fraumeni syndrome and hereditary TP53-related cancer syndrome – remain scarce, as there is rarely long-term follow-up before the onset of secondary malignant neoplasms and the prognosis tends to be poor (Hendrickson et al. 2020). However, it can be assumed that some CPS are characterised by increased radiation sensitivity, although the strength of the correlation between radiation sensitivity and cancer predisposition has yet to be clarified.

Increased radiation sensitivity has been confirmed in lymphocytes in Nijmegen breakage syndrome, as have germline mutations resulting in loss of function in the Nibrin gene, a protein involved in the repair of double-strand breaks (DSBs) (Walsh et al. 2017). Increased sensitivity to radiation has also been described, for example, in ataxia–telangiectasia, Rothmund–Thomson syndrome and other rare CPS. For high-dose examinations involving ionising radiation, adverse radiation effects have generally been confirmed in terms of cancer induction. According to a systematic review, there is insufficient evidence to suggest that leukaemia, lymphoma, and brain and thyroid cancer occur more frequently in people with CPS (Canet et al. 2022).

Using PubMed, Scopus, Web of Science and EMBASE, an evaluation was made of epidemiological studies on the cancer risk in people under the age of 25 with CPS in whom examinations with low (< 100 mGy) to moderate dose (< 500 mGy) were performed. Of the 16,315 articles identified in the initial literature search in 2020, only 15 publications were ultimately included in the analysis, and two of these described the same study population. Ultimately, eight cohort studies and six case-control studies remained. Ten studies evaluated the effects of diagnostic procedures – CT scans in four studies and chest X-rays in six studies. However, these studies were also highly heterogeneous, particularly with regard to the reported dose values. With regard to the types of cancer, Canet et al. (2022) found no evidence of an increased risk (ERR) of leukaemia following low- to moderate-dose exposure (i.e. X-rays and CT scans) in children with a corresponding CPS. However, given the small number of cases, the team of authors were unable to rule out a potential effect and concluded that there was insufficient evidence to suggest an increased risk of radiation-induced leukaemia with CPS. Similar findings were reported for lymphomas and CNS malignancies. Insufficient evidence was reported for retinoblastoma or thyroid carcinoma. According to the review, however, there are studies on breast cancer that indicate a higher risk of breast cancer following low-dose examinations for carriers of the BRCA1 or BRCA2 mutation, although these findings are not consistent. For example, studies by Andrieu et al. (2006), Gronwald et al. (2008), Pijpe et al. (2012) and Lecarpentier et al. (2011) described an increased risk even at extremely low doses (typically equivalent to a few days' natural radiation exposure), whilst this is not confirmed by John et al. (2013). The increased risk, which has been widely reported, rises with the number of examinations involving ionising radiation and is considered to be highest when exposure occurs at a younger age. Other major reviews on the link between CT exposure and malignancies in children do indeed include CPS, but only in terms of their total number – the heterogeneity of these rare diseases has already been noted (Journy et al. 2016a, Berrington de Gonzalez et al. 2016).

A literature review on the link between radiation exposure from CT scans and the risk of leukaemia and brain tumours in patients with CPS – combined with expert opinions – suggests that the radiation-related relative risk of leukaemia is not significantly confounded by Down syndrome, Noonan's syndrome and other CPSs (Meulepas et al. 2016, Smith-Bindman et al. 2025a). Similar conclusions were reached for tuberous sclerosis complex, von Hippel-Lindau disease, neurofibromatosis type 1 and other CPSs in relation to brain tumours. It should be noted that these conclusions are based solely on empirical evidence relating to people with Down's syndrome, as provided by the RIC Study (Smith-Bindman et al. 2025a, Marlow et al. 2023). Otherwise, the conclusions are based on assumptions about CT use on people with CPS, as there is currently no robust empirical data available apart from the RIC Study.

As an alternative to imaging techniques involving ionising radiation, whole-body MRI is playing an increasingly important role in early detection in the presence of CPS, alongside ultrasound (Greer et al. 2017). The S1 guideline on whole-body (WB) MRI (AWMF 2021a) from the Society for Paediatric Radiology (GPR) identifies CPS as a relevant indication for this method. For various CPS, there are now also protocol recommendations regarding the scope and frequency of whole-body MRI scans (e.g., Li-Fraumeni syndrome: annual whole-body MRI; NF1: baseline scan between the ages of 16 and 20; hereditary retinoblastoma: annual scans from age 8). For Li-Fraumeni syndrome, the Toronto Protocol recommends an annual whole-body MRI, an annual MRI of the central nervous system, and abdominal and pelvic ultrasound scans every 3 to 4 months (Kratz et al. 2017). In constitutional mismatch repair deficiency (CMMRD) syndrome, which has a very poor prognosis (average survival time < 30 months after diagnosis) due to various, recurrent malignant tumours, an annual whole-body MRI is recommended from 6 years of age, in addition to twice-yearly cranial MRI and abdominal ultrasound examinations and an annual endoscopy (Tabori et al. 2017).

Certain risk and safety considerations must also be taken into account in the case of whole-body MRI (e.g., field strength, high-frequency fields, contrast agents), as well as the possibility of false-positive findings, which must then be verified by dedicated localised MRI scans or by combining MRI with functional methods such as positron emission tomography (PET-MRI). Not least because of the very low incidence of these diseases and syndromes, diagnosis should be carried out at centres for rare diseases that are suitably staffed and equipped. The risks associated with sedation or anaesthesia for MRI scans must also be taken into account and weighed against the radiation risk. As a general rule, children with CPS require screening or early detection examinations for many years; given the frequency of these tests, it is preferable to carry them out without the use of ionising radiation wherever possible.

Literature

- Abalo et al. 2021 Abalo KD, Rage E, Leuraud K, Richardson DB, Le Pointe HD, Laurier D, Bernier MO. Early life ionizing radiation exposure and cancer risks: systematic review and meta-analysis. *Pediatr Radiol*. 2021 Jan;51(1):45-56, doi: 10.1007/s00247-020-04803-0, Epub 20200910
- Abuhamed et al. 2025 Abuhamed J, Nikkilä A, Raitanen J, Lohi O, Auvinen A. Risk of childhood brain tumors after exposure to CT radiation: A nationwide population-based case-control study in Finland. *Int J Cancer*. 2025 Jun 1;156(11):2148-57, doi: 10.1002/ijc.35318, Epub 20241229
- Achenbach et al. 2012 Achenbach S, Barkhausen J, Beer M, Beerbaum P, Dill T, Eichhorn J, Fratz S, Gutberlet M, Hoffmann M, Huber A, Hunold P, Klein C, Krombach G, Kreitner KF, Kühne T, Lotz J, Maintz D, Mahrholdt H, Merkle N, Messroghli D, Miller S, Paetsch I, Radke P, Steen H, Thiele H, Sarikouch S, Fischbach R. [Consensus recommendations of the German Radiology Society (DRG), the German Cardiac Society (DGK) and the German Society for Pediatric Cardiology (DGPK) on the use of cardiac imaging with computed tomography and magnetic resonance imaging]. *Rofo*. 2012 Apr;184(4):345-68, doi: 10.1055/s-0031-1299400, Epub 20120317
- ACR 2019 American College of Radiology (ACR). ACR–ASER–SCBT–MR–SPR PRACTICE PARAMETER FOR THE PERFORMANCE OF PEDIATRIC COMPUTED TOMOGRAPHY (CT). <https://gravitas.acr.org/PPTS/GetDocumentView?docId=77>, zuletzt aufgerufen am 25.04.2025
- Andrieu et al. 2006 Andrieu N, Easton DF, Chang-Claude J, Rookus MA, Brohet R, Cardis E, Antoniou AC, Wagner T, Simard J, Evans G, Peock S, Fricker JP, Nogues C, Van't Veer L, Van Leeuwen FE, Goldgar DE. Effect of chest X-rays on the risk of breast cancer among BRCA1/2 mutation carriers in the international BRCA1/2 carrier cohort study: a report from the EMBRACE, GENEPSO, GEO-HEBON, and IBCCS Collaborators' Group. *J Clin Oncol*. 2006 Jul 20;24(21):3361-6, doi: 10.1200/jco.2005.03.3126, Epub 20060626
- Avet-Loiseau et al. 1995 Avet-Loiseau H, Mechinaud F, Harousseau JL. Clonal hematologic disorders in Down syndrome. A review. *J Pediatr Hematol Oncol*. 1995 Feb;17(1):19-24, doi: 10.1097/00043426-199502000-00003

- AWMF 2016a Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S1-Leitlinie Hepatoblastom. Version: 7.0, Stand: 02.06.2016, gültig bis: 01.06.2021 (in Überarbeitung). <https://register.awmf.org/de/leitlinien/detail/025-011>, zuletzt aufgerufen am 25.04.2025
- AWMF 2016b Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S1-Leitlinie Nephroblastom (Wilms-Tumor). Version: 8.0, Stand: 14.06.2016, gültig bis: 13.06.2021 (in Überarbeitung). <https://register.awmf.org/de/leitlinien/detail/025-004>, zuletzt aufgerufen am 25.04.2025
- AWMF 2019 Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S1-Leitlinie Trauma des muskuloskelettalen Systems im Kindes- und Jugendalter – Bildgebende Diagnostik. Version: 1.0, Stand: 01.06.2019, gültig bis: 31.05.2024 (in Überarbeitung). <https://register.awmf.org/de/leitlinien/detail/064-019>, zuletzt aufgerufen am 25.04.2025
- AWMF 2020 Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S2k-Leitlinie Polytraumaver-sorgung im Kindesalter. Version 2.1, Stand: 31.10.2020, gültig bis 30.10.2025. <https://register.awmf.org/de/leitlinien/detail/006-120>, zuletzt aufgerufen am 25.04.2025
- AWMF 2021a Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S1-Leitlinie Ganzkörpermag-netresonanztomografie im Kindes- und Jugendalter. Version 2.0. Stand: 31.10.2021. Gültig bis: 31.10.2024 (in Überarbeitung). <https://register.awmf.org/de/leitlinien/detail/064-018>, zuletzt auf-gerufen am 28.04.2025
- AWMF 2021b Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S1-Leitlinie Ewing-Sarkom des Kinder- und Jugendalters. Version: 8.0, Stand: 31.12.2021, gültig bis: 31.12.2026. <https://register.awmf.org/de/leitlinien/detail/025-006>, zuletzt aufgerufen am 25.04.2025
- AWMF 2021c Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S1-Leitlinie Osteosarkome. Stand: 30.06.2021, gültig bis: 29.06.2026. <https://register.awmf.org/de/leitlinien/detail/025-005>, zuletzt aufgerufen am 25.04.2025
- AWMF 2022 Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S2k-Leitlinie Schädel-Hirn-Trauma im Kindes- und Jugendalter. Version 3.2, Stand: 14.02.2022, red. überarbeitet am 01.03.2023, gültig bis 13.02.2027. <https://register.awmf.org/de/leitlinien/detail/024-018>, zuletzt aufgerufen am 02.12.2024

- AWMF 2023 Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S1-Leitlinie Rhabdomyosarkome. Version: 8.0, Stand: 31.07.2023, gültig bis: 30.07.2028. <https://register.awmf.org/de/leitlinien/detail/025-007>, zuletzt aufgerufen am 25.04.2025
- AWMF 2025 Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S2k-Leitlinie Down-Syndrom im Kindes- und Jugendalter. In Überarbeitung. Geplante Fertigstellung: 31.03.2025. <https://register.awmf.org/de/leitlinien/detail/027-051>, zuletzt aufgerufen am 28.04.2025
- Badampudi et al. 2015 Badampudi D, Wohlin C, Petersen K Hrsg. 19th International Conference on Evaluation and Assessment in Software Engineering. 2015
- Bellamy et al. 2024 Bellamy MB, Bernstein JL, Cullings HM, French B, Grogan HA, Held KD, Little MP, Tekwe CD. Recommendations on statistical approaches to account for dose uncertainties in radiation epidemiologic risk models. *Int J Radiat Biol.* 2024;100(10):1393-404, doi: 10.1080/09553002.2024.2381482, Epub 20240726
- Berrington de Gonzalez et al. 2009 Berrington de Gonzalez A, Mahesh M, Kim KP, Bhargavan M, Lewis R, Mettler F, Land C. Projected cancer risks from computed tomographic scans performed in the United States in 2007. *Arch Intern Med.* 2009 Dec 14;169(22):2071-7, doi: 10.1001/archinternmed.2009.440, Epub 2009/12/17
- Berrington de Gonzalez et al. 2016 Berrington de Gonzalez A, Salotti JA, McHugh K, Little MP, Harbron RW, Lee C, Ntowe E, Braganza MZ, Parker L, Rajaraman P, Stiller C, Stewart DR, Craft AW, Pearce MS. Relationship between paediatric CT scans and subsequent risk of leukaemia and brain tumours: assessment of the impact of underlying conditions. *Br J Cancer.* 2016 Feb 16;114(4):388-94, doi: 10.1038/bjc.2015.415
- BfS 2022 Bundesamt für Strahlenschutz (BfS). Bekanntmachung der aktualisierten diagnostischen Referenzwerte für diagnostische und interventionelle Röntgenanwendungen. Vom 17. November 2022. https://www.bfs.de/SharedDocs/Downloads/BfS/DE/fachinfo/ion/drw-roentgen.pdf?__blob=publicationFile&v=13, zuletzt aufgerufen am 22.01.2025
- BfS 2025 Bundesamt für Strahlenschutz (BfS). CT-Untersuchungen vor der Schwangerschaft: Negative Auswirkungen auf Verlauf der Schwangerschaft und Gesundheit des Kindes? <https://www.bfs.de/DE/bfs/wissenschaft-forschung/medizin/stellungnahmen/auswirkungen-ct-schwangerschaft.html>, zuletzt aufgerufen am 28.10.2025

- Bochtler et al. 2018 Bochtler T, Haag GM, Schott S, Kloor M, Krämer A, Müller-Tidow C. Hematological Malignancies in Adults With a Family Predisposition. *Dtsch Arztebl Int.* 2018 Dec 14;115(50):848-54, doi: 10.3238/arztebl.2018.0848, Epub 2019/02/07
- Boice 2015 Boice JD, Jr. Radiation epidemiology and recent paediatric computed tomography studies. *Ann ICRP.* 2015 Jun;44(1 Suppl):236-48, doi: 10.1177/0146645315575877, Epub 20150324
- Bosch de Basea Gomez et al. 2023 Bosch de Basea Gomez M, Thierry-Chef I, Harbron R, Hauptmann M, Byrnes G, Bernier MO, Le Cornet L, Dabin J, Ferro G, Istad TS, Jahn A, Lee C, Maccia C, Malchair F, Olerud H, Simon SL, Figuerola J, Peiro A, Engels H, Johansen C, Blettner M, Kaijser M, Kjaerheim K, Berrington de Gonzalez A, Journy N, Meulepas JM, Moissonnier M, Nordenskjöld A, Pokora R, Ronckers C, Schuz J, Kesminiene A, Cardis E. Risk of hematological malignancies from CT radiation exposure in children, adolescents and young adults. *Nat Med.* 2023 Dec;29(12):3111-9, doi: 10.1038/s41591-023-02620-0, Epub 2023/11/10
- Bosch de Basea et al. 2015 Bosch de Basea M, Pearce MS, Kesminiene A, Bernier MO, Dabin J, Engels H, Hauptmann M, Krille L, Meulepas JM, Struelens L, Baatout S, Kaijser M, Maccia C, Jahn A, Thierry-Chef I, Blettner M, Johansen C, Kjaerheim K, Nordenskjöld A, Olerud H, Salotti JA, Andersen TV, Vrijheid M, Cardis E. EPI-CT: design, challenges and epidemiological methods of an international study on cancer risk after paediatric and young adult CT. *J Radiol Prot.* 2015 Sep;35(3):611-28, doi: 10.1088/0952-4746/35/3/611, Epub 20150730
- Bosch de Basea et al. 2016 Bosch de Basea M, , Salotti JA, , Pearce MS, , Muchart J, , Riera L, , Barber I, , Pedraza S, , Pardina M, , Capdevila A, , Espinosa A, , Cardis E, . 2016. Trends and patterns in the use of computed tomography in children and young adults in Catalonia — results from the EPI-CT study. In: Springer Verlag. S. 119-29
- Bougeard et al. 2015 Bougeard G, Renaux-Petel M, Flaman JM, Charbonnier C, Fermey P, Belotti M, Gauthier-Villars M, Stoppa-Lyonnet D, Consolino E, Brugières L, Caron O, Benusiglio PR, Bressac-de Paillerets B, Bonadona V, Bonaïti-Pellié C, Tinat J, Baert-Desurmont S, Frebourg T. Revisiting Li-Fraumeni Syndrome From TP53 Mutation Carriers. *J Clin Oncol.* 2015 Jul 20;33(21):2345-52, doi: 10.1200/jco.2014.59.5728, Epub 20150526
- Brady et al. 2016 Brady Z, Forsythe AV, Mathews JD. The changing use of pediatric CT in Australia. *Pediatr Radiol.* 2016 Jul;46(8):1199-208, doi: 10.1007/s00247-016-3563-5, Epub 20160307

- Brenner et al. 2001 Brenner D, Elliston C, Hall E, Berdon W. Estimated risks of radiation-induced fatal cancer from pediatric CT. *AJR Am J Roentgenol.* 2001 Feb;176(2):289-96, doi: 10.2214/ajr.176.2.1760289, Epub 2001/02/13
- Brenner et al. 2007 Brenner DJ, , Hall EJ, . 2007. Computed Tomography - An Increasing Source of Radiation Exposure. In. S. 2277-84
- Brodeur et al. 2017 Brodeur GM, Nichols KE, Plon SE, Schiffman JD, Malkin D. Pediatric Cancer Predisposition and Surveillance: An Overview, and a Tribute to Alfred G. Knudson Jr. *Clin Cancer Res.* 2017 Jun 1;23(11):e1-e5, doi: 10.1158/1078-0432.Ccr-17-0702
- Bull 2020 Bull MJ. Down Syndrome. *N Engl J Med.* 2020 Jun 11;382(24):2344-52, doi: 10.1056/NEJMra1706537
- Burton et al. 2023 Burton CS, Frey K, Fahey F, Kaminski MS, Brown RKJ, Pohlen JM, Shulkin BL. Fetal Dose from PET and CT in Pregnant Patients. *J Nucl Med.* 2023 Feb;64(2):312-9, doi: 10.2967/jnumed.122.263959, Epub 20220908
- Canet et al. 2022 Canet M, Harbron R, Thierry-Chef I, Cardis E. Cancer Effects of Low to Moderate Doses of Ionizing Radiation in Young People with Cancer-Predisposing Conditions: A Systematic Review. *Cancer Epidemiol Biomarkers Prev.* 2022 Oct 4;31(10):1871-89, doi: 10.1158/1055-9965.Epi-22-0393
- Cao et al. 2022 Cao C-F, Ma K-L, Shan H, Liu T-F, Zhao S-Q, Wan Y, Jun Z, Wang H-Q. CT Scans and Cancer Risks: A Systematic Review and Dose-response Meta-analysis. *BMC Cancer.* 2022 2022/11/30;22(1):1238, doi: 10.1186/s12885-022-10310-2
- Carroll et al. 2006 Carroll RJ, Ruppert D, Stefanski LA, Crainiceanu CM. *Measurement Error in Nonlinear Models: A Modern Perspective.* Chapman and Hall/CRC, 2006, ISBN 9781420010138
- Chodick et al. 2006 Chodick G, Ronckers C, Ron E, Shalev V. The utilization of pediatric computed tomography in a large Israeli Health Maintenance Organization. *Pediatr Radiol.* 2006 Jun;36(6):485-90, doi: 10.1007/s00247-005-0091-0, Epub 20060322
- Chu et al. 2023 Chu PW, Kofler C, Mahendra M, Wang Y, Chu CA, Stewart C, Delman BN, Haas B, Lee C, Bolch WE, Smith-Bindman R. Dose length product to effective dose coefficients in children. *Pediatr Radiol.* 2023 Jul;53(8):1659-68, doi: 10.1007/s00247-023-05638-1, Epub 20230316

- COCIR 2023 European Coordination Committee of the Radiological, Electromedical and Healthcare Information Technology (IT) - Industry (COCIR). COCIR Medical Imaging Equipment Age Profile & Density - 2023 Edition. <https://www.cocir.org/publication/cocir-medical-imaging-equipment-age-profile-density-2023-edition-2/>, zuletzt aufgerufen am 28.04.2026
- Cooke et al. 2013 Cooke R, Jones ME, Cunningham D, Falk SJ, Gilson D, Hancock BW, Harris SJ, Horwich A, Hoskin PJ, Illidge T, Linch DC, Lister TA, Lucraft HH, Radford JA, Stevens AM, Syndikus I, Williams MV, Swerdlow AJ. Breast cancer risk following Hodgkin lymphoma radiotherapy in relation to menstrual and reproductive factors. *Br J Cancer*. 2013 Jun 11;108(11):2399-406, doi: 10.1038/bjc.2013.219, Epub 20130507
- Cooper 2000 Cooper GM. The Development and Causes of Cancer. The Cell: A Molecular Approach. 2nd edition. Sinauer Associates, Sunderland (MA), 2000
- Council 2006 Council NR. Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2. The National Academies Press, Washington, DC, 2006 422°Seiten, ISBN 978-0-309-09156-5
- Daltveit et al. 2025 Daltveit DS, Morgan E, Colombet M, Steliarova-Foucher E, Bendahhou K, Marcos-Gragera R, Rongshou Z, Smith A, Wei H, Soerjomataram I. Global patterns of leukemia by subtype, age, and sex in 185 countries in 2022. *Leukemia*. 2025 Feb;39(2):412-9, doi: 10.1038/s41375-024-02452-y, Epub 20241120
- Destatis Destatis. Fachserie. 12, Gesundheit. 6, Krankenhäuser. 1.1, Grunddaten der Krankenhäuser. https://www.statistischebibliothek.de/mir/receive/DESerie_mods_00000124, zuletzt aufgerufen am 11.04.2025
- Dickman et al. 2003 Dickman PW, Holm L-E, Lundell G, Boice Jr. JD, Hall P. Thyroid cancer risk after thyroid examination with ¹³¹I: A population-based cohort study in Sweden. *International Journal of Cancer*. 2003;106(4):580-7, doi: <https://doi.org/10.1002/ijc.11258>
- Dreger et al. 2015 Dreger S, Poettgen S, Samkange-Zeeb F, Merzenich H, Ningo A, Breckow J, Zeeb H. Retrospective assessment of self-reported exposure to medical ionizing radiation: results of a feasibility study conducted in Germany. *BMC Res Notes*. 2015 Jul 10;8:300, doi: 10.1186/s13104-015-1268-8, Epub 20150710

- Ebenebe et al. 2019 Ebenebe CU, Barreau C, Waschkewitz J, Schlattl H, Pinnschmidt HO, Deindl P, Singer D, Herrmann J. Radiation exposure by digital radiographic imaging in very low birth weight infants. *J Perinatol.* 2019 Jan;39(1):115-9, doi: 10.1038/s41372-018-0276-7, Epub 20181120
- Elbakri 2014 Elbakri IA. Estimation of dose-area product-to-effective dose conversion factors for neonatal radiography using PCXMC. *Radiat Prot Dosimetry.* 2014 Jan;158(1):43-50, doi: 10.1093/rpd/nct192, Epub 20130728
- Erdmann et al. 2019 Erdmann F, Ghantous A, Schüz J. Environmental Agents and Childhood Cancer☆. In: Nriagu J, Hrsg. *Encyclopedia of Environmental Health (Second Edition)* Elsevier, Oxford, 2019, Seiten 347-59, ISBN 978-0-444-63952-3
- ESPR ESPR. CT & Dose. <https://www.espr.org/taskforces/ct-dose/>, zuletzt aufgerufen am 25.04.2025
- Esser et al. 2018 Esser M, Hess S, Teufel M, Kraus MS, Schneeweiß S, Gatidis S, Schaefer JF, Tsiflikas I. Radiation Dose Optimization in Pediatric Chest CT: Major Indicators of Dose Exposure in 1695 CT Scans over Seven Years. *Rofo.* 2018 Dec;190(12):1131-40, doi: 10.1055/a-0628-7222, Epub 2018/10/12
- European Commission 2018 European Commission. *European Guidelines on Diagnostic Reference Levels for Paediatric Imaging.* Radiation Protection 185. Luxembourg, 2018, ISBN 978-92-79-89876-1
- Farkas et al. 1992 Farkas LG, Posnick JC, Hreczko TM. Anthropometric growth study of the head. *Cleft Palate Craniofac J.* 1992 Jul;29(4):303-8, doi: 10.1597/1545-1569_1992_029_0303_agsoth_2.3.co_2, Epub 1992/07/01
- Fiebich et al. 2021 Fiebich M, Block A, Borowski M, Geworski L, Happel C, Kamp A, Lenzen H, Mahnken AH, Müller WU, Östreicher G, Rudolf F, Stamm G, Starck P, Steiniger B, Wicke JH, Wolf U, Wucherer M, Zankl M, Zink K, Zweig C. Prenatal radiation exposure in diagnostic and interventional radiology. *Röfo.* 2021 Jul;193(7):778-86, doi: 10.1055/a-1313-7527, Epub 20201216
- Francone et al. 2022 Francone M, Gimelli A, Budde RPJ, Caro-Dominguez P, Einstein AJ, Gutberlet M, Maurovich-Horvat P, Miller O, Nagy E, Natale L, Peebles C, Petersen SE, Semple T, Valverde I, Voges I, Secinaro A, Di Salvo G. Radiation safety for cardiovascular computed tomography imaging in paediatric cardiology: a joint expert consensus document of the EACVI, ESCR, AEPC, and ESPR. *European Heart Journal - Cardiovascular Imaging.* 2022;23(8):e279-e89, doi: 10.1093/ehjci/jeac048

- Frush 2011 Frush DP. The role of CT in professionalism: accreditation, certification and the welfare of our children. *Pediatr Radiol*. 2011 Sep;41 Suppl 2:571-5, doi: 10.1007/s00247-011-2100-9, Epub 20110817
- Galanski et al. 2006 Galanski M, , Nagel HD, , Stamm G, . 2006. Pädiatrische CT-Expositionspraxis in der Bundesrepublik Deutschland. In:
- Garcia et al. 2023 Garcia TB, Kliemt R, Claus F, Neumann A, Soltmann B, Baum F, Schwarz J, Swart E, Schmitt J, Pfennig A, Häckl D, Weinhold I. Agreement between self-reports and statutory health insurance claims data on healthcare utilization in patients with mental disorders. *BMC Health Serv Res*. 2023 Nov 11;23(1):1243, doi: 10.1186/s12913-023-10175-6, Epub 20231111
- GBE GBE. Die umfangreichste Datensammlung über unser Gesundheitswesen. <https://www.gbe-bund.de/gbe/>, zuletzt aufgerufen am 11.04.2025
- Gislason-Lee 2021 Gislason-Lee AJ. Patient X-ray exposure and ALARA in the neonatal intensive care unit: Global patterns. *Pediatr Neonatol*. 2021 Jan;62(1):3-10, doi: 10.1016/j.pedneo.2020.10.009, Epub 20201118
- Glutig et al. 2021 Glutig K, Pfeil A, Renz DM. Bildgebung bei Tumorprädispositionssyndromen. *Der Radiologe*. 2021 2021/07/01;61(7):658-66, doi: 10.1007/s00117-021-00861-z
- Gohmann et al. 2022 Gohmann RF, Sieren MM, Gutberlet M. [Computed tomography and magnetic resonance imaging in cardiac diagnostics-how to choose the right modality : A guide based on the new guidelines of the European Society of Cardiology (ESC)]. *Radiologie (Heidelb)*. 2022 Nov;62(11):902-11, doi: 10.1007/s00117-022-01066-8, Epub 20221012
- Greer et al. 2017 Greer MC, Voss SD, States LJ. Pediatric Cancer Predisposition Imaging: Focus on Whole-Body MRI. *Clin Cancer Res*. 2017 Jun 1;23(11):e6-e13, doi: 10.1158/1078-0432.Ccr-17-0515

Gröbner et al. 2018

Gröbner SN, Worst BC, Weischenfeldt J, Buchhalter I, Kleinheinz K, Rudneva VA, Johann PD, Balasubramanian GP, Segura-Wang M, Brabetz S, Bender S, Hutter B, Sturm D, Pfaff E, Hübschmann D, Zipprich G, Heinold M, Eils J, Lawerenz C, Erkek S, Lambo S, Waszak S, Blattmann C, Borkhardt A, Kühlen M, Eggert A, Fulda S, Gessler M, Wegert J, Kappler R, Baumhoer D, Burdach S, Kirschner-Schwabe R, Kontny U, Kulozik AE, Lohmann D, Hettmer S, Eckert C, Bielack S, Nathrath M, Niemeyer C, Richter GH, Schulte J, Siebert R, Westermann F, Molenaar JJ, Vassal G, Witt H, Lichter P, Weber U, Eils R, Korshunov A, Witt O, Pfister S, Reifemberger G, Felsberg J, von Kalle C, Schmidt M, Bartholomä C, Taylor M, Pfister S, Jones D, Lichter P, Jäger N, Buchhalter I, Korbel J, Stütz A, Rausch T, Radlwimmer B, Yaspo M-L, Lehrach H, Warnatz H-J, Landgraf P, Borkhardt A, Brors B, Zapatka M, Eils R, Eils R, Eils J, Lawerenz C, Siebert R, Wagner S, Haake A, Richter J, Richter G, Eils R, Lawerenz C, Eils J, Kerssemakers J, Jaeger-Schmidt C, Scholz I, Bergmann AK, Borst C, Burkhardt B, Claviez A, Dreyling M, Eberth S, Einsele H, Frickhofen N, Haas S, Hansmann M-L, Karsch D, Kneba M, Lisfeld J, Mantovani-Löffler L, Rohde M, Ott G, Stadler C, Staib P, Stilgenbauer S, Trümper L, Zenz T, Hansmann M-L, Kube D, Küppers R, Weniger M, Hummel M, Klapper W, Kostezka U, Lenze D, Möller P, Rosenwald A, Ott G, Szczepanowski M, Ammerpohl O, Aukema SM, Binder V, Borkhardt A, Haake A, Hoell JI, Leich E, Lichter P, López C, Nagel I, Pischmariov J, Radlwimmer B, Richter J, Rosenstiel P, Rosenwald A, Schilhabel M, Schreiber S, Vater I, Wagener R, Siebert R, Bernhart SH, Binder H, Brors B, Doose G, Eils R, Hoffmann S, Hopp L, Hübschmann D, Kleinheinz K, Kretzmer H, Kreuz M, Korbel J, Langenberger D, Loeffler M, Rosolowski M, Schlesner M, Stadler PF, Sungalee S, Burkhardt B, Kratz CP, Witt O, van Tilburg CM, Kramm CM, Fleischhack G, Dirksen U, Rutkowski S, Frühwald M, von Hoff K, Wolf S, Klingebiel T, Koscielniak E, Landgraf P, Koster J, Resnick AC, Zhang J, Liu Y, Zhou X, Waanders AJ, Zwijsen DA, Raman P, Brors B, Weber UD, Northcott PA, Pajtler KW, Kool M, Piro RM, Korbel JO, Schlesner M, Eils R, Jones DTW, Lichter P, Chavez L, Zapatka M, Pfister SM, Project IP-S, Project IM-S. The landscape of genomic alterations across childhood cancers. *Nature*. 2018 2018/03/01;555(7696):321-7, doi: 10.1038/nature25480

Gronwald et al. 2008

Gronwald J, Pijpe A, Byrski T, Huzarski T, Stawicka M, Cybulski C, van Leeuwen F, Lubiński J, Narod SA. Early radiation exposures and BRCA1-associated breast cancer in young women from Poland. *Breast Cancer Research and Treatment*. 2008 2008/12/01;112(3):581-4, doi: 10.1007/s10549-008-9892-9

- Han et al. 2025 Han S, Soh J, Nah S, Han K, Jung JH, Park J, Hwang Y, Lee C, Hong JY. Pediatric computed tomography scan and subsequent risk of malignancy: a nationwide population-based cohort study in Korea using National Cancer Institute dosimetry system for computed tomography (NCICT). *BMC Med.* 2025 Jul 1;23(1):355, doi: 10.1186/s12916-025-04235-3, Epub 20250701
- Hart et al. 1991 Hart D, Jones D, Wall B. 1991. Normalized organ doses for medical x-ray examinations calculated using Monte Carlo techniques. In. National Radiological Protection Board, Harwell (United Kingdom)
- Hasle et al. 2000 Hasle H, Clemmensen IH, Mikkelsen M. Risks of leukaemia and solid tumours in individuals with Down's syndrome. *Lancet.* 2000 Jan 15;355(9199):165-9, doi: 10.1016/S0140-6736(99)05264-2, Epub 2000/02/16
- Hauptmann et al. 2020 Hauptmann M, Daniels RD, Cardis E, Cullings HM, Kendall G, Laurier D, Linet MS, Little MP, Lubin JH, Preston DL, Richardson DB, Stram DO, Thierry-Chef I, Schubauer-Berigan MK, Gilbert ES, Berrington de Gonzalez A. Epidemiological Studies of Low-Dose Ionizing Radiation and Cancer: Summary Bias Assessment and Meta-Analysis. *J Natl Cancer Inst Monogr.* 2020 Jul 1;2020(56):188-200, doi: 10.1093/jncimonographs/lgaa010
- Hauptmann et al. 2023 Hauptmann M, Byrnes G, Cardis E, Bernier MO, Blettner M, Dabin J, Engels H, Istad TS, Johansen C, Kaijser M, Kjaerheim K, Journy N, Meulepas JM, Moissonnier M, Ronckers C, Thierry-Chef I, Le Cornet L, Jahnen A, Pokora R, Bosch de Basea M, Figuerola J, Maccia C, Nordenskjold A, Harbron RW, Lee C, Simon SL, Berrington de Gonzalez A, Schüz J, Kesminiene A. Brain cancer after radiation exposure from CT examinations of children and young adults: results from the EPI-CT cohort study. *Lancet Oncol.* 2023 Jan;24(1):45-53, doi: 10.1016/s1470-2045(22)00655-6, Epub 20221206
- Hendrickson et al. 2020 Hendrickson PG, Luo Y, Kohlmann W, Schiffman J, Maese L, Bishop AJ, Lloyd S, Kokeny KE, Hitchcock YJ, Poppe MM, Gaffney DK, Tao R. Radiation therapy and secondary malignancy in Li-Fraumeni syndrome: A hereditary cancer registry study. *Cancer Med.* 2020 Nov;9(21):7954-63, doi: 10.1002/cam4.3427, Epub 20200915
- Hill 1965 Hill AB. THE ENVIRONMENT AND DISEASE: ASSOCIATION OR CAUSATION? *Proc R Soc Med.* 1965 May;58(5):295-300, doi: 10.1177/003591576505800503
- Hogan et al. 2018 Hogan AH, Bellin E, Douglas L, Levin TL, Esteban-Cruciani N. Radiation Exposure of Premature Infants Beyond the Perinatal Period. *Hosp Pediatr.* 2018 Nov;8(11):672-8, doi: 10.1542/hpeds.2018-0008, Epub 20181009

- Hoppen 2021 Hoppen T. Bestandsaufnahme gut 150 Jahre nach der Erstbeschreibung. *Pädiatrie*. 2021;33(1):40-5, doi: 10.1007/s15014-020-3657-2
- Hsu et al. 2013 Hsu WL, Preston DL, Soda M, Sugiyama H, Funamoto S, Kodama K, Kimura A, Kamada N, Dohy H, Tomonaga M, Iwanaga M, Miyazaki Y, Cullings HM, Suyama A, Ozasa K, Shore RE, Mabuchi K. The incidence of leukemia, lymphoma and multiple myeloma among atomic bomb survivors: 1950-2001. *Radiat Res*. 2013 Mar;179(3):361-82, doi: 10.1667/rr2892.1, Epub 2013/02/13
- Huang et al. 2014 Huang WY, Muo CH, Lin CY, Jen YM, Yang MH, Lin JC, Sung FC, Kao CH. Paediatric head CT scan and subsequent risk of malignancy and benign brain tumour: a nation-wide population-based cohort study. *Brit J Cancer*. 2014 2014/04/01;110(9):2354-60, doi: 10.1038/bjc.2014.103
- IAEA 2023 IAEA. 2023. Attribution of Radiation Health Effects and Inference of Radiation Risks: Considerations for Application of the IAEA Safety Standards. In. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna
- IARC 2000 IARC. Ionizing Radiation, Part 1: X- and Gamma (γ)-Radiation, and Neutrons. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. World Health Organization International agency for Research on cancer, 2000, ISBN 978-92-832-1275-1
- Icks et al. 2017 Icks A, Dittrich A, Brüne M, Kuss O, Hoyer A, Haastert B, Begun A, Andrich S, Hoffmann J, Kaltheuner M, Chernyak N. Agreement found between self-reported and health insurance data on physician visits comparing different recall lengths. *J Clin Epidemiol*. 2017 Feb;82:167-72, doi: 10.1016/j.jclinepi.2016.10.009, Epub 20161105
- ICRP 2000 ICRP. 2000. Pregnancy and Medical Radiation. ICRP Publication 84. In. Ann. ICRP
- ICRP 2003 International Commission on Radiological Protection (ICRP). Biological Effects after Prenatal Irradiation (Embryo and Fetus). ICRP Publication 90. Ann ICRP 33(1-2), Pergamon, Oxford, 2003, ISBN 008044265X
- Ilic and Ilic 2023 Ilic I, Ilic M. International patterns and trends in the brain cancer incidence and mortality: An observational study based on the global burden of disease. *Heliyon*. 2023 Jul;9(7):e18222, doi: 10.1016/j.heliyon.2023.e18222, Epub 20230713

- Jassim et al. 2023 Jassim A, Rahrman EP, Simons BD, Gilbertson RJ. Cancers make their own luck: theories of cancer origins. *Nat Rev Cancer*. 2023 Oct;23(10):710-24, doi: 10.1038/s41568-023-00602-5, Epub 20230724
- John et al. 2013 John EM, McGuire V, Thomas D, Haile R, Ozcelik H, Milne RL, Felberg A, West DW, Miron A, Knight JA, Terry MB, Daly M, Buys SS, Andrulis IL, Hopper JL, Southey MC, Giles GG, Apicella C, Thorne H, Whittemore AS. Diagnostic chest X-rays and breast cancer risk before age 50 years for BRCA1 and BRCA2 mutation carriers. *Cancer Epidemiol Biomarkers Prev*. 2013 Sep;22(9):1547-56, doi: 10.1158/1055-9965.Epi-13-0189, Epub 20130712
- Jones and Shrimpton 1993 Jones D, Shrimpton P. 1993. Normalized organ doses for X-ray CT calculated using monte Carlo techniques. In. National Radiological Protection Board
- Jongmans et al. 2016 Jongmans MC, Loeffen JL, Waanders E, Hoogerbrugge PM, Ligtenberg MJ, Kuiper RP, Hoogerbrugge N. Recognition of genetic predisposition in pediatric cancer patients: An easy-to-use selection tool. *Eur J Med Genet*. 2016 Mar;59(3):116-25, doi: 10.1016/j.ejmg.2016.01.008, Epub 20160126
- Journey et al. 2016a Journey N, Roué T, Cardis E, Le Pointe HD, Brisse H, Chateil JF, Laurier D, Bernier MO. Childhood CT scans and cancer risk: impact of predisposing factors for cancer on the risk estimates. *J Radiol Prot*. 2016a Mar;36(1):N1-7, doi: 10.1088/0952-4746/36/1/n1, Epub 20160215
- Journey et al. 2016b Journey NM, McHugh K, Harbron RW, Pearce MS, Berrington de González A. 2016b. Medical conditions associated with the use of CT in children and young adults, Great Britain, 1995-2008. In. S. 10-2
- Kalra et al. 2004 Kalra MK, Maher MM, Toth TL, Hamberg LM, Blake MA, Shepard JA, Saini S. Strategies for CT radiation dose optimization. *Radiology*. 2004 Mar;230(3):619-28, doi: 10.1148/radiol.2303021726, Epub 20040122
- Kalra et al. 2011 Kalra MK, Singh S, Thrall JH, Mahesh M. Pointers for optimizing radiation dose in abdominal CT protocols. *J Am Coll Radiol*. 2011 Oct;8(10):731-4, doi: 10.1016/j.jacr.2011.06.026
- kinderkrebsinfo 2016 Informationsportal zu Krebserkrankungen bei Kindern und Jugendlichen (kinderkrebsinfo). Aktuelle Empfehlungen internationaler Arbeitsgruppen zur Langzeitnachsorge und Früherkennung von Zweitkrebserkrankungen. https://www.gpoh.de/kinderkrebsinfo/content/patienten/nachsorge/spaetfolgen_langzeitnachsorge/spaetfolgen_der_krebstherapie/zweitkrebserkrankungen/nachsorgeempfehlungen/krebsfrueherkennung_in_der_nachsorge/index_ger.html, zuletzt aufgerufen am 28.04.2025

- Kleinerman 2009 Kleinerman RA. Radiation-sensitive genetically susceptible pediatric sub-populations. *Pediatric Radiology*. 2009 2009/02/01; 39(1):27-31, doi: 10.1007/s00247-008-1015-6
- Kojimahara et al. 2020 Kojimahara N, Yoshitake T, Ono K, Kai M, Bynes G, Schüz J, Cardis E, Kesminiene A. Computed tomography of the head and the risk of brain tumours during childhood and adolescence: results from a case-control study in Japan. *J Radiol Prot*. 2020 Aug 6, doi: 10.1088/1361-6498/abacff, Epub 20200806
- Konrad et al. 2019 Konrad R, Zhang W, Bjarndottir M, Proano R. Key considerations when using health insurance claims data in advanced data analyses: an experience report. *Health Syst (Basingstoke)*. 2019 Mar 1;9(4):317-25, doi: 10.1080/20476965.2019.1581433, Epub 2019/03/01
- Kopp et al. 2020 Kopp M, Loewe T, Wuest W, Brand M, Wetzl M, Nitsch W, Schmidt D, Beck M, Schmidt B, Uder M, May M. Individual Calculation of Effective Dose and Risk of Malignancy Based on Monte Carlo Simulations after Whole Body Computed Tomography. *Sci Rep-Uk*. 2020 2020/06/11;10(1):9475, doi: 10.1038/s41598-020-66366-2
- Kratz et al. 2017 Kratz CP, Achatz MI, Brugières L, Frebourg T, Garber JE, Greer MC, Hansford JR, Janeway KA, Kohlmann WK, McGee R, Mullighan CG, Onel K, Pajtler KW, Pfister SM, Savage SA, Schiffman JD, Schneider KA, Strong LC, Evans DGR, Wasserman JD, Villani A, Malkin D. Cancer Screening Recommendations for Individuals with Li-Fraumeni Syndrome. *Clin Cancer Res*. 2017 Jun 1;23(11):e38-e45, doi: 10.1158/1078-0432.Ccr-17-0408
- Krille et al. 2015 Krille L, Dreger S, Schindel R, Albrecht T, Asmussen M, Barkhausen J, Berthold JD, Chavan A, Claussen C, Forsting M, Gianicolo EAL, Jablonka K, Jahnke A, Langer M, Laniado M, Lotz J, Mentzel HJ, Queißer-Wahrendorf A, Rompel O, Schlick I, Schneider K, Schumacher M, Seidenbusch M, Spix C, Spors B, Staatz G, Vogl T, Wagner J, Weisser G, Zeeb H, Blettner M. Risk of cancer incidence before the age of 15 years after exposure to ionising radiation from computed tomography: results from a German cohort study. *Radiat Environ Biophys*. 2015 Mar;54(1):1-12, doi: 10.1007/s00411-014-0580-3, Epub 2015/01/09
- Kulkarni et al. 2016 Kulkarni A, Hsu HH, Ou P, Kutty S. Computed Tomography in Congenital Heart Disease: Clinical Applications and Technical Considerations. *Echocardiography*. 2016;33(4):629-40, doi: <https://doi.org/10.1111/echo.13147>

- Kwan et al. 2022 Kwan ML, Miglioretti DL, Bowles EJA, Weinmann S, Greenlee RT, Stout NK, Rahm AK, Alber SA, Pequeno P, Moy LM, Stewart C, Fong C, Jenkins CL, Kohnhorst D, Luce C, Mor JM, Munneke JR, Prado Y, Buth G, Cheng SY, Deosaransingh KA, Francisco M, Lakoma M, Martinez YT, Theis MK, Marlow EC, Kushi LH, Duncan JR, Bolch WE, Pole JD, Smith-Bindman R. Quantifying cancer risk from exposures to medical imaging in the Risk of Pediatric and Adolescent Cancer Associated with Medical Imaging (RIC) Study: research methods and cohort profile. *Cancer Causes Control*. 2022 May;33(5):711-26, doi: 10.1007/s10552-022-01556-z, Epub 20220202
- Kwon et al. 2016 Kwon D, Hoffman FO, Moroz BE, Simon SL. Bayesian dose-response analysis for epidemiological studies with complex uncertainty in dose estimation. *Stat Med*. 2016 Feb 10;35(3):399-423, doi: 10.1002/sim.6635, Epub 20150913
- Lecarpentier et al. 2011 Lecarpentier J, Noguès C, Mouret-Fourme E, Stoppa-Lyonnet D, Lasset C, Caron O, Fricker JP, Gladieff L, Faivre L, Sobol H, Gesta P, Frenay M, Luporsi E, Coupier I, Lidereau R, Andrieu N. Variation in breast cancer risk with mutation position, smoking, alcohol, and chest X-ray history, in the French National BRCA1/2 carrier cohort (GENEPSO). *Breast Cancer Res Treat*. 2011 Dec;130(3):927-38, doi: 10.1007/s10549-011-1655-3, Epub 20110715
- Lee et al. 2015 Lee C, Kim KP, Bolch WE, Moroz BE, Folio L. NCICT: a computational solution to estimate organ doses for pediatric and adult patients undergoing CT scans. *J Radiol Prot*. 2015 Dec;35(4):891-909, doi: 10.1088/0952-4746/35/4/891, Epub 20151126
- Lee et al. 2019 Lee C, Journy N, Moroz BE, Little M, Harbron R, McHugh K, Pearce M, Berrington de Gonzalez A. ORGAN DOSE ESTIMATION ACCOUNTING FOR UNCERTAINTY FOR PEDIATRIC AND YOUNG ADULT CT SCANS IN THE UNITED KINGDOM. *Radiat Prot Dosimetry*. 2019 Jul 1;184(1):44-53, doi: 10.1093/rpd/ncy184
- Lee et al. 2022 Lee C, Yeom YS, Folio L. CT organ dose calculator size adaptive for pediatric and adult patients. *Biomed Phys Eng Express*. 2022 Oct 19;8(6), doi: 10.1088/2057-1976/ac9845, Epub 20221019
- Lee et al. 2024 Lee C, Moroz B, Thome C, Gaudreau K, Emami P, Little MP. Reconstruction of organ doses for patients undergoing computed tomography examinations in Canada 1992–2019. *Radiation Protection Dosimetry*. 2024;200(4):379-86, doi: 10.1093/rpd/ncad315

- Lindor et al. 2008 Lindor NM, McMaster ML, Lindor CJ, Greene MH. Concise Handbook of Familial Cancer Susceptibility Syndromes - Second Edition. JNCI Monographs. 2008;2008(38):3-93, doi: 10.1093/jncimonographs/lgn001
- Little et al. 2022a Little MP, Brenner AV, Grant EJ, Sugiyama H, Preston DL, Sakata R, Cologne J, Velazquez-Kronen R, Utada M, Mabuchi K, Ozasa K, Olson JD, Dugan GO, Pazzaglia S, Cline JM, Applegate KE. Age effects on radiation response: summary of a recent symposium and future perspectives. Int J Radiat Biol. 2022a;98(11):1673-83, doi: 10.1080/09553002.2022.2063962, Epub 20220502
- Little et al. 2022b Little MP, Wakeford R, Bouffler SD, Abalo K, Hauptmann M, Hamada N, Kendall GM. Review of the risk of cancer following low and moderate doses of sparsely ionising radiation received in early life in groups with individually estimated doses. Environ Int. 2022b Jan 15;159:106983, doi: 10.1016/j.envint.2021.106983, Epub 2021/12/28
- Little et al. 2023 Little MP, Wakeford R, Zablotska LB, Borrego D, Griffin KT, Allodji RS, de Vathaire F, Lee C, Brenner AV, Miller JS, Campbell D, Pearce MS, Sadetzki S, Doody MM, Holmberg E, Lundell M, French B, Adams MJ, Berrington de González A, Linet MS. Radiation exposure and leukaemia risk among cohorts of persons exposed to low and moderate doses of external ionising radiation in childhood. Br J Cancer. 2023 Oct;129(7):1152-65, doi: 10.1038/s41416-023-02387-8, Epub 20230818
- Little et al. 2024a Little MP, Bazyka D, Berrington de Gonzalez A, Brenner AV, Chumak VV, Cullings HM, Daniels RD, French B, Grant E, Hamada N, Hauptmann M, Kendall GM, Laurier D, Lee C, Lee WJ, Linet MS, Mabuchi K, Morton LM, Muirhead CR, Preston DL, Rajaraman P, Richardson DB, Sakata R, Samet JM, Simon SL, Sugiyama H, Wakeford R, Zablotska LB. A Historical Survey of Key Epidemiological Studies of Ionizing Radiation Exposure. Radiat Res. 2024a Aug 1;202(2):432-87, doi: 10.1667/rade-24-00021.1
- Little et al. 2024b Little MP, Eidemüller M, Kaiser JC, Apostoaei AI. Minimum latency effects for cancer associated with exposures to radiation or other carcinogens. Br J Cancer. 2024b Mar;130(5):819-29, doi: 10.1038/s41416-023-02544-z, Epub 20240111
- Marlow et al. 2023 Marlow EC, Ducore JM, Kwan ML, Bowles EJA, Greenlee RT, Pole JD, Rahm AK, Stout NK, Weinmann S, Smith-Bindman R, Miglioretti DL. Medical imaging utilization and associated radiation exposure in children with down syndrome. PLoS One. 2023;18(9):e0289957, doi: 10.1371/journal.pone.0289957, Epub 20230906

- Mathews et al. 2013 Mathews JD, Forsythe AV, Brady Z, Butler MW, Goergen SK, Byrnes GB, Giles GG, Wallace AB, Anderson PR, Guiver TA, McGale P, Cain TM, Dowty JG, Bickerstaffe AC, Darby SC. Cancer risk in 680,000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. *BMJ*. 2013 May 21;346:f2360, doi: 10.1136/bmj.f2360, Epub 2013/05/23
- Mese et al. 2024 Mese I, Altintas Mese C, Demirsoy U, Anik Y. Innovative advances in pediatric radiology: computed tomography reconstruction techniques, photon-counting detector computed tomography, and beyond. *Pediatr Radiol*. 2024 Jan;54(1):1-11, doi: 10.1007/s00247-023-05823-2, Epub 2023/12/02
- Meulepas et al. 2016 Meulepas JM, Ronckers CM, Merks J, Weijerman ME, Lubin JH, Hauptmann M. Confounding of the association between radiation exposure from CT scans and risk of leukemia and brain tumors by cancer susceptibility syndromes. *J Radiol Prot*. 2016 Dec; 36(4):953-74, doi: 10.1088/0952-4746/36/4/953, Epub 20161128
- Meulepas et al. 2017 Meulepas JM, Smets AMJB, Nievelstein RAJ, Gradowska P, Verbeke J, Holscher HC, Rutten MJCM, Kieft M, Ronckers CM, Hauptmann M. Trends and patterns of computed tomography scan use among children in The Netherlands: 1990-2012. *European Radiology*. 2017;27:2426-33, doi: 10.1007/s00330-016-4566-1
- Meulepas et al. 2018 Meulepas JM, , Hauptmann M, , Lubin JH, , Shuryak I, , Brenner DJ, . 2018. Is there Unmeasured Indication Bias in Radiation-Related Cancer Risk Estimates from Studies of Computed Tomography? In. S. 128-35
- Miglioretti et al. 2013 Miglioretti DL, Johnson E, Williams A, Greenlee RT, Weinmann S, Solberg LI, Feigelson HS, Roblin D, Flynn MJ, Vanneman N, Smith-Bindman R. The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. *JAMA Pediatr*. 2013 Aug 1;167(8):700-7, doi: 10.1001/jama.pediatrics.2013.311
- Mokubangele et al. 2022 Mokubangele C, Ebongue A, Bongue D, Ndontchueng M, Moifo B. Evaluation of the Fetal-Maternal Radiation Doses in CT-Pelvimetry and Estimation of the Fetal Radiation Risks in 03 Radiology Departments in Douala-Cameroon. *Open Journal of Radiology*. 2022 (12):113-24, doi: doi: 10.4236/ojrad.2022.123013
- Morgan et al. 2018 Morgan RL, Whaley P, Thayer KA, Schünemann HJ. Identifying the PECO: A framework for formulating good questions to explore the association of environmental and other exposures with health outcomes. *Environ Int*. 2018 Dec;121(Pt 1):1027-31, doi: 10.1016/j.envint.2018.07.015, Epub 20180827

- Nekolla et al. 2017 Nekolla EA, Schegerer AA, Griebel J, Brix G. Häufigkeit und Dosis diagnostischer und interventioneller Röntgenanwendungen. *Der Radiologe*. 2017 2017/07/01;57(7):555-62, doi: <https://doi.org/10.1007/s00117-017-0242-y>
- NICE 2023 National Institute for Health and Care Excellence (NICE). Head injury: assessment and early management. <https://www.nice.org.uk/guidance/ng232/resources/head-injury-assessment-and-early-management-pdf-66143892774085>, zuletzt aufgerufen am 10.04.2025
- Nikkilä et al. 2018 Nikkilä A, Raitanen J, Lohi O, Auvinen A. Radiation exposure from computerized tomography and risk of childhood leukemia: Finnish register-based case-control study of childhood leukemia (FRECCLE). *Haematologica*. 2018 Nov;103(11):1873-80, doi: [10.3324/haematol.2018.187716](https://doi.org/10.3324/haematol.2018.187716), Epub 20180705
- NRDR NRDR. CT Standardized Dose Index Report. <https://nrdrsupport.acr.org/support/solutions/articles/11000044407>, zuletzt aufgerufen am 11.04.2025
- OECD OECD. OECD Data Explorer - Archive. [https://data-explorer.oecd.org/vis?tenant=archive&df\[ds\]=DisseminateArchiveDMZ&df\[id\]=DF_HEALTH_REAC&df\[ag\]=OECD&dq=IPI NSCAN.NOMBRENB.DEU&pd=2008%2C2021&to\[TIME_PERIOD\]=false&vw=tb](https://data-explorer.oecd.org/vis?tenant=archive&df[ds]=DisseminateArchiveDMZ&df[id]=DF_HEALTH_REAC&df[ag]=OECD&dq=IPI NSCAN.NOMBRENB.DEU&pd=2008%2C2021&to[TIME_PERIOD]=false&vw=tb), zuletzt aufgerufen am 11.04.2025
- Ohuma et al. 2023 Ohuma EO, Moller AB, Bradley E, Chakwera S, Hussain-Alkhateeb L, Lewin A, Okwaraji YB, Mahanani WR, Johansson EW, Lavin T, Fernandez DE, Domínguez GG, de Costa A, Cresswell JA, Krasevec J, Lawn JE, Blencowe H, Requejo J, Moran AC. National, regional, and global estimates of preterm birth in 2020, with trends from 2010: a systematic analysis. *Lancet*. 2023 Oct 7;402(10409):1261-71, doi: [10.1016/s0140-6736\(23\)00878-4](https://doi.org/10.1016/s0140-6736(23)00878-4)
- Osei and Faulkner 1999 Osei EK, Faulkner K. Fetal doses from radiological examinations. *Br J Radiol*. 1999 Aug;72(860):773-80, doi: [10.1259/bjr.72.860.10624343](https://doi.org/10.1259/bjr.72.860.10624343)
- Osei et al. 2003 Osei EK, Darko JB, Faulkner K, Kotre CJ. Software for the estimation of foetal radiation dose to patients and staff in diagnostic radiology. *J Radiol Prot*. 2003 Jun;23(2):183-94, doi: [10.1088/0952-4746/23/2/305](https://doi.org/10.1088/0952-4746/23/2/305)
- Osei und Darko 2013 Osei EK, Darko J. Foetal radiation dose and risk from diagnostic radiology procedures: a multinational study. *ISRN Radiol*. 2013;2013:318425, doi: [10.5402/2013/318425](https://doi.org/10.5402/2013/318425), Epub 20120925

- Osmond et al. 2010 Osmond MH, Klassen TP, Wells GA, Correll R, Jarvis A, Joubert G, Bailey B, Chauvin-Kimoff L, Pusic M, McConnell D, Nijssen-Jordan C, Silver N, Taylor B, Stiell IG. CATCH: a clinical decision rule for the use of computed tomography in children with minor head injury. *Cmaj*. 2010 Mar 9;182(4):341-8, doi: 10.1503/cmaj.091421, Epub 20100208
- Park et al. 2018 Park MJ, Kim SS, Park GY, Hong HS. Radiation exposure of very-low-birth-weight infants in neonatal intensive care units in Korea. *Radioprotection*. 2018;53(4):279-86
- Paulo et al. 2020 Paulo G, Damilakis J, Tsapaki V, Schegerer AA, Repussard J, Jaschke W, Frija G, Hierath M, Clark J, European Society of R. Diagnostic Reference Levels based on clinical indications in computed tomography: a literature review. *Insights into Imaging*. 2020 2020/08/17;11(1):96, doi: 10.1186/s13244-020-00899-y
- Pearce et al. 2012a Pearce MS, Salotti JA, Howe NL, McHugh K, Kim KP, Lee C, Craft AW, Berrington de González A, Parker L. CT Scans in Young People in Great Britain: Temporal and Descriptive Patterns, 1993-2002. *Radiol Res Pract*. 2012a;2012:594278, doi: 10.1155/2012/594278, Epub 20120626
- Pearce et al. 2012b Pearce MS, Salotti JA, Little MP, McHugh K, Lee C, Kim KP, Howe NL, Ronckers CM, Rajaraman P, Sir Craft AW, Parker L, Berrington de Gonzalez A. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet*. 2012b Aug 4;380(9840):499-505, doi: 10.1016/S0140-6736(12)60815-0, Epub 2012/06/12
- Perin et al. 2022 Perin J, Mulick A, Yeung D, Villavicencio F, Lopez G, Strong KL, Prieto-Merino D, Cousens S, Black RE, Liu L. Global, regional, and national causes of under-5 mortality in 2000-19: an updated systematic analysis with implications for the Sustainable Development Goals. *Lancet Child Adolesc Health*. 2022 Feb;6(2):106-15, doi: 10.1016/s2352-4642(21)00311-4, Epub 20211117
- Peuchot and Libshitz 1987 Peuchot M, Libshitz HI. Pulmonary metastatic disease: radiologic-surgical correlation. *Radiology*. 1987 1987/09/01;164(3):719-22, doi: 10.1148/radiology.164.3.3615867
- Pijpe et al. 2012 Pijpe A, Andrieu N, Easton DF, Kesminiene A, Cardis E, Noguès C, Gauthier-Villars M, Lasset C, Fricker J-P, Peock S, Frost D, Evans DG, Eeles RA, Paterson J, Manders P, van Asperen CJ, Ausems MGEM, Meijers-Heijboer H, Thierry-Chef I, Hauptmann M, Goldgar D, Rookus MA, van Leeuwen FE. Exposure to diagnostic radiation and risk of breast cancer among carriers of BRCA1/2 mutations: retrospective cohort study (GENE-RAD-RISK). *BMJ : British Medical Journal*. 2012;345:e5660, doi: 10.1136/bmj.e5660

- Pokora et al. 2016 Pokora R, Krille L, Dreger S, Lee C, Günster C, Zeeb H. 2016. Computed tomography in Germany - Results and insights from a cohort study and health insurance data (AOK). In. S. 721-8
- Pola et al. 2018 Pola A, Corbella D, Righini A, Torresin A, Colombo PE, Vismara L, Trombetta L, Maddalo M, Introini MV, Tinelli D, Strohmenger L, Garattini G, Munari A, Triulzi F. Computed tomography use in a large Italian region: trend analysis 2004-2014 of emergency and outpatient CT examinations in children and adults. *Eur Radiol.* 2018 Jun;28(6):2308-18, doi: 10.1007/s00330-017-5225-x, Epub 20180109
- Porter 2016 Porter CC. Germ line mutations associated with leukemias. *Hematology Am Soc Hematol Educ Program.* 2016 Dec 2;2016(1):302-8, doi: 10.1182/asheducation-2016.1.302, Epub 2016/12/04
- Qu et al. 2023 Qu S, Liu H, Xie T, Giger ML, Quan G, Zaidi H. Patient-specific fetal radiation dosimetry for pregnant patients undergoing abdominal and pelvic CT imaging. *Med Phys.* 2023 Jun;50(6):3801-15, doi: 10.1002/mp.16304, Epub 20230225
- Radiopaedia 2020 Radiopaedia (Radiopaedia). CHALICE rule. <https://radiopaedia.org/articles/chalice-rule>, zuletzt aufgerufen am 10.04.2025
- Raimondi and Warin-Fresse 2016 Raimondi F, Warin-Fresse K. Computed tomography imaging in children with congenital heart disease: Indications and radiation dose optimization. *Arch Cardiovasc Dis.* 2016 Feb;109(2):150-7, doi: 10.1016/j.acvd.2015.11.003, Epub 20160115
- Renz et al. 2025 Renz D, Werncke T, Sorantin E, Deng M, Gill S, Hauptmann M, Klein D, Stamm G, Wollschläger D, Mentzel H Hrsg. ROFO-FORTSCHR RONTG., 2025
- Renz et al. 2022 Renz DM, Herrmann K-H, Kraemer M, Boettcher J, Waginger M, Krueger P-C, Pfeil A, Streitparth F, Kentouche K, Gruhn B, Mainz JG, Stenzel M, Teichgräber UK, Reichenbach JR, Mentzel H-J. Ultrashort echo time MRI of the lung in children and adolescents: comparison with non-enhanced computed tomography and standard post-contrast T1w MRI sequences. *European Radiology.* 2022 2022/03/01;32(3):1833-42, doi: 10.1007/s00330-021-08236-7
- Richardson and Ashmore 2005 Richardson DB, Ashmore JP. Investigating time patterns of variation in radiation cancer associations. *Occup Environ Med.* 2005 Aug;62(8):551-8, doi: 10.1136/oem.2004.017368

- RKI and GEKID 2023 Robert Koch-Institut (Hrsg) und die Gesellschaft der epidemiologischen Krebsregister in Deutschland e.V. (Hrsg) (RKI, GEKID). Krebs in Deutschland für 2019/2020. https://www.krebsdaten.de/Krebs/DE/Content/Publikationen/Krebs_in_Deutschland/krebs_in_deutschland_2023.pdf, zuletzt aufgerufen am 06.03.2024
- Roizen and Patterson 2003 Roizen NJ, Patterson D. Down's syndrome. *Lancet*. 2003 Apr 12;361(9365):1281-9, doi: 10.1016/s0140-6736(03)12987-x
- Romanyukha et al. 2016 Romanyukha A, Folio L, Lamart S, Simon SL, Lee C. Body size-specific effective dose conversion coefficients for CT scans *Radiat Prot Dosimetry*. 2016 Dec;172(4):428-37, doi: 10.1093/rpd/ncv511, Epub 20160110
- Ronckers et al. 2005 Ronckers CM, Erdmann CA, Land CE. Radiation and breast cancer: a review of current evidence. *Breast Cancer Res*. 2005;7(1):21-32, doi: 10.1186/bcr970, Epub 20041123
- Ronckers et al. 2025 (Ronckers CM, Spix C, Grabow D, Erdmann F). German Childhood Cancer Registry - Annual Report 2022 (1980-2021). https://www.kinderkrebsregister.de/fileadmin/kliniken/dkkr/pdf/jb/jb2022/JB_2022_final.pdf, zuletzt aufgerufen am 03.06.2025
- Ryan et al. 2020 Ryan ME, Pruthi S, Desai NK, Falcone RA, Jr., Glenn OA, Joseph MM, Maheshwari M, Marin JR, Mazzola C, Milla SS, Mirsky DM, Myseros JS, Niogi SN, Partap S, Radhakrishnan R, Robertson RL, Soares BP, Udayasankar UK, Whitehead MT, Wright JN, Karmazyn B. ACR Appropriateness Criteria® Head Trauma-Child. *J Am Coll Radiol*. 2020 May;17(5s):S125-s37, doi: 10.1016/j.jacr.2020.01.026
- Saida 2017 Saida S. Predispositions to Leukemia in Down Syndrome and Other Hereditary Disorders. *Curr Treat Options Oncol*. 2017 Jul;18(7):41, doi: 10.1007/s11864-017-0485-x
- Schubauer-Berigan et al. 2020 Schubauer-Berigan MK, Berrington de Gonzalez A, Cardis E, Laurier D, Lubin JH, Hauptmann M, Richardson DB. Evaluation of Confounding and Selection Bias in Epidemiological Studies of Populations Exposed to Low-Dose, High-Energy Photon Radiation. *J Natl Cancer Inst Monogr*. 2020 Jul 1;2020(56):133-53, doi: 10.1093/jncimonographs/lgaa008, Epub 2020/07/14
- Schüz and Erdmann 2016 Schüz J, Erdmann F. Environmental Exposure and Risk of Childhood Leukemia: An Overview. *Archives of Medical Research*. 2016 2016/11/01;47(8):607-14, doi: <https://doi.org/10.1016/j.arcmed.2016.11.017>

- Seifi et al. 2022 Seifi A, Jafari S, Mirmoeeni S, Azari Jafari A, Naderi N, Safdarpour A, Seifi S. Trends in Inpatient Utilization of Head Computerized Tomography Scans in the United States: A Brief Cross-Sectional Study. *Cureus*. 2022 Jun;14(6):e26018, doi: 10.7759/cureus.26018, Epub 20220616
- Shimada 2021 Shimada A. Profile of down syndrome-associated malignancies: Epidemiology, clinical features and therapeutic aspects. *Pediatric Hematology Oncology Journal*. 2021 2021/06/01;6(2):63-72, doi: <https://doi.org/10.1016/j.phoj.2021.01.001>
- Simon et al. 2014a Simon SL, Hoffman FO, Hofer E. The Two-Dimensional Monte Carlo: A New Methodologic Paradigm for Dose Reconstruction for Epidemiological Studies. *Radiation Research*. 2014a;183(1): 27-41, 15
- Simon et al. 2014b Simon SL, Hoffman FO, Hofer E. 2014b. The Two-Dimensional Monte Carlo: A New Methodologic Paradigm for Dose Reconstruction for Epidemiological Studies. In. S. 27-41
- Smith-Bindman et al. 2025a Smith-Bindman R, Alber SA, Kwan ML, Pequeno P, Bolch WE, Bowles EJA, Greenlee RT, Stout NK, Weinmann S, Moy LM, Stewart C, Francisco M, Kofler C, Duncan JR, Ducore J, Mahendra M, Pole JD, Miglioretti DL. Medical Imaging and Pediatric and Adolescent Hematologic Cancer Risk. *N Engl J Med*. 2025a Sep 17, doi: 10.1056/NEJMoa2502098, Epub 20250917
- Smith-Bindman et al. 2025b Smith-Bindman R, Chu PW, Azman Firdaus H, Stewart C, Malekheadayat M, Alber S, Bolch WE, Mahendra M, Berrington de González A, Miglioretti DL. Projected Lifetime Cancer Risks From Current Computed Tomography Imaging. *JAMA Intern Med*. 2025b Apr 14, doi: 10.1001/jamainternmed.2025.0505, Epub 20250414
- Smoll et al. 2023 Smoll NR, Brady Z, Scurrah KJ, Lee C, Berrington de González A, Mathews JD. Computed tomography scan radiation and brain cancer incidence. *Neuro Oncol*. 2023 Jul 6;25(7):1368-76, doi: 10.1093/neuonc/noad012
- SSK 1989 Strahlenschutzkommission (SSK). Wirkungen nach pränataler Bestrahlung. Veröffentlichungen der Strahlenschutzkommission, Band 2, Gustav-Fischer Verlag, Stuttgart, 1989, ISBN 3-437-11293-7
- SSK 2022 Strahlenschutzkommission. Bildgebende Diagnostik bei Kindern. Empfehlung der Strahlenschutzkommission, verabschiedet in der 321. Sitzung der Strahlenschutzkommission am 22./23. September 2022. https://www.ssk.de/SharedDocs/Beratungsergebnisse/DE/2022/2022-09-22_Empf_Bildgebende_Diagnostik_Kind.html

- SSK 2025a Strahlenschutzkommission. Effekte nach pränataler Strahlenexposition. Empfehlung der Strahlenschutzkommission, verabschiedet in der 339. Sitzung der SSK am 27./28. Oktober 2025
- SSK 2025b Strahlenschutzkommission. Orientierungswerte für die Patientenexposition bei röntgendiagnostischen Anwendungen. Empfehlung der Strahlenschutzkommission, verabschiedet in der 337. Sitzung der Strahlenschutzkommission am 29.04.2025. <https://nbn-resolving.org/urn:nbn:de:101:1-2509101542331.194137005442>. Bekanntmachung im BAnz AT 27.10.2025 B1
- Steliarova-Foucher et al. 2017 Steliarova-Foucher E, Colombet M, Ries LAG, Moreno F, Dolya A, Bray F, Hesselting P, Shin HY, Stiller CA. International incidence of childhood cancer, 2001-10: a population-based registry study. *Lancet Oncol.* 2017 Jun;18(6):719-31, doi: 10.1016/s1470-2045(17)30186-9, Epub 2017/04/16
- Stewart et al. 2025 Stewart C, Alber S, Mahendra M, Kofler C, Tran T, Domal S, Bowles EJA, Weinmann S, Greenlee RT, Stout NK, Pequeno P, Moy LM, Duncan JR, Pole JD, Bolch WE, Kwan ML, Miglioretti DL, Smith-Bindman R. Quantifying and Contextualizing Radiation Doses in Common Pediatric Medical Imaging Examinations. *J Pediatr Clin Pract.* 2025 Sep;17:200166, doi: 10.1016/j.jpdc.2025.200166, Epub 20250723
- Strauss et al. 2019 Strauss KJ, Somasundaram E, Sengupta D, Marin JR, Brady SL. Radiation Dose for Pediatric CT: Comparison of Pediatric versus Adult Imaging Facilities. *Radiology.* 2019 Apr;291(1):158-67, doi: 10.1148/radiol.2019181753, Epub 20190205
- Streffer et al. 2003 Streffer C, Shore R, Konermann G, Meadows A, Uma Devi P, Preston Withers J, Holm LE, Stather J, Mabuchi K, H R. Biological effects after prenatal irradiation (embryo and fetus). A report of the International Commission on Radiological Protection. *Ann ICRP.* 2003;33(1-2):5-206
- Su et al. 2023 Su YT, Chen YS, Yeh LR, Chen SW, Tsai YC, Wu CY, Yang YN, Tey SL, Lin CH. Unnecessary radiation exposure during diagnostic radiography in infants in a neonatal intensive care unit: a retrospective cohort study. *Eur J Pediatr.* 2023 Jan;182(1):343-52, doi: 10.1007/s00431-022-04695-2, Epub 20221110
- Tabori et al. 2017 Tabori U, Hansford JR, Achatz MI, Kratz CP, Plon SE, Frebourg T, Brugières L. Clinical Management and Tumor Surveillance Recommendations of Inherited Mismatch Repair Deficiency in Childhood. *Clin Cancer Res.* 2017 Jun 1;23(11):e32-e7, doi: 10.1158/1078-0432.Ccr-17-0574

- Thierry-Chef et al. 2021 Thierry-Chef I, Ferro G, Le Cornet L, Dabin J, Istad TS, Jahnén A, Lee C, Maccia C, Malchair F, Olerud HM, Harbron RW, Figuerola J, Hermen J, Moissonnier M, Bernier MO, Bosch de Basea MB, Byrnes G, Cardis E, Hauptmann M, Journy N, Kesminiene A, Meulepas JM, Pokora R, Simon SL. Dose Estimation for the European Epidemiological Study on Pediatric Computed Tomography (EPI-CT). *Radiat Res.* 2021 Jul 1;196(1):74-99, doi: 10.1667/rade-20-00231.1
- Toscan et al. 2024 Toscan M, de Araujo BF, Martini JC, Ravazio R, de Souza VC. Our estimates of neonatal radiation exposure fall short of reality. *Eur J Pediatr.* 2024 Apr;183(4):1911-6, doi: 10.1007/s00431-024-05466-x, Epub 2024/02/09
- Travis et al. 2003 Travis LB, Hauptmann M, Gaul LK, Storm HH, Goldman MB, Nyberg U, Berger E, Janower ML, Hall P, Monson RR, Holm LE, Land CE, Schottenfeld D, Boice JD, Jr., Andersson M. Site-specific cancer incidence and mortality after cerebral angiography with radioactive thorotrast. *Radiat Res.* 2003 Dec;160(6):691-706, doi: 10.1667/rr3095, Epub 2003/12/04
- Tsapaki et al. 2021 Tsapaki V, Damilakis J, Paulo G, Schegerer AA, Repussard J, Jaschke W, Frija G. CT diagnostic reference levels based on clinical indications: results of a large-scale European survey. *Eur Radiol.* 2021 Jul;31(7):4459-69, doi: 10.1007/s00330-020-07652-5, Epub 20210115
- UNSCEAR 1986 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Genetic and somatic effects of ionizing radiation , UNSCEAR 1986, Report to the General Assembly with Scientific Annexes. United Nations, New York, 1986, ISBN 92-1-142123-3
- UNSCEAR 2012 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources, Effects and Risks of Ionizing Radiation, UNSCEAR 2012 Report, Annex B. Uncertainties in Risk Estimates for Radiation-Induced Cancer. United Nations, New York, 2012, ISBN 978-92-1-142307-5
- UNSCEAR 2013 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources, Effects and Risks of Ionizing Radiation, UNSCEAR 2013 Report, Volume II: Scientific Annex B. Effects of radiation exposure of children. United Nations, New York, 2013, ISBN 978-92-1-142293-1
- UNSCEAR 2017 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources, Effects and Risks of Ionizing Radiation, UNSCEAR 2017 Report to the General Assembly with Scientific Annexes. Annex A: Principles and Criteria for Ensuring the Quality of the Committee's Reviews of Epidemiological Studies of Radiation Exposure. United Nations, Vienna, 2017, ISBN 978-92-1-142322-8

- Villani et al. 2011 Villani A, Tabori U, Schiffman J, Shlien A, Beyene J, Druker H, Novokmet A, Finlay J, Malkin D. Biochemical and imaging surveillance in germline TP53 mutation carriers with Li-Fraumeni syndrome: a prospective observational study. *Lancet Oncol.* 2011 Jun;12(6):559-67, doi: 10.1016/s1470-2045(11)70119-x, Epub 20110519
- Walsh et al. 2014 Walsh L, Shore R, Auvinen A, Jung T, Wakeford R. Risks from CT scans—what do recent studies tell us? *Journal of Radiological Protection.* 2014 2014/03/04;34(1):E1, doi: 10.1088/0952-4746/34/1/E1
- Walsh et al. 2017 Walsh MF, Chang VY, Kohlmann WK, Scott HS, Cunniff C, Bourdeaut F, Molenaar JJ, Porter CC, Sandlund JT, Plon SE, Wang LL, Savage SA. Recommendations for Childhood Cancer Screening and Surveillance in DNA Repair Disorders. *Clin Cancer Res.* 2017 Jun 1;23(11):e23-e31, doi: 10.1158/1078-0432.Ccr-17-0465
- Wang et al. 2023 Wang WH, Sung CY, Wang SC, Shao YJ. Risks of leukemia, intracranial tumours and lymphomas in childhood and early adulthood after pediatric radiation exposure from computed tomography. *Cmaj.* 2023 Apr 24;195(16):E575-e83, doi: 10.1503/cmaj.221303
- Wechsler et al. 2002 Wechsler J, Greene M, McDevitt MA, Anastasi J, Karp JE, Le Beau MM, Crispino JD. Acquired mutations in GATA1 in the megakaryoblastic leukemia of Down syndrome. *Nat Genet.* 2002 Sep;32(1):148-52, doi: 10.1038/ng955, Epub 20020812
- Weiße et al. 2025 Weiß D, Beeres M, Rochwalsky U, Vogl TJ, Schlößer R. Radiation exposure and estimated risk of radiation-induced cancer from thoracic and abdominal radiographs in 1307 neonates. *Eur Radiol.* 2025 Jan;35(1):297-308, doi: 10.1007/s00330-024-10942-x, Epub 20240716
- Wollschläger et al. 2023 Wollschläger D, Jahnen A, Hermen J, Giussani A, Stamm G, Borowski M, Huisinga C, Mentzel HJ, Braun J, Sigmund G, Wagner J, Adolph J, Gunschera J, Koerber F, Schiefer A, Müller B, Lenzen H, Doering T, Entz K, Kunze C, Starck P, Staatz G, Mildemberger P, Pokora R. Pediatric computed tomography doses in Germany from 2016 to 2018 based on large-scale data collection. 2023 6;163, doi: 10.1016/j.ejrad.2023.110832
- Wootton-Gorges et al. 2017 Wootton-Gorges SL, Soares BP, Alazraki AL, Anupindi SA, Blount JP, Booth TN, Dempsey ME, Falcone RA, Jr., Hayes LL, Kulkarni AV, Partap S, Rigsby CK, Ryan ME, Safdar NM, Trout AT, Widmann RF, Karmazyn BK, Palasis S. ACR Appropriateness Criteria(®) Suspected Physical Abuse-Child. *J Am Coll Radiol.* 2017 May;14(5s):S338-s49, doi: 10.1016/j.jacr.2017.01.036

- Yang et al. 2022 Yang S, Shan F, Shi Y, Liu T, Wang Q, Zhang H, Zhang X, Yang S, Zhang Z. Sensitivity and specificity of magnetic resonance imaging in routine diagnosis of pulmonary lesions: a comparison with computed tomography. *J Thorac Dis.* 2022 Oct;14(10):3762-72, doi: 10.21037/jtd-22-370
- Zeeb et al. 2024 Zeeb H, Gill S, Dreger S. Erweiterte Erhebung der medizinischen Strahlenexposition in der NAKO-Gesundheitsstudie und Verknüpfung mit Sekundärdaten. Vorhaben 3620S42270. Ressortforschungsberichte zum Strahlenschutz. BfS-RESFOR-239/24. 2024
- Zhang et al. 2015 Zhang J, Walsh MF, Wu G, Edmonson MN, Gruber TA, Easton J, Hedges D, Ma X, Zhou X, Yergeau DA, Wilkinson MR, Vadodaria B, Chen X, McGee RB, Hines-Dowell S, Nuccio R, Quinn E, Shurtleff SA, Rusch M, Patel A, Becksfort JB, Wang S, Weaver MS, Ding L, Mardis ER, Wilson RK, Gajjar A, Ellison DW, Pappo AS, Pui CH, Nichols KE, Downing JR. Germline Mutations in Predisposition Genes in Pediatric Cancer. *N Engl J Med.* 2015 Dec 10;373(24):2336-46, doi: 10.1056/NEJMoa1508054, Epub 2015/11/19
- Zhang et al. 2017 Zhang Z, Preston DL, Sokolnikov M, Napier BA, Degteva M, Moroz B, Vostrotin V, Shiskina E, Birchall A, Stram DO. Correction of confidence intervals in excess relative risk models using Monte Carlo dosimetry systems with shared errors. *PLoS One.* 2017;12(4):e0174641, doi: 10.1371/journal.pone.0174641, Epub 20170403

Abbreviations

ALL	Acute lymphocytic leukaemia
AWMF	Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e.V.
BfS	Federal Office for Radiation Protection
BMUKN	Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety
BMUV	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
CLL	Chronic lymphocytic leukaemia
CT	Computed tomography
cCT	cranial computed tomography
CTDI	Computed Tomography Dose Index
DLP	Dose length product
DRG	Diagnosis Related Group
DRW	Diagnostic reference values
EOR	Excess odds ratio
EPI-CT	European Epidemiological Study to Quantify Risks for Paediatric Computerized Tomography
err	Excess risk ratio
ESR	European Society of Radiology
ESPR	European Society of Paediatric Radiology
GPOH	Society of Paediatric Oncology and Haematology
IARC	WHO International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
ICD	International Classification of Diseases
ICD-O	International Classification of Diseases for Oncology
ICCC	International Classification of Childhood Cancer
CI	Confidence interval

LBW	Low birth weight
LNT	Linear no-threshold
LSS	Life Span study
MRI	Magnetic resonance imaging
NAKO	National Cohort
NCICT	National Cancer Institute Dosimetry System for CT
OECD	Organisation for Economic Co-operation and Development
OSCC	Oxford Survey of Childhood Cancers
RIC	Risk of Pediatric and Adolescent Cancer Associated with Medical Imaging
SHT	Trauma of the skull
SOP	Standard Operating Procedure
SPECT/PET-CT	Single Photon Emission Computed Tomography/ Positron Emission Tomography CT scans
SSDE	Size Specific Can Estimate
SSK	Commission on Radiological Protection
TPS	Tumour predisposition syndromes
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
VLBW	Very low birth weight

Glossary of terms

Adverse effect

An adverse effect is an undesirable, detrimental or harmful effect of a measure (e.g. the use of ionising radiation).

Confounding

When investigating the effect of radiation exposure on the risk of disease, confounders are factors that affect both the level of exposure and the risk of disease. Confounders can lead to a statistical association between exposure and disease risk even when exposure has no actual causal effect. Similarly, confounders can mean that exposure is not statistically associated with the risk of disease despite actually having a causal effect.

The extent to which a confounder can influence the assessment of the association between exposure and disease risk depends on how strongly the confounder influences the exposure, how strongly the confounder affects the disease risk, and the prevalence of the confounder.

If the confounder is fundamentally known about and it is possible to collect data on its characteristics, the statistical dose–response analysis can be adjusted so that the confounder does not influence the assessment of the association between exposure and disease risk.

See also: Confounding by indication

Confounding by indication

In studies investigating the effect of medical radiation exposure on the risk of developing disease later in life, the reason for the exposure – that is, its medical indication – can act as a confounding factor. Even prior to exposure, individuals for whom medical radiation exposure is indicated can therefore be systematically distinguished from those who have not been exposed in terms of their risk of the health endpoint considered in the study.

These relationships can also be quantitative, in that people with a medical indication for more frequent or higher levels of radiation exposure may already have a higher risk of developing a disease prior to exposure than those for whom such an indication is less common or who have a medical indication for lower levels of exposure.

See also: Confounding

Dose report

The dose report is a record of a patient's medical radiation exposure.

Dose–response relationship	The dose–response relationship refers to the functional relationship between the dose of an agent and the resulting effect. In the context of radiation, this typically refers to the relationship between a radiation dose and the probability of a biological effect occurring or the severity of that effect (see also LNT model).
DRG statistics	DRG stands for diagnosis-related group. The DRG statistics are hospital statistics based on diagnosis-related groups and constitute a comprehensive annual survey of the services provided by hospitals subject to reporting requirements. A record is made of continuous inpatient treatment in hospital (treatment pathway). Accordingly, the statistics only include inpatient treatment – especially surgical procedures and other forms of treatment.
Echocardiography	Echocardiography is an ultrasound examination of the heart used to assess heart structure, blood flow and pumping function.
Effective dose	The effective dose is the sum of the organ equivalent doses (H_T) in relevant organs and tissues, multiplied by the corresponding tissue weighting factors (w_T) recommended by the ICRP and specified in the Radiation Protection Ordinance. $E = \sum_T w_T \cdot H_T = \sum_T w_T \sum_R w_R \cdot D_{T,R},$ where H_T is the organ equivalent dose in a tissue or organ T, w_T is the tissue weighting factor, and w_R is the radiation weighting factor. The unit of effective dose is $J\ kg^{-1}$. To make it clear that this is a weighted dose, the sievert (Sv) is used as the unit instead of the gray (Gy), as is the case with the equivalent dose.
Longitudinal epidemiological study	A longitudinal epidemiological study analyses the relationship between an exposure and a health endpoint based on data on exposure, endpoint and other relevant variables collected over an extended period of the participants' lives. Longitudinal epidemiological studies can be retrospective or prospective in design. Two examples of study design are the case-control study and the cohort study. See also: Case-control study, cohort study
Excess relative risk (ERR)	Excess relative risk redirects to this page: The excess relative risk (ERR) is the ratio of the risk of an event (e.g. illness or death) in an exposed population to the risk in a non-exposed population, minus 1. The excess relative risk can be estimated in radiation epidemiological studies as the ratio of the event rates in

the two groups minus 1. In the literature, this relationship is often not presented, and the excess relative risk is equated with the event rate ratio reduced by 1.

Excess odds ratio (EOR)

See ERR in SSK glossary:

In the literature, the excess odds ratio (EOR) is sometimes used instead of the ERR; when the prevalence of a condition is low (less than around 10% in a population), the EOR is numerically roughly equivalent to the ERR.

Exclusion period

In a longitudinal epidemiological study, the exclusion period is the period following exposure during which any occurrences of the health endpoint under investigation are not taken into account. This period is therefore not considered to be a period of risk.

The purpose of applying an exclusion period is to prevent reverse causation. The chosen length of the exclusion period is based on considerations regarding the minimum time required for the disease to develop from the point of exposure until it can be diagnosed.

See also: Longitudinal epidemiological study, reverse causation

Case-control study

A case-control study is a longitudinal, observational epidemiological study. In this design, the first step is to identify a group of people who have experienced a relevant health event, such as a cancer diagnosis or death. The resulting individuals constitute the cases. Each case is individually matched to individuals as controls who are equivalent to the corresponding case in terms of key basic characteristics, such as gender and age. Retrospectively, past exposure to one or more risk factors is then reconstructed on an individual basis for both cases and controls. By analysing the collected data, it is possible to quantify the association between exposure and the occurrence of the health event used in the case definition.

See also: Longitudinal epidemiological study

Tissue weighting factor

The tissue weighting factors (w_T) provide an approximate description of the proportion of radiation risk that arises from the irradiation of a tissue or organ T in the context of homogeneous whole-body irradiation, relative to the total risk. The tissue weighting factors represent average values, calculated across people of both sexes and all age groups, and therefore do not refer to the characteristics of individual people. The tissue weighting factors are used to weight the individual organ equivalent doses (H_T) in order to calculate the effective dose (E). These factors (w_T) reflect the varying sensitivity of different organs,

tissues and body parts T to stochastic radiation effects (cancer induction, induction of genetic damage).

Cohort study

A cohort study is a longitudinal, observational epidemiological study. In this design, a group of individuals is first defined as a cohort based on inclusion and exclusion criteria. For the members of this cohort, individual exposure to one or more risk factors is recorded along with other personal characteristics. The cohort is monitored longitudinally over an extended period in order to record any health events that occur – such as a new cancer diagnosis or death – on an individual basis. Analysing the collected data can quantify the link between exposure and the occurrence of health events. Cohort studies can be conducted both prospectively and retrospectively.

See also: Longitudinal epidemiological study

LAR

The lifetime attributable risk (LAR) is the attributable risk (AR) for a health event – such as cancer – calculated over the entire lifespan.

If, over a fixed period, R_1 denotes the risk among those exposed, R_0 the risk among those not exposed, RR the relative risk (R_1/R_0), and ERR the excess relative risk, then the following formula applies:

$$AR = \frac{R_1 - R_0}{R_1} = \frac{RR - 1}{RR} = \frac{ERR}{1 + ERR}$$

The terminology is not consistent. AR is also known as the “attributable fraction among the exposed”. Subject to certain additional conditions, AR is the proportion of the risk of exposed individuals for which the exposure could be responsible. The term “etiologic fraction” is also used to describe this interpretation. Subject to certain conditions, AR is equivalent to the probability that a health event that occurs could be caused by the exposure (“probability of causation”, “assigned share”).

LNT model

Linear no-threshold model. This model describes the assumption made in radiation protection that the incidence of a stochastic effect observed in the medium to high dose range (approximately 0.1 to 5 Gy) can be extrapolated linearly down to zero dose (i.e. without a threshold dose).

Morbidity

Morbidity refers to the frequency with which diseases occur in a population.

Mortality

Mortality refers to the number of deaths occurring in a specific population within a given period.

Operations and Procedure Codes (OPS codes)

Classification of operations, procedures and medical interventions. The primary purpose of OPS codes is to provide a coding system for billing the relevant health insurance funds (both statutory and private). The OPS codes are used for billing in the inpatient sector. For billing in the outpatient sector, which is not covered here, classification is carried out using the Uniform Assessment Standard (EBM) (statutory health insurance funds) or the Fee Schedule for Doctors (GOÄ) (private health insurance funds).

PECO scheme

In the PECO framework, P stands for population, E for exposure, C for comparator and O for outcome. The framework is used to precisely define an epidemiological research question. It can serve as a guide both when planning a study and when determining the search strategy for a systematic literature review.

Polytrauma

Polytrauma refers to life-threatening injuries affecting several organ systems or body regions that occur simultaneously.

Radiography

Radiography (also known as “conventional X-ray”) is an imaging technique that uses X-rays to produce two-dimensional images of objects. In medicine, it was based on film-screen technology until the 1980s, then on the use of digital storage screens. Since the 1990s, it has increasingly been based on the use of digital solid-state detectors.

Reverse causation

The central question underlying a radiation epidemiological study is typically whether radiation exposure is a causal factor in an increased risk of disease. Reverse causation describes a situation in which the disease under investigation has already developed in a study participant prior to exposure but has not yet been diagnosed and the progression of the disease results in increased radiation exposure.

Size-specific dose estimate (SSDE)

The size-specific dose estimate (SSDE) takes account of variations in patient diameter, unlike the $CTDI_{vol}$, which is limited to two phantom sizes (head 16 cm and body 32 cm). The value is calculated as $SSDE = CTDI_{vol} \times f$ (where f is a factor based on the effective patient diameter). The effective diameter is calculated as the square root of the product of the patient’s antero-posterior (a.p.) and lateral (lat.) diameters.

Ultrasound

Refers to an imaging technique that uses ultrasound.

Staging	Staging refers to the process of determining the stage of a malignant tumour in order to assess the extent of its spread.
Standard operating procedures (SOPs)	The SOPs set out standardised procedures and parameters for carrying out examinations.
Radiation carcinogenicity	The property of radiation to cause cancer (malignant tumours) or to promote the development of cancer.
Surrogate markers	An indirect indicator for recording an effect. A surrogate marker is used when the actually relevant variable through which an effect is observed cannot be measured.
Cancer predisposition syndrome	A genetic condition that increases an individual's risk of developing malignant tumours.
Additional filters	These filters used in CT scans are made, for example, of an aluminium alloy, silver or tin. They are used to improve the quality of the radiation by absorbing soft, non-image-forming rays that would otherwise cause unnecessary radiation exposure for the patient.