

# Internal absorbed dose estimation by a TLD method for $^{18}\text{F}$ -FDG and comparison with the dose estimates from whole body PET

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**Abstract.** The thermoluminescent dosimeter (TLD) method has been proposed as a useful tool for estimating internal radiation absorbed dose in nuclear medicine. An efficient approach to verify the accuracy of the TLD method has been performed in this study. Under the standard protocol for 2-[F-18]fluoro-2-deoxy-D-glucose ( $^{18}\text{F}$ -FDG), whole body PET experiments and simultaneous body surface dose measurements by TLDs were performed on six normal volunteers. By using the body surface dose measured with TLDs, the cumulated activities of nine source organs were estimated with a mathematical unfolding technique for three different initial guesses. The accuracy of the results obtained by the TLD method was investigated by comparison with the actual cumulated activity of the same source organs measured by whole body PET. The cumulated activities of the source organs obtained by the TLD method and whole body PET show a significant correlation (correlation coefficient,  $r > 0.98$ , level of confidence,  $p < 0.001$ ) with each other. The mean effective doses in this study are  $3.2 \times 10^{-2}$  mSv MBq<sup>-1</sup> obtained from the TLD method and  $2.9 \times 10^{-2}$  mSv MBq<sup>-1</sup> obtained from the whole body PET. Good agreement between the results of the TLD method and whole body PET was observed.

## 1. Introduction

In nuclear medicine, the accuracy of absorbed dose of an internally distributed radiopharmaceutical estimated by the MIRD (medical internal radiation dose) method (Loevinger *et al* 1991) depends on the cumulated activity of the source organs and their mass. The usual methods for obtaining the cumulated activities are: (i) direct measurements by positron emission tomography (PET) (Jones *et al* 1982, Kearfott 1982, Meyer *et al* 1987, Herzog *et al* 1990, Mejia *et al* 1991, Deloar *et al* 1998a, b) and single photon emission tomography (SPECT) (Dey *et al* 1994, Kuhl *et al* 1994, Schmidt *et al* 1997); (ii) extrapolation from animal data (Gallagher *et al* 1977, Jones *et al* 1982, Harvey *et al* 1985, Thonoor *et al* 1988, Worbel *et al* 1997); and (iii) calculations based on the mathematical biokinetic model (Subramanian *et al* 1978, Charkes *et al* 1978, Bigler and Sgorous 1983, Brihaye *et al* 1995). Among these methods, extrapolation of animal data to humans includes inevitable inaccuracy due to large interspecies metabolic differences with regard to the administered radiochemical. Biokinetic modelling requires adequate knowledge of various kinetic parameters, which is based on some

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biological assumptions. Direct measurements can provide cumulated activity distributions with fewer biological assumptions. For positron-emitting radiopharmaceuticals, among the above-mentioned direct measurements by PET, only three studies (Herzog *et al* 1990, Deloar *et al* 1998a, b) have reported estimations of cumulated activities using whole body PET. But direct measurements of PET/SPECT are difficult to perform routinely. Since cumulated activity estimation requires the activity measurements of all source organs as a function of time, the repeated dynamic whole body emission scans take much longer than the usual clinical study.

In our previous studies, a method has been developed to obtain the cumulated activities of organs of interest through the use of TLDs (Matsumoto *et al* 1993, Deloar *et al* 1997, Nakamura *et al* 1998). In this TLD method a number of TLDs are placed on the body surface, just above the source organs during the clinical PET study, and the cumulated activities of source organs can be calculated by a mathematical inverse transformation method. Without impeding clinical studies, this method is suitable for calculating the cumulated activities of organs for the administered radiopharmaceutical.

We first investigated the accuracy of this method by calibration studies using a water phantom in which several gamma-ray volume sources containing known activities were arranged to simulate the source organs (Nakamura *et al* 1998). We then applied this method to estimate the organ cumulated activities and absorbed doses of subjects to whom  $^{15}\text{O}$ - and  $^{11}\text{C}$ -labelled radiopharmaceuticals were administered (Deloar *et al* 1997, Nakamura *et al* 1998). Here, in the present study, we further investigated the accuracy of this TLD method by using the body surface dose measurements with TLDs simultaneously with whole body PET experiments (Deloar *et al* 1998a) for  $^{18}\text{F}$ -FDG injection, on six normal volunteers, since  $^{18}\text{F}$ -FDG is one of the most popular and important radiopharmaceuticals used worldwide in clinical study. To obtain the actual organ volumes, on each subject, a whole body magnetic resonance imaging (MRI) scan was also performed (Deloar *et al* 1998a). This comparison gave the most accurate direct evaluation of the TLD method, since the combination of measured organ volumes (ml) from MRI and activity concentration ( $\text{MBq ml}^{-1}$ ) from whole body PET gave the actual individual cumulated activities with good accuracy, and has been described in our previous study (Deloar *et al* 1998a).

## 2. Materials and methods

### 2.1. Subjects

Six normal volunteers participated in this study (age 22–56 years, average  $30 \pm 13$  years). None of them had a prior history of any major physical illness. On each volunteer an MRI scan and PET study were performed to measure organ volume (ml) and organ activity concentration ( $\text{MBq ml}^{-1}$ ). Body surface dose measurements with TLDs were done simultaneously with the PET study. All volunteers were asked to refrain from eating and drinking for 4 h before the PET study. All subjects gave their written consent and the Ethics Committee for Clinical Radioisotope Research of Tohoku University approved the study protocol.

### 2.2. Whole body PET and body surface dose measurements with TLD

Body surface dose measurements by TLD were done during the PET study with a whole body PET scanner (SET-2400W, Shimadzu Co. Ltd, Kyoto, Japan) at the Cyclotron and Radioisotope Center, Tohoku University. The scanner provides 63 continuous transaxial slices with a resolution of 3.9 mm FWHM in the plane and 4.5 mm axially. The transaxial field of view is 59 cm and the axial field of view is 20 cm (Fujiwara *et al* 1997).

Whole body transmission scans at nine positions were performed with a  $^{68}\text{Ge}$  rod source for attenuation correction of the emission data. Nine bed positions covered a length of 168.5 cm. The duration of the scan at each position was 4 min. The total duration of transmission scans was 36 min (4 min  $\times$  9). After the transmission scan, the TLDs were placed on the body surface near the source organs. These organs are the brain, thyroid, heart, lung, liver, spleen, kidney, pancreas and bladder. After bolus injection of  $^{18}\text{F}$ -FDG three repeated whole body emission scans were performed. Whole body emission scanning at nine positions covered the length of the whole body and the duration of the scan in each position was 3 min. The total duration of emission scans was 81 min (3 min  $\times$  9  $\times$  3). The average injected dose was 120 MBq (from 78 MBq to 196 MBq). After the last emission scan the TLDs were removed from the body surface and TLD doses were measured by a TLD reader (Panasonic-UD-512P). A built-in calibration of the reader was done by the company with a  $^{137}\text{Cs}$  source. As organ activity measurement by whole body PET is the gold standard, *dose estimates* were compared with the results obtained from the TLD method for validation of that method.

### 2.3. Whole body MRI scan and organ volume measurement

To determine the size and position of source and target organs, whole body  $T_1$ -weighted MRI scans were performed on each volunteer using a 0.5 T magnetic resonance scanner (MRH-500SS, Hitachi, Japan), since we could visualize only several organ images of  $^{18}\text{F}$ -FDG, such as brain, heart, liver, bladder and kidney by the above whole body emission scans. Whole body scanning was performed at seven positions, where a slice thickness of 1 cm with an intervening gap of 0.5 cm between slices covered 157.5 cm of the body. Individual organ volumes were measured from the sequential slices of MRI images using the technique described in our previous study (DeLoar *et al* 1998a).

### 2.4. Basic theory of TLD method

In the MIRD method (Loevinger *et al* 1991), the internal absorbed dose from source to target organs is given as follows

$$\begin{aligned} D_k &= \sum_h S(k \leftarrow h) \tilde{A}_h \\ &= \sum_h S_{k,h} \tilde{A}_h \end{aligned} \quad (1)$$

where  $D_k$  is the mean absorbed dose in the  $k$ th target organ,  $S_{k,h}$  the absorbed dose in the  $k$ th target organ per unit cumulated activity of the  $h$ th source organ and  $\tilde{A}_h$  the cumulated activity of the  $h$ th source organ.

In the TLD method a number of TLDs are placed on the body surface near the source organs described previously, and the body surface doses are measured by TLDs. The measured TLD doses can be expressed as

$$T_k(t_0) = \sum_h R_{k,h} X_h \quad (2)$$

where  $T_k$  is the body surface dose at the  $k$ th TLD position during the measuring time period  $t_0$ ,  $R_{k,h}$  is the absorbed dose at the  $k$ th TLD position per unit cumulated activity of the  $h$ th source organ and  $X_h$  is the activity of the  $h$ th source organ cumulated during the TLD attachment. The body surface dose for infinite time ( $T_k(\infty)$ ) is calculated as

$$T_k(\infty) = \frac{\int_0^\infty e^{-\lambda t} dt}{\int_0^{t_0} e^{-\lambda t} dt} T_k(t_0) \quad (3)$$

where  $\lambda$  is the physical decay constant.

In equation (3) biological excretion and uptake are both neglected, and the effect of this approximation is discussed in section 2.7. Hence, from equations (2) and (3), the organ cumulated activity,  $\tilde{A}_h$  can be obtained as

$$T_k(\infty) = \sum_h R_{k,h} \tilde{A}_h. \quad (4)$$

For a particular time  $t_0$  and radiopharmaceutical, the integral part of equation (3) is a constant number. In this  $^{18}\text{F}$ -FDG study, the contribution of residual dose to total dose after  $t_0$  of 81 min is approximately 60%. The procedure for estimating residual doses of the TLDs from equation (3) may be a conservative estimate for the total TLD doses as well as the cumulated activities of the organs. Equation (3) is not applicable for calculating total dose to the bladder, because patients urinate immediately after the TLD (or PET) measurements. To estimate the cumulated activity of the bladder, the TLD dose  $T_{\text{bladder}}(t_0)$  for just the time period during the PET study was considered, with the assumption that the radiopharmaceutical is no longer accumulated in the bladder.

The concept of SAF (specific absorption fraction) calculation in the MIRD method was applied to calculate the  $R$ -matrix in equation (2) or (4) with the MIRD phantom (Cristy and Eckerman 1987) and the VADMAP (SAF calculation) code (Yamaguchi *et al* 1987) based on the point kernel method. The procedure to calculate SAF and the  $R$ -matrix for an individual with the VADMAP code has been described in our previous papers (Matsumoto *et al* 1993, DeLoar *et al* 1997, Nakamura *et al* 1998). When the  $R$ -matrix is given, an inverse transformation of equation (4) as described later can give the  $\tilde{A}$ -vector, which represents the cumulated activities of the source organs.

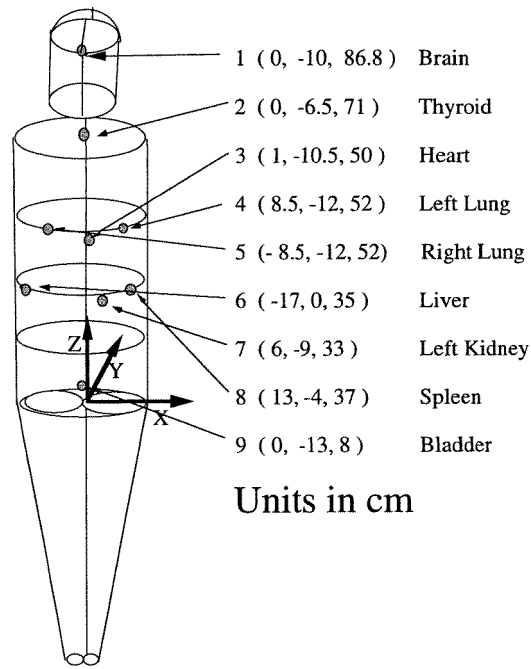
### 2.5. Measurement of activity concentrations of the organs using whole body PET

The organs having a higher uptake of  $^{18}\text{F}$ -FDG were considered as the source organs in this study. These organs are brain, heart, lung, liver, spleen, kidney, pancreas, bladder and the remainder of the body. ROI analysis was carried out with built-in PET image analysis software running on a workstation. The radioactivities in the organs were obtained as  $\text{cps ml}^{-1}$  (counts per second per unit of volume) from reconstructed PET images (DeLoar *et al* 1998a). To obtain quantitative radioactivity data for every clinical session the PET system was calibrated by doing the phantom experiment including an  $^{18}\text{F}$ -FDG solution of known radioactivity (Mejia *et al* 1991, DeLoar *et al* 1998a). Thus, the pixel counts of the PET image in  $\text{cps ml}^{-1}$  could be converted to activity concentration as  $\text{MBq ml}^{-1}$ .

### 2.6. TLD dose

The TLDs used in this study are BeO (Matsushita Electric Co. Ltd, Osaka, Japan). Since the SAF (response) calculation procedure by the VADMAP code is independent of energy, the TLD sensitivity to photons for the body surface dose measurement should also be independent of energy. Therefore, we selected BeO which is almost independent of photon energy.

Before the intravenous injection of  $^{18}\text{F}$ -FDG, the TLDs were placed on the body surface at nine positions close to the centres of nine source organs to measure the body surface dose at those positions during the PET study. At each TLD position a set of five TLDs were placed under the directions of the medical doctors to obtain the average dose. The TLDs were attached directly to the skin surface with adhesive tape under the clothes, since the TLDs are greatly influenced by geometrical ambiguities such as air gaps. The coordinates of the positions for adults were calculated from the MIRD phantom and the TLD positions are shown as Cartesian



**Figure 1.** TLD positions on the body surface near to the source organs on an adult MIRDO phantom with the Cartesian coordinates.

coordinates together with nearby source organs in figure 1, although the thyroid is not targeted as a source organ.

To obtain the background radiation dose, a set of TLDs were placed inside the PET room but away from the subject. The background dose was subtracted from the body surface doses, which are used in equation (2).

### 2.7. Cumulated activities of source organs

Combination of the organ activity concentrations from the three emission scans by whole body PET and the volume of these organs from the MRI scan gave the total organ activity. The actual cumulated activities of nine source organs were obtained from the time–activity curves which have been described in a previous study (Deloar *et al* 1998a). After the PET measurements, when no biological information is available, the residual cumulated activity of an organ was estimated by considering only the physical decay, and this approximation is acceptable from the time–activity curves of source organs as described in our previous study (Deloar *et al* 1998a). These contributions to the total cumulated activities were around 10 to 25%, depending on the individual organ. As the simultaneous whole body PET study and body surface dose measurements by TLDs were done on the six subjects, the cumulated activities obtained from the whole body PET were used as reference data to evaluate the results obtained by the TLD method for the same subjects.

By using  $T_k(0)$  measured by TLDs,  $T_k(\infty)$  of nine TLD positions were obtained from equation (3). The cumulated activities of nine source organs,  $A$ -vector, were then calculated through an inverse transformation of equation (4) by utilizing a slightly modified SAND-II unfolding code (Oster *et al* 1976) as described in our previous study (Nakamura *et al* 1998)

based on the successive iteration method. This unfolding method starts from the initial guess values  $\tilde{A}_h^{(0)}$ . Although the unfolded results are influenced by the initial guess values, previous studies (Matsumoto *et al* 1993, Deloar *et al* 1997, Nakamura *et al* 1998) assumed only uniform cumulated activity distribution throughout the body, since no prior distribution was available. In this study, to investigate the effect of the initial guess, three types of initial guess  $\tilde{A}_h^{(0)}$  were considered. The first guess is selected to be equal to the results obtained from the whole body PET, which is probably the most accurate guess. The second guess is a uniform distribution assuming that the activity concentration is uniform throughout the body, which is generally used *in the absence of a priori information*. In the third case the SAND-2 unfolding is repeated twice. In the first unfolding the initial guess is set to be uniform as in the second case, and the repeated unfolding starts with the initial guess of the first unfolding results.

In the calculation, the body surface doses which are calculated from equation (4) with the initial guess values  $\tilde{A}_h^{(0)}$  are compared with the measured values of the  $T$ -vector. The iteration is repeated until the former converges to the latter within a certain convergence value. This iteration is continued under the constraint condition that the sum of the cumulated activities of all source organs is equal to the total accumulation of administered activity, such as

$$\tilde{A}_{\text{tot}} = \sum_h \tilde{A}_h = \int_0^{\infty} A_0 e^{-kt} dt = \frac{A_0}{k} \quad (5)$$

where  $A_0$  is the total injected activity in MBq and  $k$  includes the physical decay and biological disappearance constant of  $^{18}\text{F}$ -FDG, as the biological disappearance constant will be radiopharmaceutical dependent.

## 2.8. Absorbed dose calculation

For cumulated activities thus obtained, the absorbed doses in target organs were calculated by using equation (1) with the IIDES code (Individual Internal Dose Estimation System on Nuclear Medicine) (Narita *et al* 1997) based on the MIRD method, which was originally developed by Hongo *et al* (1992). To calculate the absorbed doses in the major airway and nasal cavity wall, the  $S$ -values calculated by Deloar *et al* (1997) were used. A transformation method by Yamaguchi (1975) described in our previous papers (Deloar *et al* 1997, Nakamura *et al* 1998) was applied to the MIRD  $S$  tables (Cristy and Eckerman 1987) for the Caucasian reference man of 70 kg weight, both for the penetrating and non-penetrating radiations, to obtain the  $S$  values of the measured individual organs (Deloar *et al* 1998a).

In the absorbed dose estimates, cumulated activities of the other organs, which were included in the remainder of the body, were calculated from their mass fractions, because the activity concentration in the remainder of the body was considered to be uniform.

According to ICRP 60 (ICRP 1990) the effective dose was calculated from the following formula

$$H_E = \sum_i w_i H_i = \sum_i w_i D_i Q = \sum_i w_i D_i \quad (6)$$

where  $H_i$  is the dose equivalent of the  $i$ th target organ,  $D_i$  is the absorbed dose of the  $i$ th target organ,  $Q$  is the quality factor ( $Q = 1$  for  $\beta$ - and  $\gamma$ -rays) and  $w_i$  is the tissue weighting factor. To calculate the effective dose, in ICRP 60, the colon includes only LLI (lower large intestine). According to the suggestion of Zankle and Drexler (1995), we defined the colon as both LLI and ULI (upper large intestine) and its weighting factor was divided equally on ULI and LLI. An equal tissue weighting factor was applied for all target organs in the remainder of the body.

### 3. Results

The body surface doses measured by TLDs were obtained for the entire length of PET procedure (time for three emission scans) as described in the PET protocols. The average dose (of five TLDs on each position) was used as  $T_k(t_0)$  in equation (3) and the total dose  $T_k(\infty)$  was estimated. Cumulated activities of nine source organs were calculated from equation (4) by using the SAND-2 unfolding technique with the individual  $R$ -matrix values obtained with the VADMAP code. In the cumulated activity calculation by the unfolding technique, the effects of standard deviations of the  $R$ -matrix and of TLD doses for each TLD position were included. The mean cumulated activities of six subjects, obtained by the TLD method with the initial guesses resolved from the whole body PET values, are shown in table 1 and compared with the reference cumulated activities directly obtained from the whole body PET (Deloar *et al* 1998a).

**Table 1.** Average (for six subjects) cumulated activities (kBq-hr MBq<sup>-1</sup>) of the source organs with standard deviation obtained by the TLD method and whole body PET (Deloar *et al* 1998a).

Source organs	Average TLD	Average PET	TLD/PET
Brain	260 ± 29	230 ± 40	1.13
Heart	65 ± 4	24.6 ± 7	2.64
Lung	52 ± 4	55 ± 8	0.95
Liver	88 ± 10	84 ± 16	1.05
Kidney	32 ± 4	36 ± 19	0.89
Spleen	8.4 ± 2	7.9 ± 3	1.06
Pancreas	7.5 ± 2.7	4.1 ± 3	1.83
Bladder	156 ± 49	151 ± 39	1.03
Remainder of the body	1966 ± 46	1975 ± 97	1.00

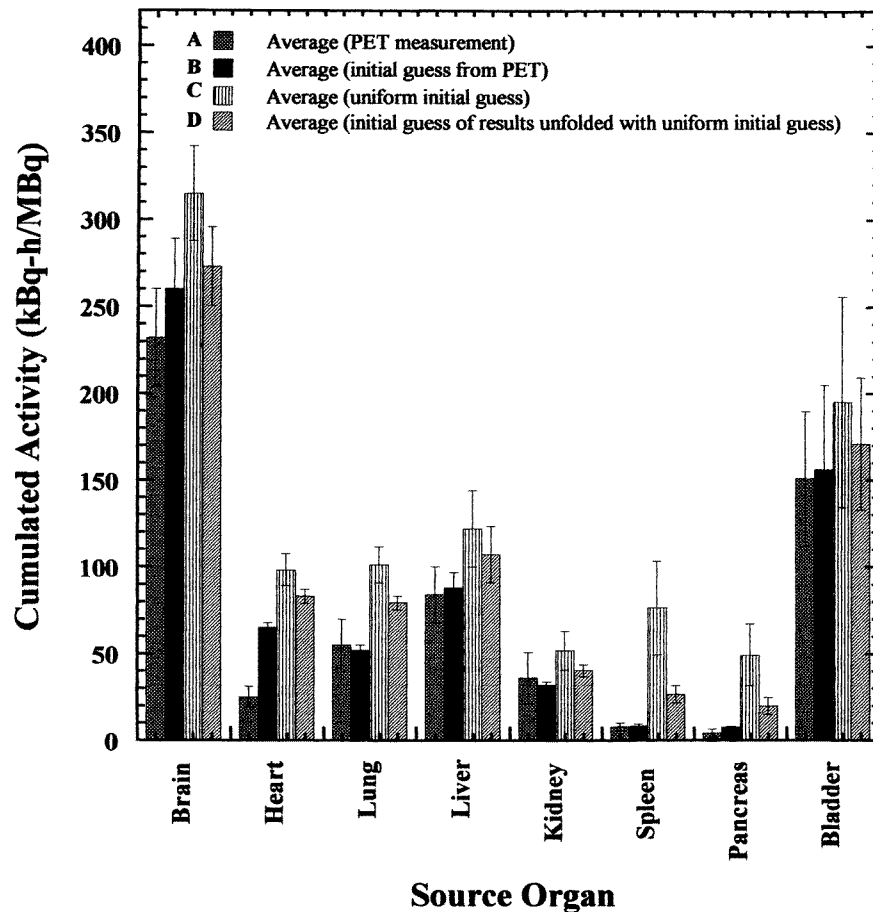
The effect of three types of initial guess on the cumulated activities is shown in figure 2 with the reference organ cumulated activities obtained from the whole body PET (A). The initial guesses,  $\hat{A}_h^{(0)}$ , were the initial guess from PET (B), the uniform initial guess considering the uniform radioactivity distribution throughout the body (C) and the initial guess of the results unfolded with uniform initial guess (D) as described before. A correlation of cumulated activities obtained from the TLD method and whole body PET is shown in figure 3.

For each individual, the absorbed dose estimate in the target organs for the cumulated activities of the TLD method and whole body PET were calculated by using equation (1). The mean absorbed doses to some major organs with their standard deviations for six subjects are shown in table 2. These results are compared with the data published in ICRP 53 (ICRP 1987). In the TLD method the target organs receiving the highest absorbed doses are bladder wall, brain and kidney; those values are  $3.7 \times 10^{-1}$ ,  $4.1 \times 10^{-2}$  and  $2.6 \times 10^{-2}$  mGy MBq<sup>-1</sup>, respectively, in this descending order. Those values are comparable with the results obtained by whole body PET.

### 4. Discussion

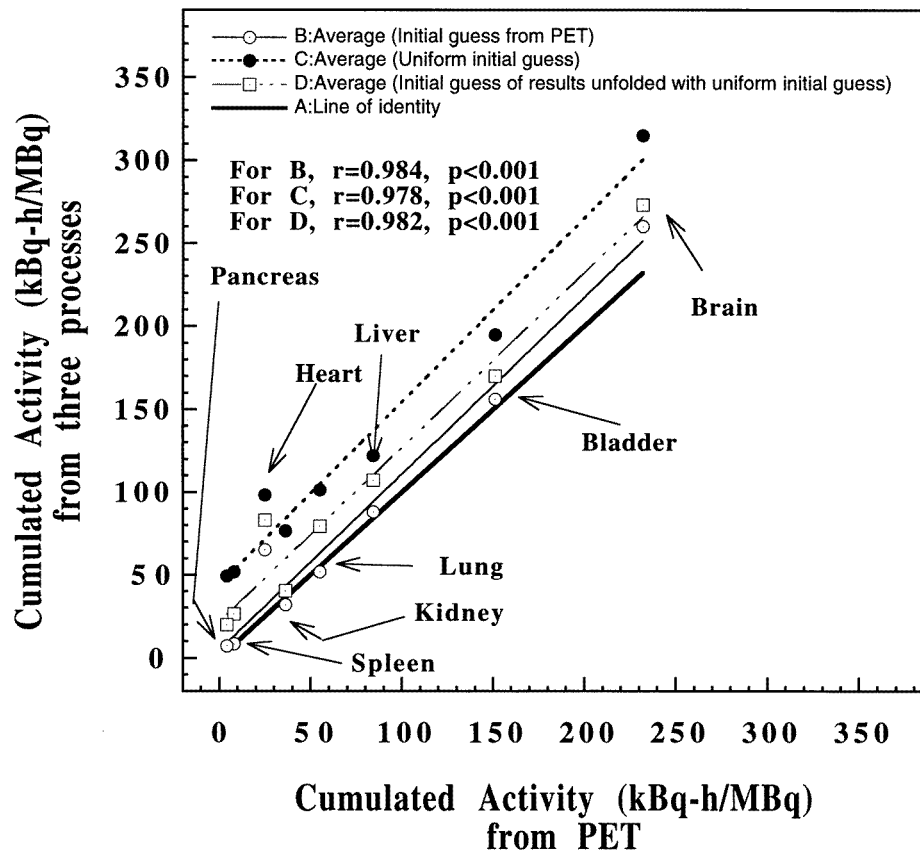
#### 4.1. Cumulated activities of source organs

The mean cumulated activities of the source organs for three different types of initial guess are shown in figure 2. Among these results, the cumulated activities estimated by the TLD method with the initial guesses obtained from the whole body PET values might be more accurate to



**Figure 2.** Average cumulated activities of the source organs for six adult volunteers obtained from the TLD method for three initial guesses of (B) initial guess from PET, (C) uniform initial guess, (D) initial guess from the unfolded results of uniform initial guess and comparison with the results of whole body PET (A).

evaluate the accuracy of the TLD method. In table 1, the mean cumulated activities of the source organs for six subjects obtained by the TLD method and whole body PET agree well to within around 90%, except for the results of the pancreas and the heart. In the TLD method, the  $R$ -matrix was obtained simply by correcting the MIRD organ sizes with a factor related to individual total weight as given by Yamaguchi (1975); however, actual individual organ sizes may practically deviate from organ sizes corrected in this manner. It may also happen that the TLD positions used to measure the individual body surface doses and those positions used for calculation of  $R$  matrices are different. All these effects introduce some variations between the results of the TLD method and whole body PET, especially for small source organs. The cumulated activity of the heart in the PET study (table 1) is 2.6 times lower than the result obtained by the TLD method. The reason for this big difference is not clear, but may be partly due to some contribution to the TLD dose from the highly concentrated blood activity through the heart just after the FDG injection which could not be measured by the whole body PET owing to the delayed scanning time.



**Figure 3.** A correlation of average cumulated activities of six adult volunteers obtained by the TLD method and whole body PET. The values of correlation coefficient,  $r$ , and level of confidence,  $p$ , are given for three initial guesses, B, C and D.

It is clearly seen that the cumulated activities obtained with the initial guess from the PET data (B) give the best fit to the direct PET data, compared with other two initial guesses (C) and (D). The TLD results for the initial guess (D) show better agreement with the PET results than for the initial guess (C). The correlation between the PET results and the TLD results for three different initial guesses is shown in figure 3 as a function of average cumulated activities in eight source organs for six subjects. Those three results were fitted individually to the straight line equation of  $y = mx + c$ . A bold full line represents the true line of identity. For all three cases of initial guesses, a good correlation can be seen in figure 3.

For radiopharmaceuticals with known organ biodistribution of cumulated activities, the initial guess for unfolding with the TLD data must be adjusted to that of *a priori* values. But for new radiopharmaceuticals this study shows that the unfolding should be performed twice; the first unfolding with the uniform initial guess and second unfolding with the initial guess of results of the first unfolding, and that results thus obtained will provide the agreement with the PET reference results within about 15% difference for organs of higher cumulated activities and within a factor of 1.6 for organs (pancreas) of lower activity. Even when we perform only one unfolding with the uniform initial guess, however, we can get comparatively good results to within about 40% difference for highly accumulating organs.

**Table 2.** Absorbed dose estimates (mGy MBq<sup>-1</sup>) (mean ± standard deviation) to the target organs in this study and compared with ICRP 53 (ICRP 1987).

Target organs	TLD method†	Whole body PET	TLD/PET	ICRP 53
Adrenal	$1.4 \times 10^{-2} \pm 2.0 \times 10^{-3}$	$1.6 \times 10^{-2} \pm 2.8 \times 10^{-3}$	0.88	$1.4 \times 10^{-2}$
Major airway (wall)	$1.9 \times 10^{-2} \pm 2.2 \times 10^{-3}$	$2.2 \times 10^{-2} \pm 3.5 \times 10^{-3}$	0.86	
Nasal cavity (wall)	$2.1 \times 10^{-2} \pm 1.8 \times 10^{-3}$	$2.2 \times 10^{-2} \pm 2.8 \times 10^{-3}$	0.95	
Bladder (wall)	$3.7 \times 10^{-1} \pm 3.2 \times 10^{-1}$	$3.1 \times 10^{-1} \pm 1.8 \times 10^{-1}$	1.19	$1.7 \times 10^{-1}$
Stomach (wall)	$1.4 \times 10^{-2} \pm 1.8 \times 10^{-3}$	$1.2 \times 10^{-2} \pm 1.2 \times 10^{-3}$	1.17	$1.2 \times 10^{-2}$
Small intestine	$1.4 \times 10^{-2} \pm 1.9 \times 10^{-3}$	$1.5 \times 10^{-2} \pm 2.1 \times 10^{-3}$	0.93	$1.3 \times 10^{-2}$
ULI (wall)	$1.4 \times 10^{-2} \pm 1.9 \times 10^{-3}$	$1.5 \times 10^{-2} \pm 2.4 \times 10^{-3}$	0.93	$1.3 \times 10^{-2}$
LLI (wall)	$1.4 \times 10^{-2} \pm 1.9 \times 10^{-3}$	$1.5 \times 10^{-2} \pm 2.2 \times 10^{-3}$	0.93	$1.6 \times 10^{-2}$
Kidney	$2.6 \times 10^{-2} \pm 5.2 \times 10^{-3}$	$2.8 \times 10^{-2} \pm 8.9 \times 10^{-3}$	0.93	$2.1 \times 10^{-2}$
Liver	$1.9 \times 10^{-2} \pm 3.7 \times 10^{-3}$	$1.8 \times 10^{-2} \pm 4.5 \times 10^{-3}$	1.06	$1.2 \times 10^{-2}$
Lung	$1.9 \times 10^{-2} \pm 4.3 \times 10^{-3}$	$1.8 \times 10^{-2} \pm 1.6 \times 10^{-3}$	1.06	$1.1 \times 10^{-2}$
Pancreas	$3.6 \times 10^{-2} \pm 1.8 \times 10^{-2}$	$2.6 \times 10^{-2} \pm 2.3 \times 10^{-2}$	1.38	$1.2 \times 10^{-2}$
Spleen	$1.6 \times 10^{-2} \pm 3.8 \times 10^{-3}$	$1.4 \times 10^{-2} \pm 2.1 \times 10^{-3}$	1.14	$1.2 \times 10^{-2}$
Testes	$1.4 \times 10^{-2} \pm 1.9 \times 10^{-3}$	$1.5 \times 10^{-2} \pm 2.2 \times 10^{-3}$	0.93	$1.5 \times 10^{-2}$
Thymus	$1.3 \times 10^{-2} \pm 1.8 \times 10^{-3}$	$1.2 \times 10^{-2} \pm 1.6 \times 10^{-3}$	1.08	
Thyroid	$1.3 \times 10^{-2} \pm 1.6 \times 10^{-3}$	$1.3 \times 10^{-2} \pm 2.4 \times 10^{-3}$	1.00	$9.7 \times 10^{-3}$
Breast	$1.0 \times 10^{-2} \pm 1.4 \times 10^{-3}$	$1.0 \times 10^{-2} \pm 1.3 \times 10^{-3}$	1.00	
Brain	$4.1 \times 10^{-2} \pm 6.1 \times 10^{-3}$	$3.7 \times 10^{-2} \pm 3.0 \times 10^{-3}$	1.11	$2.6 \times 10^{-2}$
Heart wall	$3.2 \times 10^{-2} \pm 1.1 \times 10^{-2}$	$1.7 \times 10^{-2} \pm 5.4 \times 10^{-3}$	1.88	$6.5 \times 10^{-2}$
Red marrow	$5.7 \times 10^{-3} \pm 5.5 \times 10^{-4}$	$5.6 \times 10^{-3} \pm 7.7 \times 10^{-4}$	1.02	$1.1 \times 10^{-2}$
Bone surface	$8.0 \times 10^{-3} \pm 8.4 \times 10^{-4}$	$8.0 \times 10^{-3} \pm 1.0 \times 10^{-3}$	1.00	$1.0 \times 10^{-2}$
ED (mSv MBq <sup>-1</sup> )	$3.2 \times 10^{-2} \pm 1.7 \times 10^{-2}$	$2.9 \times 10^{-2} \pm 9.2 \times 10^{-3}$	1.10	$2.7 \times 10^{-2}$

† Present study with initial guess from PET.

ULI = Upper large intestine; LLI = Lower large intestine, ED = Effective dose.

#### 4.2. Absorbed doses in target organs

The mean absorbed doses for six individuals (table 2) obtained from the TLD method with an initial guess from PET (B) and whole body PET show good agreement with each other. The TLD results agree with the PET results to within 20%, except for the pancreas and heart wall, similarly as in section 4.1. Our results are also compared with the reported values of ICRP 53 (ICRP 1987). Our TLD results are higher by a factor of 2.2 for bladder, 1.6 for liver, 1.7 for lung, 3 for pancreas and 1.6 times for brain, but *lower* (0.5) for heart wall than the ICRP 53 (ICRP 1987) data. For other organs, both results agree to within about 30%. The reported values of ICRP 53 are summarized from the reported values of Gallagher *et al* (1977), Jones *et al* (1982) and Phelps *et al* (1978), where in the study of Jones *et al* all the data except brain and bladder are extrapolated from animal data. These mostly underestimated results in ICRP 53 may be partly attributed to the metabolic difference between humans and animals.

#### 5. Conclusions

This study gave the cumulated activities of nine source organs and absorbed doses to the 21 target organs. A significant correlation (correlation coefficient,  $r > 0.98$ , level of confidence,  $p < 0.001$ ) was found between the cumulated activities obtained by the TLD method and whole body PET. This TLD method is very simple and cost-effective and can play an important role in calculating the organ biodistribution of cumulated activities, regardless of subject or

radiopharmaceutical, especially for the PET study of child patients for which the repeated whole body emission scans become an intolerable burden.

Here in this study, we investigated the usefulness of the TLD method to internal dosimetry on intakes of radiopharmaceuticals in the PET procedure. The TLD method is applicable to internal dosimetry in a SPECT study, and the TLD must be attached to a human body for a longer time than in the PET study because of the longer half-lives of radionuclides used in SPECT. This method may also be useful for targeted radioimmunotherapy using monoclonal antibodies, which needs further investigation.

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