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Deliverable 2.8

Report on the current use of multi-modality systems in nuclear medicine

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1. Introduction

Deliverable 2.8 is part of Task 2.3 "Dose evaluation and optimisation of multimodality imaging", and is more specifically linked to Subtask 2.3.1 "European study on the current use of multi-modality systems and first-time establishment of European diagnostic reference levels (DRLS) for specific applications of computed tomography (CT) in multi-modality systems".

This deliverable aims to present the current status of CT instrumentation and the clinical use of CT in diagnostic nuclear medicine. In addition, a study on the availability of DRLs for these CT examinations was carried out.

First, a literature review of published data on CT doses in nuclear medicine was conducted, with specific emphasis on the availability of local or national DRLs for nuclear medicine related CT studies. Since it is possible that not all available DRLs are published in peer reviewed literature, the Heads of the European Radiological Protection Competent Authorities (HERCA) was contacted and requested to provide information on CT DRLs in nuclear medicine among their members.

Next, an EU-wide online survey was set up on the current status of multi-modality instrumentation and the clinical use of CT in nuclear medicine.

In the last part of this study, a detailed analysis of the clinical use of CT in diagnostic nuclear medicine was carried out in a selection of nuclear medicine departments. The main aim was to set up a database to establish European CT DRLs for nuclear medicine applications.

2. Literature review

PET and SPECT imaging often lack morphological information needed to localise the disease [1]. The combination of PET or SPECT with CT provides essential anatomical information, thereby improving the quality of and the confidence in the nuclear medicine diagnosis [2]. Another advantage of the CT component in hybrid imaging is that it can be used for attenuation correction of the functional images. This reduces the scan time significantly and reduces the additional costs associated with the replacement of transmission sources [1]. Today, hybrid imaging modalities such as PET/CT and SPECT/CT are well-established tools in nuclear medicine departments and play a vital role in the daily workflow of clinicians [3,4].

The risks from PET/CT and SPECT/CT are generally far outweighed by the benefits of the procedure when used appropriately. However, dual-modality imaging results in increased radiation exposures due to the combined dose from the CT component and the radiopharmaceutical. In nuclear medicine, CT acquisitions may be performed for different reasons. So, depending on the clinical task and the image quality requirements, the radiation dose to the patient may differ. For attenuation correction and localisation of the emission data, the CT dose can be relatively small. However, for hybrid systems with diagnostic CT capabilities, higher exposure levels are more likely. In addition, multimodality examinations are often used to monitor treatment responses which require multiple examinations. It is thus important to be aware of the additional dose to the patient from the CT component of the scan. Several studies have reported comparable or higher effective doses resulting from the CT component of a 18F-FDG whole body PET/CT examination, compared to the dose from a radiopharmaceutical [5-9]

Unlike in diagnostic radiology, published dose reference levels (DRLs) for CT used in hybrid imaging are limited. A review of published information on the clinical use of CT in nuclear medicine along with the corresponding CT doses and CT DRLs was conducted. Peer-reviewed articles on the subject of hybrid or multi-modality imaging were gathered from the Web of Science and PubMed databases.

Most hybrid imaging systems use a separate, conventional CT system in combination with a SPECT or PET gantry. They often have separate protocols for diagnostic-, localisation- and/or attenuation correction-exclusive purposes. Also, hybrid imaging devices exist that are only able to perform localisation and/or attenuation correction CT scans. These systems are called low-dose CT devices. Some examples are the GE Hawkeye SPECT/CT and Philips BrightView XCT SPECT/CT which make use of a conventional CT and CBCT, attached to the SPECT gantry, respectively.

Reported effective doses resulting from the CT component range from 1 to 16 mSv [8,10]. This large variation in dose levels is due to different factors such as the clinical use of the CT data and the range of CT technologies that are used in hybrid imaging systems. Since CT images can only be used for attenuation correction, attenuation correction and anatomical localisation, or diagnostic purposes, lower patient exposures are often sufficient to answer the relevant clinical question. This justifies the requirement for DRLs that are specific to nuclear medicine practice, and which may be different to existing DRLs for CT procedures.

To compare the dose levels of different national and international nuclear medicine departments, CT dose index ($CTDI_{vol}$) is the most relevant metric, whereas dose-length product (DLP) depends directly on the scan length applied at individual centres [11]. However, only a limited number of studies have published $CTDI_{vol}$ and DLP values resulting from the CT acquisition of dual-modality imaging protocols.

Below is an overview of the reported CT radiation doses for the most commonly performed hybrid imaging procedures in different countries. The data reported from Australia, Brazil, Bulgaria, France, Korea, Switzerland, the United Kingdom, the USA and recently also New Zealand are derived from nation-wide surveys in which participants were asked to provide as much information as possible about CT protocol settings utilised, the examined patients, the radiation dose and the intended aim of the scan. For the other reported countries, radiation doses were extracted from one to four hybrid imaging modalities mostly collected by university hospitals.

Table 1 and Table 2 display mean $CTDI_{vol}$ and DLP values reported in the literature for frequently performed ^{18}F-FDG PET/CT examinations within and outside Europe, respectively. Table 3 and Table 4 give an overview of the mean $CTDI_{vol}$ and DLP values reported in the literature for the most frequently performed SPECT/CT examinations within and outside Europe, respectively.

Diagnostic reference levels (DRLs) are intended to promote harmonisation and good standards of practice such that radiation doses to patients undergoing clinical procedures involving ionising radiation are minimised [11]. However, for the most part in nuclear medicine only DRLs for injected activities are currently available. Table 5 gives an overview of the published proposed national DRLs (nDRLs) for CT used in hybrid imaging. The SPECT/CT nDRLs for $CTDI_{vol}$ are all in reasonable agreement with each other, except those of bone imaging protocols in Switzerland which is due to the discrete categorizations of individual bone protocols according to the different anatomical structures commonly scanned [11]. There is also some variance in proposed nDRLs for PET/CT examinations which is probably due to differences in the descriptions of whole-body examinations. Generic descriptions used to describe some CT procedures can thus be a potential source of ambiguity since a protocol with the same name can be applied to different body regions [8,11]. For all examinations, high variability in nuclear medicine practice was observed. This highlights the need for optimisation in hybrid imaging to ensure that patient exposures are as low as reasonably possible and practicably consistent with the examination purpose [8].

Table 1: Overview of the mean $CTDI_{vol}$ and DLP values reported in literature, for the most frequently performed ^{18}F-FDG PET/CT examinations in Europe (Bulgaria [12], France [5], Germany [6], Switzerland [11] and the United Kingdom [8]). For each examination, the objective of the CT scan is indicated as AC (Attenuation Correction), L (Localisation) or D (Diagnostic) or as a combination of different objectives.

Examination	**Purpose**	**Country**	**N° of systems included**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy.cm)**
Brain	AC + L	Swiss [a]	8	7.1	97
		United Kingdom [a]	7	12.6	236
Brain	AC + D	United Kingdom [a]	3	16.4	315
		Swiss [a]	3	36.2	389
Tumour imaging	AC + L	Bulgaria [a]	6	4.0	392
		France [a]	56	6.6	628
		Swiss [a]	12	4.4	416
		United Kingdom [a]	28	3.4	326
		Germany [b]	4	2.0	-
Tumour imaging	AC + D	Swiss [a]	6	7.0	583
		United Kingdom [a]	6	5.0	363
		Germany [b]	4	11.7	-

[a] Data from a national survey

[b] Data from 4 university hospitals (4 PET/CT modalities)

Table 2: Overview of the mean $CTDI_{vol}$ and DLP values reported in literature, for the most frequently performed ^{18}F-FDG PET/CT examinations outside Europe (Australia [13,14], Brazil [15], Canada [9], India[16], Korea [17], New Zealand [13], USA [18, 19]). For each examination, the objective of the CT scan is indicated as AC (Attenuation Correction), L (Localisation) or D (Diagnostic) or as a combination of different objectives.

Examination	**Purpose**	**Country**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy.cm)**
Brain	AC + L	Australia [a]	-	325
		Brazil [a]	5.11	-
		India [b]	13.1	197
Brain	AC + D	India [b]	20.6	309
Tumour imaging	AC + L	Australia [a]	4.41	474
		Brazil [a]	6.76	-
		Canada [b]	4.3	368
		India [b]	4.3	434
		Korea [a]	4.6	429.2
		New Zealand [a]	13.07	1319.05
		USA [a]	7.0	-
Tumour imaging	AC + D	India [b]	6.6	674
		USA [a]	11.7	672

[a] Data from a national survey

[b] Data from 1 PET/CT modality

Table 3: Overview of the mean $CTDI_{vol}$ and DLP values reported in literature, for the most frequently performed SPECT/CT examinations in Europe (Bulgaria [20], Switzerland [11] and the United Kingdom [8]). For each examination, the objective of the CT scan is indicated as AC (Attenuation Correction), L (Localisation) or D (Diagnostic) or as a combination of different objectives.

Examination	**Purpose**	**Country**	**N° of systems included**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy.cm)**
Bone scan (^{99m}Tc)	AC + L	Bulgaria [a]	4	5.7	236
		United Kingdom [a]	32	4.5	150
Bone scan (^{99m}Tc)	AC + D	United Kingdom [a]	3	13.5	444
Cardiac (^{99m}Tc)	AC	Bulgaria [a]	4	1.5	27
		Swiss [a]	11	2.2	75
		United Kingdom [a]	30	2.0	33
mIBG/octreotide	AC + L	Swiss [a]	6	4.6	210
		United Kingdom [a]	14	4.5	201
Thyroid scan (^{99m}Tc)	AC + L	Bulgaria [a]	4	2.1	86
		Swiss [a]	8	4.4	142
Parathyroid imaging (^{99m}Tc)	AC + L	Bulgaria [a]	4	5.7	192
		Swiss [a]	8	4.4	142
		United Kingdom [a]	36	7.4	164
Parathyroid imaging (^{99m}Tc)	AC + D	Swiss [a]	5	15.6	500
		United Kingdom [a]	5	13.4	287
Post-thyroid ablation (^{131}I)	AC + L	Bulgaria [a]	4	4.1	120
		United Kingdom [a]	15	4.5	141

[a] Data from a national survey

Table 4: Overview of the mean $CTDI_{vol}$ and DLP values reported in literature, for the most frequently performed SPECT/CT examinations outside Europe (Australia[14], Canada [3], Iran [21], USA [22]). For each examination, the objective of the CT scan is indicated as AC (Attenuation Correction), L (Localisation) or D (Diagnostic) or as a combination of different objectives.

Examination	**Purpose**	**Country**	**$CTDI_{vol}$ (mGy)**	**DLP (mGy.cm)**
Bone scan (^{99m}Tc)	AC + L	Australia [a]	-	240
		Canada [b]	6.5	281
Cardiac (^{99m}Tc)	AC	Australia [a]	-	45
		Canada [b]	0.5	7
		Iran [b]	1.3	-
Parathyroid imaging (^{99m}Tc)	AC + L	Australia [a]	-	255
		USA [a]	4.3	152
Post-thyroid ablation (^{131}I)	AC + L	Canada [b]	6.5	281

[a] Data from a national survey

[b] Data from 1 SPECT/CT modality

Table 5: Overview of the proposed nDRLs for CT in hybrid imaging of Australia[13,14], Bulgaria [20], France [5], Korea [17], New Zealand [13], Switzerland [11], the USA [19] and the United Kingdom [8]. For the SPECT/CT examinations the objective of the CT scan is indicated as AC (Attenuation Correction) or AC + L (Attenuation Correction + Localisation).

Modality	Examination	Country	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)
PET/CT	^{18}F-FDG whole body	Australia	4.41	474
		France	8.0	750
		Korea	5.96	560
		New Zealand	13.07	1319.05
		Swiss	5.0	720
		USA	9.8	-
	^{18}F-FDG half body	United Kingdom	4.3	400
SPECT/CT	^{99m}Tc bone imaging (AC + L)	Australia	-	240
		Bulgaria	3.0	200
		United Kingdom	4.9	150
	^{99m}Tc bone pelvis (AC + L)	Swiss	10.0	410
	^{99m}Tc bone spine (AC + L)		5.0	190
	^{99m}Tc bone extremities (AC + L)		17.0	380
	^{99m}Tc cardiac imaging (AC)	Australia	-	45
		Bulgaria	3	70
		Swiss	2.0	40
		United Kingdom	2.1	36
	^{99m}Tc mIBG/octreotide (AC + L)	Swiss	5.0	250
		United Kingdom	5.5	240
	^{99m}Tc parathyroid imaging (AC + L)	Australia	-	255
		Bulgaria	6.0	160
		Swiss	4.0	160
		United Kingdom	5.6	170
	^{131}I post-thyroid ablation (AC + L)	Bulgaria	4.0	160
		Swiss	4.0	160
		United Kingdom	5.9	210
	^{99m}Tc thyroid imaging (AC + L)	Bulgaria	4.0	170
		Swiss	4.0	160

3. HERCA information on available CT DRLs for multimodality imaging

HERCA was contacted through the Belgian Federal Agency of Nuclear Control and was kindly willing to collect information in the HERCA working group on medical applications on available DRL values as well as within ongoing projects for establishing CT DRLs in nuclear medicine.

We received the following information:

- **Czech Republic:** In the early stages of data collection from hospitals and conducting research on CT DRLs in nuclear medicine.
- **Denmark:** Only DRLs available for the administered activities.
- **France:** A national survey of patient doses from whole-body FDG PET/CT examinations in France was conducted in 2011[1]. The corresponding DRLs were recently updated in May 2019: CTDI of 7 mGy, DLP of 650, or 1200 mGycm for a half-body or full body CT [23].
- **Germany:** No specific DRLs for CT in hybrid imaging~~,~~; for the CT part, the DRLs for CT-imaging of adults and children are used [24].
- **Slovenia:** A student is currently collecting CT doses for the CT part of PET/CT imaging as part of her master thesis research. Due to the very low number of PET/CT scanners in Slovenia (only 3), they will not use the data to set actual DRLs but will use them to compare the practices with each other and with DRLs established in other countries. The data is expected to be available by the end of 2019 or early 2020.
- **Switzerland:** CT DRLs in nuclear medicine are available as published earlier [11,25]
- **UK:** CT DRLs in nuclear medicine are available as published earlier [8,26]

For the remaining countries there are no current values or plans, or no information has been provided to the working group.

4. Online survey

4.1 Survey design

An EU-wide online survey to gather information on the current implementation and use of multi-modality imaging in nuclear medicine was set up using the online Qualtrics software tool. This survey is available on the website http://www.medirad.ugent.be (Figure 1).

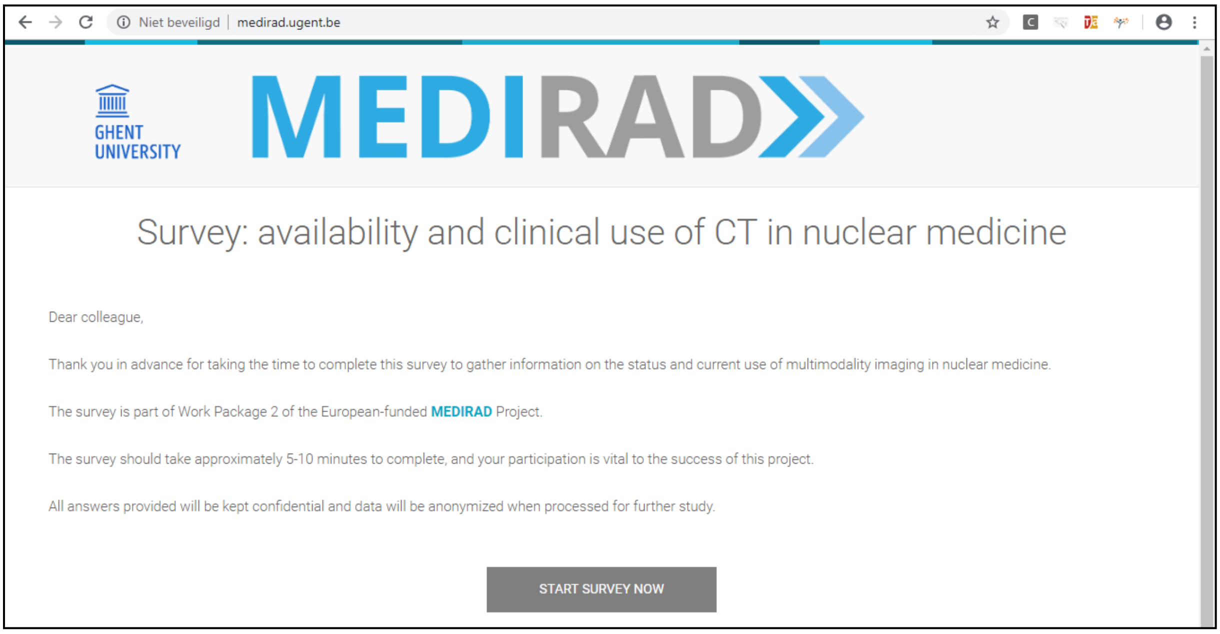


Figure 1: Screenshot of the start page of the online survey

The survey gathers information on:

- Country
- Type of hospital: university/non-university
- Number of hybrid systems available
- Used tracers for SPECT and PET studies
- Specifications of the CT system: brand/type; number of CT slices; availability of tube current modulation, iterative reconstruction and adaptive collimation
- Clinical use of CT: fraction on diagnostic nuclear medicine studies using CT for different indications (bone, cardiac, thyroid, brain, oncology, etc.); purpose of the CT scan (attenuation correction (AC), anatomical localisation (AL) or diagnostic CT (D)); use of CT contrast
- CT protocol: acquisition parameters; are dose reduction tools used?
- CT dosimetry data: are CT dose data stored in dose management databases and regularly evaluated?
- CT training: are staff (nuclear medicine physicians, medical physicists, nuclear medicine technologists) properly trained in CT technology and dosimetry?

4.2 Survey distribution

The survey was initially sent out to 305 nuclear medicine departments. Later, the survey was advertised through different newsletters and Twitter posts of the European Association of Nuclear Medicine (EANM). The International Atomic Energy Agency (IAEA) also kindly distributed this survey through their network.

4.3 Survey results

A total of 191 responses from 38 countries were received until October 2019 (Table 6). 58.3% of the responses came from university hospitals.

Table 6: Number of responses per country

Country	N° of responses	Country	N° of responses
Albania	2	Latvia	1
Austria	7	Lithuania	4
Azerbaijan	1	Luxembourg	1
Belarus	1	Macedonia	4
Belgium	19	Malta	2
Bosnia and Herzegovina	3	Netherlands	10
Bulgaria	8	Norway	2
Croatia	4	Poland	2
Czech Republic	3	Portugal	6
Denmark	3	Romania	2
Estonia	3	Russia	3
Finland	3	Serbia	2
France	16	Slovakia	1
Germany	32	Slovenia	1
Greece	4	Spain	6
Hungary	3	Sweden	4
Ireland	3	Switzerland	2
Italy	18	Turkey	1
Kazakhstan	2	Ukraine	2

Overall, 85% of the PET systems available in the hospitals of the responders are equipped with a CT, whereas SPECT CT is available in only 40% of the cases. In the latter case, often low-end CT systems are implemented (single-slice to 4 slice CT scanners without tube-current modulation and iterative reconstruction), whereas with PET state-of-the art CT instrumentation can be found (64 slice CT scanners equipped with modern dose-reduction tools).

Most frequently performed diagnostic SPECT studies are ^{99m}Tc-bone, ^{99m}Tc-parathyroid, ^{99m}Tc-sentinel node and ^{99m}Tc-cardiac, whereas for PET, ^{18}FDG half/whole body, ^{18}FDG-brain and ^{18}FDG-cardiac are the most frequently preformed studies. In Table 7, reported administered activities for a reference adult of 70 kg are represented. The latter values are in agreement with published data and reference levels [27].

Table 7: Administered activities for the most common nuclear medicine examinations (70kg adult)

Application	Average activity (MBq)	Standard deviation (MBq)	3rd quartile value (MBq)
^{99m}Tc-bone	640	96	740
^{99m}Tc-parathyroid	525	162	600
^{99m}Tc-cardiac	725	220	850
^{99m}Tc-sentinel node	63	37	80
^{18}FDG half/whole body	270	70	310
^{18}FDG-brain	205	60	220
^{18}FDG-cardiac	290	80	370

The frequency of CT use in diagnostic SPECT and PET imaging is illustrated in Figure 2 and Figure 3, respectively. For SPECT and PET, the clinical purpose of the CT study is documented in Figure 4 and Figure 5, respectively. Especially in PET examinations, CT is routinely performed in clinical practice. In the latter case, full diagnostic CT scans (with and without CT contrast medium) are more often implemented in comparison with SPECT/CT studies. However, for both SPECT/CT and PET/CT, the majority of CTs are linked to attenuation correction and anatomical localisation. In cardiac SPECT/CT, CT is mainly used for attenuation correction of the emission scans.

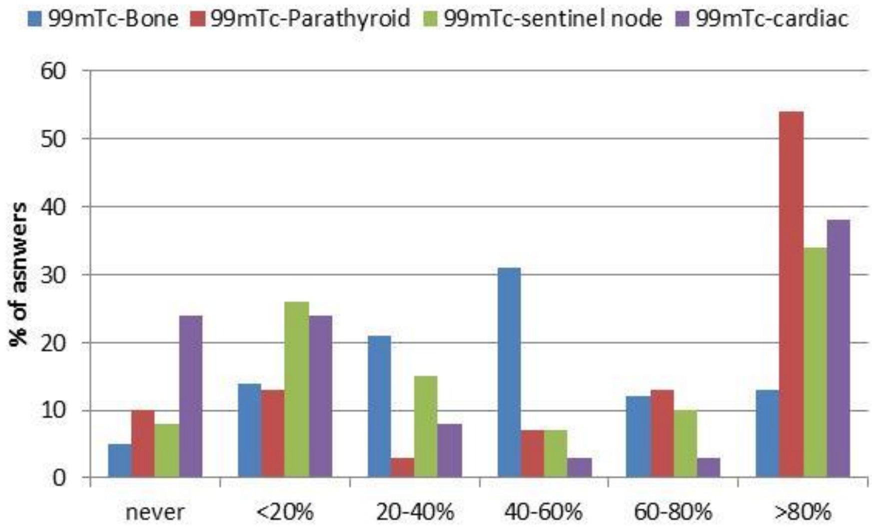


Figure 2: The relative use (%) of CT in the most common SPECT examinations

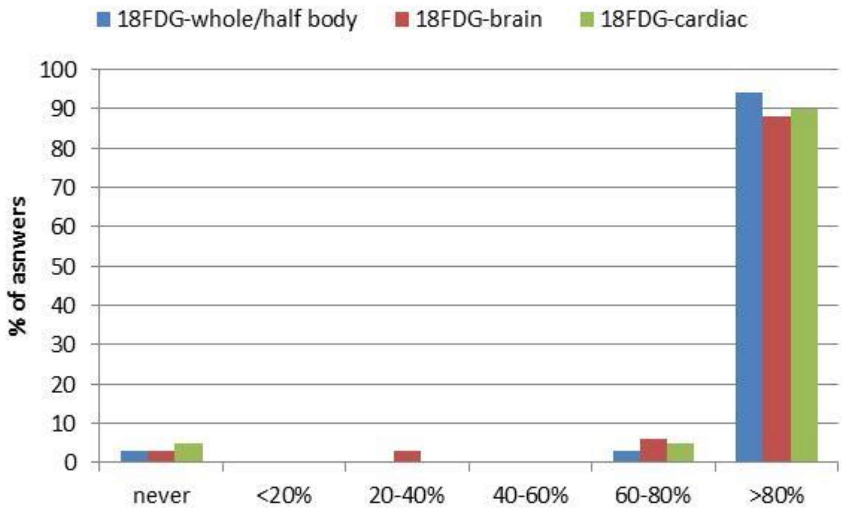


Figure 3: The relative use (%) of CT in the most common PET examinations

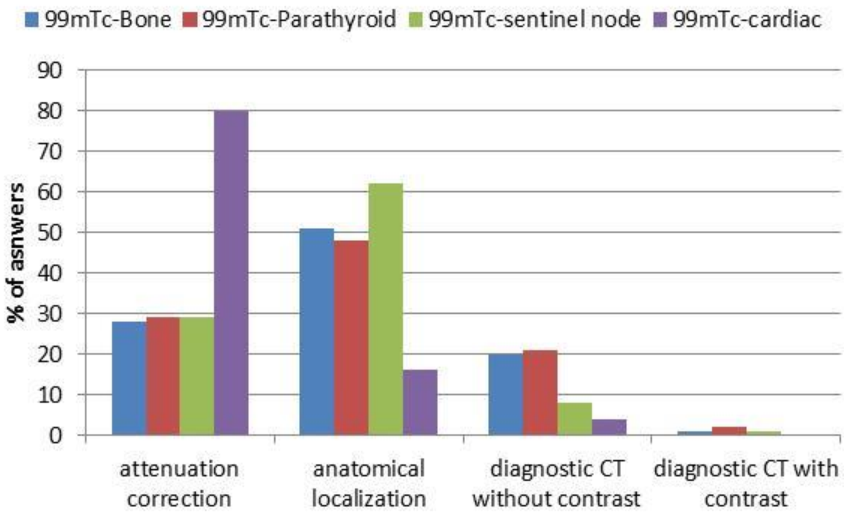


Figure 4: Clinical purpose of the CT acquisition in SPECT/CT studies

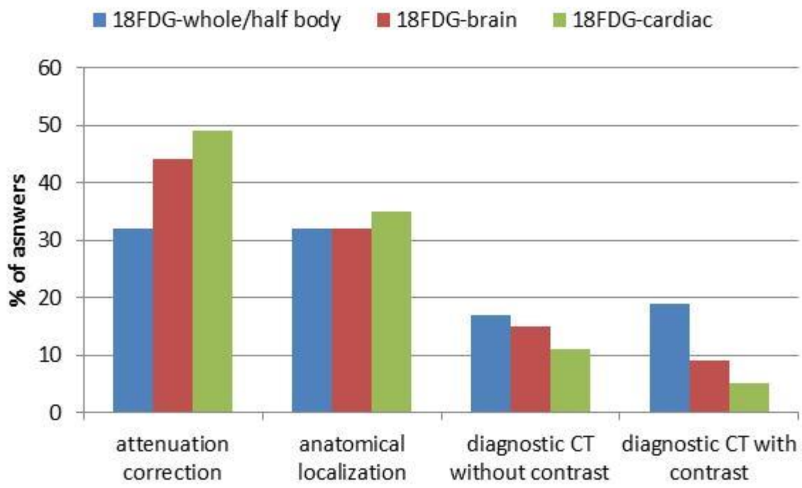
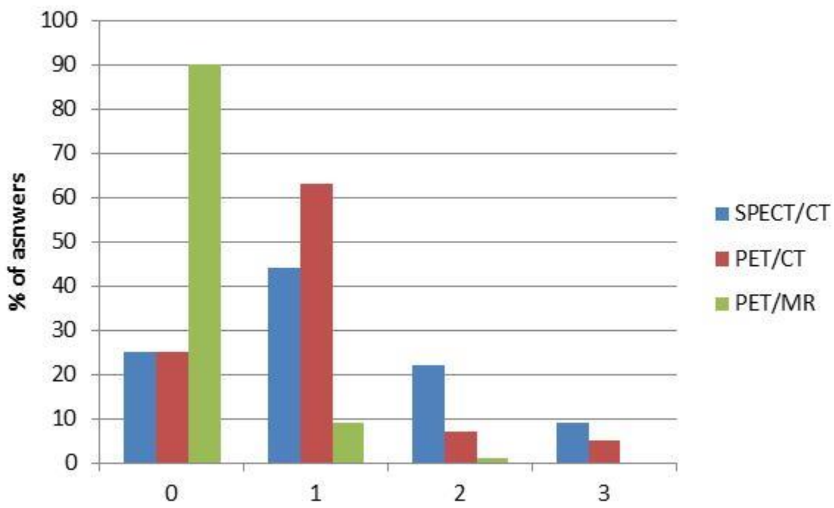


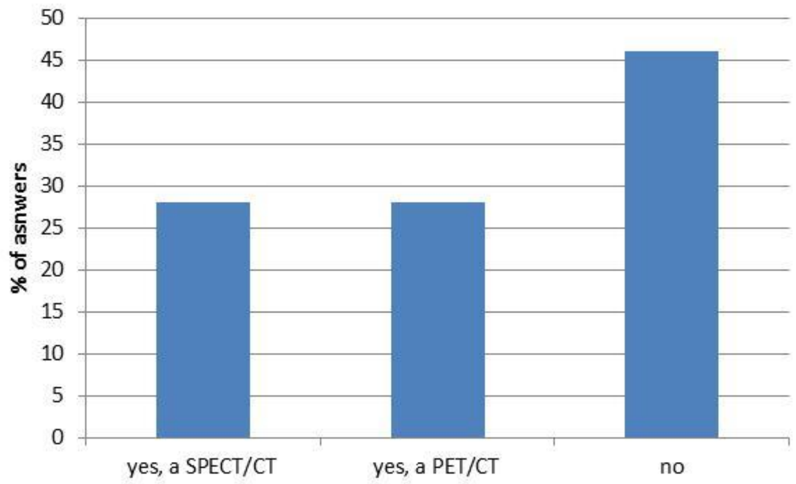
Figure 5: Clinical purpose of the CT acquisition in PET/CT studies

A summary of other specific survey questions and corresponding answers is presented below.

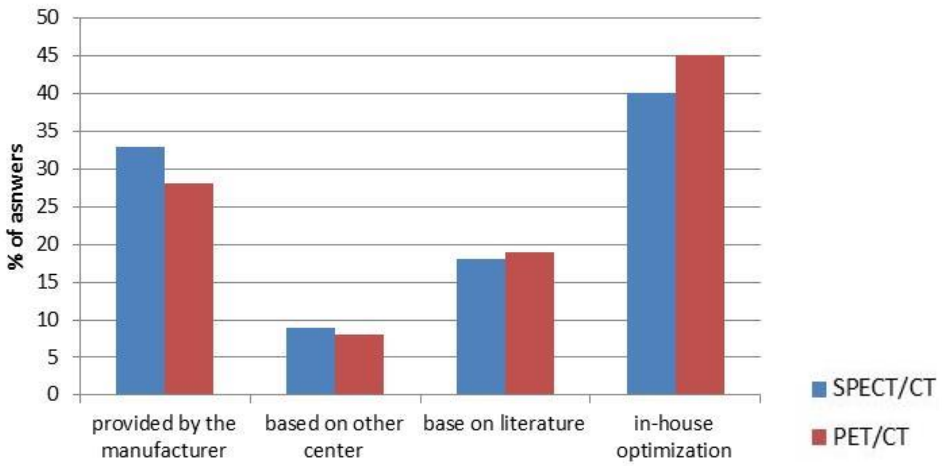
- **How many SPECT/CT, PET/CT and/or PET/MR systems are available in your hospital?**



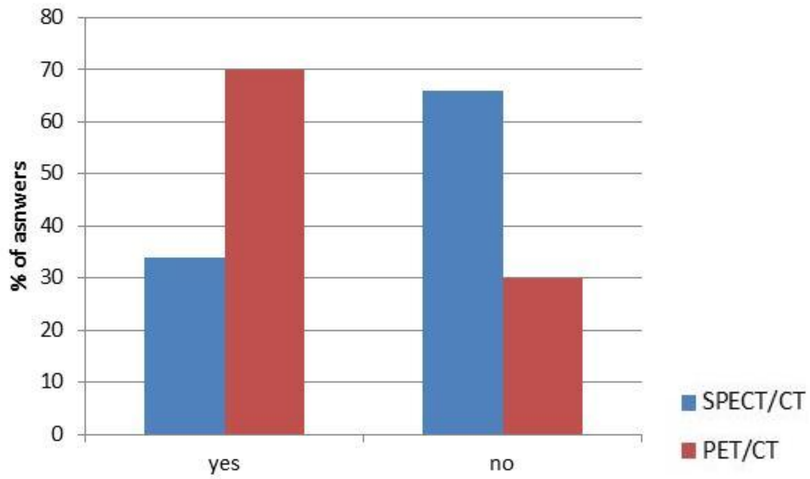
- **Do you plan to buy a new hybrid system in the near future (2019/2020)?**



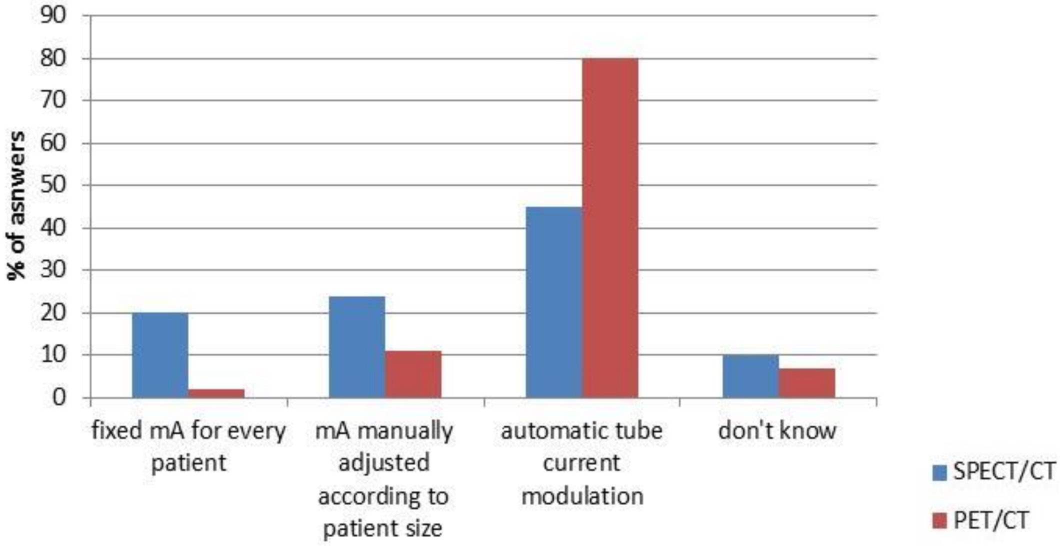
- **How were the CT protocols set up for your SPECT/CT and/or PET/CT system?**



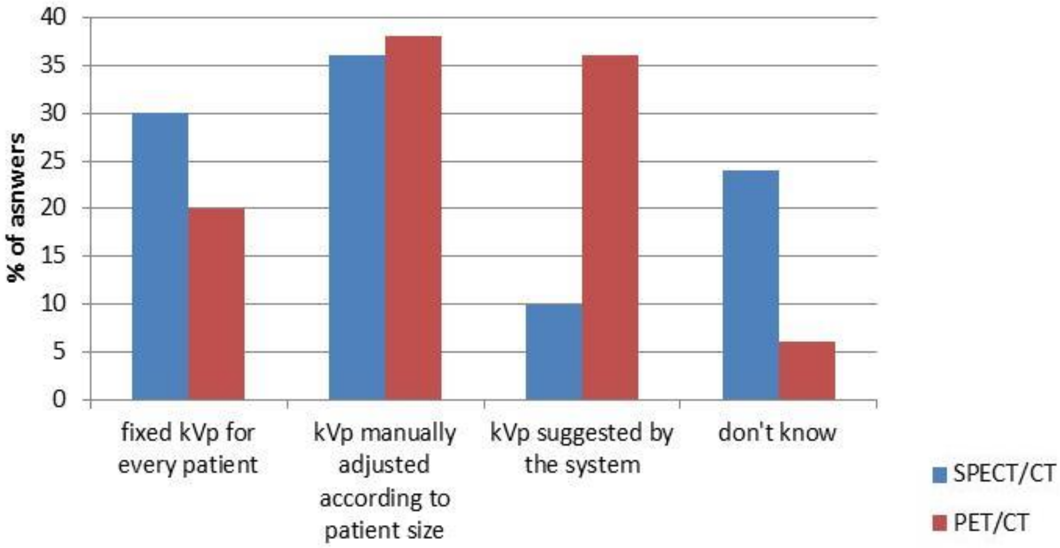
- **Are dedicated paediatric CT protocols available on your SPECT/CT and/or PET/CT system?**



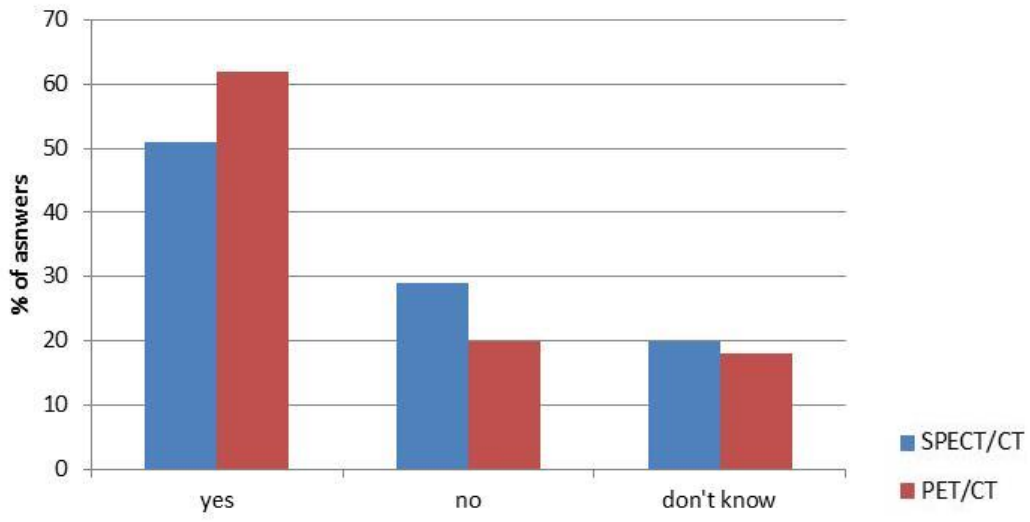
- **How is the tube current (mA) for CT scanning set on your SPECT/CT and/or PET/CT system?**



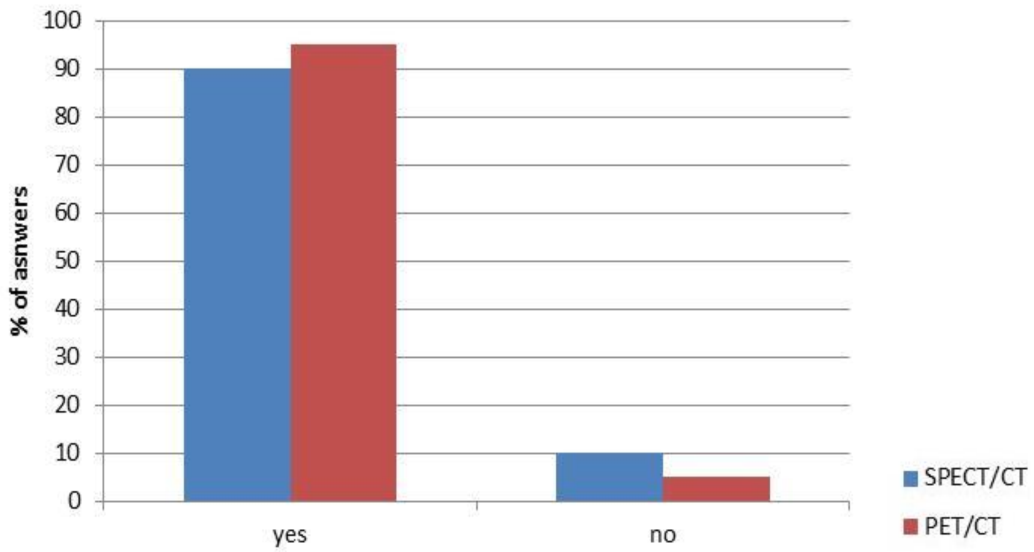
- **How is the tube voltage (kVp) for CT scanning set on your SPECT/CT and/or PET/CT system?**



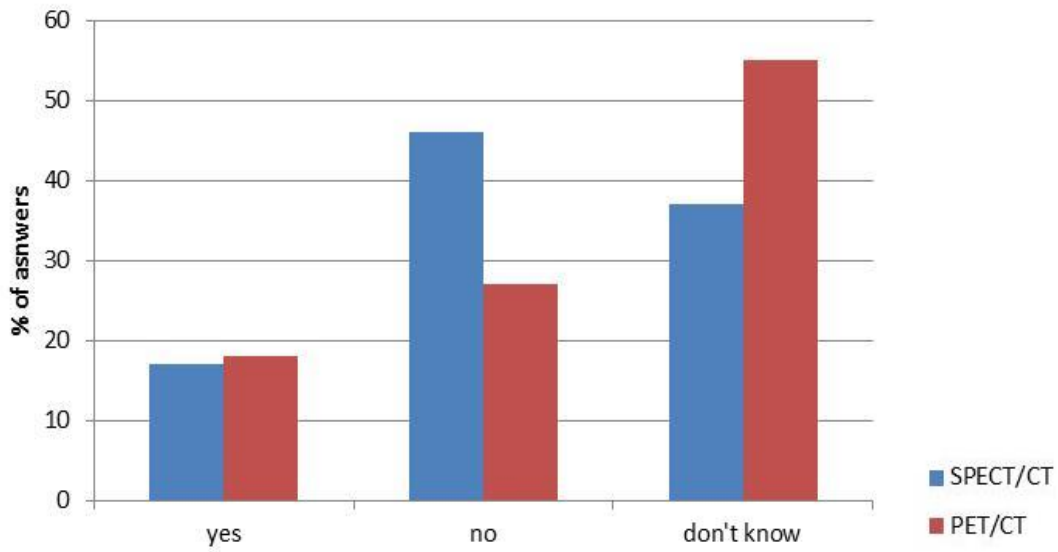
- **Is iterative reconstruction available on your SPECT/CT and/or PET/CT system?**



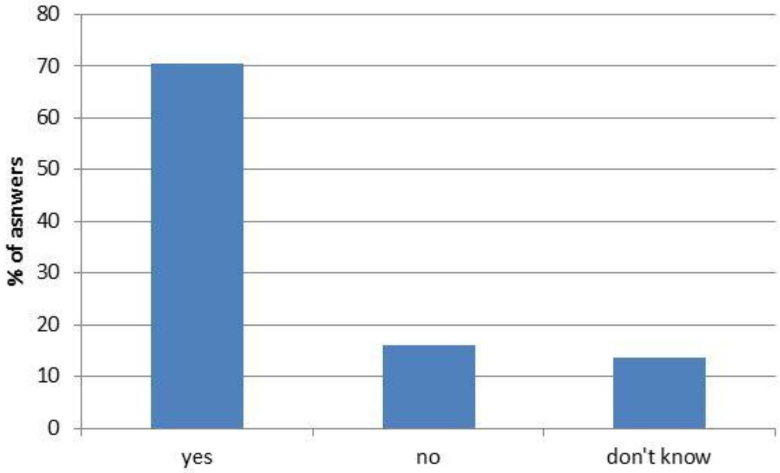
- **If iterative reconstruction is available, is it used in routine clinical practice?**



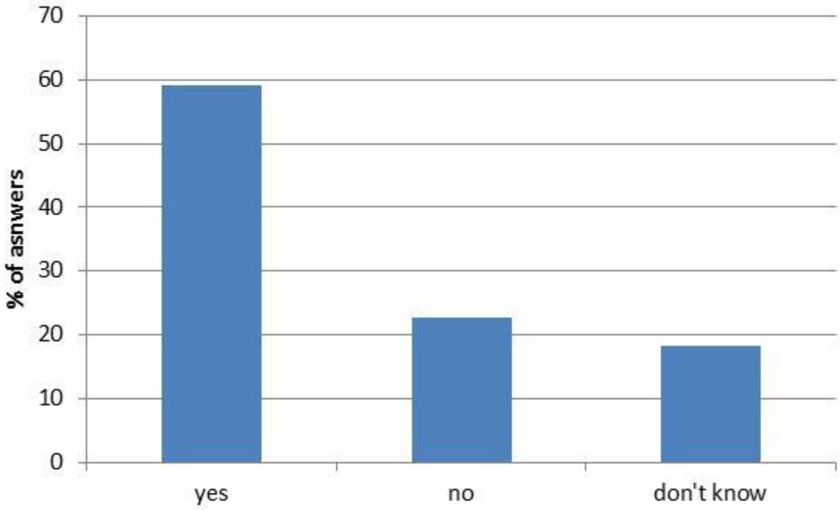
- **Is adaptive collimation available on your SPECT/CT and/or PET/CT system?**



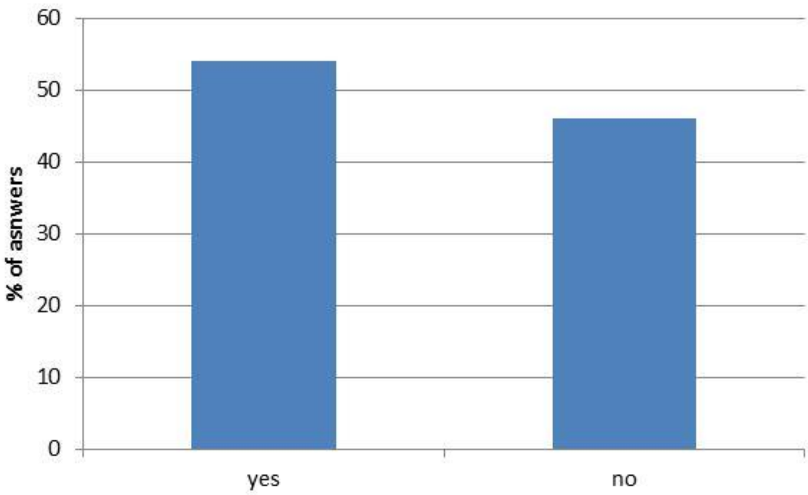
- **Are CTDI and DLP values for each exam stored in a local CT dose database / dose management system?**



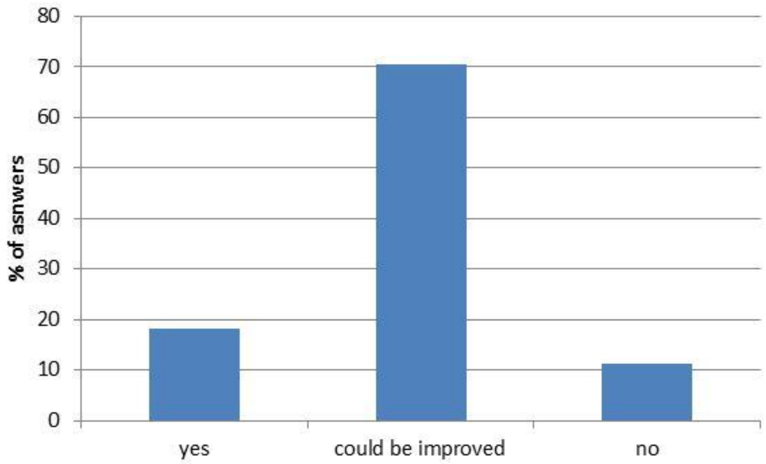
- **Are CTDI and DLP values regularly analysed?**



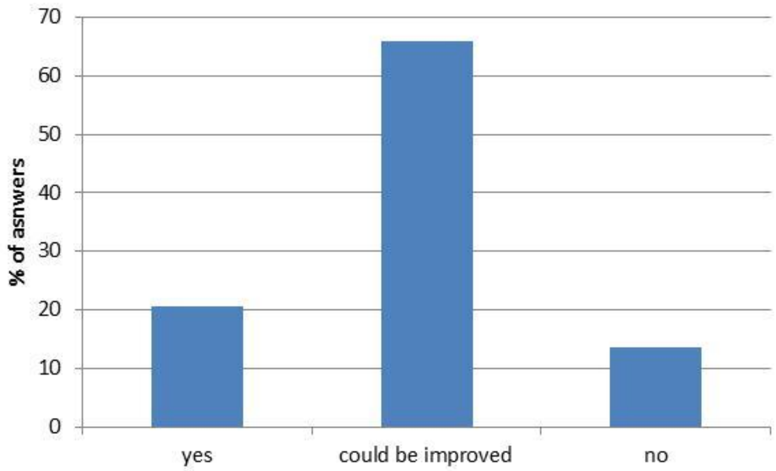
- **Are you willing to share CT dose information of a sample group of your patients? The latter data will help to establish European diagnostic reference levels for CT acquisitions in nuclear medicine.**



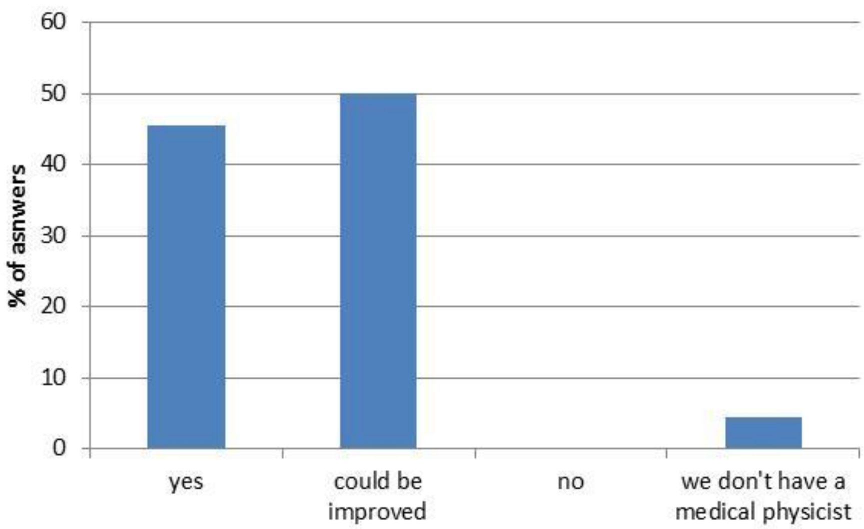
- **In your opinion, are the nuclear medicine <u>physicians</u> in your department sufficiently trained in CT dosimetry?**



- **In your opinion, are the nuclear medicine <u>technologists</u> in your department sufficiently trained in CT dosimetry?**



- **In your opinion, are the nuclear medicine <u>physicists</u> in your department sufficiently trained in CT dosimetry?**



5. Clinical use of CT: a study in 20 departments of nuclear medicine

In addition to the online survey, an analysis of the clinical use of CT in nuclear medicine was carried out in 10 Belgian nuclear medicine departments (pilot study) and 10 other European nuclear medicine departments in 8 European countries (Netherlands, France, Germany, Czech Republic, UK, Luxembourg, Sweden, Poland). The main aim was to generate a database on the CT dose parameters $CTDI_{vol}$ and DLP as a basis to establish European CT DRLs for nuclear medicine applications. To do so, an electronic data collection form (using MS Excel) was developed to capture information related to both the CT scanner protocol and patient-specific information. Participating centres were asked to complete the form for up to 30 patients per examination for the most frequently performed hybrid imaging studies.

As the technical variability in SPECT/CT and PET/CT systems among nuclear medicine departments is large, and since there are substantial differences in applied CT protocols, a dataset retrieved from 20 departments is far too limiting for European DRLs. Moreover, a better representation of different European countries is required in order to ensure the validity and acceptance of the derived MEDIRAD DRLs in Europe. Therefore, we sent the form to 95 nuclear medicine departments that expressed their interest in the survey to share CT dose data. CT dose dataset collection is still ongoing and will end December 2019. Currently, data from 45 departments of nuclear medicine from 15 countries have been received. The latter data will be analysed in Deliverable 2.10.

6. Conclusions

- Published national DRLs for CT applications in nuclear medicine are scarce. The latter highlights the need to establish EU-wide reference levels, which will be covered in Deliverable 2.10 of the MEDIRAD Project.
- The currently available SPECT/CT nDRLs for $CTDI_{vol}$ are overall in reasonable agreement with each other; nDRL variations are considerably larger for PET/CT examinations.
- The administered activities for the most commonly performed nuclear medicine studies reported in the survey are in good agreement with published reference levels of the EU Radiation Protection N°180 publication.
- The majority (75%) of the survey responders have one or more SPECT/CT and/or PET/CT devices in the department of nuclear medicine. More than half of the respondents indicated that they will invest in a new SPECT/CT or PET/CT in the coming months, thereby most probably further increasing the number of hybrid imaging systems in Europe.
- Modern dose reduction techniques (such as iterative reconstruction, tube current modulation, automated kVp suggestion) are widely available in hybrid imaging systems, especially in the case of PET/CT
- In about 90% of the PET examinations, CT acquisitions are performed. The use of CT in SPECT examinations seems less systematic and standardized. For both SPECT/CT and PET/CT, the main purpose of the CT acquisition is attenuation correction and/or anatomical localisation.
- The use of diagnostic CT in hybrid imaging is associated with strong differences between hospitals. In some centres, hybrid CTs are always classified as a diagnostic CT, while other departments never perform diagnostic scans.
- The survey reveals that there are no specific paediatric CT protocols available in about 30% and 65% of the PET/CT and SPECT/CT systems, respectively.
- In the large majority (70%) of nuclear medicine departments, CT doses are centrally stored in a database or dose management system. Yet, only half of the responders is willing to share CT dose data to establish European CT DRLs in nuclear medicine.

- About 70% of nuclear medicine physicians and nuclear medicine technologists indicate that their knowledge on CT technology and dosimetry could be improved. The latter could be achieved by addressing this issue in CME sessions of radiological and nuclear medicine conferences.

7. References

1. Lee, T.C., et al., Morphology supporting function: attenuation correction for SPECT/CT, PET/CT, and PET/MR imaging. Quarterly Journal of Nuclear Medicine and Molecular Imaging, 2016. 60(1): p. 25-39.
2. Bockisch, A., et al., Hybrid Imaging by SPECT/CT and PET/CT: Proven Outcomes in Cancer Imaging. Seminars in Nuclear Medicine, 2009. 39(4): p. 276-289.
3. Tonkopi, E. and A.A. Ross, Assessment of Effective Dose from Cone Beam Ct Imaging in Spect/Ct Examination in Comparison with Other Modalities. Radiation Protection Dosimetry, 2016. 172(4): p. 438-442.
4. Salvatori, M., et al., Radiation dose in nuclear medicine: the hybrid imaging. La Radiologia medica, 2019.
5. Etard, C., et al., National survey of patient doses from whole-body FDG PET-CT examinations in France in 2011. Radiation Protection Dosimetry, 2012. 152(4): p. 334-338.
6. Brix, G., et al., Radiation exposure of patients undergoing whole-body dual-modality 18F-FDG PET/CT examinations. Journal of nuclear medicine: official publication, Society of Nuclear Medicine, 2005. 46(4): p. 608-13.
7. Avramova-Cholakova, S., et al., Patient Doses from Pet-Ct Procedures. Radiation Protection Dosimetry, 2015. 165(1-4): p. 430-433.
8. Iball, G.R., et al., A national survey of computed tomography doses in hybrid PET-CT and SPECT-CT examinations in the UK. Nuclear Medicine Communications, 2017. 38(6): p. 459-470.
9. Tonkopi, E., A.A. Ross, and A. MacDonald, JOURNAL CLUB: CT Dose Optimization for Whole-Body PET/CT Examinations. American Journal of Roentgenology, 2013. 201(2): p. 257-263.
10. Brix, G., et al., Radiation exposure of patients undergoing whole-body dual-modality 18F-FDG PET/CT examinations. Journal of nuclear medicine: official publication, Society of Nuclear Medicine, 2005. 46(4): p. 608-13.
11. Lima, T.V.M., et al., Swiss survey on hybrid imaging CTs doses in Nuclear Medicine and proposed national dose reference levels. Zeitschrift fur medizinische Physik, 2018. 28(4): p. 265-275.
12. Avramova-Cholakova, S., et al., SECOND NATIONAL SURVEY OF PATIENT DOSES FROM PET/CT EXAMINATIONS IN BULGARIA, in International Conference on Radiation Protection in Medicine. 2017: Vienna Austria. p. 4.
13. Alkhybari, E.M., et al., Diagnostic reference levels for 18F-FDG whole body PET/CT procedures: Results from a survey of 12 centres in Australia and New Zealand. Journal of Medical Imaging and Radiation Oncology, 2019: p. 9.
14. Australian Radiation Protection and Nuclear Safety Agency. Nuclear Medicine Diagnostic Reference Levels (DRLs). 2017; Available from: https://www.arpansa.gov.au/sites/default/files/nuclear-medicine-diagnostic-reference-levels.

15. Willegaignon, J., et al., Diagnostic reference level: an important tool for reducing radiation doses in adult and pediatric nuclear medicine procedures in Brazil. Nuclear medicine communications, 2016. 37(5): p. 525-33.
16. Kaushik, A., et al., Estimation of patient dose in 18F-FDG and 18F-FDOPA PET/CT examinations. Journal of Cancer Research and Therapeutics, 2013. 9(3): p. 477-483.
17. Kwon, H.W., et al., Radiation Dose from Whole-Body F-18 Fluorodeoxyglucose Positron Emission Tomography/Computed Tomography: Nationwide Survey in Korea. Journal of Korean Medical Science, 2016. 31: p. S69-S74.
18. Alessio, A., et al., Survey of CT radiation dose levels during PET/CT from ACR CT Dose Index Registry. Journal of Nuclear Medicine, 2015. 56(3).
19. Jallow, N., et al., Diagnostic Reference Levels of CT Radiation Dose in Whole-Body PET/CT. Journal of Nuclear Medicine, 2016. 57(2): p. 238-241.
20. Avramova-Cholakova, S., et al., Patient Doses from Hybrid Spect-Ct Procedures. Radiation Protection Dosimetry, 2015. 165(1-4): p. 424-429.
21. Abdollahi, H., et al., Radiation dose in cardiac SPECT/CT: An estimation of SSDE and effective dose. European journal of radiology, 2016. 85(12): p. 2257-2261.
22. Nye, J., et al., Survey of CT dose for parathyroid SPECT/CT scans within the VA system. Journal of Nuclear Medicine, 2014. 55.
23. https://nrd.irsn.fr/Ressources/Documents/Decision_NRD_2019.pdf
24. http://www.bfs.de/SharedDocs/Downloads/BfS/DE/fachinfo/ion/drw-roentgen.pdf?__blob=publicationFile&v=9
25. https://www.bag.admin.ch/bag/fr/home/gesetze-und-bewilligungen/gesuche-bewilligungen/bewilligungen-aufsicht-im-strahlenschutz/wegleitungen.html
26. https://www.gov.uk/government/publications/diagnostic-radiology-national-diagnostic-reference-levels-ndrls/ndrl#national-drls-for-computed-tomography-ct (Table 2c)
27. RP 180 - Medical Radiation Exposure of the European Population, Part 2. Luxembourg: Publications Office of the European Union, 2014.