Discover Applied Sciences

Case Study

Optimization and image quality in CT studies: application of DRLs based on clinical indication

Carmine Picone[1] · Annamaria Porto[1] · Roberta Fusco[1] · Claudio Granata[2] · Maria Chiara Brunese[3] · Vincenza Granata[1] · Alessandro Ottaiano[4] · Marialuisa Barretta[1] · Ferdinando Caranci[5] · Biagio Pecori[1] · Eugenio Sorgente[1] · Sergio Salerno[6] · Raffaella Mormile[7] · Fabio Pinto[8] · Antonio Pinto[9] · Andrea Magistrelli[10] · Antonella Petrillo[1]

Received: 14 November 2024 / Accepted: 9 May 2025
Published online: 22 May 2025
© The Author(s) 2025 OPEN

Abstract
The use of ionizing radiation in computed tomography (CT) has significantly enhanced diagnostic accuracy and clinical decision-making. However, optimizing CT protocols is crucial to balance the diagnostic benefits with potential radiation risks, particularly for vulnerable populations. Diagnostic Reference Levels (DRLs), introduced to guide dose optimization, highlight variations in dose indices due to local protocol differences rather than patient or equipment characteristics. This underscores the importance of standardizing technical parameters to ensure consistent image quality and minimize dose variability. Recent advancements, including iterative reconstruction algorithms and artificial intelligence, offer promising avenues for dose reduction without compromising diagnostic value. Effective optimization strategies require a multidisciplinary approach, incorporating continuous protocol evaluation, adherence to quality assurance programs, and clinical audits. Standardized DRLs tailored to clinical indications further enhance imaging practices, reducing variability and fostering safer, more effective patient care. The purpose of this article is to demonstrate, through a review of the literature and recent papers, applied to clinical practice, the role of diagnostic reference levels (DRLs) in CT optimization and image's quality.

Article Highlights

- DRLs has been shown to be an effective tool for optimizing radiation exposure but should not be used as dose limits or to assess image quality.
- The application of DRL is not sufficient for the optimization of radiation protection, but the diagnostic quality of the corresponding images should also be evaluated.
- CT utilises $CTDI_{vol}$ and DLP as DRL quantities of a single scan and total DLP as DRL quantity of the entire examinations.

Keywords Computed tomography · Optimization · Diagnostic reference levels · Radiation protection

✉ Carmine Picone, c.picone@istitutotumori.na.it | [1]Department of Radiology, National Cancer Institute IRCCS Foundation Pascale, Naples, Italy. [2]Department of Radiology, Burlo Garofalo Pediatric Institute, Trieste, Italy. [3]Department of Radiology, University of Molise, Cambobasso, Italy. [4]Department of Innovative Therapies of Abdominal Cancer, Istituto Nazionale Tumori IRCCS Fondazione G.Pascale, Naples, Italy. [5]Division of Neuroradiology, University of Campania Luigi Vanvitelli, Naples, Italy. [6]Department of Radiology, University of Palermo, Palermo, Italy. [7]Department of Pediatry, San Giuseppe Moscati Hospital, Aversa, Italy. [8]Department of Radiology, Local Health Authority Caserta, Caserta, Italy. [9]Department of Radiology Traumatological Orthopaedic Centre, Naples, Italy. [10]Department of Radiology, Department of Paediatrics, Bambino Gesu Pediatric Hospital, Rome, Italy.

Abbreviations

DRLs Diagnostic reference levels
$CTDI_{vol}$ Volumetric computed tomography dose index
MPE Medical physics expert
RP Radiation protection
ICRP International commission on radiological protection
DLP Dose length product
TCM Tube current modulation

1 Introduction

According to several studies, ionizing radiation should be considered carcinogenic to humans [1]. In medicine, it is essential to manage the radiation dose to patients in relation to the medical purpose. The goal is to use an appropriate dose to achieve the desired image quality or therapeutic outcome [2].

The use of ionizing radiation for diagnostic purposes has been a significant achievement, particularly with the advent of computed tomography (CT), which has greatly enhanced information compared to plain radiography. CT scans have revolutionized diagnostic performance and, consequently, the clinical decision-making process, significantly increasing accuracy [3, 4]. However, CT studies now represents the main source of medical radiation exposure for the general population, posing potential health risks, especially for pediatric and younger patients [2, 5].

It is, therefore, critical to strike a balance between the diagnostic benefits of ionizing radiation and the associated risks. The introduction of Diagnostic Reference Levels (DRL) has been pivotal, providing a reference standard to be achieved. DRLs do not represent dose limits and are not applicable to individual patients. Establishing national DRLs involves complex and thorough investigations, which can be burdensome in terms of data collection and analysis. Furthermore, DRLs are not always sensitive to rapid technological developments. As a solution, the concept of defining DRLs specific to clinical indications has emerged, aiming to simplify the optimization process and increase consistency of these values.

2 Optimization of the computed tomography exam

Dose optimization is defined as the use of the minimum amount of ionizing radiation necessary to achieve a result (ie images) that satisfies the clinician's diagnostic question [6].

To evaluate the quality of CT studies, several factors are considered, including achieving a balance between the clinical need for high-quality images and the risks from radiation exposure is key. Poor image quality due to low radiation can lead to misdiagnosis, while excessive radiation increases patient risk. As required by national regulations and best practices, the quality of CT images and the dose of CT studies are continuously reviewed through quality assurance programs. In the process of protocol optimization, after an initial evaluation by the medical physics expert (MPE), the images are clinically validated (i.e. the images provide sufficient diagnostic information) by experienced radiologists.

It must be considered that individual optimization in medical exposures does not necessarily mean reduction of the dose to the patient or providing a higher dose of radiation where needed.

Given the evidence of potential cancer risks associated with ionizing radiation, optimizing the dose is critically important [1, 2]. Various strategies exist for dose optimization in CT studies, focusing on aspects such as modulation of kilovoltage (kV) and tube current (mA), reduction of scan length and number of phases, and the use of iterative reconstruction algorithms [6]. In this regard, very interesting possibilities relate to machine learning that is actively explored in CT imaging, demonstrating impressive results and significant potential for dose reduction [2, 7].

Machine learning and radiomics are particularly promising in supporting clinical work.

These technologies enable advancements in dose estimation, image post-processing, and radiological image quality enhancement [8]. Radiomics, in particular, can provide valuable support by creating predictive models based on features extracted from imaging data- This is especially evident in oncology, which remains the primary field of application of radiomics [9].

In the context of dose optimization strategies, defining a structured optimization process is essential.

Key steps to achieving an effective optimization process include: (1) Establishing a quality program: a defined quality assurance program is the foundation of dose optimization; (2) Assembling a multidisciplinary team: a team of specialists,

each with a clear role in the process, is critical; (3) defining appropriate dose parameters; ensure that the radiation dose provides sufficient image quality to answer the clinical question; (4) implementing and updating protocols: continuous refinement of protocols is essential; (5) evaluating the optimization process: conduct a final assessment to ensure the best image quality is achieved with the lowest possible dose [6].

A practical illustration of key points 4 and 5 is shown in Figs. 1 and 2.

Vessels and liver lesion (cysts) are well depicted in all phases. Image noise is considered acceptable by radiologists. The total DLP of CT examination is 1235 mGycm (Italian DRLs for adult CT trunk scan are $CTDI_{vol}$ 17 mGy, DLP 1200 mGycm, Total DLP 2115 mGycm).

3 Computed tomography dose and image quality

The quality of a radiological image directly influences diagnostic accuracy and the subsequent clinical management of the patient. A radiological image is considered of good quality when it meets specific technical requirements (e.g. acceptable levels of image noise) and is deemed of diagnostic value.

Low-quality images are more likely to be rejected, necessitating a repeat of the procedure to produce images suitable for diagnosis. This leads to unnecessary additional exposure to ionizing radiation for both patients and radiological staff [10].

When modifying imaging protocols, it is essential to ensure that the resulting image quality remains appropriate for the diagnostic purpose. The optimization process must balance image quality and patient dose: while reducing radiation exposure is desirable, image quality must be maintained at a diagnostically acceptable level [11]. Like any optimization process, dose optimization requires careful consideration of multiple factors. It can be hindered by an inadequate weighing of all relevant aspects or by a lack of awareness of potentially significant external factors.

Several challenges make the dose optimization process complex. The primary barriers include: (1) resistance to change: radiologists may be reluctant to adopt low-dose protocols due to concerns about compromising diagnostic quality; (2) variability in radiation protection education and training: inconsistent levels of knowledge among radiologists can hinder optimization efforts; (3) limited time and resources: a lack of commitment or encouragement from management can stifle optimization initiatives; (4) technical challenges: technological variability, inconsistency in protocols and equipement limitations add further complexity [12].

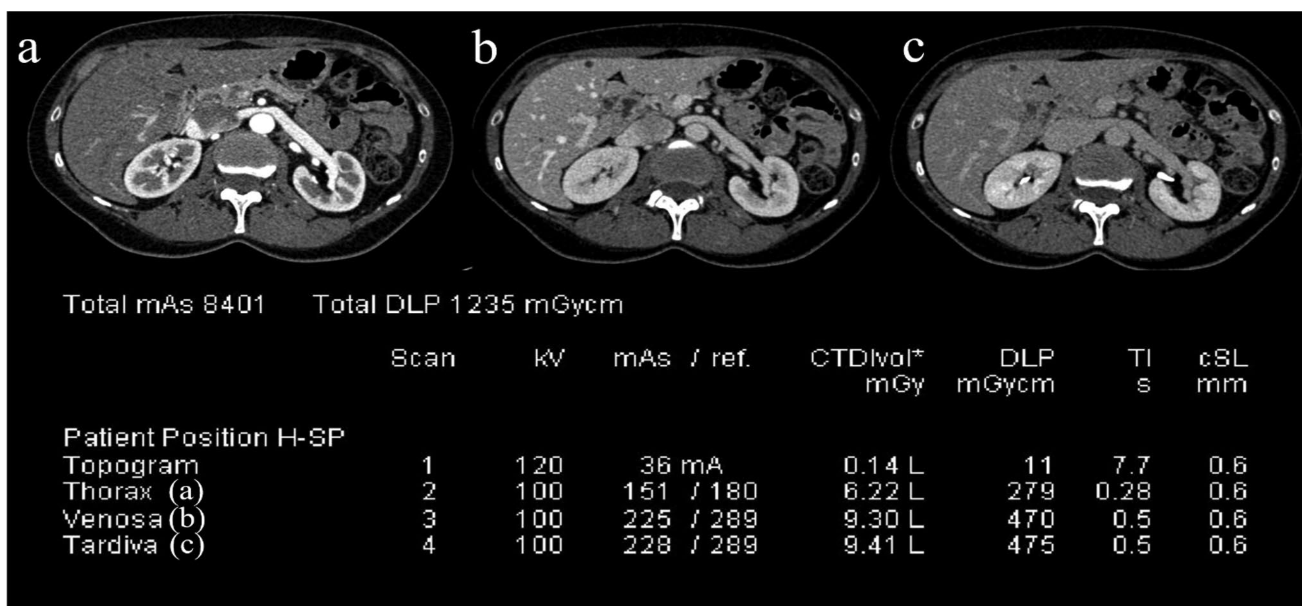

Fig. 1 Female, 54 years old (55 kgs). Triple-phase liver CT examination for a female oncological patient. Scanner Siemens Somatom Definition Flash. Arterial phase (**a**) uses fixed kV (100 kV) and tube current modulation (TCM) optimized for vascular enhancement. The same protocol is used for portal- (**b**) and equilibrium-phase (**c**), with fixed kV (100 kV) and TCM optimized for parenchymal enhancement

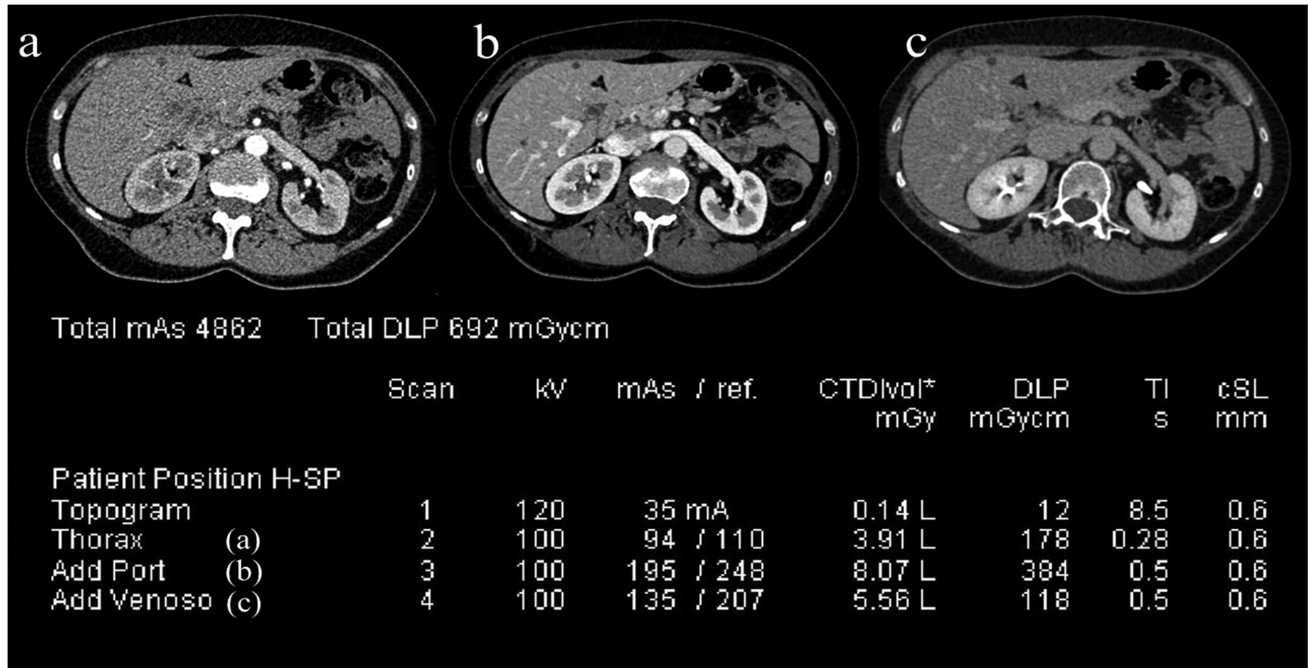

Fig. 2 Female, 56 years old (56 kgs)**.** Triple-phase (**a**, **b**, **c**) liver CT examination in the same patient 12 months later with the same equipment (Siemens Somatom Definition Flash) but different technical settings due to CT protocols optimization. If compared to the previous exam the TCM values are lowered in all protocols (see ref mAs and $CTDI_{vol}$ compared to those of Fig. 1), especially in equilibrium-phase (**c**) where the late contrast-enhancement of liver lesions is evaluated and an increased image noise is acceptable. Note that the total DLP is halved if compared to Fig. 1 (total DLP is 692 mGycm vs 1235 mGycm)

A practical example of inconsistency in protocols is shown in Fig. 3.The same patient had three abdominal CT studies at three different dates using the same equipment (Siemens Somatom Definition Flash) and for the same clinical purpose (kidney stones, peritoneal abscesses).

Dose indices of the three examinations comply to Italian national DRLs for abdominal CT (7 mGy $CTDI_{vol}$, 227 mGycm DLP and 392 mGycm total DLP in patients weighing 15–30 kgs or aged 5 years); see Fig. 3. Despite these, there are differences in number of phases per examination (exams a and b: two phases, exam c: one phase) and in TCM settings (exam a: 120 ref mAs; exam b: 150 ref mAs; exam c: 90 ref mAs).

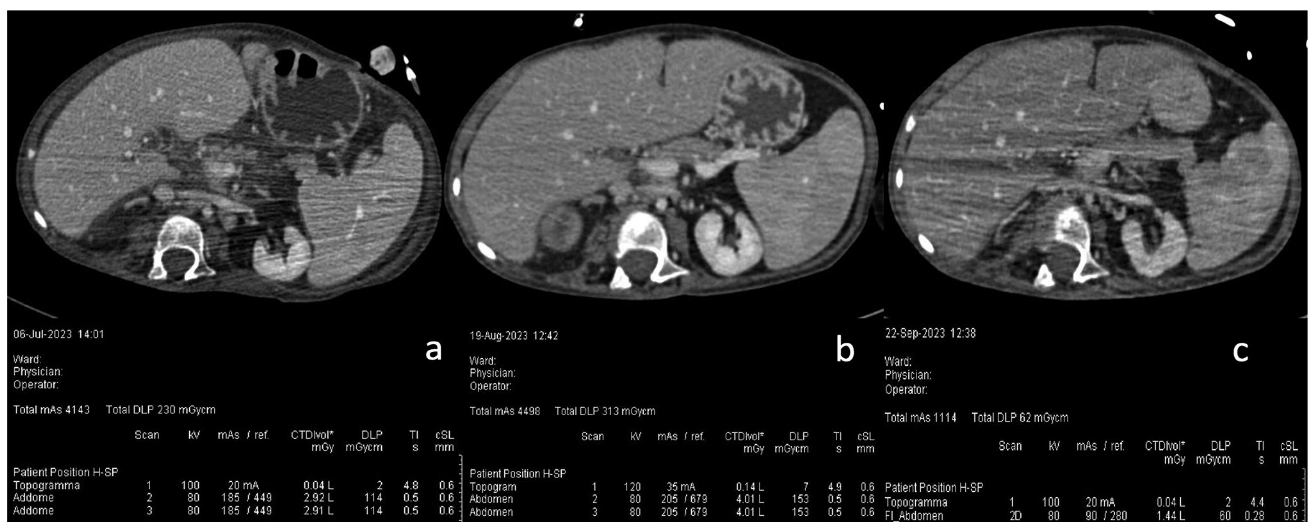

Fig. 3 Male, 6 years old (22 kgs). The same patient had three abdominal CT studies (**a**, **b**, **c**) at three different dates respectively with the same equipment and clinical task (peritoneal abscesses, right kidney stones). The exams were performed using different protocols, exposure settings and with variability in the number of phases

4 Diagnostic reference levels based on clinical indications

The use of ionizing radiation for diagnostic purposes has necessitated the establishment of a specific regulatory framework for this sector, and the introduction of DRLs was very important in this sense. DRLs were first introduced by the International Commission on Radiological Protection (ICRP) in its publication 73 of 1996 [11] and they have to be considered as part of this optimization process, as described also in recent DRLs recommendations in ICRP Publication 135 [13].

The DRL value is defined as a national arbitrary value set at the 75 th percentile of the distribution of medians obtained from relevant surveys [11, 13]. Viewing DRLs as a boundary between "good" and "bad" medical practice is misleading. Instead, DRLs should be considered dose thresholds prompting a review of practices if values consistently exceed (or fall below) them. Such reviews should take into account the specific circumstances of each case [13].

In Italy, DRLs were initially introduced with Legislative Decree 187/2000 [14]. Article 4 of this decree outlines the principle of optimization, stating that all doses must be kept as low as reasonably achievable while still obtaining the necessary diagnostic information.

More recently, the Italian Government adopted the 59/2013/Euratom Directive [15] with Legislative Decree 101/2020 [16] reinforcing the safety standard of radiation protection.

The updated definition of DRLs in Legislative Decree 101/2020, based on definition (20) of Article 4 of EURATOM Directive 59/2013, describes them as follows: *"means dose levels in medical radio diagnostic or interventional radiology practices, or, in the case of radio-pharmaceuticals, levels of activity, for typical examinations for group of standard-sized patients or standard phantoms for broadly defined types of equipment"* [15].

Advancements in both equipment and data analysis have naturally influenced this field, resulting in a general reduction of DRL values over time.

Recent developments are reported in the Istisan 20/22 Report [17], which provide a comprehensive reference and represents the Italian guideline on DRLs establishment.

This document [17] defines medical procedures for which DRLs must be established, providing CT dosimetric indices ($CTDI_{vol}$, DLP and total DLP exams) and criteria as well as sample size, value in the distribution used to define the quantity of interest and scope.

5 Classification of diagnostic reference levels

DRLs are classified as Regional (European), National, Local and Typical.

National DRLs require extensive investigations, which can be resource-intensive in terms of data collection and analysis. They may not respond quickly to rapid technological advancements.

Local DRLs or typical values based on smaller scale surves (e.g. within individual hospital or a few radiology rooms) are more adaptable. The ICRP defines "local DRLs" as values derived from surveys conducted in 10–20 radiology rooms, while "typical values" are obtained at the hospital or clinic level. These values facilitate comparisons between radiology rooms or reflect the adoption of a new technology [17].

6 Computed tomography diagnostic process and diagnostic reference levels

The CT diagnostic process requires special attention, particularly in two areas: (1) Total DLP reporting: while total DLP is required by law, the regulations provide indications only for specific anatomical regions. There is no further detail or clinical context for these values [17]; (2) Technological progress: a comparison of DRL values for adult CT studies in Italian radiological practice, as expressed in legislation and earlier reports, shows a significant decrease over time due to advancements in CT technology (Fig. 4).

A practical example is shown in Fig. 4 where the same patient underwent two abdominal CT examinations at different dates using a 2nd generation dual source scanner Siemens Somatom Definition Flash (Fig. 4a,b) and six months later with a 3rd generation dual source scanner Siemens Somatom Force (Fig. 4 c,d) for the same clinical purpose (Wilms tumor follow up). Dose indices of the two examinations comply to Italian national DRLs for abdominal CT (5.7 mGy $CTDI_{vol}$, 151 mGycm DLP, 193 mGycm total DLP) in patients weighing 5–15 kgs or aged 1 year. Respectively $CTDI_{vol}$ values are: (a) 1.33 mGy; (b) 2.70 mGy; (c) 0.96 mGy; (d) 0.67 mGy. All 1 mm slice thickness reconstruction images are diagnostic,

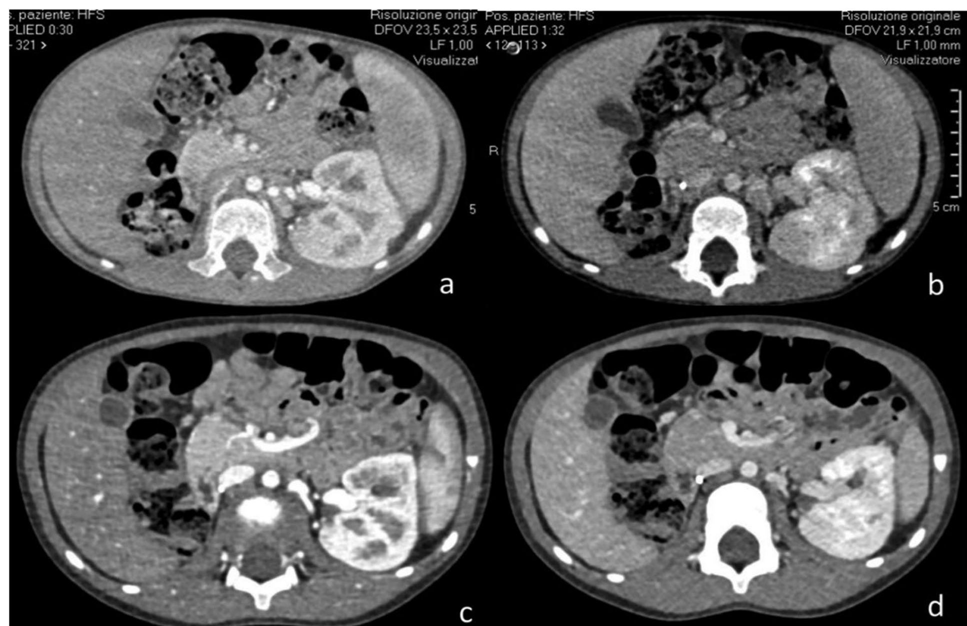

Fig. 4 Female, 17 months old (22 kgs). The same patient had two abdominal CT studies within 6 months with a 2 generation dual source scanner (**a**, **b**) and a 3rd generation dual source scanner (**c**, **d**). Technical settings of scan (**a**) and (**c**) are similar, so that dose indices reduction depends on equipment technological advancement

despite the use of different equipment and technical settings (a: 80 kV, 90 ref mAs; b: 100 kV, 90 ref mAs; c: 80 care-kV, 90 ref mAs; d: 70 care-kV, 90 ref mAs).

7 International study findings

A 2019 retrospective study re-evaluated approximately 2 million CT scans performed between 2015 and 2017 across seven countries. The dataset included scans of different body regions using 290 machines from four manufacturers and covered 151 hospital facilities.

The study revealed heterogeneity in mean effective dose values between countries, particularly for abdominal and combined chest/abdomen scans [18]. Differences in technical parameters, such as kV or TCM settings and number of phases, have been identified as the main factors contributing to these variations [19] as illustrated in Figs. 5 and 6.

8 Diagnostic reference levels and image quality

The study mentioned in the previous section was followed by the publication of Radiation Protection publication 195 [20] which led to several important considerations:a) image quality classification is not standardized, and European guidelines on image quality criteria should be developed, particularly in relation to clinical indications for examination; and b) common terminology for DRLs is needed. There is a need for a standardized lexicon to define DRLs to avoid confusion arising from different terminologies. Procedures that are essentially identical may be named differently, which can create heterogeneity in sample data.

The introduction of "standardized" DRLs could benefit from the standardization of multi-phases examination techniques and protocols [18].

As highlighted earlier, and in the ICRP Publication 135 [13], a key challenge is to strike the right balance between image quality (e.g. noise levels) and the dose to the patient. This balance is crucial for dose optimization and image clarity. As reported in ICRP Publication 135 it is essential to ensure that appropriate image quality for diagnostic purposes is achieved when imaging protocols are changed. DRL quantities are very useful in providing information on radiation dose, but they are not descriptors of image quality.

Evaluating the quality of CT images involves balancing multiple considerations to ensure diagnostic accuracy and patient safety. One critical aspect is managing the trade-off between image quality and radiation dose, where excessive radiation increases risks but inadequate doses may compromise diagnostic value. Quality assurance programs ensure

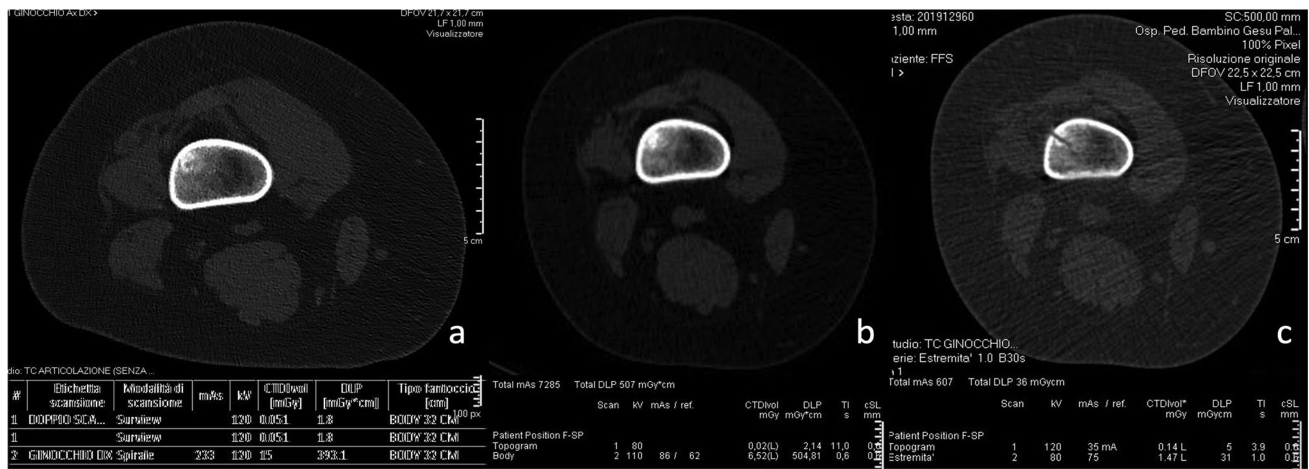

Fig. 5 Female 15 years old (kg unknown). The same patient underwent three CT examinations of the limbs (femoral) in three different facilities for the same clinical task (follow-up of osteoid osteoma) with different equipment and technical settings. The lesion is well represented in all images despite the large variability of dose indices, determined by different technical parameters: **a** 15 mGy CTDIvol, 393.1 mGycm DLP; total DLP not reported **b** 6.52 mGy CTDIvol, 504.81 mGycm DLP; 507 mGycm total DLP **c** 1.47 mGy CTDIvol, 31 mGycm DLP, 36 mGycm total DLP

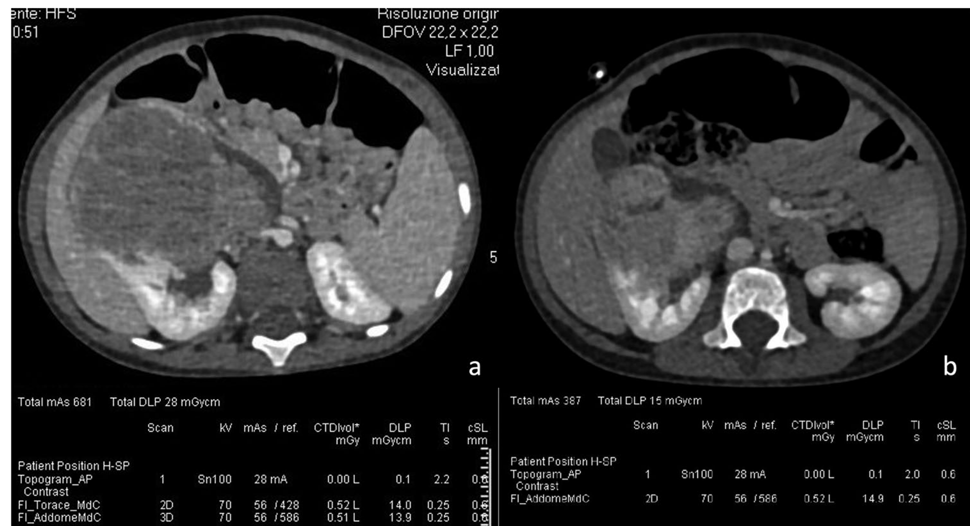

Fig. 6 Female 18 months old patient had two abdominal CT studies at different dates due to a right kidney Wilms Tumor. CT examinations were performed with the same equipment (Siemen Somatom Force) and the same optimized protocol, named (abdomen_5_15 kgs). Abdominal scans dose indices are identical: **a** 0.51 mGy $CTDI_{vol}$, 13.9 mGycm DLP; **b** 0.52 mGy $CTDI_{vol}$, 14.9 mGycm DLP. The use of a standardized weight-based protocol is helpful in reproducibility of image quality and patient dose

consistency through routine checks, reject analyses, and monitoring of radiation dose levels. The Medical Physics Expert (MPE) is responsible for performing physical and technical assessments, analyzing parameters such as contrast, noise, spatial resolution, and advanced metrics like Modulation Transfer Function and Detective Quantum Efficiency. However, image quality also requires clinical evaluation by experienced radiologists to determine whether the images meet diagnostic needs [22].

As radiation dose decreases, image quality must be maintained at an appropriate level. This is especially important in optimizing image quality while reducing dose (Fig. 6).

9 Clinical audits in Italy

Article 168 of Italian Legislative Decree 101/2020 [16] promotes the use of clinical audits for radiological practices.

Clinical audits, as described in the ESR Esperanto document [21], are continuous and systematic evaluations of medical radiological procedures aimed at improving the quality and outcomes of patient care.

The purpose of clinical audits is to evaluate results against established standards of good practice, and to modify procedures or implement new standards when necessary [21]. The process can be broken down into three main steps: (1) a standard is selected; (2) a comparison is made between the standard and the local condition; (3) if there is a deviation, changes are made and results are re-evaluated [21].

10 Conclusions

Several studies have evaluated the usefulness of Diagnostic Reference Levels (DRLs) based on clinical indications. In our daily practice, at the beginning of CT protocol optimization, we observe significant variations in dose indices.

These variations, observed even for the same anatomical area and same clinical task, are primarily attributed to local choices in technical parameters rather than differences in patient characteristics or scanner specifications.

These variations highlight that first step of optimization relates to technical parameters, balancing image quality (e.g., noise) with the dose to the patient. As radiation dose decreases, image quality should be maintained at an appropriate level. It is essential to optimize image quality in accordance with the potential for dose reduction. These insights highlight that dose optimization in CT imaging can significantly benefit from the standardization of protocols.

DRLs based on clinical indications offer valuable potential for improving practice, but greater uniformity is needed to minimize variability across institutions.

Achieving an optimal balance between image quality and DRL benchmarks is essential, avoiding unnecessary personalization of protocols by radiologists and instead focusing on standardization. Additionally, clinical audits play a crucial role in addressing discrepancies between DRLs and image quality, ensuring that the best radiological practices are consistently implemented while maintaining high diagnostic standards.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Carmine Picone and Andrea Magistrelli. The first draft of the manuscript was written by Annamaria Porto, Roberta Fusco, Vincenza Granata, Marialuisa Barretta, Maria Chiara Brunese, Ferdinando Caranci, Biagio Pecori, Eugenio Sorgente, Sergio Salerno, Raffaella Mormile, Fabio Pinto, Antonio Pinto and Claudio Granata, Alessandro Ottaiano and Antonella Petrillo commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the Italian Ministry of Health Ricerca Corrente funds.

Data availability The authors confirm that the data supporting the findings of this study are available within the article. All data generated or analyzed during this study are included in this published article.All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval Ethical approval was not required. This study was performed in line with the principles of the Declaration of Helsinki.

Informed consent Written informed consent was obtained from all participants for using anonymized medical images obtained from the facility where the tests were performed.

Consent for publication Informed consent for publication was provided by the participants or a legally authorized representative.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

References

1. International Agency for research on cancer. IARC Monographs on the Identification of Carcinogenic Hazards to Humans.; 2023. Available from: https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans.
2. Picone C, Fusco R, Granata V. Dose reduction strategies for pregnant women in emergency settings. J Clin Med. 2023;12(5):1847. https://doi.org/10.3390/jcm12051847.
3. Seidel J, Bissell MB, Vatturi S, Hartery A. Retrospective analysis of emergency computed tomography imaging utilization at an academic centre: an analysis of clinical indications and outcomes. Canadian Assoc Radiol J. 2019;70(1):13–22.
4. Pandharipande PV, Reisner AT, Binder WD, Zaheer A, Gunn ML, Linnau KF. 2016 CT in the emergency department: a real-time study of changes in physician decision making. Radiology. 2016;278(3):812–21. https://doi.org/10.1148/radiol.2015150473.
5. Brenner DJ, Hall EJ, et al. Computed tomography—an increasing source of radiation exposure. N Egl J Med. 2017;357(22):2277–84. https://doi.org/10.1056/NEJMra072149.
6. Tsapaki V. Radiation dose optimization in diagnostic and interventional radiology: current issues and future perspectives. Physica Med. 2020;79:16–21.
7. Wang G, Ye JC, De Man B. Deep learning for tomographic image reconstruction. Nat Mach Intell. 2020;2(12):737–48.
8. Choy G, Khalilzadeh O, Michalski M, Do S, Samir AE, Pianykh OS. Current applications and future impact of machine learning in radiology. Radiology. 2018. https://doi.org/10.1148/radiol.2018171820.
9. Langs G, Röhrich S, Hofmanninger J, Prayer F, Pan J, Herold C, Prosch H. Machine learning: from radiomics to discovery and routine. Radiologe. 2018;58(Suppl 1):1–6. https://doi.org/10.1007/s00117-018-0407-3.
10. Kjelle Elin, Chilanga Catherine. The assessment of image quality and diagnostic value in X-ray images: a survey on radiographers' reasons for rejecting images. Insights Imaging. 2022. https://doi.org/10.1186/s13244-022-01169-9.
11. ICRP, 1996. Radiological Protection and Safety in Medicine. ICRP Publication 73. Ann. ICRP 26 (2). Available from:https://www.icrp.org/publication.asp?id=ICRP%20Publication%2073
12. Whitebird RR, Solberg LI, Bergdall AR, López-Solano N, Smith-Bindman R. Barriers to CT dose optimization: the challenge of organizational change. Acad Radiol. 2021;28(3):387–92.
13. ICRP, 2017. Diagnostic reference levels in medical imaging. ICRP Publication 135. Ann. ICRP 46(1).
14. DECRETO LEGISLATIVO 26 maggio 2000, n. 187 Attuazione della direttiva 97/43/Euratom in materia di protezione sanitaria delle persone contro i pericoli delle radiazioni ionizzanti connesse ad esposizioni mediche. Available from: https://www.gazzettaufficiale.it/eli/gu/2000/07/07/157/so/105/sg/pdf
15. Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. Available from: https://eur-lex.europa.eu/eli/dir/2013/59/oj
16. DECRETO LEGISLATIVO 31 luglio 2020, n. 101 Attuazione della direttiva 2013/59/Euratom, che stabilisce norme fondamentali di sicurezza relative alla protezione contro i pericoli derivanti dall'esposizione alle radiazioni ionizzanti, e che abroga le direttive 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom e 2003/122/Euratom e riordino della normativa di settore in attuazione dell'articolo 20, comma 1, lettera a), della legge 4 ottobre 2019, n. 117. (20G00121) (GU Serie Generale n.201 del 12–08–2020 - Suppl. Ordinario n. 29). Available from: https://www.gazzettaufficiale.it/eli/gu/2020/08/12/201/so/29/sg/pdf
17. Padovani, R., Compagnone, G., & D'Ercole, L. Livelli diagnostici di riferimento per la pratica nazionale di radiologia diagnostica e interventistica e di medicina nucleare diagnostica.2020 Aggiornamento del Rapporto ISTISAN, 17, 33. Available from: https://www.iss.it/rapporti-istisan/-/asset_publisher/Ga8fOpve0fNN/content/rapporto-istisan-20-22-livelli-diagnostici-di-riferimento-per-la-pratica-nazionale-di-radiologia-diagnostica-e-interventistica-e-di-medicina-nucleare-diagnostica.-aggiornamento-del-rapporto-istisan-17-33.-r.-padovani-g.-compagnone-l.-d-ercole-a.-orlacchio
18. Smith-Bindman R, Wang Y, Chu P, Chung R, Einstein AJ, Balcombe J. International variation in radiation dose for computed tomography examinations: prospective cohort study. Bmj. 2019. https://doi.org/10.1136/bmj.k4931.
19. Tsapaki V, Damilakis J, Paulo G, Schegerer AA, Repussard J, Jaschke W, Frija G. CT diagnostic reference levels based on clinical indications: results of a large-scale European survey. Eur Radiol. 2021;31:4459–69.
20. Damilakis J, Frija G (2019). European Study on Clinical Diagnostic Reference Levels for X-ray Medical Imaging (EUCLID). 2019. European Congress of Radiology-EuroSafe Imaging 2019.
21. Esperanto ESR (2019) The ESR Guide to Clinical audit and Clinical Audit Tool. Available from: https://www.icrp.org/publication.asp?id=ICRP%20Publication%2073
22. Russell MT, Fink JR, Rebeles F, Kanal K, Ramos M, Anzai Y. Balancing radiation dose and image quality: clinical applications of neck volume CT. AJNR Am J Neuroradiol. 2008. https://doi.org/10.3174/ajnr.A0891.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.