ABCs of Pediatric CT radiation: Recommended reading for pediatric radiology residents.

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ABSTRACT

In this review article, three important issues regarding radiation exposure to pediatric patients during Computed Tomography (CT) are discussed: basic knowledge of CT dose index volume ($CTDI_{vol}$) and dose length product (DLP), the concept of diagnostic reference levels, and the risk of cancer development from pediatric CT examinations. First, young pediatric radiology residents should know that there are only two units of CT radiation dose: $CTDI_{vol}$ and DLP. These units are definitive and universal but represent the radiation produced by the CT scanner, rather than the radiation dose delivered to the patient. The second topic is that pediatric radiology residents should understand the clinical usefulness of diagnostic reference levels and that nationwide regulation of CT radiation might be necessary. The third topic is in regard to the relationship between CT radiation and cancer development. The number of DNA double-strand breaks induced by CT was found to be linearly dependent on DLP.

Keywords: pediatric CT, medical radiation, CT dose index, diagnostic reference level

INTRODUCTION

CT imaging is essential in daily pediatric practice to quickly obtain a wide range of information pertaining to the physical status of the patient, from head to thigh. Also, multiplanar reconstructed and three-dimensional images are immediately available upon completion of the scan. Despite these benefits, the radiation exposure associated with CT scans is a major disadvantage.

This review article addresses essential pediatric CT radiation issues, especially directed to young pediatric radiology resident members of the Asian and Oceanic Society for Paediatric Radiology (AOSPR). Many aspects of medical radiation are complicated, including basic knowledge of medical physics, technology of CT equipment, indications referring to domestic or international radiological guidelines, diagnostic reference levels, and low-dose protocols, and so on. It is very important for medical physicists and radiology technologists to comprehend these issues. Although most radiology residents prefer implementation in clinical practice to such fundamental knowledge

The aim of this review article is to simply teach the most important points of CT radiation to pediatric radiology residents. The subjects discussed in this review should prove useful for daily work in the radiology reading room, CT room, and regular conferences. These contents are also important in the setting of risk communication with patients and family members, pediatricians, and other medical staff.

I. Only two dose units are required to evaluate CT radiation

Since there are so many different dose units and items to evaluate for medical radiation, sometimes we feel difficult to evaluate CT dose. Actually, only two dose units are necessary to evaluate the amount of CT radiation. One is the CT dose index volume [$CTDI_{vol}$ (mGy)], and the other is dose length product [DLP (mGy·cm)] (Fig. 1).

What is $CTDI_{vol}$ and DLP?

$CTDI_{vol}$ is a measure of the dose in the scan plane from a single rotation

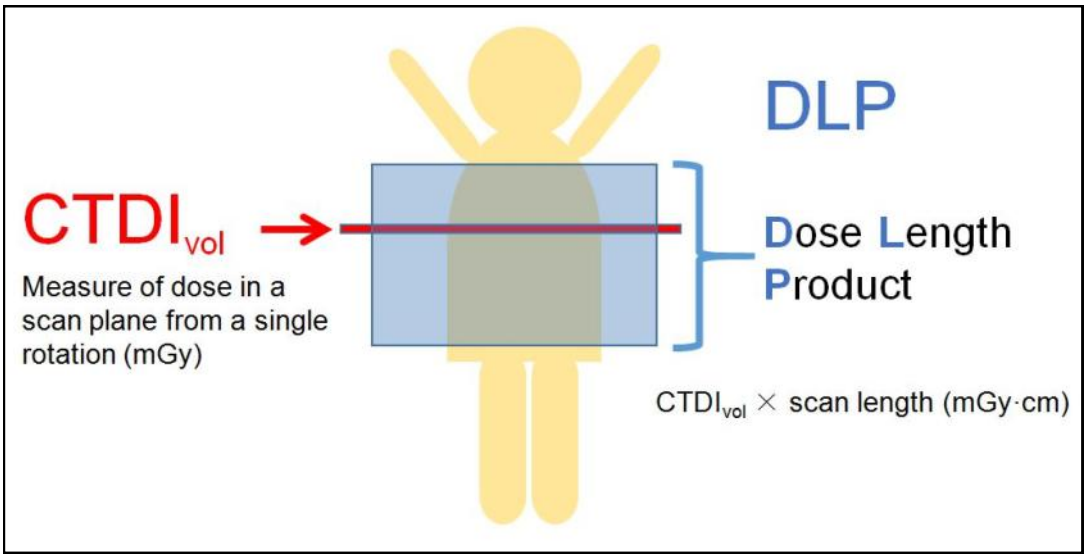


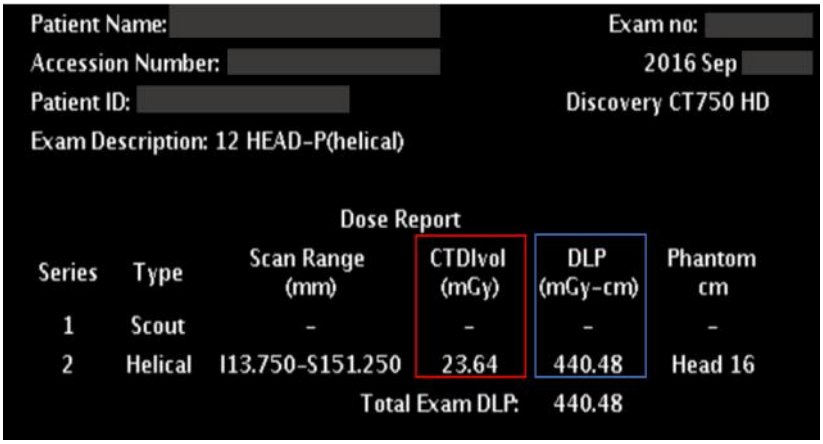
Figure 1: CT dose units: $CTDI_{vol}$ and DLP

DLP = $CTDI_{vol}$ × scan length

CTDI is calculated based on one of two standard CTDI phantoms (16-cm or 32-cm diameter). $CTDI_{vol}$ represents the radiation produced by the CT scanner not the radiation dose delivered to the patient. Although pediatric radiologists are aware of this discrepancy, there remains a need for a method to estimate the radiation dose based on the body size of the pediatric patient or small adult [1].

How is dose information calculated?

As an example, the dose information for a cranial CT of a 4-year-old boy is shown in Fig. 2. This information is available on the CT control panel during the examination, and more recently, this information is supplied by PACS systems. In Fig. 2, $CTDI_{vol}$ (mGy) is shown in area shaded in red and DLP (mGy·cm) in blue - shaded area.


Patient Name: [redacted] Exam no: [redacted]
Accession Number: [redacted] 2016 Sep [redacted]
Patient ID: [redacted] Discovery CT750 HD
Exam Description: 12 HEAD-P(helical)

Dose Report

Series	Type	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy-cm)	Phantom cm
1	Scout	-	-	-	-
2	Helical	113.750-S151.250	23.64	440.48	Head 16

Total Exam DLP: 440.48

Figure 2: CT dose information: cranial CT of a 4-year-old boy.

As an example, the dose information for a cranial CT of a 4-year-old boy is shown. This information is available on the CT control panel during the examination, and more recently, this information is supplied by picture archiving and communication systems. CTDIvol (mGy) is shown in the red square and DLP (mGy·cm) in the blue square.

$CTDI_{vol}$ as a definitive and universal tool

$CTDI_{vol}$ includes the influence of all scan parameters, e.g., tube current, tube voltage, pitch factor, and table speed. The use of the unit of $CTDI_{vol}$ allows comparison with any previous generation of CT system, CT vender, or detector array. Because of its convenience and universality, this dose unit is used worldwide and all CT scanners are required to display this unit on the control panel.

$CTDI_{vol}$ and DLP as a hallmark of dose regulation

In many children's hospital throughout the world, the diagnostic reference level (DRL, see section II) is established by $CTDI_{vol}$ and DLP calculations. Every hospital can evaluate the dose setting using a 75th percentile value of the national DRL, which is obtained by $CTDI_{vol}$ and DLP.

Region of body	K (mSv · mGy^{-1} · mGy$^{-1)}$				
	0 years	1 year	5 years	10 years	Adult
Head and neck	0.013	0.0085	0.0057	0.0042	0.0031
Head	0.011	0.0067	0.004	0.0032	0.0021
Neck	0.017	0.012	0.011	0.0079	0.0059
Chest	0.039	0.026	0.018	0.013	0.014
Abdomen and pelvis	0.049	0.03	0.02	0.015	0.015
Trunk	0.044	0.028	0.019	0.014	0.015

Calculation of effective dose:
Effective dose = k × DLP
For example, the DLP in Fig. 2 was 440 mGy·cm (red square)
Effective dose = 0.004 × 440 = 1.76 mSv

Table 1. Normalized effective dose per dose length product (DLP) for adults and pediatric patients for various body regions. The conventional factors for adult head and neck and pediatric patients assume the use of a head CT dose phantom (16 cm). All other conventional factors assume the use of a CT body phantom with a 32-cm diameter [2].

$CTDI_{vol}$ and DLP as a dialect for CT scanners

The concept of $CTDI_{vol}$ and DLP is called dialect because these dose units are specific for CT radiation dosages. $CTDI_{vol}$ and DLP cannot be compared with dosages delivered by other types of radiological examinations (e.g., plain radiograph, fluoroscopy, nuclear medicine, and angiography). Moreover, translation from dialect to standard language is required to compare with other radiation imaging modalities, such as background natural radiation or boarding airplane [2].

How to translate from dialect to standard language?

$CTDI_{vol}$ and DLP as a local dose description should be translatable for effective comparisons of dose measured in millisievert (mSv) units to other medical radiation or background radiation. A formula to calculate an effective dose is described in Table 1 [2].

Some disadvantages of $CTDI_{vol}$

Unfortunately, $CTDI_{vol}$ represents the radiation produced by the CT scanner not the radiation dose delivered to the patient. However, $CTDI_{vol}$ was not intended to be an indicator of patient dose. Because it does not represent patient dose, $CTDI_{vol}$ should not be recorded in the patient's medical record as such. Most pediatric radiologists are aware of this discrepancy [1]. $CTDI_{vol}$ is an index of CT exposure, which is calculated from polymethyl methacrylate phantoms that come in two sizes, 16 cm and 32 cm. However, these settings are based on measurements of the adult head and abdomen. Therefore, $CTDI_{vol}$ does not reflect the body size of infants, children, and young adults [2].

(8) New dose unit instead of $CTDI_{vol}$

The American Association of Physicists in Medicine (AAPM) devised a new unit of CT radiation exposure, namely size-specific dose estimates (SSDE), which takes into account the patient's body size. The development of SSDE has solved the problem of the two CTDI phantoms described above and has enabled radiologists to obtain a more accurate measurement of radiation dose based on the body size of the pediatric patient [3].

II. Diagnostic Reference Levels

What dose "Diagnostic Reference Level" mean?

Diagnostic reference levels (DRLs) were determined

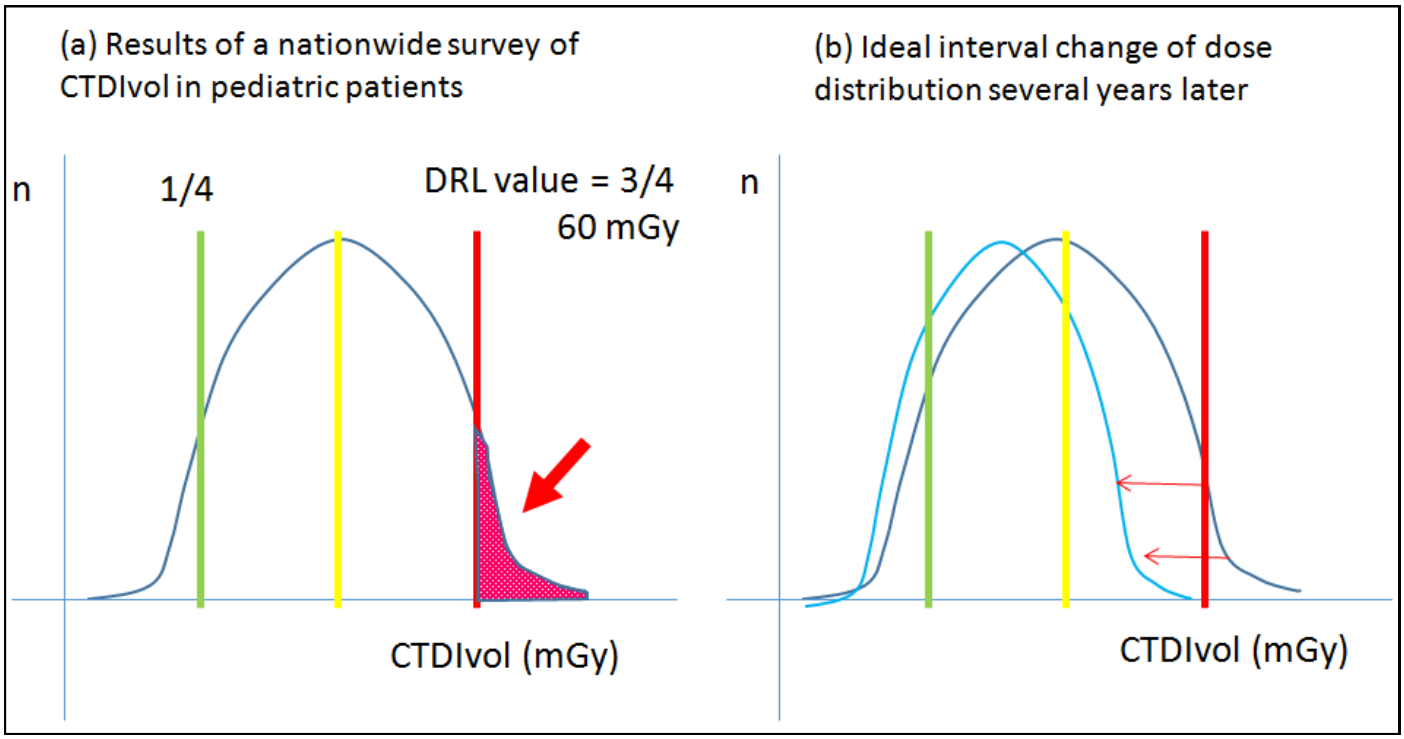


Figure 3: What does dose diagnostic reference level mean?

The particular user (e.g., radiologist, radiology technologist, physician, or medical physicist) can refer to the national DRL level for comparison of individual dose levels (usually the average dose level of a particular institution). If the local dose level is greater than the published DRL (higher quartile group), each institution should reset the local dose to a value lower than DRL. For the vast majority of users of this self-check system, the national dose level can be regulated and the curve peak deviates to the left

based on the results of a nationwide survey or specific groups and hospitals (e.g., group of children's hospitals, etc.). DRLs may include the dose level of several modalities, including CT scan, plain radiograph, fluoroscopy, and nuclear medicine. Moreover, many countries have unique DRLs for pediatric patients as well as adults, although international DRLs are available in the literature [4].

The most common DRLs represent the 75th percentile (third quartile) of the results of a nationwide dose survey.

How to use DRLs?

A representative DRL with a normal distribution curve is depicted in Fig. 3a. This particular DRL value ($CTDI_{vol}$ = 60 mGy, 6–10 years of age) was sampled from pediatric cranial CT values cited in Japan DRLs 2015. The particular users (e.g., radiologists, radiology technologists, physicians, and medical physicists) can refer the national DRL level for comparison of individual dose levels (usually the average dose level of a particular institution). If the local dose level is greater than the published DRL (higher quartile group), each institution should reset the local dose to a value lower than DRL. For the vast majority of users of this self-check system, the national dose level can be regulated and the curve peak deviates to the left, as shown in Fig. 3b.

Japanese DRLs were not published until 2015. The Japan DRLs 2015 pediatric CT values are based on a nationwide survey conducted by Takei et al. of 164 hospitals, 195 CT scanners, and 3,324 examinations (Table 2) [5, 6].

It is advisable to check and compare local pediatric $CTDI_{vol}$ volumes with national DRLs of the home country. If there are no national DRLs available for a particular country, international DRLs are available online.

	<1 year		1–5 years		6–10 years	
	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP	$CTDI_{vol}$	DLP
Head	38	500	47	660	60	850
Chest	11 (5.5)	210 (105)	14 (7)	300 (150)	15 (7.5)	410 (205)
Abdomen	11 (5.5)	220 (110)	16 (8)	400 (200)	17 (8.5)	530 (265)

$CTDI_{vol}$ [16cm (32cm), mGy), DLP (mGy·cm)

Table 2. Japan DRLs 2015 for pediatric CT issued by J-RIME

Japan Network for Research and Information on Medical Exposure (J-RIME) released Japan DRLs 2015, which includes DRLs for pediatric CT. Downloading is available from the J-RIME website (http://www.radher.jp/J-RIME/index.html)

III. Relationship between CT radiation and cancer development

There have been many complicated mechanisms and theories proposed regarding the association between ionizing radiation exposure and cancer. The details of physics and biological principles underlying this mechanism are available in textbooks. Important points for pediatric radiology residents are listed below:

- Ionizing radiation exposure can induce DNA double-strand breaks.
- DNA double-strand breaks can trigger several detrimental cellular responses, including carcinogenesis.
- The number of DNA double-strand breaks induced by radiation exposure is linearly dependent on DLP [7].
- Repair of DNA double-strand breaks occurs between 30 and 60 min after irradiation, and radiation-induced DSBs are virtually undetectable within 24 hours after exposure [7].

A clinically important experiment was carried out by Lobrich et al. with adult patients who underwent abdominal CT exam. They collected blood samples soon after CT scanning and evaluated the presence of γH2AX foci, which are a hallmark of DNA double-strand breaks. These parameters provided $CTDI_{vol}$ measurements between 4.8 and 17.4 mGy. CT of the thorax was performed in one phase, abdomen was performed in two or three phases, and combined thorax-abdomen CT was performed in three phases. The DLPs ranged from 157 to 1,514 mGy·cm. The parameter showed that scans were obtained with usual settings without excess ionizing radiation.

Does ionizing radiation exposure induce DNA double-strand breaks in neonatal and pediatric patients as well as in adult patients?

To determine whether ionizing radiation exposure induces DNA double-strand breaks in neonatal or pediatric CT conducted with relatively low-dose setting, Halm et al. performed an experiment similar to that performed by Lobrich et al, as describe above [8]. In this study, blood samples were collected soon after CT scanning from three volunteer pediatric patients aged 3, 15, and 21 months with the following typical pediatric settings: $CTDI_{vol}$ (16 cm) of 6.4-21.3 mGy; DLP of 92-426 mGy·cm; and an effective dose of 1.57-2.86 mSv. The results established that the number of DNA double-strand breaks

induced by CT examination was found to linearly depend on DLP, in accordance with the findings of Lobrich et al. with adult patients [8].

The findings of these two studies support the "linear non -threshold theory."

Two recently published retrospective studies investigated the onset of cancer in children and adolescents with a history of low-dose ionizing radiation exposure. According to Pearce et al., the relative risk of leukemia in children was increased by approximately three-fold after receiving 5–10 head CT scans. Moreover, the relative risk of brain cancer was increased by approximately three-fold in children younger than 15 years of age after receiving 2–3 head CT scans [9]. Accordingly, Mathews et al. found a greater incidence (24%) for all cancer types in children and adolescents exposed to radiation from CT scans. The average effective dose per scan was estimated to be 4.5 mSv [10].

It is true that these two articles created a sensation among pediatric radiology worldwide. However, many important points remain unclear. Therefore, further pediatric radiology studies are needed to elucidate the influence of CT radiation on the onset of cancer in pediatric patients.

AAPM have mentioned that CT scans are a very important tool for the diagnosis and assessment of response to treatment. The detailed assessment of anatomy and pathology provided by CT imaging does require the use of X-rays, which results in a small, but not zero, risk for cancer [11]. Guillerman explained the risk of cancer from pediatric CT as an "approximate likelihood that a coin toss will come up heads 12 times in a row (lifetime attribute risk (2 mSv), mortality: 1/4300)" [12].

CONCLUSION

This review article discussed three important issues regarding pediatric CT radiation exposure: the understanding of basic knowledge about $CTDI_{vol}$ and DLP, the concept of diagnostic reference levels, and the risk of cancer from pediatric CT examinations. The author dedicates this important information to young pediatric radiology residents of members of AOSPR.

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