1. Introduction

Computed Tomography (CT) imaging accounts for the highest contributor of the imaging radiation dose in children, which is estimated to be 40%–70% even if it only accounts for 5%–10% of total imaging procedures [1]. Therefore, it is essential to control the CT dose to avoid the potential risks [2]. This radiation risk is even greater in children where they have a significant risk from ionising radiation compared to adults [3]. Therefore, reasonable radiation dose estimation is necessary to optimise the exposure used for a particular CT procedure. However, current CT dose descriptors, volume CT dose index (CTDI_voI) and dose length product (DLP) are based on a standard size homogeneous phantom only. Hence, these parameters fail to reflect the dose variation due to variable body sizes of the patient and tissue inhomogeneity, and were found to underestimate the absorbed dose of average size adult and paediatric patients by 40%–70% [4,5]. To resolve this issue, the American Association of Physicists in Medicine (AAPM) introduced a new dose indicator, size-specific dose estimate (SSDE), taking into account both X-ray output and patient size [6]. The anteroposterior diameter (D_{AP}), lateral diameter (D_{LAT}), a combination of AP and LAT diameters (D_{AP+LAT}), and effective diameter (D_{eff}) methods were introduced for SSD calculations. Based on the above methods, a set of conversions factors were derived to translate CTDI_voI into SSDE. In addition, age-based conversion coefficients were also suggested by AAPM in cases where geometric data are unavailable [6]. However, SSD values vary between different approaches used in the calculation [7]. According to a study reported by Brady & Kaufman [8], SSDE derived using D_{eff} or D_{AP+LAT} varied 0.9%–2% where its individual measurements (D_{AP} or (D_{LAT}) showed comparatively larger variation of 2%–12%. Compared to size based approach, age derived SSDE varied only 2% for 0–13 years but 44% for 14–18 years. Also, weight was identified as a surrogate in determining size based conversion factors based on the strong correlation that exist between body weight and body diameter.

Keywords:
Paediatric radiation dose
Diagnostic reference level
Computed tomography
DRL
Achievable dose

A B S T R A C T

Introduction: The paediatric radiation dose has never been studied in Sri Lanka, nor has a national diagnostic reference level (NDRL) established. Therefore, the primary aim of this study was to propose diagnostic reference levels (DRL) and achievable dose (AD) values for paediatric CT examinations based on size.

Methods: A total of 658 paediatric (0–15 years) non-contrast-enhanced (NC) studies of head, chest and abdomen regions performed during six months in two dedicated paediatric hospitals (out of the three such institutions in the country) were included. For head examinations, the dose indexes were analysed based on age, while for body examinations, both age and effective diameter (D_{eff}) were used. The median and the third quartile of the pooled dose distribution were given as AD and NDRL, respectively.

Results: The AD ranges for the head, chest and abdomen regions based on CTDI_voI were 45.8–57.2 mGy, 2.9–10.0 mGy and 3.8–10.3 mGy. The corresponding NDRL ranges were 45.8–95.8 mGy, 3.5–14.1 mGy and 4.5–11.9 mGy. The AD ranges based on SSDE_{eff} and D_{eff} were 3.5–9.6 mGy and 4.1–10.3 mGy in chest and abdomen regions. The corresponding NDRL were 4.5–14.1 mGy and 6.1–10.6 mGy.

Conclusion: Other institutions can use the present study DRLs as a reference dose for paediatric CT. The AD values can be used as a baseline for target dose optimisations, reducing doses up to 90%.
for the abdomen region [9]. Nevertheless, the size measuring location is also significantly impacted the derived SSDEs. Osoyokal et al. [10] showed that the mean SSDE calculated over the scan volume and central slice-SSDE values varied between 1.2%–11% for chest, abdomen and pelvis (CAP).

Although the SSDE allows dose estimation for a given body size, it does not take into account variations in attenuation of the scanned body region. Therefore, later the SSDE based on water equivalent diameter (SSDE\(_{\text{w}}\)) was introduced to reflect the actual size specific dose in response to the attenuation characteristics of the scanned region. The AAPM report 220 [11] describes the attenuation-based method in deriving SSDE for chest and abdomen regions, while report 293 [12] continued the same for the head. However, as in any SSDE approach, the SSDE\(_{\text{w}}\) also varied based on the size measuring method. Abuhaimed & Martin [13] found that the \(D_{\text{w-midslice}}\) underestimate average \(D\) measured over the scan length by up to 13% and SSDE calculated using above two methods had root mean square difference’s (RMSD) of 1.2–4.0% for paediatrics. Also in case of truncated field of view (FOV), the calculated SSDE\(_{\text{w}}\) differs 0.22%, 0.0% and 2.21% form the non truncated cases for head, abdomen and chest respectively [14].

Regardless of varying approaches and inherent limitations, the SSDE is now being incorporated in to the Diagnostic Reference Levels (DRL) process of dose optimisation specially in paediatrics [15–18]. The DRLs were first introduced by the International Commission on Radiological Protection (ICRP) in 1990 as a tool for radiation protection and optimisation [19]. Although the DRL concept was initially recommended for diagnostic radiology and nuclear medicine examinations, it is now being adopted in radiation oncology to assess the CT dose during radiotherapy treatment planning [20–22]. Furthermore, the DRL ensures the delivery of optimum radiation dose during interventional radiology, including diagnostic and therapeutic procedures [23–25]. The DRLs were typically set at the third quartile of the dose distribution so that it can be used as a reference level to identify abnormally higher exposures. Besides, median is recommended as the achievable dose (AD) for given country on the basis that 50% of the facilities already have doses below this value [26]. Further, the DRL values have been established locally and nationally for a procedure type or clinical indication [27,28].

To date, DRLs have only been defined for adult CT procedures in Sri Lanka [29] and the radiation dose from CT examinations and its variation in the paediatric population has never been studied. The purpose of this study was to suggest DRLs and AD values for non-contrast CT examinations of paediatric head, chest and abdomen regions based on CTDI\(_{\text{vol}}\), DLP and SSDE which can be used as a national reference until the most recent studies. In addition, patients who underwent chest and abdomen CT procedures were further grouped in to four size groups based on their effective body diameter (0–14.5, 14.5–18.0, 18.0–22 and 22.0–25.0 cm). The DRLs were calculated for each size and age group per procedure type based on CTDI\(_{\text{vol}}\), DLP, SSDE based on effective diameter (SSDE\(_{\text{eff}}\)) and SSDE based on water equivalent diameter (SSDE\(_{\text{w}}\)).

2.4. Size specific dose calculation

The dose descriptor CTDI\(_{\text{vol}}\) refers to the average radiation dose per slice, and DLP refers to the total radiation dose for the scan [29,32]. SSDE reflects the dose calculated at the mid-CT slice of an individual patient corrected for the patient’s size and tissue inhomogeneity [7]. In this work, the AAPM report 204 [6] and 220 [11] was followed when calculating SSDE. The SSDE is defined by Eq. (1) where \(f\) is the conversion coefficient expressed by Eq. (2). The water-equivalent diameter (\(D_w\)) and effective diameter (\(D_{\text{eff}}\)) were the choice of size metrics and estimated using Eqs. (3) and (4). A region of interest (ROI) was drawn manually at the central axial slice of the head and chest scans. For abdomen scans, two ROIs were drawn at the level of the end plate of the second lumbar vertebrae, and the iliac crest, respectively and the average size was determined. The grey-scale windowing was adjusted to facilitate the visualisation of the skin margin to minimise the inclusion of air and table within the ROI. The areas (\(A_{\text{ROI}}\)) and the average CT numbers (\(C_{\text{ROI}}\)) were recorded for each ROI. In addition, the anteroposterior (\(D_{\text{AP}}\)) and lateral (\(D_{\text{LAT}}\)) diameters were measured for chest and abdomen scans using the distance measuring tool available with the post-processing software.

\[
\text{SSDE} = C T D I_{\text{vol}} \times f 
\]

\[
f = a e^{b D} 
\]

\[
D_w = \sqrt{\frac{1}{1000} \frac{C T_{(x,y)\text{ROI}}}{x} + 1} \times \frac{A_{\text{ROI}}}{\pi} 
\]

\[
D_{\text{eff}} = \sqrt{\frac{(D_{\text{AP}}) \times (D_{\text{LAT}})}{2}} 
\]

The measured body diameter, \(D_w\) or \(D_{\text{eff}}\) and values \(a\) and \(b\) extracted from the AAPM report 204 [6] were used to calculate the corresponding conversion coefficients. The values \(a\) and \(b\) for 16 cm diameter phantom (head) were 1.9852 and −0.0486 while 4.3781 and −0.0433 for 32 cm diameter phantom (chest and abdomen).
Table 1
Descriptive statistics of the scan parameters and body region dimensions for different CT scan regions and various age groups. $D_w$: water equivalent diameter, $D_{eff}$: effective diameter, mAs: product of tube current and time, kVp: tube voltage. The range within and mean outside the brackets.

<table>
<thead>
<tr>
<th>Region</th>
<th>Age (years)</th>
<th>Count</th>
<th>$D_w$ (cm)</th>
<th>$D_{eff}$ (cm)</th>
<th>kVp$^a$</th>
<th>mAs (total)</th>
<th>mAs (average)</th>
<th>Scan time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0–1</td>
<td>64</td>
<td>9.8 (6.9–13.4)</td>
<td>–</td>
<td>120 (100–140)</td>
<td>1086 (104–1713)</td>
<td>256 (240–335)</td>
<td>5.7 (3.4–6.8)</td>
</tr>
<tr>
<td></td>
<td>1–5</td>
<td>54</td>
<td>10.8 (9.0–14.1)</td>
<td>–</td>
<td>120 (100–140)</td>
<td>1265 (247–1665)</td>
<td>250 (5.9–8.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5–10</td>
<td>73</td>
<td>11.3 (8.4–14.5)</td>
<td>–</td>
<td>120 (120–140)</td>
<td>1497 (1281–1750)</td>
<td>249 (240–250)</td>
<td>6.3 (5.5–7.0)</td>
</tr>
<tr>
<td></td>
<td>10–15</td>
<td>65</td>
<td>11.4 (9.1–14.4)</td>
<td>–</td>
<td>120 (120–140)</td>
<td>1501 (656–1823)</td>
<td>250 (6.1–7.3)</td>
<td></td>
</tr>
<tr>
<td>Chest</td>
<td>0–1</td>
<td>52</td>
<td>10.7 (6.9–14.1)</td>
<td>11.4 (8.8–14.2)</td>
<td>100/120</td>
<td>232 (117–392)</td>
<td>139 (99–179)</td>
<td>2.8 (1.5–3.9)</td>
</tr>
<tr>
<td></td>
<td>1–5</td>
<td>45</td>
<td>13.8 (7.5–16.0)</td>
<td>13.3 (10.6–15.3)</td>
<td>120 (100–120)</td>
<td>436 (245–748)</td>
<td>192 (179–205)</td>
<td>2.4 (2.2–4.8)</td>
</tr>
<tr>
<td></td>
<td>5–10</td>
<td>55</td>
<td>14.6 (10.6–21.0)</td>
<td>12.5 (7.4–20.1)</td>
<td>120 (100–120)</td>
<td>837 (394–1776)</td>
<td>179 (179–179)</td>
<td>3.9 (2.3–6.8)</td>
</tr>
<tr>
<td></td>
<td>10–15</td>
<td>40</td>
<td>19.5 (10.6–26.1)</td>
<td>19.7 (8.4–23.6)</td>
<td>120 (100–120)</td>
<td>1127 (195–1901)</td>
<td>296 (197–395)</td>
<td>4.7 (2.6–6.8)</td>
</tr>
<tr>
<td>Abdomen</td>
<td>0–1</td>
<td>47</td>
<td>9.1 (8.8–11.3)</td>
<td>11.7 (10.9–12.8)</td>
<td>120</td>
<td>909 (789–1000)</td>
<td>–</td>
<td>5.8 (5.8–5.8)</td>
</tr>
<tr>
<td></td>
<td>1–5</td>
<td>43</td>
<td>10.6 (8.9–13.2)</td>
<td>13.6 (10.7–15.4)</td>
<td>100 (100–120)</td>
<td>627 (500–760)</td>
<td>138 (119–187)</td>
<td>5.4 (4.4–6.5)</td>
</tr>
<tr>
<td></td>
<td>5–10</td>
<td>51</td>
<td>11.9 (10.2–14.5)</td>
<td>15.7 (13.1–18.2)</td>
<td>120 (100–120)</td>
<td>926 (623–1245)</td>
<td>142 (127–158)</td>
<td>5.9 (5.5–6.2)</td>
</tr>
<tr>
<td></td>
<td>10–15</td>
<td>69</td>
<td>14.6 (11.9–20.4)</td>
<td>18.9 (17.2–22.0)</td>
<td>120 (100–120)</td>
<td>1418 (823–1776)</td>
<td>155 (149–160)</td>
<td>6.3 (5.5–6.6)</td>
</tr>
</tbody>
</table>

$^a$Mode is given instead of mean.

Fig. 1. Distribution of effective diameter ($D_{eff}$) and water equivalent diameter ($D_w$) of paediatric patients (0–15 years) against different age groups for (a) abdomen, (b) chest and (c) head regions.

2.5. Statistical analysis

Descriptive and inferential statistics were performed using Minitab® 17.1.0 statistical software. Graphical analysis was done using Originpro® 2021 graphical software. The median and third quartile of the pooled dose distribution for each age category were proposed as the AD and NDRL. In addition, the relationship between body dimensions and age was determined using the fitted function. Moreover, the results of this study were compared with similar studies in other countries.

3. Results

3.1. Study sample

A total of 658 non-contrast CT examinations (head (256), chest (192), and abdomen (210)) of patients (age 0–15 years) belonging to two paediatric hospitals were included for size-specific dose determination. The majority (68%) of the studies were extracted in the h1. Automatic exposure control (AEC) was used for 91.4% of abdomen CT...
scans and 93.5% of chest CT scans. None of the head CT scans used the AEC of any type.

### 3.2. CT exposure parameters and patient characteristics

Table 1 summarises the descriptive analysis of the scan parameters and the patient body dimensions. Fig. 1, illustrates the distribution of body diameters \(D_{\text{eff}}\) and \(D_{w}\) against different age groups for head, chest and abdomen regions. Due to the large attenuation variation of the brain tissue and skull vault of the head, the most appropriate parameter to determine size is \(D_{w}\) [33].

The average \(D_{\text{eff}}\) increases from 0–15 years by 72.8% and 61.5% for the chest and abdomen, respectively. The \(D_{w}\) increases by 16.3%, 82.2% and 60.4% for head, chest and abdomen regions, respectively.

According to Table 1, the average \(D_{w}\) of the head does not change much after the first year of life. A nearly similar trend was observed in the geometric measurements (The AP and lateral diameters) of Kleinman et al. [34] study (22.8% and 20.1%). Therefore, the average \(D_{w}\) of the head can be similar within different age categories even if narrow age groups were used. Also, it is clearly noted that the increase in \(D_{w}\) is higher than the increase in \(D_{\text{eff}}\) for the chest region. Moreover, the diameter of the abdomen region \(D_{w}\) of children aged 10–15 years showed a wide variation. This finding was consistent with the recent study done by Densie et al. [35].

The correlations of body diameters \(D_{\text{AP}}, D_{\text{LAT}}, D_{\text{AP+LAT}}, D_{\text{eff}}, \) and \(D_{w}\) with patient’s age for abdomen and chest procedures are illustrated in Figs. 2 and 3. The lines indicate the linear fit of the function, \(y=a+bx\). The corresponding Pearson’s correlation coefficients...
Table 2

Descriptive statistics of the resultant dosimetric parameters for different CT scan regions. third quartile is given as the national diagnostic reference level (NDRL) while median is given as the achievable dose (AD), $D_{we}$: water equivalent diameter, $D_{eff}$: effective diameter. The range within and mean outside the brackets.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Age or $d_{eff}$</th>
<th>CTDI$_{vol}$ (mGy)</th>
<th>DLP (mGy cm)</th>
<th>SSDE ($D_{eff}$)</th>
<th>SSDE ($D_{we}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>NDRL</td>
<td>Median</td>
<td>NDRL</td>
<td>Median</td>
</tr>
<tr>
<td>Head NC</td>
<td>0–1 years</td>
<td>45.8</td>
<td>(2.2–95.8)</td>
<td>45.8</td>
<td>850.0</td>
</tr>
<tr>
<td></td>
<td>1–5 years</td>
<td>50.4</td>
<td>(4.1–95.8)</td>
<td>95.8</td>
<td>1057</td>
</tr>
<tr>
<td></td>
<td>5–10 years</td>
<td>57.2</td>
<td>(21.6–95.8)</td>
<td>95.8</td>
<td>1163</td>
</tr>
<tr>
<td></td>
<td>10–15 years</td>
<td>57.2</td>
<td>(22.9–95.8)</td>
<td>57.2</td>
<td>1206</td>
</tr>
<tr>
<td>Chest NC</td>
<td>0–14.5 cm</td>
<td>3.4</td>
<td>(2.1–7.3)</td>
<td>95.8</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>14.5–18.0 cm</td>
<td>5.6</td>
<td>(4.8–13.2)</td>
<td>95.8</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>18.0–22.0 cm</td>
<td>8.8</td>
<td>(6.4–15.5)</td>
<td>95.8</td>
<td>292</td>
</tr>
<tr>
<td>Abdomen NC</td>
<td>0–14.5 cm</td>
<td>3.8</td>
<td>(3.1–6.3)</td>
<td>95.8</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>14.5–18.0 cm</td>
<td>4.1</td>
<td>(3.1–9.0)</td>
<td>95.8</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>18.0–22.5 cm</td>
<td>10.3</td>
<td>(3.4–14.1)</td>
<td>95.8</td>
<td>346</td>
</tr>
</tbody>
</table>

3.3. Variation of dosimetric parameters

Table 2 displays the descriptive statistics of the CT dose indexes CTDI$_{vol}$, DLP, SSDE$_{D_{eff}}$, and SSDE$_{D_{we}}$ extracted for the most common age stratification hierarchy for children [32]. In addition to the age groups provided in Table 1, four size groups based on the patient $D_{eff}$ has also been given for chest and abdominal CT examinations. As expected, the dose indexes increased with age and size. Figs. 4 and 5 illustrate the distribution of CTDI$_{vol}$, DLP, SSDE$_{D_{eff}}$, and SSDE$_{D_{we}}$ using Box and Whisker plots. The average CTDI$_{vol}$ values for the chest and abdomen regions were lower than that of SSDE$_{D_{eff}}$ and SSDE$_{D_{we}}$, irrespective of the age ranges. Also, the average CTDI$_{vol}$ of the head is lower than SSDE$_{D_{we}}$ for all age groups. Fig. 6, illustrates the relationship of water equivalent diameter ($D_{we}$) against volume computed tomography dose index (CTDI$_{vol}$) and dose length product (DLP) for chest and abdomen regions. The CTDI$_{vol}$ and DLP increases with increasing body diameter ($D_{we}$).

3.4. Dose comparison between institutions.

Fig. 7 compares the resultant institutional DRLs (medians) based on CTDI$_{vol}$, SSDE$_{D_{eff}}$, and SSDE$_{D_{we}}$ for head, chest and abdomen regions in order to identify the degree of optimisation required for institutions, h1 and h2 The head CT typical values based on SSDE$_{D_{we}}$ for h2 (66.1 mGy–99.9 mGy) were significantly higher compared to h1 (56.8 mGy–65.7 mGy) for all age ranges. This variation can be attributed to the
high tube voltages (140 kVp) used during head CT scans of the children in that specific institution. The h1 reported the highest typical values of the abdomen region based on SSDE$_{Dw}$ for 5–10 years (12.8 mGy) and 10–15 years (18 mGy) compared to h2 reported doses, 10.4 mGy and 6.6 mGy. The age group 0–1 year was not presented for comparison due to the unavailability of sufficient data from h2. Also, the chest CT typical values (SSDE$_{Dw}$) were highest in h2 for all age ranges (12.1 mGy–19.2 mGy), while the resultant range of typical values for h1 was 7.3 mGy–16.6 mGy. The higher doses in h2 for the chest can be due to the use of 120 kVp for all age ranges, while the choice of kVp in h1 was shifted between 100 kVp and 120 kVp due to the routine use of age-specific scanning protocols.

3.5. International DRL comparison

Figs. 8 and 9 illustrate the comparison of present study DRLs based on CTDI$_{vol}$ and SSDE$_{D_{eff}}$ with internationally published DRLs. The CTDI$_{vol}$ for head and torso studies were defined for 16 cm and 32 cm diameter phantoms which were similar in both institutions. A wide variation in DRLs based on both CTDI$_{vol}$ and SSDE$_{D_{eff}}$ was observed between the similar age groups in different countries. The head DRLs based on CTDI$_{vol}$ were higher than most of the compared countries. The abdomen and chest DRL based on SSDE were comparable with the Iran 2019 [36] and the Japan 2019 [37] studies. However, the DRL based on CTDI$_{vol}$ for the chest and abdomen region was comparable with most of the countries. In addition, Table 3 presents a DLP/CTDI$_{vol}$ comparison, which facilitates the evaluation of scan length variation for different scan regions and age groups.

4. Discussion

Sri Lanka has a national policy that provides free healthcare for all citizens, and most hospitals are therefore state-owned. It is reported that there are about 63 CT machines in the country, where only three are dedicated paediatric units [29]. More than 70% of the CT scanners are 16-slice or lesser, having primitive dose reduction capabilities [29]. Therefore, routine monitoring of radiation doses is essential to ensure patients receive the lowest possible doses always. The first known study
Table 3
Comparison of present study DLP/CTD\text{vol} ratios for head, chest and abdomen CT with the data extracted from listed countries and international reports.

<table>
<thead>
<tr>
<th>Country/Organisation</th>
<th>Head DLP/CTD\text{vol} ratios</th>
<th>Chest DLP/CTD\text{vol} ratios</th>
<th>Abdomen DLP/CTD\text{vol} ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-1 years</td>
<td>1-5 years</td>
<td>5-10 years</td>
</tr>
<tr>
<td>Present study</td>
<td>10.5</td>
<td>11.0</td>
<td>12.1</td>
</tr>
<tr>
<td>Japan [38]</td>
<td>5.3</td>
<td>6.3</td>
<td>–</td>
</tr>
<tr>
<td>Turkey [39]</td>
<td>9.3</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Italy [40]</td>
<td>–</td>
<td>16.5</td>
<td>–</td>
</tr>
<tr>
<td>France [41]</td>
<td>15.5</td>
<td>20.5</td>
<td>21.6</td>
</tr>
<tr>
<td>Jordan [42]</td>
<td>15.5</td>
<td>–</td>
<td>17.4</td>
</tr>
<tr>
<td>European Commission [43]</td>
<td>13.2</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>Sudan [18]</td>
<td>14.8</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Thailand [44]</td>
<td>25</td>
<td>19</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Fig. 7. Variation of typical dose values (median) between two centres (h1 and h2) based on CTDI\text{vol}, SSDE\text{Dc}, and SSDE\text{Da} for head, chest and abdomen regions.

conducted by a group of independent researchers in Sri Lanka had identified dose optimisation requirements for some of the CT units in the country [29]. However, a formal dose evaluation program has not been implemented in Sri Lanka which can be due to the limited physical and human resources in the country. Also, paediatric CT practices have not been evaluated in Sri Lanka. Unlike adult DRLs, which are set for an average subject, pediatric DRL requires collecting sufficient data for several weight groups per procedure [51]. This makes it inherently a mammoth task to establish a pediatric DRL. Therefore, the present study evaluated dose data from two paediatric units to represent the current national practice based on age and body size.

The patient dose indicator CTDI\text{vol} is usually defined with respect to a cylindrical PMMA (polymethylmethacrylate) phantom of 16 cm or 32 cm in diameter. In the present study, 16 cm diameter phantom was used to define CTDI\text{vol} of the head, while 32 cm diameter phantom was used to define CTDI\text{vol} of the chest and abdomen. However, the resultant D\text{eff} of paediatric chest and abdomen regions (0–15 years) ranged between 7.4 cm to 23.6 cm, which is lower than the diameter of the phantom (32 cm) used to define the CTDI\text{vol}. Therefore, CTDI\text{vol} will underestimate the paediatric chest and abdomen CT, which emphasises the importance of a dose index where the size of the individual patient is taken into account.

Nevertheless, when patient body size is not taken into consideration, the CTDI\text{vol} underestimates the dose by a factor between 1.8 to 2.8 for chest and abdomen regions. Moreover, CTDI\text{vol} underestimate the dose by a factor of 1.6–2.8 for chest and abdomen regions when changes in attenuation differences are not considered. However, the CTDI\text{vol} underestimate the dose in the head region only by a factor of 1.1–1.3 when changes in attenuation differences are not considered. This suggests that the CTDI\text{vol} considerably underestimates the paediatric radiation dose in CT.

The SSDE based on body diameters facilitates the demonstration of size-dependent dose variation for CT scanning. However, it is not always possible to measure the body diameters in the clinical routine.
Fig. 8. Comparison of present study DRL based on CTDI<sub>v</sub> with internationally published DRLs. Thailand 2012 [44], Turkey 2015 [45], France 2009 [46], Kenya 2016 [47], South Korea 2017 [48], Japan 2019 [37], Sudan 2019 [49], Jordan 2019 [42], Italy 2015 [40], Switzerland 2008 [50].

to determine SSDE. The age, weight and body mass index (BMI) were proposed as an effective alternative quantity to successfully determine the body diameters given their ready availability [8,9,16,54,55]. Therefore, age was suggested as a surrogate in estimating SSDE [7,56]. Khawaja et al. [9] reported age and D<sub>AP</sub>, D<sub>LAT</sub> and D<sub>eff</sub> correlations of 0.69, 0.68 and 0.67 respectively for abdomen region whereas the corresponding coefficients resulted in the present study were 0.66, 0.82 and 0.79. A similar study done by Mohammadbeigi et al. [16] had resulted moderate correlations of age with D<sub>AP</sub> (0.62) and D<sub>eff</sub> (0.54) for chest and abdomen regions respectively.
The AAPM report 204 [6] recommended a set of age-based $D_{eff}$ values for the abdomen region that can be used whenever the geometric data are unavailable. However, the corresponding age-based $D_{eff}$ values derived from the fitted function in Figs. 2 and 3 were found to be lower (2%–32%) than the AAPM suggested values. This is attributed to the rather smaller physique of the Sri Lankan children compared to European children. Therefore, the function $y = a + bx$ can be used to estimate the $D_{eff}$ for a particular age whenever an Asian child is concerned for SSDE calculation. The corresponding values of $a$ and $b$ for abdomen and chest regions were 11.62, 0.59 and 10.20, 0.72 respectively.

Dose monitoring at a regular interval is essential for a proper quality control program. DRL is a tool to identify radiation doses, whether abnormally high or low. According to the DRL guideline, the quantities used to define DRL should adequately reflect the amount of ionising radiation used for a particular medical imaging task [30]. Besides, dose variation due to the size and composition of different patient groups and body regions must be considered effectively during the dose optimisation. Therefore, the present study attempted to establish DRLs for children aged 0–15 years based on SSDE. According to the literature and ICRP-135, the weight or size-specific paediatric DRLs are the most appropriate [30,32]. In the past, age has been used to group children, and DRLs have been defined accordingly. The frequently used age groups in the literature were (0–1, 1–5, 5–10, and 10–15 years) [31,32]. However, large variations of body sizes exist even within these age groups. Further, Kleinman et al. [34] have demonstrated that the individual patient size does not correlate well with patient age, even though the average patient sizes depend on age. Since body size mainly influences the CT dose under ATCM, it is recommended to use stratification based on body sizes rather than the age when evaluating CT radiation dose [30]. Also, weight is identified as a more reliable factor to be used along with the DRL quantity than age [57]. The European Commission (EC) [43] has proposed a set of weight bands for the paediatric DRL process with their corresponding age bands. However, these age-specific body weights substantially vary with ethnicity. Given its limitations, age should only be used as a grouping parameter if it is the only available measure. Moreover, age-based DRLs will primarily facilitate the DRL comparison since most of the available paediatric DRLs are set for age groups [32]. Therefore, in the present study, the DRLs were grouped based on patient age and effective body diameter regardless of the DRL quantity. Finally, comparisons were made of the DRLs defined per age group due to the substantial availability of similar studies in the literature.

Approximately similar DRLs resulted in $SSDE_{D_{eff}}$ and $SSDE_{D_{w}}$ methods along the compared age and size groups. In contrast, most of the DRL based on CTDI$_{vol}$ were lower for all three body regions. The chest and abdomen CT DRL based on CTDI$_{vol}$ for all age ranges were comparable with the internationally published DRLs. However, the head CT DRLs based on CTDI$_{vol}$ is approximately doubled in the 1–5 and 5–10 years group compared to other countries. The use of high kVp (140 kVp) in h2 can be identified as the major contributor to the rise in CTDI$_{vol}$. Although DRL serves as a margin to identify higher doses, it does not guide the lowest possible dose that can be used to obtain an adequate quality image. Therefore, DRL alone cannot be used to
make decisions for optimisation. Nevertheless, AD provides a margin for target dose optimisation. In the present study, dose optimisations could lead to maximum dose reductions of 90.0%, 64.4% and 58.5% for head, chest and abdomen regions if AD values were followed. However, DRL and AD should not be applied for the individual patient dose index comparisons because DRL is defined for standard patients only [30].

Moreover, CTDI$_{vol}$ or SSDE comparisons alone cannot conclude that the delivered radiation doses are satisfactory since those reflect the dose to the central slice only. Sometimes a patient with a similar cross-sectional area might receive varying effective doses (ED) due to the differences in scan lengths [58]. Therefore, the scan length plays a critical role in limiting radiation dose. The DLP/CTDI$_{vol}$ ratio is the suitable reflector of the scan length used for a specific CT procedure. The DLP/CTDI$_{vol}$ ratios obtained for head, chest and abdomen regions were comparable with the internationally published and the European Commission (EC) recommended values. However, further reduction in head CT ratios (DLP/CTDI$_{vol}$) can be achieved since some countries still reported lower ratios for various body regions and age groups.

The CTDI$_{vol}$ and conversion factors will only estimate the dose at the central axial slice. Therefore, the determined SSDE can be slightly higher than the SSDE averaged over the entire scan volume. In addition, the sources of variability with the dose-measuring location, the size measurement technique can also significantly contribute to the uncertainties. In the present study, the ROI and diameter measurements were done only once by a single investigator, which can affect the accuracy of the measurements. Even though measures were taken to minimise the inclusion of air within the ROI, total exclusion of air is impossible in manual ROI selection. Also, Li et al. [59] had reported that the CT table within the ROI increased the total attenuation by 12%. Wang et al. [60] described that the careful placing of manual ROI without attempting to exclude all portions of the patient table still provides reasonably accurate results. In addition, the sub-optimal attenuation calibration and edge enhancing filters also add uncertainties to the measured D$_{vol}$.

However, the accuracy of pixels was ensured in the present study by the routine calibrations done at the two CT centres.

Given the retrospective nature of this study, there were difficulties in obtaining some information such as weight and height. This limited the use of more appropriate stratification methods such as weight and BMI in DRL process. This was identified as the major limitation of this study. Also, the present study only evaluated the CT doses from two major paediatric hospitals in the country. The designated children’s hospitals are supposedly more experienced in paediatric radiology. Furthermore, the referred medical indications might be significantly different from other CT centres, and perhaps the radiation doses are not representative of the country. However, the ICRP-135 states that it is sufficient to focus primarily on the main hospitals that provide paediatric imaging during the initial attempt to provide paediatric DRL for a country with no reference to use as guidance [30]. Regardless of these limitations, the present study provides a better initiative for dose optimisation in Sri Lanka, specially the pediatric CT doses.

5. Conclusion

The current CT dose descriptor, CTDI$_{vol}$, underestimates paediatric CT dose, and hence it will provide false DRLs leading to inadequate optimisation. The degree of underestimation depends on the size of the phantom used to define the CTDI$_{vol}$. The 32 cm diameter phantom recommended for paediatric torso studies underestimates the dose by a factor of 1.8–2.8. Therefore, when defining DRLs for the children more reliable dose descriptor is required, such as SSDE. The D$_{vol}$ or D$_{vol}$/D$_{vol}$ can be used to determine the corresponding conversion coefficient to translate CTDI$_{vol}$ to SSDE in children. However, if age is used as a surrogate in determining the size of a local child, the correction suggested in the present work should be used. Moreover, the DRLs and ADs suggested in this study can be used as a baseline for a dose optimisation program for paediatric CT procedures in Sri Lanka.

References


