Journal of Radiation Research, Vol. 58, No. 1, 2017, pp. 135–141
doi: 10.1093/jrr/rrw074
Advance Access Publication: 29 July 2016

Pediatric computed tomography practice in Japanese university hospitals from 2008–2010: did it differ from German practice?

Koji Yoshida[1,2†], Lucian Krille[3,4†], Steffen Dreger[5], Lars Hoenig[4], Hiltrud Merzenich[4], Kiyotaka Yasui[2], Atsushi Kumagai[2], Akira Ohtsuru[6], Masataka Uetani[7], Peter Mildenberger[8], Noboru Takamura[9], Shunichi Yamashita[10], Hajo Zeeb[5‡] and Takashi Kudo[11*‡]

[1]Department of Health Sciences, Nagasaki University Graduate School of Biomedical Sciences, 1-12-4 Sakamoto, Nagasaki 852-8523, Japan
[2]Education Center for Disaster Medicine, Fukushima Medical University, 1 Hikarigaoka, Fukushima 960-1295, Japan
[3]Section of Environment and Radiation, International Agency for Research on Cancer, 150 Cours Albert Thomas, 69372, Lyon CEDEX 08, France
[4]Institute of Medical Biostatistics, Epidemiology and Informatics, University Medical Center of the Johannes Gutenberg University Mainz, Langenbeckstr. 1 D 55131, Mainz, Germany
[5]Department of Prevention and Evaluation, Leibniz Institute for Prevention Research and Epidemiology—BIPS, Achterstrasse 30, 28359 Bremen, Germany
[6]Department of Radiation Health Management, Fukushima Medical University School of Medicine, 1 Hikarigaoka, Fukushima 960-1295, Japan
[7]Department of Radiological Sciences, Graduate School of Biomedical Sciences, Nagasaki University, 1-7-1 Sakamoto, Nagasaki 852-8501, Japan
[8]Department of Diagnostic and Interventional Radiology, University Medical Center of the Johannes Gutenberg University Mainz, Langenbeckstr. 1 D 55131, Mainz, Germany
[9]Department of Global Health, Medicine and Welfare, Atomic Bomb Disease Institute, Nagasaki University, 1-12-4 Sakamoto, Nagasaki 852-8523, Japan
[10]Department of Radiation Medical Sciences, Atomic Bomb Disease Institute, Nagasaki University, 1-12-4 Sakamoto, Nagasaki 852-8523, Japan
[11]Department of Radioisotope Medicine, Atomic Bomb Disease Institute, Nagasaki University, 1-12-4 Sakamoto, Nagasaki 852-8523, Japan
†These authors contributed equally to this work.
‡HZ and TK are joint senior authors.
*Corresponding author. Department of Radioisotope Medicine, Atomic Bomb Disease Institute, Nagasaki University, 1-12-4 Sakamoto, Nagasaki 852-8523, Japan. Tel: +81-95-819-7103; Fax: +81-95-819-7104; Email: tkudo123@nagasaki-u.ac.jp
Received March 8, 2016; Revised May 20, 2016; Accepted May 25, 2016

ABSTRACT

Computed tomography (CT) is an essential tool in modern medicine and is frequently used to diagnose a wide range of conditions, particularly in industrial countries, such as Japan and Germany. However, markedly higher doses of ionizing radiation are delivered during CT imaging than during conventional X-ray examinations. To assess pediatric CT practice patterns, data from three university hospital databases (two in Japan and one in Germany) were analyzed. Anonymized data for patients aged 0 to 14 years who had undergone CT examinations between 2008 and 2010 were extracted. To assess CT practice, an interdisciplinary classification scheme for CT indications, which incorporated the most common examination types and radiosensitive tissues, was developed. The frequency of CT examinations was determined according to sex, age at examination, and indications. A total of 5182 CT examinations were performed in 2955 children. Overall, the frequency of CT examinations at the Japanese university hospitals did not differ significantly from that at the German hospital. However, differences were detected in the age distribution of the patients who underwent CT examinations (the proportion of patients <5 years of age was significantly higher in Japan than in Germany) and in the indications for CT. Substantial practice differences regarding the use of CT in pediatric health care were detected between the three hospitals. The results of this study point towards a need for approaches such as clinical guidelines to reduce unwarranted medical radiation exposures, particularly abdominal and head CT, in the Japanese health system.

KEYWORDS: computed tomography, ionizing radiation, children, practice pattern, international comparison

INTRODUCTION

Computed tomography (CT) is an essential tool in modern diagnostic radiology. Compared with conventional X-ray, ultrasound, and magnetic resonance imaging (MRI) examinations, CT scans deliver 3D images within seconds and are not affected by the physician's skills level [1]. These attributes can be life-saving, especially in emergency situations, when rapid decision-making is essential. Consequently, the use of CT is steadily increasing in all industrialized countries [2]. However, considerably higher doses of ionizing radiation are involved than those used in conventional X-ray examinations. Ionizing radiation is a well-established risk factor for cancer [3]; the risk increases in a dose-dependent manner and is higher in younger patients [4]. Furthermore, children are assumed to be more radiosensitive than adults and at higher risk of developing cancer due to their long lifespan after the radiation exposure [5].

In pediatric patients, the doses delivered to exposed organs from repeated examinations can add up to 100–200 mGy [6–8], and this level is associated with an elevated risk of cancer [9]. In 2001, Brenner *et al.* estimated the CT-attributable cancer mortality rate of 600 000 children who were exposed to CT in the US in 2000. According to their findings, 500 children were expected to die from cancer attributable to CT examinations, i.e. they detected an attributable lifetime cancer mortality risk of 0.25% [6]. Several modeling studies have subsequently estimated the attributable cancer mortality and cancer incidence rates for various groups of pediatric and adolescent patients who had undergone CT [10]. Recent large epidemiological cohort studies that attempted to empirically confirm these results suggest that CT examinations might cause childhood cancers, such as leukemia and solid cancers [11–15]. However, this association has not yet been definitively confirmed. One major issue with these studies relates to the non-exclusion of CT examinations that have been performed because of a suspected malignancy, which might have introduced confounding bias. As a consequence, the indications that prompt the use of CT should be assessed when estimating cancer risk after CT exposure [16].

Recent research has also indicated that knowledge gaps regarding CT doses and the associated health risks exist among referring physicians [17, 18]. Furthermore, little is known about the indications under which CT examinations are most commonly performed and how such parameters vary among countries. This lack of information hampers efforts to assess CT practices and quantify unwarranted exposure.

Japan and Germany both exhibit higher X-ray examination rates than other industrialized countries (the rates seen in the two countries are similar). However, the X-ray examination attributable cancer risk is estimated to be higher in Japan (the highest globally) than in Germany [19]. In addition, unlike other countries such as Germany, the USA and the UK, Japan does not have commonly agreed clinical guidelines for the use of ionizing radiation in diagnostic radiology, especially in the pediatric field [20].

We assessed pediatric CT practice patterns, including the associated indications, in Japan. In addition, German data were used to identify potential differences compared with Japanese CT practices, which could aid the development of best-practice guidelines for CT use in Japan.

MATERIALS AND METHODS

Study population and data collection

We extracted anonymized examination data from the Radiological Information Systems (RISs) at three university hospitals: two in Japan (Nagasaki University Hospital and Fukushima Medical University Hospital) and one in Germany (Mainz University Medical Center). All pediatric patients who had undergone at least one CT examination during the study period (1 July 2008 to 30 June 2010) and were between 0 and 14 years of age at the time of the first CT examination were included in this study. Only residents of the respective countries were eligible. Data regarding sex, date of birth, the date of the examination, and the indications under which the examinations were conducted were extracted for all eligible patients.

Data management and analysis

We calculated the mean number of CT examinations for the whole study population and according to sex, age at the time of the examination (hereafter referred to as 'age at examination'), indication, and the hospital at which the scan was carried out. The Chi-squared test for independent samples was used to assess the differences in the mean of the examination number, number of each sex, or age at examination between the two countries. An interdisciplinary classification scheme combining the most common examination types and radiosensitive tissues was jointly developed by a small team led by senior physicians from each country. The classification scheme was piloted on a randomly drawn subset of the original data. The categories included tumor-related examinations ('tumor diagnoses and therapy' or 'tumor exclusion'), trauma, congenital/other typical childhood diseases, and general examination regions ('cranium', 'spine', 'thorax', and 'abdomen'), as well as 'other' examinations (Fig. 1). We separated out the cases involving tumor- or tumor-related or trauma indications because CT examinations are usually essential in such cases. As our aim was to develop best practice guidelines based on an international comparison, it was considered that separating cases in which CT examinations were essential from other cases might provide some insight into the number of 'non-essential' (i.e. potentially unnecessary) examinations. Statistical analysis was performed using SPSS Statistics 22.0 (IBM Japan, Tokyo, Japan).

Ethics statement

This study was approved by the Ethics Committees of Nagasaki University Hospital, Fukushima Medical University and the

Medical Chamber of Mainz, and from the Data Protection Officer of Mainz University Medical Center before the start of the study. The study was conducted in accordance with the guidelines outlined in the Declaration of Helsinki. All of the data used in this study were analyzed anonymously and securely protected under the guidance of the Data Protection Officer of each hospital.

RESULTS

The three university hospitals differ considerably in size. Compared with the two Japanese hospitals, Mainz University Medical Center has twice as many beds and 2-fold and 5-fold higher numbers of physicians and annual inpatients, respectively. However, the number of out-patients was highest at Fukushima Medical University Hospital, while similar numbers of outpatients visited the other two

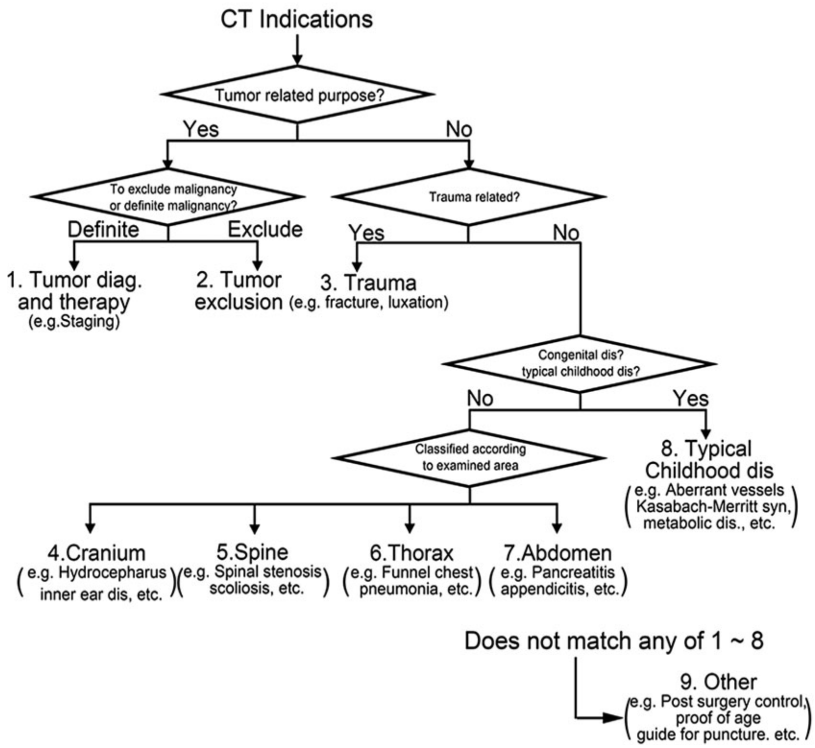

Fig. 1. Classification scheme for CT indications.

Table 1. Hospital and study population characteristics for Nagasaki University Hospital, Fukushima Medical University Hospital, and Mainz University Medical Center (2008–2010)

	Nagasaki University Hospital Number	Fukushima University Hospital Number	Mainz University Medical Center Number
Physicians	436	488	960
Annual in-hospital patients	13 586	12 995	68 661
Annual out-hospital patients	280 162	373 393	241 429
Number of beds	861	778	1640
Examination and patients			
All CT examinations	40 746	40 609	46 489
Pediatric CT examinations (% from all)	1962 (4.8%)	2220 (5.5%)	1000 (2.2%)
Pediatric patients examined with CT	1203	1138	614
Mean age at CT examination (SD)	5.7 ± 4.7	5.0 ± 4.8	7.7 ± 4.2

hospitals (Table 1). At Mainz, CT procedures were managed by specialized pediatric radiologists in the Radiology Department, whereas at Nagasaki and Fukushima CT examinations were conducted by general radiologists who did not specialize in pediatric radiology.

In total, 5182 CT examinations were performed on 2955 patients between 1 July 2008 and 30 June 2010 at the three hospitals (Nagasaki: 1962 CT examinations, 1203 children; Fukushima: 2220 CT examinations, 1138 children; Mainz: 1000 CT examinations, 614 children) (Table 1). The sex distribution of the patients that underwent CT examinations was similar at each hospital, with males undergoing CT scans slightly more often than females. The mean age at examination for the Japanese hospitals (5.5 years) was significantly lower than that for the German hospital (7.7 years) ($P < 0.001$; Table 2).

At the Japanese hospitals, almost 20% of all pediatric CT examinations involved children younger than 12 months of age. In contrast, at the Mainz University Medical Center significantly fewer CT examinations were performed on patients below 12 months (2.2%). The proportion of pediatric CT scans that involved patients of <5 years old was significantly higher at the Japanese hospitals than at the German hospital (49.1% vs 28.8%, $P < 0.001$; Table 2). On the other hand, the proportions of patients aged 5–9 years and 10–14 years who underwent CT examinations were significantly lower at the Japanese hospitals than at the German hospital ($P < 0.001$, respectively; Table 2).

Of the 5182 extracted CT examinations, 5115 were classified according to the classification scheme developed for this study (Fig. 1). No unambiguous indications could be extracted from the RIS at Mainz University Medical Center for the remaining 67 examinations, and so these cases had to be excluded from the analysis. Among the 4182 examinations performed at the Japanese hospitals, cranial indications were the most common indications for CT (42% of all CT scans), followed by tumor-related (18%), trauma-related (16%), and abdominal (11%) indications (Table 3). In comparison, trauma-related was the most common indication for CT at the German hospital ($n = 933$) (34%), followed by cranial and tumor-related indications, which accounted for 27% and 23% of all CT examinations, respectively. The proportions of patients who underwent CT examinations of the cranium, thorax and abdomen were significantly higher at the Japanese hospitals than at the German hospital ($P < 0.001$, $P < 0.01$, $P < 0.001$, respectively; Table 3). On the other hand, the proportion of patients who underwent CT examinations under tumor-related, trauma-related, or spine indications were significantly higher at the German hospital than at the Japanese hospitals ($P < 0.01$, $P < 0.001$, $P < 0.05$, respectively; Table 3). Overall, the three most common indications (cranial, trauma-related, and tumor-related) accounted for ~80% of all examinations in both countries. Additional analyses showed that at the Japanese hospitals the majority of CT examinations performed on patients below 12 months of age were cranial scans (61%, $n = 553$), while at Mainz, the majority of these examinations were tumor-related (45%, $n = 10$).

The mean number of CT examinations per patient was 1.79 (standard deviation (SD): 2.03, range: 1–27) at the Japanese hospitals, and 1.63 (SD: 1.39, range: 1–12) at the German hospital. The frequency distributions for the number of scans performed in each individual did not differ significantly between the two countries (1 scan: $P = 0.14$, 2–6 scans: $P = 0.38$, ≥7 scans: $P = 0.10$, respectively; Table 4). Approximately one-third of the patients at each university hospital underwent more than one CT examination (30% at the Japanese hospitals, 26% at the German hospital). Of these, the majority had two to three CT scans (Fig. 2).

DISCUSSION AND CONCLUSION

To the best of our knowledge, this is the first study to assess the CT practice pattern in Japan and to compare detailed information regarding the number of CT examinations performed and the corresponding indications with those from another industrialized country that exhibits similar levels of X-ray use. In the present study, the overall frequency of pediatric CT examinations did not differ significantly between the examined Japanese and German university hospitals. However, substantial differences, in the age distribution of the examined patients and the most common CT indications, particular for abdominal and cranial CT scans, were seen between the Japanese and German hospitals.

The differences observed in the present study might reflect variations in the availability and use of CT scanners between the two countries, as Japan has a 5.7-fold higher number of CT scanners per

Table 2. Proportion of pediatric CT examinations by gender and age

	Japan (two hospitals)		Germany		*P* value
	Number	%	Number	%	
Pediatric CTs/ All CTs	4182/81 355	5.1	1000/46 489	2.2	<0.001***
Sex					
Female/Male	1856/2320	44.5/55.5	430/570	43.0/57.0	0.42
Age	5.5 ± 4.8		7.7 ± 4.2		<0.001***
<5 years old	2055	49.1	288	28.8	<0.001***
5–9 years old	1055	25.2	293	29.3	<0.001***
10–14 years old	1072	25.7	419	41.9	<0.001***

***$P < 0.001$.

Table 3. Proportion of pediatric CT examinations by indication

Indication category	Japan (two hospitals) $n = 4182$ Number	%	Germany $n = 933^{\#}$ Number	%	P value
Tumor	749	17.9	216	23.2	<0.01**
Tumor exclusion	45	1.1	26	2.8	<0.01**
Trauma	674	16.1	315	33.8	<0.001***
Cranium	1754	41.9	255	27.3	<0.001***
Spine	102	2.4	38	4.1	<0.05*
Thorax	366	8.8	59	6.3	<0.01**
Abdomen	444	10.6	16	1.7	<0.001***
Childhood disease	36	0.9	6	0.6	0.56
Others	12	0.3	2	0.2	0.99

$^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, $^{\#}$67 CTs could not be classified.

Table 4. Proportion of pediatric CT examinations by frequency

	Japan (two hospitals) Number	%	Germany Number	%	P value
Pediatric patients	2341		600[a]		
Frequency					
1 scan	1652	70.6	442	73.7	0.14
2–6 scans	616	26.3	147	24.5	0.38
≥7 scans	73	3.1	11	1.8	0.1

[a]The data for 14 people from Germany had to be excluded from the analysis.

capita than Germany [21]. Also, 5.1% of the CT examinations performed at the Japanese university hospitals involved pediatric patients, compared with only 2.2% at the German reference hospital (Table 2). These findings might indicate that CT is overused in Japan, which would directly affect the radiation risks of the Japanese population [22]. These observations are consistent with the results of a previous study that indicated that both Japan and Germany have high annual medical radiation exposure rates, However, the same study found that the Japanese population has a 2-fold higher CT-attributable cancer risk than the Germany population, probably due to less frequent usage of CT in Germany [18]. This might be particularly relevant when considering the large proportion of very young children examined in Japan, as children are considered to be more radiosensitive than adults and have longer to live and so are more likely to develop cancer [4].

In the Japanese hospitals, the proportion of CT examinations involving patients aged <12 months was not only considerably higher than the equivalent values for all other age groups at the Japanese hospitals, but was also higher than those for all age groups at the Mainz University Medical Center. In contrast, the lower frequency of CT examinations involving very young patients recorded at the Mainz University Medical Center might indicate that the clinicians at that institution are acutely aware of the pediatric radiation risk associated with CT examinations. However, recent studies have reported mixed results regarding physicians' knowledge of the CT-related risks of pediatric and adult patients [17, 18].

In the current study, we found large differences in the frequencies of various indications for CT between hospitals in Japan and Germany. In Germany, the Radiation Protection Commission together with clinical experts has developed guidelines for diagnostic radiological procedures [20]. Consequently, the low overall number of CT examinations (Table 1) and the distribution pattern of CT indications at Mainz University Medical Center might reflect the effects of these guidelines.

In Japan, at present these are no standardized clinical guidelines for pediatric CT. In 2013, guidelines for medical imaging were published in Japan [23], but merely 6 out of the 476 pages were devoted to pediatric imaging. In addition, it appears that these guidelines have not yet found wide acceptance among Japanese referring physicians. The large variations in CT examination patterns between the examined hospitals in Japan and Germany might be associated with the lack of commonly accepted diagnostic guidelines in Japan, but this has not been empirically verified. It has been reported that the use of CT examinations varies significantly between individual doctors, even under similar conditions [24, 25]. Thus, standardized clinical guidelines might be useful for promoting the consistent use of CT examinations. Furthermore, in Japanese university hospitals CT examinations are conducted by general radiologists rather than by specialized pediatric radiologists (in Germany, specialized pediatric radiologists generally perform pediatric CT, when available). This might partly explain the differences between the two countries.

We assumed that differences in common medical practice played the most important role in the observed differences in CT practice, since the Japanese and German health systems (including the reimbursement schemes for radiological examinations employed as part of the health insurance systems in operation in each country) are quite similar [26]. Therefore, the standardization and appropriate use of CT practice is essential. Some professional societies, such as the American College of Radiology (ACR) and the US Society for Pediatric Radiology, have produced recommendations and guidelines for pediatric CT use [27, 28]. Moreover, the ACR recently developed a CT dose index registry in the USA as a quality control and safety instrument, and the European Society of Radiology recently launched the 'Eurosafe Imaging' campaign, which aims to educate clinicians about the appropriate usage of medical radiation [29]. Unlike in the USA and the EU, no nationwide framework or campaign about the appropriate use of medical radiation in pediatrics exists in Japan.

In addition to clinical guidelines, clinical ordering aids and the exchange of CT images via electronic imaging communication

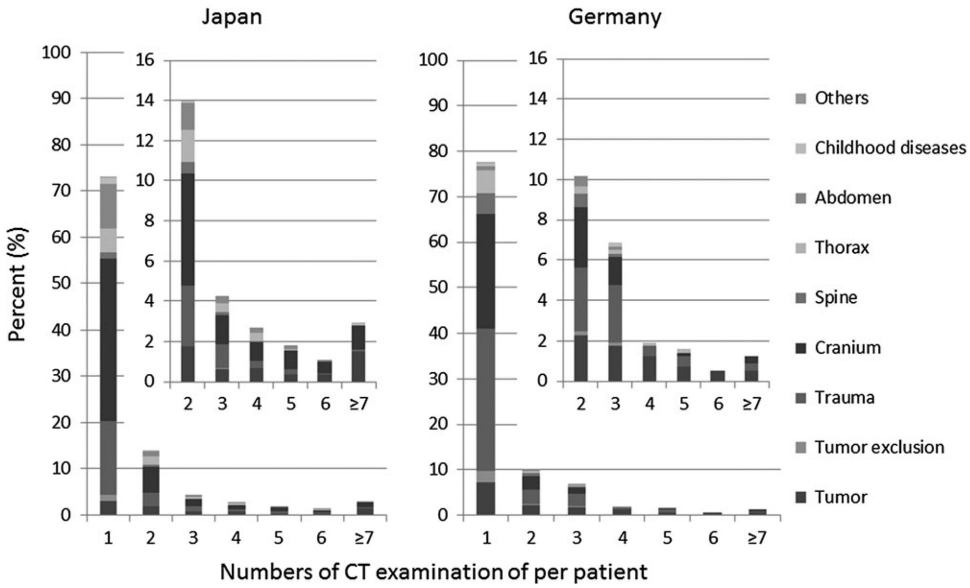

Fig. 2. Number of CT examinations per patient and by indication category at the Japanese and German hospitals (2008–2010).

platforms (e.g. the 'Image Share project'; www.rsna.org/Image_Share.aspx) can also help to reduce unnecessary diagnostic imaging. The use of non-ionizing imaging techniques, such as ultrasound and MRI, instead of ionizing imaging is another approach that can be used to further reduce ionizing radiation exposure. In cases of suspected appendicitis, the ACR recommends that non–contrast-enhanced ultrasound or MRI examinations should be performed instead of abdominal CT in pediatric patients [26]. Moreover, innovations in medical technology have resulted in the development of pre- and post-processing methods that make it possible to reduce the radiation dose delivered during CT without a deterioration of image quality [30–32]. In addition to such measures, education regarding radiation and the associated risks might contribute to optimizing the use of radiological examinations.

Our study had several limitations. We could not identify the reason why the frequencies of CT examinations involving very young patients and cranial/abdominal CT are so high in Japan. The radiological report data for the Japanese hospitals indicated that many of the CT examinations were performed for hydrocephalus or suspected appendicitis. However, these observations were incomplete, and no radiological report data were available for the German hospital. In addition, the study data related to the years 2008–2010 and, hence, were not up to date. However, we assume that any major changes in pediatric CT practice would have been influenced by the initial report about CT risk prediction by Brenner *et al.*, which was published in 2001 [6], and thus, would have occurred before our study period. In addition, a 2004 study obtained similar findings regarding the number of CT examinations and the age distributions of patients who had undergone CT scans to those we obtained for the Nagasaki University Hospital [22], confirming our observations. Furthermore, the current study only analyzed data from three university hospitals. Thus, the results are unlikely to accurately reflect the general practice patterns in the respective countries and hospitals. We consider that the basic characteristics of the three examined hospitals were similar because they were all general university hospitals. However, it is possible that differences between the characteristics of the examined hospitals affected the results of the present study. Finally, we consider that dose estimation is also important for risk assessments of pediatric CT examinations; however, the data available from the RIS did not allow us to calculate organ doses. Another limitation of this study was that we only had data about CT examinations and were not able to acquire data about the other diagnostic imaging techniques employed at the target hospitals. The increased use of MRI might explain the differences in the use of CT for tumor diagnostics between the hospitals. However, analyzing all of the indications for diagnostic imaging at the target hospitals was beyond the scope of this study.

In conclusion, variations in CT examination practices were detected between hospitals in Japan and Germany, with large differences being observed in the age distribution of the patients who underwent CT and in the most common indications for CT examinations among pediatric patients. To reduce unwarranted medical radiation exposure in pediatric patients, simple and useful clinical guidelines that have been designed for use by referring physicians should be developed. Risk communication and educational materials for parents that aim to reduce the number of unnecessary CT examinations performed should also be produced. In addition, the active implementation of technical dose-reduction approaches should be promoted in cases in which CT cannot be replaced by another diagnostic modality.

CONFLICT OF INTEREST

There are no conflicts of interest for any of the authors of this manuscript.

ETHICS STATEMENT

Approvals for the study were obtained before the beginning of the study from the Ethics Committee of the Nagasaki University

Hospital (No. 11042553) in Japan, and from the Ethics Committee of the Medical Chamber of Rhineland Palatinate and the Data Protection Officer of the University Medical Center Mainz in Germany. All the data used in this study were analyzed anonymously and was securely protected under the guidance of the Data Protection Officer of each hospital.

REFERENCES

1. Prokop M. Radiation dose in computed tomography. Risks and challenges. *Radiologe* 2008;48:229–42.
2. UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). Sources and effects of ionizing radiation. *UNSCEAR 2008 Report, Vol. I. Sources—Report to the General Assembly Scientific Annexes A and B*. United Nations, United Nations Office at Vienna, 2010.
3. IARC Working Group. *Ionizing Radiation, Part 1: X- and Gamma (γ)-Radiation, and Neutrons. In: IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 75*. Lyon: International Agency for Research on Cancer, 1999.
4. National Research Council. *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2*. Washington DC: The National Academies Press, 2006.
5. UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). Effects of radiation exposure of children. Sources, effects and risks of ionizing radiation, UNSCEAR 2013 Report, Vol. II. New York, 2013, p. 265.
6. Brenner D, Elliston C, Hall E, et al. Estimated risks of radiation-induced fatal cancer from pediatric CT. *AJR Am J Roentgenol* 2001;176:289–96.
7. Mettler FA, Wiest PW, Locken JA, et al. CT scanning: patterns of use and dose. *J Radiol Prot* 2000;20:353–9.
8. Shrimpton PC, Hillier MC, Lewis MA, et al. National survey of doses from CT in the UK: 2003. *Br J Radiol* 2006;79:968–80.
9. Preston DL, Pierce DA, Shimizu Y, et al. Dose response and temporal patterns of radiation-associated solid cancer risks. *Health Phys* 2003;85:43–6.
10. Krille L, Zeeb H, Jahnen A, et al. Computed tomographies and cancer risk in children: a literature overview of CT practices, risk estimations and an epidemiologic cohort study proposal. *Radiat Environ Biophys* 2012;51:103–11.
11. Pearce MS, Salotti JA, Little MP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet* 2012;380:499–505.
12. Mathews JD, Forsythe AV, Brady Z, et al. Cancer risk in 680,000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. *BMJ* 2013;346:f2360.
13. Huang W-Y, Muo C-H, Lin C-Y, et al. Paediatric head CT scan and subsequent risk of malignancy and benign brain tumour: a nation-wide population-based cohort study. *Br J Cancer* 2014;110:2354–60.
14. Journy N, Rehel J-L, Ducou Le Pointe H, et al. Are the studies on cancer risk from CT scans biased by indication? Elements of answer from a large-scale cohort study in France. *Br J Cancer* 2015;112:185–93.
15. Krille L, Dreger S, Schindel R, et al. Risk of cancer incidence before the age of 15 years after exposure to ionising radiation from computed tomography: results from a German cohort study. *Radiat Environ Biophys* 2015;54:1–12.
16. Walsh L, Shore R, Auvinen A, et al. Risks from CT scans—what do recent studies tell us? *J Radiol Prot* 2014;34:E1–5.
17. Krille L, Hammer GP, Merzenich H, et al. Systematic review on physician's knowledge about radiation doses and radiation risks of computed tomography. *Eur J Radiol* 2010;76:36–41.
18. Merzenich H, Krille L, Hammer G, et al. Paediatric CT scan usage and referrals of children to computed tomography in Germany: a cross-sectional survey of medical practice and awareness of radiation related health risks among physicians. *BMC Health Serv Res* 2012;12:47.
19. Berrington de González A, Darby S. Risk of cancer from diagnostic X-rays: estimates for the UK and 14 other countries. *Lancet* 2004;363:345–51.
20. SSK (Strahlenschutzkommission). *Orientierungshilfe für bildgebende Untersuchungen*. Bonn: Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit, 2006. (in German)
21. OECD. Computed tomography scanners, total X-ray machines per million population. Health: Key Tables from OECD, 2014, No. 37. http://www.oecd-ilibrary.org/social-issues-migration-health/computed-tomography-scanners-total_comptomoscan-table-en (28 June 2015, date last accessed).
22. Ghotbi N, Ohtsuru A, Ogawa Y, et al. Pediatric CT scan usage in Japan: results of a hospital survey. *Radiat Med* 2006;24:560–7.
23. Japanese Radiological Society, Japanese College of Radiology. *Gazou Shindan Guidelines 2013*. Tokyo: Kanehara Shuppan, 2013. (in Japanese)
24. Prevedello LM, Raja AS, Zane RD, et al. Variation in use of head computed tomography by emergency physicians. *Am J Med* 2012;125:356–64.
25. Stern RG. Imaging utilization and the obsessive-compulsive physician. *Am J Med* 2012;125:321.
26. Hossein Z, Gerard A. Trends in cost sharing among selected high income countries—2000–2010. *Health Policy* 2013;112:35–44.
27. Rosen MP, Ding A, Blake MA, et al. ACR Appropriateness Criteria® right lower quadrant pain—suspected appendicitis. *J Am Coll Radiol* 2011;8:749–55.
28. Strauss KJ, Goske MJ, Kaste SC, et al. Image gently: ten steps you can take to optimize image quality and lower CT dose for pediatric patients. *AJR Am J Roentgenol* 2010;194:868–73.
29. Robinson TJ, Robinson JD, Kanal KM. Implementation of the ACR dose index registry at a large academic institution: early experience. *J Digit Imaging* 2013;26:309–15.
30. Jończyk-Potoczna K, Frankiewicz M, Warzywoda M, et al. Low-dose protocol for head CT in evaluation of hydrocephalus in children. *Pol J Radiol* 2012;77:7–11.
31. Brady SL, Moore BM, Yee BS, et al. Pediatric CT: implementation of ASIR for substantial radiation dose reduction while maintaining pre-ASIR image noise. *Radiology* 2014;270:223–31.
32. Zacharias C, Alessio AM, Otto RK, et al. Pediatric CT: strategies to lower radiation dose. *AJR Am J Roentgenol* 2013;200:950–6.