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A study on the reduction of radiation dose using carbon fiber-reinforced plastic during X-ray examination of children and infants

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Abstract: The purpose of this study was to investigate the suitability of an assistive device for radiological examination. A Carbon Fiber-Reinforced Plastic (CFRP) with relatively high transmission factor was used to reduce unnecessary radiation exposure for patients and examiners and maintain a stable examination posture and reduce falling of the infant. An average of 10 entrance surface doses (ESDs) were used for the ATOM Phantom T-spine (T6) and the Rando Phantom Thyroid (T), Inguinal Area (I), and Eye Ball (E) for patients and examiners during each infant chest X-ray examination. Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were also measured and analyzed via paired sample T-test and Pearson's correlation analysis using SPSS statistics version 21.0 (Chicago, IL, U.S.A.) to quantitatively evaluate changes in image quality before and after using the ancillary device. During infant chest X-ray examination, EST results were as follow: ESDT6 of infants, 233.70 ± 5.74 μGy; ESTs for the examination assistant: ESDT151.40 ± 4.01 μGy; ESDI, 143.20 ± 3.22 μGy; and ESDE, 146.20 ± 3.19 μGy. When the SNR and CNR values of chest X-ray images involving infants were compared using Pearson's correlation analysis, significant ($p < 0.001$) differences were found between values obtained before and after applying the ancillary device. The radiological examination assist device can stabilize the infant's posture during examination. Thus, it can reduce unnecessary exposure of patients and examination assistants to radiation, ultimately improving the safety of infant X-ray examinations.

Keywords: Accelerator Applications; Hardware and accelerator control systems

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Contents

1 Introduction

The development of techniques for high-sensitivity radiation detection and diagnosis has facilitated rapid and precise diagnosis using images. The number of X-ray examinations used during the initial diagnosis of disease has increased, leading to a drastic elevation in exposure to medical radiation by patients during the medical checks [1]. Since the occurrence of Fukushima nuclear accident in March 2011, there has been a widespread societal concern and fear of radiation. Efforts have been made to decrease radiation exposure in accordance with the principle of "as low as reasonably achievable," even if the exposure is necessary for medical practice. Although whether a low amount of radiation exposure during a diagnosis can cause cancer remains controversial, the 2006 National Academy of Sciences Biological Effects of Ionizing Radiation VII (BEIR VII) report has accepted the linear-no threshold (LNT) model and concluded that low-dose radiation may be associated with cancer and genetic disorders [2]. Consequently, minimizing exposure to radiation is important based on the assumption that even a small dose of radiation can increase the risk of cancer.

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The Nuclear Energy Promotion Act of Korea provides standards for medical radiation exposure. However, it does not describe an upper limit. Therefore, the benefit obtained by a patient from radiation exposure should be greater than the related loss. The International Commission on Radiological Protection (ICRP 103) recommends that a diagnostic reference level (DRL) should be used to optimize patient protection against unnecessary radiation exposure during radiological examinations aimed at medical diagnosis [3]. In particular, for infants whose tissues and organs are very sensitive to radiation, the risk of low-dose radiation-induced disease should be considered very carefully. It is important to obtain optimum images required for a diagnosis via minimum exposure to radiation [4]

It usually takes a long time to acquire images necessary for radiological diagnosis of infants due to their anxiety in an unfamiliar environment and their lack of communication ability. In addition, since infants cannot control their movement during an examination, a larger area is exposed to radiation. Furthermore, unstable postures during the examination may increase the risk of falls or other accidents, requiring re-examination. Due to these concerns, individuals responsible for infant safety along with the examiner are allowed into the examination room during radiological examination. Thus, the examiners and protectors are unnecessarily exposed to radiation, although they wear clothes for radiation protection. Radiation exposure accumulates during repeated examinations.

This study evaluated image qualities depending on the use of an ancillary device made of carbon fiber-reinforced plastic (CFRP) for infants' radiological examination in order to protect examination assistants against needless exposure to radiation during chest X-rays for infants and reduce the frequency of re-examination. This study also verified the relevance of radiological examination assist device.

2 Objects and methods

2.1 Research equipment

1. X-ray Phantoms: ATOM Dosimetry Phantom (model 705 / CIRS / U.S.A.)

2. X-ray Phantoms: Rando Phantom (Alderson Research Laboratories Inc., U.S.A.)

3. X-ray Device: SHIMADZU UDI 150B-40 (R-1000-150)

4. Carbon Fiber Reinforced Plastic (CFRP) Holder

5. PLD: AGC Techno Glass Dose Ace Glass Dosimeter Type GD-352M

6. SPSS Statistics 21.0, Chicago, IL

7. PACS (Marotech Marosis view version 5.4, Republic of Korea)

2.2 Research methods

2.2.1 Production of ancillary device for radiological examination of infants

An ancillary device for infants undergoing radiological examination was made of CFRP to eliminate unnecessary radiation exposure to protectors and examiners by preventing infants from moving

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during their Chest AP and to reduce the number of re-examinations caused by unstable posture (figure 1).

The ancillary device for X-ray examination of infants is designed to stabilize and restrain body movements of infants using a band attached to the CFRP Holder device groove. The infant's body is securely fastened using bands attached to the CFRP holder to restrain the infant's movement while obtaining the AP view of infant's chest. It prevents parents and examination assistants from being exposed to radiation and reducing the risk of re-examination.

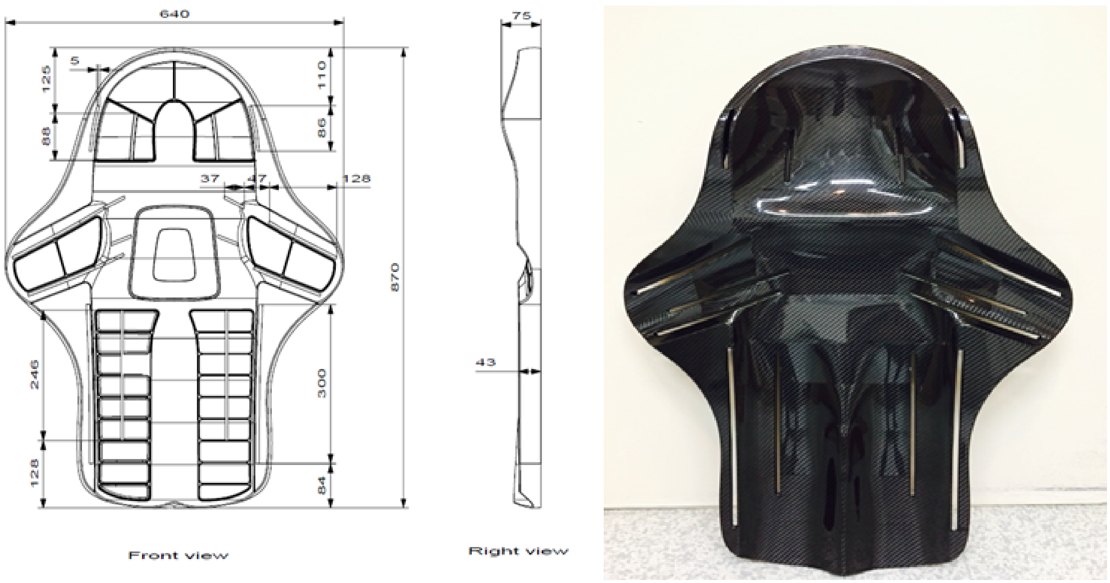

Figure 1. A schematic and an actual image of X-ray examination assistance device for infants.

2.2.2 Measurement of radiation exposure during chest X-ray examination of infant

In order to determine the radiation exposure of the infant and examination assistants during the chest X-ray, the ATOM Phantom was placed in a supine position on the table. The Rando Phantom was placed next to the examination table (figure 2).

Exposure to radiation doses by infant and examination assistants was measured using the ATOM Phantomand Rando Phantom. Entrance surface dose (ESD) was measured 10 times under conditions of 55 kVp, 5mAs, SID110 cm, and Collimation 14"×14". The dose measurement was performed using two PLD devices attached at 1 cm intervals on an ATOM Phantom T6. The two PLD devices were attached at each of Rando Phantom Lens, thyroid, and inguinal areas at 1-cm intervals.

2.2.3 Image quality analysis of chest X-ray images before and after using the radiologic ancillary device in infants

In order to compare the image quality of chest X-ray images, the chest AP examination was first performed in supine position on the examination table without using the ancillary device, and then repeating the procedure using the device attached to the Rando Phantom Lens (figure 3). Image quality was assessed using the Rando Phantom and the radiologic ancillary device. Tests were

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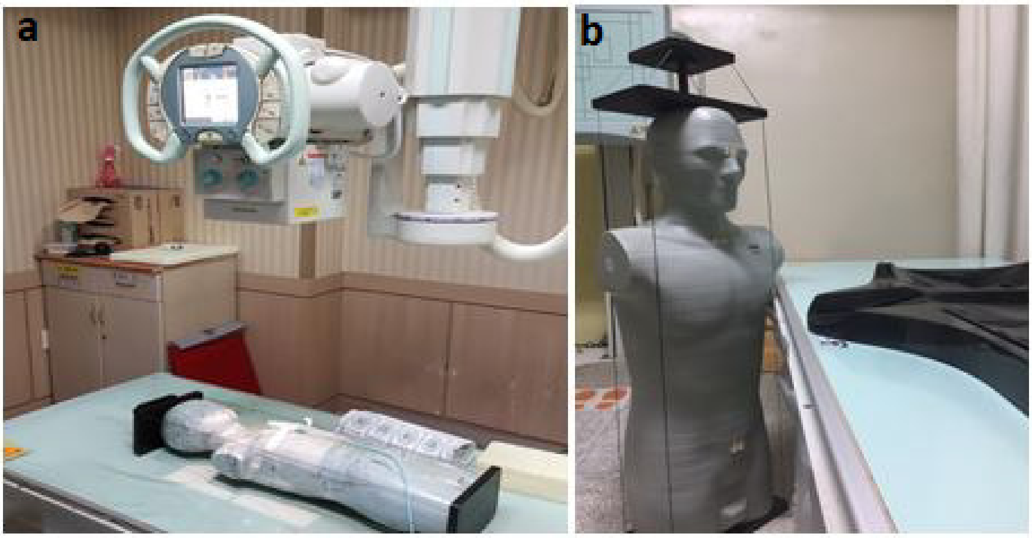

Figure 2. Measurement of radiation exposure in infant and examination assistants. a) ATOM Dosimetry Phantom (for infant); b) Rando Phantom.

performed 30 times before and after application of the ancillary device under conditions of 80 kVp, 5 mAs, SID 110 cm, and Collimation 17"×17".

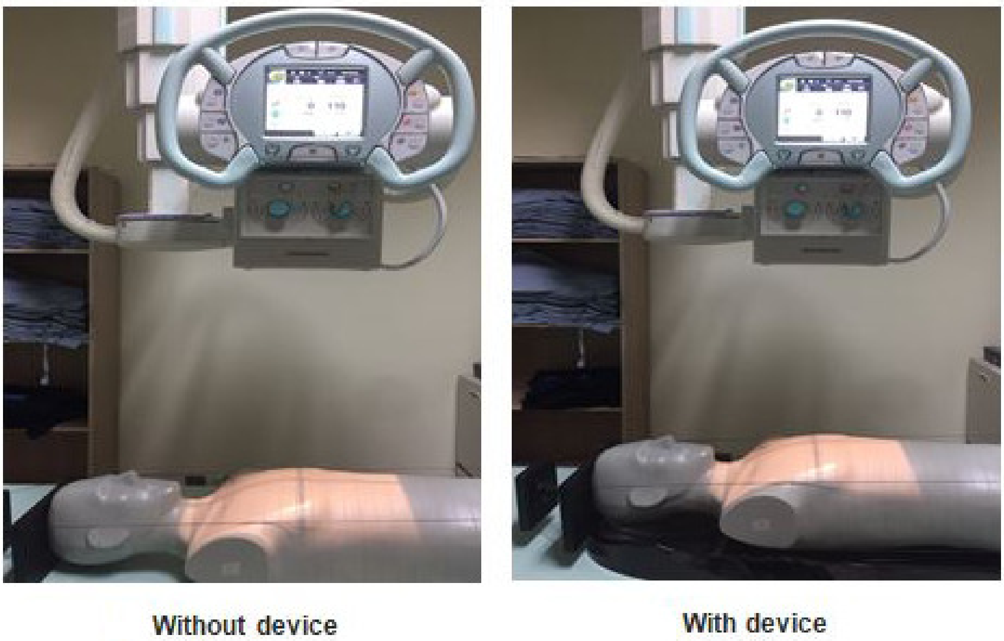

Figure 3. Rando Phantom position before and after using the CFRP radiologic device.

Regions of interest (ROI) were set (size: 51.51 mm^2) on the acquired chest AP image in four areas: lung, T6, cardiac, and background (figure 4). The signal-to-noise ratio (SNR) and contrast-

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to-noise ratio (CNR) values were calculated. SNR and CNR were calculated using the following equation (2.1).

$$\mathrm{SNR} = \frac{\text{Mean of ROI}}{\text{Average of BG}}, \qquad \mathrm{CNR} = \frac{(\text{Region 1} - \text{Region 2})}{\text{Average of BG}} \tag{2.1}$$

* Mean of ROI: average signal strength of region of interest

* Average of BG: average of background

* Region: average signal strength of region of interest

Figure 4. Image of ROIs before and after applying the radiologic ancillary device for comparision of SNR & CNR.

A qualitative visual assessment of 23 infants younger than 4 years was conducted with or without the radiological ancillary device as shown in figure 5. A radiologic reader of this institute scored chest X-ray images obtained with or without the radiologic ancillary device in accordance with the evaluation criteria for diagnostic radiologic images [5] as shown in table 1.

2.3 Statistical analysis

Analysis of SNR and CNR was performed for images obtained before and after applying the CFRP holder. All experimental data are expressed as mean ± standard deviation. Image quality of chest X-ray images obtained with and without the CFRP holder was assessed via normality test using a SPSS Statistics Ver. 21.0. Significance was determined using parametric methods of paired sample t-test and Pearson correlation analysis. Qualitative visual assessment was performed via correlation analysis of radiologic ancillary device and image reading applications. Statistical significance was considered when P-value was less than 0.05 at 95% confidence level.

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Figure 5. The examination device on the X-ray table is used to stabilize the infant's arms and legs with bands.

Table 1. Quantitative assessments performed with and without the CFRP holder.

Diagnostic requirements	← Score →									
	Poor			**Satisfactory**					**Good**	
Image criteria	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
① Performed at peak inspiration, except for suspected foreign body aspiration										
② Reproduction of the thorax without rotation and tilting										
③ Reproduction of the chest extending from immediately above the lungs to T12 / L1										
④ Reproduction of the vascular pattern in the lung, about two-thirds from the center										
⑤ Reproduction of the trachea and the proximal bronchi										
⑥ High-resolution images of the diaphragm and costophrenic angles										
⑦ Reproduction of the spine and paraspinal structures and visualization of the retrocardiac lung and mediastinum										
Total:										

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3 Results

3.1 Measurement of radiation exposure of infant and examination assistant during infant chest X-ray examination

The incident surface dose measured at the T6 position of infant using the ATOM phantom was 233.70 ± 5.74 µGy. Incident surface doses at thyroid, inguinal area, and lens of examination assistant (measured using the Rando Phantom) were 151.40 ± 4.01 µGy, 143.20 ± 3.22 µGy, and 146.20 ± 3.19 µGy, respectively (table 2).

Table 2. Measurement of radiation doses used for patients and assistants.

	kVp	mAs	SID	Screen size	ESD
			cm	inch	(µGy)
Young patient (T6)	55	5	110	14 * 14	233.70 ± 5.74
Thyroid	55	5			151.40 ± 4.01
Inguinal area	55	5			143.20 ± 3.22
Lens	55	5			146.20 ± 3.19

3.2 Qualitative analysis of chest X-ray images before and after application of the radiologic ancillary device in infants

The SNR and CNR were calculated based on infants' chest X-ray images before and after the ancillary device was used in radiological examinations. Results are shown in table 3. The use of the device did not adversely affect the image quality. on SNR and CNR measurements after using the device, revealed a significant improvement in image quality (figure 4).

The correlation coefficient between chest AP X-ray image and SNR was 0.998. The correlation coefficient of chest AP X-ray and CNR was 0.999 (table 4). The results suggest significant differences in both SNR and CNR ($p < 0.001$).

Table 3. SNR and CNR before and after application of the radiologic assist device.

	Signal-to-noise ratio (SNR)		p	Contrast-to-noise ratio (CNR)		p
	without CFRP	with CFRP		without CFRP	with CFRP	
Lung	8.17 ± 0.11	8.18 ± 0.04	0.000	5.60 ± 0.09	5.60 ± 0.05	0.000
T6	18.16 ± 0.21	18.26 ± 0.06		9.98 ± 0.13	10.64 ± 0.33	
Cardiac	13.77 ± 0.17	13.81 ± 0.03		5.60 ± 0.09	5.62 ± 0.33	

3.3 Qualitative visual evaluation of chest X-ray images conducted using an ancillary device

As shown in figure 6 and table 5, a visual examination of chest X-ray images of 23 infants showed improved quality after the radiological ancillary device was used. The visual evaluation led to

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Table 4. Correlation of SNR & CNR before and after application of the radiologic device.

	Signal-to-noise ratio (SNR)	**Contrast-to-noise ratio (CNR)**
r*	0.998	0.999
p	0.000	0.000

*r: correlation coefficient.

the following findings. Infant ① breathed stably in the examination environment, suggesting a favorable outcome. Infant ② maintained a stable posture during the examination, resulting in images without body rotation or reclination. Infants ③, ④, ⑤, ⑥ showed images of structures around lungs suggesting a stable posture and comfortable breathing. However, in the case of ⑦, which is about reproduction of the spine and paraspinal structures and visualization of the retrocardiac lung and mediastinum, images with the ancillary device obtained lower evaluation than those without ancillary device. In order to acquire images with high contrast of the spine and paraspinal structures, retrocardiac lung and mediastinum, a large amount of dose is required. In the present research, however, the same dose condition was applied; thus, the dose condition of the spine and paraspinal structures and retrocardiac lung and mediastinum was lower than in an actual test. It was for this reason that the evaluation of image quality taken with the ancillary device showed a lower result than that without the ancillary device, within tolerance. Statistical similarity was analyzed by dividing the data according to the use of radiological ancillary device. A paired-sample t-test for scores of qualitative visual assessment revealed that all items except ④ ($p = 0.0181$) showed no significant difference ($p > 0.05$).

In addition, statistical significance was verified via correlation analysis to determine the degree of association between the use of radiological ancillary device and qualitative visual assessment scores. Correlation coefficients of respective items measured using the radiological ancillary device and qualitative visual assessment scores were as follows: ① 0.402, ② 0.356, ③ 0.391, ④ 0.473, ⑤ 0.355, ⑥ 0.147, and ⑦ 0.328. P-values of all items except for ④ ($P = 0.0219$) were higher than 0.05, suggesting lack of significant difference. These results demonstrate that the use of radiological ancillary device and qualitative visual assessment scores show a negligible level of linear correlation.

4 Review

Our institute performed X-ray examinations in infants using a tube voltage of 55 kVp and a tube current of 5 mAs, which was higher than the levels of 50 kVp and 1 mAs prescribed by the Ministry of Food and Drug Safety of Korea [6]. However, it is difficult to implement X-ray conditions recommended by the Ministry of Food and Drug Safety universally due to differences in function and efficiency associated with X-ray device manufacturers and models, quantum detection efficiency of detectors, and imaging systems of respective institutes. It is reasonable to conduct examinations with a low dose to minimize radiation exposure of infants who are sensitive to radiation. However, if this approach decreases the quality of images, it may be due to diagnostic difficulties. It is the responsibility of radiographers to set appropriate conditions to maintain image quality while controlling radiation exposure to patients. Although there are limitations that X-ray conditions in

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Figure 6. Results of visual evaluation before and after CFRP infant holder application.

this institute were set higher than the recommendations of the Ministry of Food and Drug Safety, the current X-ray conditions facilitated the use of device and enhanced diagnostic quality.

To reduce the frequency of re-examinations and prevent unnecessary radiation exposure of protectors and examiners during general imaging procedures on infants, it is recommended to use various ancillary devices. Such ancillary devices should not interfere with imaging protocol or trigger patient resistance. It should have adequate strength to limit the movement of infants without affecting the efficacy of radiation.

The radiological ancillary device produced in this study was made of CFRP with high radiation permeability. Thus, it does not interfere with diagnostic imaging outcomes [7]. Application of the radiological ancillary device not only facilitates precise examination, but also reduces the radiation dose to other body parts than the examination area by limiting the area of examination and maintaining a stable position. The radiological ancillary device can replace protectors and examiners who enter the examination room by stabilizing the infants and reducing their movement. Thus, it prevents undesirable radiation exposure. Also, it remarkably decreased the re-examination frequency in infants. After measuring the surface incident radiation during a chest AP X-ray examination of an infant, the ESDT6 of the infant was 233.70 ± 5.74 μGy. For the examination

Table 5. Results of qualitative assessment before and after using X-ray CFRP infant holder.

Diagnostic criteria	**Score**		**r ***	**t ****	**p**
	without CFRP	**with CFRP**			
① Performed at peak inspiration, except for suspected foreign body aspiration	7.65 ± 0.78	7.96 ± 0.82	0.402	2.01	0.06
② Reproduction of the thorax without rotation and tilting	8.00 ± 1.17	8.09 ± 1.00	0.356	1.75	0.09
③ Reproduction of the chest extended from immediately above the lungs to T12/L1	8.26 ± 1.74	8.57 ± 0.84	0.391	1.95	0.06
④ Reproduction of the vascular pattern in the central two-thirds of the lung	7.22 ± 1.48	7.96 ± 1.19	0.473	2.46	0.02
⑤ Reproduction of the trachea and the proximal bronchi	5.22 ± 1.31	6.61 ± 1.44	0.355	1.74	0.10
⑥ Visually sharp reproduction of the diaphragm and costo-phrenic angles	7.22 ± 1.48	7.87 ± 1.39	0.147	0.68	0.50
⑦ Reproduction of the spine and paraspinal structures and visualization of the retrocardiac lung and the mediastinum	7.48 ± 0.90	7.39 ± 1.03	0.328	1.59	0.13

*r: correlation coefficient.
**t: test statistic.

assistant, ESDT was 151.40 ± 4.01 μGy, ESDI was 143.20 ± 3.22 μGy, and ESDE was 146.20 ± 3.19 μGy. The Nuclear Energy Promotion Act of Korea prescribes that the upper limit of radiation exposure for a general person in addition to natural exposure is 1 mSv. Even if a person is exposed to a small dose of 150 μGy during a single examination, accumulated doses during 10 additional examinations can exceed the total amount of radiation exposure beyond 1 mSv. However, the use of ancillary device during the radiation examination of infants will prevent unnecessary radiation exposure to protectors and examination assistants during the examination. At the same time, SNR and CNR values were significantly increased in images obtained with the ancillary device compared with those acquired without using the ancillary device ($p < 0.001$). The correlation coefficient between the infant chest AP X-ray image and SNR was 0.998. The correlation coefficient between infant chest AP X-ray image and CNR was 0.999. The infant chest AP X-ray image showed significant differences in both SNR and CNR ($p < 0.001$).

In conclusion, results of this study demonstrate that the use of an ancillary device made of CFRP during chest X-ray of infants does not affect the imaging quality or results of disease diagnosis.

The ancillary device enables efficient and precise examination while reducing infant stress during the procedure and prevents unnecessary radiation exposure sustained by protectors and

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examiners. It also provides high-quality images with high diagnostic value, thereby contributing to improved medical services.

5 Conclusion

Infants are accompanied by their protectors and examiners during medical or diagnostic examination because of separation anxiety. They are also stressed by the unfamiliar environment. In addition, they exhibit communication difficulties. In order to address these challenges under conditions involving the risk of exposure to unnecessary secondary radiation for protectors and examiners and the difficulty in maintaining stable posture, we developed a radiologic examination assist device for infants' radiological examination. This radiologic assist device can be used to restrain the infants during the examination and protects against radiation-induced accidents such as falling. In addition, it can reduce re-examinations by maintaining a stable posture in infants, thereby decreasing the waiting time.

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