Imaging and Radiation Research (2023) Volume 6 Issue 1
doi: 10.24294/irr.v6i1.2218

ORIGINAL RESEARCH ARTICLE

Lowering head computed tomography radiation dose for craniosynostosis: An institutional change and review of literature

Luke Bauerle[1], Steven Lin[1,*], Cody Tucker[1], Ramin Eskandari[2]

[1] *College of Medicine, Medical University of South Carolina, Charleston, SC 29425, USA*

[2] *Department of Neurological Surgery, Medical University of South Carolina, Charleston, SC 29425, USA*

*** Corresponding author:** Steven Lin, linst@musc.edu

ABSTRACT

Definitive diagnosis of Craniosynostosis (CS) with computed tomography (CT) is readily available, however, exposure to ionizing radiation is often a hard stop for parents and practitioners. Lowering head CT radiation exposure helps mitigate risks and improves diagnostic utilization. The purpose of the study is to quantify radiation exposure from head CT in patients with CS using a 'new' (ultra-low dose) protocol; compare prior standard CT protocol; summarize published reports on cumulative radiation doses from pediatric head CT scans utilizing other low-dose protocols. A retrospective study was conducted on patients undergoing surgical correction of CS, aged less than 2 years, between August 2014 and February 2022. Cumulative effective dose (CED) in mSv was calculated, descriptive statistics were performed, and mean ± SD was reported. A literature search was conducted describing cumulative radiation exposure from head CT in pediatric patients and analyzed for ionizing radiation measurements. Forty-four patients met inclusion criteria: 17 females and 27 males. Patients who obtained head CT using the 'New' protocol resulted in lower CED exposure of 0.32 mSv ± 0.07 compared to the prior standard protocol at 5.25 mSv ± 2.79 ($p < 0.0001$). Five studies specifically investigated the reduction of ionizing radiation from CT scans in patients with CS via the utilization of low-dose CT protocols. These studies displayed overall CED values ranging from 0.015 mSv to 0.77 mSv. Our new CT protocol resulted in 94% reduction of ionizing radiation. Ultra-low dose CT protocols provide similar diagnostic data without loss of bone differentiation in CS and can be easily incorporated into the workflow of a children's hospital.

Keywords: children; computed tomography optimization; craniosynostosis; head; radiation dose; skull

ARTICLE INFO

Received: 8 March 2023
Accepted: 27 April 2023
Available online: 15 May 2023

1. Introduction

Computed tomography (CT) scans are among the most common diagnostic imaging techniques used in pediatric medicine secondary to their ease of use, speed of results and widespread availability at most children's hospitals. In pediatrics the head is the most frequently imaged body part, with craniosynostosis (CS) being a common condition requiring the use of pediatric head CT[1]. Craniosynostosis, the pathologically premature fusion of one or more cranial sutures during infancy, occurs approximately one in every 2000 live births[2–4]. Increasing rates of positional plagiocephaly have made definitive diagnosis with low radiation dose CT more desirable. In the majority of cases, head CT for diagnosis confirmation, surgical planning, and occasionally for post-operative follow-up is standard practice[5–7].

Bone differentiation, speed of image acquisition and lack of sedation requirement are significant advantages of CT over other imaging modalities (i.e., x-ray, magnetic resonance imaging and ultrasound)[8]. Radiation exposure over a lifetime raises concerns from both parents and physicians for radiation induced malignancies, such as reported by Pearce et al.[9], Boice[10], Mathews et al.[11], and Montoya et al.[12]. Many children's hospitals utilize lower average dose of CT radiation for children, however they have not dramatically lowered doses for infants with CS. By altering the diagnostic yield to only concentrate on the skull, but not the brain, we have lowered ionizing radiation doses to a fraction of our prior standard pediatric CT imaging. We propose that quality head CT scans in CS patients can be achieved while simultaneously using the lowest level of ionizing radiation possible.

2. Methods

A retrospective study was conducted on patients undergoing surgical correction of CS, aged less than 2 years, between August 2014 and February 2022. Demographic information included the patient's date of birth, sex, craniosynostosis etiology, date of CT scan(s), the CT scanner type, CTDIvol in mGy, and DLP in mGy-cm. For each patient cumulative effective dose (CED) in millisieverts (mSv) was calculated using previously published methods[13]. The "Old" CT protocol utilized 4 mm thinly collimated unenhanced spiral CT images from a SOMATOM Definition Flash scanner (Siemens Medical Solutions USA, Inc, Pennsylvania, USA). The "New" protocol altered image acquisition with 1 mm slice thickness from a SOMATOM Drive CMPCT scanner. Two-tailed Student's *t*-tests were performed to analyze the differences between the 'Old' and 'New' protocols, with a significance level of $p \leq 0.05$.

A systematic literature review using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines was conducted to analyze low-dose CT imaging protocols utilized in pediatric head CT scans. The search included published articles in the National Library of Medicine (PubMed) database, with no restriction on publication year. Search terms included: (["low-dose head CT"] and ["craniosynostosis" or "synostosis" or "cranial suture"] and ["pediatric" or "child"]). Two reviewers independently screened titles and abstracts for identification of articles for inclusion.

3. Results

Forty-four patients met inclusion criteria for our institutional study: 17 females and 27 male patients below the age of two years (**Table 1**). Of the 44 patients included, 20 (45.5%) had sagittal, 8 (18.2%) metopic, 4 (9.1%) coronal, 1 (2.3%) squamous, 1 (2.3%) lambdoid, and 10 (22.7%) multisuture synostosis (**Table 1**). Syndromic CS was noted in 4 (9.1%) of the included patients. Additionally, 24/44 (54.5%) of the patients were exposed to CT scans utilizing the 'Old' protocol and 20/44 (45.5%) were exposed to CT scans utilizing the 'New' protocol (**Table 2**). No patients required repeat imaging secondary to non-diagnostic scans.

Table 1. Patient demographics.

Gender	**N (%)**
Female	17 (38.6)
Male	27 (61.4)
Type of CS	**N (%)**
Sagittal	20 (45.5)
Metopic	8 (18.2)
Coronal	4 (9.1)
Lambdoidal	1 (2.3)
Squamosal	1 (2.3)
Multisutural	10 (22.7)

Patients who obtained CT scans using the 'New' protocol had a lower overall CTDIvol (2.03 mGy ± 0.31) compared to patients who had head CT using the 'Old' protocol (21.78 mGy ± 6.54, $p < 0.0001$) (**Table 2**). There was also statistically significant difference in the overall DLP between patients that were exposed to CT scans using the 'Old' and 'New' protocol, 517.28 mGy-cm ± 263.91 versus 34.20 mGy-cm ± 7.51 respectively ($p < 0.0001$). After determining each patient's CED, we determined that patients exposed to CT scans using the 'New' protocol had a significantly lower overall CED (0.32 mSv ± 0.07) compared to patients exposed to CT scans using the 'Old' protocol (5.25 mSv ± 2.79, $p < 0.0001$).

Table 2. Radiation dose in "Old" and "New" protocols for head CT in pediatrics.

Protocol	CTDIvol (mGy) (mean ± SD)	DLP (mGy-cm) (mean ± SD)	CED (mSv) (mean ± SD)
Old (n = 24)	21.78 ± 6.54	517.28 ± 263.91	5.25 ± 2.79
New (n = 20)	2.03 ± 0.31	34.20 ± 7.51	0.32 ± 0.07
p	<0.0001	<0.0001	<0.0001

Literature published using modern CT methods since the advent of rapid multi-detector image acquisition, revealed seventeen studies that investigated cumulative ionizing radiation doses from head CT scans in pediatric patients (**Figure 1**)[1,12,14–27]. These studies included numerous pediatric patients ranging in age from newborn to 17 years old, with the seventeen studies reporting calculated effective doses ranging from 0.015 mSv to 8.91 mSv[1,12,14–27].

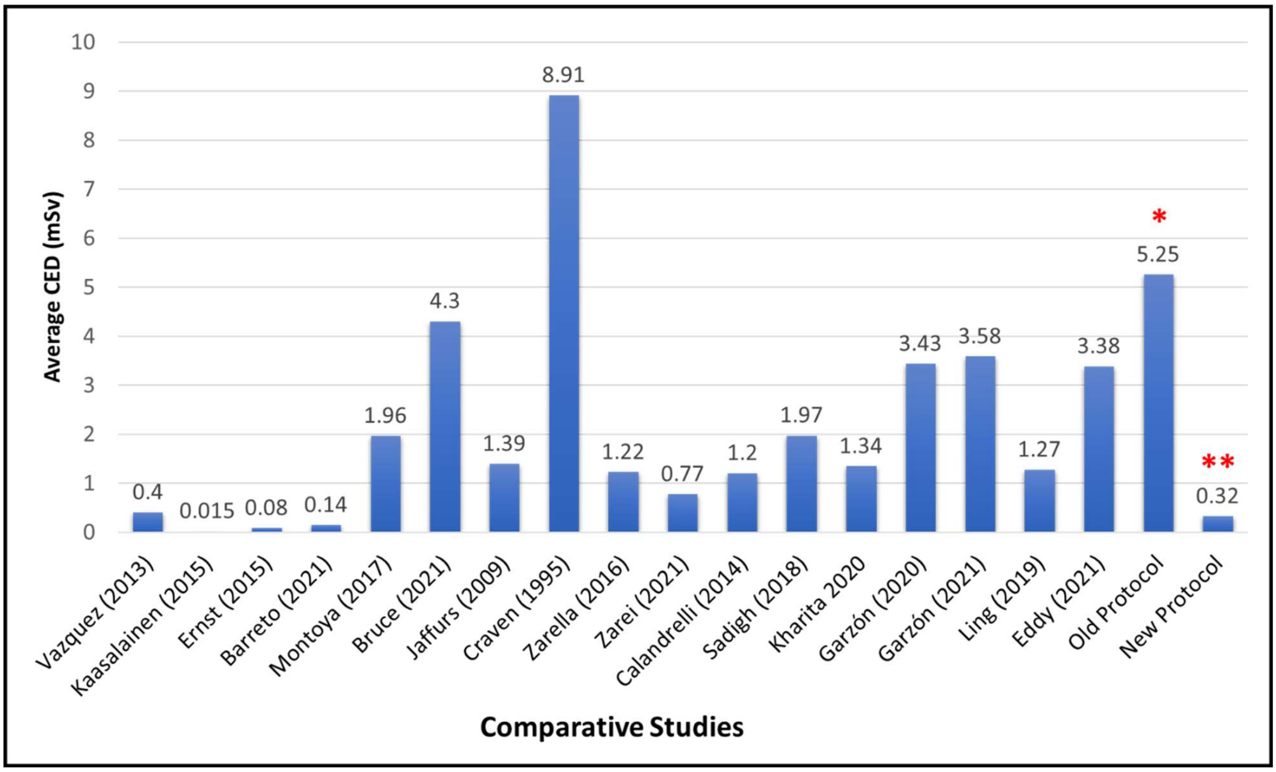

Figure 1. Mean CED (mSv) from comparative pediatric head CT studies alongside 'Old' (*) and 'New' (**) protocols.

Of the seventeen studies included, five were found to specifically investigate ionizing radiation exposure from CT scans in pediatric patients with CS, with these studies also emphasizing the utilization of low-dose CT protocols that yielded effective doses of less than 1 mSv[17–20,26]. One study utilized anthropomorphic phantoms and was able to achieve the lowest effective dose of 0.015 mSv[20]. These studies included a total of 344 patients with ages ranging from newborn to 5 years old (**Table 3**).

These five studies had DLP, CTDIvol, and CED values ranging from 4.65–85.9 mGy-cm, 0.22–5.4 mGy, 0.015–0.77 mSv, and mean values of 32.9 mGy-cm, 1.99 mGy, 0.281 mSv, respectively (**Table 5**)[17–20,26]. Compared to the DLP, CTDIvol, and CED values from our 'New' protocol, our values were slightly higher than the mean values from the five studies, with differences of 3.8% for DLP, 1.97% for CTDIvol, and 12.2% for CED, respectively. Radiation dose reduction corresponds with alteration in CT acquisition parameters. A majority of the studies were performed with a fixed tube current of 10 mA and a tube voltage of 80 kVp, which is commonly the lowest setting available on most CT scanners (**Table 4**).

Table 3. Low-dose CT studies for pediatric CS included in present study.

Source	Year of publication	Journal	Country	Study type	No. of patients	Age (years)
Vazquez JL et al.[19]	2013	European Radiology	Spain	Prospective Comparative	80	0–5
Kaasalainen T et al.[20]	2015	Pediatric Radiology	Finland	Prospective Comparative	2[a]	0–5
Ernst CW et al.[18]	2015	European Radiology	Belgium	Retrospective Comparative	48	0–3
Barreto IL et al.[17]	2021	Pediatric Radiology	U.S.A.	Prospective Comparative	157	0.5–3
Zarei F et al.[26]	2021	Iranian Journal of Medical Physics	Iran	Prospective Comparative	57	0–3

[a]Anthropomorphic phantoms of pediatric newborn and 5-year-old were utilized.

Table 4. Low-dose CT acquisition parameters for pediatric CS studies.

Source	Detector rows	Detector configuration (mm)	Rotation time (sec)	Tube voltage (kVp)	Tube current (mA)	Pitch factor
Vazquez JL et al.[19]	64	40 × 0.625	0.4	80	50-150[a]	0.984
Kaasalainen T et al.[20]	64	64 × 0.625	0.4	80	10	0.9
Ernst CW et al.[18]	64	32 × 0.525	0.8	80	10	0.53
Barreto IL et al.[17]	80	40 × 0.5	0.5	100	10	0.625
Zarei F et al.[26]	8	8 × 1.25	0.8	80	70	1.35

[a]Tube current modulation used to adjust mA in order to achieve acceptable image quality.

Table 5. Corresponding mean CED, CTDIvol, and DLP for low-dose CT imaging of pediatric CS studies.

Source	CED (mSv)	CTDIvol (mGy)	DLP (mGy-cm)
Vazquez JL et al.[19]	0.4	2.3	40
Kaasalainen T et al.[20]	0.015	0.22	4.65
Ernst CW et al.[18]	0.08	0.94	15.04
Barreto IL et al.[17]	0.14	1.1	19.1
Zarei F et al.[26]	0.77	5.4	85.9

4. Discussion

Since its development in the early 1970s, computed tomography scanner design advancements and computational processing have reduced the time needed for image acquisition and have resulted in images with progressively better resolution[28,29]. The very first CT scan took nearly two days of processing at an off-site mainframe computer[30]. The first-generation of practically sized CT scanners, which utilized a "translate/rotate method" of imaging reduced single-image processing time to only 4.5 min however carried a median effective radiation dose of 2.67 mSv-greater than the average background radiation exposure per person each year[28,31,32].

Subsequent generations achieved faster processing times with better image quality, but most importantly lowered ionizing radiation exposures.

Eventually, multi-slice or “multi-detector” CT scanners utilized the indefinitely revolving tube concept from previous generations while adding multiple detectors for much faster image acquisition[31]. When combined with increased tube rotation velocity, the addition of multiple detectors allowed for the creation of detailed images with greater overall coverage in mere fractions of a second. In 2004, with the introduction of the 64-detector scanner, detailed axial images were obtained in approximately 1/3 of a second[28]. These “modern” CT scanners not only allowed for faster scanning times but the creation of detailed cross-sectional images with much better resolution, especially of highly dense structures such as bone[33,34]. Additionally, the amount of ionizing radiation was significantly lower compared to their predecessors. Median effective radiation dose of only 0.93 mSv has been reported from the newest 320-detector scanners, which represents a nearly 66% reduction compared to the doses from first-generation scanners[32].

Most of our knowledge regarding radiation effects on humans came from nuclear disasters such as atomic bombs used during World War II in Japan and the Chernobyl Reactor explosion in Ukraine. A typical adult can expect to receive an approximate dose of 3.10 mSv of radiation over their lifetime from sources such as the Sun and certain soil types[35]. It has long been known that the harmful effects of ionizing radiation are enhanced in children both in low doses accumulated over time and large doses accumulated in single exposures[35]. However the medicinal use of ionizing radiation is quite substantial as 12% of the total human radiation exposure comes from nuclear medicine alone[36]. Radiation preferentially targets dividing cells, which typically is quite minimal in the brain. However, compared with the fully developed brain of adults, infants’ developing and differentiating brain cells suffer far greater from effects of ionizing radiation[37]. In 2001, Brenner and colleagues estimated the risks of radiation-induced fatal cancer from pediatric CT examinations[38]. According to their findings, a cumulative absorbed organ dose of 60 mGy (1 mGy = 1 mSv) in pediatric patients tripled the risk of brain cancer[38]. This risk is further compounded by the fact that the number of diagnostic radiologic examinations have increased almost 10-fold from 1950 to 2006[39].

Due to this increase in frequency of radiologic studies, exposure to ionizing radiation from medical imaging has significantly increased in the general population, with per-capita annual effective dose from medical procedures rising nearly six-fold from 0.5 mSv in 1980 to 3.0 mSv in 2006 in the United States alone[39,40]. CT is recognized as the largest contributor to this increase. One recent European cohort study demonstrated an increase in the number of head or neck CT scans in patients less than 22 years old led to increased cumulative brain doses of radiation and increased reported cases of gliomas and other types of brain cancer[41]. Despite the reported risks, much is still unknown about the lower thresholds of radiation exposure damage. Two things, however, are certain: high radiation exposure (>3000 mSv), particularly in a short amount of time, is widely known to cause harm and possible death, and the susceptibility of children with rapid cell turnover is even greater, and effects may not show themselves for 10–30 years after exposure[38,40].

Best practice continues to minimize radiation exposure whenever possible. Our recently developed ultra-low dose protocol achieved dose reduction by lowering head CT CED by roughly 94% compared to our previously utilized dose protocol (**Figure 1**). In order to reach the threshold, set by Brenner et al of 60 mSv to the head, a child would need to undergo more than 188 CT scans using the ‘New’ ultra-low dose protocol. Low-dose CT imaging for pediatric craniosynostosis can be achieved through adjustments to various acquisition parameters, such as tube voltage (kVp), tube current (mA), pitch ratio, and tube rotation time (s) or altering the field of exposure through collimation and protective shielding (**Tables 4** and **5**)[17–20,26]. These parameters can be adjusted to reduce the radiation dose while still producing high-quality images of the bony calvarium, which is the main focus of imaging in craniosynostosis.

One of the challenges of low-dose CT imaging is an increase in image noise. Advanced image reconstruction techniques, such as model-based iterative reconstruction (MBIR), can be used to improve image quality and resolution while still reducing the patient dose[18]. MBIR uses forward and backward projections to obtain projection data and images, respectively, and takes into account the optics of the scanner (e.g., focal spot and detector size) to reduce image noise[42,43]. These techniques can be used to reconstruct low-dose CT images in order to maintain image quality while still reducing the patient dose. It is important to carefully balance all of these factors in order to minimize the patient dose while still producing images that are sufficient for diagnosis and treatment planning.

Our current study is limited by small sample size, and the retrospective nature of the analysis and review. Although the population was homogenous in their diagnosis of CS, the age difference between a 3-month-old and 2-year-old alters the effective radiation dose as total body surface area is a key variable in the equation. Combining our efforts of lowering effective dose with those of other pediatric institutions, we can see that a new standard of care is emerging.

5. Conclusion

Our study, along with the multiple other institutions providing ultra-low dose head CT for CS patients, demonstrate evidence for diagnostic equipoise while lowering radiation exposure in these children. The utilization of this optimized protocol resulted in a 94% reduction in CED compared to our previous standard protocol. These findings align with similar efforts from other institutions, suggesting the potential for a new standard of care that prioritizes radiation reduction in CT imaging for CS. Children, especially infants, present with much higher susceptibility to the hazardous effects of ionizing radiation. Our study highlights the importance of implementing dose-reducing protocols, such as adjusting acquisition parameters and utilizing advanced image reconstruction techniques in order to minimize radiation risks in pediatric patients. While our study contributes to the growing body of evidence supporting low-dose CT protocols in CS, further research is needed to explore the long-term outcomes and benefits of these protocols. The use of an ultra-low dose CT protocol offers a promising approach to mitigate radiation exposure in pediatric patients with CS. The adoption of such protocols represents an opportunity for broader implementation and should be further investigated to optimize diagnostic imaging while prioritizing patient safety.

Author contributions

Conceptualization, LB and RE; methodology, LB, SL and RE; validation, LB, SL and RE; formal analysis, LB, SL and RE; data curation, LB, SL and CT; writing—original draft preparation, LB, SL and CT; writing—review and editing, LE, SL and RE; supervision, RE.

Conflict of interest

The authors declare no conflict of interest.

References

1. Sadigh G, Kadom N, Karthik P, et al. Noncontrast head CT in children: National variation in radiation dose indices in the United States. *American Journal of Neuroradiology* 2018; 39(8): 1400–1405. doi: 10.3174/ajnr.A5719
2. Jaskolka MS. Current controversies in metopic suture craniosynostosis. *Oral & Maxillofac Surgery Clinics* 2017; 29(4): 447–463. doi: 10.1016/j.coms.2017.07.003
3. van der Meulen J. Metopic synostosis. *Child's Nervous System* 2012; 28(9): 1359–1367. doi: 10.1007/s00381-012-1803-z
4. Beckett JS, Chadha P, Persing JA, et al. Classification of trigonocephaly in metopic synostosis. *Plastic and Reconstructive Surgery* 2012; 130(3): 442e–447e. doi: 10.1097/PRS.0b013e31825dc244
5. Sharma RK. Craniosynostosis. *Indian Journal of Plastic Surgery* 2013; 46(1): 18–27. doi: 10.4103/0970-0358.113702

6. Binaghi S, Gudinchet F, Rilliet B. Three-dimensional spiral CT of craniofacial malformations in children. *Pediatric Radiology* 2000; 30(12): 856–860. doi: 10.1007/s002470000343
7. Massimi L, Bianchi F, Frassanito P, et al. Imaging in craniosynostosis: When and what? *Child's Nervous System* 2019; 35(11): 2055–2069. doi: 10.1007/s00381-019-04278-x
8. Bruce MK, Mittal AM, Whitt DS, et al. Computed tomography associated radiation exposure in children with craniosynostosis. *Child's Nervous System* 2021; 37(8): 2635–2641. doi: 10.1007/s00381-021-05254-0
9. Pearce MS, Salotti JA, Little MP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: A retrospective cohort study. *The Lancet* 2012; 380(9840): 499–505. doi: 10.1016/S0140-6736(12)60815-0
10. Boice JD. Radiation epidemiology and recent paediatric computed tomography studies. *Annals of the ICRP* 2015; 44(1 Suppl): 236–248. doi: 10.1177/014664531557587
11. Mathews JD, Forsythe AV, Brady Z, et al. Cancer risk in 680,000 people exposed to computed tomography scans in childhood or adolescence: Data linkage study of 11 million Australians. *The BMJ* 2013; 346: f2360. doi: 10.1136/bmj.f2360
12. Montoya JC, Eckel LJ, DeLone DR, et al. Low-dose CT for craniosynostosis: Preserving diagnostic benefit with substantial radiation dose reduction. *American Journal of Neuroradiology* 2017; 38(4): 672–677. doi: 10.3174/ajnr.A5063
13. Valentin J. Managing patient dose in multi-detector computed tomography (MDCT). *Annals of the ICRP* 2007; 37(1): 1–79. doi: 10.1016/j.icrp.2007.09.001
14. Kharita MH, Al-Naemi H, Arru C, et al. Relation between age and CT radiation doses: Dose trends in 705 pediatric head CT. *European Journal of Radiology* 2020; 130: 109138. doi: 10.1016/j.ejrad.2020.109138
15. Garzón WJ, Aldana DFA, Cassola VF. Patient-specific organ doses from pediatric head CT examinations. *Radiation Protection Dosimetry* 2020; 191(1): 1–8. doi: 10.1093/rpd/ncaa126
16. Jaramillo-Garzón W, Caballero MA, Alvarez-Aldana DF. Size-specific dose estimates for pediatric non-contrast head CT scans: A retrospective patient study in Tunja, Colombia. *Radiation Protection Dosimetry* 2021; 193(3–4): 221–227. doi: 10.1093/rpd/ncab051
17. Barreto IL, Tuna IS, Rajderkar DA, et al. Pediatric craniosynostosis computed tomography: An institutional experience in reducing radiation dose while maintaining diagnostic image quality. *Pediatric Radiology* 2021; 52(1): 85–96. doi: 10.1007/s00247-021-05205-6
18. Ernst CW, Hulstaert TL, Belsack D, et al. Dedicated sub 0.1 mSv 3DCT using MBIR in children with suspected craniosynostosis: Quality assessment. *European Radiology* 2016; 26(3): 892–899. doi: 10.1007/s00330-015-3870-5
19. Vazquez JL, Pombar MA, Pumar JM, et al. Optimised low-dose multidetector CT protocol for children with cranial deformity. *European Radiology* 2013; 23(8): 2279–2287. doi: 10.1007/s00330-013-2806-1
20. Kaasalainen T, Palmu K, Lampinen A, et al. Limiting CT radiation dose in children with craniosynostosis: Phantom study using model-based iterative reconstruction. *Pediatric Radiology* 2015; 45(10): 1544–1553. doi: 10.1007/s00247-015-3348-2
21. Ling LLL, Fitt G, Begbie M, et al. Retrospective review of CT brain image quality, diagnostic adequacy and radiation dose in a paediatric population imaged at a non-paediatric tertiary hospital. *Journal of Medical Imaging Radiation Oncology* 2019; 63(5): 596–601. doi: 10.1111/1754-9485.12894
22. Eddy FK, Ngano SO, Jervé FA, et al. Radiation dose evaluation of pediatric patients in CT brain examination: Multi-center study. *Scientific Reports* 2021; 11(1): 4663. doi: 10.1038/s41598-021-84078-z
23. Jaffurs D, Denny A. Diagnostic pediatric computed tomographic scans of the head: Actual dosage versus estimated risk. *Plastic and Reconstructive Surgery* 2009; 124(4): 1254–1260. doi: 10.1097/PRS.0b013e3181b59d2d
24. Craven CM, Naik KS, Blanshard KS, et al. Multispiral three-dimensional computed tomography in the investigation of craniosynostosis: Technique optimization. *The British Journal of Radiology* 1995; 68(811): 724–730. doi: 10.1259/0007-1285-68-811-724
25. Calandrelli R, D'Apolito G, Gaudino S, et al. Identification of skull base sutures and craniofacial anomalies in children with craniosynostosis: Utility of multidetector CT. *La Radiologia Medica* 2014; 119: 694–704. doi: 10.1007/s11547-014-0387-y
26. Zarei F, Mashayekhi Z, Chatterjee VV, et al. Evaluation of low-dose 3D skull CT images in craniosynostosis. *Iranian Joural Medical Physics* 2022; 19(4): 258–263. doi: 10.22038/IJMP.2021.59399.1997
27. Zarella C, Didier R, Bergquist C, et al. A reduction in radiation exposure during pediatric craniofacial computed tomography. *Journal of Craniofacial Surgery* 2016; 27(2): 331–333. doi: 10.1097/SCS.0000000000002374
28. Hurlock GS, Higashino H, Mochizuki T. History of cardiac computed tomography: Single to 320-detector row multislice computed tomography. *The International Journal of Cardiovascular Imaging* 2009; 25(Suppl 1): 31–42. doi: 10.1007/s10554-008-9408-z
29. Hounsfield GN. Computerized transverse axial scanning (tomography): Part 1. Description of system. *The British Journal of Radiology* 1973; 46(552): 1016–1022. doi: 10.1259/0007-1285-46-552-1016
30. Schulz RA, Stein JA, Pelc NJ. How CT happened: The early development of medical computed tomography. *Journal of Medical Imaging* 2021; 8(5): 052110. doi: 10.1117/1.JMI.8.5.052110

31. Garvey CJ, Hanlon R. Computed tomography in clinical practice. *The BMJ* 2002; 324: 1077. doi: 10.1136/bmj.324.7345.1077
32. National Institutes of Health. Next-generation CT scanner provides better images with minimal radiation. Available online: https://www.nih.gov/news-events/news-releases/next-generation-ct-scanner-provides-better-images-minimal-radiation (accessed on 3 August 2022).
33. Hata A, Yanagawa M, Honda O, et al. Effect of matrix size on the image quality of ultra-high-resolution CT of the lung: Comparison of 512 × 512, 1024 × 1024, and 2048 × 2048. *Academic Radiology* 2018; 25(7): 869–876. doi: 10.1016/j.acra.2017.11.017
34. Jinzaki M, Yamada Y, Nagura T, et al. Development of upright computed tomography with area detector for whole-body scans: Phantom study, efficacy on workflow, effect of gravity on human body, and potential clinical impact. *Investigative Radiology* 2020; 55(2): 73–83. doi: 10.1097/RLI.0000000000000603
35. Backgrounder on biological effects of radiation. Available online: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/bio-effects-radiation.html (accessed on 17 March 2023).
36. Subpart C—Occupational dose limits. Available online: https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1201.html (accessed on 17 March 2023).
37. Strauss KJ, Goske MJ. Estimated pediatric radiation dose during CT. *Pediatric Radiology* 2011; 41(Suppl 2): 472. doi: 10.1007/s00247-011-2179-z
38. Brenner DJ, Elliston CD, Hall EJ, Berdon WE. Estimated risks of radiation-induced fatal cancer from pediatric CT. *American Journal of Roentgenology* 2001; 176(2): 289–296. doi: 10.2214/ajr.176.2.1760289
39. Mettler FA, Bhargavan M, Faulkner K, et al. Radiologic and nuclear medicine studies in the United States and worldwide: Frequency, radiation dose, and comparison with other radiation sources—1950–2007. *Radiology* 2009; 253(2): 520–531. doi: 10.1148/radiol.2532082010
40. Kutanzi KR, Lumen A, Koturbash I, et al. Pediatric exposures to ionizing radiation: Carcinogenic considerations. *International Journal of Environment Research and Public Health* 2016; 13(11): 1057. doi: 10.3390/ijerph13111057
41. Hauptmann M, Byrnes G, Cardis E, et al. Brain cancer after radiation exposure from CT examinations of children and young adults: Results from the EPI-CT cohort study. *The Lancet Oncology* 2023; 24(1): 45–53. doi: 10.1016/S1470-2045(22)00655-6
42. Yamasaki Y, Kamitani T, Sagiyama K, et al. Model-based iterative reconstruction for 320-detector row CT angiography reduces radiation exposure in infants with complex congenital heart disease. *Diagnostic and Interventional Radiology* 2021; 27(1): 42–49. doi: 10.5152/dir.2020.19633
43. Sun J, Yu T, Liu J, et al. Image quality improvement using model-based iterative reconstruction in low dose chest CT for children with necrotizing pneumonia. *BMC Medical Imaging* 2017; 17(1): 24. doi: 10.1186/s12880-017-0177-9