REVIEW PAPER, REVIEW ARTICLE (PREGLEDNI RAD)

Between minimal dose and optimal image: Challenges of paediatric CT diagnostics

Ira Gabela[1,2], **Tatjana Matijaš**[1]

[1] University of Split, Faculty of Health Sciences, Ruđera Boškovića 35, Split, Croatia

[2] Health Centre of Split-Dalmatia County, Kavanjinova 2, Split, Croatia

Corresponding author: Ira Gabela, email: igabela0@gmail.com

DOI: https://doi.org/10.55378/rv.50.2.5

Abstract

Computed tomography (CT) plays an important role in paediatric imaging due to its rapid acquisition, widespread availability, and high diagnostic value. At the same time, the increased sensitivity of children to ionising radiation requires particular attention to the justification of examinations and dose optimisation. The aim of this review was to summarise current evidence on the risks associated with exposure to ionising radiation during paediatric CT examinations and contemporary approaches to dose reduction. The literature indicates that advances in CT technology, the implementation of paediatric-specific protocols, automatic exposure control, iterative reconstruction techniques, and diagnostic reference levels enable reductions in radiation exposure while maintaining diagnostic image quality. Further risk reduction can be achieved through appropriate justification of each examination and adjustment of imaging protocols according to the child's age and body size. Standardisation of procedures, implementation of international recommendations, and the professional expertise of radiographers are important for further improving radiation protection and patient safety in paediatric imaging.

Keywords: dose optimisation; ionising radiation; paediatric computed tomography; radiation protection; radiation risks

Introduction

Ionising radiation has the ability to ionise matter and is classified as electromagnetic or particulate radiation (1, 2). Biological effects occur when electromagnetic radiation scatters or is absorbed in tissues, transferring energy (1). DNA damage may result from direct radiation action or from free-radical effects and may lead to malignant diseases and hereditary genetic damage (3). Deterministic effects occur after a threshold dose is exceeded, with their severity increasing with dose, whereas stochastic effects have no clearly defined threshold and their probability increases with dose, including the development of malignant tumours and leukaemia (4).

Paediatric patients are exposed to relatively high radiation doses during CT examinations, raising concerns about potential carcinogenic effects (5). Their increased radiosensitivity is associated with physiological, anatomical, developmental, and behavioural factors, particularly in younger children (6). Lower body mass, different body proportions, a thinner layer of visceral adipose tissue, and longer life expectancy further increase the significance of radiation exposure (6, 7). Children are more susceptible to developing certain cancers and leukaemia (6), while certain genetic conditions further increase radiosensitivity (6, 8). Radiation protection follows the ALARA principle, which aims to keep radiation doses as low as reasonably achievable (9).

CT is an important component of paediatric imaging, with head trauma being its most common indication (10). It is also used for other intracranial conditions (11) and in the evaluation of patients with multiple trauma (12). Its use has increased exponentially since its introduction (10), and CT accounts for almost half of the collective medical radiation dose in the USA (13) and up to 68% in the UK (14). In non-paediatric centres, children received twice the radiation doses observed in paediatric trauma centres (15), while inappropriate use is influenced by requests from consultants, patient expectations, and concerns about litigation (16).

At least four million paediatric CT examinations are performed annually in the USA (17), and between 2000 and 2006, head CT use increased by 23% and abdominal CT by 49% (18). Over the past decade, CT use has declined due to increased awareness of radiation risks (19–23), which had previously been insufficient (24), while subsequent studies demonstrated changes in clinical practice (25) and greater awareness of CT overuse (26).

CT is used more frequently in general than in paediatric emergency departments (27), as well as in non-paediatric trauma centres and non-academic emergency departments (28). Whole-body CT was performed in 3% of children at a paediatric centre compared with 9% at adult facilities (29), and differences have also been observed among physicians (30, 31). CT use has also increased

in cases of acute appendicitis (22, 32–34), particularly among children initially evaluated at general hospitals (35, 36), where CT is used more frequently and ultrasound less frequently (37), possibly due to its lower availability and a lack of trained personnel (38).

Most studies have reported more frequent CT use among older children (18, 27, 32, 39–43), White children (32, 42, 43), and boys (28, 32, 44). International comparisons have demonstrated differences among Japan, the USA, and Germany (45); unlike the USA, Japan did not experience an increase in CT use (46), and 1.22 million paediatric CT examinations were estimated to have been performed in Japan in 2003 (47). Japanese and German hospitals differed in terms of patient age and clinical indications (48). In Finland, an increase between 1996 and 2002 was followed by a decline through 2010 (49), with utilisation rates comparable to those in the UK and the Netherlands and lower than those in the USA (20, 50, 51). CT use may be influenced by financial incentives within healthcare systems (20, 52, 53), whereas universal healthcare systems place greater emphasis on the rational use of diagnostic procedures (54).

The aim of this review was to describe the potential risks associated with exposure to ionising radiation in paediatric CT imaging and to analyse approaches to radiation dose optimisation while maintaining diagnostic image quality.

Methods

This review was based on a search of the scientific literature on radiation doses, risks associated with exposure to ionising radiation, and approaches to dose optimisation in paediatric CT imaging. The literature was searched in the Scopus and PubMed databases during April 2026, while Google Scholar and ResearchGate were used for additional searches and access to full-text articles. Scopus was used as the starting point due to the larger number of available papers related to the research topic.

Two search strategies were applied in Scopus and PubMed. The first included the terms *paediatric CT, radiation dose, dose reduction,* and *dose optimisation, while the second included paediatric CT, radiation risk, cancer risk, and ionising radiation*. The inclusion criteria were articles published within the previous ten years, full-text availability (*Open Access* or *Free Full Text*), and publication in English. The time restriction was selected because of advances in CT technology, imaging protocols, dose optimisation, and updates to radiation protection guidelines.

Results

The first Scopus search strategy identified 460 articles, of which 53 were included after applying the inclusion criteria and assessing titles, abstracts, and full texts. The second strategy identified 165 articles, and 8 additional articles were included after applying the inclusion criteria, removing overlapping articles, and assessing relevance.

In PubMed, the first search strategy identified 165 articles, of which an additional 5 were included after applying the inclusion criteria, removing previously identified articles, and assessing relevance. The second strategy identified 58 articles, with an additional 4 included after applying the inclusion criteria, removing duplicates, and assessing relevance.

A total of 70 scientific articles were included in the final analysis, covering radiation doses, risks associated with ionising radiation exposure, dose optimisation methods, the role of radiographers, and alternative diagnostic imaging methods. Relevant guidelines and recommendations from professional societies were also used, together with articles identified by reviewing the reference lists of the included studies.

Discussion

Radiation Doses in Paediatric CT Imaging

Assessment of radiation dose during CT examinations is most commonly based on standardised dosimetric indicators: the volume computed tomography dose index (CTDIvol) and dose-length product (DLP). CTDIvol represents the radiation output of the CT scanner and depends on acquisition parameters such as mAs, kVp, pitch factor, and gantry rotation time (55-57). Although it enables comparison of radiation output between CT scanners, its ability to estimate the actual patient dose is limited because it does not account for body size, body shape, or tissue attenuation properties (55,58,59). A more accurate estimate is provided by the size-specific dose estimate (SSDE), which accounts for patient size by applying correction factors to CTDIvol (55), thereby providing a more realistic dose estimate in paediatric patients (60). Organ doses are also important when assessing biological effects because of differences in tissue radiosensitivity (61), although data on the actual doses received by individual organs during CT examinations have not yet been fully established (62–71). A summary of the most commonly used dosimetric indicators is presented in Table 1.

Table 1. Comparison of the most commonly used dosimetric indicators in paediatric CT imaging (55–71)

Indicator	Unit	Description
CTDIvol	mGy	Represents the radiation output of the CT scanner and depends on acquisition parameters
DLP	mGy·cm	Product of CTDIvol and scan length
SSDE	mGy	Patient size-specific dose estimate based on CTDIvol
Effective dose	mSv	Indicator of the patient's overall exposure to ionizing radiation during a CT examination
Organ (absorbed) dose	mGy	Dose absorbed by an individual organ or tissue

Chu et al. found that during routine head CT, the skin, brain, and eye lens received the highest absorbed doses, while the colon received the highest dose during high-dose abdominal and pelvic CT, and the thyroid during CT examinations of the neck, cervical spine, and chest. The youngest children, particularly those under one year of

age, received higher doses in most CT categories. Considerable variability among institutions was also observed: for abdominal and pelvic CT in children aged 6–10 years, the mean colon dose ranged from 5.6 to 116.6 mGy, while for head CT, the mean brain dose ranged from 29.6 to 59.1 mGy (72). Comparison with the European Epidemiological Study on Paediatric Computerised Tomography (EPI-CT) showed comparable brain doses during routine head CT in most age groups, whereas higher organ doses were reported in children under one year of age in the study by Chu et al. Higher thyroid and red bone marrow doses were also observed in the youngest children (70).

Poosiri et al. showed that DLP, brain dose, and eye lens dose increased with age. CTDIvol remained nearly constant within individual age groups despite differences in head size, whereas the size-specific dose estimate based on water-equivalent diameter (SSDEDw) varied according to patient size and more accurately reflected actual radiation exposure (73). Inoue et al. also reported an increase in DLP with age; however, the effective dose (ED) was highest in newborns and gradually decreased with age. Thus, despite higher DLP values in older children, younger children had a higher ED due to the age-dependent conversion factor and greater radiosensitivity (74).

Increased exposure in the youngest children is particularly important in the context of repeated CT examinations. Biegała et al. found the highest exposure in children under one year of age with hydrocephalus and concluded that age-adjusted paediatric protocols can significantly reduce radiation exposure (75).

Özsoykal et al. showed that CTDIvol remains nearly constant throughout the scan range, whereas SSDE varies according to patient size and anatomical region and was approximately twice as high as CTDIvol (76). Khan et al. also demonstrated that SSDE, by accounting for patient size, provides a more accurate estimate of actual radiation exposure than CTDIvol, with the highest SSDE values observed for head CT (77).

The importance of protocol adjustment was confirmed by Keshtkar et al. Compared with the routine chest CT protocol (RC-CT), the CT protocol for diagnosing COVID-19 (CD-CT) was associated with lower CTDIvol, DLP, SSDE, and ED values across all age groups. The lungs received the highest organ doses, while the estimated risk of malignancy was highest in the youngest age group, particularly for lung and breast cancer (78).

Risks of Exposure to Ionising Radiation in Paediatric CT Imaging

Brenner et al. were among the first to estimate the risk of cancer associated with paediatric CT, with the estimated risk of a fatal outcome ranging from 1 in 10,000 to 1 in 1,000 examined children, depending on age and the body region scanned (79). Subsequent epidemiological studies further indicated a possible association between CT examinations performed during childhood and early adulthood and an increased risk of malignancy (69, 80, 82).

The EPI-CT study demonstrated increased standardised mortality ratios (SMRs), particularly during the first five years after the first CT examination. After five years, the SMR decreased, and malignancy-associated mortality reached the level observed in the general population (83).

A meta-analysis by Huang et al. showed a 1.32-fold higher risk of malignancy in children exposed to CT radiation, with the risk increasing with dose. The risk of leukaemia was 1.23-fold higher and that of brain tumours 1.54-fold higher compared with unexposed children. The risk of malignancy was 1.24-fold higher within two years, 1.38-fold higher after five years, and 1.26-fold higher after ten years, with the highest risk observed in children who underwent their first CT examination between 0 and 5 years of age (84). De Gonzalez et al. found that predisposing conditions did not significantly affect the association between CT exposure and leukaemia or brain tumours. Previously unreported cancers may have partially influenced the estimates, particularly for brain tumours, but the association persisted after adjustment for potential sources of bias (85).

Bosch et al. found an association between cumulative dose and haematological malignancies. They observed an increased relative risk at doses ≥10 mGy, and at doses ≥50 mGy it was 2.66 times higher than at doses <5 mGy. The risk increased with dose, was more pronounced for non-Hodgkin lymphoma than for Hodgkin lymphoma, and exposure at a younger age was associated with a higher risk of leukaemia. The highest risk was observed 2 to <5 years after exposure. Each additional CT examination was associated with a 43% increase in the risk of haematological malignancies, a 42% increase in lymphoid malignancies, and a 48% increase in myeloid malignancies and acute leukaemias (86).

In the Dutch Paediatric CT Study, the risk of brain tumours increased with radiation dose to the brain, with the highest relative risk observed at doses >120 mGy (87). Wang et al. found no increased risk of intracranial tumours, leukaemia, Hodgkin lymphoma, or non-Hodgkin lymphoma after a single CT examination. After 2–3 examinations, the risk of intracranial tumours increased, while four or more examinations were associated with an increased risk of intracranial tumours, leukaemia, and non-Hodgkin lymphoma, but not Hodgkin lymphoma. The overall incidence of the malignancies investigated was 2.3 times higher after four or more examinations (88).

Kojimahara et al. found no association between head CT and an increased risk of brain tumours; however, due to the small sample size, the statistical power was insufficient to reliably detect a possible association (89). Journy et al. estimated that the excess lifetime cancer risk following a single CT examination decreased by 50–70% between 2000–2008 compared with 1990–1994. A single CT examination during childhood could result in approximately one additional cancer per 1,000 spontaneous cancers, and among 130,750 CT examinations performed in 2015, an estimated 64 additional lifetime cancer cases were projected, with brain tumours being the most common. The distribution of body regions examined by CT and the proportion of estimated future cancers associated with radiation exposure are shown in Figure 1 (90).

A meta-analysis by Al-Shangeeti et al. showed a 1.49-fold higher overall risk of cancer in children exposed to CT radiation. A single CT examination was not associated with a statistically significant increase in risk, whereas the risk was 2.51-fold higher after two or more examinations. The increase was particularly pronounced for brain tumours, while findings for leukaemia were less consistent (91).

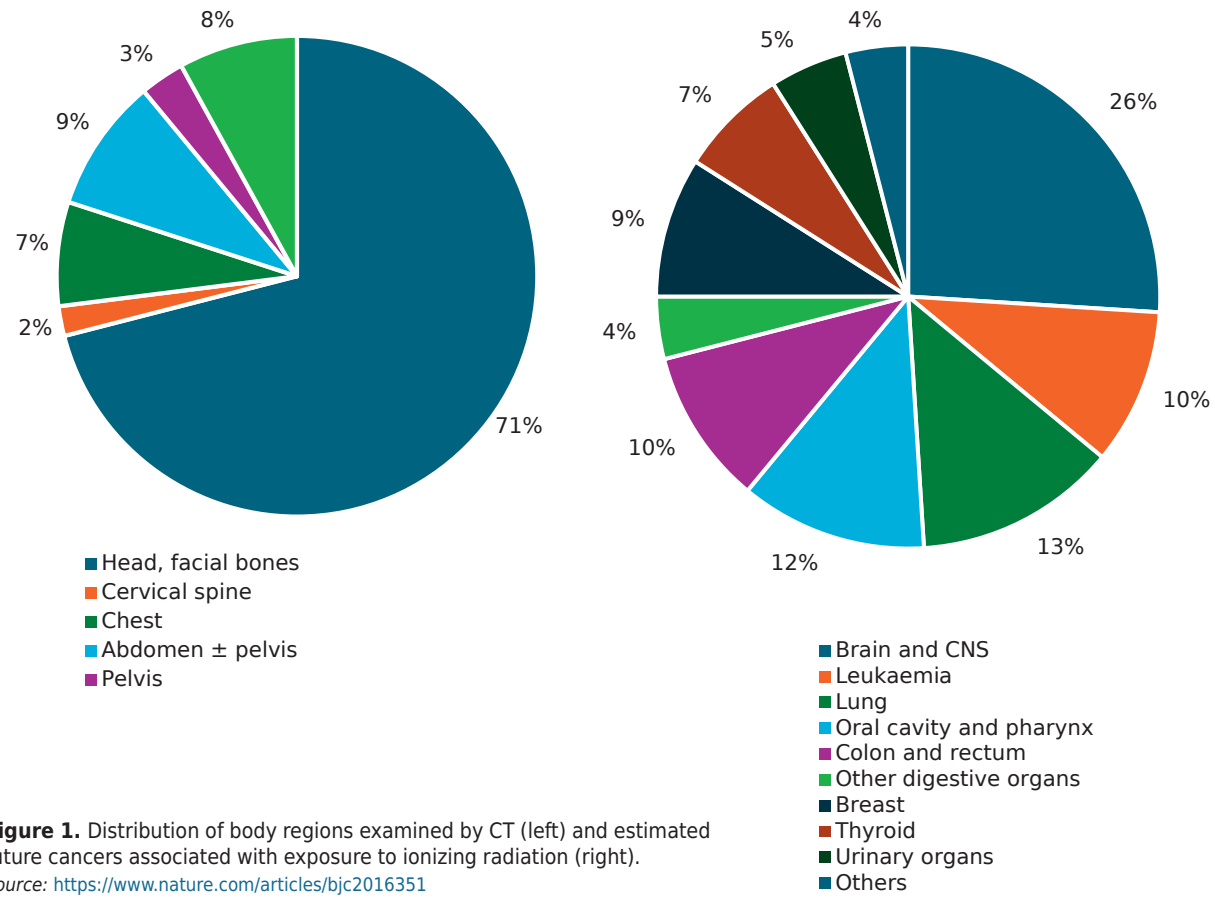


Figure 1. Distribution of body regions examined by CT (left) and estimated future cancers associated with exposure to ionizing radiation (right).
Source: https://www.nature.com/articles/bjc2016351

Dose Optimisation in Paediatric CT Imaging

Dose optimisation in paediatric CT imaging aims to achieve diagnostically acceptable image quality while keeping the ionising radiation dose as low as possible (92). Main strategies include adjusting kV, mAs, and pitch according to the child's age and size, limiting scan length to the region of interest, positioning the patient appropriately, and avoiding unnecessary multiphase examinations. Diagnostic reference levels (DRLs), achievable doses (ADs), automatic modulation of exposure parameters, iterative reconstruction techniques, and artificial intelligence-based methods also play an important role, together with protocol standardisation, staff education, and interdisciplinary collaboration (93).

The clinical application of the principles of justification and optimisation can directly reduce unnecessary radiation exposure in children, as demonstrated by Solomon et al., who reported that 11% of children were spared unnecessary exposure (94). Education of healthcare professionals and collaboration between specialised centres and local hospitals can also improve knowledge of radiation risks and the implementation of dose-reduction practices (95). Assessment of diagnostic image quality is additionally important for preventing the use of unnecessarily high radiation doses. Padole et al. developed Image Quality Scoring Criteria (IQSC), which may serve as a practical tool for protocol optimisation (96), while Samei et al. proposed a quantitative approach that enables individualisation of protocols according to patient size and the desired dose or image quality level (97).

Diagnostic Reference Levels and Radiation Dose Monitoring

Diagnostic reference levels (DRLs), proposed by the International Commission on Radiological Protection (ICRP) in 1990, represent an important tool for assessing dose levels during CT examinations (98). They are most commonly established as the 75th percentile of the CTDIvol and DLP distributions (99) and enable comparison of dose levels and identification of opportunities for further optimisation (100). Achievable doses (ADs) are defined as the median, or 50th percentile, of the dose distribution, and in paediatric CT imaging, DRL and AD values are often adjusted according to patient age, body weight, or size (101,102).

National and multicentre studies confirm the importance of regularly monitoring and updating DRLs. Based on a national audit, Worrall et al. proposed new DRLs for paediatric CT examinations in the United Kingdom (103), while Wagner et al. proposed values in Switzerland that were up to 20% lower than those previously used, indicating the potential for further optimisation (104). In Shanghai, Yang and Gao reported AD values approximately 60% lower than the corresponding DRLs, also indicating potential for reducing variability in radiation doses among institutions (105).

Studies from Japan demonstrated the need to establish national paediatric DRLs (106) and reported dose reductions following their introduction in 2015 (107). In Korea, CTDIvol and DLP increased with age, with substantial variability among hospitals despite the use of the same

protocols (108), while similar interhospital and regional differences were observed in China (109).

In addition to age, adjustment of DRLs according to patient size and body weight is increasingly being considered. Tonkopi et al. emphasised the importance of standardised data collection and the inclusion of SSDE in dose assessment (110), while Bos et al. demonstrated an increase in DRL values with age and differences among CT examination categories (111). A meta-analysis by Zakariaee et al. showed an increase in all dosimetric indicators with body size, with substantial heterogeneity among studies and a need to adjust protocols according to patient size (112). Significant differences according to hospital, age, protocol, and type of CT scanner were reported by Rawashdeh et al. (113), while Dastikas et al. demonstrated a strong positive association between body weight and CTDIvol and DLP, as well as the usefulness of body weight-based reference curves (114).

Dose levels may also be influenced by organisational factors. van der Merwe and Mahomed reported higher DLP values outside regular working hours, which may be related to staff experience and protocol selection (115). Aloufi et al. reported the highest doses during abdominal and head CT examinations, particularly in children under one year of age (116), while Bibbo et al. found higher DLP values with helical than with axial scanning (117).

Variability in exposure parameters and radiation doses within and between hospitals has also been confirmed in other studies (118). Differences were observed in radiation doses, image noise, and effective mAs, kVp, and pitch values among different CT examinations and age groups (119). Interhospital differences, particularly for chest CT and abdominal and pelvic CT, also indicate the need to review individual protocols (120). In Greece, CTDIvol values for head CT were comparable to European DRLs, whereas DLP values were higher (121), while in Cameroon, CTDIvol and DLP exceeded French DRLs in all age groups (122). In contrast, values in Ghana were generally lower than those reported in other studies, with the exception of head CT in children aged 11–15 years (123).

A systematic review by Priyanka et al. confirmed substantial international variability in CTDIvol and DLP, as well as differences in protocols and methods used to establish DRLs (124). Similar variability was observed in African countries, where the number of available studies remains limited (125). Table 2 provides a summary of the analysed studies, their key findings, and their contributions to dose optimisation associated with the use of DRLs in paediatric CT imaging.

The studies presented in this section confirm the importance of DRLs and systematic radiation dose monitoring in the optimisation of paediatric CT examinations. Despite the increasing implementation of national and local DRLs, substantial variability in protocols and dose levels persists among institutions and countries. Accordingly, continuous dose monitoring, protocol standardisation, and adjustment of CT examinations to individual patient

Table 2. Overview of key findings on diagnostic reference levels in paediatric CT imaging (103–125)

Research topic	Representative studies	Key findings	Key contribution to optimization
National DRLs and comparison with international values	Worrall et al.; Wagner et al.; Takei et al.; Matsunaga et al.; Kim et al.; Kang et al.	Substantial variability in radiation doses was observed among countries and institutions, while the introduction and regular updating of DRLs were associated with reductions in radiation dose.	Establishing and updating national DRLs enables comparison of radiation doses among institutions and identification of opportunities for further optimization.
Achievable doses (ADs) as an indicator of further optimization potential	Yang and Gao	Achievable doses were approximately 60% lower than the corresponding DRL values, indicating potential for further dose reduction.	They enable the identification of protocols in which radiation exposure can be further optimized.
Size-specific approach, SSDE, and adjustment according to patient size	Tonkopi et al.; Zakariaee et al.; Rawashdeh et al.; Dastikas et al.	CTDIvol, DLP, and SSDE values increase with increasing age, body weight, and patient size, while SSDE more accurately reflects actual radiation exposure.	Enables individualisation of dose assessment and adjustment of protocols according to patient characteristics.
DRLs according to clinical indications and CT examination categories	Bos et al.	Differences among individual CT categories were more pronounced than differences among individual indications within the same category.	Enables more precise standardization and optimization of protocols according to the clinical task.
Local DRLs, audits, and interinstitutional comparisons	van der Merwe and Mahomed; Aloufi et al.; Bibbo et al.; Alhailiy et al.; Muhammad et al.; Bouchareb et al.; Ploussi et al.; Eddy et al.; Amedzoame et al.	Substantial differences in radiation doses, acquisition parameters, and protocol quality were observed among institutions, with some variations associated with staff experience and protocol selection.	Enables the identification of areas for optimization, protocol standardization, and targeted staff education.
Systematic reviews of DRLs	Priyanka et al.; Gyan et al.	Considerable heterogeneity in DRL methodology, acquisition protocols, and reference values was confirmed among countries.	Highlights the need for harmonization of methodology and standardization of paediatric CT protocols.

characteristics represent important factors in the further optimisation of paediatric CT imaging.

Automatic Exposure Control and Optimisation of Acquisition Parameters

Adjustment of exposure parameters according to the child's age and size is a fundamental dose-reduction strategy. Kamdem et al. demonstrated that the introduction of age- and size-adjusted parameters, staff education, and optimised protocols can significantly reduce radiation dose even on CT scanners designed for adult patients (126). Age- and size-adjusted protocols and adjustment of mAs also enabled a significant reduction in effective dose during brain CT without a significant loss of diagnostic image quality (127).

Automated systems further enable exposure to be tailored to the individual patient. The CAREkV automatic tube voltage selection system can improve standardisation and reduce inter-operator variability but requires appropriate adjustment for paediatric patients to avoid the automatic selection of unnecessarily high kV values. For example, in patients with a pronounced difference between abdominal and pelvic width, automatic selection of a higher tube voltage was observed (Figure 2), further emphasising the importance of appropriate patient positioning and adjustment during paediatric CT examinations (128).

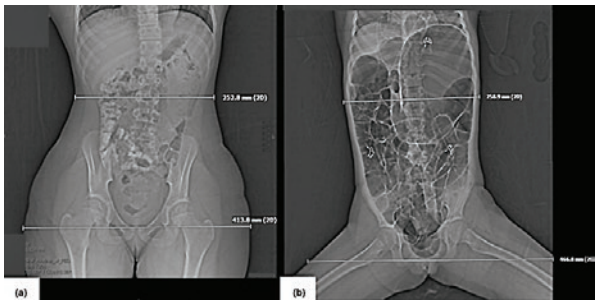


Figure 2. Example of automatic selection of a higher kV value due to differences in abdominal and pelvic width during a paediatric CT examination
Source: https://aapm.onlinelibrary.wiley.com/doi/epdf/10.1002/acm2.13098?getft_integrator=scopus&src=getftr&utm_source=scopus

Papadakis and Damilakis demonstrated that automatic tube current modulation (ATCM) can reduce CTDIvol by 8–24% for head CT, 16–39% for chest CT, and 25–41% for abdominal and pelvic CT. The additional use of automatic tube voltage selection (ATVS) enabled even greater dose reductions, reaching 70–79% for certain contrast-enhanced examinations, although it did not always result in dose reduction for non-contrast head CT (129).

Combining ATVS and ATCM during paediatric chest CT enabled better exposure adjustment to patient size and reduced high-dose outliers, with CTDIvol reductions observed in four of five age groups (130). Further optimisation can be achieved by using a lower tube voltage while monitoring the contrast-to-noise ratio (CNR), thereby reducing radiation dose while maintaining image quality (131). The main characteristics of the analysed studies are summarised in Table 3.

The studies presented confirm the importance of adjusting exposure parameters to reduce radiation dose while maintaining diagnostic image quality. The use of ATCM and ATVS, together with individualisation of parameters according to patient size and clinical indication, may further contribute to protocol standardisation, reduced inter-operator variability, and the safety of paediatric CT imaging.

Iterative Reconstruction and Artificial Intelligence

Iterative reconstruction methods and artificial intelligence-based systems enable reductions in image noise and artefacts while maintaining diagnostic image quality at lower radiation doses. The use of iDose iterative reconstruction during low-dose chest CT in neonates and young children can maintain diagnostic image quality at lower radiation doses (132).

In low-dose brain CT, iterative model reconstruction resulted in an approximately twofold improvement in the contrast-to-noise ratio and a more than twofold improvement in the signal-to-noise ratio of grey and white matter compared with filtered back projection (FBP) (133). Villanueva-Meyer et al. demonstrated that ultra-low-dose chest CT can be diagnostically acceptable for certain indications, particularly for excluding airway foreign bodies. Model-based iterative reconstruction (MBIR) reduced image noise compared with adaptive statistical iterative reconstruction (ASIR); however, ultra-low-dose CT did not

Table 3. Overview of studies on the optimisation of exposure parameters in paediatric CT imaging (126–131)

Optimization method	Studies	Key findings	Effect on dose
Age and size adjusted protocols	Kamdem et al.; Karappara et al.	Adjustment of kV, mAs, pitch, and other parameters according to the child's age and size enables dose reduction while maintaining diagnostic image quality.	CTDIvol reduced by up to 32% and effective dose by up to 71%.
Automatic tube voltage selection (CAREkV)	Browne et al.	Automated kV selection enables protocol standardization, reduces inter-operator variability, and decreases the risk of inappropriate parameter selection.	Image quality maintained while optimizing radiation dose.
Automatic tube current and voltage modulation (ATCM + ATVS)	Papadakis and Damilakis; Hojreh et al.	Automatic adjustment of kV and mAs according to patient size enables protocol individualization, reduces operator-related errors, and maintains diagnostic image quality.	Dose reduction of up to 79%, with CTDIvol reduced by up to approximately 46%.
Reduction of tube voltage using CNR	Masuda et al.	Maintaining an appropriate contrast-to-noise ratio (CNR) enables the use of lower kVp values while preserving diagnostic image quality and improving contrast.	Dose reduction of up to 56% at 80 kVp.

achieve the image quality of standard-dose CT for all indications (134).

Contemporary iterative reconstruction techniques such as ASIR and MBIR enable image quality to be maintained at lower radiation doses compared with FBP, with ASIR allowing dose reductions of approximately 40–50% and MBIR providing further dose reduction while maintaining diagnostic image quality (93). More recent methods include iterative model reconstruction (IMR), advanced modelled iterative reconstruction (ADMIRE), iDose4, and deep learning image reconstruction (DLIR). By applying artificial intelligence and deep learning, DLIR reduces image noise and artefacts while preserving anatomical detail and, in some studies, has enabled dose reductions of up to approximately 85% while maintaining diagnostically acceptable image quality. Compared with ASIR and FBP, improved lesion detection, a higher signal-to-noise ratio (SNR), better grey–white matter differentiation, and lower image noise have been reported (135). Table 4 summarises the reconstruction methods and their contribution to the optimisation of paediatric CT imaging.

Table 4. Reconstruction methods described in the systematic review by Patil et al. (2026) and their contribution to the optimization of paediatric CT imaging (135)

Reconstruction method	Brief description	Main findings of the systematic review
ASIR	Adaptive statistical iterative reconstruction.	Reduction in image noise and improvement in CNR, with radiation dose reductions of approximately 13–48%.
MBIR	Model-based iterative reconstruction.	Maintenance of high image quality with ultra-low-dose protocols, with radiation dose reductions of approximately 83–97%.
ADMIRE	Advanced modeled iterative reconstruction.	Average reductions in CTDIvol, DLP, and effective dose of approximately 30%.
IMR	Iterative model reconstruction.	Improved qualitative and quantitative image quality with lower CTDIvol values compared with FBP reconstruction.
DLIR	Deep learning image reconstruction.	Improved SNR, visualization of anatomical details, and lesion detection, with radiation dose reductions of up to approximately 85%.

Iterative reconstruction and deep learning technologies represent important contemporary approaches to the optimisation of paediatric CT imaging, as they enable substantial dose reductions while maintaining or improving diagnostic image quality. However, their implementation depends on the technical capabilities of the institution and the availability of modern CT scanners, which may limit the adoption of advanced optimisation strategies (135).

Radiographers in the Safety and Quality of Paediatric CT Examinations

Radiographers play an important role in the preparation and performance of paediatric CT examinations, the application of radiation protection principles, and communication with children, parents, and other members of the healthcare team. Working with children requires knowledge of paediatric protocols, adaptation of the approach to the patient, and the creation of appropriate conditions for the safe performance of diagnostically adequate examinations.

Aipanda et al. demonstrated that the active involvement of radiographers in communicating with parents about the risks and benefits of radiation contributes to professional satisfaction and confidence in practice, while the lack of formal communication training and disagreements regarding the justification of CT examinations were identified as important challenges (136). Insufficient knowledge of radiation doses and risks has also been identified among some healthcare professionals, including underestimation of radiation doses and limited awareness of the use of non-adapted adult protocols in paediatric patients (137).

The presence of a parent or caregiver may help reassure the child and reduce motion artefacts. During paediatric chest CT, Overhoff et al. found very low levels of radiation exposure to accompanying persons when contemporary protocols were used, while no measurable exposure was detected at the lateral side of the gantry (138).

Specific training and experience further influence the confidence of radiographers when working with children. Greenberg and Davis found lower levels of confidence when performing paediatric compared with adult CT examinations, particularly due to a lack of experience and specific training, while a significant increase in self-reported confidence was observed after training (139). The importance of continuing education, standardised protocols, and interdisciplinary collaboration has been particularly emphasised in smaller hospitals with limited experience in paediatric imaging (95). Education is also important for the appropriate adjustment of kV and mAs, the application of reconstruction methods, and limiting the number of acquisitions, as insufficient training may result in the use of automatically predefined parameters without appropriate adjustment for children (126).

In addition to technical competence, the psychological approach is also important. A child-friendly environment, distraction techniques, and effective communication with children and parents can reduce anxiety and improve cooperation, while clear explanations of the procedure and appropriate positioning can reduce motion artefacts and the need for repeat examinations (140).

European and International Recommendations for Dose Optimisation and Radiation Protection in Paediatric CT

The importance of dose optimisation and radiation protection in paediatric CT imaging is emphasised in international and European guidelines addressing the justification of examinations, adjustment of exposure parameters, implementation of diagnostic reference levels, and quality assurance of radiological procedures.

The guidelines of the British Institute of Radiology emphasise the increased radiosensitivity of children and the need to adapt CT protocols according to their age and body size. The use of protective shielding during CT is considered controversial because of the potential for artefacts, interference with automatic exposure control (AEC), and the need for repeat imaging. Protocol adjustment according to body weight, body mass index, and age, together with automatic exposure modulation, is recommended as a more effective approach. In a paediatric phantom, a lead apron reduced scattered radiation by only 0.2% at a distance of 10 cm and by 0.7% of the primary dose at 1 cm from the scanned region, which is very small relative to the total examination dose (141).

The International Atomic Energy Agency (IAEA) publication Radiation Protection in Paediatric Radiology emphasizes the strict justification of each CT examination based on the patient's age, clinical indication, and expected diagnostic benefit. Review of previous radiological records, avoidance of prematurely performed follow-up examinations, and reduction of multiphase, repeated, and unnecessary non-contrast acquisitions are recommended. Appropriate preparation of the child, reduction of anxiety, immobilization, and, when necessary, sedation or anaesthesia may reduce the need for repeat imaging. Interdisciplinary collaboration, clinical reviews, and audits of examination justification are also emphasized (7).

ICRP Publication 121 also emphasizes justification and optimization, including limiting the scan range according to the clinical indication, which can reduce radiation dose by up to 55% during follow-up examinations of patients with cystic fibrosis. A higher level of image noise is acceptable provided that diagnostic value is maintained, with the required image quality depending on the clinical indication. Lower tube voltages than those used in adults, often 80–100 kVp, are recommended in children, together with appropriate reconstruction and image post-processing methods (9).

ICRP Publication 135 highlights the complexity of establishing paediatric DRLs because of the substantial differences in body size among children and emphasizes the importance of precise collimation. Age alone is not a sufficiently reliable parameter for establishing DRLs; therefore, weight groups of <5 kg, 5–<15 kg, 15–<30 kg, 30–<50 kg, and 50–<80 kg are recommended for examinations of the trunk, whereas age groups are more appropriate for head CT. CTDIvol and DLP are recommended as dosimetric quantities, with SSDE providing an option for a more realistic assessment of radiation exposure. The document also highlights the limitations of AEC systems developed primarily for adults, which may require manual adjustment of exposure parameters in the smallest children (142).

The European Commission's European Guidelines on Diagnostic Reference Levels for Paediatric Imaging emphasize DRLs as one of the main tools for optimization. They highlight the lack of national paediatric DRLs in some European countries, as well as differences in the methods used to establish them and in the grouping of children according to age, weight, or body size. Accordingly, the guidelines emphasize the need to standardize dosimetric data collection and the establishment of DRLs. Comparison of local doses with DRL values is recommended at least annually, together with analyses and corrective measures when reference values are consistently exceeded (143).

International and European guidelines are consistent with the studies presented above and confirm the importance of individualizing paediatric CT protocols, monitoring dosimetric indicators, and standardizing procedures and DRL values to reduce variations in clinical practice and improve diagnostic quality.

Use of Alternative Diagnostic Imaging Methods to Reduce the Number of CT Examinations

Despite the development of dose optimisation strategies, the number of paediatric CT examinations continues to increase, and repeated examinations during long-term follow-up may result in substantial cumulative exposure to ionising radiation. Therefore, the justification of follow-up CT examinations should be carefully assessed, and alternative imaging methods should be considered whenever clinically appropriate (145). Minimising unnecessary CT examinations requires stricter justification, education of healthcare professionals, and restriction of their use to clinically justified cases (146).

ICRP and IAEA recommendations emphasise the use of imaging methods that do not involve ionising radiation whenever clinically appropriate. Ultrasound is particularly important in abdominal imaging and in cases of suspected acute appendicitis, while Magnetic Resonance Imaging (MRI) offers advantages in the evaluation of soft tissues, the nervous system, and bone marrow. CT retains an important role in emergency conditions, polytrauma, and the evaluation of cortical bone, whereas the use of MRI may be limited by its availability, particularly in emergency settings (7,9).

The World Health Organisation highlights that the development of new ultrasound techniques has expanded its use in paediatric radiology, while MRI, owing to its high soft-tissue contrast resolution and absence of ionising radiation, has gradually replaced CT and conventional radiography in certain areas. MRI is used in the diagnosis of diseases of the central nervous, urinary, musculoskeletal, and cardiovascular systems, as well as in the evaluation of malignant diseases. Despite the advantages of alternative imaging methods, the use of CT continues to increase because of its availability and rapid image acquisition (8).

A systematic review by Aziz et al. also emphasises the importance of ultrasound and MRI as non-ionising imaging methods. Ultrasound provides real-time imaging and plays an important role in emergency diagnostics and focused assessment with sonography for trauma (FAST), while MRI provides detailed visualisation of soft tissues and may represent an alternative to CT for certain clinical indications. However, ultrasound is operator-dependent, while MRI is more expensive and time-consuming and may require sedation in younger children. Additional limitations include risks associated with gadolinium-based contrast agents in patients with impaired renal function and the greater complexity of interpreting paediatric MRI findings (93). The higher cost, lower availability, and poorer tolerability of MRI in younger children have also been confirmed in other studies (10).

The increased use of ultrasound and MRI reflects the growing application of non-ionising imaging methods in paediatric diagnostics. However, the simultaneous

increase in the number of CT examinations emphasises the need for continuous assessment of their justification and the use of imaging methods without ionising radiation whenever possible (146).

Conclusion

CT imaging plays an important role in modern paediatric medicine; however, children's increased sensitivity to ionising radiation and the potential for long-term adverse effects require careful, justified use. The literature analysis showed differences in radiation exposure levels across healthcare institutions and countries, while modern optimisation approaches reduce dose while maintaining diagnostic image quality. Key measures include adapting protocols for paediatric patients, implementing diagnostic reference levels, automatic exposure control, and contemporary reconstruction methods. The safe use of CT requires justification of each examination, consistent radiation protection, and interdisciplinary collaboration, with radiographers playing an important role in protocol implementation, parameter optimisation, and continuing professional development. Rational use of CT, together with alternative imaging methods that do not involve ionising radiation whenever clinically appropriate, may further reduce unnecessary radiation exposure in paediatric patients.

All data in this paper are part of the results of the master's thesis "Potential risks of ionising radiation and dose optimisation in paediatric CT diagnostics", written at the Faculty of Health Sciences, University of Split (147).

References

1. Hill MA, Ullrich RL. Ionizing radiation. In: Stewart BW, Wild CP, editors. World Cancer Report: Cancer Research for Cancer Prevention. Lyon: International Agency for Research on Cancer; 2014. p. 175–183.
2. International Atomic Energy Agency. Radiation biology: a handbook for teachers and students. Vienna: IAEA; 2010.
3. International Atomic Energy Agency. Radiation, people and the environment. Vienna: IAEA; 2004.
4. Janković S, Mihanović F. Uvod u radiologiju. Split: Sveučilište u Splitu, Sveučilišni odjel zdravstvenih studija; 2014.
5. Tajaldeen A, Kheiralla OAM, Alghamdi SS, Alsleem H, Al-Othman A, Abuelhia E, et al. Evaluation of pediatric imaging modalities practices of radiologists and technologists: a survey-based study. J Multidiscip Healthc. 2022;15:443-53. doi:10.2147/JMDH.S351696.
6. United Nations Children's Fund. Radiation and Children's Health [Internet]. New York: UNICEF; 2026 [Accessed 6 April 2026.]. Available at: https://www.unicef.org/reports/radiation-and-childrens-health
7. International Atomic Energy Agency. Radiation protection in paediatric radiology. Vienna: International Atomic Energy Agency; 2012. (Safety Reports Series No. 71).
8. World Health Organization. Communicating radiation risks in paediatric imaging: information to support health care discussions about benefit and risk. Geneva: World Health Organization; 2016.
9. International Commission on Radiological Protection. Radiological protection in paediatric diagnostic and interventional radiology. ICRP Publication 121. *Ann ICRP.* 2013;42(2):1-63.
10. Ohana O, Soffer S, Zimlichman E, Klang E. Overuse of CT and MRI in paediatric emergency departments. The British Journal of Radiology. 2018;91(1085):20170434. doi:10.1259/bjr.20170434.
11. Pastila R, editor. Guidelines for paediatric CT examinations. Helsinki: Radiation and Nuclear Safety Authority (STUK); 2014.
12. Appelhaus S, Schönberg SO, Weis M. CT in pediatric trauma patients. Rofo. 2025;197(3):257-265. doi:10.1055/a-2341-7559.
13. Schauer DA, Linton OW. National Council on Radiation Protection and Measurements report shows substantial medical exposure increase. Radiology. 2009;253(2):293-296. doi:10.1148/radiol.2532090494.
14. Hart D, Wall B, Hillier M, Shrimpton P. Frequency and collective dose for medical and dental X-ray examinations in the UK, 2008. London: Health Protection Agency; 2010.
15. Nabaweesi R, Ramakrishnaiah RH, Aitken ME, Rettiganti MR, Luo C, Maxson RT, et al. Injured children receive twice the radiation dose at nonpediatric trauma centers compared with pediatric trauma centers. J Am Coll Radiol. 2017;14:S1546-1440(17)30825-6. doi:10.1016/j.jacr.2017.06.035.
16. Weigner MB, Dewar KM, Basham HF, Rupp VA, Greenberg MR. Impact of education on physician attitudes toward computed tomography utilization and consent. J Emerg Med. 2012;43(5):e349-e353. doi:10.1016/j.jemermed.2011.09.005.
17. Brenner DJ, Hall EJ. Computed tomography: an increasing source of radiation exposure. N Engl J Med. 2007;357(22):2277-2284. doi:10.1056/NEJMra072149.
18. Broder J, Fordham LA, Warshauer DM, Ansley FL. Increasing utilization of computed tomography in the pediatric emergency department, 2000-2006. Emerg Radiol. 2007;14(4):227-232. doi:10.1007/s10140-007-0618-9.
19. Hoshiko S, Smith D, Fan C, Jones CR, McNeel SV, Cohen RA. Trends in CT scan rates in children and pregnant women: teaching, private, public and nonprofit facilities. Pediatr Radiol. 2014;44(5):522-528.
20. Miglioretti DL, Johnson E, Williams A, Greenlee RT, Weinmann S, Solberg LI, et al. The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. JAMA Pediatr. 2013;167(8):700-707. doi:10.1001/jamapediatrics.2013.311.
21. Lodwick DL, Cooper JN, Kelleher KJ, Brilli R, Minneci PC, Deans KJ. Variation in utilization of computed tomography imaging at tertiary pediatric hospitals. Pediatrics. 2015;136(5):e1212-e1219. doi:10.1542/peds.2015-1671.
22. Menoch MJ, Hirsh DA, Khan NS, Simon HK, Sturm JJ. Trends in computed tomography utilization in the pediatric emergency department. Pediatrics. 2012;129(3):e690-e697. doi:10.1542/peds.2011-2548.
23. Townsend BA, Callahan MJ, Zurakowski D, Taylor GA. Has pediatric CT at children's hospitals reached its peak? AJR Am J Roentgenol. 2010;194(5):1194-1196. doi:10.2214/AJR.09.3682.
24. NG CI, Haims AH, Monico EP, Brink JA, Forman HP. Diagnostic CT scans: assessment of patient, physician, and radiologist awareness of radiation dose and possible risks. Radiology. 2004;231(2):393-398. doi:10.1148/radiol.2312030767.
25. Wylie MC, Merritt C, Clark M, Garro AC, Rutman MS, Klein BL. Imaging of pediatric head injury in the emergency department. Pediatr Emerg Care. 2014;30(10):680-685. doi:10.1097/PEC.0000000000000227.
26. Griffey RT, Jeffe DB, Bailey T. Emergency physicians' attitudes and preferences regarding computed tomography, radiation exposure, and imaging decision support. Acad Emerg Med. 2014;21(7):768-777. doi:10.1111/acem.12410.
27. Adelgais KM, Browne L, Holsti M, Metzger RR, Murphy SC, Dudley N. Cervical spine computed tomography utilization in pediatric trauma patients. J Pediatr Surg. 2014;49(2):333-337. doi:10.1016/j.jpedsurg.2013.10.006.
28. Marin JR, Wang L, Winger DG, Mannix RC. Variation in computed tomography imaging for pediatric injury-related emergency visits. J Pediatr. 2015;167(4):897-904. doi:10.1016/j.jpeds.2015.06.052.
29. The Royal College of Radiologists. Paediatric trauma protocols. London: The Royal College of Radiologists; 2014.
30. Shahi V, Brinjikji W, Cloft HJ, Thomas KB, Kallmes DF, Waleed BJ. Trends in CT utilization for pediatric fall patients in US emergency departments. Acad Radiol. 2015;22(7):898-903. doi:10.1016/j.acra.2015.02.016.
31. Miescier MJ, Dudley NC, Kadish HA, Mundorff MB, Corneli HM. Variation in computed tomography use for evaluation of head injury in a pediatric emergency department. Pediatr Emerg Care. 2017;33(3):156-160. doi:10.1097/PEC.0000000000000500.
32. Fahimi J, Herring A, Harries A, Gonzales R, Alter H. Computed tomography use among children presenting to emergency departments with abdominal pain. Pediatrics. 2012;130(5):e1069-e1075. doi:10.1542/peds.2012-0739.
33. Frei SP, Bond WF, Bazuro RK, Richardson DM, Sierzega GM, Reed JF. Appendicitis outcomes with increasing computed tomographic scanning. Am J Emerg Med. 2008;26(1):39-44. doi:10.1016/j.ajem.2007.06.027.
34. Tsao K, St Peter SD, Valusek PA, Spilde TL, Keckler SJ, Nair A, et al. Management of pediatric acute appendicitis in the computed tomographic era. J Surg Res. 2008;147(2):221-224. doi:10.1016/j.jss.2008.03.004.
35. Neff LP, Ladd MR, Becher RD, Jordanhazy RA, Gallaher JR, Pranikoff T. Computerized tomography utilization in children with appendicitis: differences in referring and children's hospitals. Am Surg. 2011;77(8):1061-1065.

36. Michailidou M, Sacco Casamassima MG, Karim O, Gause C, Salazar JH, Goldstein SD, et al. Diagnostic imaging for acute appendicitis: interfacility differences in practice patterns. Pediatr Surg Int. 2015;31(4):355-361. doi:10.1007/s00383-015-3669-0.
37. Saito JM, Yan Y, Evashwick TW, Warner BW, Tarr PI. Use and accuracy of diagnostic imaging by hospital type in pediatric appendicitis. Pediatrics. 2013;131(1):e37-e44. doi:10.1542/peds.2012-1665.
38. Burr A, Renaud EJ, Manno M, Makris J, Cooley E, DeRoss A, et al. Glowing in the dark: time of day as a determinant of radiographic imaging in the evaluation of abdominal pain in children. J Pediatr Surg. 2011;46(1):188-191. doi:10.1016/j.jpedsurg.2010.09.088.
39. Larson DB, Johnson LW, Schnell BM, Goske MJ, Salisbury SR, Forman HP. Rising use of CT in child visits to the emergency department in the United States, 1995-2008. Radiology. 2011;259(3):793-801. doi:10.1148/radiol.11101939.
40. Blackwell CD, Gorelick M, Holmes JF, Bandyopadhyay S, Kuppermann N. Pediatric head trauma: changes in use of computed tomography in emergency departments in the United States over time. Ann Emerg Med. 2007;49(3):320-324. doi:10.1016/j.annemergmed.2006.09.025.
41. Grim PF. Emergency medicine physicians' and pediatricians' use of computed tomography in the evaluation of pediatric patients with abdominal pain without trauma in a community hospital. Clin Pediatr (Phila). 2014;53(5):486-489. doi:10.1177/0009922813517170.
42. Mannix R, Bourgeois FT, Schutzman SA, Bernstein A, Lee LK. Neuroimaging for pediatric head trauma: do patient and hospital characteristics influence who gets imaged? Acad Emerg Med. 2010;17(7):694-700. doi:10.1111/j.1553-2712.2010.00797.x.
43. Natale JE, Joseph JG, Rogers AJ, Mahajan P, Cooper A, Wisner DH, et al. Cranial computed tomography use among children with minor blunt head trauma: association with race/ethnicity. Arch Pediatr Adolesc Med. 2012;166(8):732-737. doi:10.1001/archpediatrics.2012.307.
44. Roudsari BS, Psoter KJ, Vavilala MS, Mack CD, Jarvik JG. CT use in hospitalized pediatric trauma patients: 15-year trends in a level I pediatric and adult trauma center. Radiology. 2013;267(2):479-486. doi:10.1148/radiol.13120865.
45. Ideguchi R, Yoshida K, Ohtsuru A, Takamura N, Tsuchida T, Kimura H, et al. The present state of radiation exposure from pediatric CT examinations in Japan: what do we have to do? J Radiat Res. 2018;59(Suppl 2):ii130-ii136. doi:10.1093/jrr/rrx095.
46. Ono K, Yoshitake T, Hasegawa T, et al. Estimation of the number of CT procedures based on a nationwide survey in Japan. Health Phys. 2011;100(5):491-496.
47. Miyazaki O, Kitamura M, Masaki H, et al. Current practice of pediatric MDCT in Japan: survey results of demographics and age-based dose reduction. Nihon Igaku Hoshasen Gakkai Zasshi. 2005;65(3):216-223.
48. Yoshida K, Krille L, Dreger S, et al. Pediatric computed tomography practice in Japanese university hospitals from 2008-2010: did it differ from German practice? J Radiat Res. 2017;58(1):135-141.
49. Abuhamed J, Nikkilä A, Lohi O, Auvinen A. Trends of computed tomography use among children in Finland. Eur J Radiol Open. 2020;7:100290. doi:10.1016/j.ejro.2020.100290.
50. Meulepas JM, Holscher HC, Hauptmann M, Rutten MJCM, Gradowska P, Verbeke J, et al. Trends and patterns of computed tomography scan use among children in the Netherlands: 1990-2012. Eur Radiol. 2017;27(6):2426-2433. doi:10.1007/s00330-016-4566-1.
51. Pearce MS, Salotti JA, McHugh K, Metcalf W, Kim KP, Craft AW, et al. CT scans in young people in Northern England: trends and patterns 1993-2002. Pediatr Radiol. 2011;41(7):832-838. doi:10.1007/s00247-011-2110-7.
52. Smith-Bindman R, Kwan ML, Marlow EC, Theis MK, Bolch W, Cheng SY, et al. Trends in use of medical imaging in US health care systems and in Ontario, Canada, 2000-2016. JAMA. 2019;322(9):843-856. doi:10.1001/jama.2019.11456.
53. Hendee WR, Becker GJ, Borgstede JP, Bosma J, Casarella WJ, Erickson BA, et al. Addressing overutilization in medical imaging. Radiology. 2010;257(1):240-245. doi:10.1148/radiol.10100063.
54. Modi N, Clarke J, McKee M. Health systems should be publicly funded and publicly provided. BMJ. 2018;362:k3580. doi:10.1136/bmj.k3580.
55. Bushberg JT, Seibert JA, Leidholdt EM Jr, Boone JM. The essential physics of medical imaging. 4th ed. Philadelphia (PA): Lippincott Williams & Wilkins; 2021.
56. American Association of Physicists in Medicine. Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations (AAPM Task Group 204). College Park (MD): American Association of Physicists in Medicine; 2011.
57. Zhao A, Fopma S, Agrawal R. Demystifying the CT radiation dose sheet. Radiographics. 2022;42:1239-50.
58. Mayo-Smith WW, Hara AK, Mahesh M, Sahani DV, Pavlicek W. How I do it: managing radiation dose in CT. Radiology. 2014;273:657-72.
59. McCollough CH, Leng S, Yu L, Cody DD, Boone JM, McNitt-Gray MF. CT dose index and patient dose: they are not the same thing. Radiology. 2011;259:311-6.
60. American Association of Physicists in Medicine. Size-specific dose estimate (SSDE) for head CT (AAPM Task Group 293). Alexandria (VA): American Association of Physicists in Medicine; 2019.
61. Damilakis J. CT dosimetry: what has been achieved and what remains to be done. Invest Radiol. 2021;56(1):62-8.
62. 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;35(4):891-909.
63. Jansen JT, Shrimpton PC. Development of Monte Carlo simulations to provide scanner-specific organ dose coefficients for contemporary CT. Phys Med Biol. 2016;61(14):5356-77.
64. Gao Y, Quinn B, Mahmood U, Long D, Erdi Y, St Germain J, et al. A comparison of pediatric and adult CT organ dose estimation methods. BMC Med Imaging. 2017;17(1):28.
65. Gao Y, Mahmood U, Liu T, Quinn B, Gollub MJ, Xu XG, et al. Patient-specific organ and effective dose estimates in adult oncologic CT. AJR Am J Roentgenol. 2020;214(4):738-46.
66. Lee C, Journy N, Moroz BE, Little M, Harbron R, McHugh K, et al. Organ dose estimation accounting for uncertainty for pediatric and young adult CT scans in the United Kingdom. Radiat Prot Dosimetry. 2019;184(1):44-53.
67. Brady Z, Forsythe A, McBain-Miller J, Scurrah KJ, Smoll N, Lin Y, et al. CT dosimetry for the Australian cohort data linkage study. Radiat Prot Dosimetry. 2020.
68. Kim KP, Berrington de Gonzalez A, Pearce MS, Salotti JA, Parker L, McHugh K, et al. Development of a database of organ doses for paediatric and young adult CT scans in the United Kingdom. Radiat Prot Dosimetry. 2012;150(4):415-26.
69. Pearce MS, Salotti JA, Little MP, McHugh K, Lee C, Kim KP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. Lancet. 2012;380(9840):499-505.
70. Thierry-Chef I, Ferro G, Le Cornet L, Dabin J, Istad TS, Jahnen A, et al. Dose estimation for the European Epidemiological Study on Pediatric Computed Tomography (EPI-CT). Radiat Res. 2021;196(1):74-99.
71. Ngaile JE, Msaki PK. Estimation of patient organ doses from CT examinations in Tanzania. J Appl Clin Med Phys. 2006;7(3):80-94.
72. Chu PW, Stewart C, Kofler C, Mahendra M, Wang Y, Chu CA, Lee C, Bolch WE, Smith-Bindman R. Representative organ doses from computed tomography (CT) exams from a large international registry. Radiat Res. 2025;203(1):1-9. doi:10.1667/RADE-24-00178.1.
73. Poosiri S, Chuboonlap K, Kaewlaied N. An age-based size-specific dose estimate for pediatric computed tomography head examinations performed at Songklanagarind Hospital, Thailand, from 2017 to 2019. Appl Sci (Switz). 2024;14(17):7848. doi:10.3390/app14177848.
74. Inoue Y, Mori M, Itoh H, Mitsui K, Miyatake H, Yamane T, Hata H. Age-dependent changes in effective dose in pediatric brain CT: comparisons of estimation methods. Tomography. 2024;10(1):14-24. doi:10.3390/tomography10010002.
75. Biegała M, Skoczylas K, Matera K, Grzelak P, Staniszewska MA. Head computed tomography examination as a factor of radiation exposure in children treated for hydrocephalus. Int J Occup Med Environ Health. 2025;38(2):163-9. doi:10.13075/ijomeh.1896.02572.
76. Özsoykal İ, Yurt A, Akgüngör K. Size-specific dose estimates in chest, abdomen, and pelvis CT examinations of pediatric patients. Diagn Interv Radiol. 2018;24(4):243-8. doi:10.5152/dir.2018.17450.
77. Khan R, Shah MA, Wahab S, Khan RA. Size-specific dose estimate and effective dose for pediatric computed tomography. J Med Phys. 2025;50(1):173-83. doi:10.4103/jmp.jmp_55_24.
78. Keshtkar M. Paediatric cancer risks associated with chest computed tomography (CT) scans: comparison of routine chest and COVID-19 diagnosis CT protocols. Radioprotection. 2024;59(2):131-7. doi:10.1051/radiopro/2024008.
79. Brenner DJ, Elliston CD, Hall EJ, Berdon WE. Estimated risks of radiation-induced fatal cancer from pediatric CT. AJR Am J Roentgenol. 2001;176(2):289-296.
80. Mathews JD, Forsythe AV, Brady Z, Butler MW, Goergen SK, Byrnes GB, et al. Cancer risk in 680 000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. BMJ. 2013;346:f2360.
81. Huang WY, Muo CH, Lin CY, Jen YM, Yang MH, Lin JC, et al. Paediatric head CT scan and subsequent risk of malignancy and benign brain tumour: a nation-wide population-based cohort study. Br J Cancer. 2014;110(9):2354-2360.
82. Journy N, Roué T, Cardis E, Le Pointe HD, Brisse H, Chateil JF, et al. Childhood CT scans and cancer risk: impact of predisposing factors for cancer on the risk estimates. J Radiol Prot. 2016;36(1):N1-N7.
83. Bernier MO, Baysson H, Pearce MS, Moissonnier M, Cardis E, Hauptmann M, et al. Cohort profile: The EPI-CT study: a European pooled

epidemiological study to quantify the risk of radiation-induced cancer from paediatric CT. Int J Epidemiol. 2019;48(2):379-381g.
84. Huang R, Liu X, He L, Zhou PK. Radiation exposure associated with computed tomography in childhood and the subsequent risk of cancer: a meta-analysis of cohort studies. Dose Response. 2020;18(2):1559325820923828.
85. de Gonzalez AB, Salotti JA, McHugh K, Little MP, Harbron RW, Lee C, et al. Relationship between paediatric CT scans and subsequent risk of leukaemia and brain tumours: assessment of the impact of underlying conditions. Br J Cancer. 2016;114(4):388-394.
86. Bosch de Basea Gomez M, Thierry-Chef I, Harbron R, Hauptmann M, Byrnes G, Bernier MO, et al. Risk of hematological malignancies from CT radiation exposure in children, adolescents and young adults. Nat Med. 2023;29(12):3111-3119.
87. Meulepas JM, Ronckers CM, Smets AMJB, Nievelstein RAJ, Gradowska P, Lee C, et al. Radiation exposure from pediatric CT scans and subsequent cancer risk in the Netherlands. J Natl Cancer Inst. 2019;111(3):256-263.
88. Wang WH, Sung CY, Wang SC, Shao YHJ. Risks of leukemia, intracranial tumours and lymphomas in childhood and early adulthood after pediatric radiation exposure from computed tomography. CMAJ. 2023;195(16):E575-E583.
89. Kojimahara N, Yoshitake T, Ono K, Kai M, Bynes G, Schüz J, et al. 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;40(4):1010-1023.
90. Journy NMY, Lee C, Harbron RW, McHugh K, de González AB. Projected cancer risks potentially related to past, current, and future practices in paediatric CT in the United Kingdom, 1990-2020. Br J Cancer. 2017;116(1):109-116.
91. Al-Shangeeti T, Ahmad R, Alshehade SA, Elzaki M, Alothaim FA, Alsharif W, Soliman K, Al-Shangeeti A, Al-Shamrani B, Hanbali A, Almuzaini T, Alnasser M, Althubyani T, Aljohani A, Baba AM, Alruwaili AZ, Hamid Osman HO, Alshawsh MA. Factors associated with CT scan repetition in pediatrics and its relationship with cancer risk: a systematic review and meta-analysis. Dose Response. 2026;24(2):15593258261419666. doi:10.1177/15593258261419666.
92. Nagy E, Tschauner S, Schramek C, Sorantin E. Paediatric CT made easy. Pediatr Radiol. 2023;53(4):581-588. doi:10.1007/s00247-022-05526-0.
93. Aziz MM, Onyejesi C, Pyala R, Alattar O, Abdul AA, Alagarswamy K, Butt I, Gamboa LL, Alsabri M. Reducing radiation exposure in pediatric CT imaging: strategies and alternatives in emergency medicine-a narrative review. J Emerg Crit Care Med. 2025;9:12. doi:10.21037/jeccm-24-102.
94. Solomon DZ, Ayalew B, Dellie ST, Admasie D. Justification and optimization principles of ALARA in pediatric CT at a teaching hospital in Ethiopia. Ethiop J Health Sci. 2020;30(5):761-766. doi:10.4314/ejhs.v30i5.16.
95. Armao D, Hartman T, Shea CM, Sams C, Ivanovic M, Fordham LA, Smith JK. A toolkit for pediatric CT dose reduction in community hospitals. J Am Coll Radiol. 2016;13(11):1337-1342.e11. doi:10.1016/j.jacr.2016.04.032.
96. Padole AM, Sagar P, Westra SJ, Lim R, Nimkin K, Kalra MK, Gee MS, Rehani MM. Development and validation of image quality scoring criteria (IQSC) for pediatric CT: a preliminary study. Insights Imaging. 2019;10(1):95. doi:10.1186/s13244-019-0769-8.
97. Samei E, Li X, Frush DP. Size-based quality-informed framework for quantitative optimization of pediatric CT. J Med Imaging (Bellingham). 2017;4(3):031209. doi:10.1117/1.JMI.4.3.031209.
98. International Commission on Radiological Protection. Radiological protection and safety in medicine. Oxford: Pergamon Press; 1996.
99. International Commission on Radiological Protection. Diagnostic reference levels in medical imaging. Oxford: Pergamon Press; 2017.
100. International Commission on Radiological Protection. The 2007 recommendations of the International Commission on Radiological Protection. Oxford: Pergamon Press; 2007.
101. Kanal KM, et al. U.S. diagnostic reference levels and achievable doses for 10 pediatric CT examinations. Radiology. 2022;302:164-174.
102. Zamani H, Kavousi N, Masjedi H, Omidi R, Rahbar S, Perota G, Razavi E, Zare MH, Abedi-Firouzjah R. Estimation of diagnostic reference levels and achievable doses for pediatric patients in common computed tomography examinations: a multi-center study. Radiat Prot Dosimetry. 2021;194:214-222.
103. Worrall M, Holubinka M, Havariyoun G, Hodgson K, Edyvean S, Holroyd J, Davis A, Dunn M, Gardiner A. Analysis and results from a UK national dose audit of paediatric CT examinations. Br J Radiol. 2022;95(1129):20210796. doi:10.1259/bjr.20210796.
104. Wagner F, Bize J, Racine D, Le Coultre R, Verdun F, Trueb PR, Treier R. Derivation of new diagnostic reference levels for neuro-paediatric computed tomography examinations in Switzerland. J Radiol Prot. 2018;38(3):1013-1036. doi:10.1088/1361-6498/aac69c.
105. Yang F, Gao L. Age-based diagnostic reference levels and achievable doses for paediatric CT: a survey in Shanghai, China. J Radiol Prot. 2024;44(2):021509. doi:10.1088/1361-6498/ad3ce5.
106. Takei Y, Miyazaki O, Matsubara K, Shimada Y, Muramatsu Y, Akahane K, Fujii K, Suzuki S, Koshida K. Nationwide survey of radiation exposure during pediatric computed tomography examinations and proposal of age-based diagnostic reference levels for Japan. Pediatr Radiol. 2016;46(2):280-285. doi:10.1007/s00247-015-3474-x.
107. Matsunaga Y, Chida K, Kondo Y, Kobayashi K, Kobayashi M, Minami K, Suzuki S, Asada Y. Diagnostic reference levels and achievable doses for common computed tomography examinations: results from the Japanese nationwide dose survey. Br J Radiol. 2019;92(1094):20180290. doi:10.1259/bjr.20180290.
108. Kim MC, Chang KH, Hwang JH, Nam YC, Han DK, Yoon J. Radiation dose for pediatric and young adult CT: a survey to establish age-based reference levels of 2015-2016 in Korea. Radiat Prot Dosimetry. 2017;175(2):228-237. doi:10.1093/rpd/ncw289.
109. Kang T, Zhang Z, Zhang Y, Chen E, Niu Y. A multi-provincial survey and analysis of radiation doses from pediatric CT in China. Radiat Med Prot. 2021;2(1):23-27. doi:10.1016/j.radmp.2021.02.001.
110. Tonkopi E, Iwaskow M, Lønningen CK, Johansen AM, Suganthan S, Kotlyarova Y, Badawy M, Gunn C, Kimber J, Jackson D, Tetteh MA, Holter TO, Johansen S. A multi-institutional CT practices survey of pediatric head, chest, and abdomen-pelvis examinations. Acta Radiol Open. 2025;14(5):20584601251340974. doi:10.1177/20584601251340974.
111. Bos D, Wang Y, Stewart C, Chu PW, Luong J, Haubold J, Schröer B, Zensen S, Duong PAT, Schindera S, Jeukens CRLPN, Das M, Einstein AJ, Cervantes L, Smith-Bindman R. Diagnostic reference levels for indication-based CT categories in pediatric CT: data from an international registry. Eur Radiol. 2025;35(12):7985-7999. doi:10.1007/s00330-025-11724-9.
112. Zakariaee SS, Naderi N, Kazemi-Arpanahi H. Diagnostic reference levels for pediatric CT examinations based on patient size: a meta-analysis. J Pediatr Rev. 2025;13(3):169-182. doi:10.32598/jpr.13.3.1235.1.
113. Rawashdeh M, Saade C, Al Mousa DS, Abdelrahman M, Kumar P, McEntee M. A new approach to dose reference levels in pediatric CT: age and size-specific dose estimation. Radiat Phys Chem. 2023;205:110698. doi:10.1016/j.radphyschem.2022.110698.
114. Dastikas R, Jreije A, Griciené B. Establishing local diagnostic reference levels and reference curves for thorax and abdomen-pelvis paediatric CT procedures. Acta Med Litu. 2025;32(1):107-117. doi:10.15388/Amed.2025.32.1.12.
115. van der Merwe CM, Mahomed N. An audit of radiation doses received by paediatric patients undergoing computed tomography investigations at academic hospitals in South Africa. S Afr J Radiol. 2020;24(1):a1823. doi:10.4102/SAJR.V24I1.1823.
116. Aloufi KM, Alhazmi FH, Alrehily FA, Alraddadi NS, Alharbi AS, Alamin AM, Alenezi AA, Hadi FH. Assessing effective doses and proposing DRLs for pediatric CT procedures in Madinah (single hospital), Saudi Arabia. Appl Sci (Switzerland). 2024;14(17):7583. doi:10.3390/app14177583.
117. Bibbo G, Brown S, Linke R. Diagnostic reference levels of paediatric computed tomography examinations performed at a dedicated Australian paediatric hospital. J Med Imaging Radiat Oncol. 2016;60(4):475-484. doi:10.1111/1754-9485.12488.
118. Alhailiy A, Alkhybari E, Alghamdi S, Fisal N, Aldosari S, Albeshan S. Reporting diagnostic reference levels for paediatric patients undergoing brain computed tomography. Tomography. 2023;9(6):2029-2038. doi:10.3390/tomography9060159.
119. Muhammad NA, Khalis Abdul Karim M, Hassan HA, Kamarudin MA, Ding Wong JH, Hoong Ng K. Diagnostic reference level of radiation dose and image quality among paediatric CT examinations in a tertiary hospital in Malaysia. Diagnostics (Basel). 2020;10(8):591. doi:10.3390/diagnostics10080591.
120. Bouchareb Y, Al Kharusi M, Al Maqbali A, Al Maimani A, Al Maskari H, Sirasanagandla SR, Al Jabri A, Al Kindi F, Al Shabibi S, Baawain S. Establishing diagnostic reference levels for paediatric CT imaging: a multi-centre study. Healthcare (Basel). 2025;13(14):1728. doi:10.3390/healthcare13141728.
121. Ploussi A, Syrgiamiotis V, Makri T, Hatzigiorgi C, Efstathopoulos EP. Local diagnostic reference levels in pediatric CT examinations: a survey at the largest children's hospital in Greece. Br J Radiol. 2020;93(1116):20190358. doi:10.1259/bjr.20190358.
122. Eddy FK, Ngano SO, Jervé FA, Serge A. Radiation dose evaluation of pediatric patients in CT brain examination: multi-center study. Sci Rep. 2021;11(1):4663. doi:10.1038/s41598-021-84078-z.
123. Amedzoame B, Brobbey IF, Djan B, Acquah IK, Tetteh MA. Assessment of radiation doses for paediatric head, chest, and abdominopelvic computed tomography examinations in a teaching hospital in Ghana. Pol J Med Phys Eng. 2025;31(3):256-262. doi:10.2478/pjmpe-2025-0029.

124. Priyanka, Kadavigere R, Sukumar S, Pendem S. Diagnostic reference levels for computed tomography examinations in pediatric population-a systematic review. J Cancer Res Ther. 2021;17(4):845-852. doi:10.4103/jcrt.JCRT_945_20.
125. Gyan E, Subaar C, Edusei G, Antwi Nyarko L. Paediatric computed tomography diagnostic reference levels in Africa: a systematic review. J Med Radiat Sci. 2025;72(1):139-147. doi:10.1002/jmrs.824.
126. Kamdem FE, Ngano SO, Alla Takam C, Fotue AJ, Abogo S, Fai CL. Optimization of pediatric CT scans in a developing country. BMC Pediatr. 2021;21(1):44. doi:10.1186/s12887-021-02498-2.
127. Karappara J, Koteshwar P, Panakkal NC, Sukumar S. Optimization of pediatric CT brain protocol to achieve reduced patient dose. Biomed Pharmacol J. 2020;13(1):391-397. doi:10.13005/bpj/1899.
128. Browne JE, Bruesewitz MR, Thomas V, Thomas KB, Hull NC, McCollough CH, Yu L. Procedure for optimal implementation of automatic tube potential selection in pediatric CT to reduce radiation dose and improve workflow. J Appl Clin Med Phys. 2021;22(2):194-202. doi:10.1002/acm2.13098.
129. Papadakis AE, Damilakis J. Automatic tube current modulation and tube voltage selection in pediatric computed tomography: a phantom study on radiation dose and image quality. Invest Radiol. 2019;54(5):265-272. doi:10.1097/RLI.0000000000000537.
130. Hojreh A, Homolka P, Gamper J, Unterhumer S, Kienzl-Palma D, Balassy C, Wrba T, Prosch H. Automated tube voltage selection in pediatric non-contrast chest CT. PLoS One. 2019;13(10):e0204794. doi:10.1371/journal.pone.0204794.
131. Masuda T, Funama Y, Kiguchi M, Imada N, Oku T, Sato T, Awai K. Radiation dose reduction based on CNR index with low-tube voltage scan for pediatric CT scan: experimental study using anthropomorphic phantoms. Springerplus. 2016;5(1):2064. doi:10.1186/s40064-016-3715-y.
132. Roik D, Barczuk M, Burzyńska Z, Biejat A, Żerańska M, Mierzewska-Schmidt M, Floriańczyk T, Brzewski M. Postnatal evaluation of congenital chest pathologies using a low-dose computed tomography protocol-a pictorial review. Pol J Radiol. 2017;82:466-472. doi:10.12659/PJR.900615.
133. Rabinowich A, Shendler G, Ben-Sira L, Shiran SI. Pediatric low-dose head CT: image quality improvement using iterative model reconstruction. Neuroradiol J. 2023;36(5):555-562. doi:10.1177/19714009231163559.
134. Villanueva-Meyer JE, Naeger DM, Courtier JL, Hope MD, Lambert JW, MacKenzie JD, Phelps AS. Pediatric chest CT at chest radiograph doses: when is the ultralow-dose chest CT clinically appropriate? Emerg Radiol. 2017;24(4):369-376. doi:10.1007/s10140-017-1487-5.
135. Patil NB, Priyanka, SPP, Kadavigere R, Pendem S. Advancements in radiation dose reduction for pediatric CT head imaging: a scoping review of emerging technologies, protocols, and optimization strategies. Tech Innov Patient Support Radiat Oncol. 2026;37:100374. doi:10.1016/j.tipsro.2026.100374.
136. Aipanda CN, Karera A, Kalondo L, Amkongo M. Radiation risk-benefit communication during paediatric CT imaging: experiences of radiographers at two public hospitals. Radiography (Lond). 2023;29(2):301-306. doi:10.1016/j.radi.2023.01.006.
137. Teferi S, Zewdeneh D, Bekele S. Pediatric residents' and medical interns' awareness about pediatric ionizing radiation dose from computed tomography and its associated risks in tertiary hospital in Ethiopia. Ethiop J Health Sci. 2018;28(4):383-392. doi:10.4314/ejhs.v28i4.4.
138. Overhoff D, Weis M, Riffel P, Sudarski S, Froelich MF, Fries P, Schönberg S, Gawlitza J. Radiation dose of chaperones during common pediatric computed tomography examinations. Pediatr Radiol. 2020;50(8):1078-1082. doi:10.1007/s00247-020-04681-6.
139. Greenberg H, Davis M. How confident are UK radiographers at performing paediatric computed tomography trauma scans? Radiography (Lond). 2023;29(2):362-368. doi:10.1016/j.radi.2023.01.010.
140. Sayed IS, Mohd Yusof MI. Techniques and strategies to minimize radiation exposure in pediatric computed tomography (CT) abdominal examinations: a review. Cureus. 2024;16(8):e67494. doi:10.7759/cureus.67494.
141. Hiles P, Benson E, Hughes H, Loader R, Shaw D, Edyvean S, et al. *Guidance on using shielding on patients for diagnostic radiology applications*. London: British Institute of Radiology; 2020.
142. Vaño E, Miller DL, Martin CJ, Rehani MM, Kang K, Rosenstein M, et al. Diagnostic reference levels in medical imaging. *Ann ICRP*. 2017;46(1):1-144. doi:10.1177/0146645317717209.
143. European Commission. *European guidelines on diagnostic reference levels for paediatric imaging*. Luxembourg: Publications Office of the European Union; 2018. doi:10.2768/185045.
144. Yoshitake T, Miyazaki O, Kitamura M, Ono K, Kai M. Quantitative analysis of the clinical reasons influencing the frequency of pediatric head CT examinations: a single-center observation study. *Tomography*. 2023;9(2):829-839. doi:10.3390/tomography9020067.
145. Perota G, Masjedi H, Zamani H, Dalvand S, Omidi R, Razavi E, et al. Trends of computed tomography scan usage among adults and children in Yazd Province, Iran, before the outbreak of COVID-19. *Front Biomed Technol*. 2021;8(4):246-252. doi:10.18502/fbt.v8i4.7752.
146. O'Connor M, Grassick E. A retrospective analysis of paediatric medical imaging utilisation in Ireland, 2019-2023. *J Med Imaging Radiat Sci*. 2025;56(6):102083. doi:10.1016/j.jmir.2025.102083.
147. Gabela I. Potencijalni rizici ionizirajućeg zračenja i optimizacija doze u pedijatrijskoj CT dijagnostici (Master's thesis), Split: Faculty of Health Sciences, University of Split; 2026.

Između minimalne doze i optimalne slike: izazovi pedijatrijske CT dijagnostike

Sažetak

Kompjutorizirana tomografija (engl. *Computed Tomography*, CT) zbog brzine izvođenja, dostupnosti i visoke dijagnostičke vrijednosti ima značajno mjesto u pedijatrijskoj dijagnostici. Istodobno, povećana osjetljivost djece na ionizirajuće zračenje zahtijeva posebnu pozornost pri opravdanju pretraga i optimizaciji doze. Cilj ovog preglednog rada bio je prikazati spoznaje o rizicima izloženosti ionizirajućem zračenju tijekom pedijatrijskih CT pretraga te suvremenim mogućnostima smanjenja doze. Pregled literature pokazuje da tehnološki razvoj CT uređaja, primjena pedijatrijskih protokola, automatska kontrola ekspozicije, iterativne rekonstrukcije i dijagnostičke referentne razine omogućuju smanjenje izloženosti uz očuvanje dijagnostičke kvalitete slike. Dodatnom smanjenju rizika pridonose opravdanost svake pretrage te prilagodba protokola dobi i tjelesnoj građi djeteta. Standardizacija postupaka, primjena međunarodnih preporuka i stručne kompetencije radioloških tehnologa važni su za daljnje unapređenje radiološke zaštite i sigurnosti pedijatrijskih pacijenata.

Ključne riječi: optimizacija doze; ionizirajuće zračenje; pedijatrijska kompjutorizirana tomografija (CT); zaštita od zračenja; rizici zračenja.