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A literature review of paediatric Diagnostic Reference Levels in Diagnostic and Interventional Radiology and Cardiology

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ABSTRACT

The use of Diagnostic Reference Levels (DRLs) in Radiology is imposed by the European Directive 2013/59. It is an important tool especially for the optimisation of children exposure. During the last years, guidelines regarding the establishment of DRLs have been proposed in European and International level. This manuscript is a literature review of the available national or local paediatric DRLs in diagnostic and Interventional Radiology and Cardiology. Most of the existing studies have been performed before the guidelines. Therefore, there is no common methodology between studies for the DRL calculation. This fact, in conjunction with the difficulty of obtaining a large sample of paediatric patients, has as consequence the report of non-comparable DRLs. The most recent studies seem to follow the guidelines; however further similar studies need to be realised for the establishment and renewal of paediatric DRLs by following the recommendations, e.g. weight grouping for body examinations and age grouping for head examinations. DRLs as a function of body weight are an interesting solution in case of small samples. The new approach of setting DRLs based on clinical indication should be carefully considered. A strong collaboration of all healthcare professionals is important for the establishment of reliable DRLs.

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Paediatric diagnostic reference levels; Optimisation, Diagnostic radiology; Interventional radiology/cardiology, Children, Radiation dose

Introduction

Ionising radiation in medical imaging results in an increased exposure of patients to radiation [1]. Therefore, the optimisation of patient exposure during X-ray examinations is of great importance in terms of radiation protection. According to the European Radiation Protection (RP) report No 109, the establishment of Diagnostic Reference Levels (DRLs) contributes to reducing the high radiation exposure of patients and it is necessary for all high-dose medical examinations, such as computed tomography (CT) and procedures that require long fluoroscopy times, such as interventional radiology (IR) [2]. DRLs are defined as "dose levels in medical radiodiagnostic or IR practices, or, in the case of radio-pharmaceuticals, levels of activity, for typical examinations for groups of standard-sized patients or standard phantoms for broadly defined types of equipment" [3]. The International Commission on Radiological Protection (ICRP) has recommended the establishment of DRLs in order to improve optimisation of radioprotection by identifying high patient radiation doses that might not be justified in terms of image quality requirements [4]. Their values do not represent dose limits, but their use can indicate high doses in patients [5]. They facilitate the definition of optimal dose parameters and the comparison between equipment and protocols of different health centres or regions [6].

In order to implement optimisation in paediatric patients, the European Basic Safety Standards (BSS) 2013/59/Euratom emphasises on the attention that must be paid to special practices involving the medical examinations in children [3]. The definition of DRLs is very important in medical examinations of paediatric patients, as children are extremely radiosensitive. The cells of children's tissues, in contrast to those of adults, have increased mitotic activity and thus the risk from radiation exposure is higher [7]. In addition, life expectancy in children is longer than adults', and as a consequence there is a greater possibility for the future impact caused by irradiation to occur [7]. Currently, there is an augmenting number of studies reporting an increased cancer incidence after CT examinations in childhood [8-10]. Despite the fact that epidemiological studies investigating the relationship of cancer risk to radiation from diagnostic and interventional examinations are limited, justification and dose optimisation is mandatory in paediatric patients [11-13].

DRLs can be established on local, national or European Level. The local DRL is defined as a DRL for an X-ray procedure set in healthcare facilities within a part of a country, while the national DRL is the DRL value set in a country based on data from a representative sample of healthcare facilities in that country. Local and National DRLs are defined for a specific clinical task and are based on the 75th percentile value of the distribution of the appropriate DRL quantity in a reasonable number of X-ray rooms and the distribution of the median values of the appropriate DRL quantity observed at each healthcare facility respectively. The European paediatric DRLs are defined as the median value or 50th percentile of the distribution of national paediatric DRLs [14,15]. Nowadays, it is acknowledged that an examination might require different image quality depending on the clinical indication. This leads to different radiation doses in variable protocols of the same anatomical area. For this reason, the establishment of DRLs based on clinical indication (clinical DRLs) has been introduced and supported by the recommendations [15].

According to the European BSS Directive 2013/59 [3], the establishment, use and regular review of DRLs is a mandatory procedure. In addition the directive strongly emphasises on the establishment of DRLs in paediatric population. Currently, few countries have established DRLs and have set values only for few common X-ray examinations. The purpose of this article is to review and present the existing paediatric DRLs in diagnostic and interventional Radiology and Cardiology. The DRLs included are either European or non-European and have been established either in local or national level. They will be presented in three different sections: a. Diagnostic Radiology (DR), b. Interventional Radiology (IR) and Cardiology (IC) and c. CT. We sought to present the available data, to underline the existing deficiencies and to examine and discuss the necessity of further establishing and renewing DRLs according to the European and international recommendations.

Literature review

For the purpose of this paper, a literature review of the existing studies that propose or establish paediatric DRLs was performed. The review was done using the search engines Pubmed, Science Direct, Google, Google Scholar, Mendeley platform, as well as other web engines. Various combinations of key words were used including "Diagnostic reference Levels", "paediatric", "children", "doses", "radiography", "interventional radiology", and "CT". Approximately 250 articles and data on paediatric doses and reference levels were identified. Criteria of exclusion were: a. languages other than English, French, Italian German and Spanish and b. articles published more than twenty years ago, with the exception of articles based on European level. As there were only few articles dealing with paediatric DRLs on European level, we decided to include them all in our review. Among these 250 articles, 56 articles were those that proposed or presented the established DRLs in children and met the criteria of inclusion. These 56 articles were categorised according to the type of medical practice: radiography, fluoroscopy and interventional procedures or CT. The categorisation adopted was based on important reports dealing with paediatric DRLs [14, 16]. Afterwards, a database was created where the data of the articles were categorised into spreadsheets according to the examination performed: radiography, fluoroscopic/interventional procedures or CT. For each article the following data were recorded: publication date of the article, country from which the data were derived, whether the DRLs proposed were in local, national or European level, number of institutions that participated in the study, dose quantity used as DRL, method used (75th quartile/median values), examinations included and categorisation of patients. All these data were distributed to six tables that were created in order to enable the analysis of data, the derivation of conclusions and the identification of difficulties and deficiencies that currently exist. Two tables show data for radiography (**Tables 1 and 2**), two tables for fluoroscopy/ IR (**Tables 3 and 4**) and two tables for CT examinations (**Tables 5 and 6**). All of these tables show the country where the data come from, the year of publication, the type of DRL proposed or established (local, national or European), and the values of DRLs proposed for all patient groups of each examination. Regarding radiography, the first table contains the European data while the second table contains the non-European data available in literature. Regarding fluoroscopic and interventional procedures the first table contains data about DRLs in Micturating Cystourethrography (MCU), Voiding Cystourethrography (VCUG) and barium fluoroscopic examinations; the second table comprises DRL data for diagnostic and therapeutic procedures in IR and IC. Finally regarding CT, the data were distributed to two tables: European national DRLs and non-European DRLs.

Paediatric DRLs in Radiography

The DRLs across Europe for chest/thorax, head/skull and abdomen/pelvis radiography are presented in **Table 1**. As shown, the European countries that have established national paediatric DRLs in radiography are Austria, Finland, France, Spain, Belgium, UK, Ireland and Germany [17-24]. The dose quantities used are Entrance Surface Dose (ESD), Dose Area Product (DAP), Incident Air Kerma (IAK), Kerma Area Product (KAP) and Entrance Surface Kerma (ESK). Regardless of the applied dose, all these studies used the third quartile of dose distribution as DRLs. Patients were categorised according to age. Although many publications include DRL values for newborns, there are three references that define DRL values even for premature infants [23-25]. Germany has established as national DRL for premature infants undergoing chest radiography a DAP value of 0.3 μGy*m2 [24]. Schneider et al. [24] proposed for premature infants undergoing chest radiography a mean ESD of 31 μGy or 37 μGy (75th percentile) as European DRL. One study reporting national DRLs for premature infants in Belgium [23], classified them according to body weight. The data were collected from 17 Neonatal Intensive Care Units (NICU) and three weight groups were considered: extremely low-weight infants, low weight infants, and normal weight infants. DRLs were established for chest and chest-abdomen radiographs in terms of ESK and KAP.

As the limited number of paediatric examinations and therefore the limited dose data do not often allow detailed analysis, Finland [17] proposed a new method for establishing DRLs. A DRL curve for chest X-ray examinations is presented using the ESD or DAP as a function of patient projection thickness. This methodology facilitates the comparison of patient doses against the graph, reducing the need of collecting a large number of patient data.

The non European DRLs for chest/thorax, head/skull and abdomen/pelvis radiography are presented in **Table 2**. Non-European DRLs are established or proposed in Kenya, India, Brazil and USA. Wambani et al [25] proposed preliminary local DRLs using data from one children's hospital in Kenya. The mean values of entrance surface air kerma (ESAK) was the dose quantity used for DRLs of chest, abdomen, pelvis, spine, nasal bones, skull, mandibles, hip, clavicle, shoulder, sinuses, upper and lower extremities. In examinations where grid is often used in radiography, DRLs are proposed for both techniques–with or without grid. Sonawane et al. [26] proposed DRLs using data from 22 hospitals in India for chest, abdomen, lumbar and thoracic spine, pelvis, skull and hip joint radiography. The DRL values correspond to one age group of age 5-9 years old. The American Association of Physicists in Medicine (AAPM) in cooperation with the American College of Radiology (ACR) [27] established DRLs in USA both for grid and non-grid chest X-ray examinations. Freitas et al. [28] made a study on radiation doses from radiography examinations including data from paediatric patients. Due to few paediatric data, no group categorisation was performed; the 3rd quartile of the ESD distribution of all children was considered an indication of the paediatric patient DRL.

There are three studies in literature that propose European DRLs for chest radiography [24, 29, 30]. The older study of Schneider et al. [24], published in 1998, proposes as DRL the third quartile or the mean ESD for four different age groups and determines different DRLs for chest examinations realised with mobile units. Hart et al. [30] used calculated normalisation factors in order to normalise the dose of each paediatric patient to the dose corresponding to the standard sized patient. These factors were applied to European dose data and DRLs for chest, abdomen, skull and pelvis were determined. The more recent study of Smans et al. [29], published in 2008, divides the patients into more age groups than the older study of Schneider et al. [24] and proposes DRLs for chest radiography based on the 75th percentile of ESD or DAP values (**Table 1**).

Paediatric DRLs in fluoroscopy and interventional examinations.

In diagnostic fluoroscopy, there are studies from three countries that have established national DRLs, three studies reporting local DRLs and two studies that propose preliminary European DRLs. National DRLs are reported in Spain, UK and Germany [19, 21, 23, 31], whereas local DRLs have been proposed from hospitals or health facilities in Australia, UK and Italy [32-34]. Smans et al. [29] made an effort to propose preliminary European DRLs based on 5-7 radiology centres. Hart et al. [30], used calculated normalisation factors that were applied to European dose data and DRLs for different ages were determined for MCU.

The paediatric DRLs established in diagnostic fluoroscopy for MCU, VCUG and for barium fluoroscopic examinations are shown in **Table 3**. All DRL values for the MCU, VCU and barium fluoroscopic examinations were established as the third quartile of DAP distributions. All countries have grouped their patients according to age, with the exception of Italy [33] (local study) where the patients have been categorised according to weight.

National DRLs were established mainly for MCU, barium meal and barium swallow, while local DRLs have been established for additional examinations, such as VCUG, barium enema, barium follow through, contrast enema, airway/airway and swallow, dysphagia swallow, palatal screening and intravenous urography.

One important issue is that there are very few data concerning DRLs in IR and IC [35-41]. With the exception of Costa Rica who presents national DRLs in IC [40], all the other studies propose DRLs on a local level. Five of these local studies have been performed in Europe (France, UK, Germany and Greece [36-39, 41]) while the sixth one is a non-European study, performed in Chile [35]. These data are presented in **Table 4**. The values used for DRLs are mainly DAP and Kerma Area Product (KAP). Some of the studies refer to other parameters, such as fluoroscopy time and number of cine fractions. Two local French studies [36, 41] have proposed additional DRL values in terms of fluoroscopy time or number of cine fractions and one study from Greece [39] has also provided statistical analysis of these parameters. One additional useful quantity calculated and proposed as a promising DRL quantity is DAP/body weight [35, 37]. This parameter can be useful to eliminate differences between children's weight within the same age group. Nowadays, it is acknowledged that the radiation dose in IR and IC is dependent not only on patient size but also on a variety of other parameters such as the complexity of each procedure and the technical parameters used during the examination; therefore the DRL values strongly depend on these factors [36, 37]. For this reason, the establishment of more than one DRL quantities seems a reasonable approach in this field. Finally, concerning specifically IR procedures, there is only one study that proposes reference levels for brain anteriovenous malformation embolisation, head and neck superficial vascular formation and cerebral digital subtraction angiography [41].

Strauss et al. [42] made a study to evaluate various dose indexes of paediatric peripheral and abdominal fluoroscopically guided procedures that could assist in the development of DRLs for two different techniques: a standard fluoroscope and a novel fluoroscope technique. The standard fluoroscope technique referred to the procedures that were realised with the use of a C-arm of standard technology and the novel technique referred to the procedures realised with a novel –at the time- C-arm that provided advanced image-processing and dose reduction technology. The main parameters collected and calculated were DAP, air kerma, fluoroscopy time, number of digital subtraction angiography images and patient mass for peripheral and abdominal fluoroscopic exams. As technology advances quickly, this study suggests the use of two reference levels (for standard and novel technique) in order to facilitate all departments independently of the technique used.

Paediatric DRLs in Computed Tomography

The countries that have established national DRLs in CT are Finland, France, UK, Ireland, Spain, Belgium, Switzerland and Germany [18-21, 23, 43-49]. The categorisation of paediatric patients was realised according to age or weight and the national DRL values established were the third quartile of Volume CT Dose Index (CTDIvol) - or more rarely weighted CT dose Index (CTDIw) - and Dose Length Product (DLP). The main examinations considered are head/brain CT, chest, abdomen and pelvis CT. The European national DRLs for head/brain, chest/thorax and abdomen/pelvis CT examinations are shown in **Table 5**. There are some countries that have also established DRLs for not so common examinations, such as facial bones, petrosal bone, sinus, nasal cavity and lumbar spine [19, 21, 48, 50].

In literature there is also a number of other studies that propose local DRLs in paediatric CT examinations. These DRLs concern CT examinations of head, chest, abdomen and pelvis and have been established in Italy, France, Portugal, Switzerland and Greece [50-55].

Non-European DRLs are proposed in US, Australia, Japan, Syria, Korea, Thailand, Sudan and Kenya, while international DRLs are proposed by Vassileva et al. in 2015, based on a dose survey from 32 countries [56-71]. In Kenya, Japan, Syria, Thailand and Australia, the DRL values proposed are in national Levels, or based on a nationwide survey. The non-European DRLs for head/brain, chest/thorax and abdomen/pelvis CT examinations are shown in **Table 6**.

One clear difficulty was the insufficient collection of dose data from paediatric examinations [19, 44, 73]. As a possible solution, Finland proposed a new method for body examinations in CT, as previously described in chest radiography [17, 43]. A DRL curve of CTDIvol and DLP as a function of weight was created. This curve is very useful in comparing local doses to the DRL values when the available data do not permit statistical analysis [43]. More specifically two DRL curves – the 75th and 50th percentile – have been established. The 50% curve was created for use in cases that health centres use modern technology and practices and manage to offer a reduced dose to the patients. On the other hand, patients undergoing head examinations were classified according to age, as the size of the head does not change dramatically between children of the same age [43]. In France, where the available dose data were also limited, DRLs for CT examinations were established according to weight or age groups, based not only on calculations but also on literature data [18]. These values were proposed as a starting point for CT examinations of brain, chest, abdomen-pelvis, facial and petrosal bones.

Discussion

The establishment of DRLs in paediatric patients can increase dose awareness and contribute in keeping the dose to these patients as low as possible (ALARA principle) [72]. The last years official guidelines have been published regarding the methodologies that should be used for the establishment of DRLs; The ICRP 135 [15] refers to the establishment of DRLs in adults and in paediatric population. The European Commission has also published RP 185 [14] with recommendations and guidelines for the establishment of DRLs exclusively in paediatric population. The most important is that the new European legislation [3] imposes the establishment of DRLs and emphasises on the optimisation of procedures especially in paediatric population. Our study confirms the problem that is already reported in these important documents, which is the lack of DRL data in literature [15]. Many European countries have not even established DRLs on a national level. On the other hand, countries that have established national DRLs have included only few common examinations or certain age/weight groups. The main explanation is that the number of paediatric examinations is very limited, especially in IR or IC. As the paediatric population must be further divided into groups, the data for each group become even more limited. Therefore, the establishment of DRLs can become infeasible. One possible solution could be that surveys trying to establish DRLs should be focused on hospitals that provide paediatric imaging [15]. If still the collection of data is infeasible, then the strategy proposed by Finland (DRL curves) could be followed. The creation of two DRL curves - the 75% and the 50% - is a useful proposition as the latter can be used from institutes with more recent and modern equipment that offer to the user modern dose optimisation techniques [17, 43].

Regarding IR and IC, the need for establishing DRLs is even stronger. Only Costa Rica has established national DRLs in IC procedures. There are only five studies proposing local DRLs in IC and only one study in IR procedures. This is a serious issue as these procedures can lead to high doses to the patient, and the number of these examinations performed is continuously increasing. Especially in IC, paediatric patients with complex congenital heart diseases, such as hypoplastic left heart syndrome, are often catheterised more than once [37]. Longer life expectancy of children with congenital heart diseases is also a factor that contributes to a high cumulative effective dose in children, as longer life expectancy means that they might need more than one IC procedure in their lifetime [40]. Therefore the increased risk of somatic radiation effects notes the necessity of establishing DRLs the soonest possible [37, 38]. One recommendation reported in literature is the establishment of one single DRL value for all interventional therapeutic modalities in congenital heart disease, as in one single examination different techniques are often used [38]. The authors of this study claim that this would facilitate the promoting of the ALARA principle in the training of young interventional cardiologists. Nevertheless, health centres must be encouraged to collect and publish data on doses in paediatric IR and IC to facilitate the establishment of reference levels. Ubeda et al. recently carried out one study in Chile where they calculated organ and effective doses for different types of paediatric IC procedures for different age groups in order to facilitate comparisons with other imaging procedures for justification and optimisation purposes [73].

Regarding the examinations considered of most importance, there seems to be an agreement between different countries; in radiography there are national DRLs for skull, chest, abdomen and pelvis examinations, in fluoroscopy for MCU and VCU examinations and in CT for head, chest and abdomen CT examinations. Regarding the dose quantities used for the establishment of DRLs, in CT DRLs are expressed in terms of CTDIvol and DLP while in fluoroscopy all DRLs are expressed in terms of DAP/KAP. However, in radiography there is a variety of dose quantities used with the main terms being ESD, DAP, ESAK and KAP. There is even discrepancy in the dose units that different studies use for the setting of their DRLs. As the new technological equipment has the ability to report the dose of each X-ray examination, it is suggested that the manufacturers of new radiological equipment should find a homogeneous way to report the dose in terms of dose quantity and units. As most of the equipment offer the availability to present the KAP value, RP 185 [14] suggests that this dose quantity should be used as primary DRL quantity for radiography, as well as for fluoroscopy. This should be taken into consideration in future studies. ESAK in radiography as well as fluoroscopy time, number of frames and air kerma at patient entrance reference point in fluoroscopy can be used as additional quantities for DRL setting.

The grouping of patients seems to be the main problem as it is completely different between countries and clinics. This fact along with the different quantities used, especially in radiography, between different studies and countries makes the comparison of dose data infeasible. The countries should be encouraged to follow the new European and international guidelines. It is acknowledged that there is a variety of size in children of the same age, which influences the dose levels [18, 22, 74]. Therefore weight is proposed as a more suitable diameter for grouping the patients in body examinations, instead of age [14, 15, 44, 71]. Occasionnally the size of the patient can be also considered, e.g. in CT the effective diameter which is discussed in ICRP 135 [15]. On the other hand, the size of the patient's head does not change dramatically between children of the same age and, as a consequence, age grouping should be used for head examinations [15, 44]. Regarding preterm children there is only one study that has focused solely on infants and has categorised preterm children in different groups based on weight [22]. In this study the results showed that the doses of extremely low weight infants (<1 kg) were much lower than the doses of low and normal weight infants. This could signify that the categorisation of preterm children is important. On the other hand, this can be achieved only in neonatal centres and the collection of a large sample might be difficult. However healthcare professionals in neonatal centres should be encouraged to establish DRLs by categorising the infants by weight. Weight is also appropriate for establishing DRLs for paediatric cardiac interventional procedures [36]. A useful DRL parameter, when there are differences in children's weight of the same age group, is proposed in IR: the parameter DAP/body weight [36, 38]. In the literature review, even though the majority of studies acknowledge the fact that grouping by weight seems to be more suitable in terms of dosimetry, they still set their DRLs according to age as the patient's age is practically more easily obtainable [30]. The harmonisation regarding the classification of patients is very important, as currently the difference in categorisations between different studies and countries does not permit the comparison of dose data [29, 34, 37, 44, 54].

One important issue in establishing DRLs in paediatric CT is the size of the phantom used for dose calculations. The choice of phantom size is important, as it can be confusing about the appropriate CTDIvol value in paediatric patients [58]. Some countries use the 16 cm diameter phantom for their calculations [57, 58, 64, 70] while others use the 32 cm diameter phantom [73]. There is a number of studies that have used the 16 cm phantom for head examinations and the 32 cm phantom for body examinations [62, 65, 72]. In Greece, for the proposal of DRLs on pelvic examinations, more than two phantoms were used, more specifically phantoms of 8 cm, 10 cm, 12 cm and 16 cm diameter [53]. When comparing DRLs between different countries it is important that the size of the phantom is considered. This issue may get more complicated if measurements aren't performed and DRL determination is based on doses estimated by the scanner, thus relying on the phantom used by the manufacturer.

Most of the studies have been realised before the European and international recommendations and therefore they have followed different methodologies. The existing DRLs should be renewed by following the proposed methodologies. This will enable the comparison of the DRL values between different centres and countries [30]. There seem to be large differences, not only between the methodologies of different countries, but even between protocols of the participating hospitals of one single study [23, 52]. The use of standardised paediatric protocols is very important in order to decrease the differences between doses and facilitate the dose comparison with literature data [54, 56, 59, 64]. It is important however to note that in our literature review we identified some recent studies that were published most probably after ICRP 135 and RP 185. The majority of these studies were in the field of IR and IC [34, 40-42], a fact that might signify that the need for establishing DRLs in paediatric interventional procedures -as clearly stated by the European guidelines- has been taken into consideration. The DRL quantity used was in accordance with the guidelines. All of these studies used DAP as a DRL quantity and two countries (Greece and France) also recorded fluoroscopy time and number of frames. In addition, according to the RP185 report, though the weight/size is a more appropriate parameter for patient grouping in body examinations, as currently most of the National DRLs have been reported in terms of patient age in all the three medical fields, it is acknowledged that there will be a "transition period where age will still be used until data from the recommended weight based patient dose surveys become available. In the transition period, age can be used as an additional parameter for patient grouping and for the purpose of comparison between the new proposed, weight-based DRLs with earlier values (trend analysis) [14]". From the new studies, this fact is evident, as age grouping was still used in some of these studies [40, 42]. Costa Rica classified the patients by age and weight [40], while in Italy local DRLS were set [33] by weight groups and were compared to previous data (reported on age groups).

The use of DRLs is very important as they can indicate wrong practices. A systematic excess of DRLs can be due to a dysfunction of the equipment or to inappropriate examination settings [18, 19, 23]. Inappropriate collimation in infants or the use of inappropriate protocols can increase the dose [18, 19, 23]. In addition, lack of knowledge of the radiation protection rules and untrained staff are potential reasons for high doses attributed to patients [18, 19]. Today a large number of paediatric examinations are undertaken in general hospitals, where no paediatric protocols are available, the technologists have low paediatric imaging expertise and are not trained or qualified for paediatric examinations [22, 26, 30, 33, 61, 65, 66, 70]. The use of antiscatter grid is a parameter that also affects the dose to the patient [25]. It is mentioned that grid should not be used for young patients of small size and age [35]. However, in paediatric radiography grid is often used [18] and therefore DRLs are proposed to be established separately for grid and no grid examinations [26, 76].

On the other hand, reported values much lower than DRLs might indicate poor image quality with low diagnostic value. The ALARA principle demands that the doses of the patients should be "As Low As Reasonably Achievable". However, doses reaching the 25th percentile of the distribution – or even lower - should be further investigated to ensure adequate image quality. In the literature collected for this review, it was emphasised that image quality in the examinations with dose values below the 10th or the 25th percentile of dose distribution should be interrogated [22, 60, 76]. Taking into account all the above-mentioned facts, one has to note that in order to establish reliable DRLs and enhance the protocol optimisation procedure, a strong collaboration among the physician, medical physicist and radiographer must be created. The radiographer must perform the examination under the consultation of the medical physicist and keep all the necessary data (age, weigh, radiation dose) from each examination to facilitate the establishment of DRLs. On the other hand, the physician is the one who will help the optimisation procedure by giving advice about the diagnostic quality of the examinations. If a close collaboration is not established between those healthcare professionals, the setting of reliable DRLs is almost infeasible. In addition, nowadays, new software tools are available, such as dose management systems. These tools can collect all the necessary data (recorded by the radiographer during the examination), perform categorisation of the examinations and statistical analysis of the dose data. They can even compare the dose of each examination to the values of National DRLs for each examination. This software can be a helpful tool in the procedure of data collection and analysis for the establishment of DRLs.

Further studies on reporting dose data and establishing DRLs in paediatric imaging need to be realised. Many studies are quite old and the advance of technology along with the emerge of new modern techniques necessitate the update of the existing DRL values [43, 64, 75]. In the report of UK about national CT DRLs, large variations were noted in the doses of similar procedures between different healthcare centres. This was an indication about the importance of the continuing optimisation of protocols following the advances and improved technology in relation to the type of examination and the clinical indication [45]. Finally one important issue that should be considered is the optimisation based on clinical indication [16]. It is currently acknowledged, especially in CT, that there are different protocols used for the scanning of the same anatomical region depending on clinical indication. These protocols include different exposure parameters. Therefore the dose received by the patient can be very different between these protocols even if it concerns the same anatomical region. This is also happening in the field of IR and IC, where doses between patients exposed to the same anatomical area present large variations due to different clinical indications. This has highlighted the necessity of establishing DRLs based on clinical indication instead of anatomical location. According to the results of a project launched by the European Commission called "European Study on Clinical Diagnostic Reference Levels for X-ray Medical imaging-EUCLID" there are some countries that have already established DRLs based on clinical indication for adults and some countries that are planning to establish in the near future [15]. Regarding paediatric examinations, there are only two countries that have taken into consideration clinical indication for setting their DRLs in CT: UK [45] and Finland [43]. As the new guidelines discuss the establishment of DRLs based on clinical indication [14], further studies should be carried out in order to set paediatric clinical DRLs. It must be emphasised that clinical image quality under specific clinical indications is assessed as part of the protocol optimisation procedure. As already discussed above, this can be achieved only with the establishment of a strong collaboration between the physician, the medical physicist and the radiographer. This will be a basic step for the establishment of reliable clinical DRLs.

Conclusions

Currently the data concerning the paediatric DRLs in the literature are limited. There are countries with no set DRLs or lack of DRL values for some age/weight groups. DRLs should be established in countries that have not been established yet. In addition, as most of the studies have been performed before the recent recommendations, the different methodologies used for obtaining the dose data cause difficulties in comparing the dose values between different countries. The manufacturers should facilitate this procedure by finding a homogeneous way to report the dose for each examination in terms of dose quantities and units. Furthermore, the existing DRLs should be updated by taking into consideration the modern technology and practices and by following the existing guidelines. A strong collaboration between the physician, medical physicist and radiographer will strongly facilitate this procedure. The few studies that have been published after the European guidelines refer mainly to IR and IC and their DRLs are established in accordance with the instructions of the reports. If future studies also follow the guidelines, then the comparison of the paediatric DRL data on national and even European level will be harmonised. The importance of establishing DRLs based on clinical indication has been noted in the official recommendations, therefore the setting of paediatric clinical DRLs is necessary. R

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Table 1. European DRLs (3rd quartile) in paediatric Radiography

COUNTRY	TYPE OF DRL	EXAMINATION	AGE/WEIGHT GROUP	DRL QUANTITY	DRL
Austria, 2010 [16]	National	Skull AP/PA	Newborn/1 yr/5 yrs/10 yrs/15 yrs	IAK (mGy)	0.35 / 0.6 / 0.75 / 0.9 / 1
			Newborn / 1yr / 5 yrs / 10 yrs/ 15 yrs	KAP (mGy*cm²)	150 / 250 / 350/ 450 /500
		Skull LAT	Newborn / 1yr / 5 yrs / 10 yrs/ 15 yrs	IAK (mGy)	0.3 / 0.4 / 0.5 / 0.55 / 0.6
			Newborn / 1yr / 5 yrs / 10 yrs/ 15 yrs	KAP (mGy*cm²)	100 / 200/ 250/ 300/ 350
		Abdomen	Newborn / 1yr / 5 yrs / 10 yrs/ 15 yrs	IAK (m Gy)	0.2 / 0.3 / 0.4 / 0.75 / 1
			Newborn / 1yr / 5 yrs / 10 yrs/ 15 yrs	KAP (mGy*cm²)	60 / 90/ 200 / 500/ 700
		Chest AP/PA	Newborn / 1yr / 5 yrs / 10 yrs/ 15 yrs	IAK (mGy)	0.05 / 0.06 / 0.07 / 0.09 / 0.11
			Newborn / 1yr / 5 yrs / 10 yrs / 15 yrs	KAP (mGy*cm²)	17 / 23 / 26 / 37 / 73
Finland, 2007 [17]	National	Chest	Curve ESD/DAP – patient thickness		

COUNTRY	TYPE OF DRL	EXAMINATION	AGE/WEIGHT GROUP	DRL QUANTITY	DRL
France, 2013 [18]	National	Chest AP	Newborn / 10kg (1 yr) / 20 kg (5 yrs)	ESD (mGy)	0.08 / 0.08 / 0.1
			Newborn / 10kg (1 yr) / 20 kg (5 yrs)	DAP (mGy*cm²)	10/ 30 / 50
		Chest PA	30 kg (10 yrs)	ESD (mGy) / DAP (mGy*cm²)	0.2 / 70
		Chest LAT	20 kg / 30 kg	ESD (mGy)	0.2 / 0.3
			20 kg / 30 kg	DAP (mGy*cm²)	60 / 80
		Pelvis	10 kg / 20 kg / 30 kg	ESD (mGy)	0.2 / 0.9 / 1.5
			10 kg / 20 kg / 30 kg	DAP (mGy*cm²)	40 / 200 / 400
		Abdomen	20kg / 30 kg	ESD (mGy)	1 / 1.5
			20kg / 30 kg	DAP (mGy*cm²)	350 / 700
Spain, 2015 [19]	National	Thorax PA	0 yrs / 1-5 yrs/ 6-10yrs / 11-15 yrs	DAP (mGy*cm²)	40 / 50 / 85 / 100
		Head AP	0 yrs / 1-5 yrs / 6-10yrs / 11-15 yrs	DAP (mGy*cm²)	130 / 230 / 350 / 430
		Abdomen AP	0 yrs / 1-5 yrs / 6-10yrs / 11-15 yrs	DAP (mGy*cm²)	150 / 200 / 225 / 300
		Pelvis PA	0 yrs / 1-5 yrs / 6-10yrs / 11-15 yrs	DAP (mGy*cm²)	60 / 180/ 310/ 400
Belgium, assessed in 2019 [20]	National	Thorax simple (1 acquisition)	< 1 yr / 1-<5yrs / 5-<10yrs / 10 -<15 yrs	DAP (mGy*cm²)	15 / 25/ 40 /80
		Thorax multiple (>1 acquisitions)	< 1yr/ 1-<5yrs / 5- <10yrs / 10 -<15 yrs	DAP (mGy*cm²)	30 / 50/ 100 /200
		Abdomen	< 1yr/ 1-<5yrs / 5- <10yrs / 10 -<15 yrs	DAP (mGy*cm²)	40 / 180/ 150/ 400
Ireland, 2004 [21]	National	Chest AP/PA	1 yr / 5yrs / 10 yrs / 15 yrs	ESD (mGy)	0.057 / 0.053 / 0.066/ 0.088
		Pelvis AP	1 yr / 5yrs / 10 yrs / 15 yrs	ESD (mGy)	0.265 / 0.475 / 0.807 / 0.892
		Abdomen AP	1 yr / 5yrs	ESD (mGy)	0.33 / 0.752
UK, 2004 [21]	National	Chest AP/PA	0 yrs / 1 yr / 5 yrs / 15 yrs	ESD (mGy)	0.07 / 0.09/ 0.15 /0.1
		Skull AP/LAT	5 yrs	ESD (mGy)	1.37 / 0.82
		Pelvis AP	0 yr / 10 yrs / 15 yrs	ESD (mGy)	0.21 / 0.73 / 1.32
		Abdomen AP	5 yrs / 15 yrs	ESD (mGy)	0.7 / 2.6
Belgium, 2014 [22]	National	Chest	ELWI / LWI / NWI	ESAK (mGy)	0.036 / 0.045 / 0.046
			ELWI / LWI / NWI	KAP (mGy*cm²)	4.1 / 7.2 /6.1
		Chest / Abdomen	ELWI / LWI / NWI	ESAK (mGy)	0.058

COUNTRY	TYPE OF DRL	EXAMINATION	AGE/WEIGHT GROUP	DRL QUANTITY	DRL
Germany, assessed in 2019 [23]	National	Thorax AP/PA	Premature Newborns (<3 kg) / Newborns (3-5 kg, 0-3 months)/ Infants (5-10 kg, 3-12 months)/ 1-5 yrs (10-19 kg)/ 5-10 yrs (19-32 kg)	DAP (mGy*cm^2)	0.3 / 0.5/ 1 / 2 / 3.5 3 / 5 / 10 / 20 / 35
		Thorax LAT	1-5yrs (10-19 kg)/ 5-10 yrs (19-32 kg)	DAP (mGy*cm^2)	25 / 50
		Skull AP	3 -12 months / 1-5 yrs	DAP (mGy*cm^2)	120 / 240
		Skull LAT	3 -12 months / 1-5 yrs	DAP (mGy*cm^2)	100 / 200
		Abdomen AP/PA	Newborns (3-5 kg, 0-3 months)/ Infants (5-10 kg, 3-12 months)/ 1-5 yrs (10-19 kg)/ 5-10 yrs (19-32 kg)	DAP (mGy*cm^2)	20 / 50 / 100 / 200
		Pelvis AP	1-5 yrs (10-19 kg)/ 5-10 yrs (19-32 kg)	DAP (mGy*cm^2)	120 / 250
UK, 2000 (mean values-application of adjustment factors) [74]	Local	Chest	5 yrs	ESD (mGy)	0.07
		Abdomen / pelvis	5 yrs	ESD (m Gy)	0.7
European, 1998 [24]	European	Chest AP/PA	Premature infants / 10 months / 5 yrs / 10 yrs	ESD (mGy)	37* / 67 (123)*/ 63 (68)*/ 86 (112)* 0.037 / 0.067 (0.123) / 0.063 (0.068)/ 0.086 (0.112)
		Chest LAT	5 yrs / 10 yrs	ESD (mGy)	0.125*/ 0.192*
Preliminary European, 2008 [29]	Proposes preliminary European	Chest	<1 yr / 1-2 yrs / 2-3 yrs / 3-8 yrs / 8-12 yrs/ >12 yrs	ESD (mGy)	0.131/ 0.240/ 0.143 / 0.228 / 0.434 / 0.455
			<1yr / 1-2yrs / 2-3 yrs / 4-8 yrs / 8-12 yrs	DAP (mGy*cm^2)	88 / 136 / 189 / 233 / 395
European, 2001 [30]	Proposes preliminary reference dose values	Chest AP/PA	Neonates / 1 yr/ 5 yrs/ 10 yrs	ESD (mGy)	0.05 / 0.05 / 0.07 / 0.12
		Skull AP/PA	1 yr / 5 yrs / 10 yrs / 15 yrs	ESD (mGy)	800 / 1100/ 1100 / 1100 0.8 / 1.1 / 1.1 / 1.1
		Skull LAT	1 yr / 5 yrs / 10 yrs / 15 yrs	ESD (mGy)	0.500 / 0.800 / 0.800 / 0.800
		Abdomen	1 yr / 5 yrs / 10 yrs / 15 yrs	ESD (mGy)	0.400 / 0.500 / 0.800 / 1.200
		Pelvis	1 yr / 5 yrs / 10 yrs / 15 yrs	ESD (mGy)	0.500/ 0.600/ 0.700/ 2

**Third quartile values, values in brackets correspond to DRLs for radiographs with mobile units.*

Abbreviations: DRLs: Diagnostic Reference Levels, yrs: years, AP: anterior-Posterior, PA: Posterior-Anterior, LAT: Lateral, ELWI: extremely low-weight infants (<1kgr), LWI: Low weight Infants (1-2kgr), NWI: Normal weight infants (>2kgr), ESD: Entrance Surface Dose, DAP: Dose Area Product, IAK: Incident Air Kerma, KAP: Kerma Area Product, ESAK: Entrance surface Air Kerma.

Table 2. Non-European DRLs in paediatric Radiography

COUNTRY	TYPE OF DRL	EXAMINATION	AGE/WEIGHT GROUP	DRL QUANTITY	DRL
Kenya, 2013 [25]	Local, mean values	Chest AP (non grid)	<1 mo, 1-12 mo / 13-60 mo / 61-120 mo / 121-180 mo	ESAK (mGy)	0.05 / 0.05 / 0.06 / 0.07 / 0.09
		Chest LAT (non grid)	1-12 mo / 13-60 mo / 61-120 mo	ESAK (mGy)	0.09 / 0.11 / 0.13
		Chest PA (erect-grid)	13-60 mo / 61-120 mo / 121-180 mo	ESAK (mGy)	0.12 / 0.14 / 0.15
		Chest LAT (erect-grid)	13-60 mo / 61-120 mo/ 121-180 mo	ESAK (mGy)	0.26 / 0.31 / 0.32
		Skull AP (non grid)	1-12mo / 13-60 mo / 61-120 mo/ 121-180 mo	ESAK (mGy)	0.17 / 0.21 / 0.22 / 0.3
		Skull AP (Grid)	<1 mo, 1-12 mo/ 13-60 mo/ 61-120 mo/ 121-180 mo	ESAK (mGy)	0.21 / 0.22 / 0.3/ 0.36 / 0.41
		Skull LAT (non-grid)	1-12 mo / 13-60 mo/ 61-120 mo/ 121-180 mo	ESAK (mGy)	0.14 / 0.17/ 0.2/ 0.26
		Skull LAT (grid)	<1 mo, 1-12 mo/ 13-60 mo/ 61-120 mo/ 121-180 mo	ESAK (mGy)	0.2 / 0.2 / 0.24 / 0.27 / 0.24
		Skull OM (non-grid)	13-60 mo/ 61-120 mo/ 121-180 mo	ESAK (mGy)	0.19 / 0.32 / 0.42
		Skull Townes (non-grid)	13-60 mo	ESAK (mGy)	0.2
		Abdomen AP (non-grid)	<1 mo, 1-12 mo/ 13-60 mo/ 61-120 mo / 121-180 mo	ESAK (mGy)	0.07 / 0.08 / 0.13 / 0.17 / 0.2
		Abdomen AP (grid)	<1 mo, 1-12 mo/ 13-60 mo / 61-120 mo / 121-180 mo	ESAK (mGy)	0.22 / 0.2 / 0.28 / 0.37 / 0.49
		Abdomen decubitus (non-grid)	<1 mo, 1-12 mo/ 13-60 mo/ 61-120 mo/ 121-180 mo	ESAK (mGy)	0.09 / 0.09 / 0.17 / 0.31 / 0.41
		Pelvis AP (non-grid)	1-12 mo / 13-60 mo/ 61-120 mo/ 121-18 0mo	ESAK (mGy)	0.1 / 0.12 / 0.25 / 0.36
		Pelvis AP (grid)	1-12 mo / 13-60 mo / 61-120 mo/ 121-180 mo	ESAK (mGy)	0.13 / 0.15 / 0.28 / 0.33
India, 2011 [26]	Suggest DRLs, 3rd quartile	Chest AP/PA	5-9 yrs	ESAK (mGy)	0.2
		Chest LAT	5-9 yrs	ESAK (mGy)	0.3
		Skull AP / Skull LAT	5-9 yrs	ESAK (mGy)	0.6 / 0.5
		Abdomen AP	5-9 yrs	ESAK (mGy)	0.5
		Pelvis AP	5-9 yrs	ESAK (mGy)	0.7
America, 2018 [27]	National, 3rd quartile	Chest PA non-grid/grid	-	ESAK (mGy)	0.06 / 0.12
Brazil, 2009 [28]	Indication for DRLs, 3rd quartile	Chest AP / Chest PA / Chest LAT	<15 yrs	ESD (mGy)	0.2 / 0.35 / 0.56
		Skull AP/ Skull LAT	<15 yrs	ESD (mGy)	1.06 / 0.83

Abbreviations: DRLs: Diagnostic Reference Levels, yrs: years, mo: months AP: anterior-Posterior, PA: Posterior-Anterior, LAT: Lateral, ESD: Entrance Surface Dose, OM: occipitomental, ESAK: Entrance Surface Air Kerma.

Table 3. European paediatric DRLs (3rd quartile) for MCU/MCUG , VCUG and Barium fluoroscopic examinations in terms of DAP (Gy x cm²)

COUNTRY	TYPE OF DRL	EXAMINATION	AGE/WEIGHT GROUP	DRL
Spain, 2015 [19]	National	MCU	0 yrs / 1-5 yrs / 6-10yrs / 11-15 yrs	0.5 / 0.75 / 0.9 / 1.45
UK, 2012 [31]	National	MCU	0 yrs / 1 yr / 5 yrs / 10 yrs / 15 yrs	0.12/ 0.32 / 0.34 / 0.44 / 0.89
		Barium meal	0 yrs / 1 yr / 5 yrs / 10 yrs / 15 yrs	0.13 / 0.21 / 0.24 / 0.65 / 2
		Barium swallow	0 yrs / 1 yr / 5 yrs / 10 yrs / 15 yrs	0.21 / 0.39 / 0.46 / 1.8/ 3
Germany, assessed in 2019 [23]	National	MCU	Newborns (3-5 kg, 0-3 months)/ Infants (5-10 kg, 3-12 months)/ 1-5 yrs (10-19 kg)/ 5-10 yrs (19-32 kg)	0.05 / 0.1 / 0.18 / 0.3
UK, 2006 [34]	Local	MCUG	0-12 mo / 1-7 yrs / >8 yrs	0.05 / 0.1 / 0.42
		Barium follow through	0-12 mo / 1-7 yrs / >8 yrs	0.18 / 0.14 /0.39
		Barium enema	0-12 mo / 1-7 yrs/ >8 yrs	0.16/ 0.09/ 0.49*
Australia, 2016 [32]	Local	MCU	0 - <2 yrs / 2 - <6yrs / 6 - <10 yrs / 10 - <18 yrs	0.23 / 0.41/ 0.91 / 2.30
		Barium Swallow / Meal	0 - <1 yr / 1 - < 6yrs/ 6 - <10 yrs / 10 - < 18 yrs	0.43 / 0.77 / 1.33 / 2.85
		Barium enema	0 - < 8yrs / 8 - < 18 yrs	0.21 / 4.03
		Barium follow through	0 - < 4yrs / 4 - < 12 yrs / 12 - <18 yrs	0.47 / 1.44 / 2.96
Italy, 2017 [33]	Local	MCU/VCUG	< 10 kg / 10 - <15kg / 15 - <30kg / 30 - < 60 kg	0.07 / 0.10 / 0.24 / 0.57
		Barium Meal	< 10 kg / 10 - <15kg / 15 - < 30kg/	0.09 / 0.32/ 0.28
		Barium Enema	< 10 kg / 10 - <15kg	0.08 / 0.26
		Barium Swallow	10 - <15kg	0.15
		Barium Follow through	10 - <15kg / 15 - <30 kg	0.19 / 0.43
Preliminary European, 2008 [29]	Preliminary European	VCUG	< 1yr/ 2-3 yrs / 8-12 yrs / >12 yrs	0.187 / 0.533 / 1.322 / 3.165
Preliminary European, 2001 [30]	Proposes preliminary reference dose values	MCU	Neonates / 1yr / 5 yrs/ 10 yrs	0.6 / 0.9 / 1.2 / 2.4

* *Children with barium and contrast enema included.*
Abbreviations: DRLs: Diagnostic Reference Levels, MCU/MCUG Micturating Cystourethrography, VCUG: Voiding Cystourethrogram, yrs: years, mo: months, DAP: Dose Area Product.

Table 4: Paediatric DRLs in diagnostic and therapeutic procedures of Interventional Radiology (IR) and Interventional Cardiology (IC).

COUNTRY	EXAMINATION	AGE/WEIGHT GROUP	DRL QUANTITY	DRL
Chile Local DRLs, 3rd quartile 2015 [35]	Diagnostic IC procedures	< 1 yr / 1-<5 yrs / 5-<10 yrs / 10-<16 yrs	DAP [Gy x cm²]	1.17 / 1.74 / 2.83 / 7.34
	Therapeutic IC procedures	<1 yr / 1-<5 yrs / 5-<10 yrs / 10-<16 yrs	DAP [Gy x cm²]	1.11 / 1.9 / 3.22 / 8.68
	Diagnostic/Therapeutic IC procedures	-	DAP/BW [(Gy x cm²)/kg]	0.17

COUNTRY	EXAMINATION	AGE/WEIGHT GROUP	DRL QUANTITY	DRL
France Local DRLs, mean values 2014 [36]	Diagnostic IC procedures	≤6.5 kg / 6.5–14.5 kg / 14.5–25.5 kg / 25.5–43.5 kg / >43.5 kg	DAP [Gy x cm^2] FT (min) NF	2.7 / 2.9 / 3.9 / 6.3 / 16.4 9.4 / 7.1 / 6.1 / 6.1 / 9.2 1.032 / 731 / 750 / 676 / 735
	Balloon valvuloplasty	≤6.5 kg / 6.5–14.5 kg / 14.5–25.5 kg / 25.5–43.5 kg / >43.5 kg	DAP [Gy x cm^2] FT (min) NF	1.4 / 1.7 / 12.8/ 12.1 / 46.7 9.1 / 5.9 / 17.1 / 8.3 / 12.7 280 / 308 / 1664 / 1155 / 2565
	Angioplasty	≤6.5 kg / 6.5–14.5 kg / 14.5–25.5 kg / 25.5–43.5 kg / >43.5 kg	DAP [Gy x cm^2] FT (min) NF	3.4 / 8.4 / 11 / 15.9 / 61.3 12.6 / 14.5 / 13.5 / 13.9 / 15.8 844 / 1259 / 957 / 1375 / 1804
	PDA	≤6.5 kg / 6.5–14.5 kg / 14.5–25.5 kg / 25.5–43.5 kg / >43.5 kg	DAP [Gy x cm^2] FT (min) NF	2.8 / 1.9 / 3.1 / 5.3 / 11.5 7.5 / 3.4 / 4.1 / 3.9 / 2.5 570.8 / 340 / 258 / 342 / 248
	ASD	6.5–14.5 kg / 14.5–25.5 kg / 25.5–43.5 kg / >43.5 kg	DAP [Gy x cm^2] FT (min) NF	1.7 / 0.8 / 2 / 4.5 4.7 / 1.8 / 4.4 / 3.8 470.5 / 33 / 34.4 / 31.3 /
	Electrophysiology	≤6.5 kg / 6.5–14.5 kg / 14.5–25.5 kg / 25.5–43.5 kg / >43.5 kg	DAP [Gy x cm^2] FT (min) NF	1.5 / 4.8 / 2.4 / 6.1 / 8.6 7.3 / 16.5 /6.2 / 14 / 14.9 - / - / 207 / 353 / 317
Germany Local DRLs, 3rd quartile/90% percentile 2007 [37]	Diagnostic IC procedures	-	DAP/BW [Gy x cm^2)/kg] 75% - 90% percentile	0.5 - 0.808
	Therapeutic IC Procedures	-	DAP/BW [Gy x cm^2)/kg] 75% - 90% percentile	0.656 -1.156
	Others		DAP/BW [Gy x cm^2)/kg] 75% - 90% percentile	0.117 – 0.300
UK Local DRLs, Mean values, 2013 [38]	Diagnostic+ Therapeutic IC procedures	Newborns - <1 yr / 1 - <5 yrs / 5 - <10 yrs / 10 - <15 yrs / >15 yrs	DAP [Gy x cm^2]	1.9 / 4.21 / 5.82 / 12.89 /17.76
Greece Local DRLs, Median values, 2018 [39]	Diagnostic IC procedures	<1 yr / 1-<5 yrs / 5-<10 yrs / 10-<16 yrs	P_{KA} [Gy x cm^2]	2 / 3 / 6.6 / 12.4
	Therapeutic IC procedures	<1 yr / 1-<5 yrs / 5-<10 yrs / 10-<16 yrs	P_{KA} [Gy x cm^2]	1.5 / 3.2 / 7.8 / 14.6
	Total	<1 yr / 1-<5 yrs / 5-<10 yrs / 10-<16 yrs	P_{KA} [Gy x cm^2]	2 / 3 / 7 / 14
Costa Rica National DRLs, 3rd quartile 2018 [40]	IC procedures	<5 kg / 5-<15 kg / 15-<30 kg / 30-<50 kg / 50-<80 kg	P_{KA} [Gy x cm^2]	1 / 2.3 / 4.7 / 8.4 / 49.6
		<1 yr / 1-<5 yrs / 5-<10 yrs / 10-<16 yrs	P_{KA} [Gy x cm^2]	1.79 / 2.49 / 4.19 / 23

COUNTRY	EXAMINATION	AGE/WEIGHT GROUP	DRL QUANTITY	DRL
France Local DRLs, 3rd quartile, 2017 [41]	Cerebral DSA	<2yrs / 2-7 yrs / 8-12 yrs / 13-18 yrs	DAP [Gy x cm^2] K (mGy) T (min) N	4 / 18 / 12 /32 41 / 51 / 62 / 58 11 / 5 / 6 / 5 211 / 209 / 246 / 194
	bAVM embolisation	<2yrs / 2-7 yrs / 8-12 yrs / 13-18 yrs	DAP [Gy x cm^2] K (mGy) T (min) N	33 / 70 / 105 / 88 188 /165 / 380 / 538 41 / 20 / 32 / 26 284 / 308 / 397 /505
	Head & Neck SVM sclerotherapy	<2yrs / 2-7 yrs / 8-12 yrs / 13-18 yrs	DAP [Gy x cm^2] K (mGy) T (min) N	0.35 / 0.79 / 0.49 / 0.248 5 / 4 / 3 / 5 1 / 1/ 1 / 2 38 / 25 / 33 / 54

Abbreviations: DRL: Diagnostic Reference Levels, yrs: years, IC: Interventional Cardiology, DAP: Dose Area Product, P_{KA}: Kerma Area Product, BW: Body weight, PDA: Patent Ductus Arteriosus, ASD: Atrial Septal defect, DSA: Digital Subtraction Angiography, AVM: Anteriovenous malformation embolization, SVM: Superficial vascular formation, FT: fluoroscopy time, NF: number of cine frames, K; air kerma at the reference point.

Table 5: European National DRLs (3rd quartiles) in paediatric Computed Tomography

COUNTRY	EXAMINATION	AGE/WEIGHT GROUP	DRL - CTDIvol (mGy)	DRL - DLP (mGy*cm)
Finland, 2015 [43]	Head (Routine CT)	<1 yr / 1-5 yrs / 5-10 yrs / 10-15 yrs	23 / 25 / 29 / 35	330 / 370 / 460 / 560
	Chest	DRL curve of CTDIvol/DLP as a function of patient weight		
France, 2013 [18]	Brain	1 yr-10 kg / 5 yrs-20 kg / 10 yrs-30 kg	30 / 40 / 50	420 / 600 / 900
	Chest	1 yr-10 kg / 5 yrs-20 kg / 10 yrs-30 kg	3 / 4 / 5	30 / 65 / 140
	Abdomen/Pelvis	1 yr-10 kg / 5 yrs-20 kg / 10 yrs-30 kg	4 / 5 / 7	80 / 120 / 245
UK, 2006/2014 [44, 45]	Head – Posterior Fossa	0-1 yrs / 5 yrs / 10 yrs	35 / 50 / 65	-
	Head Cerebrum	0-1 yrs / 5 yrs / 10 yrs	30 / 45 / 50	-
	Head Whole Exam	0-1 yrs / 5 yrs / 10 yrs	25 / 40 / 60	350 / 650 / 860
	Chest	0-1 yrs / 5 yrs / 10 yrs	12 / 13 / 20	200 / 230 / 370
Spain, 2015 [19]	Head	0 yrs / 1-5 yrs / 6–10 yrs / 11–15 yrs	-	250 /340 / 450 / 650
	Chest	0 yrs / 1-5 yrs / 6–10 yrs / 11–15 yrs	-	46 / 82 / 125 / 200
	Abdomen	0 yrs / 1-5 yrs / 6–10 yrs / 11–15 yrs	-	95 / 150 / 190 / 340
Ireland, 2013-2014 [47]	Head	<1 yr / 1-5 yrs / 5-10 yrs / 10-15 yrs	-	333 / 491 / 608 / 719
	Chest	<1 yr / 1-5 yrs / 5-10 yrs / 10-15 yrs	-	73 / 106 / 153 / 237
	Abdomen/Pelvis	Newborns / 1-4 yrs / 5-9 yrs / 10-15 yrs	-	130 / 160 / 230 /400

Belgium, assessed in 2019 [20]	Head	< 1 yrs / 1-<5 yrs / 5-<10 yrs / 10-<15 yrs	22 / 30 / 40 / 45	420 / 540 / 660 / 780
	Thorax	1-<5 yrs / 5-<10 yrs / 10-<15 yrs	1.5 / 2 / 3.5	35 / 55 / 130
	Abdomen	1-<5 yrs / 5-<10 yrs / 10-<15 yrs	- / 5 / 7.5	110 / 220 / 330
	Sinus	1 -< 5 yrs / 5 -< 10 yrs / 10 -<15 yrs	- / - / 4 / 6	- / 50 / 65 / 80
Switzerland, 2018 [48]	Brain	Newborns / <1 yr / 1-5 yrs / 6-10 yrs / 11-15 yrs / >15 yrs	27 / 33/ 40 / 50 / 60 / 60	290 / 390 / 520 / 710 / 920 / 1100
	Thorax	Newborns / <1yr / 1-5 yrs / 6-10 yrs / 11-15 yrs / >15 yrs	1 / 1.7 / 2.7 / 4.3 / 6.8 / 10	12 / 28 / 55 / 105 / 205 / 345
	Abdomen	Newborns / <1 yr / 1-5 yrs / 6-10 yrs / 11-15 yrs / >15 yrs	1.5 / 2.5 / 4 / 6.5 / 10 / 15	27 / 70 / 125 / 240 / 500 / 980
	Neuropaediatric Brain	<1.5 yrs / 1.5 – 5.5 yrs / 5.5 – 10.5 yrs/ 10.5 – 16 yrs	25 / 30 / 35 /40	350 / 420 / 540 / 670
Germany, assessed in 2019 [23]	Head	Infant (3-12 months) / 1-5 yrs / 5-10 yrs / 10-15 yrs	30 / 35 / 50 / 55	300 / 450 / 650 /800
	Thorax	Newborns (3-5 kg, 0-3 months) / Infants (5-10 kg, 3-12 months)/ 1-5 yrs (10-19 kg)/ 5-10 yrs (19-32 kg) 10–15 yrs (32-56 kg)	1 / 1.7 / 2.6 / 4 / 6.5	15 / 25 / 55 / 110 / 200
	Abdomen	5-10 yrs (19-32 kg) 10–15 yrs (32-56 kg)	5 / 7	185 / 310

Abbreviations: DRLs: Diagnostic Reference Levels, yrs: years, CTDIvol: Volume CT Dose Index, DLP: Dose length Product.

Table 6. Non-European DRLs in paediatric Computed Tomography

COUNTRY	TYPE OF DRL	EXAMINATION	AGE/WEIGHT GROUP	DRL - CTDIvol (mGy)	DRL – DLP (mGy*cm)
International, 2015 [70]	International 3rd quartile	Head	≤1 / 1–5 yrs / 5–10 yrs / 10–15 yrs	26 / 36 / 43 / 53	440 / 540 / 690 / 840
		Chest	≤1 / 1–5 yrs / 5–10 yrs / 10–15 yrs	5.2 / 6 / 6.8 / 7.3	130 / 140 / 170 / 300
		Abdomen	≤1 / 1–5 yrs / 5–10 yrs / 10–15 yrs	5.2 / 7 / 7.8 / 9.8	130 / 250 / 310 / 460
US, 2011-2/2018 [27, 56, 57]	National 3rd quartile	Head	1/5 yrs	35 / 40	-
		Abdomen / pelvis	5 yrs	7.5 (15)*	-
Australia, 2016 [60]	National 3rd quartile	Head	0-4 yrs / 5-14 yrs	30 / 35	470 / 600
		Chest	0-4 yrs / 5-14 yrs	2 / 5	60 / 110
		Abdopelvis	0-4 yrs / 5-14 yrs	7 / 10	170 / 390
Kenya, 2016 [67]	National 3rd quartile	Brain	0-1 yr / 2-5 yrs / 6-10 yrs / 11-15 yrs	38 / 50 / - / 55	1005 / 1395 / - /1608
		Chest	2-5yrs / 11-15 yrs	11 /11	215 / 453
		Abdomen	3-5 yrs	11	765

Australia, 2016 [58]	Local Mean values	Brain	0–6 mo / 6 mo-3 yrs / 3–6 yrs / 6–10 yrs / > 10 yrs	18 / 20 / 30 / 40 / 45	250 / 300 / 450 / 650 / 700
		Chest	< 5 yrs / 5–10 yrs / >10 yrs	2 (3)* / 5 (11)* / 12 (23)*	50 (100)* / 150 (300)* / 400 (800)*
		Abdomen/Pelvis	<5 yrs / 5–10 yrs / >10 yrs	2 (4)* / 5 (10)* / 8 (15)*	100 (150)* / 200 (400)* / 350 (750)*
Japan, 2012 [59]	Local 25th percentile/75th percentile	Head	<1 yr / 1–7 yrs / 8–12 yrs / 13-19 yrs	-	25th percentile: 270 / 470 / 590 / 730 75th percentile: 820 /1000 / 1040 / 1120
Syria, 2010 [61]	Recommends National DRLs 3rd quartile	Head	-	50 (CTDIw)	500
		Chest / Chest High resolution	-	30 (CTDIw) / 40 (CTDIw)	350 / 175
		Abdomen / Pelvis	-	35 (CTDIw) / 40 (CTDIw)	525 / 550
Korea, 2017 [62]	Local 3rd quartile	Brain	0 yrs / 1 yr / 2-5 yrs / 6-10 yrs / 11-17 yrs	18 / 23 / 26 / 31 / 36	260 / 350 / 420 / 500 / 620
		Chest	0 yrs / 1 yr / 2-5 yrs / 6-10 yrs / 11-17 yrs	2 / 3 / 4 / 6 / 8	50 / 80 / 100 / 170 / 340
		Abdomen	0 yrs / 1 yr / 2-5 yrs / 6-10 yrs / 11-17yrs	3 / 4 / 5 / 6 / 9	70 / 80 / 200 / 300 / 500
Thailand, 2012 [63]	Preliminary National survey 3rd quartile	Brain	<1 yr/ 1 - <5 yrs / 5 - <10 yrs / 10 - <15 yrs	25 / 30 / 40 / 45	400 / 570 / 610 / 800
		Chest	<1 yr/ 1 - <5 yrs / 5 - <10 yrs / 10 - <15 yrs	4.5 / 5.7 / 10 / 15.6	80 / 140 / 305 / 470
		Abdomen	<1 yr/ 1 - < 5 yrs / 5 - <10 yrs / 10 - < 15 yrs	8.5 / 9 / 14 / 17	190// 275 / 560 / 765
Australia-Saoudi Arabia, 2012 [64]	Local 3rd quartile	Head	3-6 yrs	-	383.4
		Chest	3-6 yrs	-	70.7
		Abdomen/Pelvis	3-6 yrs	-	83.4
Australia, 2016 [60]	Local 3rd quartile	Head axial	0 -0.5 yrs / 0.5 – 1.5 yrs/ 1.5 – 3 yrs / 3 – 6 yrs/ 6 – 12 yrs / 12 -18 yrs	18 / 20 / 22/ 26 / 32 /38	231 /275 / 303 / 370 / 452 / 566
		Head Helical	0 -0.5 yrs / 0.5 – 1.5 yrs / 1.5 – 3 yrs / 3 – 6 yrs / 6 – 12 yrs / 12 -18 yrs	16 / 19 / 23 / 25 /2 7 /3 7	241 / 331 / 412 / 439 / 479 / 680
		Head [combined axial and helical]	0 -0.5 yrs / 0.5 – 1.5 yrs/ 1.5 – 3 yrs / 3 – 6 yrs/ 6 – 12 yrs / 12 -18 yrs	17 / 19 / 23 / 26 / 30 / 38	232 / 283 / 332 / 396 / 467 / 596
		Chest - abdomen	0-7 kg / 7-11 kg / 11-22 kg / 22-40 kg / 40-55 kg / 55-80 kg / >80 kg	2 / 3 / 2 / 3 / 5 / 6 / 10	38 / 77 / 43 / 80 / 153 / 223 / 331
		Chest –abdomen -pelvis	0-7 kg / 7-11 kg / 11-22 kg / 22-40 kg / 40-55 kg / 55-80 kg / >80 kg	4 / - / 2 / 4 / 7 / 7 / 12	126 / - / 91 / 221 / 459 / 461 / 828
		Upper Abdomen	0-7 kg / 7-11 kg / 11-22 kg / 22-40 kg / 40-55 kg / 55-80 kg / >80 kg	4 / 8/ 4 / 4 / 5 / 6 / 24	44 / 155 / 88 / 88 / 146 / 203 / 735
		Abdomen-pelvis	0-7 kg / 7-11 kg / 11-22 kg / 22-40 kg / 40-55 kg / 55-80 kg / >80 kg	3 / 4 /3/ 5 / 6/ 8 / 9	61 / 87 / 80 / 189 / 289 / 375 / 462
		Pelvis examinations	0-7 kg / 7-11 kg / 11-22 kg / 22-40 kg / 40-55 kg / 55-80 kg / >80 kg	11 / 12 / 11/ 13 /13 / 21 /-	83 / 109 / 102 / 164 / 164 / 330 /-

Australia, 2010 [69]	Local 3rd quartile	Brain axial	0-9 kg / 10–19 kg/ >19 kg	-	75 / 80 / 260
		Brain helical	0-9 kg / 10–19 kg/ >19 kg	-	115/ 185 / 370
		Chest	0-10 kg / 11-25 kg / 26-40 kg / 41-60 kg/ 61-75 kg / >75 kg	-	35(70) / 47.5(95)/ 90(180) / 180(360) / 280(560) / 470(940)*
		Chest High resolution	0-10 kg / 11-25 kg / 26-40 kg / 41-60 kg/61-75 kg / >75 kg	-	27.5(55) / 32.5(65) / 45(90) /75(150)/ 75(150) /75 (150)*
		Abdomen /pelvis	0-10 kg / 11-25 kg / 26-40 kg / 41-60 kg/ 61-75 kg	-	48 (95) / 100 (200) / 180 (360) / 320 (640) / 805 (1610)*
Sudan, 2015 [65]	Local 3rd quartile	Head	6–10 yrs	-	1053
		Chest	6–10 yrs	-	208
		Abdomen	6–10 yrs	-	574
Japan, 2016 [68]	Proposes DRLs from nationwide survey 3rd quartile	Head	<1yr / 1–5 yrs / 6–10 yrs	39.1 / 46.9 / 67.7	526.1 / 665.5 /847.9
		Chest	< 1yr / 1–5 yrs / 6–10 yrs	11.1 / 14.3 / 15	209.1 / 296 / 413
		Abdomen	< 1yr / 1–5 yrs / 6–10 yrs	12 / 16.7 / 17	261.5 / 430.8 / 532.2
Japan, 2015 [66]	Local 3rd quartile	Abdomen/pelvis	0-1 yrs / 2-5 yrs / 6-10 yrs	1.8 (3.5) / 2 (4)/ 2.9 (5.8)*	67 (134)/ 97 (194) /167 (334)*

**values in brackets correspond to measurements with a 16 cm diameter phantom.*

Abbreviations: DRLs: Diagnostic Reference Levels, yrs: years, CTDIvol: Volume CT Dose Index, CTDIw: Weighted CT Dose Index, DLP: Dose length Product.

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