Report on the analysis of the measurement and simulation results of the doses to extremities in nuclear medicine

Work package 4, ORAMED

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1. INTRODUCTION

The present report corresponds to the third deliverable of the WP4 (Extremity dosimetry in nuclear medicine) of the ORAMED (Optimization of Radiation Protection of Medical Staff) project**.** This report compiles and summarizes the results obtained from the analysis on extremity dose distribution data from the measurement campaign and from the analysis of the different simulations that have been performed.
See Appendix 1 and 2 for the detailed results of the analysis on the measurement and simulation data.

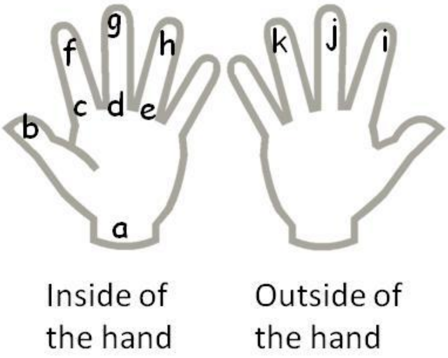
2. RESULTS OBTAINED FROM THE MEASUREMENT CAMPAIGN

2.1 GENERALITIES

The final database of the results collected from the measurement campaign comprises 34 nuclear medicine departments in Europe from 7 different countries: Belgium, France, Germany, Italy, Slovakia, Spain and Switzerland; in total 124 workers.

The analysis of the results was done according to the different procedures performed in the nuclear medicine services: for diagnostic procedures preparation with Tc-99m, administration with Tc-99m, preparation with F-18 and administration with F-18. For therapy procedures, the analysis was focused on the preparation and administration of radiopharmaceuticals with Y-90 (Radioimmunotherapy (RIT) with Zevalin® and Peptidereceptorradiotherapy (PRRT) with Dotatoc), because they were the techniques, from which the largest number of data were gathered.

All data used for the analysis are summarized in a database (see Deliverable 4.2 for more information) recording all relevant information for radiation exposure, i.e. radiation protection devices and tools, activity manipulated, measured doses, etc. As explained in the measurement protocol (see Deliverable 4.1) each worker involved wore a pair of gloves; each glove was equipped with 11 thermoluminescent (TL) dosemeters taped at different positions, labelled from “a” to “k” for the non-dominant (nd) hand (see Figure 1), from “A”-“K” for the dominant (D) hand. Additional measurements were performed by BfS for therapy procedures, taping extra TLDs directly onto the fingers under the protective gloves in order to expand the dose mapping of the hand. To have enough measured dose on the TLDs, when manipulating Tc-99m (preparation and administration) and depending on the activity manipulated, the same gloves were sometimes used for a period of an entire week. For F-18 (preparation and administration) this period was usually shortened to one day and for therapy (preparation and injection) one single procedure was enough. Those series of measurements where contamination was proved have not been taken into account for the general analysis.



Meas. points	Description
a	wrist
b	thumb tip
c	index base
d	middle base
e	ring base
f	index tip
g	middle tip
h	ring tip
i	index nail
j	middle nail
k	ring nail

Figure 1. Description of the measuring points for the nd hand.

The agreed protocols established that, among the collected data, only those belonging to workers having at least 4 measurements series had to be considered in the final analysis for diagnostic procedures. Due to the reduced number of the available practices this rule was not applied in therapy and all the collected data were considered in the analysis. In both cases, the mean, the median, the minimum and the maximum of the *H*p(0.07) values of all available series of measurements were calculated for each worker. The normalisation of *H*p(0.07) values has been done using the total activity prepared to be administrated for preparation procedures and the total activity administered for administration procedures.

A common methodology was followed for the analysis of the data of each procedure with the aim of homogenizing the evaluation of all the important aspects of extremity dosimetry. A table describing the number of measurements considered in the analysis and those discarded was produced for each procedure. The variability for each worker when repeating the same procedure and the variability among workers when doing the same procedure were checked using the minimum, median, mean and maximum values of the (minimum) 4 series of measurements of each worker. Workers were classified with respect to their maximum mean dose to identify those working in a more appropriate way. A relation between the high doses observed for each worker with the dispersion of the maximum was also checked. Furthermore, the frequencies of the corresponding positions where the maximum is found were evaluated for each procedure together with its dose value cumulated. Correction factors were calculated to estimate the impact of placing the routine monitoring dosemeter at a different position than the one corresponding to the maximum skin dose.
A step further in the analysis was centered on trying to find correlations among the different parameters of interest and to check the statistical significance of these correlations. Finally, an estimation of the maximum annual dose for workers in diagnostic procedures that were monitored during the ORAMED measurement campaign was performed to check whether the annual limit could be reached.

2.2 ANALYSIS OF THE DATA

Table 1 summarizes all the data obtained and used for the analysis for diagnostic procedures. As described above only workers with at least 4 measurements series were considered.

	Total number of measurements in the database	Total number of measurements considered for the analysis	Number of workers considered for the analysis	Number of nuclear medicine services considered for the analysis
Tc-99m preparation	202	178	36	21
Tc-99m administration	179	157	32	20
F-18 preparation	184	160	30	17
F-18 administration	169	146	30	17

Table 1. Number of measurements obtained and used for the analysis of diagnostic procedures. All the data come from 6 different European countries.

For therapy, there was no requirement on the minimum number of procedures to be done by each worker since these procedures are not as frequent as diagnostic ones. Furthermore they are often not performed by the same person. An overview on the scope of measurements for therapy procedures is given in Table 2.

THERAPY	Nuclide	Preparation/ administration	Number of workers	Number of data sets
RIT	I-131	P/A	1	4
PPT	Sm-153	P	1	2
RSO	Re-186	P A	3 3	4 4
SIRS	Y-90	P	4	20
PRRT Dotatoc	Y-90	P A	5 7	16 17
RIT Zevalin®	Y-90	P A	20 22	49 45

Table 2. Data obtained for the therapy procedures.

For therapy, the analysis has been focused on those two practices having the largest number of available data, i.e. RIT Zevalin® and PRRT Dotatoc, both involving the manipulation of unsealed Y-90 radioactive sources.

2.1.1 Classification of workers

For each worker, the doses normalized to the manipulated activity (µSv/GBq) measured at every position were averaged on the set of measurements (at least equal to 4). From these mean doses (11 for nd and 11 for D hands), the maximum was identified for each worker and the workers were classified in increasing order of these maximum values. The classification is obtained for each procedure as shown from Figure 2 to Figure 5 for the different diagnostic procedures and from Figure 6 to Figure 9 for the different therapy procedures. In those figures

the first colored values correspond to the 1st quartile, then (in different colours), the 2nd, 3rd and 4th quartiles, except in the case of Figure 8 and Figure 9 because the number of monitored workers is only 5 and 7, respectively.

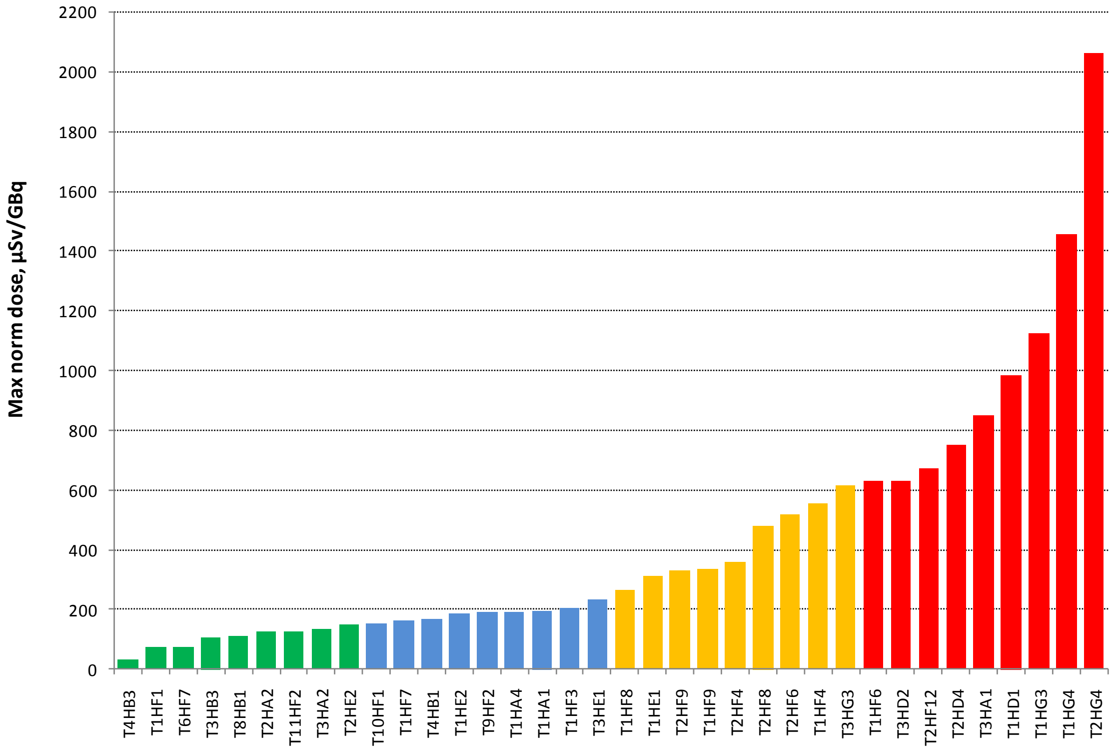


Figure 2. Classification of workers for Tc-99m preparation.

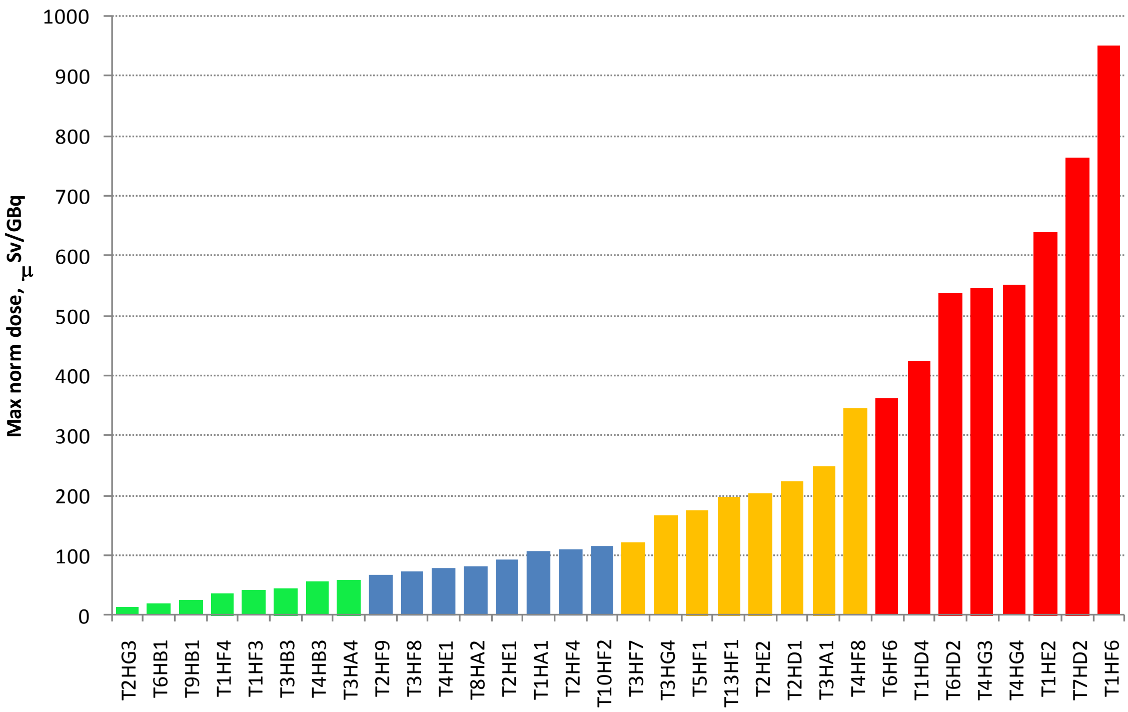


Figure 3. Classification of workers for Tc-99m administration.

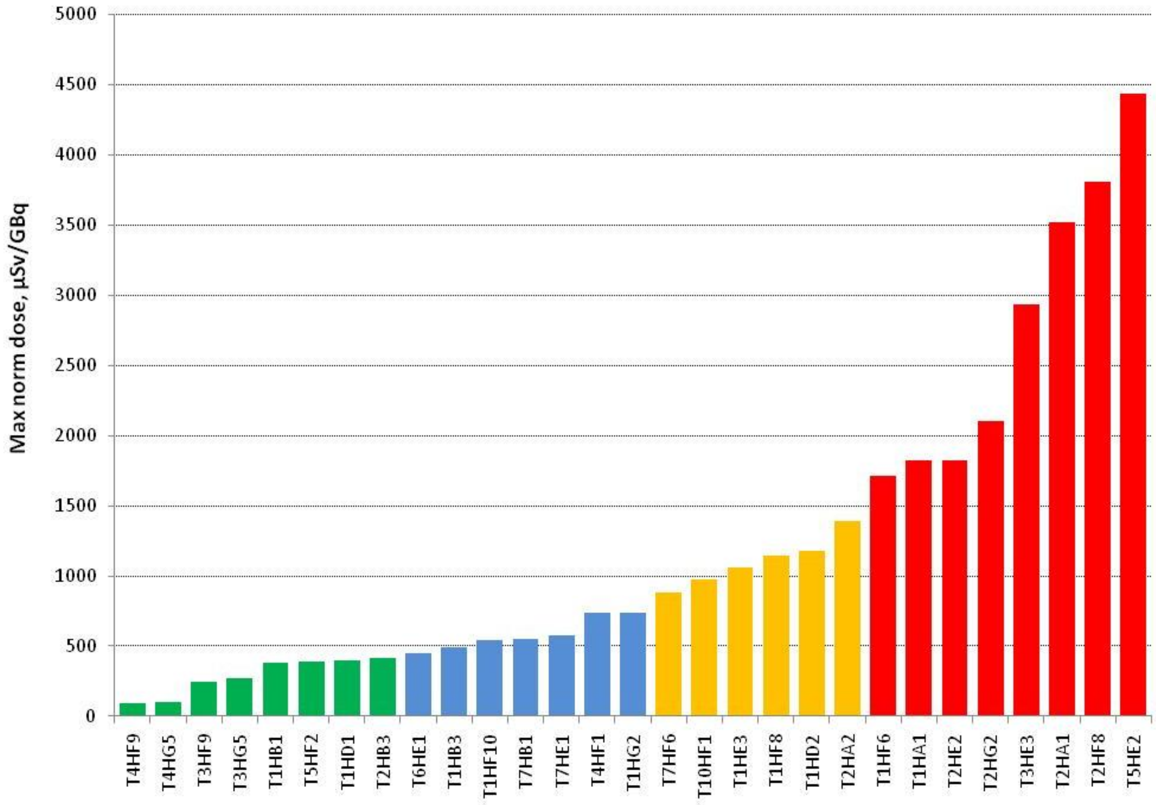


Figure 4. Classification of workers for F-18 preparation.

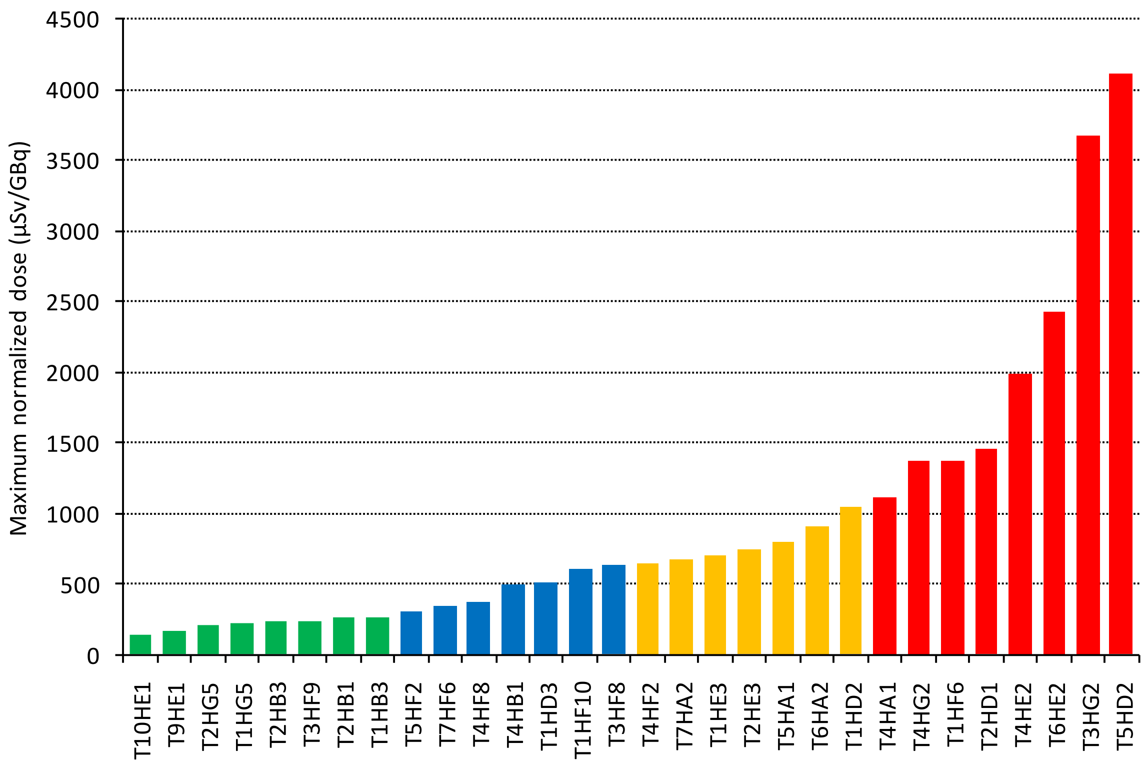


Figure 5. Classification of workers for F-18 administration.

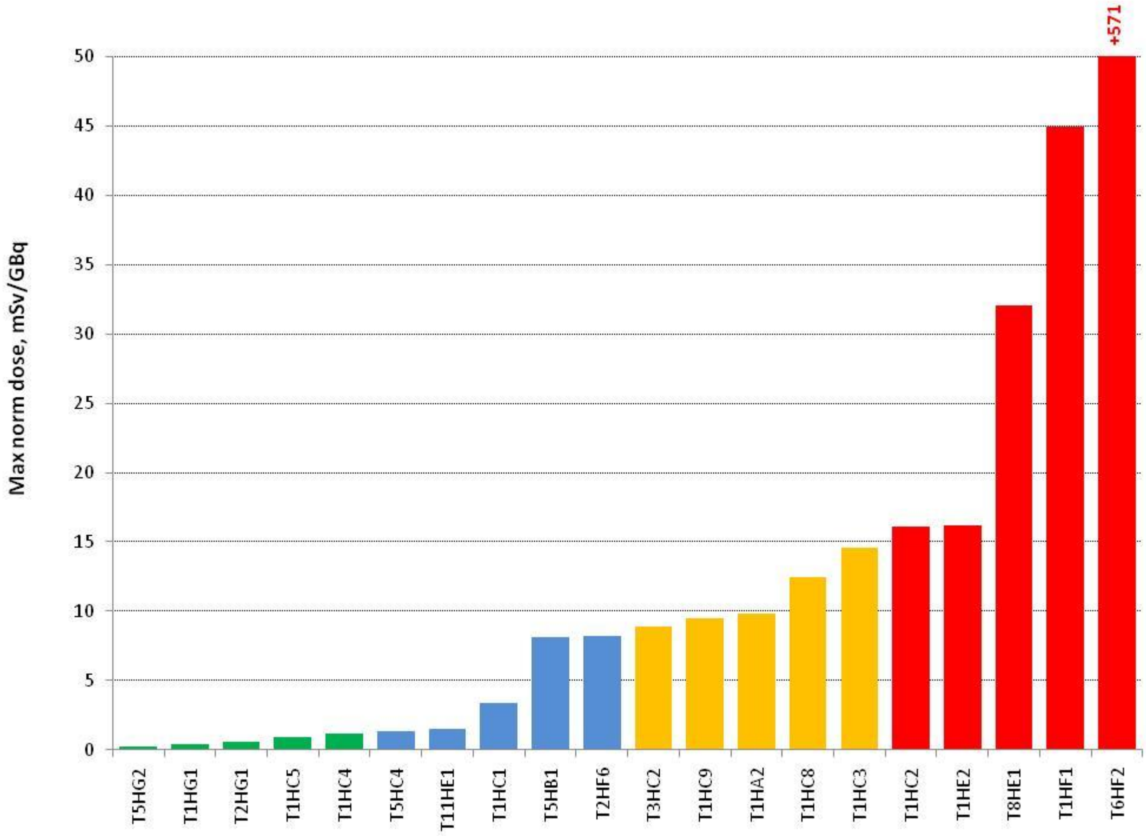


Figure 6. Classification of workers for preparation of Y-90 Zevalin®.

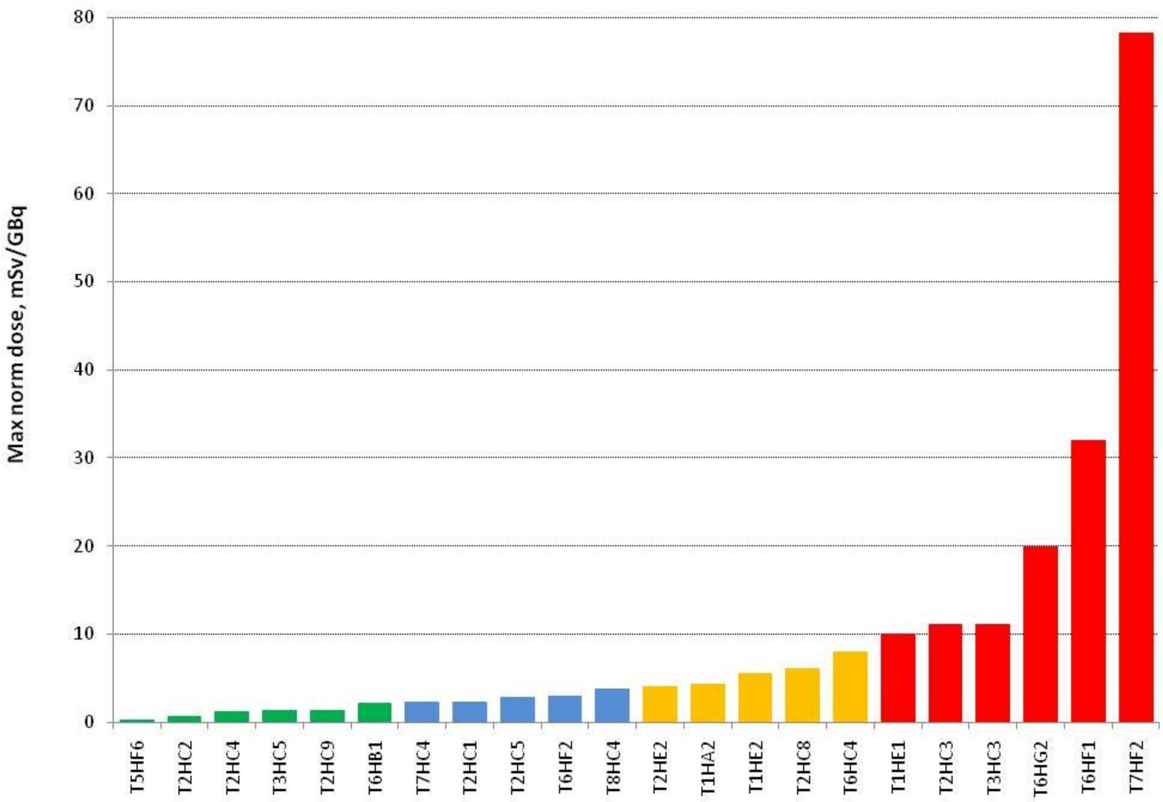


Figure 7. Classification of workers for Y-90 Zevalin® administration.

Workers situated in the 4th quartile are considered as having "bad practices" and thus should review their usual procedures. By contrast, workers in the 1st quartile can be regarded as working properly and therefore can be useful to establish guidelines for other workers.

In Figure 8 and Figure 9 a similar classification of workers was illustrated for PRRT with Y-90/Dotatoc. In this case, since the number of measurements was limited, the workers were not distributed in quartiles and the colors were used to identify workers using shielding (green) with those not using shielding (yellow).

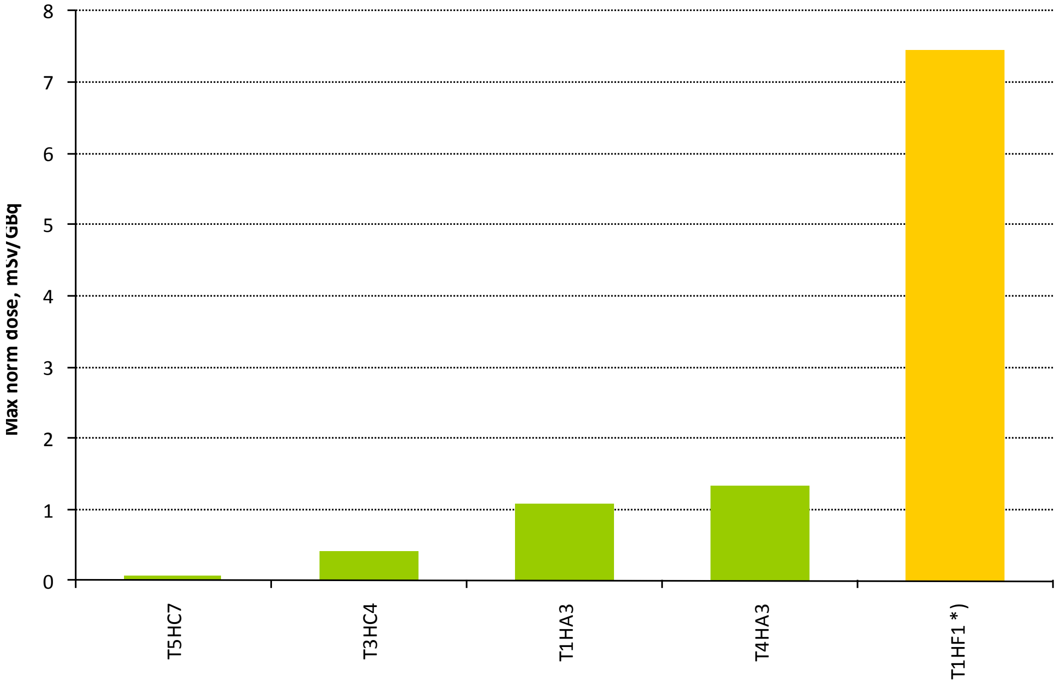


Figure 8. Classification of workers for preparation of Y-90 Dotatoc.(*) means no shielding.

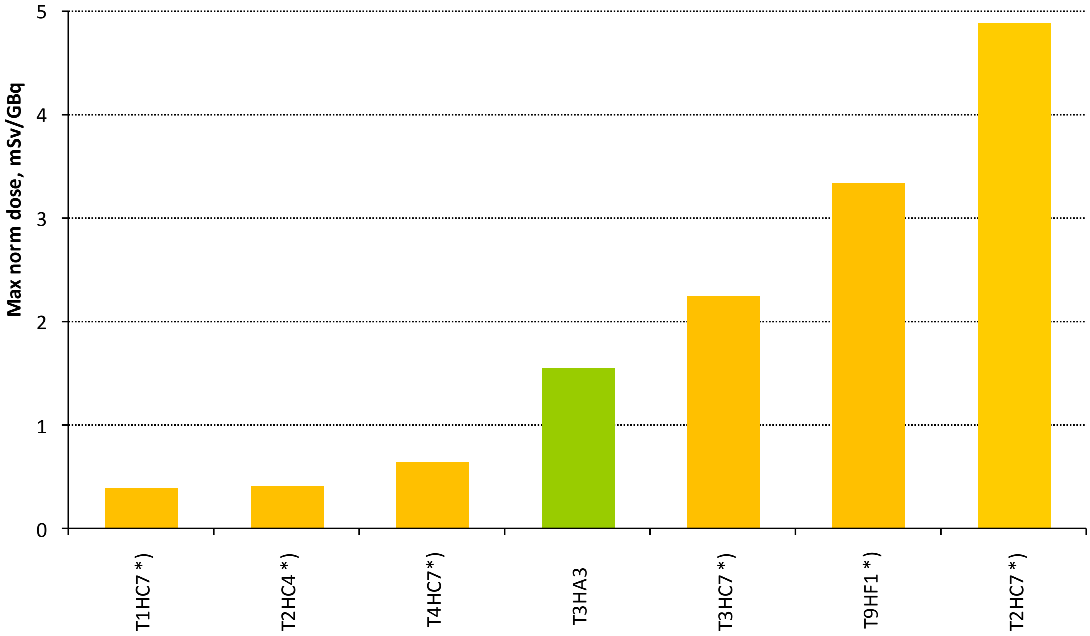


Figure 9. Classification of workers for Y-90 Dotatoc administration.(*) means no shielding.

During the data analysis the "unexpected very low" or "very high doses" that situated the workers on the lower part of the first quartile or on the upper part of the forth quartile were investigated.

For therapy, as shown in Figure 6, several workers were considered as outliers: T5HG2, T1HG1 and T2HG1 because they used different technique (semiautomatic), T1HF1 (with 4 measurement series) had extreme dose range since no shielding was used for several steps in the procedure and T6HF2 (only one measurement) had severe exposure since no shielding was used and he had direct contact to vial. In Figure 7 two workers have also been considered as outliers: T6HG2 (with 3 measurement series) had large dose range since no shielding was used and T7HF2 (with only one measurement) had high dose due to bad radiation protection measures. Those outliers were excluded for the analysis.

For diagnostics, as an example, the case of Tc-99m preparation where additional information available about influencing parameters as shielding (vial or syringe) or experience has been analyzed for a better understanding of the results. Figure 10 summarizes the results obtained for this case.

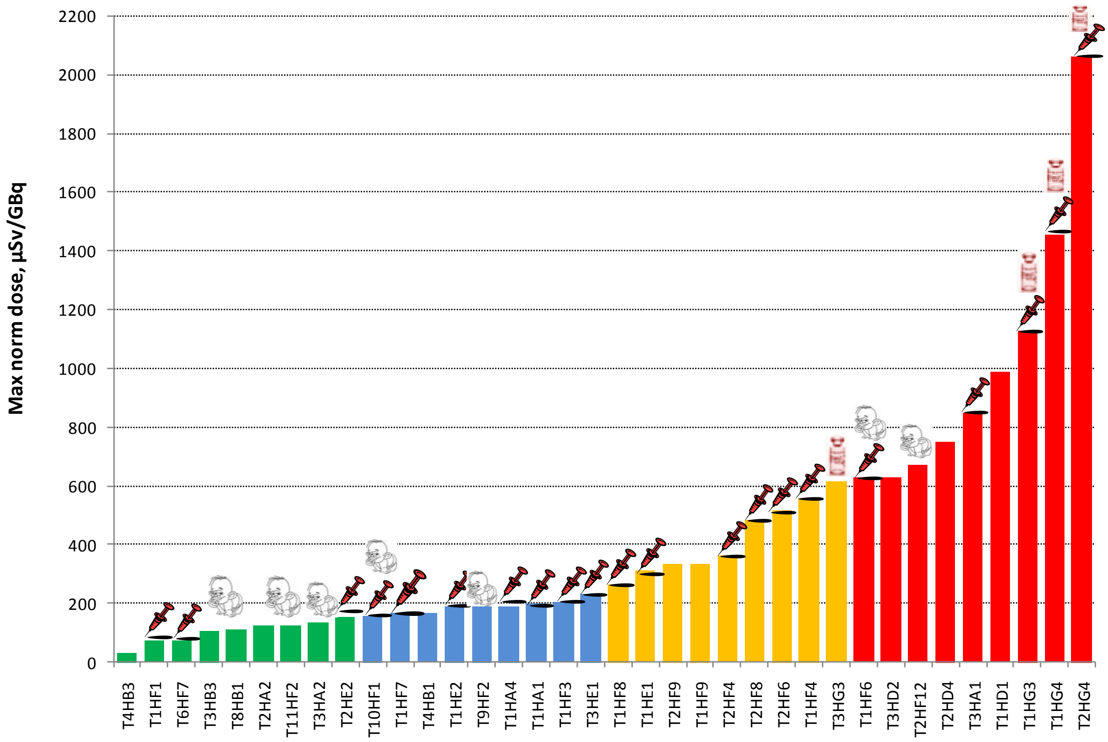


Figure 10. Classification of workers for Tc-99m preparation considering the parameters which might influence the dose (indicates unshielded vial and indicates unshielded syringe an indicates inexperienced workers).

Figure 10 highlights the importance of the correct use of the vial shielding for Tc-99m preparation, because workers manipulating the vial without shielding receive higher doses and therefore are generally situated in the forth quartile.

If the use of syringe shielding can be a matter of discussion in the case of preparation of Tc-99m, it is clearly effective in the case of administration of Tc-99m as can be seen in the second example. The second example, illustrated in Figure 11, shows that workers injecting Tc-99m with an unshielded syringe (24% of the workers) receive higher doses than dose working with shielded syringe.

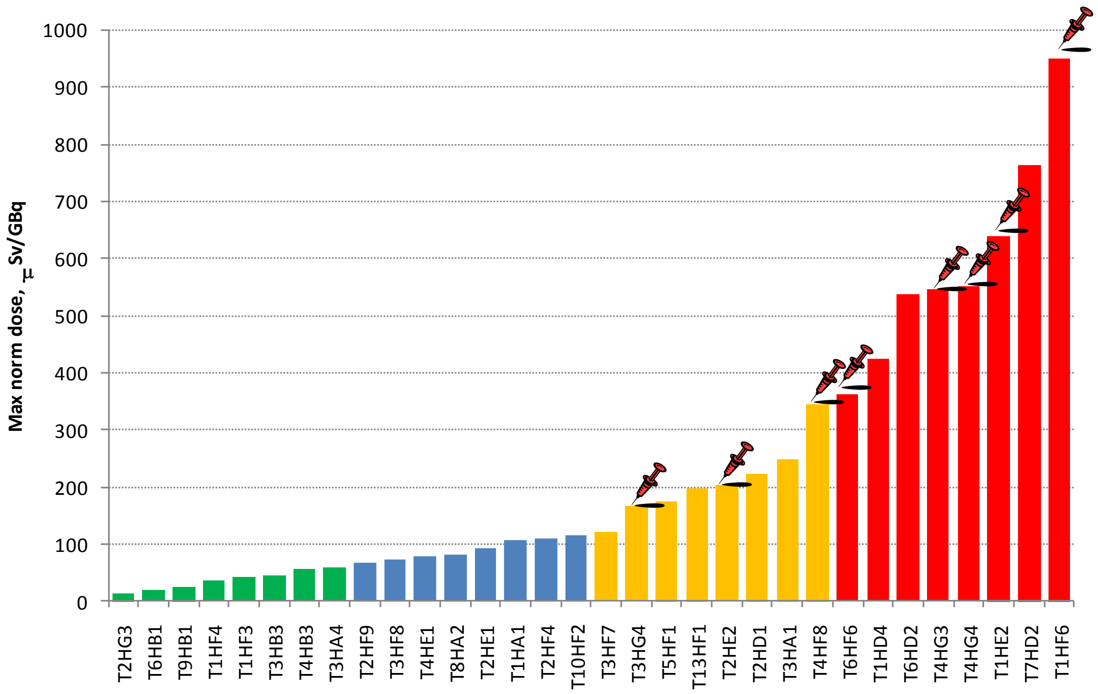


Figure 11. Classification of workers for Tc-99m administration (the symbol indicates that those workers use an unshielded syringe, 24% of the total workers).

In the case of injecting Tc-99m with an unshielded syringe, all workers are situated in the 3rd or 4th quartile indicating clearly that they received higher doses than those workers using shielding. Those workers working with an unshielded syringe have not been considered further for the analysis.

The statistical significance of these differences was assessed and is discussed later in the text.

2.1.2 Dispersion of maximum doses

The dispersion of the maximum registered *H*p(0.07) (µSv/GBq) has also been evaluated for each worker. This maximum is identified, for each individual measurement, on the nd hand and D hand independently. These variations can be very large depending on the procedures and on the worker behavior.

It can be seen that for most of the cases (examples, see Figure 12 and Figure 13) the trend follows the classification of doses, meaning that the higher the maximum of mean doses, the larger the observed range of maximum dose.
Comparing the results obtained for D hand and nd hand, it is clear that the higher ranges of maximum doses are in general found in the nd hand.

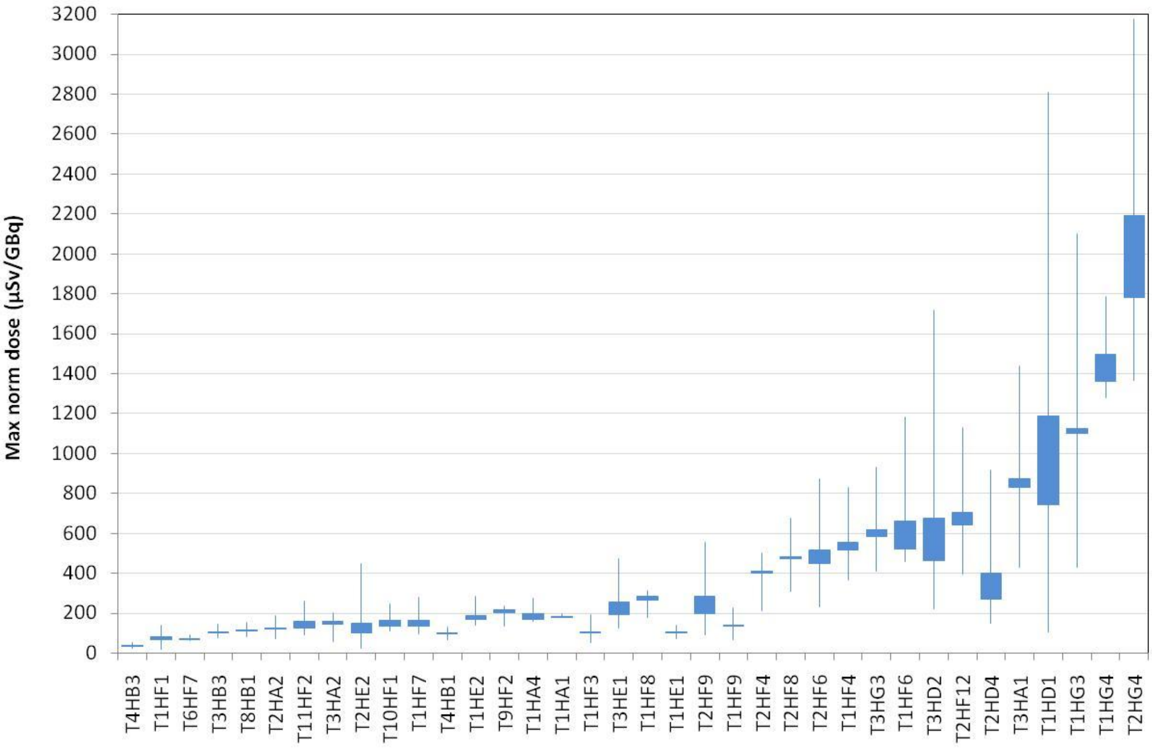


Figure 12. Dispersion of the maximum *H*p(0.07) (µSv/GBq) for each worker for the nd hand.

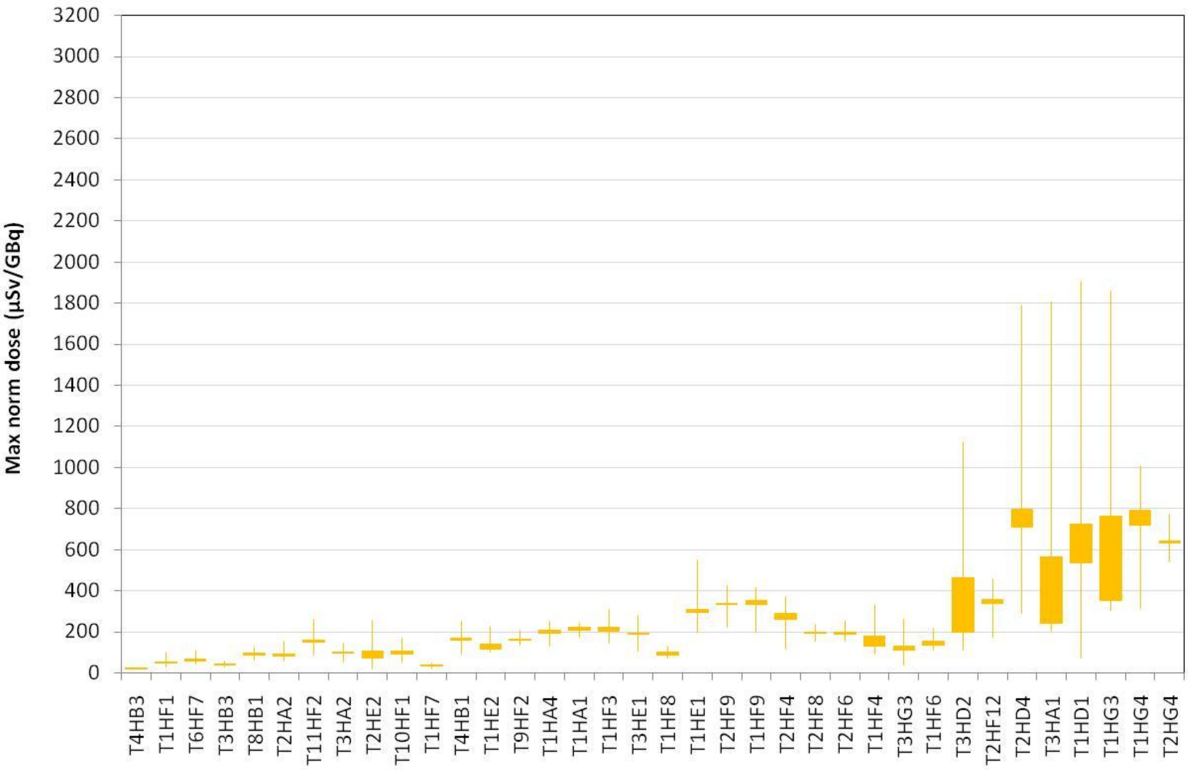


Figure 13. Dispersion of the maximum *H*p(0.07) (µSv/GBq) for each worker for the D hand.

2.1.3 Comparison of doses among different procedures

For a given procedure, the mean, median, maximum and minimum value has been determined considering the maximum doses registered for each worker for this specific procedure. This has been done for each procedure and is summarized in Table 3.

To have representative values in Table 3, the identified outliers have not been considered for this table: for Tc-99m preparation, the data of 36 workers has been used; for Tc-99m administration, 24 workers are included, those excluded are workers not using shielding syringes (T1HE2; T1HF6; T2HE2; T3HG4; T4HF8; T4HG3; T4HG4; T6HF6); for F-18 preparation all 31 workers have been considered; for F-18 administration 28 workers are included, the two workers excluded are one due to the fact that the shielding was not systematically used and the other is a suspicious case for contamination (T5HD2 and T3HG2); for Y-90 Zevalin® preparation, 15 workers are included, 2 were excluded because no shielding was used (T6HF2 and T1HF1) and 3 were excluded because they use a semi-automatic system (T5HG2, T1HG1 and T2HG1); for Y-90 Zevalin® administration, 20 workers are included, 2 were excluded because no shielding was used (T6HG2 and T7HF2).

	Mean values of maximum doses from all workers (mSv/GBq)	Median values of maximum doses from all workers (mSv/GBq)	Minimum values of maximum doses from all workers (mSv/GBq)	Maximum values of maximum doses from all workers (mSv/GBq)
Tc-99m preparation	0.43	0.25	0.03	2.06
Tc-99m administration	0.15	0.09	0.01	0.76
F-18 preparation	1.31	0.88	0.10	4.55
F-18 administration	0.72	0.62	0.14	2.42
Y-90 Zevalin® preparation	9.62	8.87	0.90	32.06
Y-90 Zevalin® administration	5.25	2.92	0.32	32.05

Table 3. Mean, median, maximum and minimum values of the maximum doses from all workers for every procedure.

As shown in Table 3 usually preparation delivers higher doses than the administration of the radiopharmaceutical. This is due to the fact that some of the preparation steps are performed with an unshielded source while the administration of the radiopharmaceutical to the patient is usually performed with a shielded syringe. Furthermore the time needed to prepare a radiopharmaceutical is longer than the time needed for administering it. As already expected, doses obtained for diagnostic procedures remain much lower than values measured for therapeutic procedures with Y-90 Zevalin®. However it has to be kept in mind that radiopharmaceuticals labeled with Tc-99m are, on average, more frequently used than those labeled with F-18 and the latter more frequently used than those labeled with Y-90. Therefore the total collective dose is higher for Tc-99m than for F-18.

2.1.4 Frequency

To comply with the definition of dose limit for the skin, the recommended position for extremity monitoring should be as close as possible to the position where the maximum dose can be found.

For each worker the maximum value of *H*p(0.07) (µSv/GBq) among the means obtained for each of the 22 monitoring positions, and its position are identified. Figure 14, Figure 15 and Figure 16 show the frequencies (%) of the corresponding positions where the maximum is found for the analysis done for both hands simultaneously.

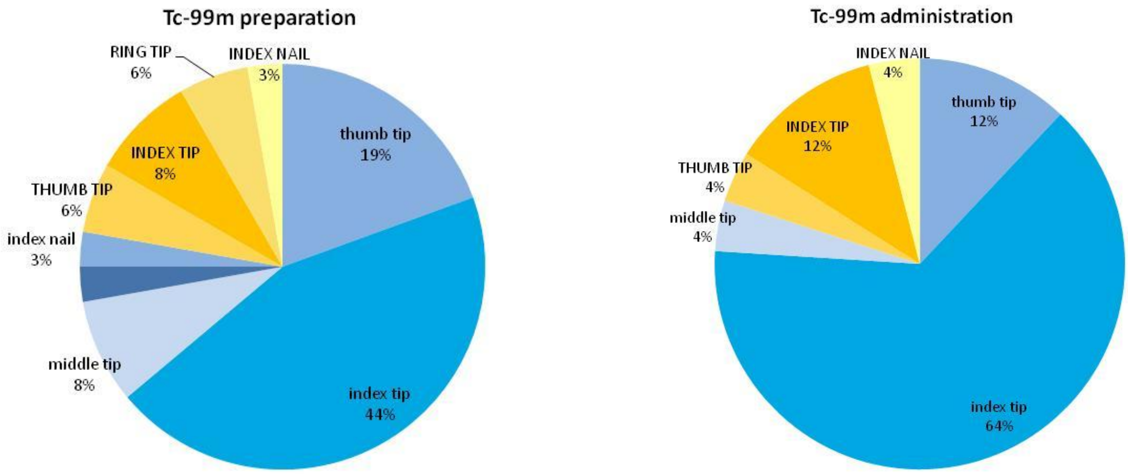


Figure 14. Frequencies of the positions where the maximum dose is found for Tc-99m preparation (left) and administration (right). Lowercase and blue colours correspond to nd hand and uppercase and orange colours correspond to D hands.

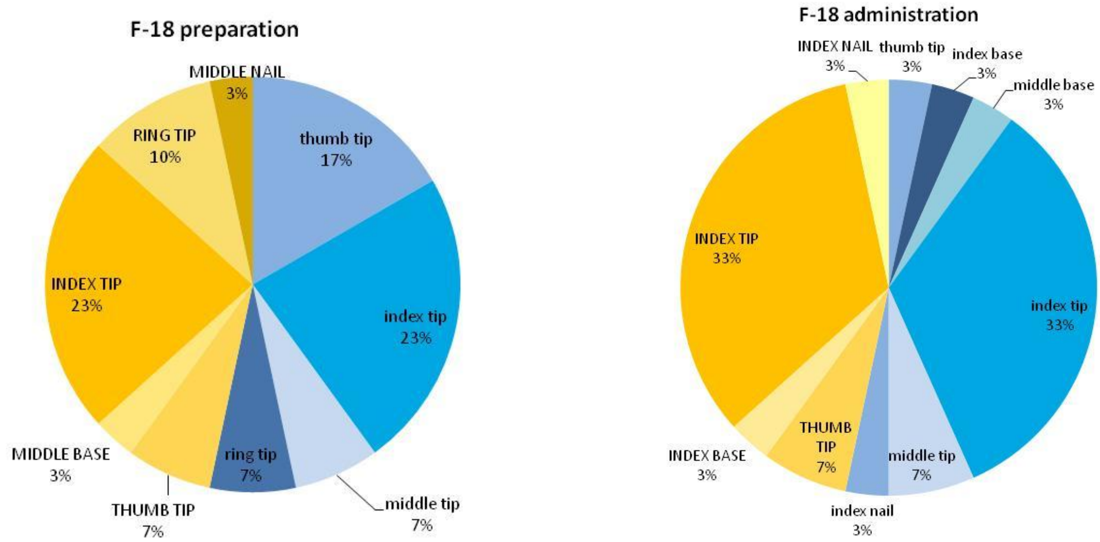


Figure 15. Frequencies of the positions where the maximum dose is found for F-18 preparation (left) and administration (right). Lowercase and blue colours correspond to nd hand and uppercase and orange colours correspond to D hands.

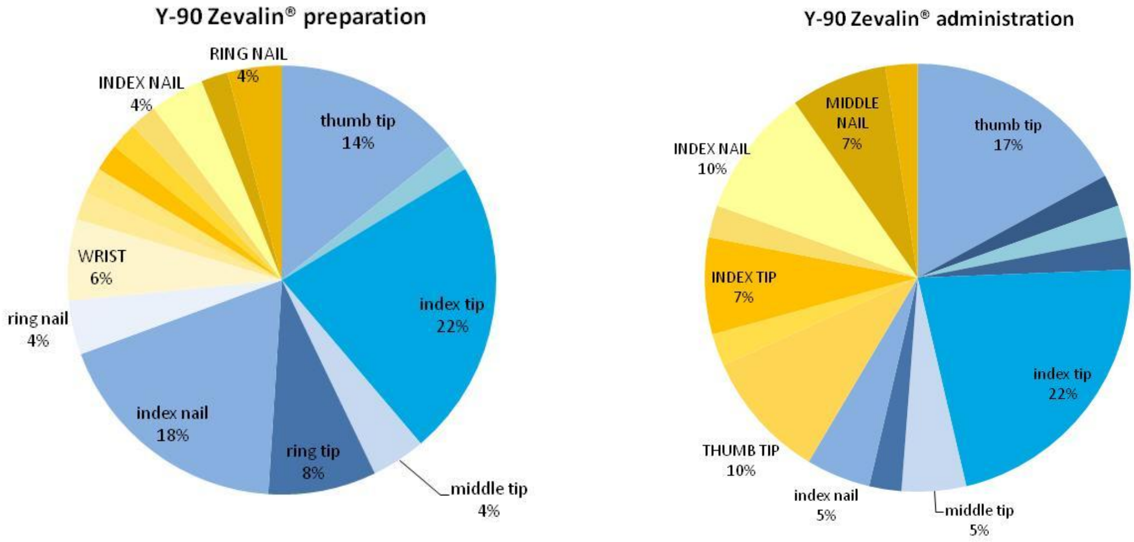


Figure 16. Frequencies of the positions where the maximum dose is found for Y-90 Zevalin® preparation (left) and administration (right). Lowercase and blue colours correspond to nd hand and uppercase and orange colours correspond to D hands.

From Figure 14, Figure 15 and Figure 16 it can be deduced that the position where most frequently the maximum is found corresponds to the index tip of the nd hand. This position differs from the one where usually the routine monitoring dosemeter is worn (usually base of the ring finger or wrist).

2.1.5 Frequency and cumulated maximum normalized dose.

Although the index tip at the non dominant hand appears to be the most frequent location of the maximum dose among the measured points, it has to be ensured that this position actually accumulates the maximum dose. Therefore every time a position is identified as the maximum, its dose value is cumulated. In that case, two parameters are gathered at the same time, how often the maximum is found at a given position and which was the dose cumulated at this position when the maximum was found there. This analysis has been done considering both hands (D and nd hand) together.

From Figure 17 to Figure 22 frequency plots with the cumulated maximum dose for all different procedures considering both hands together are presented.

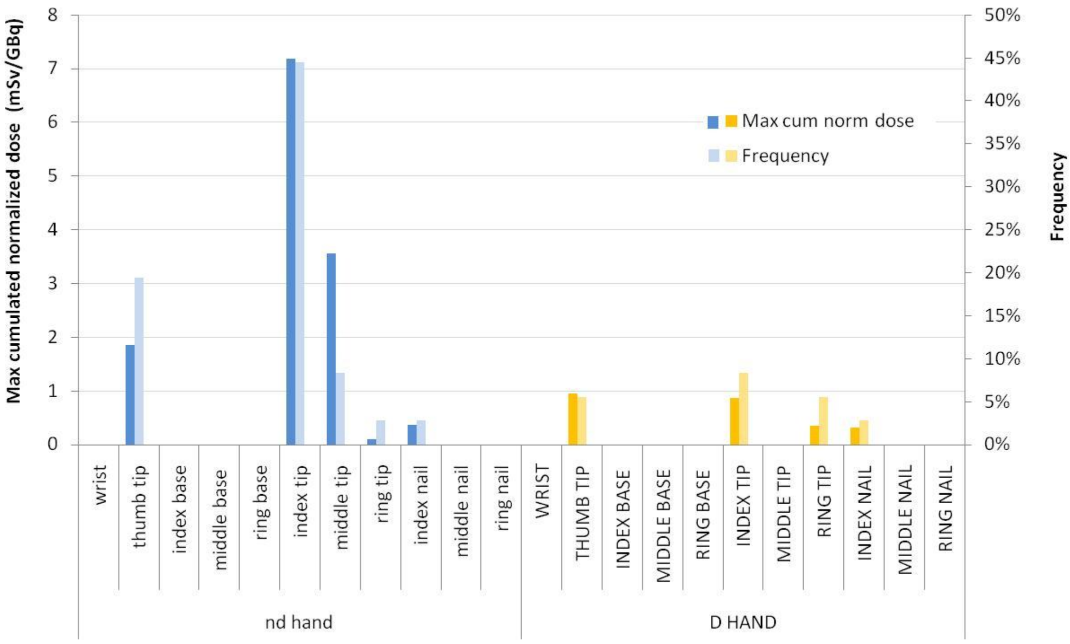


Figure 17. Frequency and cumulated maximum dose for Tc-99m preparation.

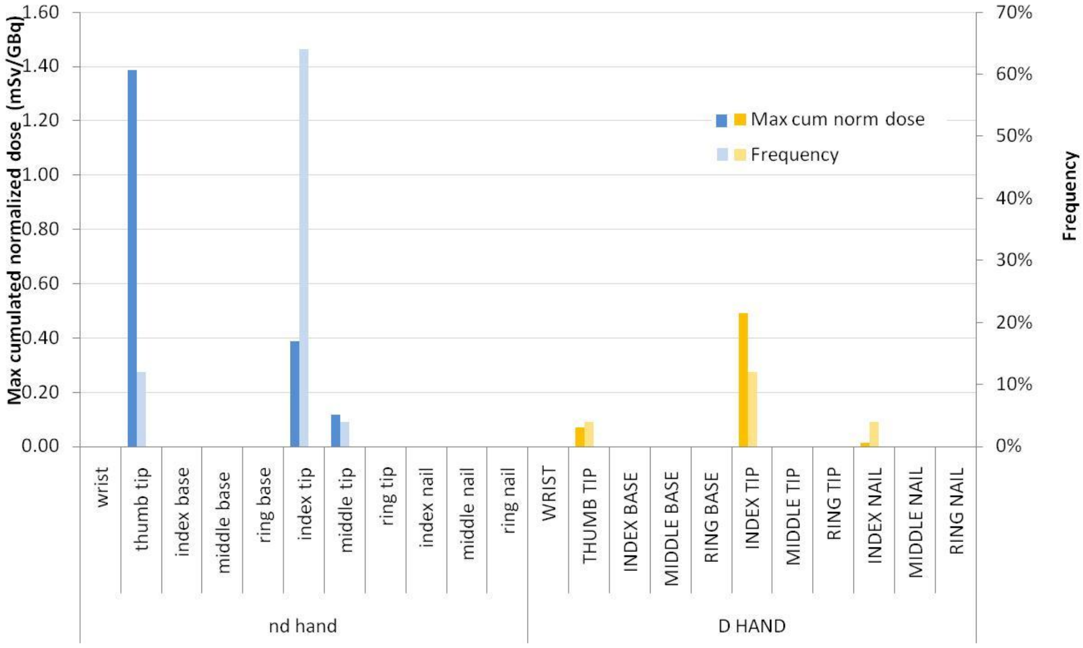


Figure 18. Frequency and cumulated maximum dose for Tc-99m administration for those workers using shielding.

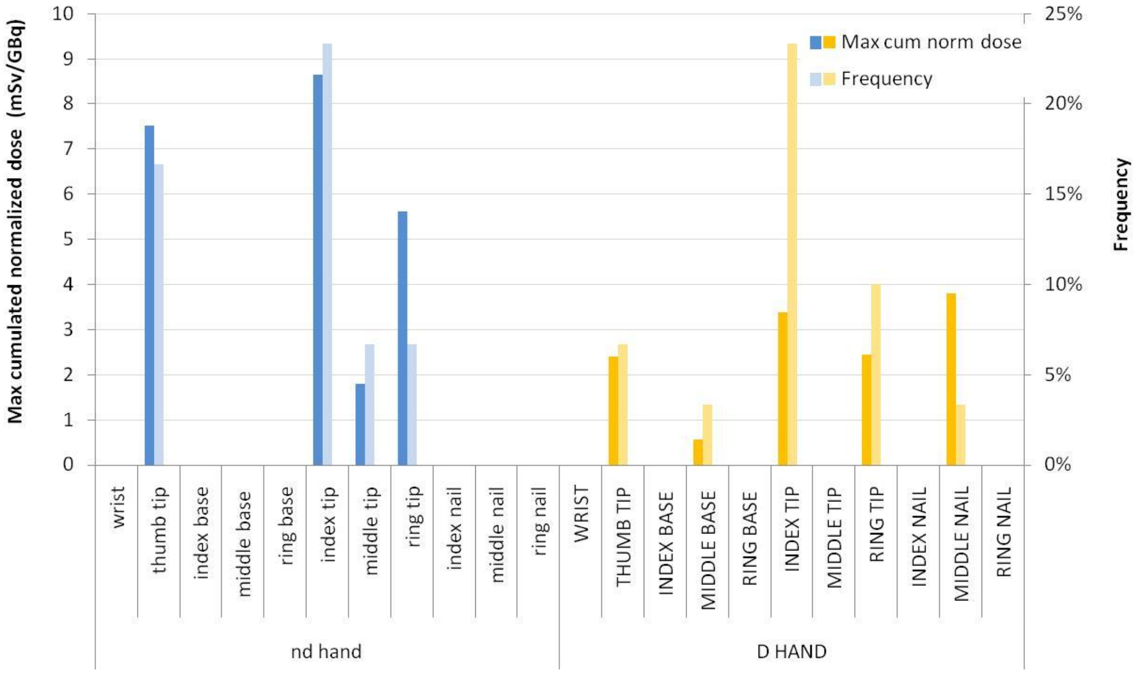


Figure 19. Frequency and cumulated maximum dose for F-18 preparation.

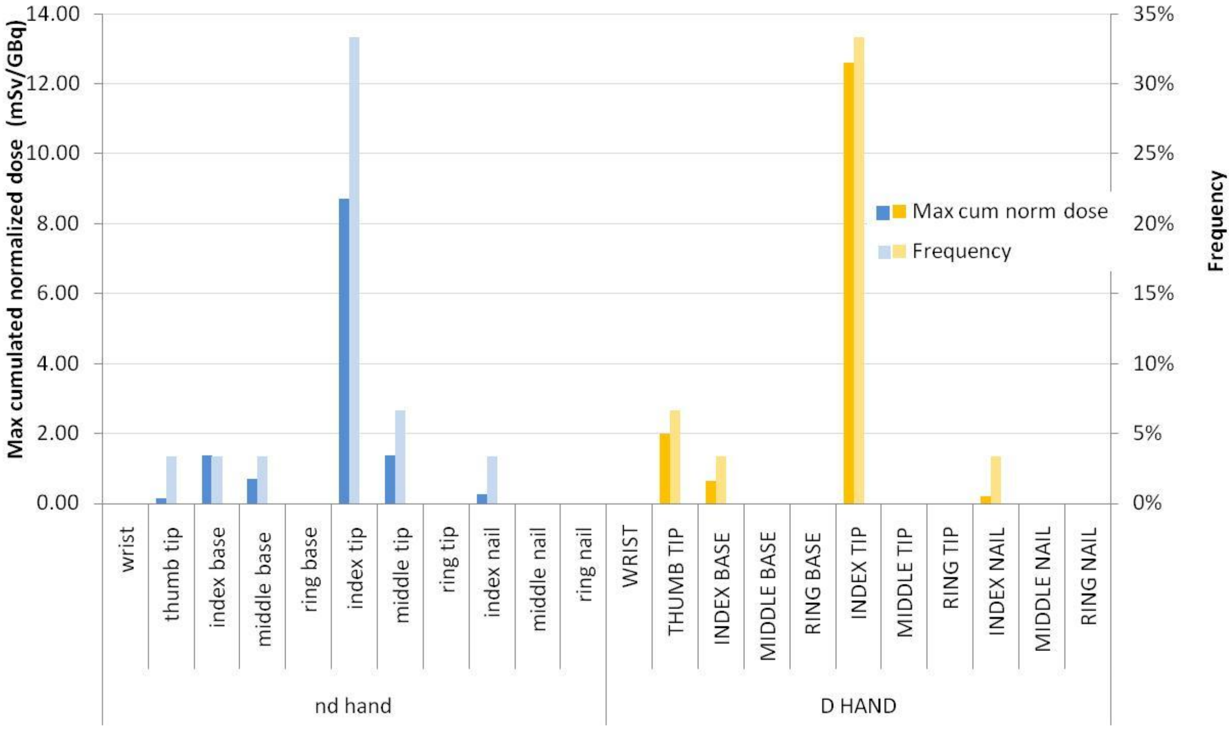


Figure 20. Frequency and cumulated maximum dose for F-18 administration.

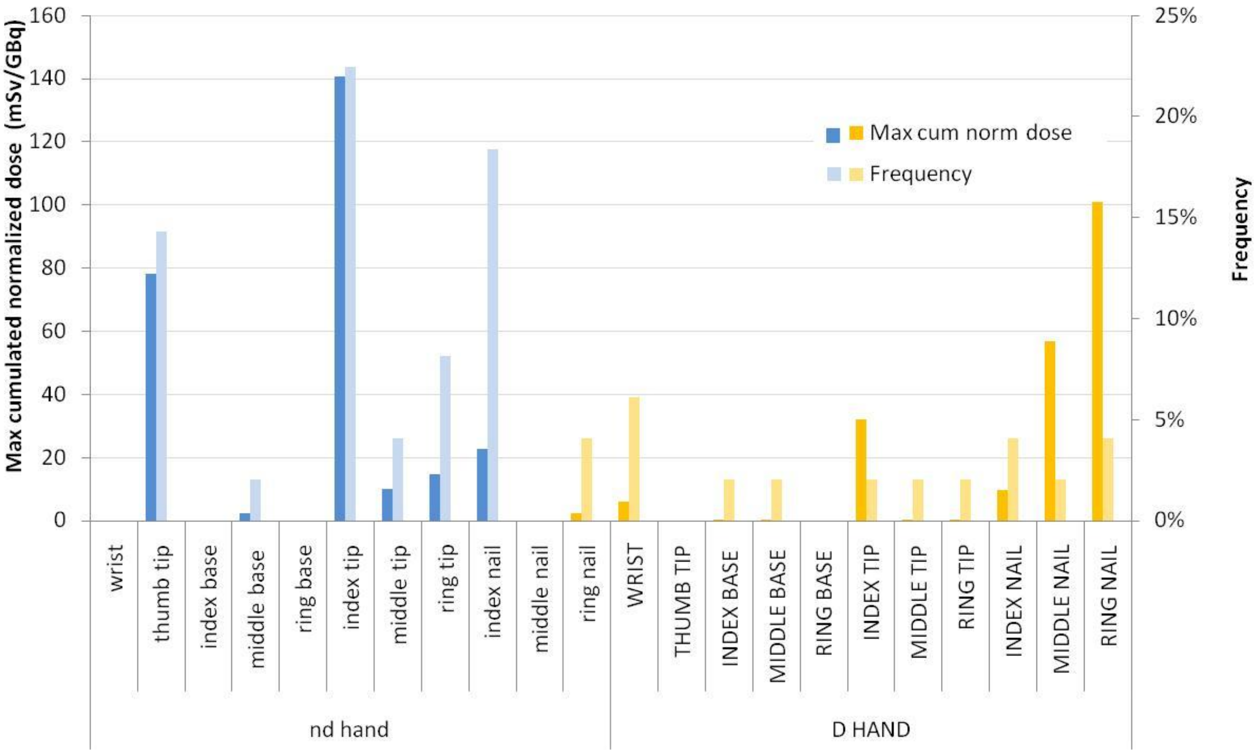


Figure 21. Frequency and cumulated maximum dose for Y-90 Zevalin preparation.

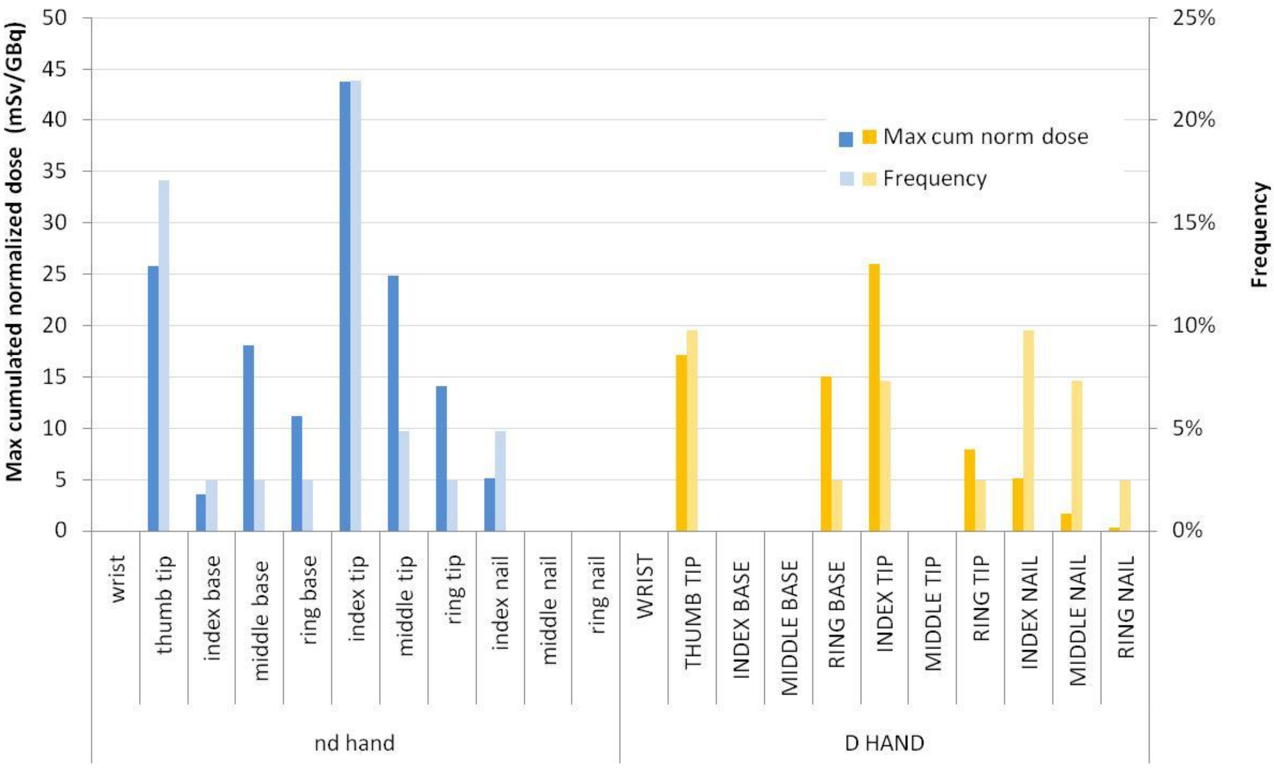


Figure 22. Frequency and cumulated maximum dose for Y-90 Zevalin administration.

Cumulated maximum doses and frequencies not always correspond. Table 4 summarizes the results obtained for all procedures and for the two cases, one considering hands together and the other one considering hands independently.

	Hands independently		Hands together	
Procedure	Position with higher cumulated dose	Most frequent position	Position with higher cumulated dose	Most frequent position
Tc-99m preparation	index tip nd hand; index tip nd hand	index tip nd hand; index tip nd hand	index tip nd hand	index tip nd hand
Tc-99m administration	index tip nd hand; INDEX TIP D hand	index tip at nd hand; INDEX NAIL at D hand	thumb nd hand	index tip nd hand
F-18 preparation	thumb at nd hand; index tip D hand	index tip at nd hand; INDEX TIP at D hand	index tip nd hand	index tip nd hand
F-18 administration	index tip nd hand; INDEX TIP D hand	index tip at nd hand; INDEX TIP at D hand	INDEX TIP D hand	index tip nd hand
Y-90 preparation	index tip nd hand; THUMB D hand	index tip nd hand; THUMB D hand	index tip nd hand	index tip nd hand
Y-90 administration	index tip nd hand; THUMB D hand	index tip nd hand; THUMB D hand	index tip nd hand	index tip nd hand

Table 4. Positions for cumulated dose and frequencies where the maximum is found.

From the available results it could be concluded that the position of the dosemeter on the hand is important to obtain a correct estimate of the extremity dose, neither the wrist or ring positions, usual routine monitoring positions are adequate for this purpose. However, as it will be presented in detail in the following paragraphs, it is possible to correlate the monitored doses with the maximum skin dose. In practice, technicians will rarely use two extremity dosemeters, so most of our recommendations will correspond to the analysis of results corresponding to the two hands together.

2.1.6 Correction factors

The impact of placing the routine monitoring dosemeter at a different position than the one corresponding to the maximum skin dose has been estimated by calculating correction factors. These correction factors are evaluated by considering the ratios $Hp_{max}/Hp_{base\ ring}$, Hp_{max}/Hp_{wrist}, $Hp_{max}/Hp_{base\ index}$, $Hp_{max}/Hp_{index\ tip}$, where Hp_{max} is the maximum of the mean $Hp(0.07)$ (µSv/GBq) when both hands are considered simultaneously, $Hp_{base\ ring}$, Hp_{wrist}, $Hp_{base\ index}$ and $Hp_{index\ tip}$ the mean dose at the base of the ring finger, the wrist, the base of the index and the tip of the index, respectively, for the nd and D hands. For therapy two extra ratios have been calculated $Hp_{max}/Hp_{2nd\ phalange\ index}$, $Hp_{max}/\ Hp_{2nd\ phalange\ index}$, where $Hp_{2nd\ phalange\ index}$ and $Hp_{2nd\ phalange\ index}$ are the mean dose at the 2nd phalange of the index and the thumb respectively.

The minimum, median, mean and maximum values of these correction factors, determined from the set of mean values at every position of all workers for a given procedure, are represented as Box plots.
Figure 23 and Figure 24 are examples of these box plots for the case of Tc-99m preparation. Figure 24 is a zoom of Figure 23.

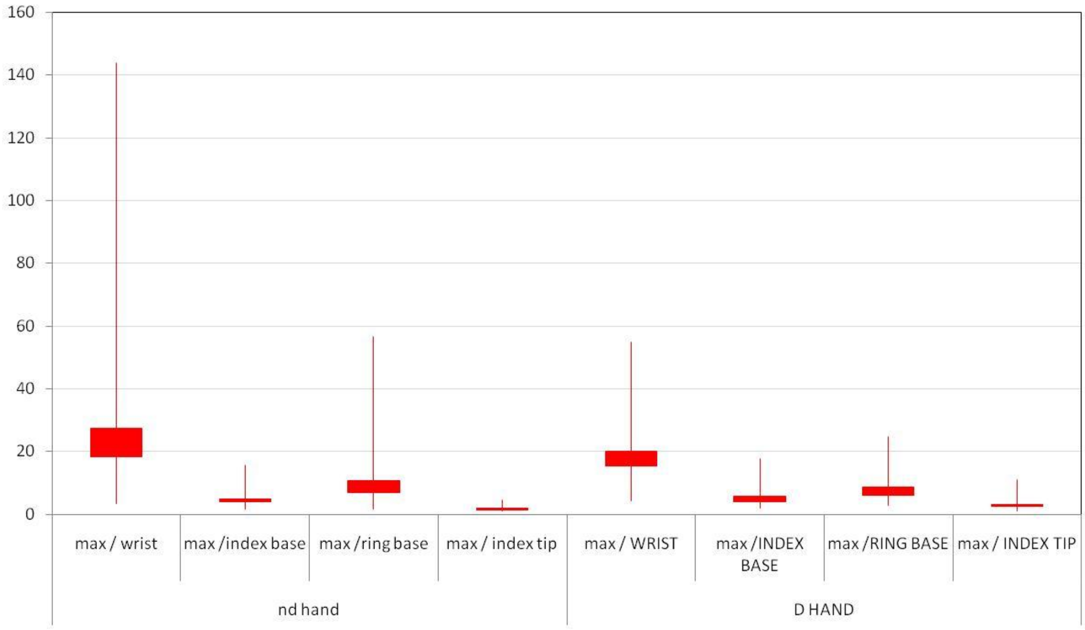


Figure 23. Box plot showing the mean, median, minimum and maximum values of dose ratios for the case of Tc-99m preparation (Outlier excluded: T2HG4).

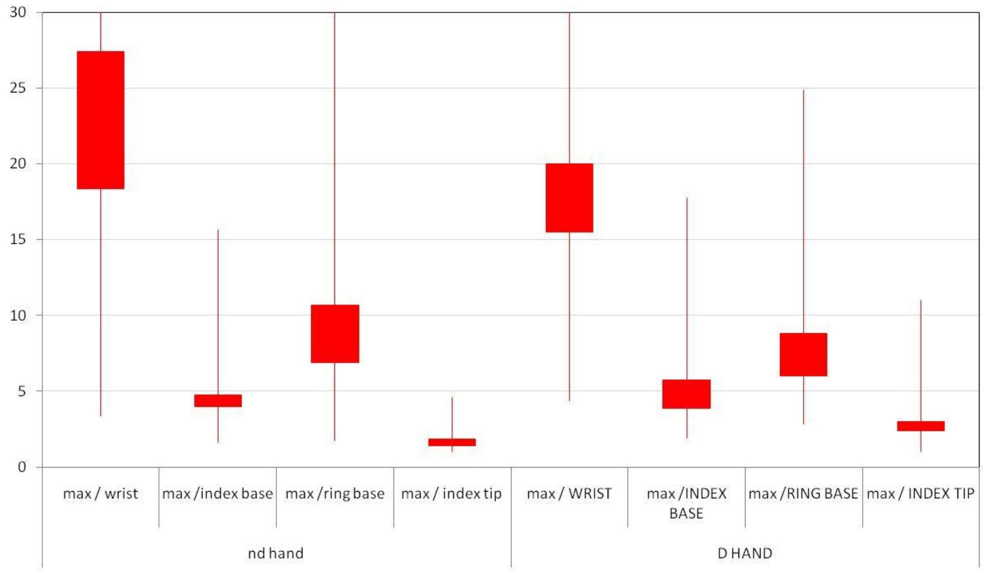


Figure 24. Zoom from Figure 23.

The summary of the corrections factors that have been computed for each procedure is shown in Table 5.

		non dominant hand						DOMINANT HAND					
		max/wrist	max/base index	max/base ring	max/index tip	max/index 2nd phalange	max/thumb 2nd phalange	max/WRIST	max/BASE INDEX	max/BASE RING	max/INDEX TIP	max/INDEX 2nd PHALANGE	max/THUMB 2nd PHALANGE
Tc-99m preparation	min	3	2	2	1	-	-	4	2	3	1	-	-
	median	18	4	7	1	-	-	16	4	6	2	-	-
	mean	**27**	**5**	**11**	**2**	**-**	**-**	**20**	**6**	**9**	**3**	**-**	**-**
	max	144	16	57	5	-	-	55	18	25	11	-	-
Tc-99m administration	min	6	2	3	1	-	-	2	2	4	1	-	-
	median	15	5	8	2	-	-	15	7	10	3	-	-
	mean	**15**	**5**	**10**	**2**	**-**	**-**	**15**	**7**	**10**	**4**	**-**	**-**
	max	32	12	20	7	-	-	33	13	18	8	-	-
F-18 preparation	min	3	2	2	1	-	-	3	2	1	1	-	-
	median	12	3	5	2	-	-	10	4	5	2	-	-
	mean	**14**	**4**	**6**	**2**	**-**	**-**	**12**	**5**	**7**	**2**	**-**	**-**
	max	30	12	22	9	-	-	46	8	23	5	-	-
F-18 administration	min	5	2	2	1	-	-	4	1	3	1	-	-
	median	19	4	8	2	-	-	18	4	9	2	-	-
	mean	**24**	**6**	**12**	**3**	**-**	**-**	**21**	**6**	**10**	**3**	**-**	**-**
	max	85	34	61	20	-	-	46	24	28	12	-	-
Y-90 preparation	min	3	2	2	1	1	1	3	2	4	1	7	7
	median	12	6	10	2	4	6	15	14	22	5	20	18
	mean	**15**	**6**	**11**	**3**	**4**	**7**	**15**	**24**	**34**	**19**	**20**	**27**
	max	42	18	51	17	7	14	32	79	85	75	40	96
Y-90 administration	min	2	2	1	1	2	2	2	3	2	1	2	3
	median	19	7	12	1	7	8	16	11	10	5	8	10
	mean	**26**	**7**	**18**	**2**	**7**	**13**	**20**	**20**	**26**	**9**	**18**	**12**
	max	102	18	89	7	16	44	46	60	90	25	63	32

Table 5. Mean, median, minimum and maximum values for the correction factors for the different positions and for each procedure.

As expected the smallest correction factors are observed for the index tip, specially of the nd hand. The highest dispersion of these ratios is observed for the wrist position and the smallest for the index tip.

The correction factors can be used for those positions where there is a statistical significant correlation between the maximum dose and the dose at that specific position. This will be seen in the section concerning the parametric analysis.

2.1.7 Dose history

In therapy, not all workers could be followed for several series of measurements, for two main reasons: therapies are not so frequent and it is not always the same worker performing the preparation of the radiopharmaceutical or administering it to the patient. Nevertheless, for some of the workers which have performed more than 3 series of measurements, their maximum dose has been plotted as a function of the number of consecutive series of the measurements. This is shown in Figure 25 and Figure 26 for Y-90/Zevalin preparation and administration respectively.

It can be observed a clear tendency that the maximum dose decreases with increasing number of measurement series. In most cases, this is due to the fact that workers have been aware of the results from one measurement series to the subsequent one and, if the dose was high, have improved their radiation protection measures and tools to reduce beta radiation exposures. Therefore, it is a clear indication that there is potential for optimization of the working procedures (or habits) of the staff when manipulating high energy beta sources.

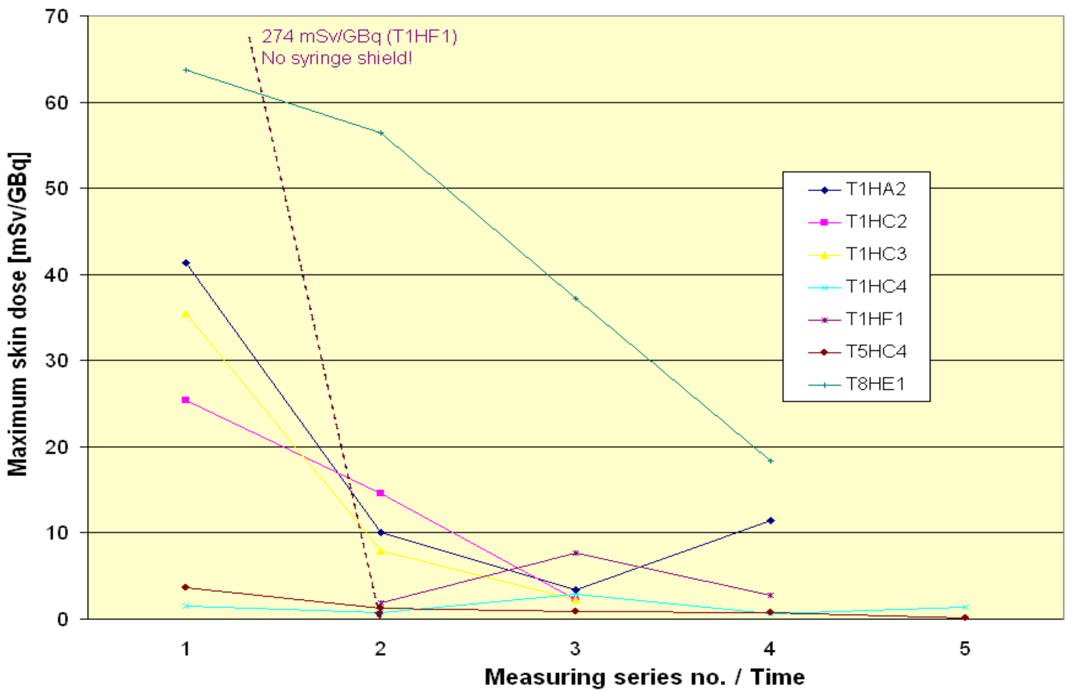


Figure 25. Maximum dose for each worker as a function of the measuring series number for Y-90 Zevalin® preparation.

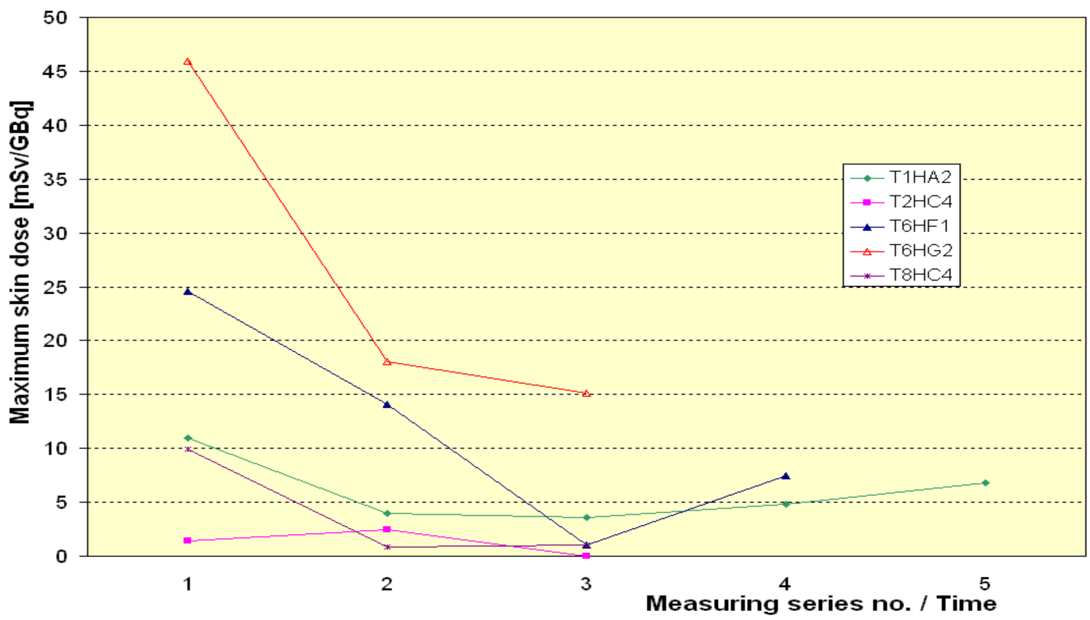


Figure 26. Maximum dose for each worker as a function of the measuring series number for Y-90 Zevalin® administration.

2.1.8 Parametric analysis

The parametric analysis of the data was based on the database of the mean normalized dose among all measurement series from one worker. Several characteristic parameters of the distributions of each measuring position were calculated: the maximum, mean, median, variance coefficient (CV), interquartile distance (IQR), asymmetry and kurtosis. Besides, the Kolmogorov-Smirnov (K-S) test was applied to examine the normality of the distributions. The distributions were not normal. Therefore non parametric tests were applied to look for possible significant differences between the parameters.

The parameters were chosen according to their influence on the dose or dose distribution. Here is the list of those items analyzed:

- Influence of the experience in the dose. For this purpose the workers were divided into two groups: work experience less than or equal to 1 year (group ≤ 1 year; beginners) and higher work experience (group > 1 year; experienced).
- Influence of the shielding (vial and syringe) on the doses.
- Differences between doses in the D hand and doses in the nd hand.
- Correlations between maximum dose and dose at the other positions.

The summary of the results obtained for those analyzed items for each procedure are presented in Table 6 and Table 7.
From these tables it can be concluded that doses in the nd hand are higher than doses obtained for the D hand. The differences are statistically significant for almost all procedures. The dose found at the maximum is also correlated to the dose found at the different positions.
It has been demonstrated that the use of shielding is a very effective way of reducing the doses. For procedure of injecting with F-18, the comparison was not possible since all workers used a shielded syringe.
Concerning the experience, even thought the doses received by the experience workers are generally lower than those received by the beginners, the statistical test concluded that this difference is not statistically significant for most of the procedures.

PART 1	Results per procedure					
Parametric test	**Tc-99m preparation**	**Tc-99m administration**	**F-18 preparation**	**F-18 administration**	**Y-90 preparation**	**Y-90 administration**
Significant differences between doses at DOMINANT and non dominant hand? (Wilcoxon test)	• Doses are higher on the nd hand. • The differences are statistically significant at the thumb, base and tip of the index and ring nail.	• Doses are higher on the nd hand for most of the positions. • The differences are statistically significant at the thumb, index tip and index nail.	• Doses are higher on the nd hand for most of the positions. • The differences are statistically significant at the base of the index finger.	• Doses are higher on the nd hand. • The dose at the nd hand is statistically significant higher than at the D hand (24% on average).	• Doses are higher on the nd hand. • The differences are statistically significant at the thumb, index nail and bases of the fingers, tips of the fingers.	• Doses are higher on the nd hand. • The differences are not statistically significant.
Significant differences between doses for experienced workers and beginners? (Mann-Whitney test)	• The differences are not statistically significant. (7 workers considered as beginners).	(Not enough data, only 3 workers considered as beginners).	• Doses received by beginners are statistically significantly higher than those received by experienced workers at the index tip of nd hand and THUMB and INDEX NAIL of D hand. (7 workers considered as beginners).	• Beginners receive on average higher doses than experienced workers. • The differences are not statistically significant. (6 workers considered as beginners).	(Not enough data, only 1 worker considered as beginner).	(Not enough data, only 3 workers considered as beginners).

Table 6. Part 1 of the results of the parametric analysis. Filled with colour are those tests with results statistically significant.

PART 2	Results per procedure					
Parametric test	**^{99m}Tc-preparation**	**^{99m}Tc-administration**	**^{18}F-preparation**	**^{18}F-administration**	**^{90}Y-preparation**	**^{90}Y-administration**
Significant differences between doses when using syringe/vial shield or not? (Mann-Whitney test)	• Doses received in all positions when using the unshielded vial are much higher than those received when using shielded vial. • The differences are statistically significant for the closest positions to the bare vial: all positions except the wrist for nd hand, and INDEX NAIL and MIDDLE NAIL for the D hand.	• Doses received when using the unshielded syringe are higher than those received when using shielded syringe. • The differences are statistically significant at the thumb and index of the nd hand and almost all positions of D hand (except WRIST and RING).	• Doses received when using unshielded syringe are higher than those received when using shielded syringe. • The differences are statistically significant in all positions except for middle, ring and ring tip position of nd hand, and WRIST of D hand. (Not enough data for workers with unshielded vial).	(Not data for workers with unshielded syringe).	(Not data for workers with unshielded syringe and vial).	(Not enough data, only 2 workers with unshielded syringe).
Correlations between the maximum dose and the dose at the rest of positions (Pearson/Spearman)	• Pearson coefficients are almost always higher for nd hand. • In the case of using shielded vial, the best correlated to the maximum dose are: thumb, index tip and index nail of the nd hand.	• There is a correlation for all measuring positions. • The best correlation is found on the nd hand for the next positions: index nail, index tip, middle, index and thumb.	• The best correlations are found for the positions: thumb, middle tip, middle nail of the nd hand, and the INDEX NAIL of the D hand.	• There is a correlation. • For all cases, coefficients are higher than 0.6 and can reach 0.9 (for the tip of the index). The D hand appears to be on average better correlated with Hp_{max} than the nd hand.	• There is a correlation for all measuring positions except for the middle of nd hand and THUMB of D hand.	• The best correlations are found for the base of the index, middle and ring fingers.

Table 7. Part 2 of the results of the parametric analysis. Filled with colour are those tests with results statistically significant

2.3 ANNUAL DOSE ESTIMATION

The estimation of the annual dose for a worker performing only one type of procedure was obtained by multiplying the maximum, among all positions in the hand, of his mean normalized doses from all his measurement series by his annual manipulated activity. For a worker performing several types of procedures, since the maximum for each procedure could be at a different place, the estimation will be done for each of the positions where a maximum is found and adding the absolute values of the dose when it is found at the same place.

Table 8 is an example for a worker performing the preparation of Tc-99m and F-18 and the administration of Tc-99m.

Procedure		Adm Tc-99m	Prep Tc-99m	Adm F-18	Prep F-18	
Amanip/year (GBq)		61	1343		186	
Norm dose of T1HA1		Norm dose (µSv/GBq)	Norm dose (µSv/GBq)	Norm dose (µSv/GBq)	Norm dose (µSv/GBq)	Total max dose per position (mSv)
Non Dominant hand	wrist					
	thumb					
	index					
	middle					
	ring					
	index tip	107.03	183.85		1085.39	455.57
	middle tip					
	ring tip					
	index nail					
	middle nail					
	ring nail					
DOMINANT HAND	WRIST					
	THUMB	11.55	209.72		960.75	461.26
	INDEX					
	MIDDLE					
	RING					
	INDEX TIP	16.61	174.61		1823.62	575.05
	MIDDLE TIP					
	RING TIP					
	INDEX NAIL					
	MIDDLE NAIL					
	RING NAIL					

Table 8. Annual dose estimation for a worker performing several procedures. In red are the maximum values obtained for a specific procedure.

Some workers were monitored for only one type of procedure for the ORAMED project (e.g. Tc-99m preparation) when actually they performed more (e.g. plus Tc-99 administration, plus F-18 preparation and administration, plus therapy). In these cases, the estimation of the annual dose has been calculated only considering the monitored procedures, from which real measured values were available. The consideration of extrapolating doses from one worker to another for a given procedure was considered very risky and not realistic due to the large variation observed between workers performing the same procedures, even in the same hospital.

Table 9 shows the estimated annual dose, from the procedures where data is available, for those workers from whom their workload is known. The annual dose estimation is above 250mSv (half of the annual limit) for 40% of the workers. 20% of the workers exceed the annual dose limit of 500mSv.

Worker	Procedures measured	Maximum annual dose (mSv/year)	% of the annual limit
T5HF7	F-18 prep and adm with posijet	1	0%
T4HF7	F-18 prep and adm with posijet	3	1%
T6HB1	Tc-99m adm	5	1%
T9HB1	Tc-99m adm	6	1%
T11HE1	Y-90 Zevalin® prep and SIRS spheres	21	4%
T10HE1	F-18 adm	22	4%
T4HF2	F-18 adm	24	5%
T5HF2	F-18 adm and prep	26	5%
T9HE1	F-18 adm	27	5%
T2HB1	F-18 adm	34	7%
T2HF7	Tc-99m adm	35	7%
T1HE3	F-18 prep	39	8%
T8HB1	Tc-99m prep	45	9%
T6HA2	F-18 adm and prep	45	9%
T5HE1	F-18 prep	53	11%
T4HB3	Tc-99m adm and prep	56	11%
T1HB1	F-18 prep	57	11%
T10HE2	P-32 +Y-90 adm	59	12%
T9HE2	Y-90 Zevalin® prep	61	12%
T2HB3	F-18 adm and prep	63	13%
T7HA2	F-18 adm	64	13%
T1HB3	F-18 adm and prep	70	14%
T7HB1	F-18 prep	81	16%
T2HA2	Tc-99m prep and F-18 prep	81	16%
T3HA2	Tc-99m prep	93	19%
T1HE3	F-18 adm	103	21%
T6HE1	F-18 prep	106	21%
T3HE3	F-18 prep	108	22%
T2HE3	F-18 adm	108	22%
T1HD3	F-18 adm	110	22%
T7HE1	F-18 prep	117	23%
T3HB3	Tc-99m adm and prep	122	24%
T4HB1	Tc-99m prep; F-18 adm	128	26%
T2HD2	F-18 prep	130	26%
T2HG5	F-18 prep	137	27%
T3HF7	Tc-99m adm	144	29%
T3HE1	Tc-99m adm and prep	151	30%
T12HF2	Tc-99m prep	154	31%
T1HE1	Tc-99m adm and prep	169	34%
T6HD2	Tc-99m adm	180	36%
T1HG5	F-18 prep	181	36%
T2HE2	F-18 prep and P-32 prep	208	42%
T7HD2	Tc-99m adm	210	42%
T1HF3	Tc-99m adm and prep	216	43%
T3HD1	Tc-99m adm	220	44%
T3HE2	Tc-99m prep	229	46%
T8HE1	Y-90 Zevalin® prep and SIRS spheres	240	48%
T4HE2	F-18 adm	242	48%
T1HD2	F-18 adm	285	57%
T3HD2	Tc-99m prep	290	58%
T1HD4	Tc-99m adm	300	60%
T10HF2	Tc-99m adm	302	60%
T8HF2	F-18 prep	315	63%
T6HD1	Tc-99m and F-18 adm	340	68%
T2HD4	Tc-99m prep	340	68%
T11HF2	Tc-99m prep	349	70%
T1HD1	Tc-99m and F-18 prep	370	74%
T2HD1	Tc-99m and F-18 adm	390	78%
T2HE2	Tc-99m prep	438	88%
T5HE2	F-18 prep	505	101%
T9HF2	Tc-99m-prep	524	105%
T6HF7	Tc-99m-prep	546	109%
T1HA1	Tc-99m adm and prep; F-18 prep	575	115%
T5HD2	F-18 adm	660	132%
T3HA1	Tc-99m adm and prep	689	138%
T4HG2	F-18 prep	809	162%
T7HE2	Tc-99m and P-32 prep	976	195%
T2HF4	Tc-99m adm and prep	1630	326%
T6HE2	F-18, Tc-99m, P-32 and Y-90 adm	1664	333%
T1HF4	Tc-99m adm and prep	1781	356%
T3HG2	F-18 prep	2175	435%
T1HF7	Tc-99m-prep	2976	595%
T1HG4	Tc-99m-prep	6994	1399%
T2HG4	Tc-99m-prep	9898	1980%

Table 9. Table of workers with the corresponding maximum annual dose estimation for the procedures that have been measured.

3 RESULTS OBTAINED FROM THE SIMULATIONS

3.1 *GENERALITIES*

The data obtained from the measurement campaign is affected by a large variability of doses among workers and hospitals, in particular, an inter-variability among workers but also an intra-variability for the same operator. Notwithstanding the general trends of the cumulated doses can be properly determined, these variabilities can easily mask, for example, the effectiveness of the shielding adopted or the effect of the different active volume of the syringe on the cumulated doses. But all these information are fundamental for a valuable radiation protection optimization purpose. For this reason, Monte Carlo simulations have been performed in 9 typical scenarios selected as the most common manipulations performed by workers when preparing and administrating radiopharmaceuticals. Those scenarios are divided in two categories, those concerning the injection and those concerning the preparation of the radiopharmaceutical.
For what concerns the injection, the scenarios have been labeled as follows: injecting scenario with and without shielding (I1S/I1N), holding the syringe when injecting with and without shielding (I2S/I2N),
For what concerns the preparation of the radiopharmaceutical the scenarios have been labeled as follows: transport of vial (PTR), syringe manipulations (PSM1, PSM2) and shielded vial manipulations (PVM).

For the voxelized models, a set of scoring cylindrical region, 12 in total, representing the dosemeters employed in the ORAMED measurement campaign with an extra position in the thumb nail, were simulated on the voxel hand surface. In order to have response in terms of the operational quantity a thin layer was defined at 0.07 mm depth from the outer sensor cell surface. Charged particle equilibrium was considered and a small amount of tissue (simulating the gloves) was added, when necessary.

These simulations have been performed for a set of combinations of the parameters with higher influence on the extremity doses in nuclear medicine. The aim was to determine the effectiveness of different radiation protection measures and to quantify the variation of the dose due to geometrical variations:

- Active volume of the source.
  For the same activity, the volume of the source was modified to check the sensitivity of the volume on the doses obtained at the different positions of the hands. For those geometries involving unshielded syringes, the volume of the source was changed between 1ml and 10ml. For those geometries involving a close contact with the vial (essentially PVM) the volume of the active solution was changed between 2.5ml and 10ml.
- Displacement of the source along its axis.
  For those geometries involving unshielded syringes, those were displaced along their axis to a maximum distance of 2.7cm. For those involving unshielded vials, the displacement was between 3 and 8 cm.
- Rotation of the source.
  For those geometries involving unshielded syringes, those were rotated with respect to their axis at an angle of 10 or 30 degrees, depending on the case. For those involving unshielded vials, only the scenario of PTR case allowed a rotation of 90 degrees.
- Shielding thickness and material.

After consultation with all nuclear medicine departments where measurements have been performed, a compilation of the most frequently used shielding material and thickness was done. The shielding parameter was changed in the simulations accordingly to this information. For a Tc-99m source, the shielding used for syringes was changed between 2 and 3mm of tungsten (W) or lead (Pb) and for the vials between 1 and 4mm of W or Pb. For a F-18 source, the shielding used for syringes was changed between 2 and 8mm of W and for the vials between 1 and 4cm of Pb and 8 and 12 mm of W. Concerning Y-90, the shielding used for syringes was changed between 5mm of W or 7 to 10 mm of PMMA and 1 cm of lead glass and for the vials between 1 and 2cm of PMMA with 0.5 to 1cm of Pb or 1cm of lead glass. For some specific geometry, the dosemeters are located, completely or partially, in a geometrical position not protected by the shielding. Therefore the effects of the shield types and thicknesses have been discussed only for the dosemeters efficiently shielded.

The physics applied for the three radionuclides and the unshielded and shielded cases are listed in Table 10. Mode P or PE means that only photons, or photons and electrons were transported, respectively. When positrons are emitted from the active volume (F-18, unshielded), subsequent 511 keV annihilation gamma-rays are generated by the Monte Carlo code used (MCNPX). The emission probabilities per disintegration are also given in Table 10.

Radionuclide	Tc-99m		F-18		Y-90	
Shield (Y/N)	N	Y	N	Y	N	Y
Mode	P		P E	P	P E	
Source emissions	Photons: 18.25 keV; 2.17 % 18.37 keV; 4.12 % 20.61 keV; 0.98 % 140.47 keV; 87.2 %		Positrons: Spectrum; 96.9 % Emax = 633.5 keV	Photons: 511 keV; 193.8 %	Electrons: Spectrum; 100 % Emax = 2280 keV	

Table 10. Radiation transport physics considered for the three radionuclides and the unshielded and shielded configurations.

3.2 ANALYSIS BY SCENARIO

The analysis of the results of the simulation studies has been organized considering the different scenarios (see deliverable 1) and following some predefined common guidelines. The purpose of the guidelines was to derive a quantification of the influence of the parameters mentioned before for the different radionuclides studied. Therefore ratios between doses obtained for the initial situation and those obtained for the disturb scenario (displacement of the source, change of shielding,…) were computed for all the parameters.

3.2.1 Analysis of the injection scenario 1: injecting (I1S/I1N)

The real geometry and the voxelized model of this scenario, for shielded syringe, are shown in Figure 27. Although left and right hands are shown here, the results do not depend on this aspect since the two geometries differ by a mirror symmetry.

Figure 27. Real geometry and voxelized model of I1S (S: shielded syringe) case. I2N (N: not shielded syringe) is the same as I1S but without shielding.

The results obtained for this scenario for the sensitivity analysis corresponding to the displacement of the source along its axis are here summarized. The displacement of the syringe along its axis can increase the dose up to a factor 3.5 for Tc-99m and F-18 but much larger for Y-90, up to a factor 8.5 for a 2.7 cm displacement.

Concerning the modification on the orientation of the syringe (+/-26 degrees maximum) almost no change is observed for Tc-99m and F-18, only a small influence for some dosemeters placed at the back of the fingers, with a factor 1.9 maximum. For Y-90 the effect is larger, the dose can increase up to a factor 3.4 but also limited to some specific positions (thumb and ring back).

Figure 28. Increasing the volume of the active solution, 1ml, 2ml, 3ml and 4ml.

As illustrated in Figure 28, increasing the active volume solution for the same activity means approaching the source to the dosemeters, therefore when increasing the volume, the doses increase at all positions. A maximum factor of 1.9 is found when manipulating a 4ml syringe for Tc-99m and F-18 instead a 1ml syringe. This factor is much higher for certain positions when the source is Y-90, going up to 170 (in case of using a 10ml syringe instead of a 1ml syringe).

As already mentioned, several shielding options have been studied. For Tc-99m the most effective shielding was found to be 3mm of W, as shown in Figure 29 (up to a factor 7000 lower doses compared with those corresponding to an unshielded syringe). For the case of F-18, Figure 30, the best shielding is 8 mm W (factor 40 in reduction of doses with respect to the unshielded syringe). For Y-90 two different shielding have been studied, 5mm W and 1cm PMMA. The shielding of 5mm W (up to a factor 10000 lower doses compared with an unshielded syringe) is more efficient than 1 cm of PMMA (up to a factor 4000 lower doses compared with an unshielded syringe) as shown in Figure 31.

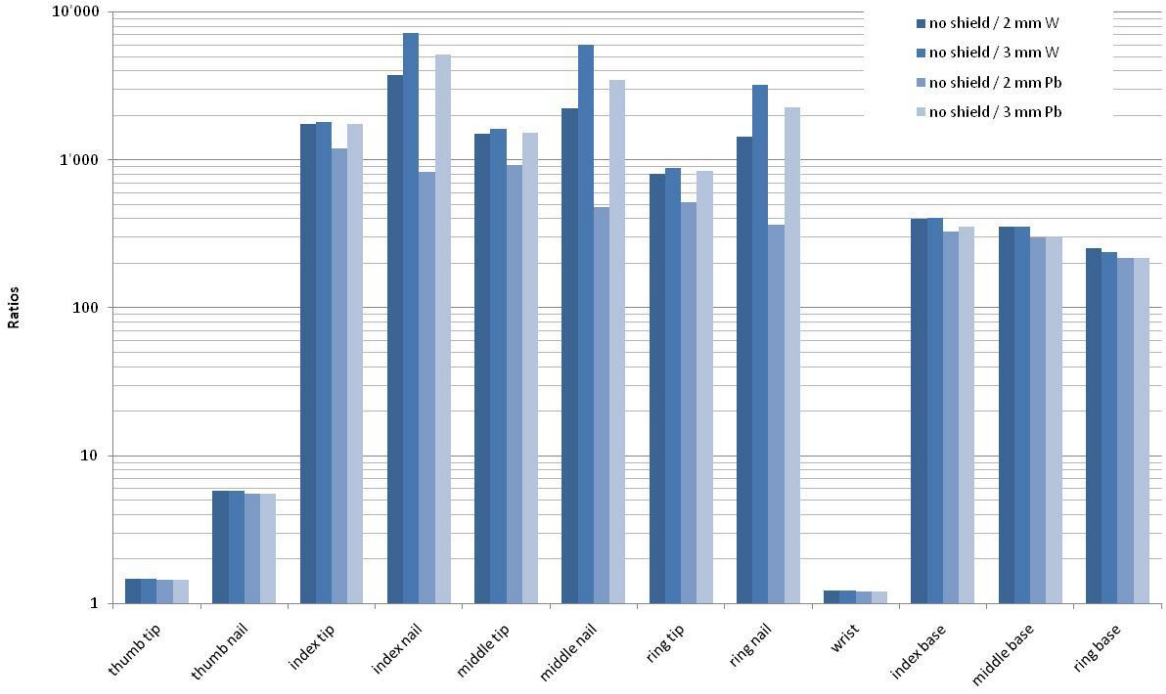


Figure 29. Ratios between unshielded syringes and syringes shielded of Tc-99m with 2mm W or Pb and 3mm W or Pb.

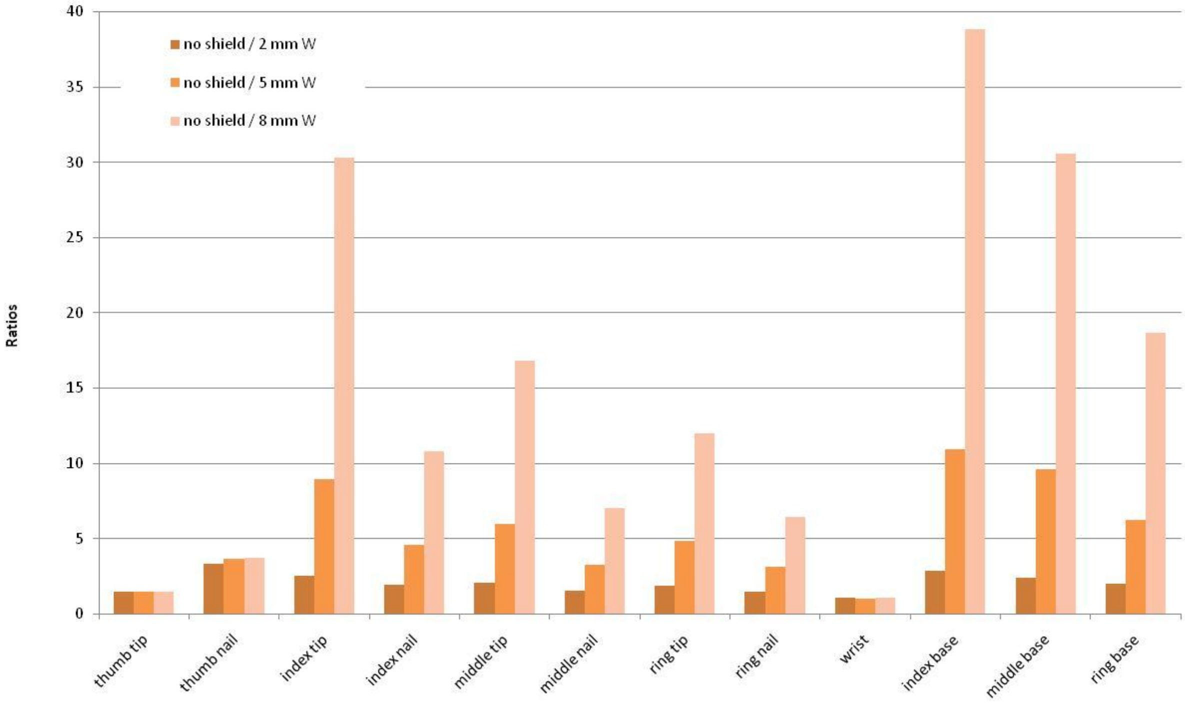


Figure 30. Ratios between unshielded syringes and syringes shielded of F-18 with 2, 5 or 8mm W.

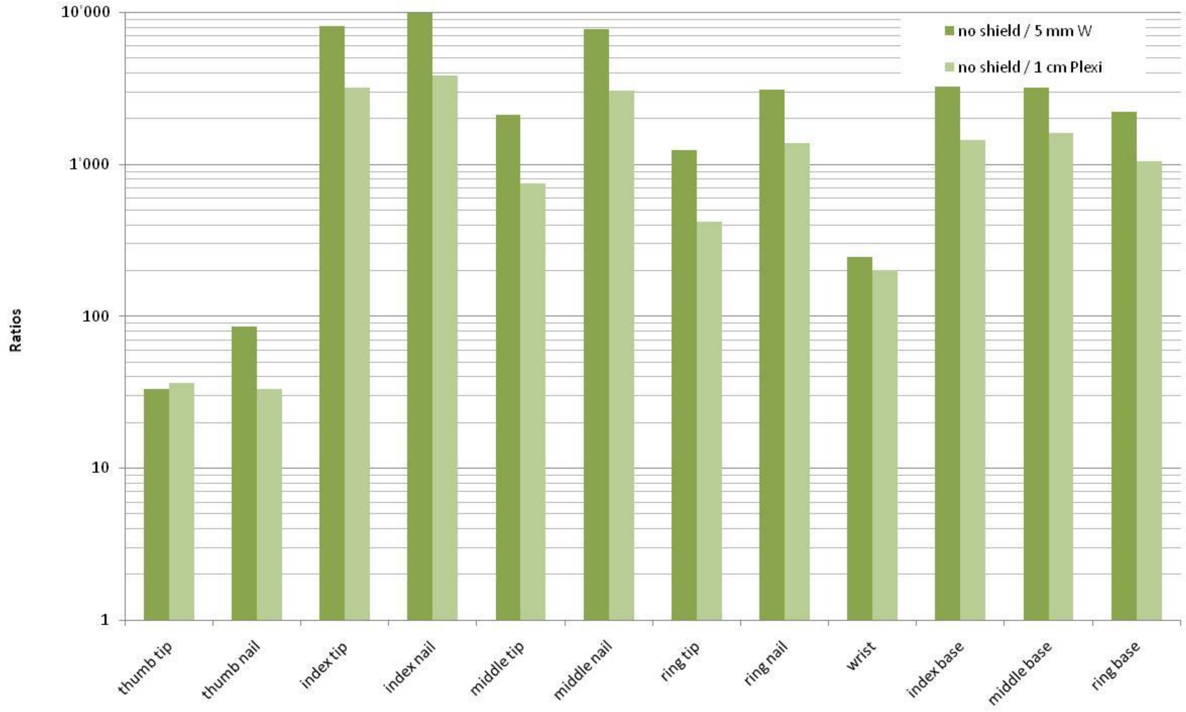


Figure 31. Ratios between unshielded syringes and syringes shielded of Y-90 with 5mm W and 1cm PMMA (Plexi in legend).

3.2.2 Analysis of the injection scenario 2: holding the syringe (I2S/I2N)

The real geometry and the voxelized model of this scenario, for shielded syringe, are shown in Figure 32.

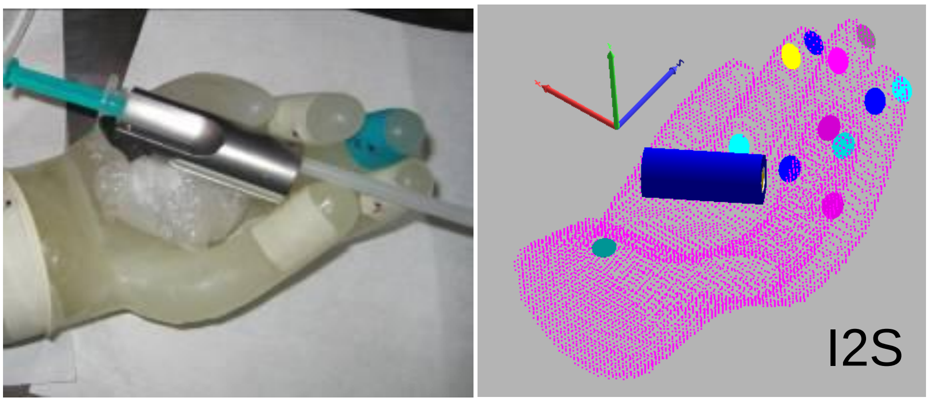


Figure 32. Real geometry and voxelized model of I2S case. I2N case is the same but without shielding.

When displacing the syringe along its axis or towards the sides, for all radionuclides, doses change with distance for each position (larger distance smaller doses). In particular, for Tc-99m the doses for the different positions could change by a factor of 0.5 to 2.1 by displacing the syringe by +1cm or -1cm along its axis from the initial position and by a factor of 0.3 to 1.2 when displacing the syringe towards the sides by a maximum of 2cm.

Rotations of 25° were applied for each radionuclide. In this case the syringe is further away from all measuring points, therefore doses could be reduced up to a factor of 0.3, 0.6 and 0.2 for Tc-99m, F-18 and Y-90, respectively.

For most of the positions corresponding to this geometry, a reduction of volume implies that the doses increase for every radionuclide. The dose can be reduced up to 50% taking a volume of 2ml instead of 1ml for the same activity for some specific locations as shown in Figure 33.

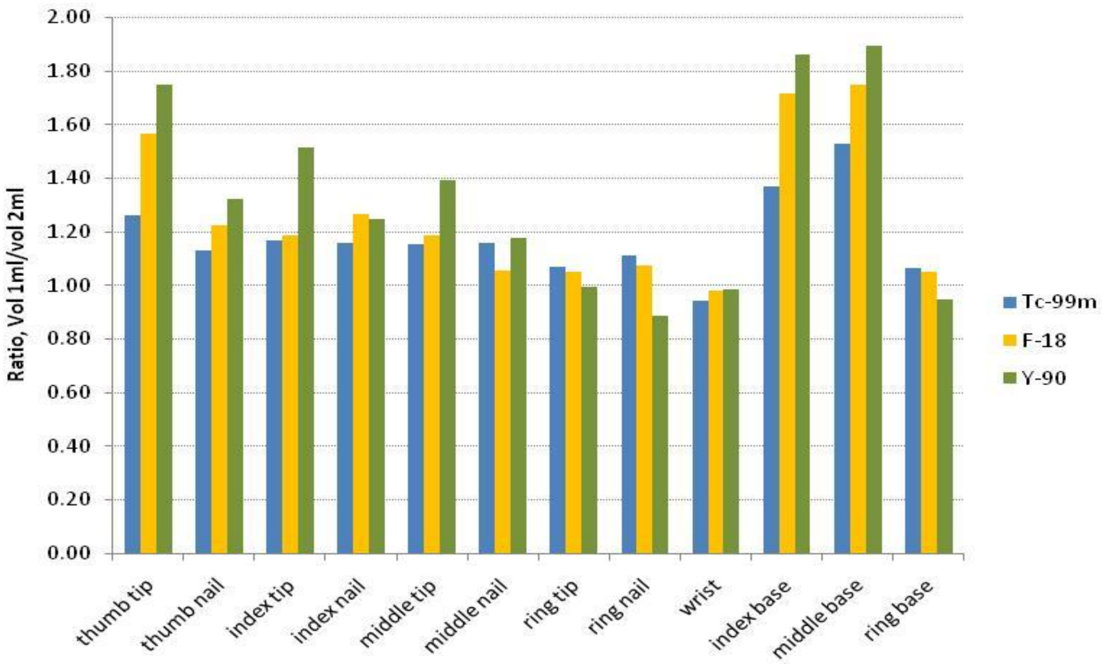


Figure 33. Ratios between doses obtained with an active volume solution of 1ml and 2ml.

For the different shielding evaluated, variations by orders of magnitude can be seen, depending on the position. For some of them, e.g. index ring and middle ring, shielding has no, or almost no, effect on the doses. This is due to the fact that the corresponding dosemeters are located, completely or partially, in the cone not protected by the cylindrical syringe-shield. The effects of the shield types and thicknesses will be discussed only for the dosemeters efficiently shielded; e.g., ring ring dosemeter. An acceptable protection is obtained with 2 mm W for Tc-99m, as shown in Figure 34. For F-18 the best protection is, as expected, obtained with 5 mm W, as shown in Figure 35. For Y-90, 5 mm W is clearly better than 5 mm PMMA, as shown in Figure 36.

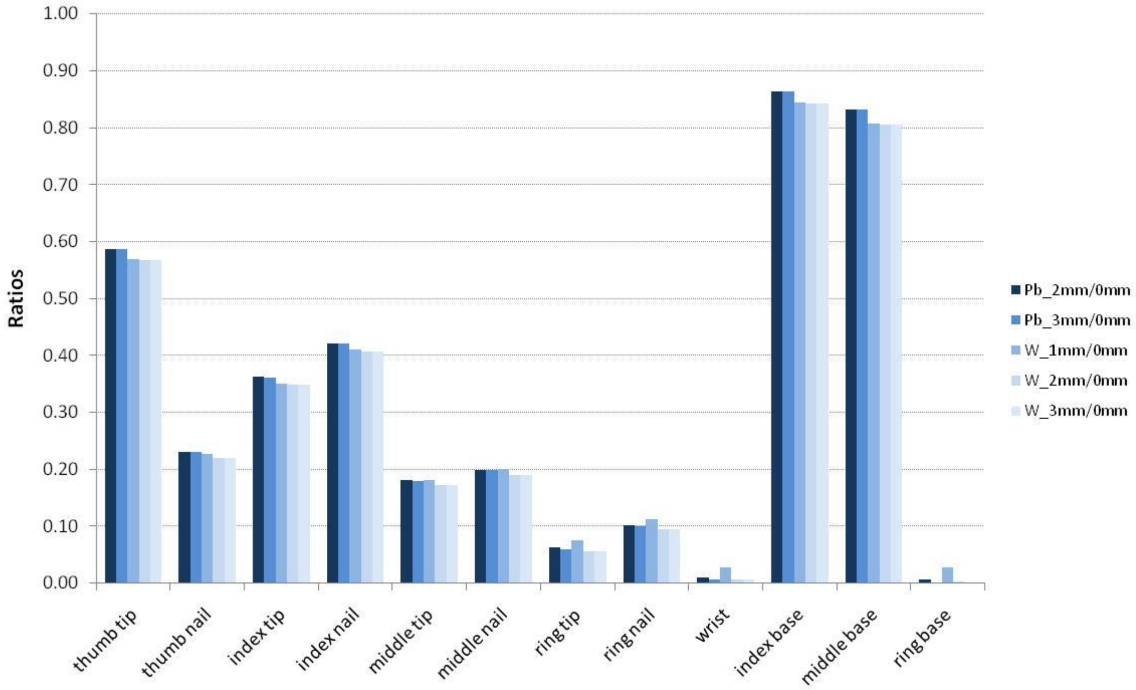


Figure 34. Ratios between unshielded syringes and syringes shielded of Tc-99m with 1 mm or 2mm W or Pb and 3mm W or Pb.

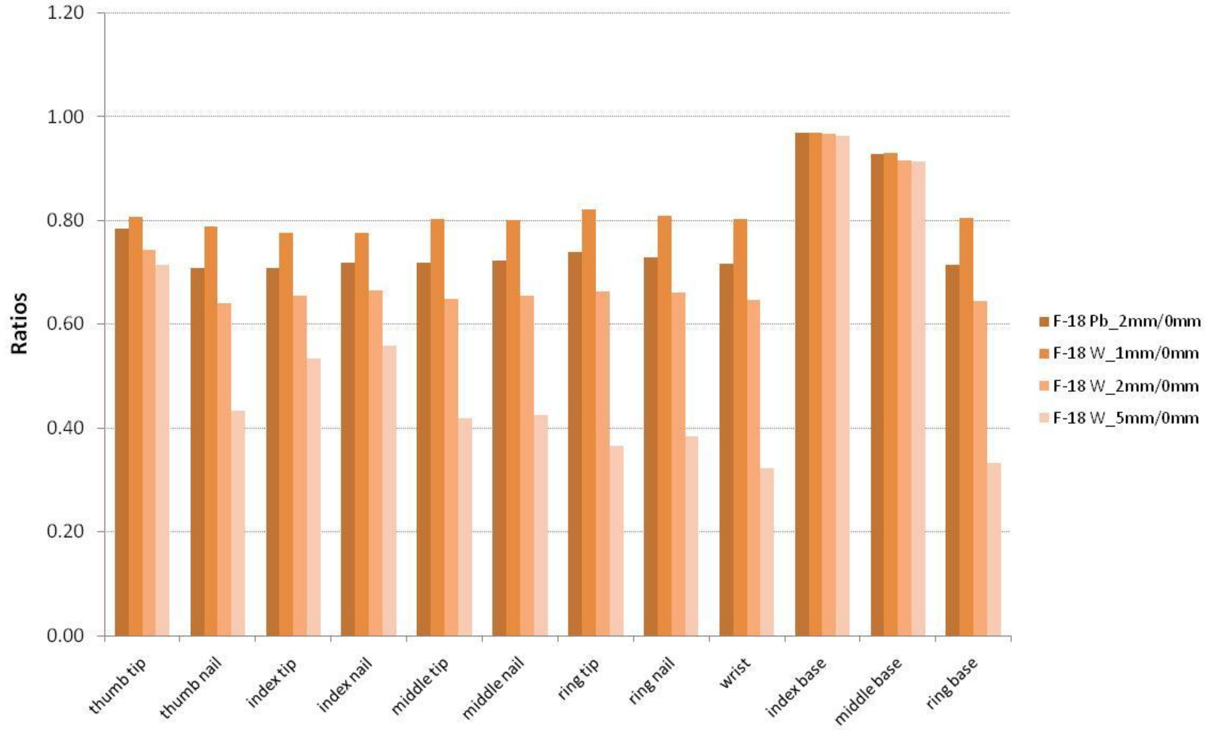


Figure 35. Ratios between unshielded syringes and syringes shielded of F-18 with 1 mm or 2mm or 3mm W or 2mm of Pb.

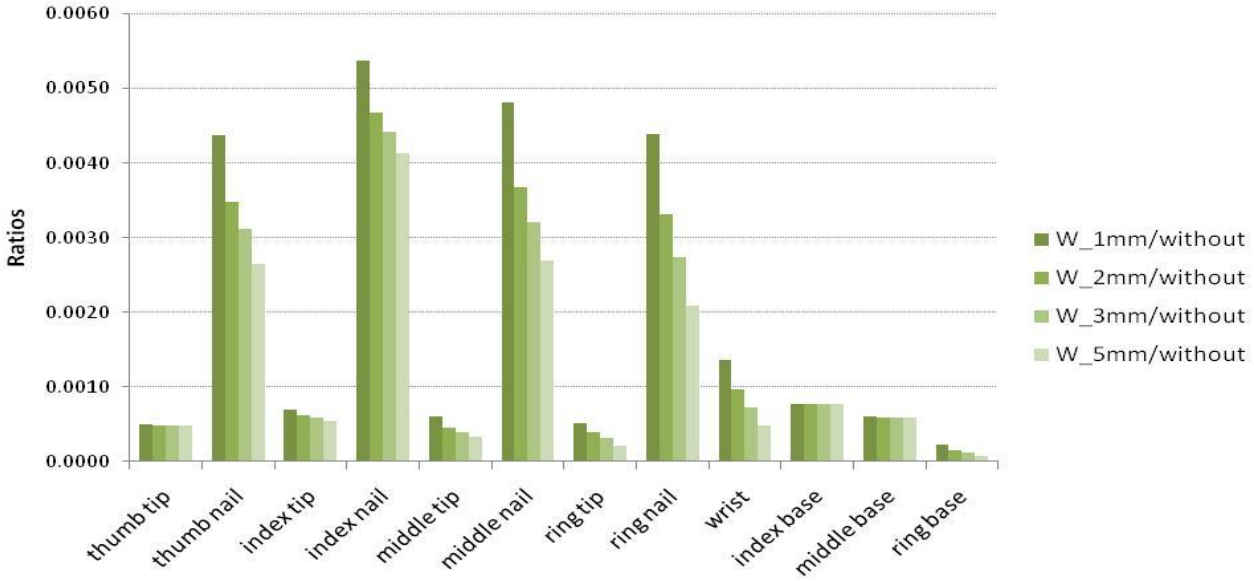


Figure 36. Ratios between unshielded syringes and syringes shielded of Y-90 with 1 mm or 2mm or 3mm or 5mm W.

3.2.3 Analysis of the preparation scenario 1: transport of vial (PTR)

The real geometry and the voxelized model of this scenario are shown in Figure 37.

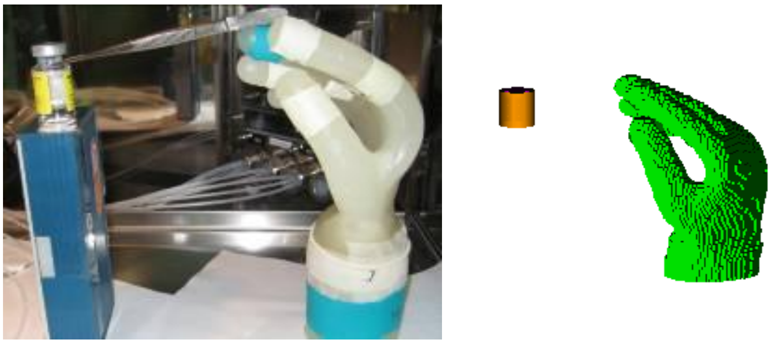


Figure 37. Real geometry and voxelized model of PTR case.

In this specific geometry the highest doses are found for the extremities of the middle and ring fingers.

Concerning the shielding of the vial, doses can be reduced two order of magnitude with a Pb shielding of 3 cm when manipulating F-18 and a factor three-thousand for 4 mm Pb (most efficient thickness among all considered) when manipulating Tc-99m. There is an effect on the long fingers (index, middle and ring) due to the fact that the vial is usually unprotected on the top. For this reason the doses collected by these fingers remain high when only lateral shielding is used, but is sufficient to cover the top of the vial with 2 cm Pb for F-18 and 1mm Pb for Tc-99m to reproduce the same dose reduction for all fingers.

Considering the displacement of the source and the solid angle through which it is seen by the detector position one should expect a factor of 0.5 - 2 for F-18 and a factor of 0.9 -3 for Tc-99m only moving the vial between 3 - 6 cm below its original position depending on the presence of the shielding.

For the same solid angle effect seen before, in case of only laterally shielded vial, the doses can increase for the "long finger" notwithstanding the distance from the source is increased. This effect is only due to the fact that the upper unshielded part of the vial, initially hidden by the edge of the lateral Pb shielding, becomes "visible" for the dosemeters placed on the extremities of those fingers when the vial is moved from its original position. Such effect is avoided if the movement is done with a Pb covering on top of the vial.

About the position of the dosemeter, for F-18, when ring or wrist dosemeter is worn in a reversed position, with the sensitive layer of the outer face oriented towards the outer face of the hand, a multiplying factor of 2 should be considered to be applied to the evaluated doses. For Tc-99m those factors are smaller around 1.4.

The situation for the Y-90 labeled Zevalin® is more complex because of the type of source. For the unshielded case the contribution due to the original beta spectrum is the main responsible factor of the collected doses as can be seen in Figure 38 and Figure 39 where the absorbed dose estimated through the electron and (bremsstrahlung) photon fluences are reported (there are 2 orders of magnitude between the doses).

In case of Zevalin® a different shielding is simulated more similar to the one really employed during Y-90 manipulation in the hot cell. In this case, the shielding has usually a top.

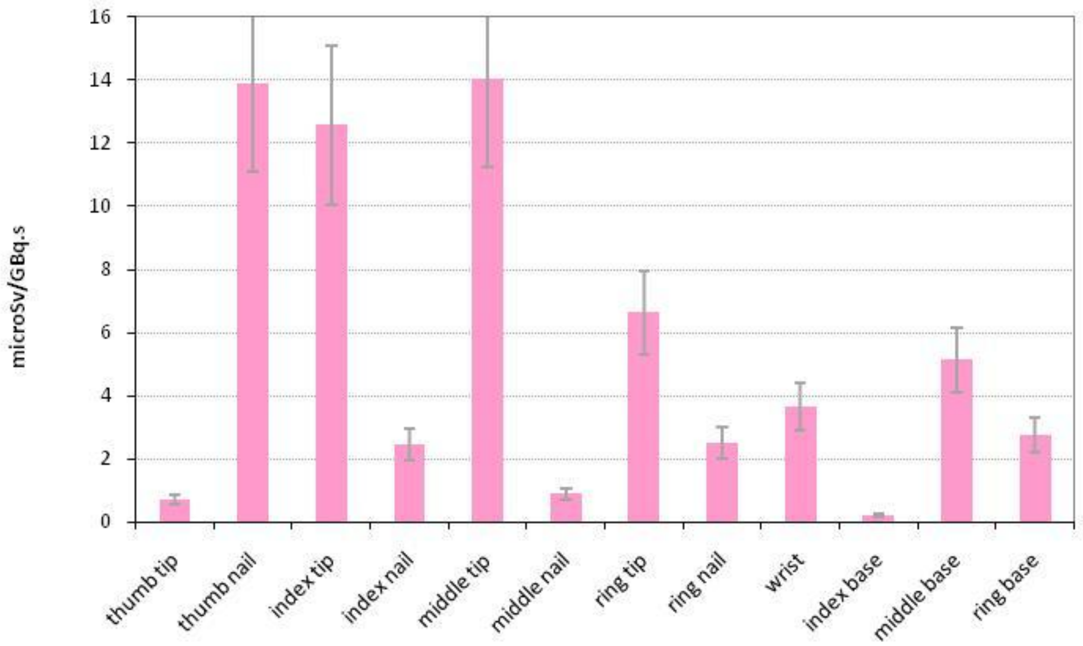


Figure 38. Y-90 doses calculated from electron fluence.

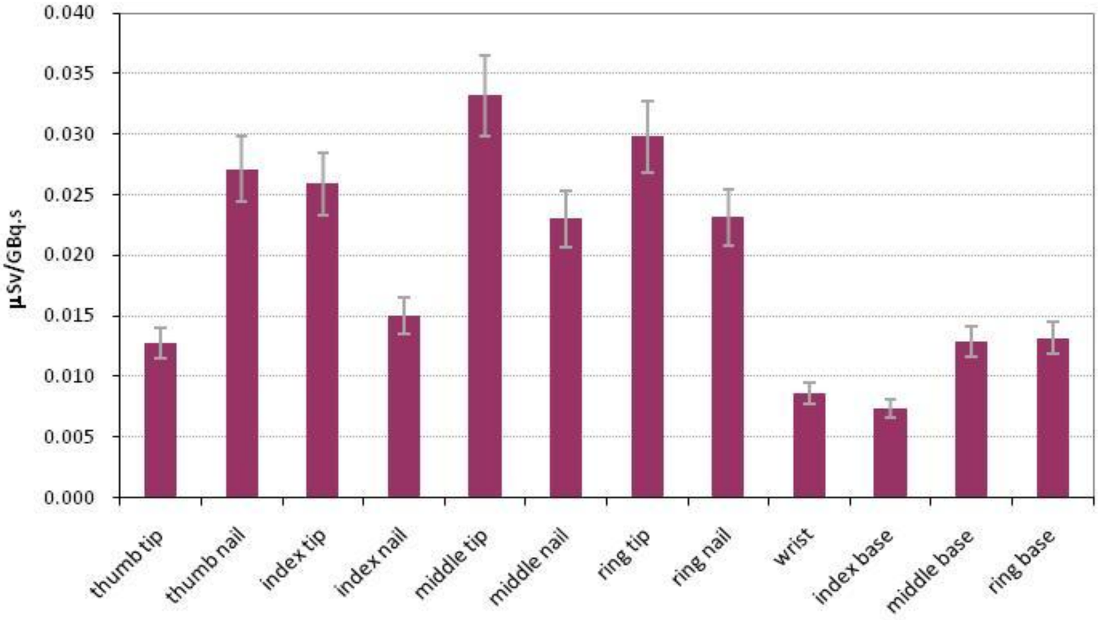


Figure 39. Y-90 doses calculated from (bremsstrahlung) photon fluence.

The maximum energy of the beta rays emitted by the source Y-90 is 2.284 MeV and the mean energy 0.9 MeV. 0.9 MeV electrons have a range of about 0.395 g/cm^2 in PMMA in the continuous slowing-down approximation (c.s.d.a.), that is 3.3 mm of PMMA. So after 5 mm of PMMA added to the PYREX© it is possible to assume that almost all the electrons produced in the source are stopped and converted into photons through the bremsstrahlung process. Therefore doses registered in TL dosemeters, when 5, 10 and 15 mm of PMMA are employed, are very similar notwithstanding the increasing layers of material used, as shown in Figure 40. This happens because the energy deposition is mostly due to the bremsstrahlung photons, not efficiently attenuated in the PMMA (their average energy is of several hundreds of keV). Therefore adding 5 mm of Pb to the 15mm PMMA reduces the doses to about one fifteenth of those obtained with 15 mm of PMMA only, as shown in Figure 41.
As a conclusion for the shielding of a vial with Y-90, the simulations show that 10 mm PMMA + 10 mm Pb or 10 mm Pb or 20 mm of lead glass have the same effect on the doses evaluated in the TL positions.

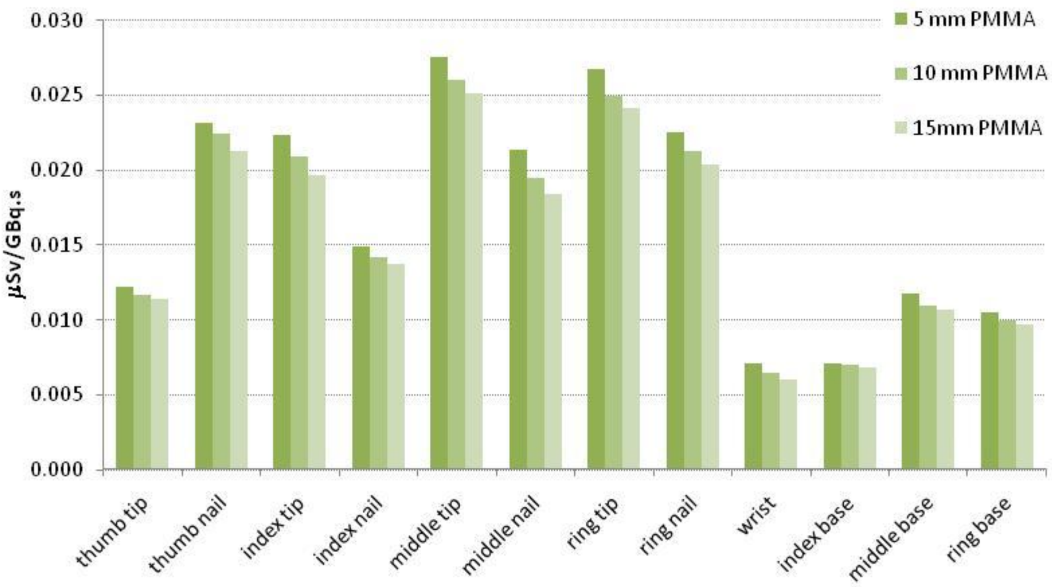


Figure 40. Y-90 PMMA shielding effect on the vial.

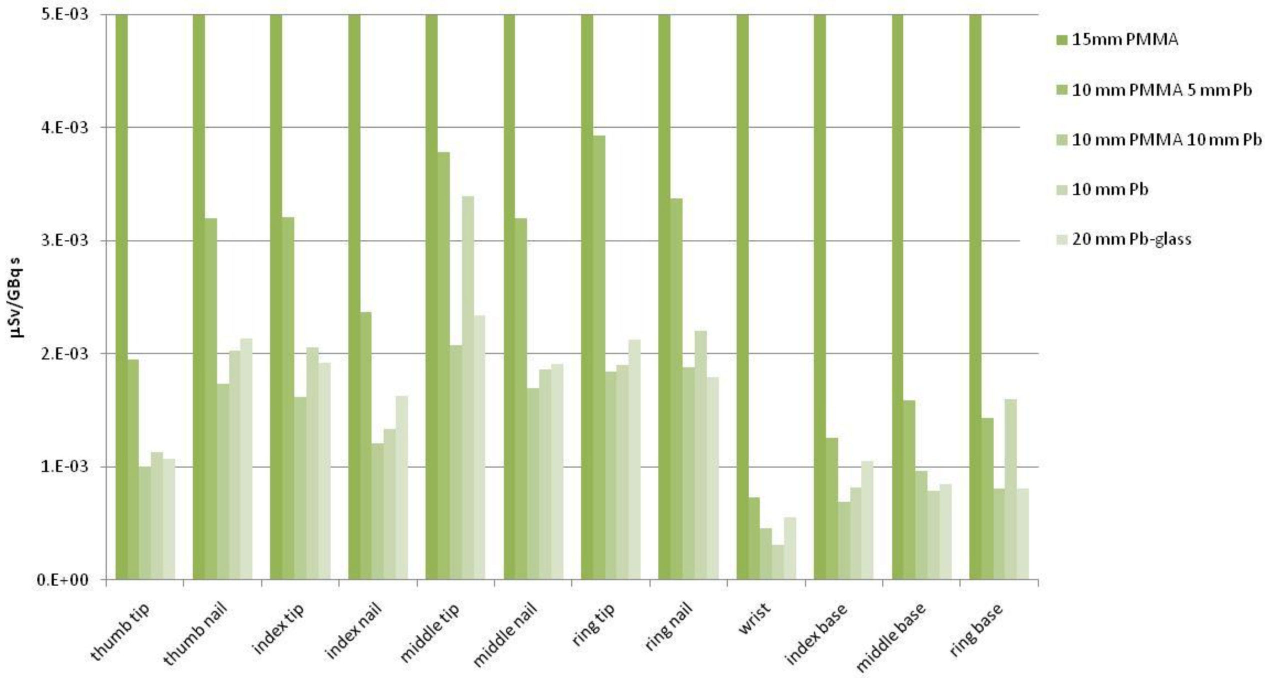
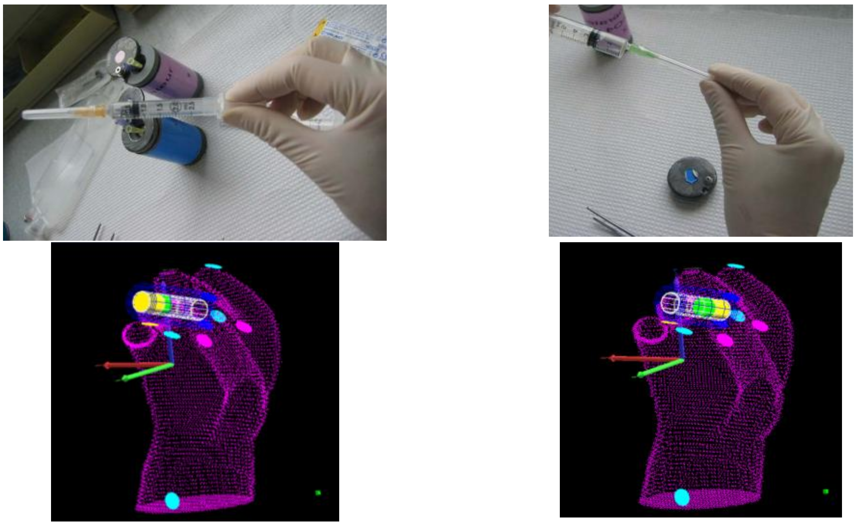


Figure 41. Y-90 multilayer shielding effect on the vial.

The variations on dose due to vial displacement in the case of Y-90 Zevalin® are only due to the increased distance of the vial that diminish the doses except for the wrist TL for which the distance with the source is reduced. The solid angle effect seen in the other case is not present for the Y-90 case because of the different shielding type used (a top shield is already present in this case).

3.2.4 Analysis of the preparation scenario 2: syringe manipulations (PSM1/PSM2)

For the process of preparation, these two cases PSM1 (holding a syringe by the piston) and PSM2 (holding a syringe by the needle) are often observed. These two configurations, with their associated model of voxelized hand, are shown in
Figure **42**.



PSM1 : Holding a syringe by the piston PSM2: Holding a syringe by the needle

Figure 42. Real geometry and voxelized model of PSM1 case (left) and PSM2 case (right).

Figure 43 shows the doses calculated at the 12 positions in the hands for an unshielded syringe for PSM1 and PSM2 cases for three different radionuclides: Tc-99m, F-18 and Y-90. As expected the doses are globally smaller for PSM1 than for PSM2 due to distance effects, except at the wrist from which the distance to the source is almost the same in both cases. The doses are also more uniformly distributed for PSM1 than for PSM2, again due to the distance effects but also because most of the high-energy beta-particles emitted from Y-90 are self-attenuated in the source volume and stopped inside the piston. The doses associated with Tc-99m are clearly smaller than those with F-18 and Y-90. When the dosemeter is very close to the source volume and/or in direct view of the side of this volume (the wrist for PSM1, thumb nail, index tip, middle tip for PSM2) the high-energy beta-rays emitted from Y-90 lead to the highest doses. Conversely, when the source is shielded by the geometry (index base for PSM1, index nail for PSM2), Y-90 does not dominate and the 511 keV gamma-rays emitted from F-18 lead to the highest doses. Among the different positions the maximum doses are seen on the index tip for PSM2 and at the middle tip and ring nail for PSM1, depending on the radionuclide.

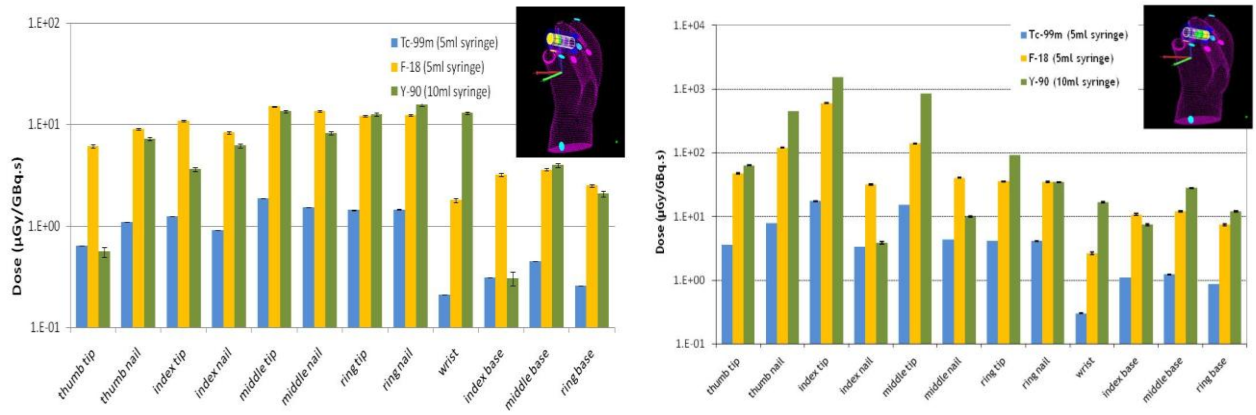


Figure 43. Comparison between Tc-99m, F-18 and Y-90 for an unshielded syringe and the respective reference cases, of the doses, in µGy/GBq.s, calculated at the 12 positions (logarithmic scale).

The effect of varying the syringe volume is small for Tc-99m and F-18 and much more pronounced for Y-90 and PSM1.

The sensitivity of the doses to the displacement of the syringe along its axis, -0.5 cm and +1 cm along its main axis (closer and away from the hand, respectively) with respect to its reference position was investigated. For PSM1 the effect is as expected, i.e. the larger the distance the smaller the doses for most positions. For PSM2, except for Tc-99m, the situation is more complex due to the proximity of the active volume, particularly for the index tip. This is probably due to the fact that the forward wall of the syringe was modeled thinner than the side wall and the index tip dosemeter is facing this side when the syringe is 1 cm away. Also self-attenuation effects certainly play an important role here.

The effect of changes in the orientation of the syringe -10° and +10° with respect to the reference case was studied. Considering the positions where high doses are received, for PSM1, the effect is within ±25 %, ±30 % and ±55 % for Tc-99m, F-18 and Y-90, respectively. For PSM2, it is within ±42 %, ±700 % and ±13 % for Tc-99m, F-18 and Y-90, respectively. The large effect observed for PSM2 and F-18 at the index tip is due to effects similar to that described in the previous paragraph.

The effects of the shield types and thicknesses can be discussed for the dosemeters efficiently shielded. For Tc-99m a better protection is provided by shields made of W than Pb, although the effect is small, as shown in Figure 44. An acceptable protection is obtained with 2 mm W. For F-18 the best protection is, as expected, obtained with 8 mm W, as shown in Figure 45. For Y-90, 5 mm W is clearly better than 10 mm PMMA by one order of magnitude is some cases, as shown in Figure 46.

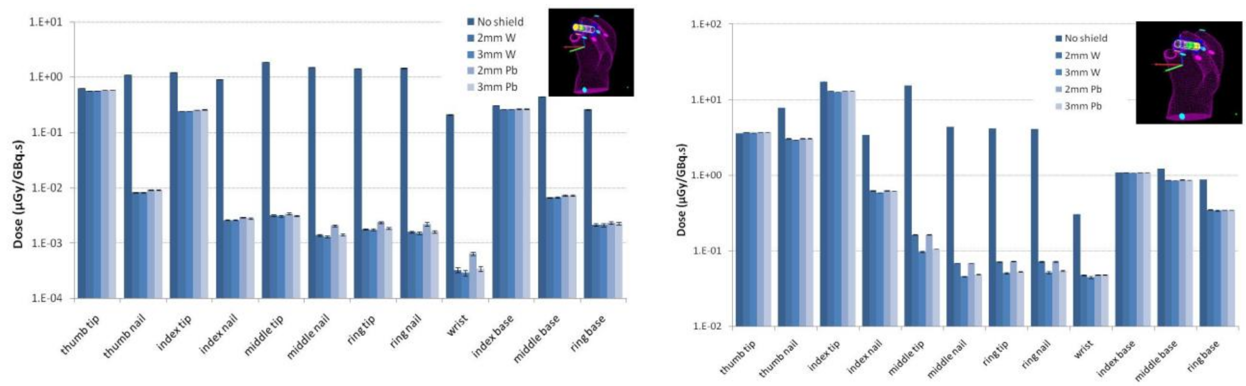


Figure 44. Effect of shielding for a Tc-99m syringe in geometries PSM1(left) and PSM2(right).

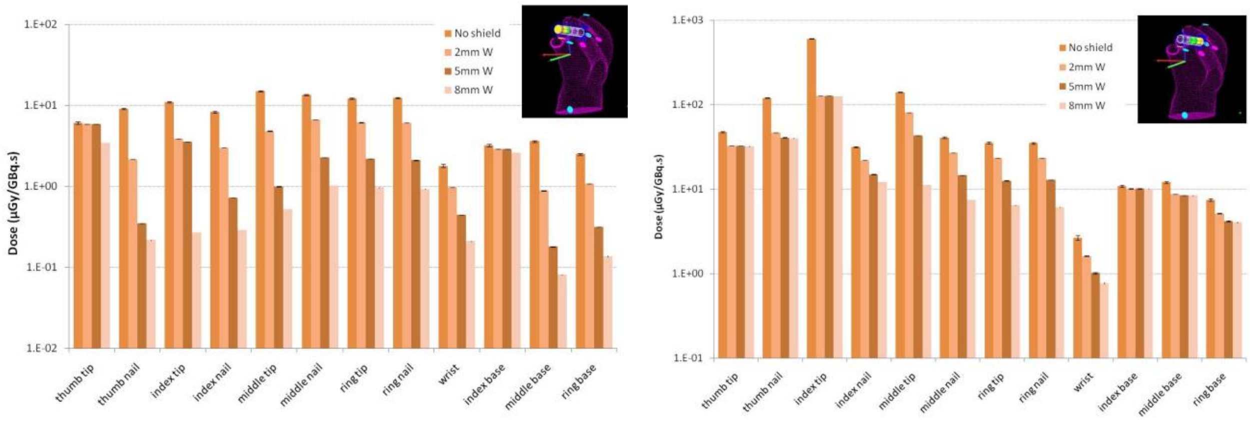


Figure 45. Effect of shielding for a F-18 syringe in geometries PSM1(left) and PSM2(right).

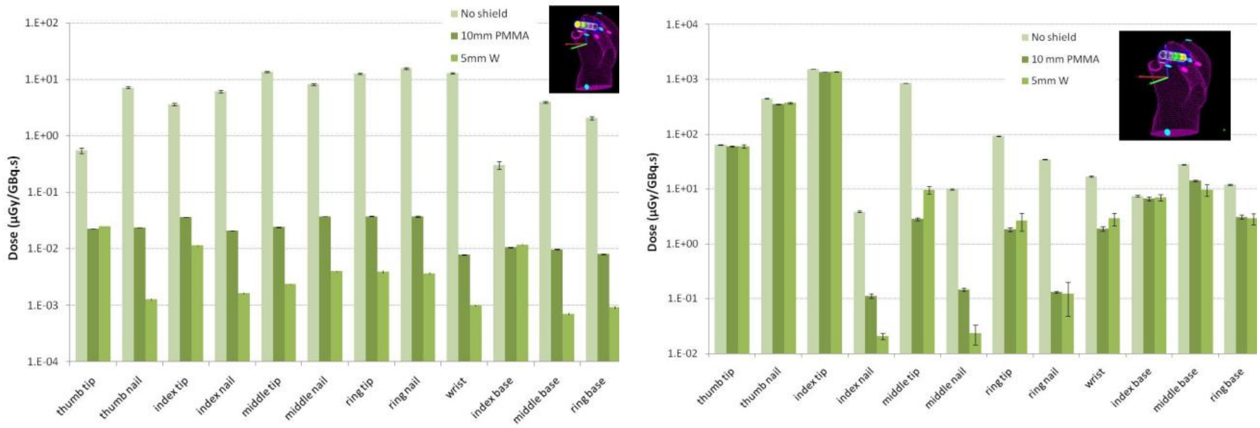


Figure 46. Effect of shielding for a Y-90 syringe in geometries PSM1(left) and PSM2(right).

3.2.5 Analysis of the preparation scenario 3: shield vial manipulations (PVM)

The real geometry and the voxelized model of this scenario are shown in Figure 47.

Figure 47. Real geometry and voxelized model of PVM case.

The effect of the different shieldings of the vial was studied for all three radionuclides in this geometry. For Y-90, the most efficient shielding was found to be a combination of PMMA with

Pb, 5mm PMMA together with 1mm Pb. Further increasing the thickness of PMMA (till 15mm) did not provide extra reduction on the doses, as shown in Figure 50. For F-18, 12.5mm of W is the best shielding among the different cases studied (8mm of W, 12mm of Pb or 12.5 mm of W), as shown in Figure 49. Concerning Tc-99m, the best dose reduction, among the 2 cases studied (1mm of W and 3mm of Pb), has been observed for 3mm of Pb, as shown in Figure 48.

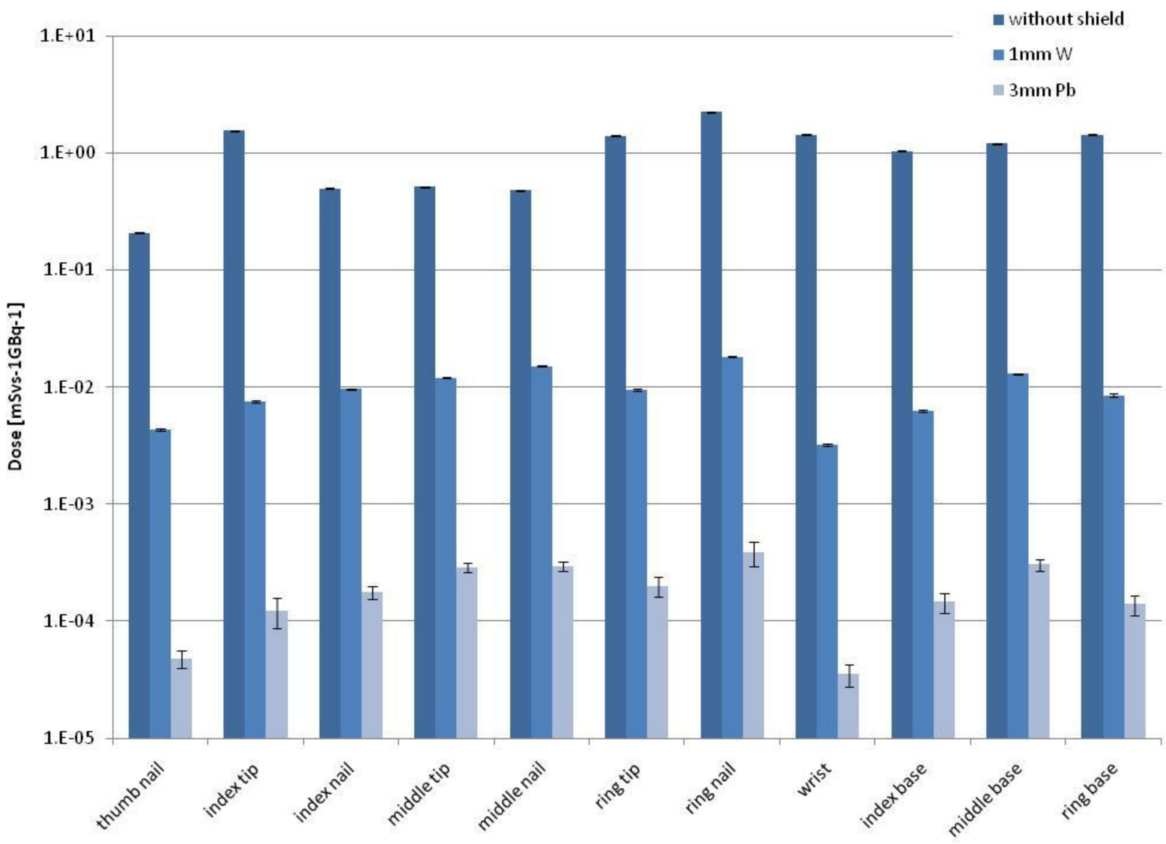


Figure 48. Effect of shielding for a Tc-99m vial in geometry PVM

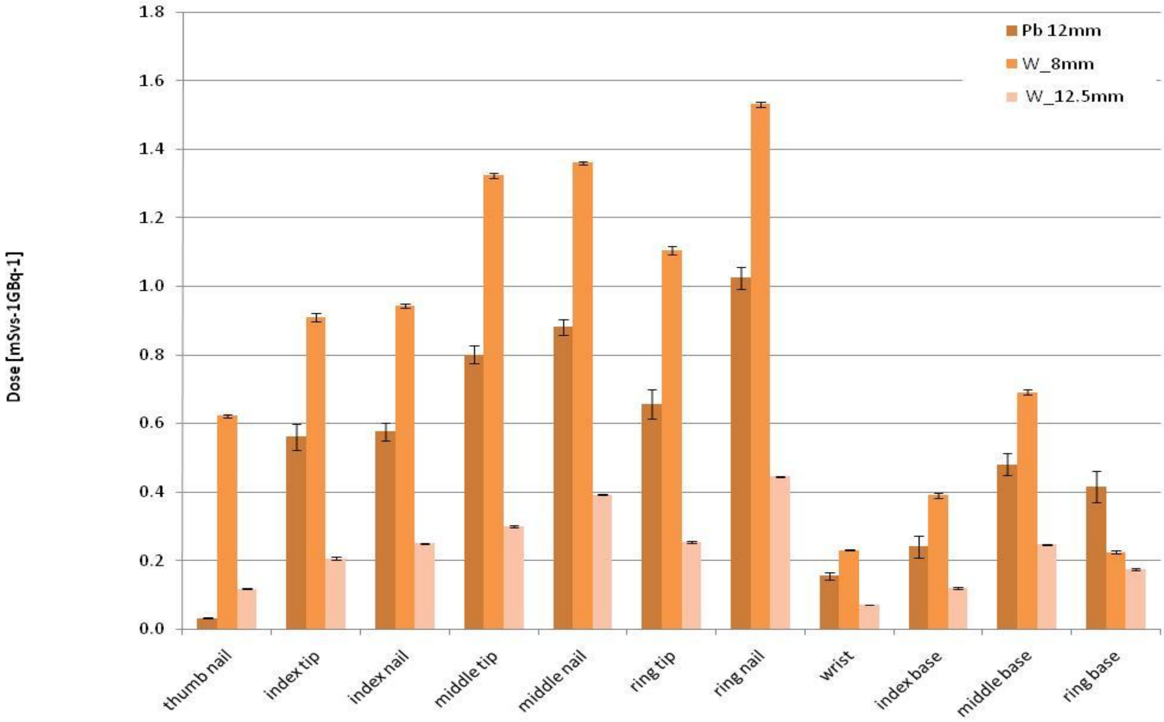


Figure 49. Effect of shielding for a F-18 vial in geometry PVM

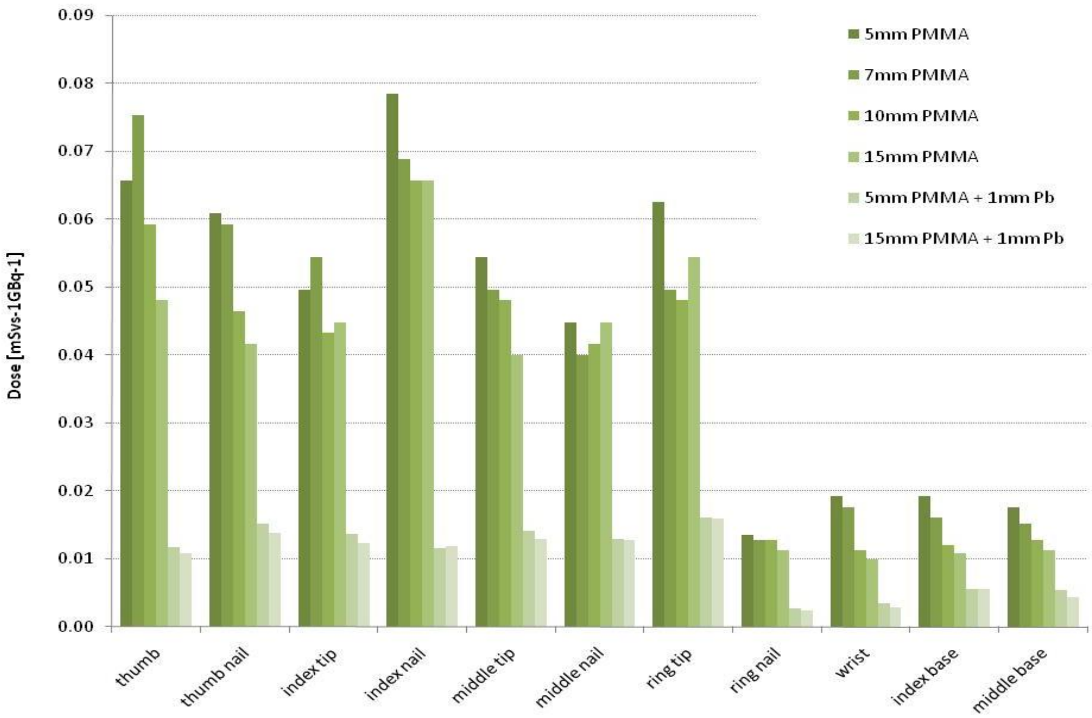


Figure 50. Effect of shielding for a Y-90 vial in geometry PVM.

The effect of the displacement of the source is clear for this case, the further away the source is taken from the hand the lower the doses are at the different positions.

3.3 *MERGING MEASUREMENTS WITH SIMULATIONS*

To be able to relate the results obtained from the sensitivity analysis of the simulations with the variation of the values observed from the measurements, the example of Tc-99m administration was taken. Only the non dominant (nd) hand, which usually corresponds to the hand holding the syringe or the canula was studied.

The differences of doses at the different positions when changing the parameters mentioned before are summarized in Table 11.

			Non Dominant hand											
			thumb	thumb back	index tip	index back	middle tip	middle back	ring tip	ring back	wrist	index ring	middle ring	ring ring
measurements without shield	MEAN doses (µSv/GBq)		262	--	76	185	175	55	32	33	63	56	40	25
	range (min-max)		73-543	--	50-100	44-547	26-553	16-93	18-40	13-55	7-210	25-92	11-77	12-36
Simulations P'/Pinitial	Displ along its axis	Po+1/Po	1.4	1.2	1.3	1.2	1.2	1.2	1.1	1.2	0.9	1.6	2.1	0.9
		Po+0.5/Po	1.2	1.1	1.1	1.1	1.1	1.1	1.0	1.1	1.0	1.3	1.6	1.0
		Po-1/Po	0.7	0.8	0.8	0.8	0.8	0.8	0.9	0.9	1.1	0.7	0.5	0.8
	Orientation of the srynge	Po+25°/Po	0.9	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.1	1.0	0.7	0.7
	srynge vol	1ml/2ml	1.3	1.1	1.2	1.2	1.2	1.2	1.1	1.1	0.9	1.4	1.5	1.1
	Displ towards the sides	Po-1cm/Po	0.9	1.0	0.9	1.1	1.0	1.0	0.9	0.9	1.1	1.0	0.7	0.5
		Po-2cm/Po	0.9	0.9	0.7	1.0	0.9	0.9	0.8	0.9	1.2	1.0	0.4	0.3

Table 11. Mean values and ranges of measured doses obtained from the measuring campaign and ratios of doses calculated when changing the parameters at the different positions.

The displacement of the syringe of maximum 1 cm along its axis can cause a change in the doses between a factor of 0.5 to 2 depending on the position and for the displacement of 2cm towards the side the dose can be changed by a factor 0.3 for the dosemeter closer to the syringe (ring dosemeter). The orientation of the syringe does not actually change significantly the doses (maximum a factor 0.7). By taking a volume of 2ml instead 1ml for the same activity the dose can be reduced up to 50% for some specific locations.

Concerning shielding for Tc-99m, a reduction of doses of 15% until 97% (depending on the location) has been observed. There are no significant difference between 2 and 3 mm of lead (or tungsten). Tungsten is slightly more efficient than lead (on the order of~3-5%).

The ratios obtained from the simulations when changing geometrical parameters applied to the mean measured values of the dose, give a range of values for the doses that is of the same order of magnitude of the variation observed in the measured doses (obtained from the measuring campaign). Therefore, the observed variation of doses obtained for the measurement could be partially explained considering the influence of the geometrical parameters here described. Indeed some ranges in the measurements are much larger (e.g. 26-553 and 7-210 µGy/GBq for the tip of the middle finger and the wrist, respectively). These cases surely correspond to variations not taken into account in the simulations, as for example inter-operator effects.

3.4 DOSE MAPPING

The sensitivity study performed within the WP4 ORAMED project was limited because the determination of the dose is restricted to certain points of the hand – the same points used in the measurements. Nevertheless the real maximum dose over all the skin of the hand could be found in any other point. The dose mapping was found to be an appropriate way to estimate the inaccuracy in the determination of the maximum dose that one can expect whenever it is not located in a measuring position. Moreover this tool is found to be very useful for training purposes and will be used in this sense.

As a first step the dose mapping was made on two of the scenarios included on the sensitivity study, which represent two situations of radiation exposure to the handling of a syringe during the administration of radiopharmaceuticals. These scenarios provide also an easier comparison with the measurements for the administration procedures, since the steps involved are many less and much more simple than in the case of preparation. Dose maps were made for almost all cases for the 3 radionuclides included in the sensitivity study (F-18, Tc-99m and Y-90) using MCNPX and Voxler.

Figure 51 shows the dose maps obtained for the 8 studied cases. The voxel where the maximum dose was found is highlighted in blue and the dose at the voxel is indicated in µGy/GBq·s.

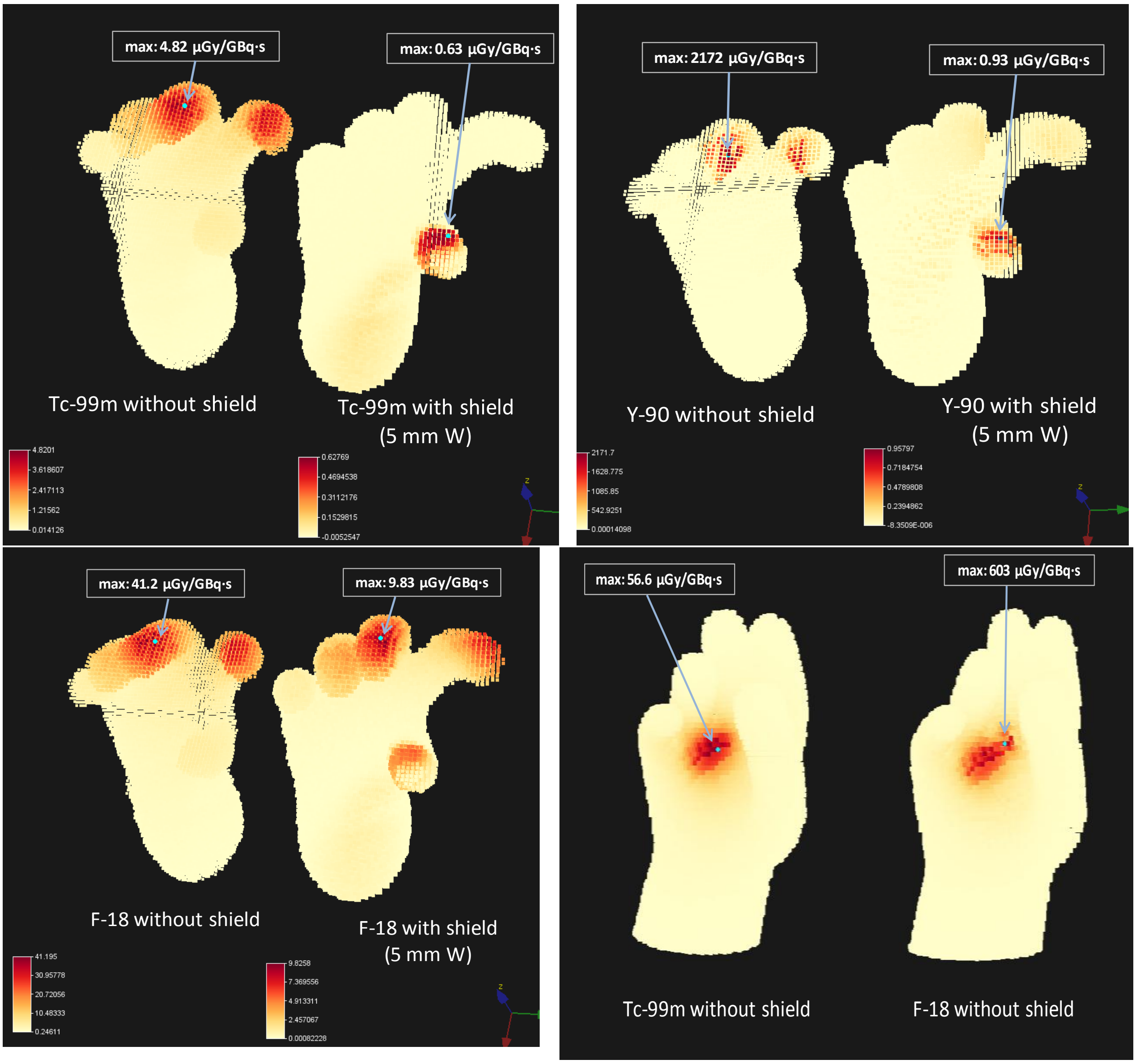


Figure 51. Dose maps obtained for scenario I1 for Tc-99m, F-18 and Y-90 sources both for shielded and unshielded syringes (pictures at the top and left picture at the bottom); and for scenario I2 (right bottom) for Tc-99m and F-18 unshielded syringes.

The dose distribution (unshielded syringe cases) is very similar for F-18 and Tc-99m. The distribution obtained for Y-90 is much more inhomogeneous. For scenario I1 the most exposed positions to the unshielded syringe are the back of the index and middle fingers, and the maximum dose is found in the latter position in all cases. When the syringe is shielded, the thumb finger is not protected because it is located on the axis of the syringe, and thus the maximum dose is received at this position, as it was observed in the sensitivity study. For scenario I1 the dose is localized in the palm of the hand because the syringe was closer.
The maximum dose obtained from the dose mapping was compared to the highest dose among the dosemeters used for the sensitivity study. It must be taken into account, though, that the shape and the mass of the voxel and of the dosemeter are very different. The voxel mass is about 20 times higher than the mass of the tally cell in the dosemeter. As an example of the comparison of maximum doses, Figure 52 shows for three cases the dose map together with the voxelized hand with the dosemeters, indicating in each case where the maximum dose was found as well as its value.

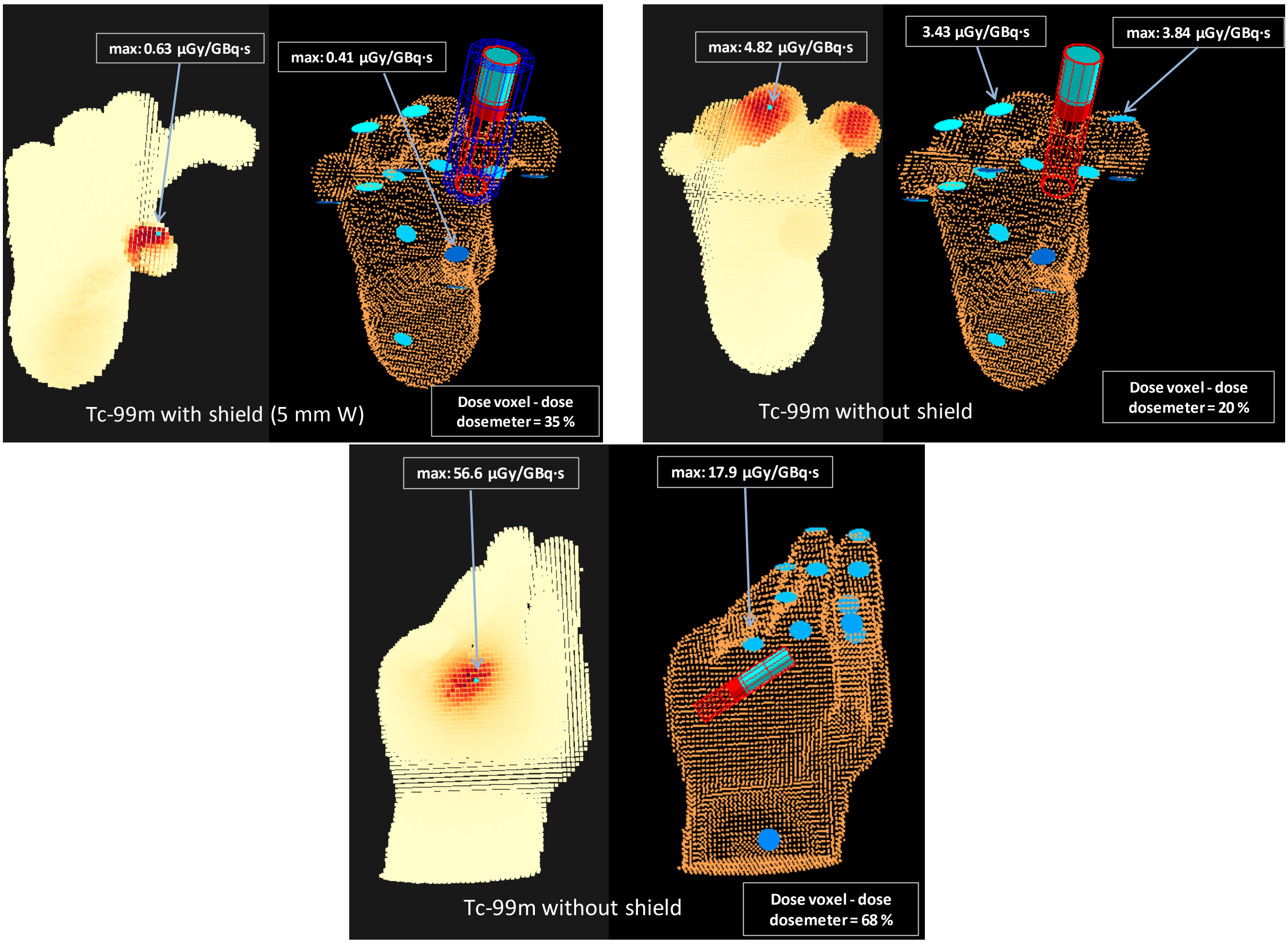


Figure 52. Comparison of the maximum dose obtained from the dose map for Tc-99m syringes and scenarios I1 (top) and I2 (bottom).

For scenario I1 and the shielded Tc-99m syringe the maximum dose is found in the same position, being the dose from the dose mapping a 35% higher than the one obtained in the sensitivity study. For the unshielded Tc-99m syringe, though, it can be observed how the sensitivity study fails from finding the real maximum dose because it was located on the side of the tip of the middle finger rather than on the nail, where the dosemeter was located. In this case the differences between the maximum doses are not high (20%) because for a source like Tc-99m the dose is distributed pretty uniformly in the most exposed area if the source is not very close to the hand. For scenario I2 the sensitivity study provides much worst results because the maximum dose shown in the dose map is very far from the closest dosemeter to this location, the ring ring dosemeter. The distribution of the dose is also more inhomogeneous than in the former scenario because the source is very close to the palm. The difference between the maximum doses found in both methods differs considerably, by almost a 70%.

The dose mapping was found to be a very appropriate tool to estimate the accuracy of the determination of the maximum dose by means of the sensitivity study, since it allows the maximum dose and its position to be found for a particular case. For F-18 and especially for Tc-99m sources, the fact that the maximum dose is not located in a measuring position is only critical if that measuring position is far from the place where the maximum dose is really located, and if the source is very close to the hand. If this is not the case differences will not be high because the dose is uniformly distributed in this area. For Y-90 the situation is more delicate because the dose distribution is highly inhomogeneous even if the source is not very close and even if the measuring position is not far from the location of the maximum dose. Thus, the

difference between the maximum doses could be very high. For the measurement campaign this problem was avoided by adding additional dosemeters on the sides of the tips of the fingers, where the maximum dose is expected to be found in most of the cases.
The dose mapping was also found to be very a very useful tool for training purposes since the characteristics of the sources and the efficiency of the shields are very clearly captured in the dose maps.

4 SUMMARY OF THE RESULTS FROM THE MEASUREMENTS AND SIMULATIONS

Here are presented the general results from the analysis of the measurement data and simulations.

Dose distribution	
General results : ➢ Doses at the nd hand are usually higher than doses at the D hand ➢ For most of the procedures, doses at the nd hand are statistically significantly higher than doses at the D hand. ➢ The highest dose was often found to be received at the index tip of the nd hand ➢ The dose mapping is a more accurate technique for the determination of the maximum dose than those methods restricted to a limited number of measuring positions (like the measurement campaign and the sensitivity study) ➢ Dose distribution over the hand it is highly inhomogeneous for Y-90 and more homogeneous for F-18 and especially for Tc-99m ➢ The presence of the shield (in case of syringes) reduces the zone of maximum dose to a spot located within the axis of the syringe.	
Tc-99m preparation	• The highest dose was often found at the index tip. • Doses at the nd hand are statistically significantly higher than doses at the D hand
Tc-99m administration	• The highest dose was often found to be received at the index tip at nd hand • Doses at the nd hand are statistically significantly higher than doses at the D hand
F-18 preparation	• The highest dose was often found to be received at the index tip of the nd hand • Doses at the nd hand are statistically significantly higher than doses at the D hand only at the base of the index finger.
F-18 administration	• The highest dose was often found to be received at the index tip (D and nd same percentage). • Doses at the nd hand are statistically significantly higher than doses at the D hand
Y-90 Zevalin® preparation	• The highest dose was often found to be received at the index tip of the nd hand. • Doses at the nd hand are statistically significantly higher than doses at the D hand.
Y-90 Zevalin® administration	• The highest dose was often found to be received at the index tip of the nd hand • The doses at the nd hand are usually higher than the doses at the D hand, but the difference is not statistically significant.

Dosemeter position for an accurate dose monitoring
General results : ➢ The ratio between the maximum skin dose and the dose at the monitoring positions in the nd hand are smaller than those in the D hand, except for the wrist. ➢ The smallest ratio between the dose at the maximum and the dose at a given position

is found in the tip of the index finger of the nd hand. However this is not a practical monitoring position. ➢ The second smallest ratio is found for the index base of the nd hand and thus the index base is the recommended monitoring position.	
Tc-99m preparation	• The base of the index finger of the nd hand leads to a mean ratio of 5. • The Pearson's correlation coefficient between the maximum dose and the base of the index finger of the nd hand is 0.79
Tc-99m administration	• The base of the index finger of the nd hand leads to a mean ratio of 5. • The Pearson's correlation coefficient between the maximum dose and the base of the index finger of the nd hand is 0.86
F-18 preparation	• The base of the index finger of the nd hand leads to a mean ratio of 4. • The Pearson's correlation coefficient between the maximum dose and the base of the index finger of the nd hand is 0.86
F-18 administration	• The base of the index finger of the nd hand leads to a mean ratio of 7. • The Pearson's correlation coefficient between the maximum dose and the base of the index finger of the nd hand is 0.63
Y-90 Zevalin® preparation	• The base of the index finger of the nd hand leads to a mean ratio of 7. • The Pearson's correlation coefficient between the maximum dose and the base of the index finger of the nd hand is 0.60
Y-90 Zevalin® administration	• The base of the index finger of the nd hand leads to a mean ratio of 7. • The Pearson's correlation coefficient between the maximum dose and the base of the index finger of the nd hand is 0.41

Shielding	
General results : ➢ Shielding is an important parameter for dose reduction. ➢ For all the procedures, except one, the doses when manipulating with shielding are statistically significantly lower than the doses obtained when manipulating without shielding ➢ W appears to be slightly more efficient in dose reduction than Pb for the radionuclides studied. ➢ The minimum acceptable shielding required for a syringe with Tc-99m is 3mm of W, with F-18 5mm of W (better 8mm W). For Y-90, 5 mm PMMA adequately and 10 mm PMMA completely shield beta radiation, but 5 mm of W are also efficient and additionally reduces bremsstrahlung.	
Tc-99m preparation	• The largest measured doses were clearly linked to the use of unshielded vial. • The doses when manipulating a shielded vial (89% of the workers) are statistically significantly lower than the doses obtained when manipulating an unshielded vial.
Tc-99m administration	• The largest measured doses are for those workers working with unshielded syringe. • The doses when manipulating a shielded syringe (76% of the workers) are statistically significantly lower than the doses obtained when manipulating an unshielded syringe.

F-18 preparation	• The largest measured doses are for those workers working with unshielded syringe. • The doses when manipulating a shielded syringe are statistically significantly lower than the doses obtained when manipulating an unshielded syringe. • There are not enough data for workers with an unshielded vial. Therefore this parameter could not be analyzed
F-18 administration	• Syringes-shields were used for all workers. Therefore this parameter could not be analyzed
Y-90 Zevalin® preparation	• The largest measured doses are for those workers working without shielding. • There is not enough data for workers working without shield for performing a statistical analysis.
Y-90 Zevalin® administration	• The largest measured doses are for those workers working without shielding.

Experience

General results :

- For some procedures doses for experience workers are smaller than those for beginners.
- For all the procedures, except one, the difference of doses for experienced workers and beginners is not statistically significant.

Sensitivity of doses to small perturbations

General results :

- As expected, displacements of the source or rotations imply a dose decrease if the position goes away from the source, or a dose increase when position is getting closer to the source. For few centimeters displacements the doses can change by a factor of 2 for Tc-99m and F-18. Distance keeping is of special importance for handling Y-90, since the dose coefficients are much higher.
- Changing the volume of the source, without changing the absolute activity, can increase or decrease the dose depending on the position. Nevertheless these changes remain relative small for Tc-99m and F-18 (maximum a factor 2 increased or reduction) but can be much larger for Y-90.

5 CONCLUSIONS

The results of the WP4 measurements campaign highlight large variations among procedures and workers. To some extent, the spread of the doses, even within the same procedure, is the expected consequence of the nature of the problem, as also partially demonstrated with the sensitivity analysis, and of the measurements, which involves many parameters. However, the very wide range of maximum doses observed (from some tenths of µSv/GBq up to more than two thousand for Tc-99m, from some hundredths of µSv/GBq up to more than four thousand for F-18 and from few mSv/GBq to more than sixty mSv/GBq for Y-90) is an indicative that good and bad practices were performed and thus, that workers with larger doses could actually optimize their working procedures or habits in order to decrease the dose. Three factors were associated to those workers with higher doses, contamination (the workers presenting contamination were considered as outliers and therefore not included in the general results from the analysis), working without shielding and direct contact with the source container. Contaminations can lead to very high doses, especially in therapy, where contaminations with Y-90 can lead to a skin dose that is about 150 times higher of that from the same activity of Tc-99m. The statistical tests confirmed that shielding produces statistically significant differences on the dose, therefore adequate shielding material and thickness for vials and syringes (see values on the section summary of the results) reduces the exposure. Specific developed tools to increase the distance between the hands and the source can be developed, specially important when working with Y-90. Staff handling Y-90 has to be aware of the fact that the skin dose rate is more than two orders of magnitude higher for the same activity and distance to the source. Those few workers associated to very low doses used advanced techniques e.g. semi-automatic dispensing tools.

The dose distribution over the hand depends first on the characteristics of the radionuclide; it is highly inhomogeneous for Y-90 and more homogeneous for F-18 and especially for Tc-99m. It also depends on the distance between the source and the hand and on whether the source is shielded or not. Moreover it depends on the manipulations performed. Therefore, even performing the same procedure with the same devices, it may strongly vary from one worker to another. However, some trends were found among the monitored workers for all procedures. Thus, the dose at the non dominant hand is usually higher than the dose at the dominant hand and that the index tip is most frequently the most exposed position in the hand.
In addition, it is also demonstrated that there are good correlations between the maximum dose in the skin and the dose in usual monitoring positions for ring dosemeters. In particular, it is found that the mean value of the ratio of the maximum dose and the dose at the base of the index for the different tested diagnostic procedures, namely preparation and administration of Tc-99m and preparation and administration of F-18, range from 4 to 7. Thus, the base of the index finger of the non dominant hand is the recommended position for routine extremity monitoring in nuclear medicine. Indeed, it is the practical position which has shown more similar correction factors as regards the maximum dose for the different diagnostic procedures, lower values and also smaller variability than other positions. Taking a mean value from the four diagnostic techniques, one can calculate a good approximate of the maximum dose equivalent from the ring dosemeter worn in the base of the index of the non dominant hand, multiplying the dosemeter reading by 5. In the case of Y-90 zevalin therapy, the correction factor should be 7, although in this case the uncertainty in the estimate is much larger.

The experience of the worker was not found to be a very determined parameter. Whereas in general experienced workers had lower doses, it was observed that some very experienced workers had deeply rooted inappropriate habits whereas beginners may work with extra carefulness. The study for the therapy procedures demonstrated that when appropriate training is given and the suitable radiation protection measures are used, doses can be reduced to an acceptable level when repeating the procedure.