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SYSTEMATIC REVIEW

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Diagnostic reference levels in nuclear medicine: A systematic review

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ABSTRACT

Aim/Background: Radiation protection for patients in nuclear medicine is based on the fundamental principles of justification, optimization, and dose limitation. In order to monitor and facilitate the dose-optimization process, the International Commission on Radiological Protection introduced the concept of diagnostic reference levels (DRLs) as an essential element of the dose-optimization system. The objective of this review is to present data from the literature on DRLs in nuclear medicine to evaluate practices and perform optimizations.

Methods: The Preferred Reporting Items for Systematic Reviews and Meta-Analyses methodology was used as a guide to conduct this study. Literature searches were performed using the ScienceDirect, PubMed, Web of Science, Scopus, and Google Scholar databases with a combination of the following keywords: DRLs, nuclear medicine, patient radiation protection, adults, positron emission tomography with computed tomography (CT), and single-photon emission computed tomography with CT.

Result: The search yielded 432 articles, of which 14 were selected because they met the selection criteria. Relevant information from the selected articles was summarized and analyzed. Some differences were observed in patient selection methodology, the activity administered, and the DRL reporting.

Conclusion: The implementation of DRLs could contribute significantly to reducing exposure, thereby offering the public risk-controlled examinations. This study provides recommendations on the establishment of future DRLs in nuclear medicine.

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Introduction

Medical imaging plays a fundamental role in patient care and is the main source of ionizing radiation exposure for the general population. In nuclear medicine, although patients exposed to ionizing radiation have the opportunity to overcome their illness, they are at an increased risk of radiation-induced damage [1].

Radiation protection for patients in nuclear medicine is based on the fundamental principles of justification, optimization, and dose limitation [2]. To achieve this, examinations must be performed with the best balance between radiation dose and image quality [2]. To achieve this, diagnostic procedures must be continuously optimized, taking into account technical advances in imaging and changes in diagnostic practices [3]. In the early 1990s, in order to monitor and facilitate the dose optimization process, the International Commission on Radiological Protection (ICRP) introduced the concept of diagnostic reference levels (DRLs) as an obvious part of the dose optimization system [4,5]. In nuclear medicine, DRLs correspond to the activity administered during a typical examination to ensure a sufficient level of quality to obtain diagnostic information [6]. In practice, they make it possible to evaluate the quality of procedures from the point of view of

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the doses delivered to patients and, in the event of unjustified exceedances, to take control and corrective action. DRLs apply to the most common and/or most irradiating examinations in standardized procedures. They are neither limits nor dose constraints, and compliance with them must never be dissociated from the concept of image quality [7]. The ICRP recommends establishing DRLs based on the third quartile (75th percentile) of the distribution of radiopharmaceutical activity administered to patients [8].

In nuclear medicine, hybrid modalities integrating positron emission tomography (PET) or single-photon emission computed tomography (SPECT) with computed tomography (CT) allow intrinsic co-registration of functional and anatomical data in a single procedure (PET/CT or SPECT/CT) [9,10]. The CT scan is often a low-dose CT scan to provide attenuation correction and anatomical localization [11,12]. McCollough [13] reported that there was no reliable evidence to demonstrate the risks of low-dose CT (< 50 mSv). The DRLs for PET/CT and SPECT/CT are determined by collecting the radiation doses from the injected activity (MBq) as well as the CT dose volume, from the dose index ($CTDI_{vol}$ in mGy) and the dose–length product (DLP in mGy·cm) [14].

The increasing use of hybrid imaging modalities, particularly PET/CT and SPECT/CT, has intensified considerably in recent years, especially in oncology for diagnosis, staging, and therapeutic follow-up [15]. This growing reliance on such examinations has led to a significant increase in cumulative patient exposure to ionizing radiation, which may reach or exceed 100 mSv.

Furthermore, although several systematic reviews have evaluated DRLs in nuclear medicine, they have mainly focused on the functional component (administered radiotracer activity) without thoroughly addressing reference levels related to the CT component of hybrid imaging. This gap is particularly important given that CT represents a substantial, and often predominant, contribution to the total radiation dose delivered during these examinations [16].

Therefore, optimization of acquisition protocols, including both CT parameters and administered activity, as well as the establishment of DRLs adapted to both components, are essential for reducing radiation exposure while maintaining optimal diagnostic image quality. The objective of this review is to present data from the literature on DRLs in nuclear medicine to evaluate practices and make optimizations.

Materials and Methods

Study type

This is a systematic review of the literature on DRLs in nuclear medicine.

Search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses methodology [17] was used as a guide to conduct this study. Documentary searches were conducted using the ScienceDirect, PubMed, Web of Science, Scopus, and Google Scholar databases with a combination of the following keywords: DRLs, nuclear medicine, patient radiation protection, adults, SPECT/CT, PET/CT.

Study selection

Articles were selected based on the titles and abstracts of all articles identified using the population, intervention, comparison, and outcome (PICO) methodology. Articles were considered if they described the DRLs of the most commonly performed nuclear medicine examinations:

PET/CT:

^{18}F FDG
^{18}F FNA
^{18}F or ^{68}Ga PSMA
^{18}F Choline
^{68}Ga Dotatate

Scintigraphy:

Bone scintigraphy: ^{99m}Tc HMDP/DPD/MDP
Myocardial scintigraphy: ^{99m}Tc Sestamibi
Parathyroid scintigraphy: ^{99m}Tc Sestamibi
Thyroid scintigraphy: ^{99m}Tc Pertechnetate
Dynamic renal scintigraphy: ^{99m}Tc MAG3 or ^{99m}Tc DTPA
Static renal scintigraphy: ^{99m}Tc DMSA
Pulmonary perfusion scintigraphy: ^{99m}Tc MAA
MIBG scintigraphy: ^{123}I MIBG or ^{131}I MIBG

Articles reporting DRLs for injected activities, dose index ($CTDI_{vol}$), and DLP in adults were included. No language restrictions were applied.

We excluded articles that did not clearly describe the methodology used for establishing DRLs, as well as those that determined DRLs using approaches

other than the 75th percentile. Case reports, conference posters, narrative reviews, review articles, and conference abstracts were also excluded.

Article quality assessment and data extraction

Two reviewers independently assessed the quality of the articles and their risk of bias to ensure that they met the inclusion criteria. Each article was reviewed using the PICO methodology. The PICO framework used in this review was defined as follows: the population (P) included patients undergoing SPECT/CT and PET/CT examinations in nuclear medicine; the intervention (I) corresponded to the establishment of DRLs; the comparison (C) involved comparisons between institutions, countries, or imaging protocols when available; and the outcomes (O) included reported DRL values, administered activities, and CT dose indices. The extracted data were compared between the two reviewers, and any disagreements were resolved through discussion. The quality of each article was rated as high (1), moderate (2), or low (3) by each reviewer. Only articles rated as high or moderate by the reviewer were included in this study.

Data extraction was performed based on the following characteristics: year of publication, country in which the study was conducted, method of establishing DRLs, and DRLs for SPECT, PET, and CT.

Due to the substantial heterogeneity across the included studies, a quantitative meta-analysis was not performed. Indeed, significant variability was observed in the reported metrics, including differences in units (MBq *vs.* MBq/kg), acquisition protocols, and imaging technologies [time-of-flight (TOF) and Cadmium Zinc Telluride (CZT). In addition, variations in patient populations, particularly in terms of body weight and age, further limited the comparability of the data. Consequently, a descriptive analysis was considered more appropriate.

Results

We identified 432 articles, of which 215 were duplicates and were deleted, leaving a total of 217 articles (Fig. 1). The eligibility of the 217 articles was assessed, and 157 were excluded due to a lack of information on the establishment of DRLs (Fig. 1). Forty-six articles were excluded due to insufficient data for evaluating the methods used to establish DRLs. As a result, 14 articles met the selection criteria (Fig. 1).

Five articles were from Europe [2,3,8,18,19], two from America [20,21], five from Asia [1,22–25], one from Africa [26], and one from Oceania [27].

The articles were published between 2015 and 2025, and the patient selection methodology in the publications was either weight-restricted or non-weight-restricted. The weight-restricted method involved selecting patients weighing 70 ± 10 or 75 ± 20 kg. Three studies opted for the weight-restricted method [3,8,25].

The establishment of DRLs in all articles was in accordance with the ICRP recommendations, which recommend establishing DRLs based on the third quartile (75th percentile) of the distribution of the radiopharmaceutical activity administered to patients. The establishment of DRLs based on mass activity (MBq/kg) was proposed in five articles [2,8,18,19,24] for certain examinations.

Of all the articles selected, nine dealt with both PET and SPECT DRLs [1–3,18,20–24]. Three articles specifically concerned SPECT [8,23,24], while two articles dealt solely with PET [19,27].

The DRLs were established based on clinical indications, as described in the methodology. However, the most frequently reported examinations in the studies were ^{18}F-FDG PET in oncology and ^{99m}Tc-diphosphonate scintigraphy. The corresponding DRLs were in the ranges of 250 to 555 MBq for ^{18}F-FDG PET (Table 1) and 740 to 1110 MBq for ^{99}Tc-diphosphonate scintigraphy (Table 2), respectively.

Among the 14 articles selected, the DRLs for the CT component based on $CTDI_{vol}$ and DLP were determined in six articles [1,18,19,23,24,27]. Low-dose CT was used for attenuation correction and anatomical localization in the majority of studies. They were distributed according to the scan regions. For whole-body PET/CT acquisitions, $CTDI_{vol}$ values ranged from 4 to 13.07 mGy, with DLP values ranging from 521 to 1,319.05 mGy·cm (Table 1). In SPECT/CT, acquisitions showed $CTDI_{vol}$ values ranging from 4.8 to 10 mGy with DLP values ranging from 211 to 410 mGy·cm (Table 2).

Discussion

This study summarizes the results of studies conducted on DRLs in nuclear medicine in several countries. In practice, DRLs make it possible to evaluate the quality of procedures from the point

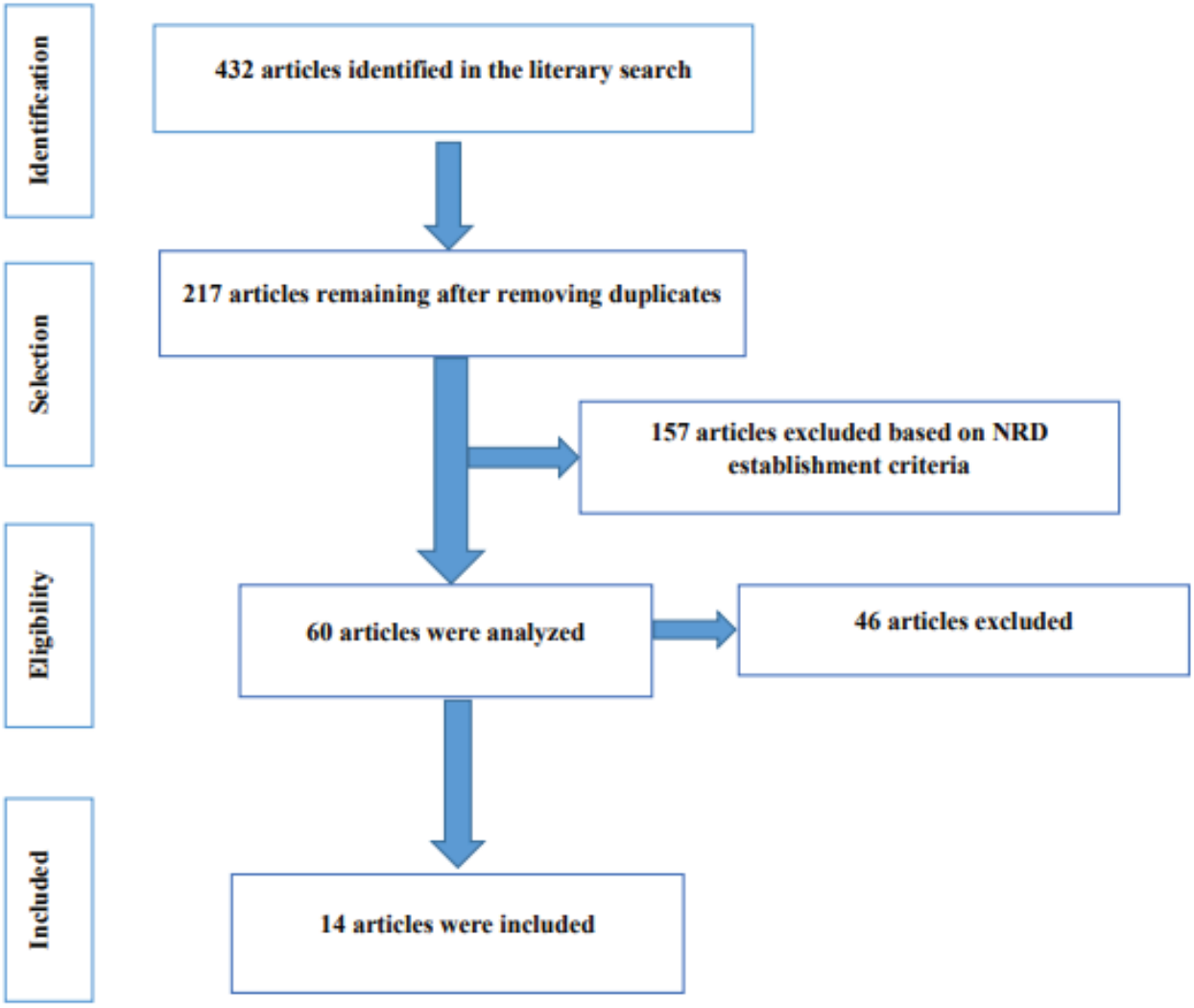


Figure 1. Flowchart of include and excluded DRLs studies.

of view of the doses delivered to patients and, in the event of unjustified exceedances, to take control and corrective action [6]. The methodology for selecting patients for establishing DRLs is based on weight-restriction and non-weight restriction. The non–weight-restricted approach offers several advantages over methods based on weight limitation. Indeed, applying strict weight criteria may reduce the available sample size and prolong the data collection period [28]. Furthermore, weight-restriction decreases the variability of administered activities by excluding extreme values, which may lead to a reduction in the 75th percentile and consequently influence the estimation of DRLs. Conversely, the absence of weight restriction allows the inclusion of a larger and more representative sample, thereby enabling a better characterization of weight distribution within the studied population [28].

According to ICRP recommendations, the weight-restriction methodology consists of selecting standard-sized patients with an average weight of 70 ± 10 or 70 ± 20 kg [10]. Three studies opted for the weight-restriction method [3,8,25]. In Japan, Watanabe et al. [29] emphasize the need to establish DRLs taking weight restriction into account, due to variability among patients indicating that weight could have a significant impact on outcomes. The use of the weight-restriction method facilitates a harmonized and fair comparison of results with DRLs from other countries applying the same methodology. Furthermore, when data come from a large sample of patients (> 100) from several institutions,

Table 1. Summary of NRDs for PET/CT in tumor indications.

			50th percentile			DRLs values (75th percentile)			
Authors	**Countries and years**	**Radiotracers**	**Activity (MBq)**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy·cm)**	**Activity (MBq)**	**Mass activity (MBq/kg)**	**CTDIvol (mGy)**	**DLP (mGy·cm)**
Roch et al. [2]	France, 2017	^{18}F FDG	-	-	-	260	3.6	-	-
	-	^{18}F FDG	228	3.68	453.6	258	-	4.49	521.75
Fayad et al. [23]	Qatar 2023	^{18}F FNA	158	-	-	187	-	-	-
	-	^{68}Ga Dotatate	135	-	-	140	-	-	-
	-	^{18}F or 68 Ga	237	-	-	260	-	-	-
	-	PSMA		-	-			-	-
Wachabauer et al. [3]	-	^{18}F FDG	272	-	-	317	-	-	-
	Austria 2015	^{18}F FNA	248	-	-	337	-	-	-
	-	^{68}Ga Dotatate	162	-	-	182	-	-	-
	-	^{68}Ga PSMA	173	-	-	189	-	-	-
	-	^{18}F Choline	272	-	-	376	-	-	-
Lima et al. [18]	Swiss 2018	^{18}F FDG	-	-	-	250	3.5	5	760
	-	^{18}F Choline	-	-	-	210	-	-	-
	-	^{18}F FNA	-	-	-	150	-	-	-
Becker et al. [20]	United States 2019	^{18}F FDG	-	-	-	555	-	-	-
Willegaignon et al. [21]	Brazil 2016	^{18}F FDG	363	-	-	370	-	-	-
	-	^{18}F FNA	296			370	-	-	-
Abe et al. [1]	Japan, 2020	^{18}F FDG	220.2	4,2	451	240	-	6.1	600
Song et al. [22]	Korea, 2019	^{18}F FDG	370	-	-	370	-	-	-
Alnaaimi et al. [24]	Kuwait, 2023	^{18}F FDG	228	-	-	230	5.18	-	-
	-	^{18}F FNA	220	-	-	230	2.22	-	-
	-	^{68}Ga Dotatate	217	-	-	217	1.85	-	-
	-	^{18}F or ^{68}Ga	217	-	-	217	1.85	-	-
	Italy 2025	PSMA ^{18}F FDG	-	-	-	236	3	6	446
Zorz et al. [19]	-	^{18}F PSMA ^{68}Ga PSMA ^{68}Ga Dotatate	-	-	-	-	-	-	-
Alkhybari et al. [27]	Australia 2019	^{18}F FDG	306.75	3.41	392.75	333.75		4.41	474
Alkhybari et al. [27]	New Zealand 2019	^{18}F FDG	282	9.67	970.49	332.87		13.07	1319.05

the ICRP recommends relaxing weight restrictions [10].

The activity administered for an [^{18}F] FDG PET scan in adults is generally between 340 and 370, or 3.7 and 5.2 MBq/kg of body weight [30]. This activity depends not only on the patient's weight and the clinical protocol but also on the technological performance of the device. PET/CT systems combining TOF and point spread function (PSF) offer

Table 2. Summary of SPECT/CT DRLs and their indications.

				50th percentile			DRLs values (75th percentile)			
Authors	**Countries and years**	**Indications**	**Radiotracers**	**Activity (MBq)**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy·cm)**	**Activity (MBq)**	**Mass activity (MBq/kg)**	**CTDIvol (mGy)**	**DLP (mGy·cm)**
Roch et al. [2]	France, 2017	Bone cintigraphy	99mTc MDP/H MDP/D PD				670	9.5		
		Myocardial perfusion scintigraphy (stress/ress)	99mTc Sestami bi				800/300	10.5/3.7		
		Dynamic renal scintigraphy	99mTc DTPA				300			
Fayad et al. [23]		Dynamic renal scintigraphy Thyroid scintigraphy	99mTc MAG3 99mTc Pertech netate				180			
		Pulmonary perfusion scintigraphy	99mTc MAA				110			
	Qatar, 2023	Bone scintigraphy	99mTc HMDP, DPD,M DP	703	4.86	211.48	740		4.86	211.48
		Myocardial perfusion scintigraphy (Stress/ress)	99mTc Sestami bi	925	3.72	103.58	926/926		4.26	103.58
		Parathyroid scintigraphy	99mTc Sestami bi	374	-	-				
		Static renal scintigraphy	99mTc DMSA	75	-	-				
		Dynamic renal scintigraphy	99mTc DTPA	186	-	-				
		Dynamic renal scintigraphy	99mTc MAG3	185	-	-				
		Thyroid scintigraphy	99mTc Pertech netate	189	-	-				
		Pulmonary perfusion scintigraphy	99mTc MAA	74	-	-				
Wacha bauer et al. [3]	Austria, 2015	Bone scintigraphy	99mTc MDP/H MDP/D PD	663	-	-	772	-	-	-
		Myocardial perfusion scintigraphy (Stress/ress)	99mTc Sestami bi	1,084/100			1,141/1,558			
		Parathyroid scintigraphy		400			578			

				50th percentile			DRLs values (75th percentile)			
Authors	**Countries and years**	**Indications**	**Radiotracers**	**Activity (MBq)**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy·cm)**	**Activity (MBq)**	**Mass activity (MBq/kg)**	**CTDIvol (mGy)**	**DLP (mGy·cm)**
		Static renal scintigraphy		98			109			
		Dynamic renal scintigraphy		223			232			
		Dynamic renal scintigraphy		98			110			
		Thyroid scintigraphy		76			85			
		Pulmonary perfusion scintigraphy		126			150			
		MIBG scintigraphy		370			370			
Lima et al. [18]	Swiss, 2018	Bone scintigraphy	99mTc MDP/H MDP/D PD				700	10	10	410
		Myocardial perfusion scintigraphy (Stress/ress)	99mTc Sestami bi				300/900		2	40
		Parathyroid scintigraphy	99mTc Sestami bi				550		4	160
		Static renal scintigraphy	99mTc DMSA				120			
		Dynamic renal scintigraphy	99mTc MAG3				100			
		Thyroid scintigraphy	99mTc Pertech netate				75		4	160
		Pulmonary perfusion scintigraphy	99mTc MAA				180		3	110
Becker et al. [20]	United state, 2019	Bone scintigraphy	99mTc HMDP/ MDP/D PD				988			
		Thyroid scintigraphy	99mTc Pertech netate				407			
		Pulmonary perfusion scintigraphy	99mTc MAA				215			
Willega ignon et al. [21]	Brazil, 2016	Bone scintigraphy	99mTc HMDP/ MDP/D PD	1036			1,110			
		Myocardial perfusion scintigraphy (Stress/ress)	99mTc Sestami bi	1,110/370			1,110/444			

				50th percentile			DRLs values (75th percentile)			
Authors	**Countries and years**	**Indications**	**Radiotracers**	**Activity (MBq)**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy·cm)**	**Activity (MBq)**	**Mass activity (MBq/kg)**	**CTDIvol (mGy)**	**DLP (mGy·cm)**
		Parathyroid scintigraphy	^{99}mTc Sestami bi	740			740			
		Static renal scintigraphy	^{99}mTc DMSA	185			185			
		Dynamic renal scintigraphy	^{99}mTc DTPA	370			449			
		Thyroid scintigraphy	^{99}mTc Pertech netate	370			444			
		Pulmonary perfusion scintigraphy	^{99}mTc MAA	185			333			
Abe et al. [1]	Japan, 2020	Bone scintigraphy	^{99}mTc HMDP/ MDP/D PD	879.9	2.9	180	950		5.03	384.1
		Myocardial perfusion scintigraphy (Stress/ress)	^{99}mTc Sestami bi	1,076.4/755	3.2	89	1,200/880		4.5	180
		Parathyroid scintigraphy	^{99}mTc Sestami bi	785	3,3	133	800		5.73	205.1
		Static renal scintigraphy	^{99}mTc DMSA	185			210			
		MIBG scintigraphy	^{123}I MIBG	128.1			130			
		Dynamic renal scintigraphy	^{99}mTc DTPA	356.5			390			
		Dynamic renal scintigraphy	^{99}mTc MAG3	286.5			380			
		Thyroid scintigraphy	^{99}mTc Pertech netate	185			240			
		Pulmonary perfusion scintigraphy	^{99}mTc MAA	201			260			
Song et al. [22]	Korea, 2019	Bone scintigraphy	^{99}mTc MDP/H MDP/D PD	740			925			
		Parthyroid scintigraphy	^{99}mTc Sestami bi	740			740			
		Static renal scintigraphy	^{99}mTc DMSA	185			185			
		Dynamic renal scintigraphy	^{99}mTc DTPA	370			555			
		Dynamic renal scintigraphy	^{99}mTc MAG3	370			500			

				50th percentile			DRLs values (75th percentile)			
Authors	**Countries and years**	**Indications**	**Radiotracers**	**Activity (MBq)**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy·cm)**	**Activity (MBq)**	**Mass activity (MBq/kg)**	**CTDIvol (mGy)**	**DLP (mGy·cm)**
Alnaaimi et al. [24]	Kuwait, 2023	Thyroid scintigraphy	^{99}mTc Pertechnetate	185			217			
		Pulmonary perfusion scintigraphy	^{99}mTc MAA	185			222			
		MIBG Scintigraphy	^{123}I MIBG	11			222			
		Bone scintigraphy	^{99}mTc HMDP/MDP/DPD	927			944	9.25	2.7	166
		Parathyroid scintigraphy	^{99}mTc Sestami bi	875			900	5.55		
		Myocardial perfusion scintigraphy (stress/ress)	^{99}mTc Sestami bi	958/958			976/976	10.73	1.2	32
		Static renal scintigraphy	^{99}mTc DMSA	200			200	1.85		
		Dynamic renal scintigraphy	^{99}mTc DTPA	85			90	2.59		
		Dynamic renal scintigraphy	^{99}mTc MAG3	260			370	3.7		
Dundara et al. D [8]	Croatia, 2020	Thyroid scintigraphy	^{99}mTc Pertechnetate	185			185	1.11		
		Pulmonary perfusion scintigraphy	^{99}mTc MAA	204			218	2.59	2,1	69
		Bone scintigraphy	^{99}mTc HMDP/MDP/DPD	663			740	10		
		Myocardial perfusion scintigraphy (Stress/ress)	^{99}mTc Sestami bi	592/703			670/720	9/10		
		Parathyroid scintigraphy	^{99}mTc Sestami bi	555			600	9		
		Static renal scintigraphy	^{99}mTc DMSA	122			160	2		
		Dynamic renal scintigraphy	^{99}mTc DTPA	130			400	2		
		Dynamic renal scintigraphy	^{99}mTc MAG3	137			150	2		
		Thyroid scintigraphy	^{99}mTc Pertechnetate	187			400	3		

				50th percentile			DRLs values (75th percentile)			
Authors	**Countries and years**	**Indications**	**Radiotracers**	**Activity (MBq)**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy·cm)**	**Activity (MBq)**	**Mass activity (MBq/kg)**	**CTDIvol (mGy)**	**DLP (mGy·cm)**
Niksirat et al. [25]	Iran, 2016	Bone scintigraphy	99mTc HMDP/ MDP/D PD				893			
		Myocardial perfusion scintigraphy (Stress/ress)	99mTc Sestami bi				549/857			
		Parathyroid scintigraphy	99mTc DMSA				207			
		Static renal scintigraphy	99mTc DTPA				399			
		Thyroid scintigraphy	99mTc Pertech netate				280			
		Pulmonary perfusion scintigraphy	99mTc MAA				210			
Dambele et al. [26]	Nigeria, 2021	Bone scintigraphy	99mTc HMDP/ MDP/D PD	832.5			895.4			

better spatial resolution and increased sensitivity. TOF technology improves event localization by measuring the arrival time difference between annihilation photons. This enhances the signal-to-noise ratio and lesion contrast, allowing diagnostic image quality to be maintained with lower injected activity and shorter acquisition times. The use of TOF technology allows for a 20% reduction in the average administered activity without loss of image quality [31]. The use of TOF technology allows for a 20% reduction in the average administered activity without loss of image quality [31].

For bone scintigraphy, the European Association of Nuclear Medicine recommends that the administered activity of ^{99m}Tc-MDP should be between 300 and 740 MBq [32]. For obese adult patients, the administered activity may be increased to 11–13 MBq/kg to ensure optimal image quality [32]. The administered activity in scintigraphy depends on the type of detectors and collimators used. The introduction of CZT semiconductor detectors, combined with innovative collimators, provides better sensitivity and resolution, allowing the use of lower activities while maintaining optimal image quality. Indeed, CZT detectors provide direct conversion of gamma photons into electrical signals, unlike conventional NaI(Tl) scintillation crystals that require an intermediate light-conversion step. This direct conversion results in higher photon sensitivity, improved energy resolution, and better count-rate performance. The enhanced detection efficiency improves image quality and contrast recovery, enabling diagnostic images to be obtained with lower administered activities. Wachabauer et al. [3] reported in their study that only 3% of centers had SPECT/CT scanners equipped with CZT semiconductor detectors, with the majority of others still using solid scintillator (NaTl) detectors.

DRLs values must be established taking into account current technological advances in PET/CT and SPECT/CT equipment, such as CZT semiconductor detectors for SPECT/CT and TOF systems for PET/CT. These innovations improve sensitivity and image quality, suggesting that DRL values could decrease with technological advances [33,34].

Although increasing the administered activity not only improves image quality but also reduces acquisition time. Conversely, it is possible to reduce the activity while maintaining good image quality by increasing the acquisition time. However, prolonged acquisition times are impractical because they require patients to remain still and increase the risk of motion artifacts, causing blurring of images.

Furthermore, from a radiation protection standpoint, it is not desirable to systematically increase the administered activity to speed up patient flow in departments [29]. Therefore, the establishment of DRL should be accompanied by the systematic collection of data on acquisition time. This information is essential for a more representative assessment of the activity detected per patient and to ensure a consistent comparison between different institutions.

For the CT component of PET/CT and SPECT/CT examinations, the dose administered to patients depends on the purpose of the examination. When CT is used for diagnostic purposes, the DRLs for the CT component must comply with the DRLs established for diagnostic imaging examinations. However, for low-dose CT performed primarily for attenuation correction and anatomical localization, acquisition parameters such as tube current and voltage, slice thickness, rotation time, and pitch must be optimized to minimize patient radiation exposure while maintaining sufficient image quality for anatomo-functional fusion [33]. Six studies determined the DRLs for the CT component of PET/CT and SPECT/CT [1,18,19,23,24,27]. They were divided according to the scan regions. For whole-body PET/CT acquisitions, $CTDI_{vol}$ values ranged from 4 to 13.07 mGy, with DLP values ranging from 521 to 1,319.05 mGy·cm. In SPECT/CT, acquisitions show $CTDI_{vol}$ values ranging from 4.8 to 10 mGy for DLP values ranging from 211 to 410 mGy·cm. In 2012, Etard et al. [31] reported in their multicenter study that the DRLs for the CT portion associated with PET were set at 8 mGy for $CTDI_{vol}$ and 750 mGy·cm for DLP. Jallow et al. [35], meanwhile, reported the DRLs for $CTDI_{vol}$ by collecting all CT acquisition parameters associated with [^{18}F] FDG oncology imaging procedures at PET/CT clinical centers in the United States. They showed that the 75th percentile of CTDIvol for these procedures varied between 9.7 and 10.2 mGy. The differences observed in DRLs for $CTDI_{vol}$ and DLP between PET/CT and SPECT/CT studies could be explained by the variability of acquisition protocols (kVp, mA, pitch, collimation), total scan length, scanner characteristics (TOF, PSF, and automatic modulation), patient profile (weight morphology), and clinical objectives of CT (attenuation correction *vs.* comprehensive diagnostic examination). These factors highlight the importance of adapting local protocols while respecting optimization principles and contextualizing DRLs.

The methods used to determine the activity administered to patients vary between centers. Some follow fixed protocols or international guidelines, while others adjust the activity based on the patient's weight. However, it is important to note that the weight-based approach is not appropriate for certain PET/CT examinations, where the activity is concentrated in a specific organ, such as thyroid examinations, sentinel lymph node examinations, and pulmonary ventilation and perfusion studies. Alessio et al. [36] reported that there were no statistically significant differences between fixed and weight-adjusted injected activities for [^{18}F] FDG PET/CT and ^{99m}Tc bisphosphonate PET/CT examinations. In contrast, Roch et al. [37] recommended that the administered activity be determined based on the patient's weight in order to explore variations in activity between different clinical departments. Consequently, studies on DRLs should report mass activities (MBq/kg) for all PET/CT and SPECT/CT examinations in order to provide appropriate guidelines to clinical centers.

It should be emphasized that regional differences may have a significant impact on the establishment of local DRLs. Variations related to the availability of imaging technologies, particularly access to advanced PET systems such as TOF and CZT, as well as differences in acquisition and reconstruction protocols, patient morphological characteristics, administered activity practices, and national regulations, may explain the differences observed between DRLs from different regions, particularly between Asia and Europe.

No formal risk-of-bias or quality assessment tool was applied to the studies included in this review, which should be acknowledged as a limitation. Furthermore, the interpretation and comparison of the reported DRLs are constrained by methodological heterogeneity among the included studies. Notably, some studies established DRLs using weight-restricted patient populations, whereas others employed non–weight-restricted approaches, potentially influencing the reported DRL values and limiting direct comparability across studies. Additional variability arises from differences in imaging technologies. Several studies were performed using advanced PET systems incorporating TOF technology, while others relied on conventional PET scanners. Likewise, in SPECT/CT imaging, the use of CZT detector technology in certain studies may have affected image quality and enabled greater dose optimization compared

with conventional gamma camera systems. These variations in patient selection criteria and imaging technologies may have contributed to the observed differences in DRL values and highlight the need for standardized methodologies. Future studies should aim to harmonize DRL determination protocols and consider stratification according to imaging technology to improve comparability and clinical applicability.

Recommendations

Based on this study, the following recommendations are made for the development of DRLs:

Adopt a method without weight restrictions, as the application of weight-restriction criteria could reduce data availability.
A description of the PET/CT and SPECT/CT devices and the radiopharmaceutical administered must be provided.
Take into account the activity administered and detected in each patient as a reference parameter when developing DRLs.
Establish different DRLs for devices equipped with TOF and CZT technology.
Plan to establish DRLs for the CT component of PET/CT and SPECT/CT examinations, taking into account the purpose of the CT scan (diagnostic CT or attenuation correction and anatomical localization).

Conclusion

The DRLs are educational tools for comparison with practices in other countries. Studies show differences in the methods used to establish and vary DRLs in nuclear medicine. The non-standardization of activities administered for the same type of examination may reflect a lack of control over exposure to ionizing radiation. The implementation of DRLs could contribute significantly to reducing exposure, thereby offering the public examinations with controlled risks. DRLs based on both the injected activity and the radiation dose in CT scans can help ensure the radiation protection of patients.

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Conflict of interest

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Ethical approval and consent to participate

Ethical approval was not required for this study, as it is a systematic review-based exclusively on previously published data and does not involve human participants or animals.

Availability of data and materials

All data analyzed during this study are included in this published article and its supplementary information files. As this study is a systematic review, no new datasets were generated.

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