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PAPER

Finger doses due to ^{68}Ga-labelled pharmaceuticals in PET departments—results of a multi-centre pilot study

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Supplementary material for this article is available online

Abstract

Introduction: Although the use of ^{68}Ga has increased substantially in nuclear medicine over the last decade, there is limited information available on occupational exposure due to ^{68}Ga. The purpose of this study is to determine the occupational extremity exposure during the preparation, dispensing and administration of ^{68}Ga-labelled radiopharmaceuticals. Method: Workers in eight centres wore a ring dosimeter for all tasks involving ^{68}Ga-labelled radiopharmaceuticals for a minimum of one month. Additionally, the fingertip dose was monitored in two centres and the hand with the highest ring dose during ^{68}Ga procedures was also identified in one centre. Results: The median normalised ring dose for ^{68}Ga procedures was found to be 0.25 mSv GBq^{-1} (range 0.01–3.34). The normalised ^{68}Ga ring doses recorded in this study are similar to that found in the literature for ^{18}F. This study is consistent with previous findings that the highest extremity dose is found on the non-dominant hand. A limited sub study in two of the centres showed a median fingertip to base of the finger dose ratio of 4.3. Based on this median ratio, the extrapolated annual ^{68}Ga fingertip dose for 94% of the workers monitored in this study would be below Category B dose limit (150 mSv) and no worker would exceed Category A dose limit (500 mSv). Conclusion: When appropriate shielding and radiation protection practices are employed, the extremity dose due to ^{68}Ga is comparable to that of ^{18}F and is expected to be well below the regulatory limits for the majority of workers.

1. Introduction

Exposure of the hands is one of the main radiation protection concerns in nuclear medicine. The risk of a significant skin dose is of particular concern for workers in positron emitting tomography (PET), who routinely work with high energy positron emitting radionuclides. While ^{18}F continues to be the most commonly used PET radionuclide, in recent years the number of commercially available positron emitting radiopharmaceuticals has increased. In particular, the routine use of ^{68}Ga-labelled radiopharmaceuticals has

grown substantially [1]. ^{68}Ga-labelled somatostatin-analog imaging with PET/computed tomography (CT) (DOTA-TATE, DOTA-TOC) has become the gold standard in neuroendocrine tumour imaging and ^{68}Ga-labelled protein specific membrane antigen (PSMA) imaging is achieving improved management of patients with prostate cancer [2, 3]. ^{68}Ga based tracers also have applications in infection and inflammation imaging [4]. ^{68}Ga combined with ^{177}Lu or ^{90}Y allow theranostic applications, with an improved selection of patients for treatment and a better prediction of their therapy outcome. Where available, ^{68}Ga and ^{177}Lu theranostic radiopharmaceutical pairs are becoming powerful tools for treatment of prostate cancer and neuroendocrine tumours [5, 6].

^{68}Ga has a more complex decay scheme than the pure positron emitter ^{18}F. Positrons emitted from the decay of ^{68}Ga possess a maximum energy significantly higher than those of ^{18}F, and are also accompanied by a number of gamma emissions, the most abundant of these being the prompt 1.077 MeV gamma emission (3.2%). Positrons emitted from the decay of ^{68}Ga possess a higher maximum energy (1.899 MeV) than ^{18}F (0.634 MeV), which has implications for the skin dose. The skin dose rate due to direct contact with an unshielded 5-ml syringe is approximately 11 times higher for ^{68}Ga than ^{18}F [7]. The use of a syringe shield can significantly reduce the contact skin dose rate for both radionuclides. The thickness and composition of the shield employed has a strong influence on the magnitude of the resultant contact skin dose rate [8, 9]. A syringe shield with sufficient thickness to absorb all the high energy positrons from ^{68}Ga will result in comparable skin exposure for both ^{18}F and ^{68}Ga.

^{68}Ga may require additional manipulation and the handling of much larger activities than routinely seen with the dispensing tasks of ^{18}F radiopharmaceuticals. In most centres ^{68}Ga is eluted from an in-house ^{68}Ge/^{68}Ga generator and routine tasks include labelling, dispensing and quality control (QC) of the radiopharmaceutical. The activity handled during the elution stage can vary significantly depending on the age of the generator, ranging from 1.3 GBq early in the lifespan of the generator to 700 MBq towards the end of it use (assuming an efficiency of 70%). The ^{68}Ge/^{68}Ga generator may be eluted up to three times a day. The generator itself is also a source of radiation exposure with high contact dose rates ($<$0.14 mSv GBq^{-1} hr^{-1} [10]). During and after the generator elution, the unshielded output line can also be a source of exposure.

From the overview above, it is clear that notable differences exist between the decay characteristics and production methods of ^{18}F and ^{68}Ga radiopharmaceuticals. Whether these differences result in an increased occupational extremity exposure for ^{68}Ga is however not clear. A recent literature review of extremity exposure of nuclear medicine workers by the European radiation dosimetry group (EURADOS) indicated that there are limited publications relating to ^{68}Ga [11]. In order to gain better insight into the actual skin dose for staff working with ^{68}Ga-labelled radiopharmaceuticals, a multi-centre ring dosimetry pilot study was set up by the EURADOS. This paper reports on the results of the pilot study.

2. Materials and methods

2.1. Extremity dose measurements

A ring dosimetry pilot study was organised amongst 8 EURADOS partners. The participating partners were from Ireland (2x), The Netherlands, Italy, Belgium, Israel, Poland and Switzerland. Workers in each of these centres wore a dedicated extremity dosimeter during ^{68}Ga manipulations on the palm side on the index finger of their non-dominant hand. Seven centres employed ring dosimeters for extremity dose monitoring and one centre (Centre 8) used bare high sensitivity thermoluminescent dosimeters (TLDs) taped to the finger at the appropriate location. For the remainder of this manuscript, the term ring dosimeter will refer to the measurements recorded by both the ring dosimeters and the bare TLD.

The following information was recorded in the measurement campaign:

- The workers dominant hand (right/left)
- The duration of the monitoring period (minimum one month)
- The total ^{68}Ga activity handled in the monitoring period per worker
- The tasks performed
- The total dose $H_p(0.07)$ recorded on the dosimeter for the period of wear
- Properties of the TLD/ring dosimeter
- ^{68}Ge/^{68}Ga generator details
- ^{68}Ga workload and administration activities
- ^{68}Ga radiopharmaceutical labelling procedure
- Local shielding and radiation protection devices used (distancing tools, vial or syringe shield)

For the elution and preparation of the ^{68}Ga-labelled radiopharmaceutical, the total activity eluted from the ^{68}Ge/^{68}Ga generator was recorded. The activity for this task was measured in most centres after the

labelling procedure was completed. One centre assayed the eluate before labelling. In each case the activity assayed reflected the activity at the time of worker manipulation. For QC tasks, the manipulated activity recorded was either assayed directly or estimated based on the volume of the ^{68}Ga-labelled pharmaceutical. For dispensing, the total activity recorded was the final activity withdrawn from the mono- or multi-dose vial. In the case of patient administration, the total activity in the syringe at the time of injection was considered. Statistical analysis was performed to compare the normalised dose distributions among the centres using a Wilcoxon two-sided test.

2.2. Ring dosimeters

Each centre provided its own ring dosimeter, the characteristics of which are summarised in table 1. The ring dosimeters employed in this study are those used in routine service in each centre's nuclear medicine (NM) department. The ring dosimeters in Centres 1–7 are calibrated, provided, and read by a national accredited dosimetry service in each centre's own country. Information about the calibration of the ring dosimeters, where available, can be found on-line at the reference listed in table 1. Dosimeters in Centre 8 were calibrated with a rod phantom in accordance with ISO 4037-3 in a secondary standards laboratory. All dosimeters used in this study comply with the ISO 17025 laboratory management standard.

In addition to the main survey and ring dosimeter collection, two sub studies were also performed.

2.3. Dominant to non-dominant hand dose comparison

The first sub study compared the dose received on the index finger of the dominant hand to that of the non-dominant hand. The purpose of this sub study was to determine which index finger received the highest skin dose.

2.4. Fingertip to base of the finger dose ratio

The second sub study compared the fingertip dose to the dose at the base of the finger. This study was performed in two centres.

2.5. Centre background information

Of the 8 participating centres, one centre received unit doses of ^{68}Ga (Centre 6), and the remaining 7 centres had an in-house ^{68}Ge/^{68}Ga generator. All ^{68}Ge/^{68}Ga generators in this study had a calibration activity of 1.85 GBq ^{68}Ge with an expected yield efficiency of approximately 70%. In all centres the elution of the ^{68}Ge/^{68}Ga generator and ^{68}Ga labelling was performed in either a laminar air flow cabinet (LAFC), isolator or hot cell. The shielding provided by these units was in the range of 30–50 mm lead. QC of the ^{68}Ga-labelled radiopharmaceutical was mostly performed on the countertop. Local shielding used during QC ranged from no shielding to 50 mm lead.

The ^{68}Ga-labelled radiopharmaceutical annual workload (number of patient administrations) varied significantly over the 8 centres. DOTA-TOC/TATE imaging of neuroendocrine tumours was the most common procedure performed, followed by PSMA for prostate cancer and one centre also performed angiogenesis imaging using ^{68}Ga-labelled arginine–glycine–aspartate tripeptide sequence (RGD). The administered activities for all ^{68}Ga-labelled radiopharmaceuticals were comparable across all centres, typically ranging from 100 MBq to 220 MBq. Of the 7 centres with a ^{68}Ge/^{68}Ga generator, 5 centres employed only synthesis methods to produce the ^{68}Ga-labelled radiopharmaceutical, one centre performed cold-kit DOTA-TOC labelling and the final centre performed both synthesis and cold-kit labelling.

All centres employed the use of vial shields ranging in wall thickness from 15 to 50 mm of lead. Syringe shields of various compositions and thickness were also employed. The most commonly used syringe shield was composed of tungsten, with wall thickness ranging from 5 mm to 9 mm. Further information regarding workload and shielding specifications can be found in the Supplementary material section (tables S1–S5).

3. Results

3.1. Ring dosimeter results

A summary of the monthly ring dosimeter readings and the total activity handled per worker per month for each centre is shown in table 2. The ring dosimeter was worn at the base of the index finger on the non-dominant hand.

Of the 132 ring dosimeter readings in this study 10 (7%) were found to be below the minimum detectable limit (MDL) and as such no dose was reported. The MDL on these badges ranged from 20 to 150 μSv (table 1). Assigning the TLD-specific MDL to these ten ring dosimeters resulted in a median extremity dose across all centres of 0.40 mSv. Omitting these ten readings resulted in a median extremity dose of 0.44 mSv. While the impact of assigning a value equal to the MDL for these dosimeters had very little

Table 1. Technical specification of ring dosimeters used in the study.

	TLD manufacturer (Country)[a]	TLD material	TLD type	Effective thickness (mg cm^{-2})	Min. detectable level (MDL) (μSv)	Min. beta energy (keV)[c]	References
Centre 1	SSDML (China)	LiF:Mg, Cu, P	GR-200 A	200	40	600 (average energy)	[12]
Centre 2	Radcard (PL)	LiF:Mg, Cu, P	MCP-N	225	20	250	[13]
Centre 3	Landauer (US)	Lif: Mg, Ti	TLD-100	225[b]	100	200 (average energy)	[14]
Centre 4	Radcard (PL)	LiF:Mg, Ti	MTS-N	225	150	700	[15]
Centre 5	Landauer (US)	LiF:Mg, Ti	TLD-100	225[b]	100	200 (average energy)	[14]
Centre 6	Thermo Fisher Scientific Corp (US)	LiF:Mg, Ti	MTS-100	100	100	1000	[16]
Centre 7	Radcard (PL)	LiF:Mg, Cu, P	MCP-Ns	8.5	100	50	[17]
Centre 8	Radcard (PL)	LiF:Mg, Cu, P	MCP-N	225	40	600 (average energy)	[18]

[a] If the TLD manufacturer information is not available the ring dosimeter supplier is listed where known. Solid Dosimetric Detector and Method Laboratory (SSDML).

[b] This information could not be obtained from the supplier; the effective thickness was estimated based on the physical dimensions and composition of the TLD.

[c] The detectable beta energy range depends on the composition and thickness of the ring material surrounding the dosimeter, not on the TLD characteristics.

Table 2. Overview of the monthly ring dosimeter readings and the total activity handled per worker per month (summarised for all tasks—preparation, dispensing and administration).

	Number of measurements	Number of workers	Ring dosimeter reading (mSv)			^{68}Ga activity handled (GBq)		
			Mean	Median	Range	Mean	Median	Range
Centre 1	29	10	0.8	0.8	0.1–3.2	5.4	2.5	0.3–23.3
Centre 2	50	19	0.4	0.1	0.02–2.6	1.7	0.4	0.1–18.9
Centre 3	9	4	0.8	0.6	0.2–1.9	3.2	2.0	1.1–7.8
Centre 4	9	9	2.7	2.5	0.8–5.0	3.1	2.9	1.7–8.6
Centre 5	11	6	0.5	0.4	0.1–1.8	1.4	1.2	0.4–2.8
Centre 6[a]	4	4	0.3	0.4	0.1–0.5	2.0	2.5	1.3–2.8
Centre 7	6	4	2.2	1.8	0.1–4.9	5.4	6.0	0.2–11.3
Centre 8	4	4	2.5	1.7	1.0–5.7	2.4	2.3	1.3–3.7
All Centres	122	61	0.9	0.4	0.02–5.7	3.0	1.5	0.1–23.3

[a] Centre 6 only administration tasks were performed in this centre.

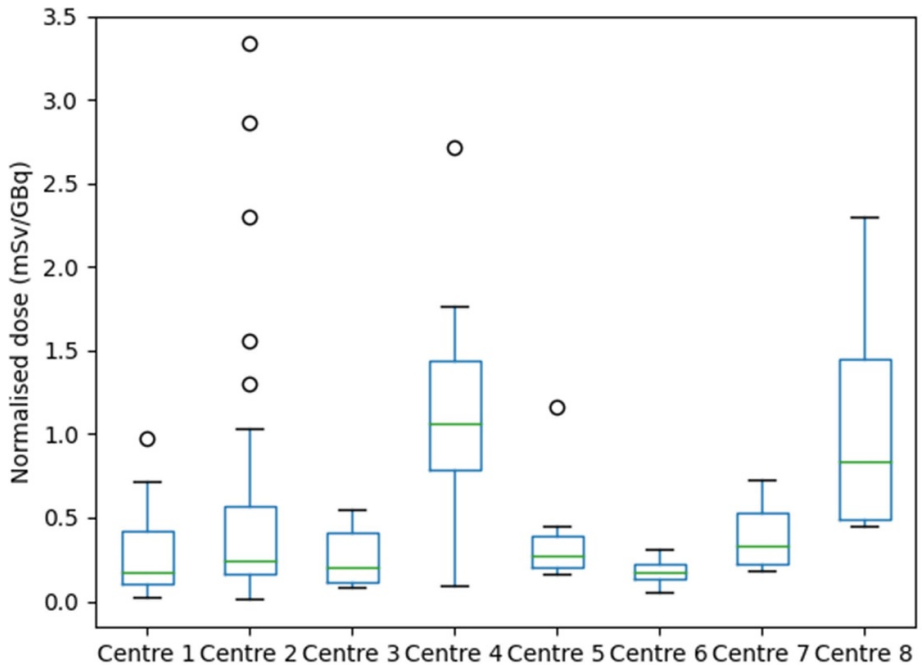

Figure 1. Monthly ring dosimeter readings normalised by activity handled for each centre (mSv GBq^{-1}). The median value for each centre is identified in the boxplot and the points outside the boxplot are outliers.

impact on the monthly dosimetry results, they could potentially skew the normalised doses. Therefore, these ten ring dosimeter results were not included in the data analysis.

The median monthly dose for all remaining ring dosimeters in the study was 0.44 mSv (range 0.02–5.7 mSv). The median activity handled per worker per month was 1.5 GBq (range 0.07–23.3 GBq).

3.2. Normalised ring dose results

Figure 1 displays the ring dosimeter readings (mSv) normalised by activity handled (GBq) for each participating centre. The median normalised dose per month for all centres was found to be 0.25 mSv GBq^{-1} (range of medians 0.18–1.07 mSv GBq^{-1}). Across the individual workers in all centres there is a very broad range of normalised doses (measurement range 0.01–3.34 mSv GBq^{-1}). The normalised doses in Centre 4 were found to be significantly higher than in Centre 1 ($p = 0.004$, difference in medians = 0.9). No significant differences were found between any other centres.

3.3. Task specific normalised dose

For 5 out of the 8 participating centres it was possible to classify the monitored workers into two distinct groups: those who were involved in the preparation/dispensing/QC stage only and those who were only involved in patient administration. In Centre 6, workers performed administration tasks only as their ^{68}Ga radiopharmaceuticals were supplied as unit doses. In Centres 3 and 8 workers performed all tasks so classification was not possible.

Table 3. Measured ring doses at the index finger of the dominant and non-dominant hands.

	Dominant hand	Non-dominant hand
Ring dose (mSv)—median (range)	0.9 (0.4–1.5)	2.5 (0.8–5.0)
Normalised ring dose (mSv.GBq^{-1})—median (range)	0.3 (0.1–0.9)	1.1 (0.1–2.7)

Table 4. Fingertip to base of the finger data for the index finger of the non-dominant hand—median (range).

	Ring dose (mSv)	Fingertip dose (mSv)	Dose ratio
Centre 5 ($n = 6$)	0.5 (0.2–0.8)	1.6 (0.7–5.0)	4.3 (1.3–10.2)
Centre 8 ($n = 4$)	1.8 (1.5–5.7)	6.9 (3.5–25.7)	4.0 (2.1–4.7)
Total	0.7 (0.2–5.7)	3.0 (0.7–25.7)	4.3 (1.3–10.2)

Statistical analysis using a two-sided Wilcoxon rank sum test confirmed no significant difference between the normalised doses of the two groups ($p = 0.59$, 95% C.I.). The median normalised ring dose was 0.23 mSv GBq^{-1} for preparation/dispensing/QC tasks and 0.26 mSv GBq^{-1} for administration tasks. A summary of the normalised doses per task for each centre can be found in table S6 in the Supplementary Materials section.

In general, higher activities are handled by workers performing preparation and dispensing tasks compared to those who perform administration only, resulting in higher monthly dosimeter readings for these workers. At the preparation stage, the activity handled depends on the generator yield and the age of the generator. Activities handled during preparation tasks are typically in the range 0.7–1.3 GBq. Activities handled during the administration stage are in the range 100–220 MBq per patient. Depending on how far in advance the patient injections are dispensed, the activities handled during dispensing may be 2–3 times that of the administration activity due to the short half-life of ^{68}Ga (68 min). Activities handled during the QC stage are low, typically <20 MBq.

3.4. Dominant to non-dominant hand dose comparison

The sub study comparing the dose at the base of the index finger for the dominant and non-dominant hand was performed for nine workers in Centre 4. It was found that the non-dominant hand received the highest dose. All nine workers were right-handed. Table 3 summarises the doses received for the nine workers.

The median ratio of the dose received by the index finger of the non-dominant to dominant hand was 2.8 with a range of 1.6–5.6.

3.5. Fingertip to base of the finger dose ratio

In Centre 5, six workers wore ^{68}Ga fingerstalls in addition to their ring dosimeter for a period of one month on the index finger of the non-dominant hand. This monitoring period was outside the data collection period of the main study so details about the specific tasks performed and activities handled, were not recorded. In Centre 8, high sensitivity TLDs were worn at the base of the finger and the fingertip position on the index finger of the non-dominant hand for four workers for one month. Combining the data from both centres resulted in a median fingertip to base of the finger dose ratio of 4.3 with a range of 1.3–10.2 (table 4).

4. Discussion/recommendations

4.1. Ring dosimeter measurements

When appropriate shielding is employed and optimal radiation protection practices are implemented, monthly ring doses due to ^{68}Ga are reasonably low in all participating centres. For all workers monitored in this study during ^{68}Ga procedures, 73% recorded a ring dose below 1 mSv per month and 95% recorded a ring dose below 3 mSv per month. There was no clear difference in the ring dose between centres that performed synthesis and those that performed cold-kit labelling of the ^{68}Ga radiopharmaceutical.

4.2. Normalised dose—comparison between centres

The median normalised dose for each centre ranged from 0.18 to 1.07 mSv GBq^{-1} per centre. The normalised doses in Centre 4 were significantly higher than in Centre 1, and no significant differences were found for the other centres.

Centre 4 used a thinner syringe shield (5 mm W) compared to all other centres, whose shields were of the order of 7.5–10 mm W. The thickness and composition of the syringe shield used is known to have a significant impact on the potential occupational exposure [8]. A comparison of the effectiveness of a 5 mm and 7.5 mm W/Ni/Cu syringe shield was performed by the Institute of Radiation Physics, Lausanne,

Centre 4: Synthesis in open LAFC

Centre 3: Synthesis performed in completely shielded LAFC (when the drawer is lowered below the surface of the cabinet).

Figure 2. LAFC set-up for ^{68}Ga radiopharmaceutical synthesis.

Switzerland [19]. They found that in contact, the skin dose for a 5 mm W shield was 3.3 times higher than for a 7.5 mm W shield, given the same ^{68}Ga activity and exposure time.

In Centre 4, the ^{68}Ge/^{68}Ga generator and synthesis unit was housed in an open LAFC with a moveable lead glass panel. Two centres housed their synthesis units in isolators. In the remaining centres, synthesis was performed in a completely shielded LAFC. For example, one centre housed the ^{68}Ge/^{68}Ga generator and synthesis modules in a self-shielded drawer which was lowered during synthesis as shown in figure 2. In addition, no local shielding was used during the QC of the ^{68}Ga radiopharmaceutical in Centre 4. The combination of all these differences may account for the higher normalised doses observed in this centre.

4.3. Normalised dose—comparison to published values

The median normalised ring dose found in this study, for all tasks, was 0.25 mSv.GBq^{-1} for the non-dominant hand (range 0.01–3.34 mSv GBq^{-1}). A study by Dwivedi *et al* [20] that monitored finger doses during ^{68}Ga procedures reported much higher ring doses, in the range of 7.6–9.1 mSv GBq^{-1}. However, the operators in Dwivedi's study did not use vial or syringe shields, which is not representative of current good radiation protection practice. The addition of the syringe and vial shielding would have reduced these exposures significantly. In a study by McCann *et al* [8], $H_p(0.07)$ skin dose rate in direct contact with the active volume of an unshielded syringe containing ^{68}Ga was found to be 34.3 mSv MBq^{-1} h^{-1}. The addition of a 7.5 mm W/Cu/Ni syringe shield reduced the skin dose rate at this location to 0.2 mSv MBq^{-1} h^{-1}, a factor of approximately 180. The vial shields used in this study provided even greater shielding (15–50 mm Pb) and would also significantly reduce the skin dose.

Grosser *et al* [21] recorded skin doses from ^{68}Ga procedures using a ring dosimeter at the base of the index finger. In Grosser's study, normalised skin doses of 0.76–1.03 mSv GBq^{-1} and 0.15–0.26 mSv GBq^{-1} were recorded on the dominant and non-dominant hand, respectively. In our study, 53% of the normalised skin dose values on the non-dominant hand were below the maximum of 0.26 mSv GBq^{-1} noted by Grosser. The TLD measurement period in Grosser's study consisted of two separate days monitoring for two workers. Additional monitoring periods would provide a better estimate of the actual dose received over the usual monthly monitoring period. Even so, the results obtained here are comparable to that observed by Grosser *et al.*

4.4. Dominant to non-dominant hand dose comparison

This study is in line with the findings of the ORAMED study [9] that the normalised skin dose was higher for the non-dominant hand than for the dominant hand. This is in contrast to the findings by Grosser *et al* [21], who found that the normalised skin dose was higher for the dominant hand.

4.5. Fingertip to base of the finger dose ratio

Although it is common to measure the extremity exposures with a ring dosimeter at the base of the finger, it is well known that this measurement position may not reflect the maximum extremity dose received. Correction factors between 1.4 and 7 have been suggested for a range of radionuclides [11, 22], but there are no published factors specifically for ^{68}Ga. In our study, the median ratio of fingertip to base of the finger dose across two centres was found to be 4.3 for the index finger of the non-dominant hand. While the results

found in this study are in the range of the published dose ratios of other radionuclides, a larger monitoring group would better estimate the average fingertip to base of the finger dose ratio for ^{68}Ga. While average values are useful, local or individualised assessment of the dose ratio is recommended for the most accurate determination.

Applying the fingertip correction factor 4.3 to the normalised doses obtained in this study, results in a mean normalised fingertip dose of 2.1 mSv GBq^{-1} (SD of 2.5). In a recent study employing the use of fingerstall dosimetry, Eakins *et al* [23] measured normalised fingertip doses during three weeks in one hospital. A mean normalised dose of 0.16 mSv GBq^{-1} (SD of 0.07) was found for the medical physicists involved in the preparation and QC of ^{68}Ga-DOTATATE, while a mean normalised dose of 1.24 mSv GBq^{-1} (SD of 0.67) was found for the radiographers involved in the dispensing and administration of the same product.

A direct comparison cannot be made as the task classification is different in Eakin's data, and the data is averaged across both hands with no information on the handiness of the worker provided. Even so the estimated fingertip dose in this study (median normalised ring doses of about 250 μSv GBq^{-1} with a dose ratio of 4.3 to the fingertip) is comparable to the values reported by Eakins.

4.6. Annual dose limits

The highest ring dosimeter reading reported in this study was 5.7 mSv per month. Factoring this up to 12 months would result in an annual ring dose of 68.4 mSv. Although this is well below the Category A (500 mSv) and Category B (150 mSv) annual occupational skin dose limits, it does not fully reflect the maximum dose that the skin of the hand may receive. Assuming a fingertip to base of the finger ratio of 4.3, the estimated annual fingertip dose for this worker would be 294 mSv. In general, most workers would not be expected to experience extremity doses of this magnitude. Applying the same factors for the median value of the entire study population (0.4 mSv), would result in a median annual fingertip dose of 23 mSv. The estimated annual fingertip dose for 94% of all ratio-corrected ring dosimeter readings in this study would be below the Category B (150 mSv) dose limit and no workers would exceed the Category A (500 mSv) dose limit.

While exposure due to ^{68}Ga alone is unlikely to exceed the regulatory dose limits, workers also received extremity dose due to the handling and manipulation of other radionuclides during the monitoring period. A simple comparison of the ring dosimeter reading for ^{68}Ga to the ring dosimeter reading for all non-gallium radionuclides in the same monitoring period, showed that ^{68}Ga accounted for a median of 7% of the total occupational exposure (range 1%–88%). This data was available from three centres only and limited information was available on the variety of radionuclides, or their activities handled. As the use of ^{68}Ga is expected to increase over the next few years, the portion of the total extremity exposure due to ^{68}Ga may also increase. The use of appropriate shielding and distancing tools and the degree to which good radiation practices are adhered to by the staff are particularly important for ^{68}Ga. In order to keep occupational exposure to a minimum, sharing of duties involving the manipulation of high ^{68}Ga activities is recommended, as is prior venous cannulation of a patient and the use of automatic dispensing and administration modules where possible [11].

4.7. Ring dosimeter performance

The use of the appropriate dosimeter is essential when dealing with mixed radiation fields such as those from ^{68}Ga. Studies have found a clear correlation between the dosimeters filter and detector thickness and response to beta particles. Carnicer *et al* [24] recommended that thin TLDs (<10 mg cm^{-2}) should be used when positrons or electrons contribute significantly to the $H_p(0.07)$, otherwise underestimations up to 50% are possible. In a recent publication investigating specifically the response of a range of TLD types to ^{68}Ga, Van Hoey *et al* [25] found that MCP-Ns TLDs (8.5 mg cm^{-2}) provided the best response, while MCP-N (225 mg cm^{-2}) and MTS-N (225 mg cm^{-2}) TLDs showed about 20% under-response when used for monitoring an unshielded syringe. The ring dosimeters employed in this study are the dosimeters used in routine practice in each centre. In general, workers wear a single ring dosimeter to monitor their $H_p(0.07)$ from a range of gamma, positron and beta-emitting radionuclides. The majority of centres in this study employed thick dosimeters (100–225 mg cm^{-2}) (table 1). Only one centre, Centre 7, employed the use of a thin TLD (8.5 mg cm^{-2}). While this suggests that the doses reported here may be underestimated by about 20% due to the use of the thicker dosimeters, which remains acceptable considering the remaining uncertainties associated with extremity monitoring, it is important to note that both Carnicer's and Van Hoey's work was based on exposure to unshielded radioactive sources. Due to good radiation practices such as the use of shielding and distance tools, workers in this study are expected to have minimal contact with unshielded sources of ^{68}Ga. The use of syringe and vial shields effectively absorbs most, if not all positrons. The main contributor to $H_p(0.07)$ for shielded sources of ^{68}Ga are the annihilation photons so the TLD

thickness related under-estimation may not be as significant in practice as these two publications suggest. Further work is required to determine the influence of shielding on TLD performance.

The uncertainty associated with each type of TLD used in this study was not provided by all manufacturers. Where this information was supplied, uncertainties of approximately ±50% at 95% confidence interval were quoted. Even though there may be additional uncertainties in the assessment by the dosimeter, this does not essentially change the observation that the measured dose is quite low compared to the dose limits. As previously mentioned, it is important to keep in mind that these values are based on their exposure to ^{68}Ga only, in practice these workers will also be exposed to radiation from other radionuclides.

4.8. Comparison to ^{18}F

In a recent review of extremity exposure, Kollaard *et al* [11] found that the mean and/or median ring doses at the base of the finger for manual procedures with ^{18}F ranged between 0.04 and 0.70 mSv GBq^{-1}. The median normalised ^{68}Ga ring dose recorded in this study was 0.25 mSv GBq^{-1} across all centres. The administered activities for ^{18}F and ^{68}Ga procedures are typically of the same order of magnitude (e.g. 75 kg patient: 100–200 MBq ^{68}Ga, 175 MBq ^{18}F-FDG assuming >30% bed overlap and 3 min per bed acquisition [26]). Therefor it can be concluded that even with the additional manipulations and the higher energy positrons, the median normalised ^{68}Ga ring dose is in practice comparable to that of ^{18}F.

4.9. Contamination

Compared to unit doses or dispensing of ^{18}F there is more manipulation required during the elution, labelling and QC of ^{68}Ga, and hence the potential risk of a spill is increased. In one of the participating centres a ring dosimeter reading of 20 mSv was recorded in one month. This was recorded prior to this study's monitoring period so the worker handled a range of radionuclides while wearing this ring dosimeter. However, the only incident of note to occur during this monitoring period was a small spill of ^{68}Ga, so it is assumed that this incident was the cause of the high ring reading. The incidence of contamination with high energy positron emitters in clinical practice is an area that requires further research.

4.10. Study limitations

The accurate analysis of extremity dose as a function of the parameters of influence is a challenging task. While efforts were made to gather as much information as possible, there was a lack of data on some potential parameters of influence, such as the amount of time the worker spent handling ^{68}Ga. In addition, the number of times the activity was manipulated was not taken into account in the analysis (e.g. number of attempts to draw the radioactive ^{68}Ga liquid into a syringe to obtain the required activity). An inter-comparison to evaluate the differences between the dosimeter types was not performed. Performing such an inter-comparison would have provided more insight in the differences across the range of the dosimeters applied. However, as all dosimeters were either obtained from an accredited dosimetry service or calibrated in a secondary standards laboratory we expect the differences between the dosimeter responses to be limited, and within the defined uncertainty range. Despite the limitations mentioned here, the study provides a good overview of extremity exposure due to ^{68}Ga in a clinical setting across several centres.

5. Conclusion

When appropriate shielding is employed and adequate radiation protection practices are applied, the extremity dose due to ^{68}Ga is comparable to that of ^{18}F and is expected to be well below the regulatory limits for most workers. Based on the estimated annual fingertip dose due to ^{68}Ga, 94% of workers in this study were below the Category B limit and no workers exceeded the Category A limit. While these values are reassuring, it is important to note that this analysis considers ^{68}Ga exposure only. The majority of NM and PET workers will be exposed to a range of additional radionuclides and other occupational sources of radiation. There was some variation in the measured extremity dose between centres in this study. The highest normalised doses were observed in Centre 4. In this centre, a thinner syringe shield was used and less local shielding was in place during the preparation tasks compared to other centres. Workers involved in the elution, preparation and dispensing of ^{68}Ga-labelled radiopharmaceuticals handle much larger activities of ^{68}Ga, and therefore receive higher skin doses than those involved in patient administration tasks. This study found that in most cases, the non-dominant hand is the most exposed. A ^{68}Ga fingertip to base of the finger dose ratio of 4.3 was found for a small study group, which is within the range of ratios found for other radionuclides.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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