# Estimated Radiation Dose to the Newborn in FDG-PET Studies

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The aim of this study was to estimate the radiation dose due to intravenous injection of 2-[$^{18}$F]fluoro-2-deoxy-D-glucose (FDG) for infants studied with PET. **Methods:** The radioactivity concentration in the brain and bladder content was measured with PET to determine the cumulated activity in these organs in 21 infant FDG studies. The individual organ masses were estimated according to the whole-body and brain masses, and they were used to calculate the absorbed dose per unit cumulated activity (S values). For organs other than brain and bladder, the cumulated activity was defined from adult studies. For each individual patient, the absorbed dose to the brain, bladder wall and selected organs were calculated. An estimation of the effective dose was determined. **Results:** Whole-body distribution of FDG in the infants differed from adults: a greater proportion of the injected activity accumulated into the brain (9% versus 7%) and less was excreted to urine (7% versus 20% respectively). The measured cumulated activity in the brain was 0.25 MBq · h/MBq and in the bladder content 0.04 MBq · h/MBq with a large individual variation in latter. The calculated absorbed dose was 0.24 mGy/MBq to the brain and 1.03 mGy/MBq to the bladder wall. The estimated effective dose was 0.43 mSv/MBq. **Conclusion:** The dose to the bladder wall was lower in infants as compared to adults with ordinary amounts of injected activity. The greater amount of activity remaining in the body may increase the dose to other organs. The effective dose was lower compared to adults and conventional nuclear medicine studies of infants. PET can be a valuable tool in pediatric nuclear medicine because of good resolution images, sensitive radiation measurement and a variety of tracers labeled with short-lived isotopes.

**Key Words:** PET; dosimetry; neonates; fluorine-18-FDG

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For adult humans, the absorbed dose calculations for FDG have been published by ICRP and others (1-4). The calculation of the mean absorbed dose to a target organ is based on the measured cumulated activity in the source organ and tabulated S values according to the MIRD model. The S values are defined as the absorbed dose per unit of cumulated activity for a particular radionuclide, source-to-target geometry and organ mass. These values are available for an average size adult man (body weight 70 kg). The organ receiving the highest absorbed dose is the bladder wall in these adult studies. For this reason, the cumulated activity, especially in bladder content and the absorbed dose of the bladder wall, has been investigated and a dynamic model for calculations was created (5).

So far, few FDG examinations have been made for newborn infants, so the distribution of the tracer in the whole body, and the absorbed dose caused by the tracer is not known. Our aims in this study were:

1. To estimate the average absorbed dose to the brain and bladder wall in a FDG examination of an infant and to approximate tracer biodistribution in the infant.
2. To compare the doses and the patient size to find out if the examination should be done after the patient has exceeded a certain body weight.
3. To compare the estimated absorbed doses due to intravenous injection of FDG with some other isotope examinations and the absorbed doses to adult patients.

We determined the absorbed doses to the brain and bladder wall by measuring the individual cumulated activities in brain and bladder content, calculating the masses of these organs and the individual S values. In addition, the absorbed doses to other organs and the rest of the body were estimated for the infant from measured cumulated activities of adult studies (3), calculated individual organ masses and S values. Because it is not ethical to study healthy children for dosimetric purposes alone, this study utilizes data from which we measured cerebral glucose utilization in infants with suspected permanent brain damage. The tracer activity measurements of brain and bladder did not interfere with this diagnostic procedure.

## MATERIALS AND METHODS

### Patients

Newborn infants (n = 21), postconceptional age 35–60 wk, with serious neurological symptoms were studied; these patients were previously described (6-8). The studies were accepted by the Ethical Committee of the Turku University Central Hospital. The body masses of the patients were 3584 ± 1289 g (mean ± s.d.) at the time of the PET study. The babies were fed before the study and were not dehydrated. No sedation was used.

### PET Imaging

The FDG was synthetized using the method of Hamacher et al. (9). Its radiochemical purity was better than 99% (10). The injected activity was 3.4 ± 0.6 MBq/kg. The PET examinations were made with ECAT 931/08-12 whole-body scanner (Siemens/CTI Inc., Knoxville, TN). A special crib was used to position and move the patient easily (6). The scanner provides images of 15 continuous transaxial slices with a resolution of 6.5 mm FWHM in plane and 6.7 mm axially (11). The axial field of view is 10.8 cm. The scanner was calibrated against a well counter with a known homogenic water solution of $^{68}$Ge in a cylinder phantom. The variation in the calibration factor was <5% over all planes and over the period during which the data were collected (March 1990–May 1993). All the images were reconstructed in a 256 × 256 matrix with a Hanning filter (0.5 cutoff frequence) and corrected for deadtime, decay and calculated photon attenuation. By avoiding the transmission scan, we could shorten the duration of the PET examination and decrease the radiation dose to the
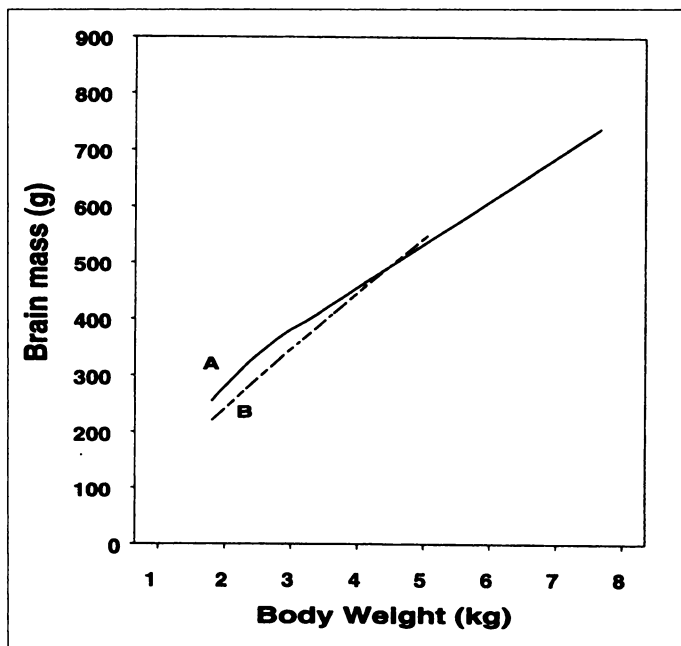
**FIGURE 1.** Correlation of infant brain mass to whole-body mass for (A) this study and (B) the same relation according to Reference Man. Curve A was defined with Equations A1 and A2 according to the Appendix and was calculated for the body masses of the patients in this study.

patient. The abdominal scanning time was about 10–30 min (n = 8) or about 20–40 min (n = 13) after the injection. An additional measurement lasting 4 min (2 × 120 sec) was done at about 64–84 min after injection for 11 patients. The frames used in the dynamic study of the abdominal region were 10 × 120 sec or 10 × 90 sec. Cerebral imaging was done after the abdominal region and was started at about 30–40 min after injection and lasted for 20 min (with 10 × 120 sec frames).

## Calculated Organ Masses

The infants' weights varied from 1800 g to 7680 g and their organ sizes varied according to body size and individual development. Because the brain is a prominent body part in infants (about 10% of the body weight compared to 2%–3% in adults) a correlation between the body mass and the size or mass of the brain was determined. The polynomial function of 3rd degree was found to best describe the dependency of brain mass to body mass up to the weight of 3200 g (Appendix 1). Over that weight, the growth of the brain is more linear and can be approximated with a straight line. The slope of the line is delivered from the growth of the head circumference (Appendix 1). In Figure 1, the calculated brain masses of each individual patient are plotted against the measured body mass; this relationship is also shown according to Reference Man (12).

Other organ masses were estimated to be linearly proportional to organ sizes of a mathematical model of an average size newborn when the mass of the brain was first subtracted, according to the formula:

$$m_{organ} = \frac{m_{organavg}}{(m_{bodyavg} - m_{brainavg})} (m_{body} - m_{brain}), \qquad \text{Eq. 1}$$

where $m_{organ}$, $m_{brain}$ and $m_{body}$ correspond to the individual patient's organ, brain and whole-body mass. The respective masses for an average size newborn are marked with subscript avg [for a whole-body mass of 3400 g and a brain mass of 374 g (16)].

Patient ages, body masses, calculated brain masses and the injected activities are shown in Table 1.

## Cumulated Brain Activity

A part of the brain time-activity curve could be measured for all 21 infants. The average $^{18}F$ concentration (kBq/ml) of the whole brain was determined from regions of interest (ROIs) placed on three to four adjacent transaxial slices visualizing the thalami. As in adult dosimetric studies (1), the decay-corrected time-activity curve of the brain for FDG was fitted to the formula:

$$C_{brain}(t) = C_{max}(1 - e^{-kt}), \qquad \text{Eq. 2}$$

where $C_{max}$ is the activity in the brain at 33 min from injection and k is 5.2/hr. The cumulated activity was calculated as an integral of the function, excluding the decay correction, from 0 to $\infty$ and multiplied by the calculated brain mass. As an example, a time-activity curve of a 60-min brain scan (5-min frames) with the corresponding fit is shown in Figure 2.

## Bladder Uptake of FDG

*Urine Analysis.* Cumulated activity in the adult bladder has been estimated by measuring the activity in the urine and the volume voided after the PET study (1,5). A newborn infant has no control over voiding. For 18 of the 21 examinations, the urine activity samples were collected using a urine collection bag which was emptied with a syringe each time it contained urine. Half of the patients voided more than once during the study (in about 85 min from injection). The volume and the concentration of $^{18}F$ (kBq/ml) were measured. The total activity voided out of the body was calculated by multiplying the activity concentration values (decay-corrected to the injection time) by the measured urine volumes and summing together the individual sample measurements for each patient.

*Activity Concentration in the Bladder Measured with PET.* One or two parts of the time-activity curve of the bladder could be measured with PET. The average $^{18}F$ concentration (kBq/ml) in the bladder was determined from ROIs placed on areas of highest accumulation of the tracer on one to three adjacent transaxial slices of the abdominal PET images visualizing the bladder. The time-activity curve was fitted to three exponential functions with the least-squares fitting method. The integral of the function was calculated and multiplied by the bladder volume to estimate the cumulated activity in the bladder content. The bladder volume was estimated from PET images or a constant value of 20 ml (14) was used, depending on which one of these two gave a higher estimate for the cumulated activity in the bladder content.

## Cumulated Activity of Other Organs

The cumulated activity values to organs other than the brain and bladder and for the unit injected activity (MBq) were approximated from dosimetric measurements published for adults (3). The cumulated activity in the remainder of the body (excluding the brain and the bladder content) of an infant per unit injected activity (MBq) was approximated to be the same as the cumulated activity in the whole body of an adult (2.13 MBqh/MBq) (3). To get the upper estimate for the radiation dose in individual infants, we were not assuming uniform tracer distribution, but rather, estimated the cumulated activities according to organ size. Because the relative organ sizes in the newborn infant are different from the relative organ sizes of an adult, the cumulated activities are multiplied with a correction factor:

$$c = \frac{m_{body} - m_{brain}}{m_{organ}} \times \frac{m_{adultorgan}}{m_{adultbody} - m_{adultbrain}}, \qquad \text{Eq. 3}$$

in which $m_{body}$ and $m_{adultbody}$ are the whole-body masses of an infant and an adult and $m_{brain}$, $m_{organ}$, $m_{adultorgan}$ and $m_{adultbrain}$ the corresponding organ masses. The individual organ masses of an infant were calculated from the organ masses of an average size newborn (Eq. 1). The cumulated activity in the rest of the body was

## TABLE 1
### Patient Data and Radioactivity Measurements

| Patient no. | Age* (wk) | Body mass† (g) | Brain mass (g) | Injected activity (MBq) | Injected activity per unit mass (MBq/kg) | % Activity in Brain | Cumulated activity in brain (MBqh/MBq) | % of Activity in Bladder | Cumulated activity in bladder (MBqh/MBq) | Urine activity‡ (kBq) | Sample volume§ (ml) | No. of urine samples | % Activity in urine |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 35 | 1800 | 254 | 5.70 | 3.17 | 2.5 | 0.061 | 2.5 | 0.001 | 220 | 36 | 1 | 3.9 |
| 2 | 35 | 1900 | 267 | 9.21 | 4.85 | 8.8 | 0.215 | 15.3 | 0.087 | 2740 | 7 | 2 | 29.8 |
| 3 | 36 | 2320 | 317 | 7.40 | 3.19 | 7.9 | 0.194 | 7.1 | 0.012 | 180 | 44 | 3 | 2.4 |
| 4 | 35 | 2340 | 319 | 7.18 | 3.07 | 9.7 | 0.237 | 8.0 | 0.017 | 140 | 10 | 3 | 1.9 |
| 5 | 36 | 2350 | 320 | 7.92 | 3.37 | 7.8 | 0.190 | 3.0 | 0.001 | 290 | 48 | 2 | 3.7 |
| 6 | 40 | 2400 | 326 | 11.02 | 4.59 | 15.0 | 0.366 | 2.7 | 0.015 | 1000 | 16 | 1 | 9.1 |
| 7 | 36 | 2800 | 364 | 12.36 | 4.41 | 7.3 | 0.178 | 3.7 | 0.011 | 1150 | 25 | 2 | 9.3 |
| 8 | 33 | 2985 | 379 | 9.73 | 3.26 | 10.3 | 0.250 | 3.4 | 0.019 | — | — | — | — |
| 9 | 35 | 3170 | 392 | 10.12 | 3.16 | 8.3 | 0.205 | 3.2 | 0.005 | — | — | — | — |
| 10 | 41 | 3200 | 394 | 10.47 | 3.27 | 12.5 | 0.306 | 4.5 | 0.008 | — | — | — | — |
| 11 | 41 | 3365 | 403 | 11.03 | 3.28 | 13.3 | 0.326 | 3.0 | 0.003 | — | — | — | — |
| 12 | 42 | 3470 | 407 | 10.43 | 3.01 | 9.1 | 0.226 | 3.1 | 0.001 | 1960 | 9 | 1 | 18.8 |
| 13 | 45 | 3640 | 413 | 13.50 | 3.71 | 8.1 | 0.203 | 1.2 | 0.001 | 40 | 44 | 1 | 0.3 |
| 14 | 41 | 3680 | 414 | 15.47 | 4.20 | 6.5 | 0.163 | 2.7 | 0.013 | — | — | — | — |
| 15 | 43 | 3780 | 419 | 9.70 | 2.57 | 7.0 | 0.179 | 2.8 | 0.003 | 730 | 48 | 3 | 7.5 |
| 16 | 35 | 3890 | 421 | 12.29 | 3.16 | 7.7 | 0.200 | 2.3 | 0.008 | 590 | 23 | 1 | 4.8 |
| 17 | 37 | 4270 | 430 | 12.87 | 3.02 | 9.0 | 0.243 | 3.4 | 0.006 | 20 | 2 | 2 | 0.2 |
| 18 | 45 | 4810 | 442 | 11.95 | 2.49 | 5.9 | 0.168 | 1.9 | 0.009 | 290 | 72 | 2 | 2.5 |
| 19 | 40 | 5100 | 449 | 18.98 | 3.72 | 8.3 | 0.244 | 6.7 | 0.569 | 2880 | 30 | 1 | 15.2 |
| 20 | 49 | 5350 | 454 | 22.24 | 4.16 | 6.8 | 0.204 | 2.1 | 0.009 | 10 | 17 | 1 | 0.1 |
| 21 | 60 | 7680 | 508 | 19.17 | 2.50 | 13.4 | 0.476 | 1.1 | 0.002 | 960 | 61 | 2 | 5.0 |
| avg. | 40 | 3584 | 389 | 11.86 | 3.40 | 8.8 | 0.215 | 4.0 | 0.038 | 888 | 31 | 1.8 | 7.2 |
| s.d. | 6 | 1289 | 61 | 4.07 | 0.63 | 2.8 | 0.068 | 3.1 | 0.120 | 1058 | 20 | | 7.8 |

*Corrected postconceptional age.
†Calculated according to formulas in Equations A1 and A2 and in Figure 1.
‡Decay-corrected sum of the individual sample activities.
§Sum of the volumes of individual urine samples.

calculated by subtracting the sum of the measured (brain and bladder) and calculated cumulated activities from the cumulated activity of the total body (15).

### Absorbed Dose Calculations

The absorbed dose per unit cumulated activity can be calculated according to the MIRD formula:

$$D_t = \sum_s \tilde{A}_s S(r_t \leftarrow r_s) + \tilde{A}_{rb} S(r_t \leftarrow RB), \quad \text{Eq. 4}$$

in which subscript t and s indicate the target and source organs, respectively. $\tilde{A}_s$ and $\tilde{A}_{rb}$ are the cumulated activities in a source organ and in the rest of the body. The S values describe the absorbed dose per unit cumulated activity and RB is the rest of the body. They have been tabulated for adults (16). For newborn infants, they can be calculated for each radiation type i and target organ mass $m_t$ according to the formula (17):

$$S(r_t \leftarrow r_s) = \sum_i \Delta_i \Phi_i(r_t \leftarrow r_s)/m_t. \quad \text{Eq. 5}$$

The specific absorbed fractions of energy $\Phi(r_t \leftarrow r_s)$ were tabulated for an average size newborn infant (18). Because the emitted energy $\Delta_i$ for both the positrons and photons is known for $^{18}$F (19), the S values can be calculated both for penetrating $(S_p)$ and nonpenetrating $(S_{np})$ radiation fractions. This was done for each organ in all of the patients. The S value used in the calculation of absorbed dose is the sum of these fractions according to Bellina et al. (20).

$$S(r_t \leftarrow r_s) = S_p(r_t \leftarrow r_s) + S_{np}(r_t \leftarrow r_s). \quad \text{Eq. 6}$$

### Effective Dose

The effective dose was calculated according to

$$E = \sum_t w_t D_t, \quad \text{Eq. 7}$$

where $w_t$ is the tissue or organ weighting factor and $D_t$ is the absorbed dose in the target organ (21). The tissue weighting factors for adults were used in the calculations and the radiation quality factor was taken as a unit (22).

## RESULTS

### Measured Time-Activity Bladder Curve

Six of the 21 bladder time-activity curves are shown in Figure 3. The curves were plotted without decay-correction and no smoothing was used. As can be seen from the curves, the babies had been voiding during the study and most of the curves showed decreasing activity concentration.

### Measured Activity in Urine Samples

The measured total activity in the urine samples is shown in Table 1. The average activity was 0.89 MBq, which ranged from 0.02 MBq to 2.88 MBq. This is 7.2% of the originally injected activity (with a range from 0.1% to 29.8%). The average volume of the individual samples was 18 ± 12 ml with a range from 1 to 44 ml per sample.

### Cumulated Activities in Newborn Infants after FDG Injection

The mean percentage uptake of FDG in the brain was 8.8% ± 2.8% for all patients. In the PET examination, the average maximum amount of the tracer in bladder was 4.0% of the
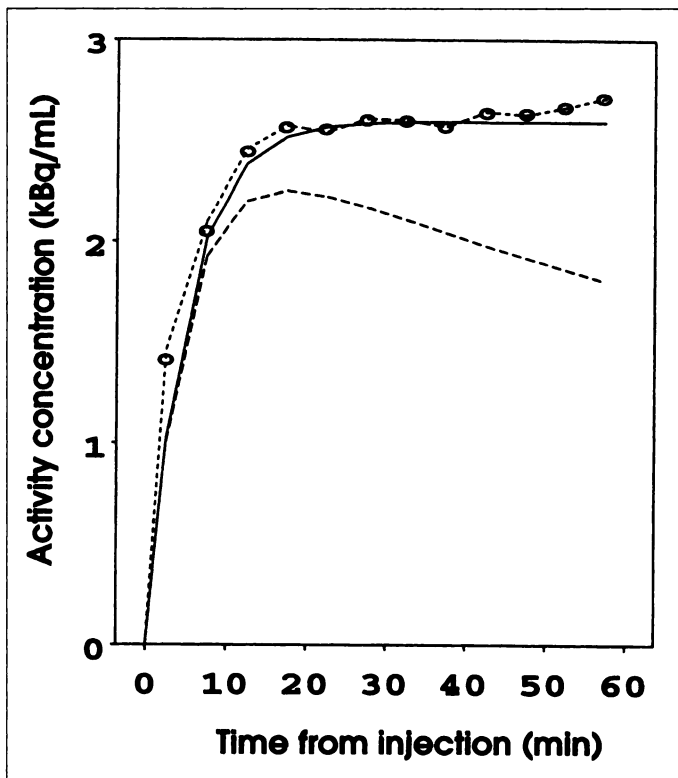
**FIGURE 2.** Time-activity curve of the brain activity of one infant (weight 3730 g, age 3 wk, injected dose 12.5 MBq) who was not included in the dosimetry study. Circles represent measured activity concentrations and the solid line is the result of the fitting. Dotted line responds to the result not corrected for decay.

injected activity (s.d., 3.1%). The calculated cumulated activities and the percentage uptake values of brain and bladder content for each individual patient are shown in Table 1. The table was organized according to infant weight so that the effect of body size (and also age) can be followed. On average, the cumulated activity per unit injected activity was in the brain 0.22 ± 0.07 MBq · h and in the bladder content 0.04 MBq · h with a s.d. of 0.12 MBq · h.

### Absorbed and Effective Doses

The absorbed doses to the patients were calculated for selected organs and the rest of the body according to Equations 4 and 6. The results are shown in Table 2. The average absorbed dose to the brain was 0.24 ± 0.05 mGy/MBq and to the bladder wall 1.03 mGy/MBq with a s.d. of 2.1 mGy/MBq, which were calculated from the measured values. All the other values are based on cumulated activities measured in adults (3) and corrected according to Equation 3. The effective dose equivalent was 0.43 ± 0.15 mSv/MBq.

### DISCUSSION

#### Comparison of FDG Distribution in Infants and Adults

The percent uptake of injected FDG activity in the infant brain was 8.8%, which is slightly higher than that reported in adults (6.9%) (3). This difference may partly be due to the greater relative brain mass (10%) of infants compared to that of adults (2%–3%). Tracer distribution in the brain is also different. FDG accumulation is lower to the gray matter areas and higher to the thalamus compared to adults (6). Thus, we defined the cumulated activity of the whole brain with the transaxial slices in which the thalamus was visible.

Average tracer activity in the bladder was 4.0% measured with PET and 7.2% measured from the urine samples excreted during the study. These values are of the same order, although

some of the patients (Patients 2, 12 and 19 for example) voided significant activity during the early phase of the examination. Individual variation in urine activity is large in both measurements, a phenomenon which we also observed in adults (1). This may be due to the difference in FDG uptake in the whole body and FDG excretion through the kidneys and bladder. Both results clearly differ from the relative amount of activity, 20% (1,4), that adults excrete after FDG injection.

A comparison of FDG distribution in the whole body of infants and adults is shown in Figure 4. To compensate for individual differences in voiding frequency, the relative activity in the bladder content of the infants was chosen to be the higher of the two measured urine activities (either from the PET measurement or urine samples of each infant). On average, the activity remaining in the body is higher in infants (84%) than in adults (73%).

### Absorbed Doses

The absorbed dose per unit of administrated activity to the infant brain (0.24 mGy/MBq) was higher than that to the adult brain (0.026 mGy/MBq) (22). The absorbed dose to the bladder wall (1.03 mGy/MBq) per unit of administrated activity was also higher than in adults (0.17 mGy/MBq) (22). The absorbed doses with normal injected amounts of the tracer were 2.85 mGy/11.9 MBq for the brain and 12.22 mGy/11.9 MBq for the bladder wall in infants, which are lower than corresponding values for adults (9.62 mGy/370 MBq for brain and 62.90 mGy/370 MBq for bladder wall). The measured cumulated activities in the bladder content and absorbed doses to the bladder wall vary in a wide range. There was no correlation between the measured absorbed doses to the brain or bladder wall of an infant and total body size. The absorbed doses to other organs were calculated from the cumulated activities measured for adults and corrected for the relative organ sizes of infants. The cumulated activities for organs such as the heart, liver and pancreas may be higher than approximated from the
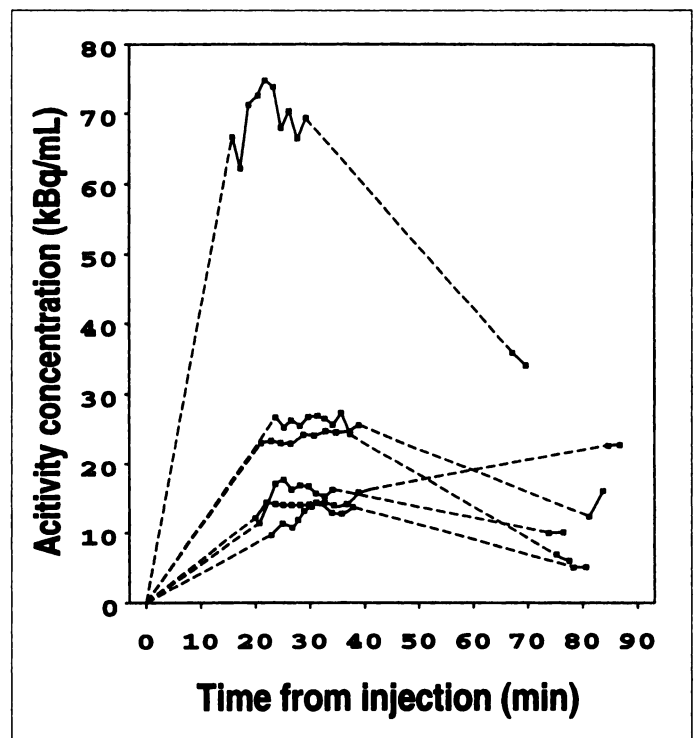


**FIGURE 3.** Six time-activity curves of bladder content measured in the infants after FDG injection. Solid line and squares represent measurements and the dotted line is the estimated time course of the time-activity curve between the measurements.

TABLE 2
### Estimated Absorbed Dose (mGy/MBq) to Selected Organs

| Organ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | Avg. | s.d. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adrenals | 0.32 | 0.28 | 0.26 | 0.25 | 0.26 | 0.23 | 0.23 | 0.21 | 0.21 | 0.20 | 0.19 | 0.20 | 0.20 | 0.20 | 0.19 | 0.19 | 0.10 | 0.17 | 0.13 | 0.16 | 0.13 | 0.21 | 0.05 |
| Bladder wall* | 0.35 | 4.30 | 0.69 | 0.89 | 0.29 | 0.24 | 0.55 | 0.77 | 0.34 | 0.41 | 0.26 | 0.22 | 0.20 | 0.50 | 0.25 | 0.35 | 0.29 | 0.33 | 9.90 | 0.30 | 0.13 | 1.03 | 2.10 |
| Brain* | 0.27 | 0.34 | 0.28 | 0.30 | 0.28 | 0.37 | 0.24 | 0.26 | 0.23 | 0.28 | 0.28 | 0.23 | 0.21 | 0.19 | 0.20 | 0.20 | 0.21 | 0.17 | 0.17 | 0.17 | 0.23 | 0.24 | 0.05 |
| Stomach wall | 0.32 | 0.28 | 0.26 | 0.25 | 0.25 | 0.23 | 0.23 | 0.21 | 0.21 | 0.20 | 0.19 | 0.20 | 0.19 | 0.19 | 0.19 | 0.19 | 0.17 | 0.17 | 0.13 | 0.16 | 0.12 | 0.21 | 0.05 |
| Small intestine wall | 0.32 | 0.29 | 0.26 | 0.25 | 0.26 | 0.23 | 0.23 | 0.21 | 0.21 | 0.20 | 0.19 | 0.20 | 0.19 | 0.20 | 0.19 | 0.19 | 0.18 | 0.17 | 0.16 | 0.16 | 0.12 | 0.21 | 0.05 |
| ULI wall | 0.32 | 0.28 | 0.26 | 0.25 | 0.26 | 0.23 | 0.23 | 0.21 | 0.21 | 0.20 | 0.19 | 0.20 | 0.19 | 0.20 | 0.19 | 0.19 | 0.18 | 0.17 | 0.15 | 0.16 | 0.12 | 0.21 | 0.05 |
| LLI wall | 0.32 | 0.28 | 0.25 | 0.24 | 0.25 | 0.23 | 0.22 | 0.21 | 0.20 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.18 | 0.17 | 0.16 | 0.18 | 0.15 | 0.12 | 0.20 | 0.04 |
| Heart wall | 1.50 | 1.40 | 1.20 | 1.10 | 1.10 | 1.10 | 0.98 | 0.92 | 0.88 | 0.86 | 0.83 | 0.81 | 0.78 | 0.78 | 0.76 | 0.74 | 0.68 | 0.63 | 0.56 | 0.58 | 0.43 | 0.89 | 0.26 |
| Kidneys | 0.83 | 0.76 | 0.65 | 0.64 | 0.65 | 0.62 | 0.56 | 0.52 | 0.50 | 0.49 | 0.47 | 0.47 | 0.45 | 0.45 | 0.44 | 0.43 | 0.40 | 0.37 | 0.32 | 0.34 | 0.26 | 0.51 | 0.14 |
| Liver | 0.66 | 0.60 | 0.52 | 0.51 | 0.52 | 0.49 | 0.45 | 0.42 | 0.41 | 0.40 | 0.38 | 0.38 | 0.37 | 0.37 | 0.36 | 0.35 | 0.33 | 0.30 | 0.27 | 0.28 | 0.22 | 0.41 | 0.11 |
| Lungs | 0.31 | 0.27 | 0.25 | 0.24 | 0.25 | 0.22 | 0.22 | 0.20 | 0.20 | 0.19 | 0.18 | 0.19 | 0.18 | 0.18 | 0.18 | 0.18 | 0.16 | 0.16 | 0.12 | 0.15 | 0.11 | 0.20 | 0.05 |
| Pancreas | 1.30 | 1.20 | 1.00 | 1.00 | 1.00 | 0.98 | 0.87 | 0.81 | 0.78 | 0.76 | 0.73 | 0.72 | 0.69 | 0.69 | 0.67 | 0.65 | 0.60 | 0.55 | 0.50 | 0.51 | 0.37 | 0.78 | 0.20 |
| Red marrow | 0.49 | 0.44 | 0.38 | 0.37 | 0.38 | 0.36 | 0.32 | 0.30 | 0.29 | 0.28 | 0.27 | 0.27 | 0.26 | 0.26 | 0.26 | 0.25 | 0.23 | 0.21 | 0.18 | 0.20 | 0.15 | 0.29 | 0.08 |
| Spleen | 0.35 | 0.31 | 0.27 | 0.27 | 0.27 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.20 | 0.21 | 0.20 | 0.21 | 0.20 | 0.20 | 0.18 | 0.18 | 0.14 | 0.17 | 0.13 | 0.22 | 0.05 |
| Testes | 0.50 | — | 0.39 | — | — | 0.36 | 0.33 | — | 0.30 | — | — | — | 0.27 | 0.27 | — | 0.25 | 0.23 | 0.22 | 0.26 | 0.20 | 0.14 | 0.29 | 0.09 |
| Thyroid | 0.31 | 0.27 | 0.24 | 0.24 | 0.24 | 0.22 | 0.22 | 0.20 | 0.20 | 0.19 | 0.18 | 0.19 | 0.18 | 0.18 | 0.18 | 0.18 | 0.17 | 0.16 | 0.11 | 0.15 | 0.12 | 0.20 | 0.05 |
| Remainder of the body | 0.30 | 0.26 | 0.23 | 0.23 | 0.23 | 0.21 | 0.20 | 0.19 | 0.19 | 0.18 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.16 | 0.15 | 0.15 | 0.12 | 0.14 | 0.11 | 0.19 | 0.04 |

*Calculated from measured cumulated activities.

dosimetric measurements of adults because a greater proportion of the injected activity remained in the body of an infant compared to an adult. The calculated absorbed doses to other organs than the brain and the bladder wall of an infant should be considered as only rough estimates until there are real measurements of cumulated activities for these organs.

The brain mass was calculated differently in this study than in Reference Man (Appendix 1). The difference in the brain masses calculated with the two methods is about 30% in the smallest infants (weight from 1800 to 3200 g) (Fig. 1). Because the cumulated activity is linearly proportional to the brain mass, our own calculation produces higher cumulated activities to the brain of the infants than with the brain mass calculated according to Reference Man. This also gives a higher absorbed dose to the brain, although the difference is only about 6% (calculated for the six smallest infants).

To calculate the effective doses from the estimated absorbed doses, one would need to know weighting factors to correct the values for various biological factors of different radiation types (in this case for positrons and photons) and organ radiation sensitivity. Stabin et al. (24) reported that these factors are in many ways unknown. We think that this is especially the case for newborn infants. A rough estimate of the effective dose was calculated only to help the comparison. The calculated effective dose in an infant study was 5.12 mSv/11.9 MBq, which was lower than that published in adult studies 9.99 mSv/370 MBq (4) with the usual injected activities.

### Error Analysis

In the PET measurement of tracer activity in the bladder, the small size of the bladder affects the measured values because of the limited resolution of the PET scanner (partial volume effect). This leads to underestimation of the absorbed dose to the bladder wall. In addition, the estimation of bladder size from the PET image is rather rough. For this reason, the estimation of constant size was included. Underestimation of activity concentration in the bladder and brain because of mathematical rather than measured attenuation correction leads to underestimation of the cumulated activity and absorbed dose (7% in the bladder

and 3% in the brain) according to a phantom study (unpublished data).

In the measurement of the activity concentration in urine samples, the possible errors are: leakage of the urine sample bag (not noticed in any of the patients) or errors in the timing and decay correction of the urine measurement (missed voiding
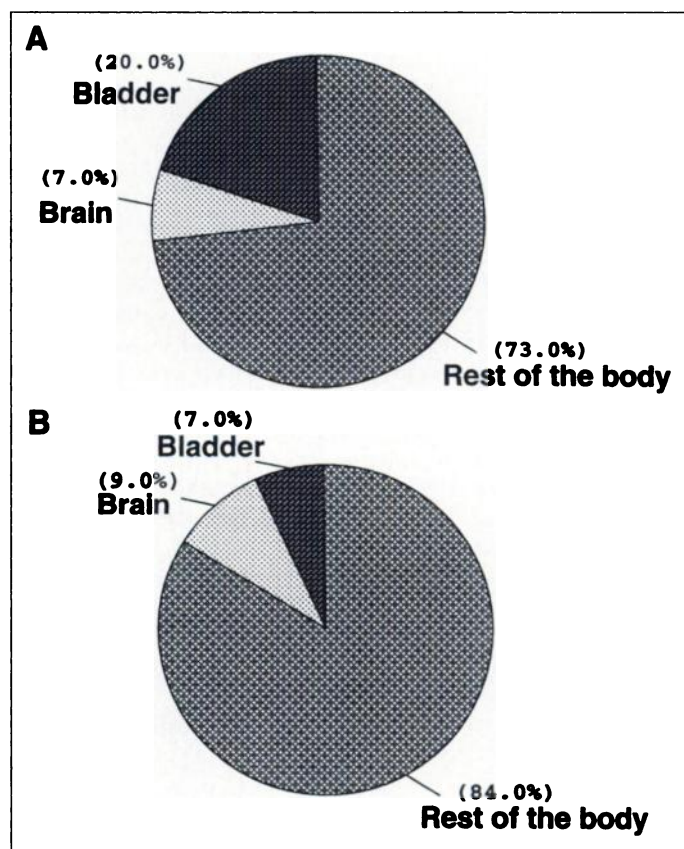


FIGURE 4. Percentage distribution of FDG in the body measured for adults (A) and infants (B).

time). Both errors lead to underestimation of the relative distribution of FDG in the bladder.

The geometry of an infant changes during growth and development. The specific fractions of energy ($\Phi_i$ in Eq. 4) were calculated according to a mathematical model of an average size newborn of 3400 g (*16*). This may cause an underestimation of the individual absorbed doses to the smallest infants because the distances between source and target organs are smaller than in an average size newborn. On the contrary, there might be an overestimation of absorbed doses in the older infants. Because this study mainly concentrates on estimation of the absorbed dose to the brain and bladder, in which the organ absorbed dose is mostly due to the activity taken in the organ itself, the error in the geometry has minimal influence on the results.

We assumed that the cumulated activities in organs other than the brain and bladder can be calculated from the cumulated activities of adult organs with the relation to individual organ mass. The metabolic rate of an organ is shown to correlate to its size during late gestation and early infancy (*25*). As a glucose analog, FDG is assumed to have a similar metabolism. The relative sizes of individual organs compared to the whole body are different in infants than in adults. Particularly, the relative amount of muscle tissue is smaller in infants than in adults. On the other hand, organs such as the heart and liver are relatively larger. Because the activity has to remain somewhere in the body if it is not excreted, we assumed that FDG uptake in an organ correlates to its relative, not absolute, mass compared to the whole body (excluding the brain). When we simultaneously approximated the cumulated activity in the total body without the brain and bladder to be the same as that in the whole body of an adult, our calculated effective dose represents the upper estimate of the radiation dose for an infant. Because tracer excretion differs so much from one individual to another, we may not be able to determine an individual radiation dose from the average radiation dose. Yet, the estimation of the maximum dose to an infant for a given tracer dose is useful in planning examinations and in estimating the risk benefit ratio for patients.

## Dose Comparisons to Other Isotope Studies

Technetium-99m-DTPA is routinely used to study pediatric patients, including infants, with renal diseases. The injected activity is 37 MBq (for a newborn weighing 3400 g). Kereiakes et al. (*25*) showed that the critical organ for this tracer is the bladder wall, which receives an absorbed dose of 1.35 mGy/1 MBq (5.0 mrad/1 $\mu$Ci) and with the ordinary injected activity 50 mGy/37 MBq. This is more than four times the dose to the bladder wall from an FDG study, although the dose per unit injected activity is of the same order. This is mainly due to the higher amount of activity administered to the patient in $^{99m}$Tc-DTPA studies. In addition, the longer tracer half-life (6 hr for $^{99m}$Tc and 109.8 min for $^{18}$F) adds the dose.

Compared to other isotope studies (*26*), the effective dose from FDG proves to be higher than $^{99m}$Tc-MDP per unit injected activity in the skeleton. The smaller amount of activity needed and the shorter tracer half-life results in a lower effective dose estimate in an FDG-PET study compared to $^{99m}$Tc-MDP skeletal study: 5.12 mSv/11.9 MBq and 5.72 mSv/52 MBq, respectively.

## CONCLUSION

FDG-PET studies in newborn infants resulted in a radiation dose lower than that in adult studies with FDG and other isotope studies in infants, although the calculation was based on the

upper estimates throughout the study. No correlation was found between the absorbed dose to the brain and bladder wall and patient body weight. The greater amount of activity remaining in an infant's body, compared to an adult, may add to the absorbed dose to organs such as the heart, liver and pancreas.

## APPENDIX

### Calculation of the Brain Mass

In infants, brain mass can be correlated to whole-body mass (weight range 500–3200 g) with the formula:

$$m_b = -4.47 \cdot 10^{-9} \cdot m^3 + 8.65 \cdot 10^{-6} \cdot m^2 + 0.14 \cdot m - 3.35,$$

<div align="right">Eq. A1</div>

where $m_b$ is the brain mass and m the whole-body mass. This curve was defined by fitting a polynomial function with a least-squares fitting method to the anatomical information from Wigglesworth (*14*). After the early phase of life, an infant's brain growth is more linear; we estimated the brain mass with the formula:

$$m_b = 0.077 \cdot m + 147.1.$$ 

<div align="right">Eq. A2</div>

The slope of the line is calculated from the head volume estimated with the help of tabulated head circumference values against the whole-body weight (*27*) and the line is adjusted to go through the point in Equation A1 at which the body weight is 3200 g.

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## FIRST IMPRESSIONS:
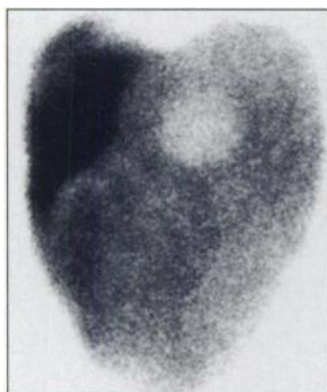


**Figure 1.**



**Figure 2.**

### PURPOSE
A 35-yr-old man with Gaucher's disease was referred for baseline evaluation of bone marrow distribution and liver and spleen size prior to starting enzyme replacement therapy. An LAO view of the liver and spleen (Fig. 1) shows a markedly enlarged spleen occupying most of the abdomen and gives the false impression of diffuse peritoneal activity. The spleen contains several photopenic areas, most likely related to infiltration by Gaucher cells; the liver is also enlarged. The whole-body images (Fig. 2) show peripheral expansion of bone marrow in both femora and proximal tibiae.

### TRACER
Technetium-99m-sulfur colloid

### ROUTE OF ADMINISTRATION
Intravenous

### TIME AFTER INJECTION
45 minutes

### INSTRUMENTATION
Vision T22, Summit Nuclear, Twinsburg, OH

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