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Image quality and radiation optimization in children‘s nonsyndromic craniosynostosis computer tomography

SUMMARY OF DOCTORAL DISSERTATION

Medical and Health Sciences
Medicine M 001

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This dissertation was written between 2013 and 2019 at Vilnius University.

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VILNIAUS UNIVERSITETAS

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Vaizdų kokybės ir apšvitos optimizavimas vaikų nesindrominių kraniosinostozių kompiuterinėje tomografijoje

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RELEVANCE

Ionizing radiation received by children during computed tomography (CT) scans is a topical problem due to the risk of exposing sensitive organs and the risk of developing cancer. The discussion is still open among radiologists regarding selection and usage of CT protocol parameters in order to not compromise the quality of diagnostic images and safeguard the patients from additional exposure due to re-examination. Ways are being sought to help select small scan parameters and not lose the diagnostic value of CT scans. One of the main means in reducing and monitoring exposure is diagnostic reference levels (DRL). When setting and periodically updating the DRL, it is necessary to properly select the CT parameters for standard procedures. Following a retrospective CT research data analysis of the children's hospital in 2010, 2012 and 2014, the local diagnostic exposure levels will be assessed and compared with national and European diagnostic reference levels. The results of the study will provide information on which CT tests are most commonly performed in children, which age groups have the highest number of CT tests, which age group has the highest risk of cancer due to exposure, and will allow the selection of key groups for dose optimization. By choosing an optimized scanning protocol based on the age of the children and adapting it to a specific clinical pathology, exposure and cancer risk can be reduced dozens of times without the loss of diagnostic information. Numerous clinical image optimization studies have been performed using image quality control or anthropomorphic phantoms, but these studies do not provide information on specific pathologies, making it impossible to accurately assess whether an optimized (lower-dose) protocol will allow proper diagnosis. We used real clinical situations to optimize the dose, i. e. CT images of a specific pathology to determine whether the image quality is appropriate for diagnosis. For this purpose, we used retrospective CT images of real patients and applied noise simulation - a noise simulation algorithm was developed for the generated special "noise bases" that correspond to the noise level generated by scanning at lower current and time product (mAs) values. Noise bases were created using the same local equipment that also produced original retrospective images. The generated noise bases are modified according to the size of the object, the influence of the scanning parameters on the image noise and added to the original patient CT images.

THE PURPOSE AND TASKS OF THE RESEARCH

The purpose - to develop a CT dose optimization algorithm based on the generation of ultra-low dose CT images from retrospective images by modifying them with simulated noises corresponding to the reduced X-ray tube current strength and time product (mAs) values.

The Tasks of the Research

1. Analyze exposure levels of children during their CT scans and compare the data with the recommended levels of medical exposure in Lithuania and Europe.

2. Create noise bases corresponding to different X-ray tube current strength and time multiplication (mAs) values.

3. Evaluate correspondence of the generated noise bases to the actual recorded noise and compare the quality and diagnostic suitability of the original and simulated CT images.

4. Develop optimized scanning protocol practical recommendations for the evaluation of specific bone pathology.

Defensive statements

1. Specialized CT scanning protocols with low parameters can be applied to high-contrast objects (bones).

2. It is possible to generate different X-ray tube current and time product values (mAs) matching the noise bases by using modeling systems - phantoms, and to generate images of different quality that correspond to real-time scanned images.

3. The obtained and evaluated images at the X-ray tube voltage of 120 kV and the product of current and time of 13 mAs are suitable for the diagnosis of bone pathology.

4. Exposure during CT scans for pediatric nonsyndromic craniosynostosis can be reduced 15 times compared to the standard CT protocol by using the 13 mAs X-ray tube current and time product value, identified in this research.

RESEARCH METHODOLOGY

The clinical study was performed at the Children's Hospital, public institution Vilnius University Hospital, Santara Clinics. Vilnius Regional Biomedical Research Ethics Committee granted permission No. 158200-15-790-302 (03/06/2015) for the research. Personal data of the subjects (name, surname, address and other personal data allowing identification) were not collected. All data collected during the research are anonymous, it will not be identifiable with persons and will not be linked to any sources allowing personal identification. The data obtained were depersonalized by the information data system - the hospital uses the Radiology Information System (RIS) and the Picture Archiving and Communication System (PACS).

Inclusion of subjects into the research

In the beginning it was decided to evaluate the CT scans performed in 2010, 2012 and 2014. Diagnostic images of children from birth to 18 years of age were scanned and analyzed according to scanned body areas and protocol parameters. The device used for CT scans was SIEMENS SOMATOM SENSATION PLUS 64 (manufactured by Siemens Medical Solutions Diagnostics, Germany, 2010).

Stages of the research

The study consisted of two stages - a retrospective data analysis and an experimental part.

In the first retrospective stage of the research, the following tasks were set: to analyze the radiation doses of CT scans in the Radiology Department of the Children's Hospital at Vilnius University Hospital Santara Clinics in 2010, 2012, 2014; and to identify the body areas that have the most CT scans as well as areas of the body receiving the highest doses of exposure. A retrospective analysis of CT single-phase uncontrast studies was performed for this purpose.
During the analysis, CT scans were grouped according to:

- Scanned body area (head, chest, pelvis / abdomen, torso, limbs)
- Patient age groups (from birth to 1 year, 1-5 years, 5-10 years, 10-15 years and 15-18 years)
- Gender of patients

To assess the patient's exposure dose, the patient scan dose protocol was used indicating mAs, kV, volumetric dose index CTDIvol (mGy), and the product of dose and length – DLP (mGy*cm).
The third quartile of data (Q3) was used to compare diagnostic reference levels (DRL) according to European Commission Publication No. 185 "European Guidelines on Diagnostic Reference Levels for Pediatric Imaging." Medium DLP values were assessed by

patient age groups and scan areas. The effective dose E (mSv) was calculated for the body area involved in most CT scans by applying the organ sensitivity factor k according to ICRP 103.

In the second experimental stage of the study, after the first stage results analysis and identification of the areas and age groups receiving the highest doses an experiment was performed with images of bone pathology digitally modifying image quality. During the experiment, the quality of the images obtained for diagnostic purposes was changed by simulating the noises corresponding to the reduced values of current and time product (mAs) in order to select suitable diagnostic images with much lower parameters and to offer a scanning protocol for bone pathology.

From January 2010 to December 2014, 60 head CT scans for skull deformities were performed in the Pediatric Radiology Department, the diagnostic images of CT patients (20 boys and 9 girls), ages from 1 month to 4.4 years (average 1.03 years) were selected for the experiment regarding uniform parameters of CT scanning protocols.

Diagnostic head CT images of all 29 children were modified by the adding specific noises to match the 120 mAs, 100 mAs, 80 mAs, 50 mAs, and 13 mAs parameter images. The simulated noises were added to all retrospective original craniosynostosis images for each patient (the same procedure was applied to each CT section of the head), thus generating the low-dose CT images.

Simulated noise algorithm methodology:

- cylindrical phantom, 215 mm in diameter, providing image quality in accordance with body size for generating primary noise,
- spherical phantom in accordance with shape – to estimate the variation of noise using the law SD object size = ax + b,
- adding simulated noise to the original images according to the shape and size of the object,
- expert random assessment of simulated and original images,
- data analysis and finding statistically reliable data.

Statistical analysis

Preliminary data processing and desctriptive statistics were performed in MS Excel. In the second stage, a statistical analysis of the experimental data was performed, hypothesizing a reduction in scan parameters without a significant change in diagnostic quality. At this stage, the data were analyzed using software package R. The quality point estimates and the 95% confidence interval were evaluated for the experimental image evaluation. Categorical variables are presented by calculating the median, minimum and maximum values as well as interquartile distance (IQR). The chi-square test was used to compare the means in the groups. Homogeneity testing in groups was examined using a nonparametric Friedman test; null hypothesis: there is no significant difference between groups; alternative: there is a significant difference between the groups compared. Hypothesis testing was performed with a significance level of 0.05.

RESULTS OF THE RESEARCH

First stage data analysis

During the study, 2042 single-phase non-contrast CT scans of the head, chest, pelvis and limbs were analyzed. Data were collected at the Radiology Department of the Children's Hospital, Vilnius University Hospital Santara Clinics in 2010, 2012 and 2014 (Fig. 1).

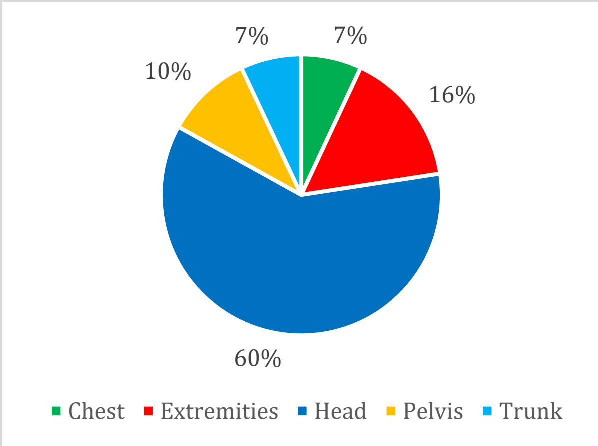


Fig. 1 Total distribution of CT scans by scanned body areas (all years, all age groups)

Having reviewed the CT examinations, we noticed that the largest number has been performed in the head area (60%), the lowest - 6.95%. – in the chest area. The distribution of CT examionations by patient age group and body area is presented in Table 1, where you can also see that head examinations were the most common in all age groups.

Table 1. Distribution of CT scan tests by patient age groups and body areas

Age group / Body area	[0,1)	[1,5)	[5,10)	[10-15)	[15-18)	Total
Chest	3	8	24	43	64	142
Limbs	-	8	30	127	154	319
Head	78	207	259	361	330	1235
Pelvis/Abdomen	5	11	22	63	80	181
Torso	1	4	4	65	91	165
Total	87	238	339	659	719	2042

The diagnostic reference levels (DRL) for radiological and interventional radiology procedures of pediatric patients have been approved only for CT scans of the head in Lithuania. The head CT examinations in 2010, 2012 and 2014 account for almost 90 percent of all CT scans in the youngest age group. The newly approved national DRL values for 2018 are significantly higher than the recommended European ones (Figure 2). Having analyzed the results we can state that the DRL values of the examinations included into our research do not exceed the Lithuanian DRL, however, if compared to the European PiDRL recommendations, DLP values of CT scans in children ages from birth to 1 year are higher than recommended.

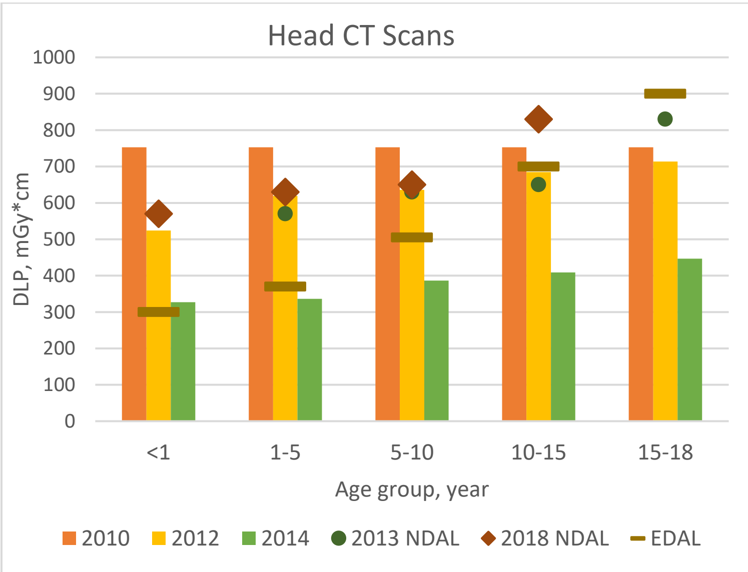


Fig. 2 Comparing the third DLP quartiles of the Children's Hospital Head CT scans with the Lithuanian national DRL (2013 and 2018) and the European DRL by study year and age group.

The main scope of the head CT scan protocol optimization in accordance with the diagnosis is the age group of infants from birth to one year of age. Selecting an optimized scanning protocol according to the age of the children and adapting it to the assessment of a specific clinical pathology could reduce exposure dozens of times avoiding losing diagnostic information. Bone pathologies, when it is sufficient to evaluate high-contrast objects (bones) with low mAs values, are skull deformities. In nonsyndromic craniosynostosis the diagnostic CT images are required corrective surgery planning, when it is sufficient to assess the ossification of cranial sutures.

The second stage of research - the noise simulation

The primary noise base was obtained by applying the formula scanning the cylindrical phantom using 120, 100, 80, 50 and 13 mAs (lowest possible), see Fig. 3

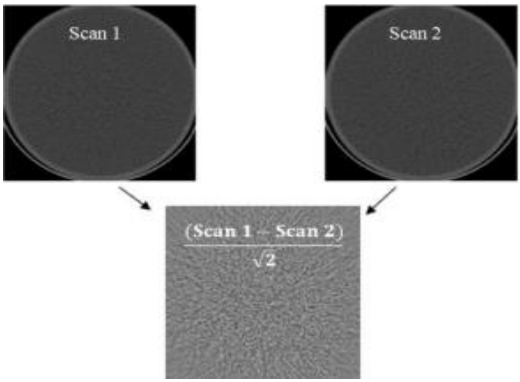


Fig. 3 Producing of the primary noise base according to the selected mAs by scanning the phantom twice.

Head areas differ in each axial section of the CT examination, therefore the head sizes were taken into account to have correct results (Fig. 4).

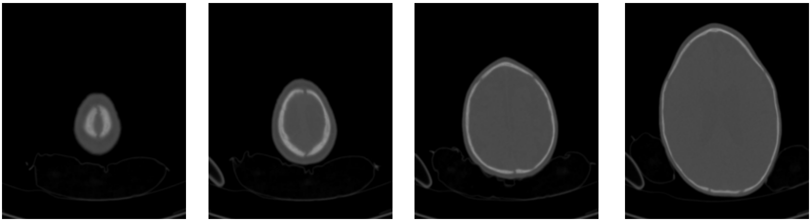


Fig. 4 Axial sections of the head in CT images

A spherical phantom was scanned for this purpose and the noise characteristic parameter (SD) in each section was evaluated. The spherical phantom and its axial CT images with corresponding noise parameters (SD) in different cross sections are shown in Fig. 5.

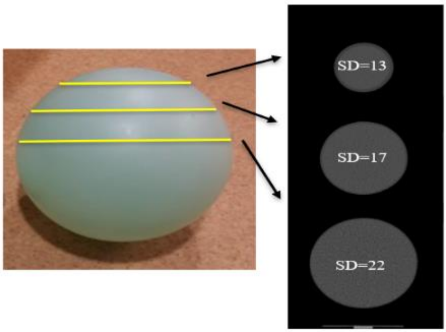


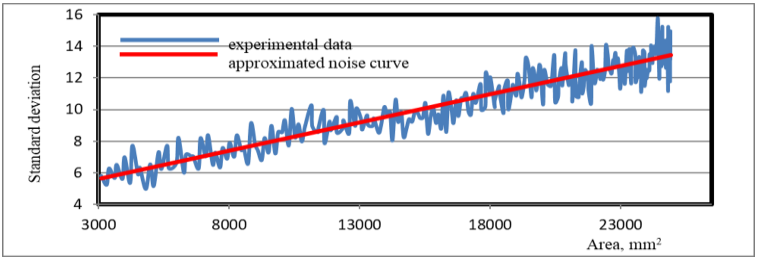
Fig. 5 Spherical phantom a) Axial sections of a spherical phantom with noise parameters (SD)

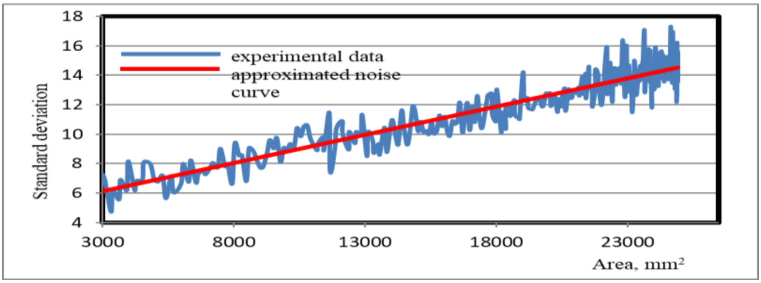
After measuring the spherical phantom the images of the phantom CT were obtained for each different section, the noise characteristic parameter SD was calculated for each section. The obtained dependence of noise on the size of the object was approximated with a straight line:

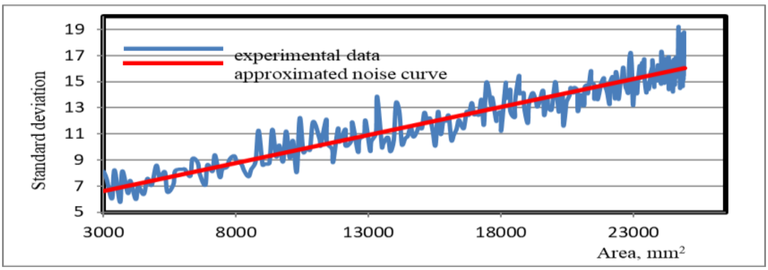
$$SD\ object\ size = ax + b,$$

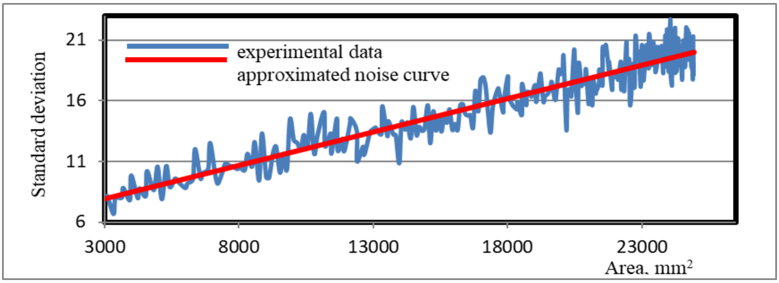
where: SD is the standard deviation, x is the area, a and b are the coefficients.

Modification of the primary noise base according to the given law was performed using Matlab software. This results in simulated noise for different areas of the section to match the area of the head in that layer. This way a noise model was created for different section (area) values and different mAs values (120, 100, 80, 50 and 13). The dependence of the standard deviation on the object size is shown in Figure 6.









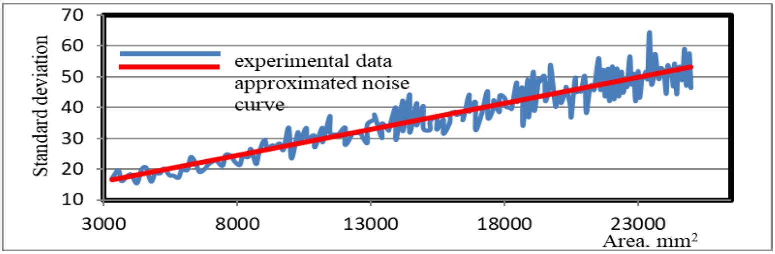


Fig. 6 Approximated noise curve at 120 mAs, 100 mAs, 80 mAs, 50 mAs, 13 mAs.

Before retrospective modification of a child's CT images with generated noise, it is necessary to assess whether the noise generation methodology is correct. Phantom CT scans with 120 mAs, 100 mAs, 80 mAs, 50 mAs and 13 mAs were obtained for this purpose and compared to phantom images simulated with noise parameters of 120 mAs, 100 mAs, 80 mAs, 50 mAs, 13 mAs. The average standard deviations of the two images measured in the same location of the same section were then compared. There was no significant difference in the F-test comparing the variances of the two images ($p = 0.6$), shown in Figure 7. Thus, the hypothesis that the images overlap is not rejected. The results indicate that the noise generation methodology is correct, and the method with simulated small mAs generates images that do not differ from the actual images.

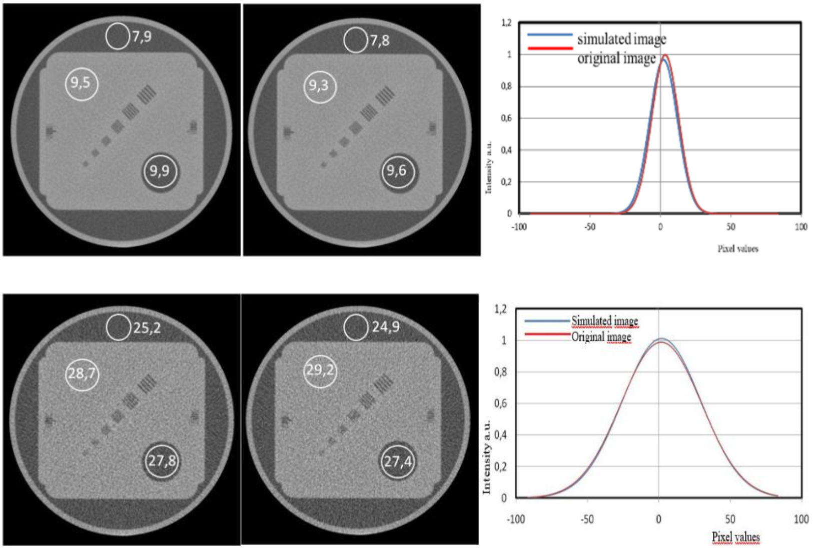


Fig. 7 For the accuracy of the noise generation methodology the original 120 mAs, 13 mAs and simulated 120 mAs, 13 mAs images were compared.

The base of the primary noise obtained by scanning the phantom at the same location twice is modified by applying the law (SD dependance on the size of the object) to different areas of the head sections. This was done for all images of the retrospective head study according to their axial areas. The final noise modeled this way was added to the axial sections of the retrospective head study, and an axial image of the low-dose CT was generated (shown in Fig. 8).

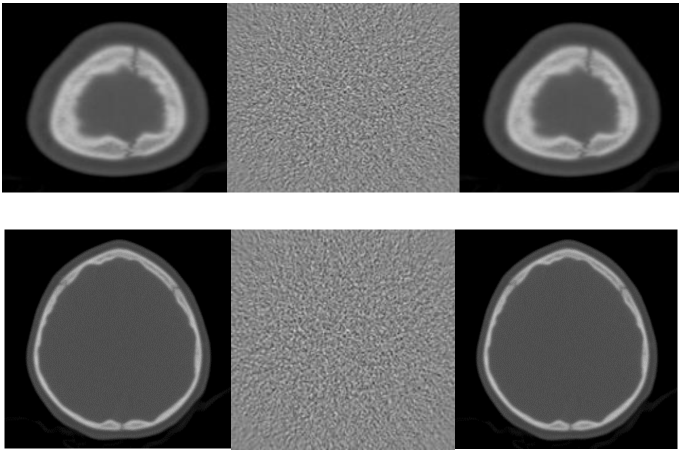


Fig. 8 For the series of axial images of one patient's original CT scan, the modeled final noise is selected according to the mAs (120, 100, 80, 50, or 13) for each image according to its cross-sectional area.

This way, a complete series of head examination images of each patient was obtained by simulating noise according to the selected mAs. Further, 3D head reconstructions corresponding to scans 120, 100, 80, 50, and 13 mAs were performed from the image series.

Fig. 9 Axial section and 3D reconstruction of the original image (195 mAs)

The same procedure with simulated noise for specific axial section areas was applied to all 29 head CT examinations. Approximately ~ 1200 axial images were generated for each patient. Axial section and 3D reconstruction of the original CT examination, axial images of small parameters generated by the same section, and complete 3D reconstructions (Fig. 9–10).

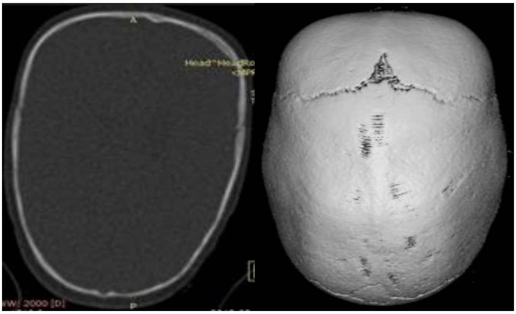


Fig. 10 Axial section of the simulated image and 3D reconstruction (13mAs)Reconstructions of 3D images were generated from the original and simulated axial sections and submitted for evaluation.

Experts also evaluated one axial section of the original and the simulated image in the middle of the arch. The images were evaluated by 3 doctors: a neurosurgeon and 2 radiologists. Evaluation criteria - visibility of skull seams and diagnostic value of images. Each expert evaluated 174 cases. The evaluation was planned, the evaluators were given randomized anonymous images, they did not know whether the images were original or simulated during the evaluation. Figure 11 shows the distribution of ratings depending on the image rating (1 - bad, 2 - good, 3 - very good) and patient ID. The figure shows that the sets with ID 6 and 16 were rated worse than the rest of the images.

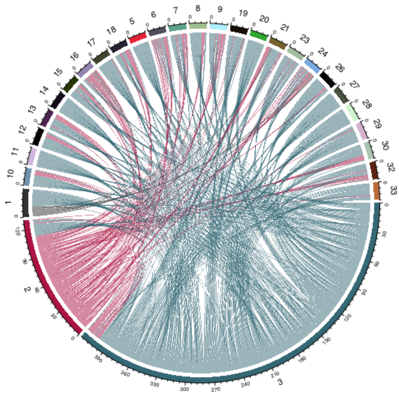


Fig. 11 Distribution of experimental evaluations by image evaluation and patient ID

The difference in evaluations of radiologists was insignificant (p = 0.12), but the difference in neurosurgeon and radiologist evaluations was found to be significant (Fig. 12).

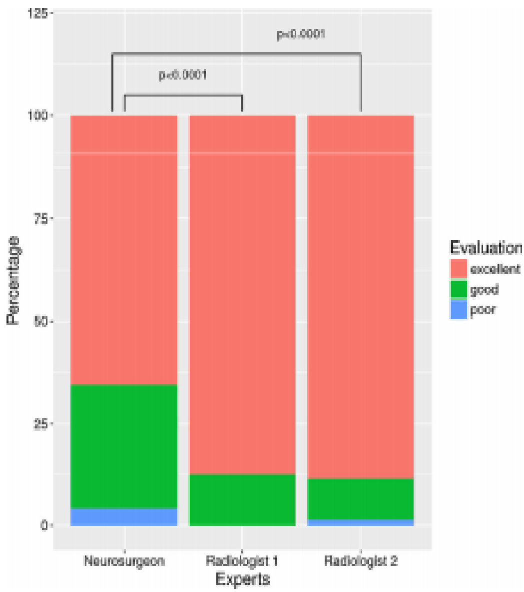


Fig. 12 Evaluation by three experts

Evaluation by a neurosurgeon is also important in the research because they are part of the team, CT images of the head are required for surgery planning, so their evaluation cannot be ruled out.

Differences in the assessment of neurosurgeons and radiologists are due to their differnt specialization, they evaluate the images differently, for example, when interpreting cranial suture blurs. Radiologists often evaluate CT images of the head because it is their daily work, therefore there is little difference between very good / good and bad images for radiologists. However, at a current of 13 mAs, there is already a significant difference between all images rated "excellent" ($p = 0.0026$). The rating "excellent" by individual expert is given in Table 2, where the maximum possible rating for each (mAs) can be 58 (29 patients, 2 questions for each case).

Table 2. Expert evaluation of a an "excellent" image at different mAs

Evaluators	X - ray tube current (mAs)						Image evaluation
	13	50	80	100	120	195	excellent
Neurosurgeon	31	37	38	41	39	42	228
Radiologist I	50	51	51	52	46	54	304
Radiologist II	42	53	54	48	56	55	308
Total number of answers	123	141	143	141	141	151	840

The rating images AS “good” by each expert is presented in Table 3. The maximum possible assessment for each (mAs) can be 58 (29 patients, 2 questions for each case).

Table 3. Expert evaluation of a “good” image at different mAs

Evaluators	X - ray tube current (mAs)						Image evaluation
	13	50	80	100	120	195	Good
Neurosurgeon	22	17	15	17	19	15	105
Radiologist I	8	7	7	6	12	4	44
Radiologist II	14	3	4	10	2	2	35
Total number of answers	44	27	26	33	33	21	184

The image rated as “excellent” depends largely on the image quality, therefore it can be concluded that lowering the mAs values generally decreases the image quality, which is characterized by a decreasing number of excellent ratings at lower mAs (Table 2). It has been mentioned that the diagnosis of craniosynostosis requires an assessment of the gap (seam) between the bones, but this does not require excellent image quality (the image quality required by the quality assurance documents). Therefore, the ratings “excellent” and “good” can be combined, and the images evaluated as such are appropriate for making a diagnosis (Table 4).

Table 4. Expert-assessed images suitable for diagnosis (combining "excellent" and "good") at different mAs

Evaluators	X - ray tube current (mAs)						Images suitable for diagnosis
	13	50	80	100	120	195	
Neuro-surgeon	53	54	53	58	58	57	333
Radiolo-gist 1	58	58	58	58	58	58	348
Radiolo-gist 2	56	56	58	58	58	57	343
Total number of answers	167	168	169	174	174	172	1024
Percentage of images evaluated as good / excellent	96% 167/174	96.6% 168/174	97.1% 169/174	100% 174/174	100% 174/174	98.9% 172/174	

In a clinically validated protocol, CT scans of pediatric head scans are performed using a current of 195 mAs, thus this image evaluation group is a benchmark. In order to determine whether the evaluation of images with smaller parameters differs significantly from the evaluation of original images, the hypothesis that there is no significant difference was tested, alternatively – a significant difference between the groups. In the absence of significant difference between the proportion of images rated good / excellent at reduced mAs and 195 mAs (reference group), we would conclude that images obtained at lower parameters were also diagnostically suitable. The confidence interval for the evaluation of the original images - when the scan modulation is 195 mAs (0.95, 0.997), and the average diagnostic evaluation is 0.989. Numerically, this corresponds to the fact that when the confidence interval is 95%, images with expert judgment within the limits of (165.3; 173,478) can be suitable for diagnosis. In Table 2, we see that none of the reduced mAs group estimates were below the lower limit of the confidence interval. Therefore, we cannot reject the hypothesis that there is no significant difference between the group of original images and images with reduced parameters. No statistically significant difference was found between all groups applying the Friedman's criterion ($p = 0.18$). The results suggest that images recorded using a 13 mAs anodic current may be suitable for the diagnosis of craniostoses without a statistically significant difference compared to the current standard protocol using 195 mAs (Fig. 13).

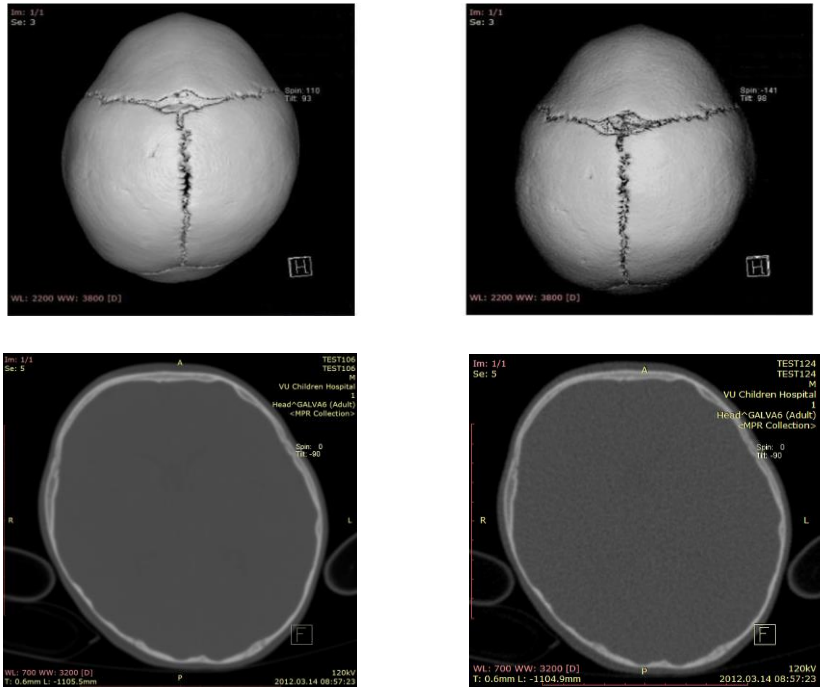


Fig. 13 The 3D images and axial sections of the head were evaluated as excellent for both the original ones (195 mAs) and simulated images at 13 mAs X-ray tube current and time product value.

The above results show that the diagnostic value at 13 mAs does not differ significantly from the diagnostic value according to the standard protocol (195 mAs), thus at this stage we evaluated the effect of the reduced dose protocol on patients' effective doses. Data from patient scan CT protocols (CTDIvol, DLP), age of patients and organ sensitivity factor of the scanned body area according to ICRP 103 were used to calculate the effective dose. A retrospective study of 29 children was done for cancer risk. The results of the calculated effective doses and the estimated exposure for each age group by sex are presented in Table 5.

Table 5 Calculated effective doses and estimated exposure for each age group by sex

Number of scans	Sex	Age groups	CTDI (mGy)	IQR	DLP mGy*cm	IQR	E (mSv)	IQR	CR	CM	Eexp (mSv)
6	F	[0,1)	29,46	(18.07, 32.05)	511	(286, 550)	6.42	(3.59, 6.9)	0.01	0.03	0.43
13	M	[0,1)	29,22	(22.53, 30.66)	524	(397, 561)	6.57	(4.98, 7.04)	0.09	0.03	0.44
19	M/F	[0,1)	29,22	(21.46, 30.66)	524	(330.5, 560)	6.57	(4.15, 7.03)	0.09	0.03	0.44
3	F	[1,5)	31,4	(31.4, 32.69)	582	(561, 612)	4.41	(4.27, 4.43)	0.06	0.02	0.29
7	M	[1,5)	32,51	(30.06, 35.15)	558	(472, 658)	4.26	(3.61, 4.52)	0.05	0.02	0.28
10	M/F	[1,5)	32,05	(31.4, 34.34)	570	(541, 633)	4.34	(4.14, 4.44)	0.05	0.02	0.29

IQR - interquartile distance, CR - cancer risk, CM - cancer mortality, E - effective dose, Eexp - expected effective dose.

The median DLP of children from birth to 1 year was 524 mGy*cm. Compared to the Lithuanian national diagnostic reference levels (570 mGy*cm) approved in 2018, the values are not exceeded, however, according to the PiDRL recommendations for children from birth to one year, the calculated test value is 1.8 times higher (524/300). The calculated median DLP for children from 1 year to 5 years of age 570 mGy*cm does not exceed the Lithuanian DRL for this age group (630 mGy*cm), but according to the European DRL (PiDRL recommendations) it is also 1.5 times higher (570/370). The estimated effective dose for a standard head CT scan protocol is 4.45 mSv for girls and 5.11 mSv for boys. Using reduced exposure protocols at a parameter of 13 mAs, an effective dose of 0.33 mSv IQR (0.26, 0.45) is expected. Examinations using reduced parameters (to the lowest possible 13 mAs) would allow to reduce the effective dose up to 15 times. The exposure dose for each patient would be reduced to 93.7% (94%).

CONCLUSIONS

1. The review of CT scans of children in 2010, in 2012 and 2014 shows that the vast majority were head scans. Comparing the DRL of the scans with the approved Lithuanian and European DRL evaluating the risk of cancer according to the effective dose, it was found that the greatest need is to optimize the CT scan protocols of the head for small children.

2. The images generated using the noise simulation algorithm correspond to real scanned images using small mAs, thus the developed algorithm is suitable for obtaining reduced mAs images without performing additional patient scans.

3. Images using the head CT protocol with parameters at 120 kV and 13 mAs can be used to diagnose nonsyndromic craniosynostosis with statistically the same accuracy as using the standard 195 mAs protocol.

4. Exposure during CT scans for pediatric nonsyndromic craniosynostosis can be reduced 15 times compared to the standard CT protocol by using the 13 mAs X-ray tube current and time product value, identified in this research.

PRACTICAL RECOMMENDATIONS

- Using model systems - phantoms - it is possible to create different noise bases corresponding to mAs and to generate images of different quality corresponding to real scanned images:
- selection of the indication and identification of findings relevant to the diagnosis;
- selectable mAs optimization range;
- phantom according to body size - to generate primary noise;
- adding simulated noise to the original images according to the shape and size of the object;
- experts random evaluation of simulated and original images;
- data analysis and finding statistically reliable data.
- The method can be used for each localization or indication when optimizing the CT protocols.

LIST OF PUBLICATIONS ON THE SUBJECT OF THE DISSERTATION

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4. M. Astrauskas, M. Burkanas, A. Neverauskienė, J. Venius. Optimisation of low dose computed tomography protocol for diagnostics of develpmental dysplasia of the hip using a phantoms based noise simulation approach. Proceedings of International Conference Medical Physics 13 (2017) 20–25, 9–11 November 2017, Kaunas, Lithuania

NOTES

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