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ORIGINAL ARTICLE

Pediatric craniosynostosis computed tomography: an institutional experience in reducing radiation dose while maintaining diagnostic image quality

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Abstract

Background Children with craniosynostosis may undergo multiple computed tomography (CT) examinations for diagnosis and post-treatment follow-up, resulting in cumulative radiation exposure.

Objective To reduce the risks associated with radiation exposure, we evaluated the compliance, radiation dose reduction and clinical image quality of a lower-dose CT protocol for pediatric craniosynostosis implemented at our institution.

Materials and methods The standard of care at our institution was modified to replace pediatric head CT protocols with a lower-dose CT protocol utilizing 100 kV, 5 mAs and iterative reconstruction. Study-ordered, protocol-utilized and radiation-dose indices were collected for studies performed with routine pediatric brain protocols (n=22) and with the lower-dose CT protocol (n=135). Two pediatric neuroradiologists evaluated image quality in a subset (n=50) of the lower-dose CT studies by scoring visualization of cranial structures, confidence of diagnosis and the need for more radiation dose.

Results During the 30-month period, the lower-dose CT protocol had high compliance, with 2/137 studies performed with routine brain protocols. With the lower-dose CT protocol, volume CT dose index ($CTDI_{vol}$) was 1.1 mGy for all patients (0–9 years old) and effective dose ranged from 0.06 to 0.22 mSv, comparable to a 4-view skull radiography examination. $CTDI_{vol}$ was reduced by 98% and effective dose was reduced up to 67-fold. Confidence in diagnosing craniosynostosis was high and more radiation dose was considered unnecessary in all studies (n=50) by both radiologists.

Conclusion Replacing the routine pediatric brain CT protocol with a lower-dose CT craniosynostosis protocol substantially reduced radiation exposure without compromising image quality or diagnostic confidence.

Keywords Children · Computed tomography · Craniosynostosis · Head · Iterative reconstruction · Radiation dose · Skull

Introduction

Craniosynostosis is the premature fusion of one or more of the cranial sutures [1]. Its incidence is estimated to occur in about 1 per 2,500 live births [2, 3]. Left untreated, it can result in cranial deformity, increased intracranial pressure, and restricted brain growth, potentially resulting in neurological consequences [4, 5]. Thus, early diagnosis and corrective action are crucial to achieving optimal outcomes in children with craniosynostosis.

Initial diagnosis may be evaluated with a 4-view skull radiography series. However, skull radiographs may not be definitive due to limited visualization of the cranial sutures. Use of ultrasound has been described, but the images are very technique dependent, do not provide three-dimensional (3-D) information, and are difficult for the surgeon to independently review [6]. Magnetic

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resonance imaging (MRI) protocols are being developed, but they typically require patient sedation and prolonged post-processing time [7, 8]. Computed tomography (CT) imaging offers excellent high-definition images of the skull. Thus, CT imaging with 3-D reconstructions of the bone are frequently used to confirm diagnosis, plan treatment and evaluate craniosynostosis post-treatment [9, 10].

However, CT imaging in the pre- and post-treatment periods leads to repeated radiation exposures. Even low doses of radiation are believed to pose an increased risk of cancer, particularly in children, who are more sensitive to the effects of ionizing radiation than adults [11]. However, at low doses, the risk is a theoretical assumption and remains controversial in the scientific community. Nonetheless, a precautionary approach supports optimizing the radiation exposure in pediatric imaging by applying the ALARA (as low as reasonably achievable) principle, which has been a key priority and standard in the radiology community for years [12–15].

Evaluating craniosynostosis involves a review of skull structures rather than the soft tissues of the brain. Since high contrast resolution is not impacted by low photon numbers, which are necessary for soft-tissue contrast, the CT study can be performed with a lower level of radiation [16, 17]. Dose reduction can be achieved by lowering tube current, rotation time, tube voltage and/or using iterative reconstruction techniques [17–20]. When lowering the tube current and tube voltage, it is important to only increase the image noise to a point where the necessary diagnostic information is still maintained.

To date, subjective image quality of clinical craniosynostosis examinations acquired with a lower-dose CT protocol using traditional iterative reconstruction algorithms has not been reported. The purpose of this study was to assess utilization compliance, quantify radiation dose reduction and review subjective image quality of a lower-dose CT craniosynostosis protocol implemented at our institution.

Materials and methods

This retrospective study was approved by our institutional review board with waiver of informed consent. The previous clinical standard of care at our institution for evaluating craniosynostosis in pediatric patients was to use routine pediatric brain CT protocols specific to patient age (0–6 months, 6 months to 3 years, 3–6 years, 6–12 years, 12–18 years). The standard of care was modified to adopt a lower-dose CT imaging protocol specific for craniosynostosis evaluation.

Computed tomography scanning

The lower-dose CT protocol was developed with preliminary lower-dose CT scans on anthropomorphic head phantoms and cadavers at our institution [21–23]. Following initial image quality review, technical parameters were gradually reduced in clinical studies on patients with physician review and approval. Compared to routine pediatric brain protocols, the tube voltage was reduced from 120 kV to 100 kV and the tube current was reduced to the lowest possible value of 10 mA. Chiefs and various attending physicians in pediatric neuroradiology, neurosurgery and craniofacial plastic surgery reviewed and approved the initial clinical studies.

The lower-dose CT protocol was created on an 80-slice CT scanner (Aquilion Prime; Canon Medical Systems USA, Tustin, CA) in our children's hospital with the following technical parameters: 100 kVp, 10 mA, 0.5-s rotation time, 0.625 helical pitch and 0.5 mm × 40 detector collimation. Unlike the routine pediatric brain protocols that varied with patient age, the lower-dose CT protocol used the same parameters for all patients between 0 and 18 years old. Sedation was not required for this protocol. Two-dimensional (2-D) axial images were reconstructed as smooth 1-mm images with a 0.8-mm interval and a soft-tissue kernel (FC49) as well as sharp 0.5-mm images with a 0.3-mm interval and a bone kernel (FC30). Both reconstructions used iterative reconstruction (AIDR-3D, Canon Medical Systems USA) with a standard strength. Furthermore, 3-D volume-rendered images were created at the scanner's workstation by CT technologists as part of the protocol's routine diagnostic review.

Initially, the examination was ordered as an unenhanced head CT study with comments requesting the use of the lower-dose CT protocol. After 13 months, a unique order for the lower-dose CT craniosynostosis study was created in the electronic medical record to streamline ordering and review of the lower-dose CT protocol.

Data collection

The radiology dictation reporting system (PowerScribe 360 Reporting; Nuance, Burlington, MA) was queried to obtain a list of all patients younger than 18 years old who were evaluated for craniosynostosis with CT between August 2017 and January 2020. The first 3 months included studies performed with the routine brain CT protocol before the lower-dose CT protocol was introduced. Patient age, sex, scan parameters and radiation dose metrics were recorded for all studies.

Protocol compliance

For each study, the study ordered by the physician, the scan protocol ordered by the radiologist and the scan protocol utilized by the CT technologist were reviewed to assess compliance of utilization of the lower-dose CT craniosynostosis protocol before and after the orderable study was created. For studies that incorrectly utilized the routine pediatric brain protocol, radiologists determined if the routine pediatric brain protocol was necessary for the clinical indication.

Radiation dosimetry

Radiation dose indices such as the volume CT dose index ($CTDI_{vol}$) and the dose–length product (DLP) were collected for all studies using a dose monitoring software (NexoDose; Bracco Diagnostics Inc., Monroe Township, NJ). The effective dose was estimated for all protocols by multiplying the DLP with age-specific kappa coefficients for the head [24–26].

Subjective image quality

Two fellowship-trained neuroradiologists with 7 and 5 years of experience (R1: D.A.R., R2: I.S.T., respectively) independently reviewed a subset of the initial consecutive studies (*n*=50) scanned with the lower-dose CT protocol on the picture archiving and communication system (PACS) workstation (Visage Imaging Inc., San Diego, CA). The radiologists rated the visibility of cranial sutures (major and squamosal), intracranial structures (ventricles, gray-white matter), the presence of image artifacts, diagnosis of craniosynostosis, confidence in diagnosing craniosynostosis and whether they thought the study needed more radiation dose. Although the lower-dose CT scan is not intended to define intracranial structures, gross brain anatomy including general brain development, any focal lesions in the brain, ventricular configuration and size, and gray-white matter differentiation were also examined. Questions and scoring scales are listed in Table 1. The major sutures were defined as sagittal, coronal, lambdoid and metopic sutures [27].

Statistical analysis

Mean and range were reported for $CTDI_{vol}$, DLP and effective dose. Linear regression analysis was performed to report the coefficient of determination (R^2) for DLP as a function of patient age. The inter-rater agreement between the two readers was measured with a Cohen's kappa correlation for questions with three scores and with an unweighted kappa test for questions with two scores [28]. The raw rate of agreement was also reported. Analyses were performed using the R software package (version 4.0.2; R Foundation for Statistical Computing, Vienna, Austria).

Results

During the 30-month study period, 157 patients were examined with CT for craniosynostosis. Patient age ranged from 19 days to 9 years old. The majority of patients were younger than 1 year old (*n*=112) and few patients were older than 6 years old (*n*=6). The population included more males (*n*=103) than females (*n*=54).

Protocol compliance

The pediatric brain protocol was utilized in 22 studies, of which only 2 occurred after the lower-dose CT protocol was introduced. The lower-dose CT protocol was correctly used in 46/47 cases before and in 89/90 cases after the orderable study was created. In the two cases where the lower-dose CT protocol was not used, the order and protocol indicated to examine for craniosynostosis, although the technologist selected the routine pediatric brain protocol. For both cases, radiologists confirmed that the patients could have been examined with the lower-dose CT protocol.

Table 1 Scoring list of subjective image quality assessment

	Score		
	3	2	1
Visibility of major sutures on 3-D	Strong visibility	Poor visibility	No visibility
Visibility of major sutures on 2-D	Strong visibility	Poor visibility	No visibility
Visibility of squamosal sutures on 3-D	Strong visibility	Poor visibility	No visibility
Visibility of squamosal sutures on 2-D	Strong visibility	Poor visibility	No visibility
Visibility of ventricles	Strong visibility	Poor visibility	No visibility
Visibility of gray-white matter differentiation	Strong visibility	Poor visibility	No visibility
Presence of artifacts	None	Few	Strong
Presence of craniosynostosis	–	Yes	No
Confidence in diagnosing craniosynostosis	High	Acceptable	Low
Needs more dose for diagnosing craniosynostosis?	–	No	Yes

2-D two-dimensional, *3-D* three-dimensional

Radiation dosimetry

$CTDI_{vol}$, DLP and effective dose are reported in Table 2 for all studies. With the pediatric brain protocol, both $CTDI_{vol}$ (range: 31.4–60.1 mGy) and DLP (range: 451.5–1,387.2 mGy·cm) increased linearly with patient age (R^2 >0.90). With the lower-dose CT protocol, $CTDI_{vol}$ was 1.1 mGy for all studies and DLP did not increase with patient age (range: 14.9–39.9 mGy·cm, R^2=0.04). $CTDI_{vol}$ was reduced from 31.4 mGy to 1.1 mGy (96.5% reduction) for patients younger than 6 months old, and from 58.7 mGy to 1.1 mGy (98.1% reduction) for patients between 6 and 12 years old. Although the $CTDI_{vol}$ for the lower-dose CT protocol was equivalent for all ages, the effective dose differs due to higher conversion factors for young patients that account for greater radiosensitivity. The lower-dose CT protocol produced effective dose ranging from 0.06 mSv for older patients to 0.22 mSv for younger patients, equal to 67-fold and 27-fold reductions, respectively. Table 3 provides the number of patients in the age ranges as well as the radiation dose indices for the 50 patients who were reviewed for subjective image quality. Dose metrics were nearly identical for the full study population listed in Table 2 and the subset of reviewed studies listed in Table 3.

Subjective image quality

Radiologists reviewed image quality for patients ranging from 19 days to 9 years old. Results of the image quality analysis are listed in Table 4 and displayed in Fig. 1. All questions received identical scores for the two radiologists, with 100% agreement, except for visibility of ventricles, which produced 94% agreement and almost perfect inter-rater agreement (k=0.85). Both radiologists rated visibility as "strong" in all studies for major sutures in 2-D and 3-D, in all studies for squamosal sutures in 2-D, and in most studies for squamosal sutures in 3-D (*n*=46). Visibility of ventricles was most often "poor" (*n*=40 for R1 and *n*=43 for R2), although some studies were rated as "strong" (*n*=9 for R1 and *n*=7 for R2). Radiologists rated visibility of gray-white matter differentiation as "none" in all studies (*n*=50). Artifacts were only detected in one study as patient motion.

Craniosynostosis was detected in 24% of studies (*n*=12) by both radiologists. Craniosynostosis was confirmed by surgery (*n*=9), clinical observation (*n*=2) or routine CT imaging done

Table 2 Radiation doses for both computed tomography (CT) protocols and all age ranges

	Age	*n*	$CTDI_{vol}$ (mGy)	DLP (mGy·cm)	ED (mSv)
Pediatric brain CT protocol[a,b]	0–6 m	10	31.4 (NA)	547.4 (451.5–617.8)	6.02 (NA)
	6 m to 3 y	7	35.4 (31.4–34.9)	648.3 (492.3–811.9)	4.34 (2.79–5.61)
	3–6 y	2	38.3 (38.3–38.3)	833.7 (659.2–1,008.1)	3.34 (2.64–4.03)
	6–12 y	3	58.7 (52.7–60.1)	1,245.9 (1,002.3–1,387.2)	3.99 (4.31–4.44)
Lower-dose CT craniosynostosis protocol[a,b,c]	0–6 m	59	1.1 (NA)	19.1 (14.9–31.7)	0.22 (0.16–0.44)
	6 m to 3 y	62	1.1 (NA)	21.3 (17.3–39.9)	0.14 (0.10–0.27)
	3–6 y	11	1.1 (NA)	22.7 (19.8–27.5)	0.08 (0.06–0.16)
	6–12 y	3	1.1 (NA)	19.9 (18.7–21.4)	0.06 (0.05–0.13)

All dose metrics were statistically significant between the two protocols (P<0.05). $CTDI_{vol}$ volume computed tomography dose index, *DLP* dose–length product, *ED* effective dose, *m* months, *NA* not applicable, *y* years

[a]Data are displayed as mean with range in parentheses

[b]Protocols with only one $CTDI_{vol}$ value for all studies do not have a reported range

[c]The low-dose protocol used the same settings independent of patient age

Table 3 Radiation doses for studies where image quality was evaluated by radiologists

	Age	*n*	$CTDI_{vol}$ (mGy)	DLP (mGy·cm)	ED (mSv)
Lower-dose CT craniosynostosis protocol[a,b]	0–6 m	31	1.1 (NA)	19.1 (14.9–24.5)	0.22 (0.17–0.28)
	6 m to 3 y	14	1.1 (NA)	21.0 (17.9–26.2)	0.14 (0.12–0.17)
	3–6 y	4	1.1 (NA)	23.9 (20.7–27.5)	0.08 (0.07–0.10)
	6–12 y	2	1.1 (NA)	20.9 (20.3–21.4)	0.06 (0.06–0.06)

$CTDI_{vol}$ volume computed tomography dose index, *DLP* dose–length product, *ED* effective dose, *m* months, *NA* not applicable, *y* years

[a]Data are displayed as mean with range in parentheses

[b]The low-dose protocol used the same settings independent of patient age

Table 4 Image quality assessment

Question	R1			R2			Agreement (%)	Kappa score
	3	2	1	3	2	1		
Visibility of major sutures on 3-D	50	0	0	50	0	0	100	1.00
Visibility of major sutures on 2-D	50	0	0	50	0	0	100	1.00
Visibility of squamosal sutures on 3-D	46	4	0	46	4	0	100	1.00
Visibility of squamosal sutures on 2-D	50	0	0	50	0	0	100	1.00
Visibility of ventricles	9	40	1	7	43	0	94	0.85
Visibility of gray-white matter differentiation	0	0	50	0	0	50	100	1.00
Presence of artifacts	49	0	1	49	0	1	100	1.00
Presence of craniosynostosis	–	12	38	–	12	38	100	1.00
Confidence in diagnosing craniosynostosis	50	0	0	50	0	0	100	1.00
Needs more dose for diagnosing craniosynostosis?	–	50	0	–	50	0	100	1.00

2-D two-dimensional, *3-D* three-dimensional

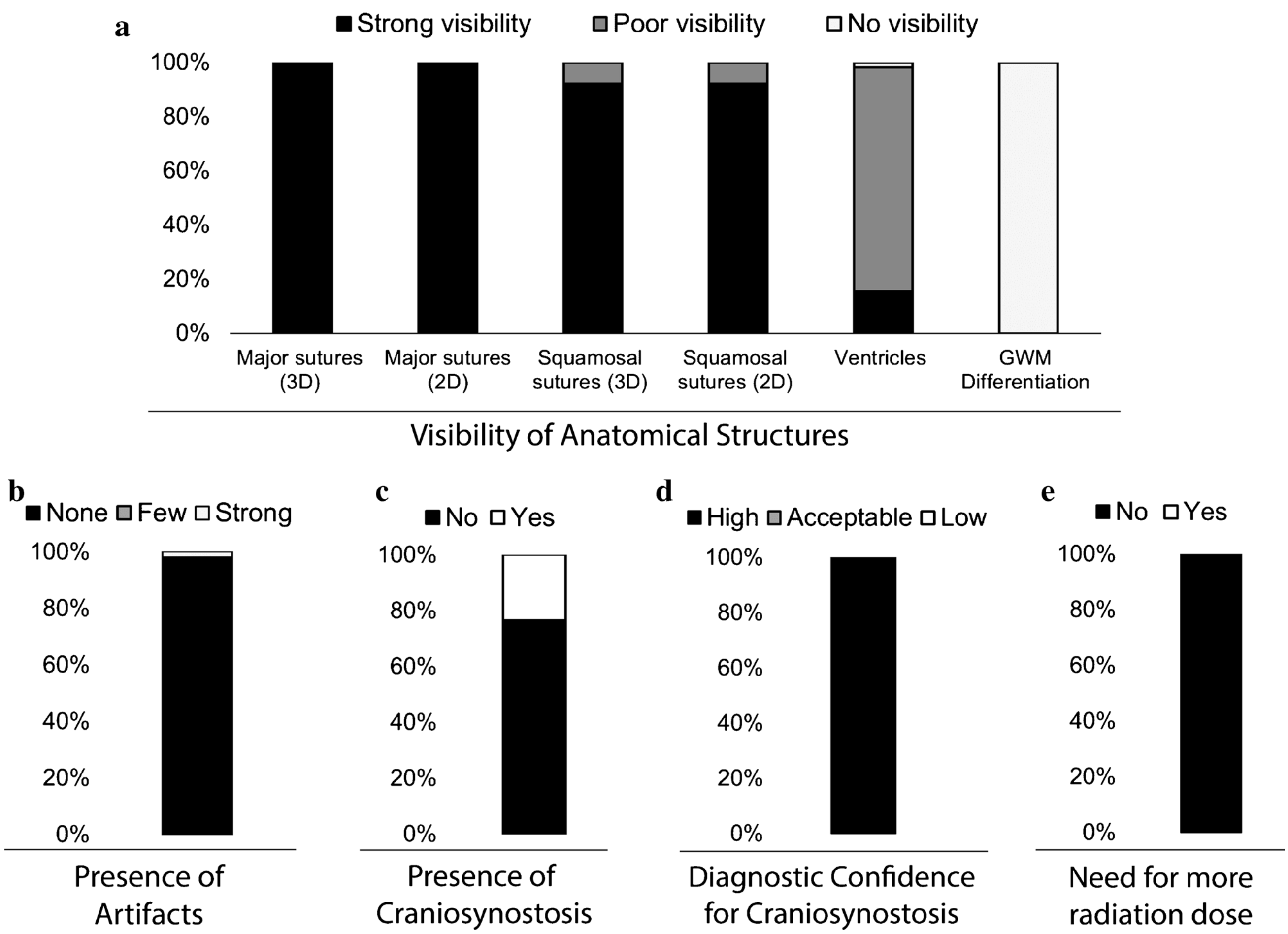

Fig. 1 Image quality assessment. **a–e** Percentage distributions of image quality assessment for visibility of anatomical structures (**a**), the presence of artifacts (**b**), the presence of craniosynostosis (**c**), confidence in diagnosing craniosynostosis (**d**) and the need for more dose for diagnosing craniosynostosis (**e**). *2D* two-dimensional, *3D* three-dimensional, *GWM* gray-white matter

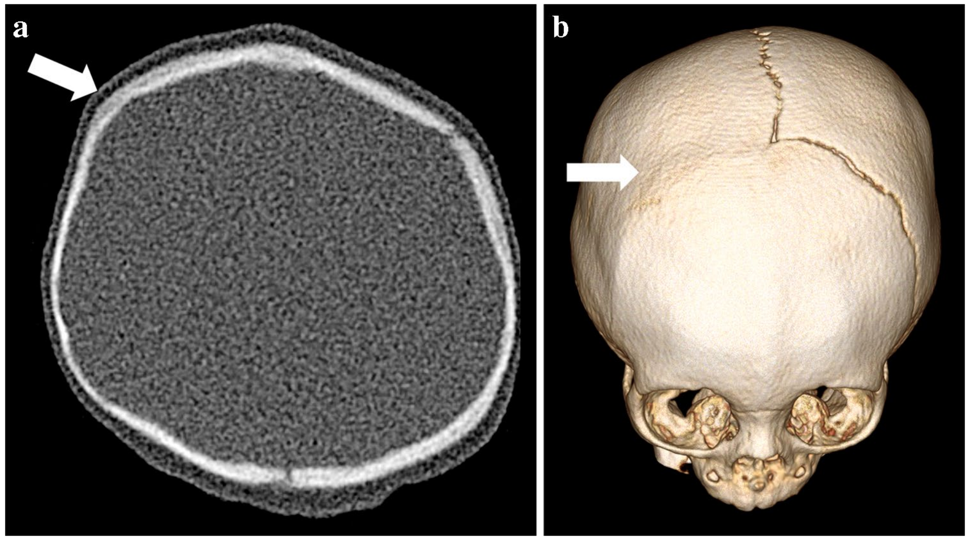

Fig. 2 Craniosynostosis in a 5-month-old boy. **a, b** Axial bone window (**a**) reformat viewed from the superior (**b**) images demonstrate right coronal (*arrows*) craniosynostosis

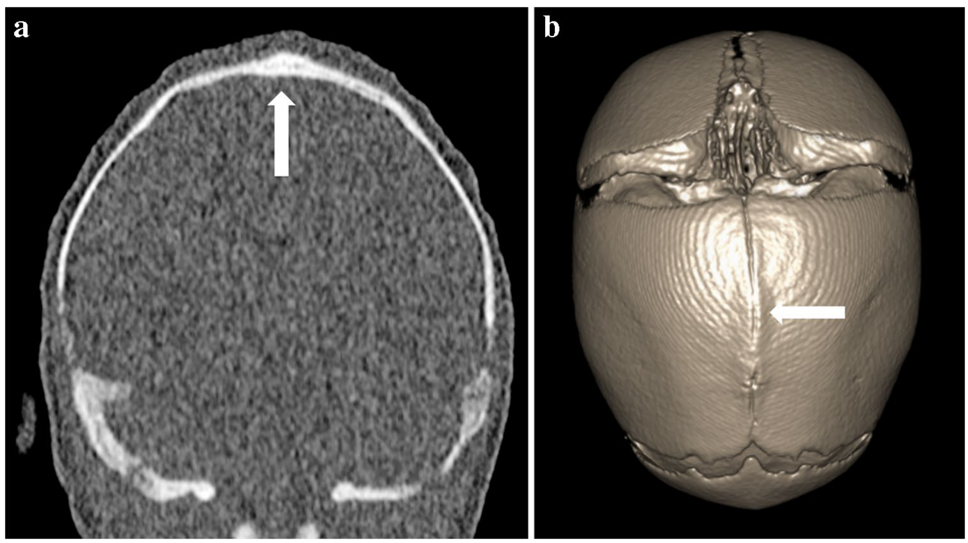

Fig. 3 Craniosynostosis in a 3-week-old boy. **a, b** Coronal bone window (**a**) reformat viewed from the superior (**b**) images demonstrate sagittal (*arrows*) craniosynostosis

for an unrelated reason (*n*=1). Figures 2, 3 and 4 show 2-D and 3-D reconstructions of three patients diagnosed with craniosynostosis, demonstrating early closure of the sutures with bony ridging causing abnormal head shape. For all studies (*n*=50), confidence in diagnosing craniosynostosis was high and more dose was deemed unnecessary by both radiologists. Figures 5 and 6 show cranial sutures well visualized on 2-D and 3-D images in a neonate and a 9-year-old patient, respectively, with clinically abnormal head shape, suggesting diagnostic evaluation with lower-dose CT regardless of patient age.

Discussion

Children with suspected craniosynostosis may undergo multiple CT examinations for diagnosis and post-treatment follow-up, resulting in cumulative radiation exposure. In an effort to reduce stochastic risks associated with radiation exposure in children, we studied the utilization compliance, radiation dose and clinical image quality associated with adopting a new lower-dose CT protocol for craniosynostosis.

Compliance was high before and after the new orderable study was created, with only 2 out of 137 studies performed with routine pediatric brain protocols over a 27-month period. Considering all patients during the first 13 months received a brain CT order with written comments to use the lower-dose CT protocol, compliance was higher than expected. The administrative delay associated with creating the orderable study is typical of a large academic center, and may be a similar obstacle in other hospitals. Our experience suggests initial implementation with adding comments in the order may be a reliable approach, especially if physicians, radiologists and CT technologists are made aware of the new lower-dose CT protocol. However, a specific order

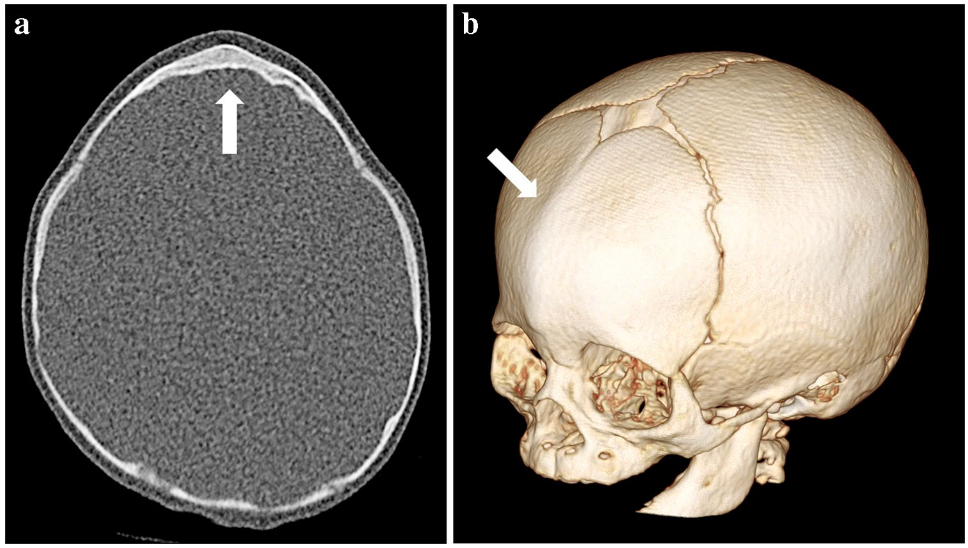

Fig. 4 Craniosynostosis in a 3-month-old boy. **a, b** Axial bone window (**a**) reformat viewed from the left anterior oblique (**b**) images demonstrate metopic (*arrows*) craniosynostosis

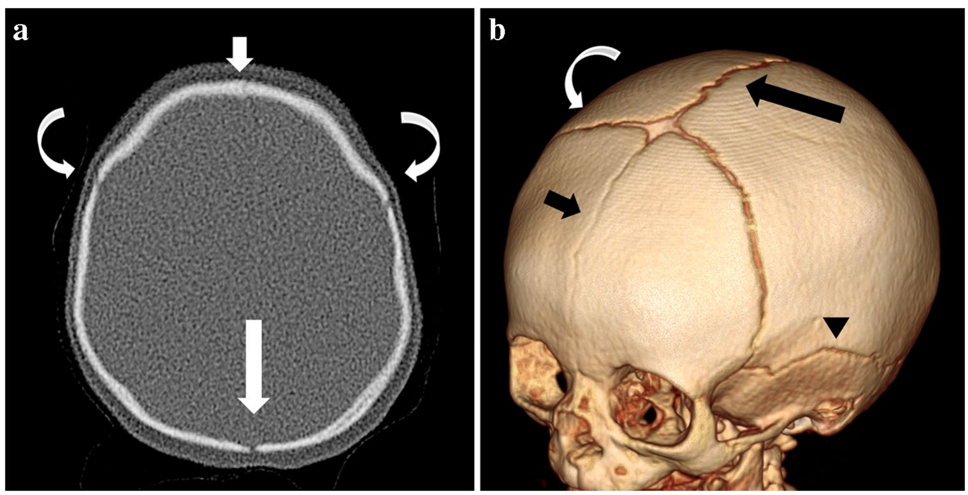

Fig. 5 Patent cranial sutures in a 3-month-old boy with clinically abnormal head shape. **a, b** Axial bone window (**a**) and three-dimensional reformat viewed from the left anterior oblique (**b**) images demonstrate patent cranial sutures: metopic suture (*short straight arrows*), coronal sutures (*curved arrows*), squamosal suture (*arrowhead*) and sagittal suture (*long straight arrows*)

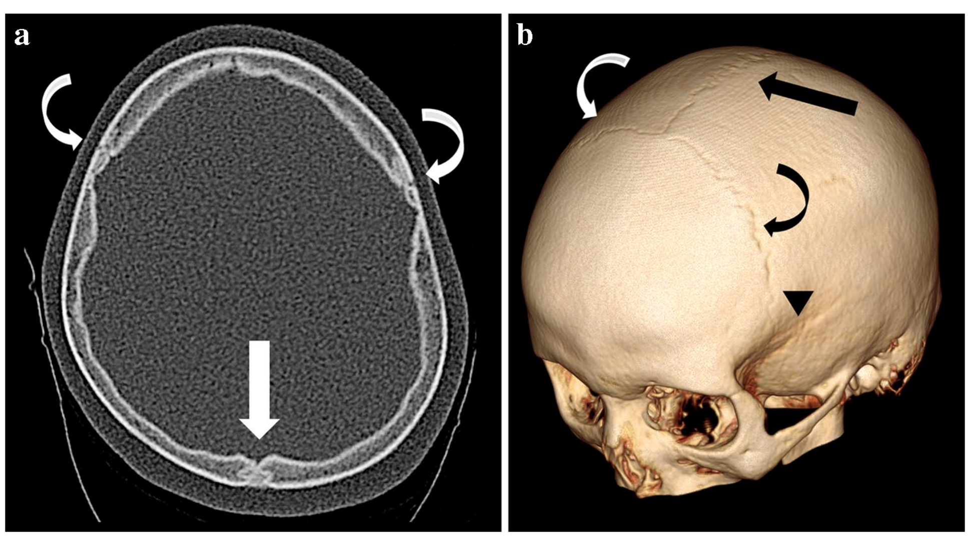

Fig. 6 Patent cranial sutures in a 9-year-old girl with clinically abnormal head shape. **a, b** Axial bone window (**a**) and three-dimensional reformat viewed from the left anterior oblique (**b**) images demonstrate patent cranial sutures: coronal sutures (*curved arrows*), squamosal suture (*arrowhead*) and sagittal suture (*straight arrows*). There is physiological closure of metopic suture without evidence of craniosynostosis

in the electronic medical record may help avoid ambiguity from physician to radiologist to technologist.

The effective doses for the lower-dose CT protocol are comparable to 4-view skull radiography, which ranges from 0.05 mSv to 0.1 mSv [29–31]. However, CT offers greater sensitivity in visualizing spatial resolution in the sutures as compared with plain radiographic examinations [4]. Studies have reported lower-dose CT for craniosynostosis with effective dose ranges of 0.08–3.36 mSv in clinical use [17, 32–34] and 0.02–0.33 mSv in simulation studies [2, 35].

Three groups reported clinical implementation of lower-dose CT protocols without iterative reconstruction; however, scan techniques and dose indices were higher than the lower-dose CT protocol presented in this study (100 kVp, 5 mAs, $CTDI_{vol}$=1.1 mGy, effective dose=0.06–0.22 mSv). Badve et al. [4] adopted a protocol using 120 kV, 62 mAs ($CTDI_{vol}$=11.4 mGy) and 75 mAs ($CTDI_{vol}$=17.7 mGy) for patients younger and older than 2 years old, respectively. Morton et al. [36] reported acceptable image quality with 120 kV, 30 mAs and 37.5 mAs for patients younger and older than 2 years old, respectively. Vazquez et al. [17] reported acceptable image quality using 80 kV and a modulating tube current (range: 50–150 mAs), with a mean $CTDI_{vol}$ of 2.4 mGy and 2.5 mGy (effective dose=0.4 and 0.3 mSv) for patients younger and older than 1 year old, respectively.

Others have simulated lower-dose CT images by adding noise into full-dose CT images. Neverauskiene et al. [2] added noise to CT images from routine pediatric head protocols without iterative reconstruction. Their simulated protocol with 120 kV and 13 mAs would theoretically reduce effective dose from 4.8 mSv to 0.33 mSv. Montoya et al. [37] inserted noise into the raw data of CT images scanned with a routine brain protocol with iterative reconstruction and proposed 90% dose reduction with a mean $CTDI_{vol}$ of 1.5 mGy. While simulated images allow the investigation of various dose levels, they are not representative of the image reconstruction performed by the scanner's proprietary reconstruction algorithms, especially considering advanced denoising or nonlinear iterative algorithms, and should be considered preliminary supportive findings for future implementation with clinical scanning.

Two studies reported lower-dose CT for craniosynostosis using the same model-based iterative reconstruction (MBIR) algorithm (VEO; GE Healthcare, Milwaukee, WI). Kaasalainen et al. [35] scanned a cranial phantom with MBIR (80 kV and 4 mAs). Objective measurements such as noise and contrast demonstrated a potential dose reduction

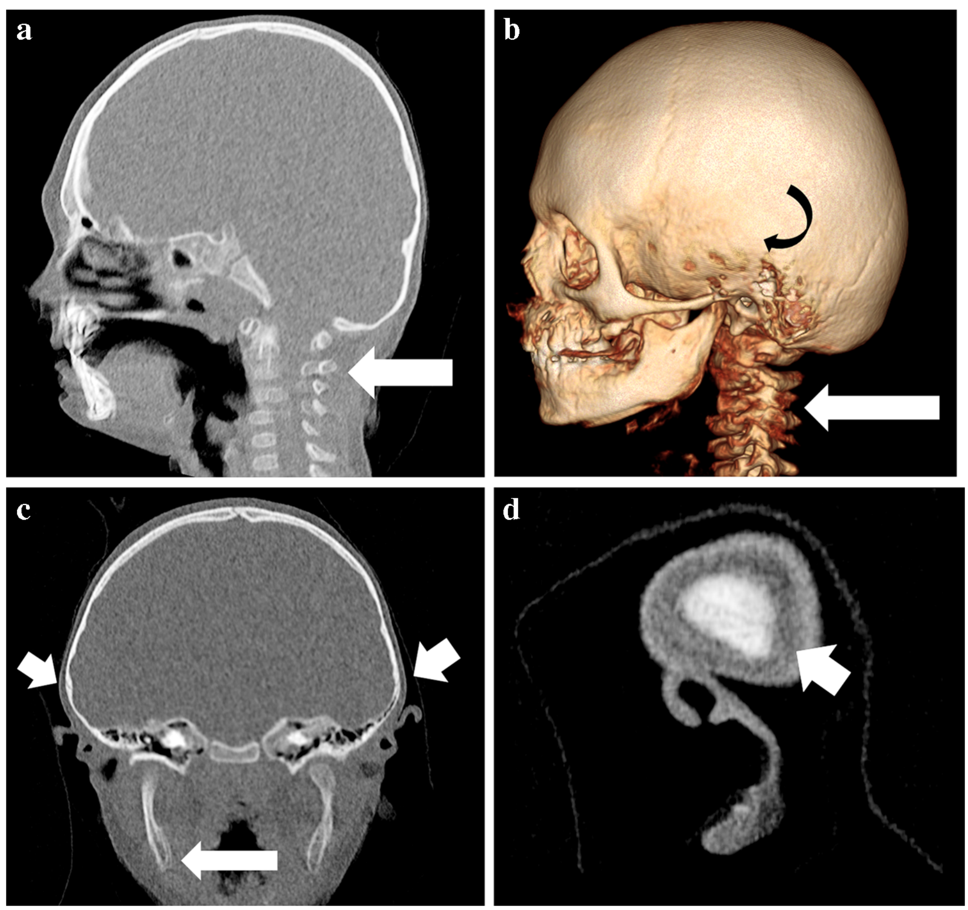

Fig. 7 Patient motion artifact in a 3-year-old boy. **a–d** Sagittal bone window (**a**), reformat viewed from the left lateral (**b**) and coronal bone window (**c**) images show patient motion artifact affecting the skull base and upper cervical spine (*long straight arrows*). The artifact contributes to poor visibility of squamosal sutures on 3-D reformat (*curved arrow*). However, bone windows in coronal (**c**) and sagittal (**d**) multiplanar reformat images do demonstrate patent squamosal sutures (*short straight arrows*)

of up to 88%. However, simple head phantoms do not represent actual anatomy, making it difficult to predict diagnostic ability, and thus the authors warn that 0.02 mSv may be too low for achieving adequate image quality in clinical practice. Ernst et al. [32] scanned 24 pediatric patients ages 0–3 years old with a lower-dose CT craniosynostosis protocol with MBIR (80 kV and 8 mAs). The protocol produced a $CTDI_{vol}$ of 0.94 mGy (0.08 mSv) with acceptable diagnostic image quality. Although the authors demonstrated successful utilization of this protocol, they warn that dose reductions achieved with the MBIR algorithm cannot be extrapolated to other types of iterative reconstruction techniques.

Thus, research in lower-dose CT for craniosynostosis has been reported in outdated protocols without iterative reconstruction, in simulation or phantom studies, or in novel MBIR approaches that are not yet widely available. Furthermore, MBIR takes a longer time to reconstruct with studies reporting reconstruction times ranging from 15 min to several hours [35, 38–42]. Our protocol differs from the aforementioned studies in that it uses traditional iterative reconstruction with reduced techniques of 100 kVp and 5 mAs. These techniques were used in all patients ranging from 0 to 9 years old, which is also distinct from the younger pediatric ages reported in the previously mentioned studies. We used a more commonly available reconstruction algorithm that requires only slightly more processing time than standard filtered back projection. This may be more attractive to hospitals considering a similar lower-dose CT protocol. While diagnosis of craniosynostosis is not urgent, reconstruction speed may affect workflow if the algorithm hinders subsequent reconstructions or affects how quickly the technologist can release the patient after verifying acceptable image quality. In addition, patients may be proceeding directly to the treating physician who would need to have the images available for review. Since commercial iterative reconstruction algorithms start with information in the filtered back projection reconstructed image, CT vendors reported an increase in reconstruction time of less than 1 s and users reported about a 2-s increase in reconstruction time [43, 44]. Lastly, both the routine pediatric brain CT protocol and the new lower-dose CT protocol used iterative reconstruction, thus updated technology was not necessary and rather simple adjustments in tube voltage and tube current offered dose reductions while producing diagnostic image quality.

Major sutures were well visualized in all 2-D and 3-D images. Squamosal sutures were well visualized in all but four studies. Craniosynostosis of the squamosal suture is typically not considered clinically relevant [45]. A 3-year-old patient's study was rated to have poor visibility of squamosal sutures on 3-D views and poor visibility of ventricles; however, this was due to patient motion and not due to technical factors of the lower-dose CT protocol. Figure 7 demonstrates the motion artifact affecting the skull base and upper

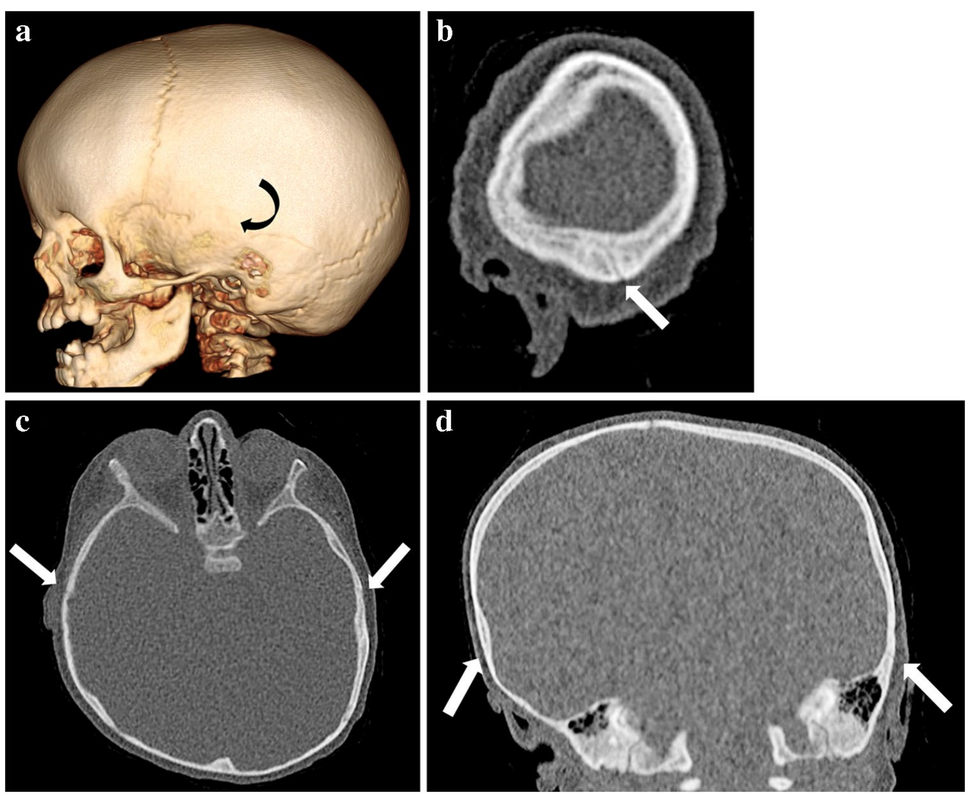

Fig. 8 Patent squamosal sutures in a 1-year-old girl. **a** The three-dimensional reformat image viewed from the left lateral shows the squamosal suture (*arrow*). **b–d** However, two-dimensional sagittal (**b**), axial (**c**) and coronal (**d**) bone window images do demonstrate patent squamosal sutures (*arrows*)

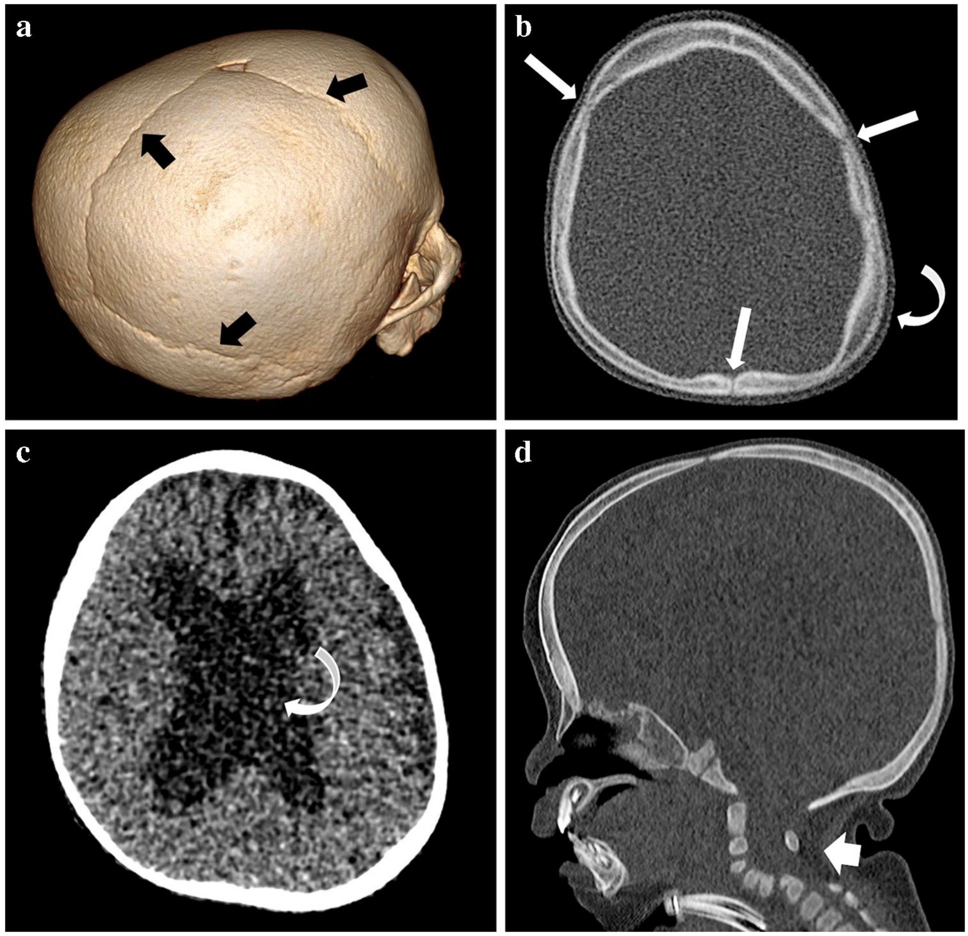

Fig. 9 Patent cranial sutures in a 1-year-old girl. **a, b** Lower-dose computed tomography three-dimensional reformat viewed from the right posterior oblique (**a**) and axial bone (**b**) images demonstrate patent cranial sutures (*straight arrows*) and an area of calvarial thickening (*curved arrows*). **c, d** ventricles (*curved arrow*) seen on axial CT image (**c**) dysmorphism (*arrow*) seen on sagittal CT (**d**). Subsequent magnetic resonance imaging of the brain and spine were obtained (not shown) that better characterized the abnormalities, including features of campomelic dysplasia, platybasia, the partial absence of septum pellucidum, and diffuse thinning of central white matter and corpus callosum

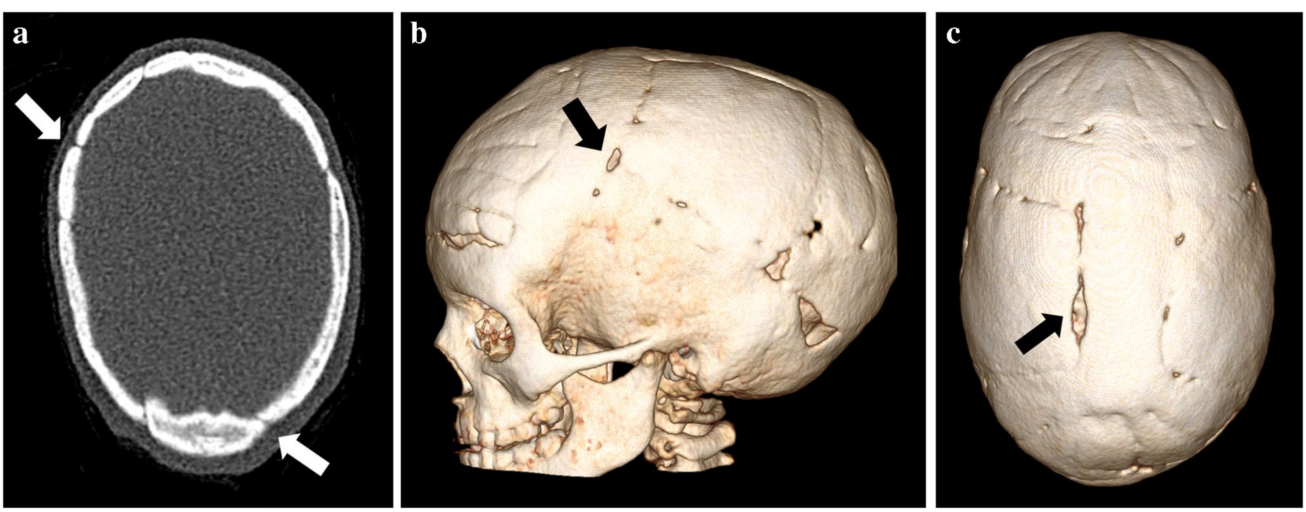

Fig. 10 Patent osteotomies in a 5-year-old girl with a history of craniosynostosis surgery. **a–c** Axial bone (**a**), lateral three-dimensional (3-D) (**b**) and superior 3-D (**c**) views of a lower-dose computed tomography image demonstrate several areas of patent osteotomies (*arrows*)

cervical spine. Squamosal sutures were not well seen with a bulging appearance of the parietotemporal regions. The motion artifact did not affect the diagnosis of craniosynostosis, since the majority of the calvarium were well visualized and rated as acceptable by both radiologists. In three other studies, the visualization of squamosal sutures in 3-D views was rated as "poor" by both radiologists. None of these four studies indicated craniosynostosis. Figure 8 shows an example of the 2-D and 3-D views for one of these studies. Radiologists mentioned the need to review the 2-D views in these cases to have better visualization of the squamosal sutures and high confidence in diagnosing craniosynostosis. It is also known that 3-D reconstructed images provide better perception of the pattern of fractures in the maxillofacial region, besides helping in the faster evaluation of fractures. However, 3-D images alone have a limited role, such as in orbital region fractures, and provide limited results in minimal displaced fractures [46]. As such, our results suggest that multiplanar-reformatted 2-D CT images of the calvarium would better identify the cranial sutures than the 3-D reconstructed images, particularly for evaluating squamosal sutures. Thus, 2-D CT should be regarded as the main tool to evaluate cranial sutures and 3-D reconstructed images should be used as a complementary tool, allowing faster evaluation of the major cranial sutures.

Radiologists identified an 11-month-old patient who had suspected intracranial abnormalities but was not diagnosed with the lower-dose CT craniosynostosis study (Fig. 9). They noted the patient also received an MRI on the same day. This example demonstrates a case where a patient who needed additional evaluation properly received the necessary follow-up to provide a complete standard of care. Radiologists confirmed they were able to evaluate all sutures and had high confidence in ruling out craniosynostosis with the lower-dose CT study. Figure 10 shows images in a 5-year-old patient with a history of craniosynostosis surgery who received a follow-up CT with the lower-dose CT craniosynostosis protocol. The images demonstrate several areas of patent osteotomies and evidence of previous sagittal craniosynostosis.

This work has limitations. While this study assessed the subjective image quality of the lower-dose CT protocol, it did not evaluate image quality for routine pediatric brain CT protocols, thus image quality was not directly compared. Furthermore, while the lower-dose CT protocol provided sufficient image quality for bony detail, it does not permit evaluation of intracranial brain structures, which requires MRI or routine CT. Also, the majority of patients reviewed subjectively were younger than 3 years old. While subjective image quality scores were favorable for patients between 3 and 12 years old, the sample size is small and might not necessarily suggest all patients older than 3 years old can be diagnosed for craniosynostosis with such a low-dose exam. In addition, the appearance of the brain windows of the lower-dose studies made it impossible to completely blind radiologists from the fact that they were reading lower-dose studies. Despite these limitations, our study demonstrates sufficient diagnostic performance of lower-dose CT for evaluating craniosynostosis. The lower-dose CT protocol described can serve as a useful reference for CT protocol optimization; however, on-site verification is prudent when adapting to scanners of different models or from different manufacturers. Different CT scanner models and manufacturers may have different characteristics, including filtration and reconstruction algorithms, and varying degrees of physician experience with diagnosing craniosynostosis may result in differing levels of diagnostic acceptance. Thus, the protocol must be adapted in a site-specific manner.

Conclusion

A lower-dose CT protocol reduced radiation dose to pediatric patients up to 98.1% and produced images that yielded confidence in diagnosing craniosynostosis in all studies. Effective doses were below 0.25 mSv, comparable to exposures from a 4-view skull radiography series. Institutions should be aware of the option to easily implement a lower-dose CT craniosynostosis protocol with high diagnostic utility and drastic radiation exposure reduction for pediatric populations.

Declarations

Conflicts of interest None

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