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PATIENT RADIATION DOSE ASSESSMENT SYSTEM FOR DIAGNOSTIC NUCLEAR MEDICINE PROCEDURES: IMPLEMENTATION AND FIRST RESULTS

by

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Dose assessment of diagnostic nuclear medicine procedures is necessary to further optimize respective procedure, estimate radiation risk, improve radiation safety and verify compliance of local practice with guidelines. In line with Council Directive 2013/59/EURATOM, patient medical documentation should include information related to radiation exposure. The aim of this work is to present the patient radiation dose assessment system designed for routine clinical use, that uses in-house designed worksheets for dose calculation based on relevant parameters introduced by the ICRP publications.
Dose reports provide information about the absorbed dose delivered to the target and non-target organs of interest and the effective dose for each diagnostic procedure. The data from the dose reports was used to investigate average patient exposure levels during a one-year period and the results are presented. The implemented system has improved the quality of services provided and understanding of radiation risks. Moreover, the presented results have stimulated further optimization of nuclear medicine processes.

Key words: nuclear medicine, radiation risk, effective dose assessment, administered activity, low-dose computed tomography

INTRODUCTION

Nuclear medicine is the medical specialty that uses radiopharmaceuticals for diagnosis, staging of disease, therapy and monitoring the response of a disease process. Radiopharmaceuticals are various types of pharmaceuticals labeled with short half-life radionuclides. They can be administered to the patient by intravenous, subcutaneous or intratumoural injection, or orally depending on the organ and the function to be studied, in order to obtain diagnostic and functional information on organs where radioactivity is cumulated. It can also be used for the therapy of some diseases, *e. g.* benign thyroid disease or thyroid cancer.

Global trends show an increase of ionizing radiation use in diagnostic procedures. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) describes an increase of about 35 % and 70 % in the collective dose from diagnostic nuclear medicine examinations and diagnostic radiology, respectively, between Report 2000 [1] and Report 2008 [2]. Therefore, awareness of the radiological risk related to the use of ionizing radiation for a diagnostic procedure and necessity of patient safety improvement has motivated national and international authorities to require that relevant information about parameters related to the patient exposure to ionizing radiation should become part of the medical documentation.

In line with EU Council Directive 2013/59/EURATOM [3], in Croatia, data related to nuclear medicine procedure to be included in a report are administered activity, target organ and administration modality. A similar request on availability of information on dose related parameters should be fulfilled in diagnostic radiology as well. Particularly, for computed tomography (CT) procedures national legislation requires that information about the volume CT dose index ($CTDI_{vol}$) and dose-length product (DLP) be specified in a medical report.

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Even though these data are sufficient to fulfill legal requirements, the dose concept is much clearer, understandable and easily comparable even for non-professionals. Having this in mind, the Department for Medical Physics and Radiation Protection of the University Hospital Rijeka (UH Rijeka) has established and implemented a patient radiation dose assessment system for diagnostic nuclear medicine procedures based on in-house designed worksheets for dose calculation and reporting. By knowing the data about the used radiopharmaceutical, the administered activity and set of relevant patient specific information, dose assessment for diagnostic nuclear medicine procedures could be carried out based on formalisms introduced by ICRP publications 80 and 128 [4, 5]. When the hybrid SPECT/CT technique is used, the dose report includes the effective dose calculation for the CT contribution by using computed tomography DLP values [6].

Similar to dose assessment in diagnostic radiology [7, 8], dose data for the respective diagnostic nuclear medicine procedure can be used to optimize procedure according to the *as low as diagnostically acceptable* (ALADA) principle, to estimate patient radiation risk, to plan and improve radiation safety, to comply with the proposed dose limits and to align local practice with national and international guidelines.

The implemented patient radiation dose system has allowed dose reporting for every patient that undergoes a diagnostic nuclear medicine procedure at UH Rijeka as a part of the specialist medical report. This is in accordance with European and national legislation, but also a step forward in clinical practice since it provides the data in a more comprehensible form.

MATERIALS AND METHODS

After administration, a radiopharmaceutical is distributed to target organs and other tissues in the patient body. Therefore, the absorbed dose in the target depends on contributions from different sources in the body [9].

The ICRP has designed a set of mathematical models of the human body that represent different groups of patients (adult female and male patients and paediatric patients of different age) and has proposed an approximation in order to simplify the dose calculation [4, 5]. The source is assumed to be the total body, and calculation of the absorbed dose delivered to different targets as well as the effective dose can be obtained multiplying the administered activity by the radiopharmaceutical specific absorbed doses per unit of administered activity (mGy MBq^{-1}) and effective doses per unit of administered activity (mSv MBq^{-1}), respectively.

For effective dose calculation in computed tomography imaging a simplified method proposed by the European Commission is used [6]. Effective dose estimates can be calculated as

$$E \quad DLP \; E_{\mathrm{DLP}} \tag{1}$$

where DLP is the displayed dose-length product for the procedure and E_{DLP} (mSv mGy^{-1} cm^{-1}) is the conversion factor that represents the region-specific normalised effective dose, which depends on the scanned region and the tube voltage [10-12]. Conversion factors for the head, neck, chest, abdomen and pelvis were calculated by using updated weighting factors given by the ICRP 103 [13]. For lower extremities, the conversion factors for male and female patients reported by Saltybaeva *et al*. [11] were used. The E_{DLP} data of interest for this work are shown in tab. 1.

At UH Rijeka ^{99m}Tc, ^{123}I, and ^{131}I are routinely used for diagnostic procedures and hybrid imaging modalities. The radiation dose from radiopharmaceuticals for every patient is calculated based on relevant procedure parameters and patient-specific data that are relevant for the adoption of an appropriate biokinetic model [4, 5]. These data are collected in a form that is divided in two parts which should be completed by a nuclear medicine technologist and nuclear medicine specialist. The first part of the form includes patient personal data (name, age, gender), diagnostic nuclear medicine procedure data such as the target organ, type and activity of the administered radiopharmaceutical, route of administration (intravenous, subcutaneous, intratumoural or oral), type of administered meal in gastric motility studies (liquid or solid) and urinary bladder emptying time after administration in renal studies. The second part includes information related to thyroid uptake, bone uptake and renal function. For hybrid imaging, which combines diagnostic information about molecular processes with functional imaging capabilities of SPECT and precise anatomical overlay of CT imaging, additionally required data are $CTDI_{\mathrm{vol}}$, *DLP* and information about the scanned anatomical region. The effective dose from the CT examination is calculated by multiplying *DLP* by the selected conversion factor, tab. 1.

The collected data are used as input in in-house designed worksheets for dose calculation. For each diagnostic nuclear medicine procedure, a procedure-specific worksheet was prepared and introduced to clinical practice. Worksheets for paediatric patients

Table 1. Published conversion factors for computed tomography effective dose calculation as a function of the scanned region, tube voltage, and gender

Tube voltage [kV]	E_{DLP} [mSv mGy^{-1} cm^{-1}] [10]				
	Head	Neck	Chest	Abdomen	Pelvis
120	0.0019	0.0051	0.0145	0.0153	0.0129
140	0.0019	0.0052	0.0147	0.0155	0.0131

Tube voltage [kV]	E_{DLP} [mSv mGy^{-1} cm^{-1}] [11]					
	Male			Female		
	Ankle	Knee	Hip	Ankle	Knee	Hip
120	0.0002	0.0004	0.0113	0.0002	0.0004	0.0122
140	0.0002	0.0004	0.0114	0.0002	0.0004	0.0123

were separately prepared and they require the correct use of the age-dependent model as described in ICRP publications, *i.e*. 1 year, 5 years, 10 years or 15 years [4, 5]. Worksheets for paediatric patients were developed for radiopharmaceutical contribution to the dose only since hybrid imaging in that patient category was not used. Consequently, the results of the absorbed and effective dose are ready for the patient dose assessment report. At the end, a hard copy of the report is prepared for each patient.

It is important to emphasize that the comprehensive quality assurance and quality control program which encompasses all the aspects of application of radioactive isotopes and CT imaging in nuclear medicine is required in order to achieve accuracy of all physical parameters [14-16] and represents a prerequisite for dose assessment implementation.

RESULTS

The intention of this paper is to introduce the concept of dose reporting in diagnostic nuclear medicine procedures and to present initial results of the implemented dose assessment system at the UH Rijeka, where more than 4000 nuclear medicine examinations were carried out from February 2018 until January 2019. For each patient a dose report with absorbed and effective doses was produced and included in the patient medical documentation. In more than 10 % of nuclear medicine examinations of adults, hybrid imaging was performed hence both radiopharmaceutical and CT contributions to the total effective dose were calculated. The percentage of paediatric patients corresponds to 5 % of the total number of nuclear medicine patients. Table 2 shows a detailed distribution of diagnostic nuclear medicine and hybrid procedures for adult and paediatric patients.

In tab. 3, the results in terms of administered activity and effective dose during a one-year period for adult and paediatric patients are presented. For each nuclear medicine procedure minimum, maximum, mean and standard deviations of administered activity and effective dose were calculated, respectively. The number of performed examinations and conversion factors as radiopharmaceutical specific effective doses per unit of administered activity (mSv MBq^{-1}) that were used for effective dose calculation are also shown. The conversion factors used for dose calculations in renal imaging with ^{99m}Tc-MAG3 depend on the selected biokinetic model that best represents the patient's renal function (normal function, abnormal function and acute unilateral renal blockage) and the urinary bladder emptying time. Detailed information on conversion factors for renal imaging with ^{99m}Tc-MAG3 can be found in the ICRP publication 128 [5]. Conversion factors for somatostatin receptor imaging with ^{99m}Tc-tektrotyd and lymphoscintigraphy with subcutaneous administration were taken from radiopharmaceutical manufacturer specifications.

Results for paediatric patients are also presented in tab. 3. Conversion factors for paediatric patients are dependent on both the patient's age and patient specific information (renal function, urinary bladder emptying time, bone uptake). Detailed information on conversion factors can be found in ICRP publication 128 [5].

The mean effective doses of investigated nuclear medicine examinations vary by a factor of over 800 (0.04-35.52 mSv). The CT examinations tend to be in a finer range and mean effective doses are significantly lower than typical doses of diagnostic CT procedures due to the use of low-dose CT imaging (approximately 0.02-5 mSv).

DISCUSSION

Comparison of mean effective doses from nuclear medicine diagnostic procedures for adult patients shows large differences between various procedures due to the different radiopharmaceuticals used, and consequently the different biokinetic model adopted. Additionally, the large effective dose range reflects the differences in mean administered activity for a diagnostic purpose, from 29 to 812 MBq. Differences in effective doses for the computed tomography contribution in hybrid imaging depend on different conversion factors between scanned regions, tab. 2. As shown in tab. 3 thyroid metastasis imaging with ^{131}I is the major contributor to the effective dose. It is followed by a two-day protocol for myocardial perfusion (stress and rest) and infection/inflammation imaging. Thyroid metastasis studies, myocardial perfusion studies and infection/inflammation examination contribute to 1 %, 10 %, and 1 % of the total number of examinations, respectively. Bone imaging with ^{99m}Tc –

Table 2. One-year of experience: number of nuclear medicine diagnostic examinations at UH Rijeka for which dose information is available

	Feb. 2018	Ma.r 2018	Ap.r 2018	May 2018	June 2018	July 2018	Aug. 2018	Sept. 2018	Oct. 2018	Nov. 2018	Dec. 2018	Jan. 2019	TOT
Number of NM examinations	357	432	385	422	314	238	276	305	403	360	259	392	4143
Number of paediatrics examinations	17	15	10	19	19	15	11	18	26	17	16	20	203
Number of CT scans (adults)	45	61	48	38	37	34	36	31	45	44	10	54	483

Table 3. Relevant data related to one-year results for nuclear medicine diagnostic examinations

Examination	Radiopharmaceutical	Number of examinations	Minimum – maximum administered activity [MBq]	Mean administered activity st.dev. [MBq]	Conversion factor [mSvMBq^{-1}]	Minimum–maximum effective dose [mSv]	Mean effective dose st.dev. [mSv]
ADULT PATIENT							
Bone imaging	^{99m}Tc – phosphonates	1274	330-792	503 53	$4.9\cdot10^{-3}/4.3\cdot10^{-3}$**	1.62-3.89	2.47 0.26
Myocardial perfusion, stress	^{99m}Tc – tetrofosmin	383	507-944	669 55	$6.9\cdot10^{-3}$*	3.50-6.51	4.62 0.38
Myocardial perfusion, rest	^{99m}Tc – tetrofosmin	308	501-811	672 46	$8\cdot10^{-3}$*	4.00-6.49	5.38 0.37
Renal imaging	^{99m}Tc – MAG3	201	71-398	178 ± 70	See table C.77*	0.18-3.25	0.76 0.57
Renal imaging	^{99m}Tc – DTPA	3	85-213	133 70	4.9·10-3/$4.6\cdot10^{-3}$***	0.42-1.34	0.80 0.48
Infection/inflammation imaging	^{99m}Tc – HMPAO leucocytes	53	518-1221	812 142	$1.1\cdot10^{-2}$ °	5.70-13.43	8.93 1.56
Somatostatin receptor imaging	^{99m}Tc – tektrotyd	69	553-852	739 44	$5\cdot10^{-3}$R	2.77-4.26	3.69 0.22
Parathyroid imaging	^{99m}Tc – pertechnetate	2	346-870	493 96	$1.3\cdot10^{-2}$*	3.11-7.83	4.44 0.87
Parathyroid imaging	^{99m}Tc – MIBI	169	381-560	471 126	$9\cdot10^{-3}$*	3.05-4.48	3.76 0.01
Thyroid imaging	^{99m}Tc – pertechnetate	1178	74-410	77	$1.3\cdot10^{-2}$*	0.96-5.33	1.00 0.25
Thyroid imaging	^{99m}Tc – MIBI	33	346-393	377 11	$9\cdot10^{-3}$*	3.11-3.54	3.39 0.10
Brain imaging	^{99m}Tc – HMPAO	4	550-800	674 119	$9.3\cdot10^{-3}$*	5.12-7.44	6.26 1.10
Liver hemangioma	^{99m}Tc – erythrocytes	8	550-580	561 10	$7\cdot10^{-3}$*	3.85-4.06	3.92 0.07
Liver imaging	^{99m}Tc – HIDA	2	193-196	195 2	$1.6\cdot10^{-2}$*	3.09-3.14	3.11 0.03
Lymphoscintigraphy	^{99m}Tc – nanocoll	10	36-76	58 16	$4\cdot10^{-3}$R	0.14-0.30	0.24 0.07
Lymphoscintigraphy -SLN	^{99m}Tc – nanocoll	43	26-32	29 2	$1.2\cdot10^{-3}$*	0.03-0.04	0.04 0.01
Dopamine transporter imaging	^{123}I – ioflupane	38	132-165	147 9	$2.5\cdot10^{-2}$*	3.30-4.13	3.67 0.22
Lung perfusion	^{99m}Tc – LYOMAA	72	40-206	91 24	$1.1\cdot10^{-1}$*	0.44-2.27	1.00 0.26
Angiocardiography	^{99m}Tc – pertechnetate	19	540-615	587 22	$1.6\cdot10^{-2}$*	2.48-2.83	2.70 0.10
Gastric motility studies	^{99m}Tc – DTPA	13	72-90	79 5	$1.9\cdot10^{-2}/2.4\cdot10^{-2}$****	1.30-1.71	1.49 0.09
Thyroid metastases (after ablation)	^{131}I	55	185-185	185 0	$2.8\cdot10^{-1}$*	35.52_{T}-35.52	35.52 0 T
Ectopic gastric mucosa imaging (Meckel's)	^{99m}Tc – pertechnetate	3	255-345	298 55	$4.6\cdot10^{-3}$*	3.82-4.61	4.20 0.39
Computed tomography – low dose	–	483	–	–	–	0.02-5.24	1.42 0.84
PAEDIATRIC PATIENT							
Renal imaging	^{99m}Tc – MAG3	185	20-148	45 20	See table C.77*	0.14-0.86	0.25 0.09
Renal imaging	^{99m}Tc – DTPA	2	141-193	167 37	See table C.61*	0.89-1.22	1.05 0.23
Renal imaging	^{99m}Tc – DMSA	2	41-75	58 24	See table C.59*	0.45-0.83	0.64 0.26
Bone imaging	^{99m}Tc – phosphonates	12	102-401	231 107	See table C.89*	1.80-3.10	2.38 0.48
Gastric motility studies	^{99m}Tc – DTPA	1	20-20	20 0	See table C.79*	1.24-1.24	1.24 0
Infection/ inflammation imaging	^{99m}Tc – HMPAO leucocytes	1	333-333	333 0	See 3.11. °	6.22-6.22	6.22 0

* ICRP 128, **Normal uptake and excretion /High bone uptake and/or severely impaired kidney function; ICRP 128,
*** Normal renal function/Abnormal renal function; ICRP 128, **** Oral administration of fluids/Oral administration of solids; ICRP 128
° ICRP 80, R Radiopharmaceuticals manufacturer specification, T Effective dose calculated subtracting thyroid contribution

phosphonates is the most commonly performed nuclear medicine diagnostic procedure at UH Rijeka and makes up over 30 % of the total number of diagnostic nuclear medicine examinations.

Results are in accordance with effective doses for adults from nuclear medicine examinations presented by Mettler *et al*. [17], Kralik *et al*. [18] and Avramova-Cholakova *et al*. [19]. The exception is thyroid metastasis imaging using ^{131}I. Namely, in the case of thyroid ablation, the presented effective dose for thyroid metastasis imaging was calculated using the conversion factor for the biokinetic model with blocked thyroid and oral administration [5]. Subsequently, thyroid contribution to the effective dose, cal-

culated using the thyroid tissue weighting factor of 0.04 [13], was later subtracted due to the thyroid removal, resulting in the effective dose of 35.52 mSv.

In paediatric patients the most common nuclear medicine procedure was renal imaging with ^{99m}Tc – MAG3 (over 90 % of total paediatric examinations). Infection/inflammation imaging causes large effective doses to the patient, but it is rarely performed.

In data analysis and comparison of dose estimates uncertainties should be taken into account. Among others, the uncertainty in the dose estimates from radiopharmaceuticals depends on differences between the patient and the mathematical model used for the simulation. It is mainly related to the mass of the organs and the distance between source and target organ. A similar problem is present for CT effective dose estimates since the conversion factor that represents the region-specific normalised effective dose is calculated using weighting factors for mathematical models rather than for the individual patient. Regularly performed QC enable the reduction of uncertainties on activity administered due to measurements using the activity meter as well as to achieve better accuracy of CT dose parameters.

CONCLUSIONS

The study presents practical aspects and results of the dose assessment system in nuclear medicine imaging implemented in clinical practice. Professionals involved in this field have become more aware on of the radiation risk related to the diagnostic procedures since the dose information is available, as a value that seems to be clear, understandable and easily comparable. Quality of provided services has been improved and a dose report for every diagnostic nuclear medicine examination is produced. Information on the absorbed dose to organs from the radiopharmaceutical and the effective dose from various imaging procedures are available in patient medical records. Also, the dose assessment system has contributed to the standardization of activity measurements by the residual activity subtraction for each administered activity in order to get the information of about the actual activity administered to the patient.

Moreover, introduction of the patient radiation dose assessment system was used as an input for setting typical values for nuclear medicine procedures at UH Rijeka. Although DRL are regularly used in diagnostic and interventional radiology [20, 21], until recently there was a lack of use of the DRL approach in nuclear medicine procedures in Croatia. Starting from results coming from the dose assessment system, the first national survey on DRL values in nuclear medicine was implemented and performed in order to introduce a valuable tool required for the optimization of diagnostic nuclear medicine procedures [22].

AUTHORS' CONTRIBUTIONS

The idea was initiated by D. D. Debeljuh, S. Jurković and I. Pribanić. The dose assessment system design was created by D. D. Debeljuh, I. Pribanić. The implementation of the dose assessment was performed by D. D. Debeljuh, S. Jurković, I. Pribanić, N. Girotto, S. Grbac-Ivanković, A. Božanić, and D. Šegota.

Data were collected and statistically analysed by D. D. Debeljuh and I. Pribanić. The manuscript was drafted by D. D. Debeljuh, S. Jurković, and I. Pribanić and revised by all authors.

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СИСТЕМ ЗА ПРОЦЕНУ ДОЗЕ У НУКЛЕАРНО-МЕДИЦИНСКИМ ДИЈАГНОСТИЧКИМ ПОСТУПЦИМА – ИМПЛЕМЕНТАЦИЈА И ПРВИ РЕЗУЛТАТИ

Процена дозе код дијагностичких нуклеарно-медицинских процедура је нужна за оптимизацију протокола, процену ризика изазваних зрачењем, планирање и оптимизацију заштите од зрачења, проверу усклађености дозних граница с прописаним вредностима те за поређење локалног начина рада с националним и међународним смерницама. Директива 2013/59ЕУРАТОМ налаже да се подаци везани за излагање пацијента јонизујућем зрачењу уписују у медицинску документацију пацијента. Циљ овог рада је да се прикаже успостављени систем за процену дозе развијен у сврху коришћења у клиничкој пракси. На темељу података и формализама објављених у публикацијама Међународне комисије за заштиту од зрачења (ICRP) израђени су радни листови за процену дозе.

Извештај о дози пацијента садржи податке о предатој апсорбованој дози циљним органима и осталим органима од интереса те податке о ефективној дози за поједину спроведену дијагностичку процедуру. Подаци из извештаја о дози пацијената у периоду од годину дана коришћени су за процену нивоа излагања јонизујућем зрачењу и резултати су приказани у овом раду. Једногодишње искуство примене система за прорачун и процену дозе показало је побољшање у квалитету спроведених медицинских процедура и боље разумевање ризика изазваних зрачењем. Осим тога, информација о дози представља корисно средство за оптимизацију нуклеарно-медицинских дијагностичких процедура и ревизију аквизицијских протокола.

Кључне речи: нуклеарна медицина, ризик изазван зрачењем, процена ефективне дозе, унета активност, ниско-дозна компјутеризована томографија