Computed tomography associated radiation exposure in children with craniosynostosis

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Abstract
Background  The role of computed tomography (CT) for diagnosis and surgical planning for craniosynostosis (CS) is well-established. The aim of this study was to quantify the cumulative medical radiation exposure from CT in patients with CS at a tertiary care children’s hospital.

Methods  Medical records of patients who presented at <2 years of age and underwent surgical intervention for CS were examined for demographic information. Effective radiation dose (ERD) in mSv was calculated for each head CT. Descriptive statistics and ANOVA were performed. Mean ± SD is reported; p < 0.05 was considered significant.

Results  Two hundred seventy-two patients met inclusion criteria: 241 nonsyndromic and 31 with syndromic diagnoses. For nonsyndromic patients, mean age at first head CT was 6.0 ± 4.9 months, mean number of CT scans obtained was 2.1 ± 1.1, and the mean total combined ERD was 9.1 ± 4.8 mSv. CT scans obtained at <6 months of age had a significantly greater ERD than those obtained at >6 months, 5.3 ± 1.9 versus 4.3 ± 1.4 mSv, respectively (p = 0.001).

Conclusions  Patients with nonsyndromic CS undergo 2 CT scans on average related to their diagnosis, with a mean total ERD of 9.1 mSv; this is equivalent to 1.5 years of the average annual background radiation dose a person living in the USA will encounter from environmental radiation, medical exposures, and consumer products. A CT obtained at <6 months is associated with a higher ERD; thus, we recommend delaying imaging from the initial presentation to the time of pre-operative planning when possible.

Keywords  Craniosynostosis · Computed tomography · Radiation exposure

Introduction

Craniosynostosis (CS) refers to the premature fusion of one or more cranial sutures [1–3] and occurs in 1 in 2500 live births [4–7]. Diagnosis of CS relies on the clinical exam; however, radiographic imaging, including computed tomographic (CT) imaging, is important for diagnosis confirmation, surgical planning, and post-operative follow-up [8–10]. While CT imaging is readily accessible at most hospitals, relatively inexpensive, and can be performed rapidly without need for sedation, cumulative radiation exposure remains a drawback of this imaging modality.

The increased use of CT with higher ionizing radiation compared to other imaging modalities has raised concern about radiation exposure, especially in younger children who may be more vulnerable to the effects of radiation [11–13]. Campaigns such as Image Gently [14] have led the effort to reduce medical radiation exposure in children, and CT protocols have been altered in order to reduce the amount of radiation per scan in addition to using other imaging modalities [15, 16]. Although the radiation doses in CT scans are too low to be classified as significant radiation exposure [17], multiple CT scans for children with CS have raised concerns from parents and physicians regarding the amount of radiation children with CS are exposed to.

The aim of this study was to quantify the cumulative medical radiation exposure from CTs in patients with CS.
Here, we analyzed the total number of CTs obtained as well as effective radiation dose (ERD) per CT, a metric initially developed in setting occupational dose limits that is now used to describe medical radiation and the potential risk of cancer development later in life [18]. This data provides relevant information for both patients and providers regarding the relative exposure dose a typical patient with CS may experience as a consequence of the diagnosis.

Methods

This retrospective study was approved by the institutional review board. Medical records of patients who presented at less than 2 years of age and underwent surgical intervention for CS at a tertiary care children’s hospital between January 2009 and January 2021 were examined for demographic information (type of CS, other diagnoses, age at CT, CT radiation dosage report). The standard CT protocol used to evaluate CS at our institution is a thin cut (0.6 mm) helical head CT from the vertex to the skull base with a 3D reconstruction. Scans from outside hospitals, where CT radiation dosage reports were unavailable, or where the CT protocol employed was other than our institution’s standard low-dose protocol, were excluded. ERD in millisieverts (mSv), a unit employed was other than our institution's standard low-dose protocol, was calculated by multiplying the dose-length product (DLP [mGy × cm]) listed in the dosage report for each head CT by an empirical weighting factor, k (mSv × mGy⁻¹ × cm⁻¹), that is a function of body region and age [19]. Descriptive statistics were analyzed for all patients. Two-tailed Student's t test and ANOVA were performed; p ≤ 0.05 was considered statistically significant. Mean ± standard deviation was reported.

Results

Two hundred seventy-two patients met inclusion criteria: 241 nonsyndromic and 31 with syndromic diagnoses. There were 101 females and 171 males (Table 1).

Of the nonsyndromic patients, there were 87 females and 154 males. The mean age at first head CT was 6.0 ± 4.9 months (range 0–23.1 months), mean number of CT scans obtained was 2.1 ± 1.1, mean ERD of a single head CT was 4.3 ± 1.7 mSv, and the mean total combined ERD was 9.1 ± 4.8 mSv. One hundred nine (45.2%) had sagittal, 58 (24.1%) metopic, 42 (17.4%) coronal, 27 (11.2%) multisutural, and 5 (2.1%) lambdoid CS (Table 1). Children with multisutural CS had a significantly greater total ERD (11.18 ± 5.65 mSv) than children with sagittal CS, 8.1 ± 4.6 mSv (p = 0.046). Children with sagittal CS had significantly fewer head CTs (1.9 ± 1.2) than children with metopic (2.5 ± 1.3, p = 0.024) or multisutural CS (3.0 ± 1.5, p < 0.001). No other significant differences in total ERD, total number of head CTs, or age at first head CT were found based on type of CS (Table 2).

Excluding patients who underwent minimally invasive surgery and had only one CT scan, there was a statistically significant difference in ERD between CT scans obtained at less than 6 months those obtained at greater than 6 months. Additionally, patients whose first CT were obtained at less than 6 months of age had a significantly greater total ERD compared to those whose first CT was obtained at greater than 6 months of age (Table 3).

A separate analysis was performed for patients with syndromic diagnoses. Thirty-one patients with syndromic diagnoses met inclusion criteria (14 female, 17 male). The most common syndromes were Apert (n = 6), Muenke (n = 6), Pfeiffer (n = 4), and Crouzon (n = 4, Table 4). The mean number of CTs obtained in this cohort was greater than in the nonsyndromic cohort, 6.6 ± 6.0 versus 2.1 ± 1.1, respectively (p < 0.001). Mean total ERD was greater in children with syndromic than nonsyndromic, 22.3 ± 12.4 mSv versus 9.1 ± 4.8, respectively (p < 0.001). Additionally, age at first CT was significantly lower in children with syndromic diagnoses than nonsyndromic, 3.2 ± 4.4 versus 6.1 ± 5.0 months, respectively (p = 0.003).

Discussion

The purpose of this study was to quantify the cumulative medical radiation exposure from CTs in patients with CS. Parents are concerned about radiation exposure in their children; not only do they want information on the purpose of the imaging and other options available, but they also want information on the radiation dose [20]. This is not an unfounded concern. The largest studies evaluating risk of cancer from radiation exposure come from the Japanese Atomic Bomb survivors which likely do not accurately represent current medical radiation exposure [21]. Some
studies have shown a higher risk of cancer from medical radiation; however, these are from the high-dose CT scans years ago [22, 23]. Other studies have not found an increased risk of cancer from diagnostic CT scan exposure; however, the follow-up is not long enough to determine a true lifetime risk [24]. It is unclear what effect modern CT technology has and whether there is a pro-neoplastic effect with this level of radiation exposure.

The average person living in the USA is exposed to 6.2 mSv yearly from natural background radiation, medical exposures, and consumer products [25, 26]. Living at higher altitudes increases radiation exposure slightly. For example, living at 8000 ft above sea level exposes individuals to an additional 0.70 mSv per year from cosmic radiation [26]. A round-trip flight between the East and West Coasts is 0.07 mSv [27]. Diagnostic imaging, such as in dentistry [28] or routine mammography, is also a common source of radiation. The yearly dose limit for radiation workers is set at 50 mSv [18]. Other studies evaluating mortality data from Japanese atomic bomb survivors found the strongest evidence of increased cancer mortality risk with ERD > 100 mSv [29]. Damage to red blood cells occurs at 500 mSv, and the lowest dose causing acute radiation syndrome is 1000 mSv which raises the risk of cancer from 22% (the average cancer risk in the US) to 27% (Fig. 1) [30].

Table 2  Total number of head CTs, total ERD, and age at first CT by suture involvement for patients with nonsyndromic diagnoses

| Suture involved | Total non-syndromic (n = 241) | Sagittal (n = 109) | Metopic (n = 58) | Lambdoid (n = 5) | Coronal (n = 42) | All single suture (n = 214) | Multisutural (n = 27) |
|-----------------|-----------------------------|-------------------|-----------------|-----------------|-----------------|--------------------------|---------------------|
| Total number of head CTs (mean ± SD) | 2.1 ± 1.1 | 1.9 ± 1.2a | 2.5 ± 1.3 | 2.0 ± 1.0 | 2.2 ± 1.1 | 2.1 ± 1.2 | 3.0 ± 1.5b |
| Total effective radiation dose in mSv (mean ± SD) | 9.1 ± 4.8 | 8.1 ± 4.6 | 9.9 ± 5.8 | 7.5 ± 4.4 | 10.1 ± 5.3 | 9.0 ± 5.1 | 11.2 ± 5.7c |
| Age at first CT in months (mean ± SD) | 6.1 ± 5.0 | 5.0 ± 4.8 | 7.2 ± 5.8 | 5.9 ± 5.7 | 7.0 ± 4.0 | 6.0 ± 5.0 | 7.3 ± 5.1 |

aVersus metopic CS, p = 0.024, versus multisutural CS, p < 0.001
bVersus all single suture, p < 0.001
cVersus all single suture, p = 0.041, versus sagittal CS, p = 0.046

In this cohort, the mean number of CTs obtained for a child without a syndromic diagnosis was 2.1 ± 1.1, with a mean total ERD of 9.1 mSv. This is equivalent to 130 round-trip flights between New York and Los Angeles [27], or 1.5 years of the average annual background radiation dose a person living in the USA is exposed to [26]. Children with sagittal CS had a smaller total number of CTs compared to children with metopic CS; this is likely due to the difference in surgical technique. For patients who undergo endoscopic/minimally invasive surgery, the current, standard protocol at our institution is to obtain only a pre-operative scan. An immediate postoperative scan is obtained only for children who undergo open cranial vault reconstruction or where there are concerns for complications. The reason for the immediate postoperative scan is only for children who undergo open cranial vault reconstruction to confirm that the surgical plan was followed correctly, rule out hematoma, and to check for symmetry, as this is not possible with clinical exam due to the extensive swelling postoperatively. Compared to children with single suture CS, children with multisutural CS had a greater total number of scans and were exposed to a higher total ERD. Children with syndromic diagnoses underwent three times the number of CT scans compared to the nonsyndromic cohort and were exposed to nearly 2.5 times the amount of radiation on average. Patients with syndromic diagnoses received such a large number of CT scans due to their comorbid pathologies; those who had the highest number of scans were due to shunt evaluation or multiple procedures requiring CT follow-up. The reason for the nonlinear relationship between number of scans and increase in ERD in the syndromic cohort is due in part to the age at scan increasing which leads to a decrease in ERD per scan, as well as the CT protocol for shunt evaluation differs from that used for craniosynostosis.

There was an inverse square relationship between age and radiation dose per scan (Fig. 2). Not all CTs have the same
ERD; slight differences may be a result of the anatomic coverage of the scan (i.e., vertex to skull base vs. vertex to C1) as influenced by patient positioning; large differences are a result of motion artifact necessitating a repeat scan. Children who had their first CT scan at less than 6 months of age had a significantly greater ERD from the first CT as well as from all CTs combined than those whose first CT was at greater than 6 months of age. Not only is this statistically significant, but this is also clinically significant. Fearon et al. found that craniofacial surgeons were able to accurately diagnose single suture craniosynostosis with clinical exam alone and recommended only relying on CT imaging when clinical exam was not diagnostic [31]. A small group of patients (n = 29) in this cohort had more than one pre-operative CT; 24 of these patients (82.8%) had their first CT at < 6 months of age. The mean time between the two pre-operative scans was 10.3 months, and the mean time between second pre-operative CT and surgery was 2.9 ± 2.9 months. The mean time between surgery and pre-operative CT for the entire cohort was 3.4 ± 3.4 months (range 0.06–16.6 months). These results support prior studies recommending avoiding obtaining CT imaging as part of the routine initial visit and waiting until closer to the date of surgery to obtain a CT for pre-operative planning.

Attempts have been made to limit medical radiation exposure in pediatric patients to conform to the as low as reasonably achievable (ALARA) principle [32]. It has been shown that implementing a low-dose head CT protocol does not significantly affect image quality or diagnostic utility and effectively reduces the amount of exposure to ionizing radiation [33]. Helical CT protocols can be adjusted from the standard adult settings to reduce radiation dose when imaging pediatric patients [15]. This is well known at pediatric centers; however, imaging obtained at facilities not specializing in pediatrics may not be as familiar with the technical parameter adjustments available, and therefore, pediatric patients may be exposed to higher radiation doses [34].

The amount of radiation exposure in patients with CS has decreased over time at our institution. This is a result of the decrease in ERD over time due to advances in CT technology, improved radiology protocols in addition to changes to the imaging protocol at our craniofacial center. The historic protocol at our institution was to obtain a pre-operative CT scan for surgical planning, an immediate post-op CT and a 2 year follow up CT; this was replaced by obtaining only a pre-operative and immediate post-operative CT, when indicated based on type of surgery, and subsequent routine follow-up imaging is

Table 4 Syndromic diagnoses and associated imaging and effective radiation dose

| Syndrome                | All combined (n = 31) | Apert (n = 6) | Muenke (n = 6) | Pfeiffer (n = 4) | Crouzon (n = 4) | Saethre-Chotzen (n = 2) | Others (n = 9) |
|-------------------------|----------------------|--------------|---------------|----------------|----------------|------------------------|--------------|
| Total number of head CTs (mean±SD) | 6.6 ± 6.0 | 6.7 ± 4.0 | 5.5 ± 1.8 | 3.3 ± 1.0 | 6.5 ± 2.1 | 11.5 ± 12.0 | 7.7 ± 9.5 |
| Total effective radiation dose in mSv (mean±SD) | 22.3 ± 12.4 | 26.7 ± 10.5 | 21.2 ± 5.3 | 13.9 ± 2.1 | 25.3 ± 7.7 | 26.1 ± 18.6 | 21.6 ± 19.1 |
| Age at first CT in months (mean±SD) | 3.2 ± 4.4 | 1.1 ± 1.3 | 4.3 ± 3.7 | 1.7 ± 1.4 | 5.2 ± 6.5 | 1.6 ± 0.1 | 4.3 ± 6.2 |
now obtained using 3-dimensional (3D) photogrammetry in clinic. Of course, if there are concerns for complications post-operatively, CT scans are obtained for further evaluation, but this is a rare occurrence. While there is an inverse square relationship between ERD and age at scan (Fig. 2), and a scan obtained at 2-year follow-up imparts a lower ERD than the initial CTs, we argue the additional scan 2 years post-operatively is not necessary. Post-operative clinical exam can assess for both visible and palpable bony defects as well as subjective aesthetic outcomes. Several studies have evaluated the use of 3D photogrammetry in craniofacial disorders and found that 3D photogrammetry was comparable to CT for evaluating head shape in diagnosis of CS [35], in addition to analyzing volume and symmetry changes following surgical correction of CS [36, 37]. 3D photogrammetry has also been shown to be valid and reliable for craniofacial anthropometry [38] as well as for treatment planning and follow-up in nonsynostotic cranial deformities [39]. Thus, we recommend using 3D photogrammetry, when appropriate, to replace CT imaging, such as in aiding diagnosis and for clinical follow-up of uncomplicated cases.

Limitations of this study include the retrospective nature of the study and the inherent limitations associated with retrospective reviews. Data before 2009 was incomplete, therefore limiting our ability to evaluate the average radiation exposure over time, such as to evaluate data from before the ALARA principle and Image Gently campaigns. Additionally, some of the children included in this study who were born in the past year or so may have not yet completed the standard CS imaging protocol and therefore the average number of head CTs obtained could be a slight underestimate. There were only a small number of children with syndromic diagnoses. We found that children with syndromic diagnoses are more likely to have a greater number of head CTs as well as a greater total ERD compared to children with nonsyndromic CS; however, the sample size was not large enough to draw global tendencies or perform subgroup analyses. Additionally, children with syndromic CS may be getting CTs for evaluation not necessarily related to their CS diagnosis which we did not control for. Other limitations include that different practitioners use different CT protocols. At our institution, while the standard protocol is routinely used by the Plastic Surgery department, it was not initially followed by other referring providers. Additionally, we did not include patients who had scans obtained at outside institutions in our analysis; thus, we are unable to examine whether these patients had a greater number of total scans, i.e., due to needing to rescan patients at our institution if the image quality was not good enough, or whether scans obtained at nonpediatric institutions exposed patients to a greater ERD. And finally, we were unable to control for the small number of instances where scans had to be repeated as a result of patient motion during imaging, this greatly increased the ERD of the scan.

**Conclusion**

A child diagnosed with nonsyndromic CS was found to undergo, on average, 2 head CTs related to their diagnosis, with a mean total ERD of 9.1 mSv. A CT obtained at less than 6 months of age is associated with a significantly higher
ERD. Based on this data, we recommend avoiding obtaining a CT scan unless otherwise necessary until the time of pre-operative planning to decrease radiation exposure. We also recommend relying on nonradiative imaging sources for follow-up including 3D photogrammetry or laser surface topography evaluations.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Madeleine K. Bruce and Aditya M. Mittal. The first draft of the manuscript was written by Madeleine K. Bruce, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declarations

Conflict of interest Not applicable.

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