Radiation and Environmental Biophysics

NUCLEAR MEDICINE: WORKPLACE MONITORING AND INTERNAL OCCUPATIONAL EXPOSURE DURING A VENTILATION/PERFUSION SINGLE PHOTON EMISSION TOMOGRAPHY

--Manuscript Draft--

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Dear Editor,
Please find enclosed a resubmission of our manuscript with the reference number "REBS-D-18-00224R1". The new version has been revised and modified according to the reviewer's comments since they contribute positively to the quality of the manuscript. In reference with those comments we have answered them point to point as following:

Reviewer # 1

1) *You have improved almost all comments reported by reviewers. At the moment, the paper looks much better. However, one fundamental problem has not been corrected. In the first review I wrote that both dosimetric models used in presented study should give similar results. Maximum intake calculated by the activity in the air reached ca. 25 000 Bq meanwhile maximum intake calculated by activity in the urine reached 800 000 Bq. The difference is so big that the results may seem doubtful and unreliable. In my opinion, the doses calculated by activity in the urine are more reliable. Besides, the table 2 is a bit pointless. Intakes and doses should be determined for people not for rooms. In my opinion, the results should be presented in the following way: Medical doctor spent in the administration room 20 min, in gamma room 40 min and in corridor 30 min so summary intake was X Bq and Y Sv.*
If the dosimetric results will be more consistent, I recommend paper for publication in REBS

RESPONSE:

Regarding the reviewer comment, we would like to point out that the present research article does not aim to compare the results obtained from both dosimetric models (this issue is clarified in lines 443 – 449 of the new version of the manuscript). In particular, the main aims are:

1- To determine the ^{99m}Tc-HDP activity in the air of different NM department areas (namely, the administration room, the gamma camera and the corridor) and check the contamination levels and verify the radioaerosol dispersion. With this data, we then tried to estimate the related doses received by a worker via inhalation in the mentioned areas for a certain time (not for the total time the worker spends in the NM department) in order to have qualitative information about the possible associated risks. This issue is also clarified in Lines 398 – 404 of the new version of the manuscript.
2- To determine the ^{99m}Tc-HDP activity in urine samples from different workers in order to find out the dose received via inhalation during one working day (and during the performance of one V/P_{SPECT}), when these individuals were developing their usual tasks in the entire NM department.

In detail, the *prospective dose assessment* used in the present study tries to evaluate and estimate the potential committed effective dose received by a worker in a specific room and during a preset time. In this regard, Table 2 shows three specific situations. As an example, one individual that spends 2 minutes in the administration room, which corresponded to the

real time a worker spent in this area in our case, inhales the measured ^{99m}Tc-HDP activity in air, and due to this, he/she receives a particular dose. The other two situations show the received dose in the other two mentioned NM department areas when the individuals spent 5 minutes. The estimated intake due to air inhalation ($I = d * t * C$), using this model, will vary depending on the time spent by a worker and the ^{99m}Tc-HDP air concentration. Therefore, with the data presented in Table 2 we tried to illustrate, in a qualitative and indicative basis, the possible doses that can be received by any individual in the studied areas.

On the other hand, the *retrospective dose assessment* is used to evaluate the potential committed effective dose received by different workers in all the NM department during their working day and developing their usual tasks when one V/P_{SPECT} has been performed. In this case, 24-h urine sample reveals the internal contamination received by a worker inhaling the ^{99m}Tc-HDP activity dispersed through the different areas of the entire NM department. With the data obtained, we have been able to observe that the highest committed effective dose corresponds to workers that spent mostly his time in areas with higher ^{99m}Tc activity concentration in the air. We are agreed with the reviewer and the estimated doses calculated using the retrospective model are more reliable than those estimated by the prospective one. This is because, as the recent report named *Technical Recommendations for Monitoring Individuals for Occupational Intakes of Radionuclides* states, "static air samplers can underestimate concentrations in air in the breathing zone of the worker and in extreme cases underestimates can be several orders of magnitude". For this reason, it will be necessary the application of correction factors (European Commission, 2018).

European Commission, 2018. Radiation Protection Nº 188. Technical Recommendations for Monitoring Individuals for Occupational Intakes of Radionuclides [WWW Document]. URL https://ec.europa.eu/energy/sites/ener/files/rp_188.pdf (accessed 1.26.19).

In view of all above, we consider that the results of the two dosimetric models could not be comparable. As already discussed, the prospective model presented here gives an estimation of the intake and resulting internal doses received by an individual if stays a certain time in a certain room of the NM department while the restrospective model illustrates a reliable estimation of the intake and the dose that an individual could received due to its exposure (via inhalation) during a working day staying in different areas of the NM department.

Further research could be done in order to establish a more accurate air sampling campaign by using for example personal air samplers, which would sample air from all the NM department areas where the individual works.

For further comments do not hesitate to contact with me,

Sincerely yours

NUCLEAR MEDICINE: WORKPLACE MONITORING AND INTERNAL OCCUPATIONAL EXPOSURE DURING A VENTILATION/PERFUSION SINGLE PHOTON EMISSION TOMOGRAPHY

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Abstract

The administration of ^{99m}Tc-HDP to diagnose pulmonary thromboembolisms implies the presence of this radionuclide in the environment of the nuclear medicine department, which could pose a potential risk of internal contamination to medical staff. Air samples from the administration room, gamma camera room and corridor were taken for the purposes of performing a workplace monitoring program of the medical centre under study, with maximum activity values of 636.9 ± 27.1 kBq/m^3, 1.47 ± 0.06 kBq/m^3 and 53.6 ± 3.0 kBq/m^3 respectively being obtained. These results were also used to assess the corresponding committed effective dose received for the exposed workers, via inhalation, when one ventilation/perfusion single photon emission tomography study was performed, with values of 0.74 μSv, 0.004 μSv and 0.07 μSv respectively. As inhalation is the workers' main exposure pathway to radioaerosol, the internal dose of the nuclear medicine department's medical staff was also evaluated via urine bioassay. Nuclear medicine nurses usually presented the highest ^{99m}Tc activity in 24-hour urine samples with a value of 2,073.8 Bq/day, resulting in a committed effective dose of 20.9 μSv for each diagnostic study performed. Even so, the performance of ventilation/perfusion diagnostic studies do not constitute a radiological risk since the annual dose limit for exposed workers is not exceeded.

1. Introduction

More than 80% of the radiopharmaceuticals used in nuclear medicine are compounds labelled with ^{99m}Tc (Silva et al. 2010). It has been documented that in 2010, in Spain, this radionuclide was the most widely-used in diagnostic studies, with over 11,000 procedures being carried out for every million inhabitants (European Commission 2015). Its use in diagnostics is common because a) its short half-life period (6 hours) avoids prolonged patient irradiation, b) its monochromatic gamma radiation emission, with an energy of 140 keV, is optimal for planar NaI (Tl) gamma camera imaging and single photon emission computed tomography (SPECT), c) it has multiple oxidation states that offer labelling versatility with a wide variety of molecules, and d) it is readily available and easy to obtain *in situ* in the nuclear medicine departments (NMDs), using a generator of ^{99}Mo/^{99m}Tc (Kwon et al. 2014).

Of all the diagnostics in which this radionuclide is used, one of the most usual proceedings is that aimed at determining the probability of pulmonary thromboembolism (PE) by ventilation/perfusion scans (V/P_{SPECT}). This is a dual study comprising two parts, the first consisting of a ventilation process and the second of a perfusion (Schiepers 2006). The ventilation study is generally performed first and several agents such as radioactive gases (^{81m}Kr, ^{127}Xe, ^{133}Xe) or radioaerosols (^{99m}Tc-compounds) are suitable for the purpose. ^{99m}Tc-diethylene triamine pentaacetic acid (^{99m}Tc- DTPA) and ^{99m}Tc-carbon compounds (Technegas) are the most widely-used (Metter et al. 2017). However, due to the high cost of ^{99m}Tc-DTPA, other technetium radiopharmaceuticals labelled with different compounds have also been considered (Opanowski et al. 2015; Schembri et al. 2015; Evbuomwan et al. 2018). As an example, ^{99m}Tc-hydroxyl ethylene diphosphonate (^{99m}Tc-HDP), traditionally used for bone scintigraphy, has also been satisfactorily tested for use as a ventilation agent (Young and Prasad 2017; Wondergem et al. 2018). The ventilation study is then followed by the perfusion, and in this process ^{99m}Tc macroaggregates of albumin are administered (^{99m}Tc-MAA) by intravenous injection (Bajc et al. 2009). After both studies, the corresponding images are acquired in the gamma camera room and a three-dimensional image that allows clear visualization of all the lung segments is obtained (Bailey et al. 2010).

One of the hazards of working in a NMD is the possibility of long-term occupational exposure to low-level radiation. The inhalation of airborne radioactive particles that could be present in the working environment, is one of the most important routes of

entry of radionuclides into the human body, i.e. ^{99m}Tc when performing one V/P$_{SPECT}$ study. For this reason, it is important to evaluate the radiological risk associated with this intake. There are different studies in the literature that focus on this topic in which the administered radiopharmaceuticals were ^{99m}Tc-DTPA, Technegas or ^{133}Xe gas (Greaves et al. 1995; Chen et al. 2000; Ferrand et al. 2010; Leners et al. 2011; Kawase et al. 2015). These studies also deal with the potential internal exposure of medical staff. However, to the best of our knowledge, there is no study on this subject that considers ^{99m}Tc-HDP. The main aim of the present study is therefore to carry out a workplace monitoring program during the administration of ^{99m}Tc-HDP radioaerosol as a ventilation agent in V/P$_{SPECT}$, assessing the presence of this radiopharmaceutical in NMD areas and evaluating the potential risk of occupational exposure through the collection of air and urine samples from the workers.

2. Materials and methods

2.1. Nuclear medicine department studied and sample collection

The present study was performed in the NMD of a hospital located in Reus, southern Catalonia. It was carried out during the administration of ^{99m}Tc-HDP radioaerosol during a V/P$_{SPECT}$ procedure, which is performed according to the following methodology. The patient is placed in supine position with their torso covered by a disposable medical soaker pad to prevent contamination of clothes. The radioaerosol delivery system used is a Venticis® II Medical, in which the mouthpiece has been replaced by a transparent facial mask to facilitate administration to patients. The activity deposited in the nebulization vial of the system is 30 mCi (1,110 MBq) of ^{99m}Tc-HDP and, after adjustment of the oxygen flow, the patient inhales the dose for twenty minutes. Approximately 10% of the initial activity is deposited in the patient's lungs (Thrall and Ziessman 2001; Fernández Tena and Casan Clarà 2012).

This radionuclide was determined in air and wipe samples to carry out a workplace monitoring program. Urine samples from the workers in this NMD were also taken.

Specifically, fourteen air samples were collected using a low-volume portable pump, DF-1E model (F&J Specialty Products), equipped with borosilicate fibre filters, FP47 (F&J Specialty Products), with a 99.98% microparticle retention efficiency of 0.3 microns (F&J Speciality Products). The holder was located at a height of 1.5 m from ground level to simulate the worker breathing zone, and the sampling time was from twenty minutes to four hours per sample depending on the sampling site, at a flow of 90

litres per minute (LPM). **Figure 1** shows the blueprint distribution of the sampling areas. Air samples were collected in a) the administration room (point 1), where the ^{99m}Tc-HDP administration via inhalation takes place, b) the image acquisition room (gamma camera, point 2), where the ventilation and perfusion images are acquired, and c) the corridor (point 3), which is a common area for all workers in the NMD. The radiological background of the sampling sites was evaluated by collecting air samples before the start of the ventilation study.

Point 4 (**Figure 1**) indicates the surface contamination sampling points corresponding to the administration room. Collection of these samples involved wiping the sampling surface with an absorbent material, a square piece of cotton dipped in ethyl alcohol. The different surfaces wiped were a) wall tiles, b) a bed rail with an area of 200 cm^2, and c) a door handle with an area of 60 cm^2.

Finally, spot and 24-hour urine samples were collected from seven workers who carry out different tasks in the NMD, these being the NM doctor and the sampler (point α), positron-emission tomography (PET) and NM technician (point β), PET and NM nurse (point χ) and secretary (point δ) (**Figure 1**). Of these, five are medical staff who had direct contact with patients and doses, whereas the secretary and the samplers had no contact with patients or radiopharmaceuticals. Regarding the spot urine samples, three different samplings were performed, corresponding to three V/P_{SPECT} studies performed on three different days. Blank urine samples were collected before the start of each ventilation study. Three hours after the study was performed, urine spot samples were collected and kept in 100 mL polyethylene beakers. As the physiological conditions of each worker could vary and urine activity concentrations fluctuate during the day, 24-hour samples were collected to provide the best basis for assessing exposure during this period and estimating the daily excretion fraction. These were kept in 3 L polyethylene bottles, of which an aliquot of 500 mL was used for gamma-ray analysis. All urine samples were identified with a reference code, date and time of collection. They were processed immediately after sampling, homogenized without any chemical preparation and recorded their total volume. The gamma-ray geometry beakers were covered with a plastic film to avoid contamination of the detector.

2.2. Instrumentation

^{99m}Tc was measured with a high-resolution germanium detector (HPGe) (model 2020, Canberra Industries, Meriden, USA) equipped with a standard multichannel analyser. The operating conditions were a voltage of 4,500 V, negative polarity and relative efficiency of 20%. Genie 2000 software (Canberra Industries, Meriden, USA) was used to acquire and analyse the information provided by the gamma-ray spectra. A gamma-ray radionuclide GC2 cocktail (^{241}Am, ^{109}Cd, ^{139}Ce, ^{57}Co, ^{60}Co, ^{137}Cs, ^{54}Mn and ^{113}Sn), covering an energy range of 59.54 to 1,332.49 keV and supplied by CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas), was used to prepare the different geometries to perform this study for the energy/efficiency calibration, these being a filter, a paper facial mask, a wipe, a 100 mL polyethylene beaker and a 500 mL Marinelli geometry. The counting efficiency of the detector was determined for each photoelectric peak and for each geometry used in this work in accordance with the specifications of Spanish Standard UNE-EN ISO 10703 (AENOR 2016).

2.3. Gamma-ray spectrometry measurement and validation

The activity concentrations of ^{99m}Tc in the air, masks, wipe and urine samples were measured using an HPGe detector. The counting time for the air, masks, wipe and spot urine samples was 1,800 s and the measurements were decay-corrected at the time of sampling. The 24-hour urine samples were counted for 3,600 s, as recommended in ISO 16637:2016 (2016) as being a normal method for quantifying gamma-ray emitting radionuclides in these types of sample. Their measurement was decay-corrected at the time of intake, corresponding to the start of the ventilation procedure.

In order to validate the measurement of the air samples under these conditions, a fibre glass filter sample taken from an intercomparison exercise conducted in 2017 by the Consejo de Seguridad Nuclear (CSN) was used. This sample contains ^{57}Co and ^{60}Co with certified activities of 0.397 ± 0.079 Bq/filter and 0.720 ± 0.144 Bq/filter respectively. The Z-score values obtained were below one in both cases, with a relative bias of 7.81% and 1.25% respectively.

^{99m}Tc was also determined in urine samples and the measurement was validated using an intercomparison sample from the IAEA conducted in 2017. This was a tap water sample from Seibersdorf, spiked with a mixture of fresh fission products (^{95}Zr, ^{99m}Tc, ^{99}Mo, ^{103}Ru, ^{132}I, ^{140}Ba, ^{141}Ce, ^{143}Ce, ^{144}Ce, ^{147}Nd, ^{239}Np). The ^{99m}Tc certified activity value was 53.8 ± 2.0 Bq/L. In this case, the Z-score value was around zero, with a relative bias of 5.4%.

Taken together, the results from the intercomparison sample measurements indicate that our procedure is robust and satisfactory for the intended purpose.

2.4. Evaluation of the committed effective dose

The concentration of ^{99m}Tc found in the collected air and urine samples was then used to estimate the committed effective dose received by exposed worker when one V/P_{SPECT} study was performed. As Etherington *et al.* (2006) stated and depending on the type of available data: a) the quantity of radionuclides to which an individual could be exposed (air) or b) biological samples, a distinction between two different types of dose assessment, prospective and retrospective, can be made.

It is also important to bear in mind that nowadays there is no specific dosimetry data or biokinetic model for ^{99m}Tc-HDP. Kwon *et al.* (2014) worked on this subject by taking into account the more reliable biokinetic models for occupational intakes described in ICRP 103 (2007) and ICRP 130 (2015). However, the results obtained had different limitations in terms of dosimetry and blood absorption. ICRP 134 (2016) was published more recently but is still not officially accepted. Taking this into consideration, the parameter values used to perform the dose assessment in the present study were those published in ICRP 119 (2012) and ICRP 68 (1994).

2.4.1. Air samples. Prospective dose assessment

The committed dose assessment due to inhalation of the radioaerosol in the previously mentioned areas was performed using the following equation (Eq. 1):

$$E_{(inh)} = I * e_{inh}(50) \quad (1)$$

where *E* is the effective dose (Sv), *I* is the intake (Bq) and $e_{inh}(50)$ is the dose coefficient per unit intake via inhalation (Sv/Bq). It should be pointed out that ^{99m}Tc behavior after uptake is dependent on the type of ligand and, in this case, the $e_{inh}(50)$ value is $2.9 \cdot 10^{-11}$ Sv/Bq, considering an activity median aerodynamic diameter (AMAD) of 5 μm (recommended for workplace exposures) and an M absorption type (ICRP 2012) (values established for ^{99m}Tc, since absorption type in the blood through the inhalation pathway of ^{99m}Tc-HDP it is not documented).

The intake was calculated using Equation 2 (ISO 2016):

$$I = d * t * C \quad (2)$$

where *d* is the breathing rate of a sedentary worker (1.2 m^3/h). This value was taken from ISO 16637:2016 (ISO 2016). *t* is the time spent by the worker in the radioactive atmosphere and *C* is the air concentration of the radionuclide (Bq/m^3).

2.4.2. Urine samples. Retrospective dose assessment

The committed effective dose in the retrospective dose assessment was evaluated using the ^{99m}Tc activity levels found in the 24-hour urine samples taken after the intake had taken place. The intake was calculated using Equation 3:

$$I = \frac{M}{m(t)} \quad (3)$$

where *I* is the intake (Bq), *M* is the ^{99m}Tc activity in the 24-hour urine samples (Bq/d) and *m(t)* is the excretion factor of this radionuclide corresponding in time to one day between the intake and the measurement and it has been obtained with AIDE (Activity and Internal Dose Estimates) software (Bertelli et al. 2008). The *m(t)* value, considering an AMAD of 5 μm and an M absorption type, is $2.88 \cdot 10^{-3}$. With this value and assuming that the pathway of the intake was via inhalation, the dose assessment was performed by using Equation 1.

3. Results and discussion

3.1. Activity levels in air samples

The presence of ^{99m}Tc in air samples from the administration room, gamma camera room and corridor was evaluated in the present research.

During the performance of a V/P_{SPECT}, particularly when carrying out the ventilation process, the medical staff of the NMD postulated the dispersion of ^{99m}Tc-HDP radioaerosol outside the administration room, since an alteration of the image obtained by the gamma camera was observed. This could suggest that the radioaerosol generated may be dispersed through the administration room and in different compartments of the NMD. The radioaerosol dispersion could happen for several reasons, such as a) losses in the ventilation system, b) non-cooperative patients or those with breathing difficulties, or c) the presence of leaks between the mask and the patient's face. Despite improvements in the air extraction system, the image alteration was usually detected after the performance of two or three ventilations per day. This suggests that the radioaerosol still remains in the environment.

In this sense, the collection of air samples from the administration room, gamma camera room and corridor was carried out to evaluate their radiological background two days after a ventilation procedure and before performing another, with results below the minimum detectable activity (MDA), $2.8 \cdot 10^{-5}$ kBq/m^3. These low activity values indicate that, although the radioaerosol could be dispersed in the ambient air, it is efficiently eliminated by the air extraction system, and it is also important to consider the decay in its disappearance. Air samples were also collected during the administration of 1,110 MBq of ^{99m}Tc-HDP via inhalation to five different patients on five different days. ^{99m}Tc was detected in all five air samples, with concentrations of 207.4 ± 8.8 kBq/m^3, 221.7 ± 9.5 kBq/m^3, 326.1 ± 18.3 kBq/m^3, 395.1 ± 20.2 kBq/m^3 and 636.9 ± 27.1 kBq/m^3. It is important to highlight that although all ventilation studies were performed under the same conditions, there is activity variability between samples. This could be because all the patients were elderly and each had their own respiratory capabilities and particular levels of willingness to cooperate. Achey *et al.* (2004) stated that when they performed a ^{99m}Tc-DTPA ventilation study, the highest ^{99m}Tc air activity values were obtained with uncooperative patients. Another factor to take into account is that NM nurses generally enter the administration room to take care of patients during the ventilation study and this can facilitate radioaerosol dispersion. The activity levels sampled in the administration room are in accordance with others found in the literature (Greaves et al. 1995; Avison and Hart 2001).

After the ventilation study, patients are moved to the gamma camera room and as a protective measure they are provided with paper facial masks. It was in this room that the ventilation image was acquired, as well as the perfusion image. The levels of ^{99m}Tc in the air during these procedures were also quantified. To this end, air samples were collected from the same five patients as before and the values obtained were noticeably lower than those obtained in the administration room (with values of 0.14 ± 0.01 kBq/m^3, 0.36 ± 0.02 kBq/m^3, 0.72 ± 0.05 kBq/m^3, 1.32 ± 0.09 kBq/m^3 and 1.47 ± 0.06 kBq/m^3), probably due to dilution through radioaerosol dispersion in the air. The presence of radioaerosol in the gamma camera room could be attributed to two causes, the first being dispersion throughout all the NMD and the second being related to the fraction that could be exhaled by the patient, since the drops are too small to enter the lungs and are expulsed during expiration (Fernández Tena and Casan Clarà 2012). As previously mentioned, patients are provided with a paper facial mask, and these were also analysed and obtained a maximum activity of 359.2 ± 18.6 kBq/mask. The higher

the activity in the paper facial masks, the lower the ^{99m}Tc activity in the gamma camera air, which indicates that this is a good radiological protective measure.

The dispersion of the radioaerosol was also evaluated in a common area i.e. the corridor, during the overall V/P_{SPECT} study (comprising the ventilation study and the acquisition of images). The air samples collected did not match the previous five case studies since it was only possible to work with one air sampling device. Sampling was performed twice when two different patients were under diagnostic study, and the values obtained were 23.7 ± 1.0 kBq/m^3 and 53.5 ± 3.0 kBq/m^3. As expected, these activities were considerably lower than those found in the administration room (one order of magnitude), but even so they were considerably higher than those obtained as background. The possible explanation was a dispersion of ^{99m}Tc during its administration. At this point it is important to highlight that the presence of radioaerosol in common areas of the NMD could be a potential source of internal exposure for anyone working in the service.

Finally, air sampling in the administration room was also performed five minutes and thirty minutes after the end of the radioaerosol administration, when the patient was no longer present in the room. The results obtained were 263.4 ± 11.4 kBq/m^3 and 0.41 ± 0.02 kBq/m^3 respectively. It was observed that after five minutes the activity levels were similar to those during dose administration. However, the activity level drastically decreased after thirty minutes. This could be mainly explained by a) radioaerosol elimination by the air extraction system, b) dispersion through the NMD area, since the door remains open after ventilation, c) the decay rate of ^{99m}Tc, and d) the deposition of the radioaerosol on the room surfaces.

Another aim of the present study was to verify ^{99m}Tc levels on different surfaces in the administration room: a) the wall tiles, b) the bed rail, and c) the door handle. The collection of wipe samples before the start of a ventilation study in order to evaluate the radiological background revealed the presence of ^{99m}Tc on the door handle and on the bed rail, probably due to radioaerosol deposition onto these surfaces, which could not be cleaned well and meant that the radionuclide could remain there until decay disappearance. Wall tile surfaces had ^{99m}Tc activities below the MDA value, 0.0014 Bq/cm^2. After carrying out four ventilation procedures, four wipe sampling campaigns were performed over the door handle, the bed rail and the wall tiles, obtaining activity values of 229.5 ± 13.1 Bq/cm^2, 337.0 ± 19.0 Bq/cm^2 and 164.0 ± 0.9 Bq/cm^2

respectively. These results indicate that the radioaerosol particles were deposited on the surfaces of the room and remained there until their decay or until they were cleaned off.

3.2. Activity levels in urine samples

From all the results obtained, we can conclude that ^{99m}Tc-HDP is dispersed in different areas of the NMD and hence it can be incorporated into the human body via inhalation. With reference to the literature, it is known that the main pathway of ^{99m}Tc-DTPA elimination is via urine excretion (Kohn et al. 1990). For this reason and because there is no published data on ^{99m}Tc-HDP elimination from the human body, it has been assumed that, like ^{99m}Tc-DTPA, ^{99m}Tc-HDP is also eliminated via urine. This was corroborated by the imaging every two hours of a young healthy patient who showed great ventilation efficiency (10.7% calculated taking into consideration the procedure used by Leners *et al.* (2011)). These images also revealed that absorption of the inhaled ^{99m}Tc-HDP twenty minutes after the ventilation performance was mainly to the lungs and urinary bladder, and after two hours it was also slightly absorbed into the skeleton.

On this basis, urine samples from different workers were collected. Specifically in the present study, seventeen spot urine samples from workers were taken three hours after the ventilation performance, in three independent V/P_{SPECT} studies performed in three different days. As can be seen in **Table 1**, the workers had been performing different tasks during the three sampling days, so depending on these, ^{99m}Tc activities in urine could be correlated. Blank urine samples were collected before the performance of the ventilation, with ^{99m}Tc activity values lower than the MDA, 3 Bq/L. NM nurses were potentially the most exposed workers in the NMD because their tasks include the dose administration and taking care of the patient. The maximum ^{99m}Tc activity found in the urine spot sample was 18,652.4 ± 1,218.7 Bq/L. The nurses carrying out the same NM tasks had different levels of ^{99m}Tc in urine (**Table 1**), probably because each person has different metabolic and excretion rates. Meanwhile NM doctors were located near reception (see **Figure 1**) and frequently visited the adjacent room with the gamma cameras. Therefore they could inhale the radioaerosol dispersed through the corridor, and the maximum activity found in urine in this case was 2,828.6 ± 275.3 Bq/L. The secretary and PET staff were the workers with the lowest activity value in urine. This may be due to their relative lack of movement from their working area during their working day. Their maximum activity was 1,014.9 ± 138.9 Bq/L and 537.0 ± 57.8 Bq/L respectively. Finally, the maximum activity level found for the sampler was 4,429.4 ±

258.7 Bq/L because this individual performed the wipe tests mentioned above immediately after the end of the dose administration when ^{99m}Tc activity in the air was higher. From all these results we can state that the activity values obtained in urine may be correlated with the working activity performed by the medical staff. Moreover, we can confirm that inhalation is an important pathway for radionuclide intake and that this can be corroborated by analysing urine samples, as reported in previous studies (Clouvas and Xanthos 2012; Ferdous et al. 2012; Ferdous 2016; Noh et al. 2016).

As mentioned earlier, spot urine samples were collected three hours after the intake had taken place. In order to obtain more information about excretion rate variations during 24 hours, urine samples from a healthy 30-year-old woman were collected. As can be observed in **Figure 2**, the maximum ^{99m}Tc activity is excreted over two hours after the collection. From this time onwards, the activity progressively decreases until it is almost completely eliminated 24 hours after the intake took place.

24-hour urine samples from exposed workers were collected, since these results are used to address internal occupational dosimetry. The corresponding results are presented in **Figure 3.** ^{99m}Tc was detected in all the 24-hour urine samples analysed. It can be seen that the NM nurse, secretary and samplers who were located near the radioaerosol administration room and who could also be present in the corridor during the performance of the V/P_{SPECT} have the highest activities. This could potentially be related to the dispersion of ^{99m}Tc in corridor because of the PE study performance. PET nurse ^{99m}Tc activity was not shown in **Figure 3** because it was < MDA, with a value of 1 Bq/L.

3.3. Radiation exposure assessment

Members of the NMD as well as the general public who frequent the area are those affected using the use of the ^{99m}Tc-HDP radioaerosol. This could potentially result in a significant risk of internal radiation exposure.

3.3.1. Prospective dose assessment

From the equations presented in the Materials and Methods section and by using the minimum and maximum ^{99m}Tc activity detected in the administration room, the gamma camera and the corridor, the related committed effective doses that a worker could potentially receive due to the performance of a certain task, during a certain time in each mentioned area were calculated. In this sense, **Table 2** shows those three different situations for a worker. The dose assessment has been performed trying to determine the

estimated intake and the related committed effective dose received by one worker, for example in case of spending 2 minutes in the administration room by inhaling the measured ^{99m}Tc activity in air. It can be observed that the worst case-scenario (the highest activity in air) result in committed effective doses of $7.39 \cdot 10^{-1}$ μSv, $4 \cdot 10^{-3}$ μSv and $6.9 \cdot 10^{-2}$ μSv for a worker present in the dose administration room, gamma camera room or corridor during the performance of one V/P$_{SPECT}$ study, respectively. There are other studies in the literature in which dose data from the same situations were calculated (Ferrand et al. 2010; Leners et al. 2011). Ferrand *et al.* (2010), for example, sampled air from the administration room while ventilating with Technegas and in the gamma camera room. The doses received by workers via inhalation were $2.2 \cdot 10^{-3}$ μSv and $7.2 \cdot 10^{-7}$ μSv, lower than the doses calculated in the present study, since the activity in air obtained by these authors was lower.

3.3.2. Retrospective dose assessment

The results in terms of the content of ^{99m}Tc in 24-h urine sample, intake and the committed effective dose for each worker exposed to one V/P$_{SPECT}$ study are presented in **Table 3**. It can be seen that the NM nurse is one of the most exposed medical workers, followed by the NM doctors. The external workers that remained in the NMD while the ventilation was performed were also exposed, at approximately the same order of magnitude as the medical staff. The PET and NM technicians were those with the lowest committed effective dose values. This could be explained by the fact that they do not tend to move towards the dose administration room but remain in the gamma camera room or their work location. In this case the PET nurse seems not to be exposed because the ^{99m}Tc was below the MDA.

Taking into account the annual number of V/P$_{SPECT}$ diagnostic studies in the NMD under study (approximately 200), the potential annual committed effective dose received by medical workers through internal contamination is below 20 mSv per year (ICRP 2007), which is the effective dose limit recommended for occupational exposure. For example, the NM nurse could potentially receive 4.18 mSv annually due to the V/P$_{SPECT}$ diagnostic studies. The secretary could potentially be exposed to the same annually committed effective dose. In this case, it is below to 6 mSv per year which is the effective dose limit recommended for exposed workers belonging to category B (Royal Decree 783/2001 2001). However, the potential annual committed effective dose

for external workers (samplers), who are categorized as general public, could probably exceed 1 mSv per year, which is the effective dose limit for a member of the public.

4. Conclusions

The workplace monitoring performed in the NMD under study revealed the dispersion of the radioaerosol throughout the entire area, which implies potential internal exposure via inhalation of all the medical staff. Of all the sampled sites, the administration room was the one with the highest ^{99m}Tc activity in air. Because of the activity levels in the air, internal occupational monitoring by using air and urine analysis was also performed. Using the prospective dose assessment model three specific situations have been shown, during which a worker could receive a related committed effective dose. The situation of maximum worker exposure is the one related with tasks performed in the administration room. According to the data obtained by the retrospective dose assessment, the performance of a V/P_{SPECT} study would not constitute a radiological risk for exposed staff. However, samplers which are considered as general public would exceed the annual limit dose for this category. On the basis of all this, further radiological protection measures should be introduced, such as applying negative pressure in the administration room to avoid dispersion of the radionuclide to other areas of the NMD.

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Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

Human and animal rights

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical

standards. This article does not contain any studies with animals performed by any of the authors.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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FIGURE CAPTIONS

Fig. 1 Schematic representation of the air, wipe and urine sampling collection points in the NMD under study

Fig. 2 Representation of ^{99m}Tc urine concentration detected in sampler spot samples collected over 24 hours

Fig. 3 Graphical representation of ^{99m}Tc concentration in 24-hour urine samples corresponding to different individual tasks

TABLE CAPTIONS

Table 1 Urine spot sample concentration related to each medical staff task

Table 2 Measurements of ^{99m}Tc concentration in the air from different areas, intakes and the corresponding committed effective doses

Table 3 Measurements of ^{99m}Tc concentration in 24-hour urine samples from different workers, intakes and the corresponding committed effective doses

TABLE 1

Worker	Worker task	^{99m}Tc concentration in spot urine samples (Bq/L)		
		28/05/2018	31/05/2018	06/06/2018
1	PET Technician	94.0 ± 50.0	537.0 ± 57.8	-
2	NM Nurse	279.3 ± 80.4	-	
	PET Nurse		-	14.5 ± 8.3
3	NM Nurse		2,939.0 ± 141.3	18,652.4 ± 1,218.7
	PET Nurse	158.0 ± 26.0		
4	NM Doctor	-	1,045.2 ± 75.5	2,828.6 ± 275.3
5	Secretary	1,014.9 ± 138.9	891.9 ± 74.0	774.3 ± 75.5
6	NM Doctor	-	1,778.7 ± 75.5	752.8 ± 69.6
7	Sampler	4,429.4 ± 258.7	774.3 ± 57.9	1,863.7 ± 224.9

- : The worker was not in the hospital these days

TABLE 2

Sampling sites	Worker exposure time, *t* [min]	^{99m}Tc concentration in air [kBq/m^3]	Intake [Bq]	Committed effective dose, $E_{inhalation}$ [µSv]
Administration room	2	207.43 ± 8.81[a]	8,297.24	0.241
		636.92 ± 27.11[b]	25,476.80	0.739
Gamma camera room	5	0.14 ± 0.01[a]	14.00	0.0004
		1.47 ± 0.06[b]	143.77	0.004
Corridor	5	23.67 ± 0.99[a]	2,367.22	0.069
		53.56 ± 2.92[b]	5,356.00	0.155

[a]Minimum ^{99m}Tc concentration detected in the area

[b]Maximum ^{99m}Tc concentration detected in the area

TABLE 3

Task	^{99m}Tc concentration in 24-h urine samples [Bq/d]	Intake [Bq]	Committed effective dose, E [μSv]
NM Doctor	1,714.5 ± 164.5	595,312.5	17.3
NM Technician	490.0 ± 103.2	170,138.9	4.9
PET Technician	362.7 ± 83.9	125,951.4	3.7
NM Nurse	2,073.8 ± 131.1	720,079.9	20.9
PET Nurse	<MDA*		-
Secretary	2,382.1 ± 164.9	827,125.0	24.0
Sampler 1	1,569.2 ± 176.6	544,861.1	15.8
Sampler 2	2,385.9 ± 251.3	828,437.5	24.0

*MDA = 1 Bq/L

Figure 1

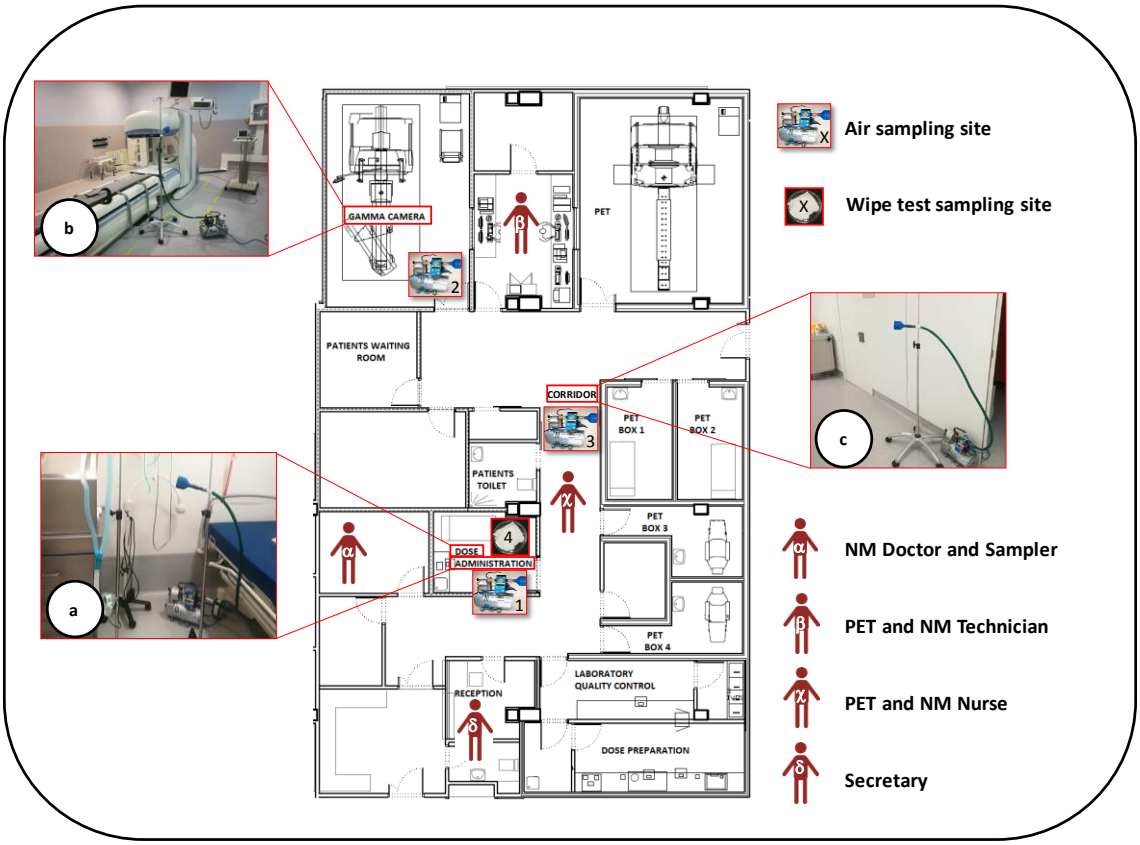


Figure 2

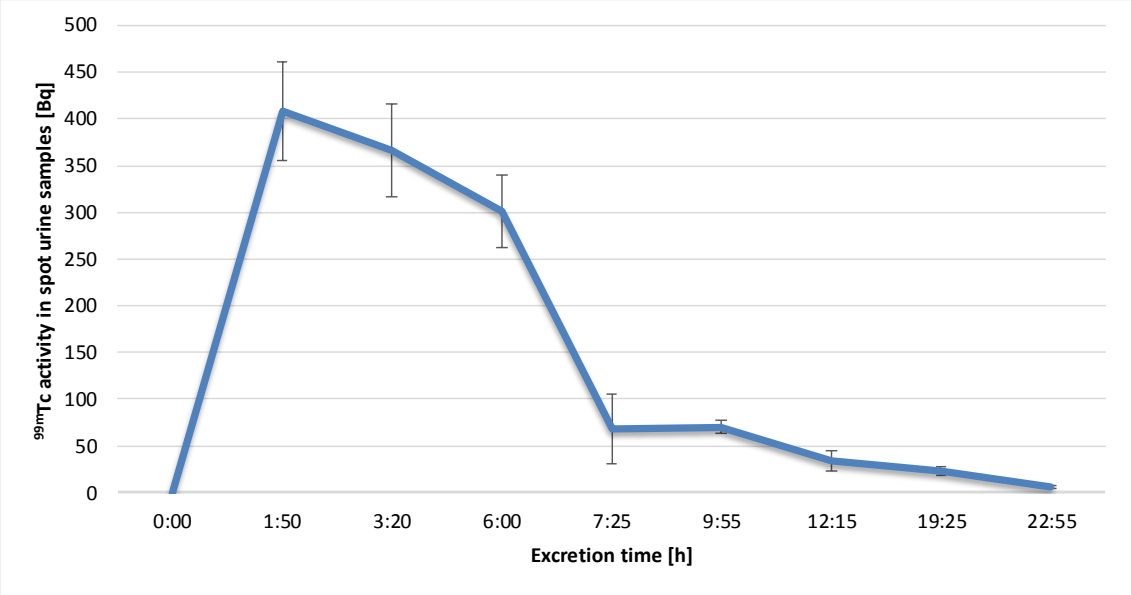
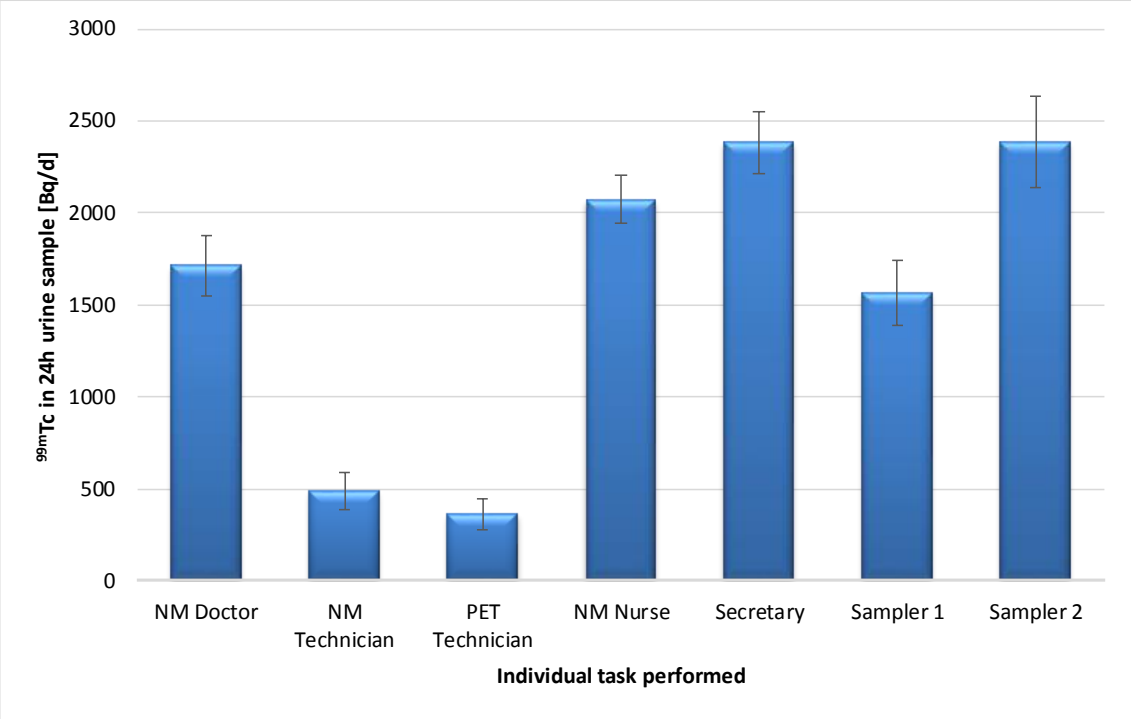

500
450
400
350
300
250
200
150
100
50
0
99mTc activity in spot urine samples [Bq]
0:00
1:50
3:20
6:00
7:25
9:55
12:15
19:25
22:55
Excretion time [h]

Figure 3


3000
2500
2000
1500
1000
500
0
99mTc in 24h urine sample [Bq/d]
NM Doctor
NM Technician
PET Technician
NM Nurse
Secretary
Sampler 1
Sampler 2
Individual task performed

Graphical abstract