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Evaluation of Low-Dose 3D Skull CT Images in Craniosynostosis

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ABSTRACT

Introduction: Computed Tomography (CT) is nowadays used widely to differentiate normal brain cranium sutures from abnormal ones in pediatric patients with the aim of early treatment. This study tried to develop a low-dose CT protocol with the acceptable image quality of skull bone in order to evaluate craniosynostosis.
Material and Methods: In this study a cranium bone of human cadaver was scanned with standard and reduced dose protocols. Two radiologists verified the quality of skull bone images acquired from the protocol in which there had been 60% dose reduction to scan pediatric patients. The quality of low dose protocol of three dimensional (3D) CT images of skull bone of 57 pediatric subjects suspected of craniosynostosis were compared with standard-dose skull CT images of 44 patients of the same age range. Volume CT dose index ($CTDI_{vol}$), dose-length product (DLP), and effective dose (ED) were used to evaluate CT dose protocols. The comparison was made by two sample t-test.
Results: Mean and standard deviations of $CTDI_{vol}$, DLP, and ED of standard and reduced doses were 12.4±2.7 mGy, 191.5±54 mGy.cm, 1.94±0.58 mSv and 5.4±0.2 mGy, 85±9 mGy.cm, 0.77±0.17 mSv, respectively, which had statistically significant difference ($\alpha=0.05$). The quality of skull bone views obtained from low-dose CT protocol were found to be as good as in standard dose.
Conclusion: Standard-dose 3D CT protocol of skull bone can be replaced by a 60%-reduced-dose 3D CT protocol with comparable image quality in pediatric patients suspected of craniosynostosis.

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Introduction

Abnormal fusions of sutures in the skull bone of infant are known as Craniosynostosis. It creates a problem for brain growth in the affected babies. Therefore, on-time diagnosis and treatment procedures such as surgery could prevent further complications (e.g., deformity of infant's skull, the disorder in brain growth, and increased brain pressure). Diagnostic imaging by the use of Computed Tomography (CT) with three dimensional (3D) image reconstruction of skull bone has an important role in on-time treatment and description of craniosynostosis [1,2].

Moreover, accurate evaluation of skull sutures is possible by 3D CT images of skull bones. In spite of its beneficial role in the diagnosis of various diseases such as craniosynostosis, the hazards of ionizing radiation dose in CT scanning should not be ignored. Children are to be treated with more consideration because they are going to have a long life ahead and their cells are very sensitive to ionizing radiation. Results of a few studies showed that the risk of leukemia and brain tumor in patients who have undergone brain CT scanning with standard-dose is two to three times higher than those who have not [3-5].

Children's eye-lenses are also highly sensitive to ionizing radiation. They are exposed to the scanning field. Thyroid glands are also in the vicinity of the scanning field; therefore, the scattered radiation could increase the risk of thyroid cancer [6-8].

To prevent complications, it is necessary to have on-time diagnosis and follow up of craniosynostosis. For these, CT imaging is an indispensable tool, but it needs radiation dose reduction because some of the patients need to repeat skull CT scan a few times as follow-up. The stochastic effect of x-ray increases with exposure the patient to more radiation doses. Also, since the nature of the radiation dose is cumulative, the hazard of radiation is likely to increase in patients' future life [9]. Therefore, to avoid excess radiation,

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this study used the skull bone of human cadaver to find an optimum dose plus an acceptable image quality.

There are some studies on reduced dose CT images of skull bone for craniosynostosis evaluation. Their results studies showed that the reduced dose protocol did not affect the image quality of 3D CT of skull bone [10-12]. Hence, due to the global scarcity of work in this area, this study needs to be confirmed and supported by detailed results. In addition, since image quality is highly machine-dependent (CT scanner) such studies are essential to be performed on CT scanners being used in Iran's hospitals.

The aim of this study was to optimize skull CT radiation dose for craniosynostosis of pediatric patients' diagnosis, surgery, and follow-up.

Materials and Methods

We conducted an investigation in a hospital affiliated to the University. A CT scanning system (8-MDCT BrightSpeed GE Health Care, USA) was used for scanning, diagnosis and follow-up, of pediatric patients suspected with craniosynostosis. It should be also noted that this study was approved by the national ethical committee.

A. Testing the performance of CT system

Performance of the CT scanner was assessed by the Gammex 464 ACR (American College of Radiology, United States) CT phantom. The quality control tests, such as accuracy of Hounsfield Unit (HU) by comparing the HU value of the standard materials shown by CT machine with that of given by the manufacturer, HU value of water (deviation of HU value of water as a reference from zero), noise measurement (standard deviation of HU value of water in the Region of Interest or ROI), and CT linearity (the ability of the CT system to measure the broad ranges of linear attenuation coefficient or different HU values) were performed. The machine's $\mathrm{CTDI}_{\mathrm{vol}}$ was also measured to evaluate the CT dose performance by Black Piranha multi-function meter (RTI group, Sweden) and PMMA (Polymethylmethaacrylate) head (16 cm diameter) and body (32 cm diameter) phantom (IBA, Germany).

B. Study on skull of human cadaver

A skull of a human cadaver was used to optimize the brain CT protocol for craniosynostosis evaluation. 3D CT images of skull bone were acquired by standard (100 kVp, 120mAs) and reduced dose (80 kVp, 96 mAs, and 80 kVp, 70 mAs) protocols. Other parameters, such as beam width (1.25mm×8), pitch factor (1.35), rotation time (0.8 sec), and reconstruction algorithm (Filter Back Projection) were the same in both standard- and low-dose protocols. Two radiologists, each with more than 10 years' experience evaluated the quality of reconstructed 3D CT images of skull of human cadaver while they were blinded to both the scanning parameters and the radiation dose used to scan skull bone.

C. Patient study

Subsequently, the study proceeded by using a low-dose protocol (80 kVp, 96 mAs) to scan the pediatric patients (2 to 36 months of age), who were referred to the hospital for craniosynostosis evaluation with 3D skull CT scanning request. 3D CT images were reconstructed through standard protocol by the use of 1.25 mm slice thicknesses. The scanning range in all the patients was from the vertex to the base of the skull. Two expert radiologists evaluated the 3D CT images of infants' skull.

Furthermore, this study divided the pediatric patients into two groups. The first group was selected retrospectively, from those pediatric patients whose 3D skull CT images were taken by the standard-dose protocol. These images were downloaded from Picture Archiving and Communication System (PACS). The second group was scanned by low-dose skull CT protocol, prospectively. These two groups were selected to avoid over-exposure of the same patient to two times scanning (with standard- and low-dose CT protocols) and to be able to compare the quality of CT images of the two groups. 3D CT images of skull bone of pediatric patients with the same age were then compared.

The quality of 3D CT images of skull bone was compared objectively by two expert radiologists. In the objective quality assessment of standard and reduced dose 3D skull CT images, the CT image quality was graded into three scores, (1) good quality images (diagnostic reportable images without any difficulty), (2) sufficient quality images (with enough quality for the diagnostic report but not as good as the first group), and (3) insufficient quality images (not diagnosable).

Additionally, dose assessment for both standard- and low-dose 3D skull CT images was performed by recording the $\mathrm{CTDI}_{\mathrm{vol}}$ (in mGy) and DLP (in mGy.cm), available on dose report page at the end of the CT images of each patient in the PACS system. The effective dose (ED) for each patient was estimated through the multiplication of the conversion factor, k, by DLP. The unit of k is mSv/mGy.cm. The k values were equal to 0.011 mSv and 0.0067 mSv for the 0-1 year and 1-5 year age groups, respectively [13].

This study evaluated the number of times or the frequency of skull CT scanning for craniosynostosis diagnosis and follow-up for each studied patient. This will help us to estimate the radiation dose associated with each pediatric patient. Since the effect of ionization radiation is cumulative, the risks of stochastic effect could raise with increasing number of CT scanning. These details were accessible from the PACS system.

D. Calculation of Signal-to-Noise Ratio in the Images

An important question is the Signal-to-Noise Ratio (SNR) for the standard and reduced dose 3D Skull CT protocol, which determines the level of clarity of the two images, which are important for diagnosis by the radiologists.

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This is determined by the photon number (υ) registered by any pixel, and the standard result, SNR = $(v)^{1/2}$ is used. We use the formula,

$$v = (b)(a)E_{total} / [<E>.n.N_1.N_2] \quad (1)$$

where $E_{total} = kVp \times mAs$ (*kVp* is the peak voltage applied to the x-ray tube in kilo-Volt and mAs is the tube current time product in the milli-ampere second) and generally <E>=kVp/2, with "a" being the conversion factor for photons (a=0.01) and <E> is the average energy of the photons,

"b" is the photoelectron conversion coefficient (b=0.8) for the detector. The detector consists of a ($N_1 \times N_2$) array (N_1=512 and N_2=512), while "n" is the number of projections per gantry rotation (n=1000) [14].

E. Statistical Analysis

For statistical analysis of the data, all demographic (such as sex and age of the patients) and dose indices (such as $CTDI_{vol}$, DLP and ED) information were tested with two-sample t-test with a significance level been $\alpha=0.05$. The corresponding *p-values* for the hypothesis were calculated.

Results

Results of the quality control tests of the CT system showed that the performance of the CT scanner was acceptable. The accuracy of HU value of water was acceptable with less than 1% error. The maximum differences between the HU value of different parts of the ACR phantom including, polyethylene (less than 5%), bone (less than 8%), air (less than 1%) and acrylic (less than 4%) were in the acceptable limits. Therefore, the linearity of the CT system was satisfactory, since it was able to measure different materials with broad ranges of HU values, accurately. The results of noise measurement showed that the maximum error is less than 1% which does not affect the quality of CT images. The results of the dose measurement reveal that the performance of the CT system to measure the $CTDI_{vol}$ was acceptable. The differences of the $CTDI_{vol}$ between the measured values and what was shown by the CT system was less than 20%.

B. Results of the skull bone of human cadaver-scanning showed that the reduced dose protocol with 80 kVp and 96 mAs produced acceptable image quality which is comparable to standard dose CT (100 kVp, 120 mAs) as is shown in Figure 1(a-d). Dose indices, $CTDI_{vol}$ and DLP, in standard protocol are 1.7 times higher than those for low-dose protocol.

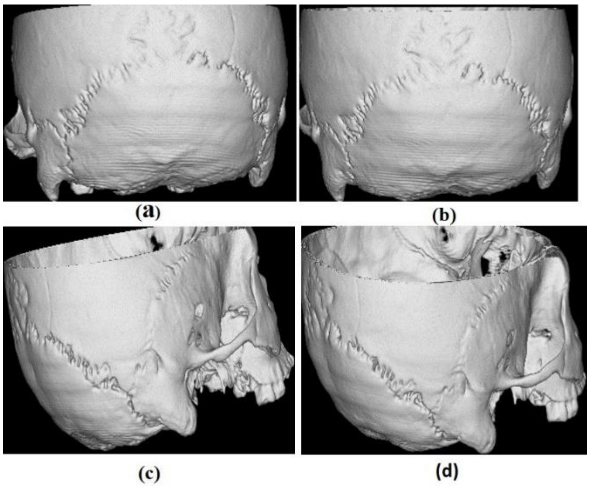

Figure 1. The image quality of three dimensional CT images of skull bone of human cadaver with standard protocol using 100 kVp, 120 mAs in (a) posterior and (c) lateral views and low dose protocol 80 kVp, 96 mAs in (b) posterior and (d) lateral views have acceptable image quality.

C. Out of 44 pediatric patients scanned with standard-dose 3D skull CT protocol, and 57 pediatric patients scanned with low-dose 3D skull CT protocol, respectively 11 and 30 pediatric patients were referred to the hospital for follow-up after surgery. The patients were followed up to evaluate the relapse of craniosynostosis.

The mean age of the patients in standard and reduced dose CT protocols were 11 and 15 months, respectively, which thus did not have significant differences. We had a total sample of 101 cases in which the youngest case was 1 month, while the oldest case was 36 months. We divided them as follows, (1) first group contains 44 cases for the normal or standard dose (selected retrospectively from PACS system), and (2) second group consisted of 57 cases for the low dose protocol who were scanned prospectively. Demographic information, such as age and sex of the patients in first (scanned with standard dose protocol) and second (scanned with low-dose dose protocol) groups' information are presented in Table 1.

Table 1. Demographic information of the pediatric patients in first (scanned with standard dose protocol) and second group (scanned by low-dose protocol)

Group	Number of cases	sex		Age in month mean±SD*
		female	male	
First (standard dose)	44	15	29	11.4±10
Second (low dose)	57	26	31	15.6±10

SD*, is standard deviation

The first group had 33% female cases while for the second it was 46%. The sex of the patients do not matter. The patient in the first and second batches were not the same because this way one avoided the risk of over exposure of the patient to x-ray. However, to compare the image quality, the data were compared for similar age groups. It is seen that the average age in the two cases of

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samples (first and second group) are different. However, standard deviations are the same (±10). We believe that the mean age in the two distributions can be considered to be not more than 1 month apart. This hypothesis on being checked with two sample t-test gave $p=0.0573$ which is greater than 0.05 implying that this hypothesis can be rejected at the significance of $\alpha=0.050$ [15].

The results of the objective evaluation on the basis of the two radiologists' report showed that the quality of 3D CT images of skull bone provided by dose reduction (low-dose) protocol in all 57 i.e. equal to 100% cases were graded with score '3' which means good image quality. This means that they have good image quality that is the image quality in low-dose case was thus comparable to that of standard dose protocol.

3D CT images of skull bone of pediatric patients are shown in Figs. 2(a-d). As seen, in 3D images of skull bone in Figs. (2b) and (2d) the quality of frontal and posterior view with dose reduction (80 kVp, 96 mAs) protocol is comparable to similar views shown in Figures (2a) and (2c) with standard-dose protocol. CT images in Figures 2 (a and c) and Figures 2(b and d) correspond to 2 and 3 months' babies, respectively. Also, 3D skull CT in frontal view of 8 and 9 months babies in Figure 3 (a and b) are independently reported as acceptable and good image quality (score 3) by two expert radiologists.

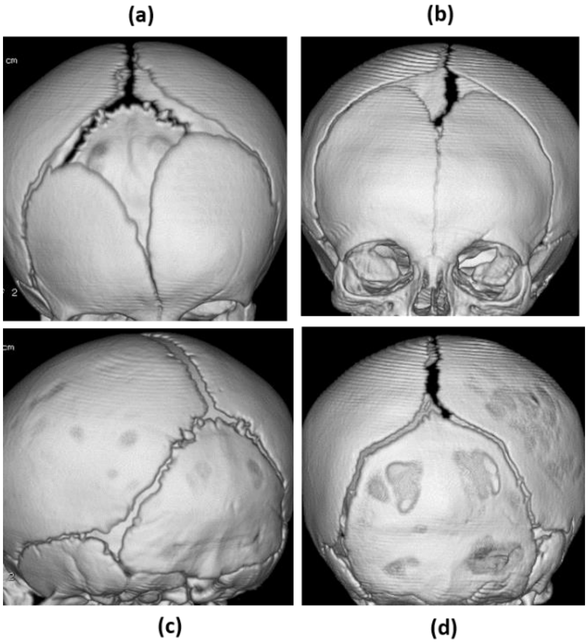

Figure 2. The diagnostic image quality of three dimensional skull CT views of Frontal (a) and postero-lateral (c) views of standard dose (100 kVp, 120 mAs) protocol of 2 months' baby are comparable to frontal (b) and posterior (d) views of reduced dose (80 kVp, 96 mAs) protocol of 3 months' baby .

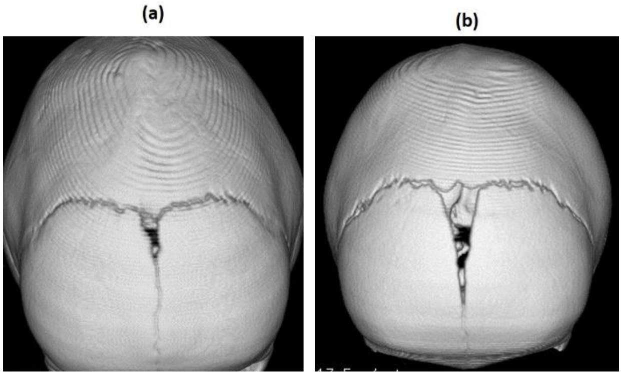

Figure 3. The diagnostic image quality of three dimensional skull CT views of frontal views of (a) standard protocol of 8 months' baby and (b) low dose protocol of 9 months' baby, are acceptable.

The results of $\mathrm{CTDI}_{\mathrm{vol}}$, DLP, and ED are listed in Table 2. It is clear (in Table 2) that there are significant differences between mean values of dose indices, including $\mathrm{CTDI}_{\mathrm{vol}}$, DLP, and ED of skull CT scanning with standard and dose reduction protocols. On the basis of the data presented in Table 2, the CT dose indices of 3D skull CT scanning with standard dose are about 2.5 times higher than that given by the reduced dose skull CT protocol. In other words, with optimized skull CT protocol, one is able to reduce dose indices, which are representatives of dose reduction up to about 60%, as mentioned earlier.

Table 2. Mean and standard deviation (SD) of volume Computed Tomography Dose Index ($\mathrm{CTDI}_{\mathrm{vol}}$ in mGy), Dose Length Product (DLP in mGy.cm) and effective dose (ED in mSv) of 3D skull CT with standard and low dose protocols.

Dose indices	Standard dose (mean±SD)	Low dose (mean±SD)	p-valve
CTDIvol (mGy)	12.4±2.7	5.4±0.3	10^{-296}*
DLP (mGy.cm)	191.5±54	85±9	10^{-157}*
ED (mSv)	1.94±0.58	0.77±0.17	10^{-92}*

Star (*) sign next to the p-values shows that the differences between standard and low-dose indices are meaningful

In these observations the total degree of freedom, df=(44+57)-2 = 99 is a very large quantity. The *t*-test thus approaches the normal distribution case. In all these cases the test statistic t was much greater than 10. The p-values in all the cases were thus extremely small as seen in Table 2 and less than the α-value which was set at 0.05. The hypothesis was thus rejected showing the dose indices in the low-dose case was substantially smaller than that in the standard case.

D. Results of SNR Estimation

For standard-dose protocol using: kVp=100, mAs=120 and <E>=50 keV, we get from Eq. (1) that $\mathrm{SNR}=6.76\times10^3$.

For the reduced dose protocol: kVp = 80, mAs=96, and <E>=40 keV therefore the $\mathrm{SNR}=6.05\times10^3$.

The results of SNR calculation thus showed that the SNR for standard and 60% dose reduction protocols were 6.76×10^3 and 6.05×10^3, respectively. The values of SNR

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for both protocols were sufficiently high and hence did not interfere with image quality.

Results of evaluating the frequency of skull CT scanning for the purpose of craniosynostosis diagnosis and its follow-up are shown in Figure (4). As seen in Figure (4), almost 60% of the cases with skull suture problems needed to repeat 3D skull CT for evaluation of craniosynostosis relapse after surgery. This had to be done frequently, e.g. more than 3 times up to the age of 36 months. Because of these multiple exposures, it would be necessary to reduce the photon number in every CT scanning.

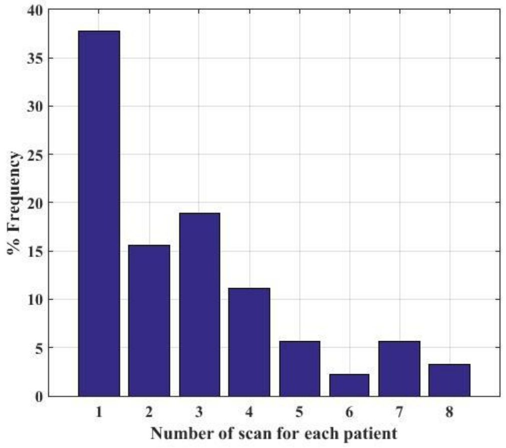

Figure 4. Frequency distribution of follow up for each patient is shown here. x-axis represents the number of times 3D skull CT scanning procedures were done for pediatric patient to evaluate craniosynostosis, and y-axis is its frequency in terms of percentage.

Discussion

This study used the skull bone of human cadaver to estimate an optimized CT dose protocol for infants with normal and abnormal sutures. The proper protocol with sufficient reduced dose and adequate image quality was selected on the basis of skull bone CT images of human cadaver. The reduced CT dose protocol was used to scan the studied pediatric patients, referred to the CT department of the hospital to undergo 3D CT scanning of skull for craniosynostosis evaluation. 3D skull CT images obtained with low-dose protocol were compared with standard dose ones. In this study, we avoided administering the unnecessary dose to the pediatric patient to estimate the optimized dose protocol with acceptable image quality.

Additionally, to reduce radiation dose in CT scanning of skull bone, we firstly reduced the kVp value. Reducing kVp in turn increased the photoelectric effect in bone; thus, image contrast improved. On the other hand, by decreasing the kVp radiation output, the radiation dose to the patient gets reduced in CT scanning [16]. In the next step of dose reduction process, mAs was reduced to 96 and 70 mAs. It should be also noted that radiation output has a direct relationship with mAs. It means that by reducing mAs by half, administered dose to the patient reduces by half as well [17]. In the present work, the radiologists selected two sets of CT images of skull bone with good image quality, one with standard (100 kVp, 120 mAs) and the other one with reduced dose with 80 kVp, 96 mAs. The latter protocol was used to scan the pediatric patients' skull bone for craniosynostosis evaluation.

This study showed that it was possible to cut down the radiation dose by almost 60% and subsequently protect the patients from several risks, particularly for those patients, who had to make regular follow-ups [18-21].

Morton et al. showed that low-dose skull CT without compromising image quality can be used for shunt placement in hydrocephalic patients and craniocynostosis follow-up [12].

Ernst et al showed that the reduced dose protocol with an effective dose less than 0.1 mSv can be used to scan pediatric patients' skull for craniosynostosis evaluation by Iterative Reconstruction (IR) [1]. The present study succeeded in reducing the effective dose by 60% (from 1.94 mSv in standard dose to 0.77 mSv in reduced dose) without using iterative reconstruction but at the same time image quality was evaluated both qualitatively and quantitatively.

In another study done by Montoya et al., CT radiation dose protocols for craniosynostosis evaluation with 2, 10, and 25 percent of dose reduction, by using 120 kVp, were examined [11]. The results of their simulation study showed that the quality of skull CT images with 10 and 25% dose reduction were acceptable. Unlike their simulation, this study used an actual skull bone of human cadaver to find the optimum dose, which was more realistic.

This study also showed that in both cases, standard as well as 60% dose reduction protocols, the SNR was very high (6.76×10^3 in standard dose and 6.05×10^3 in reduced dose protocol). Thus, even with reduction of photon number by 60%, the SNR remained at a satisfactory level. This basic physical explanation is completely new and has not been done by any researchers. So, we are going to develop this method in the forthcoming studies.

The results of this study show that 60% of the patients (Figure 4) need multiple exposure to radiation for diagnosis and follow-up purposes. This enhances several risks. It is thus necessary to do effective imaging with reduced dose but not sacrificing the quality of the image [22]. Our present study shows that this is possible and should be followed.

To evaluate skull CT scanning for craniosynostosis, we require a larger data set. Nevertheless, in this study, we dealt with sufficient number of scanned cases. In future we will continue the work with a larger data set. It has to be noted that facilities with reduced dose protocol could be collected from the university hospital, this being the only hospital in the university dedicated to pediatric patients, with skull bone problem specialists and operation room suitable for the related surgery and follow-up. Most of the pediatric patients were referred to the CT department in need of 3D imaging of skull bone and brain CT. Since the inherent contrast of brain

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tissues are very low, it was not possible to use the dose reduction protocol for brain CT evaluation.

Conclusion

The results of this study showed that 60% dose reduction protocol can be used to scan skull bone of infants with adequate diagnostic image quality. This will be of considerable benefit to patients, particularly to children because of sufficient dose reduction.

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