

movement could be particularly problematic when scans are carried out for a relatively long period.^{1,2} Problems also arise when studies are carried out during physiologically stressed conditions, e.g., a cycling exercise in the PET scanner.³ Errors can be attributed not only to the mismatch between the emission and the transmission data but also to the patient motion during each of the emission and/or the transmission scans.³

^{15}O -water PET studies provide quantitative information regarding myocardial blood flow (MBF) and coronary flow reserve (CFR), as well as a marker of myocardial viability, termed the water perfusable tissue fraction (PTF) or water perfusable tissue index (PTI).⁴⁻¹² The distribution of radioactivity during ^{15}O -water PET varies over time; this poses challenges for software-based correction of patient movement. Naum et al proposed to correct for such motion based on the rigid body model by aligning two external radioactive markers on the back of each subject. This study was conducted by performing dynamic scans while the subjects were under resting conditions and engaged in a cycling exercise.³ Although no correction was made for the misalignment between transmission and emission scans, their study demonstrated reasonable improvement in calculated MBF values.

In our previous work, we developed an alternative system that uses an optical motion-tracking device to detect and correct for the patient's global movement during a cardiac ^{15}O -water PET study.¹³ Our system provides a correction for movement during dynamic scanning, as well as for misalignment between the transmission and the emission scans, to compensate for errors in attenuation correction procedures. We evaluated and methodologically validated the inherent accuracy of this system in a cardiac phantom study. The correction for simulated global movement in a ^{15}O -water cardiac PET study of a healthy volunteer has also demonstrated reasonable regional MBF values, compared to values not adjusted for movement.

The purpose of this study was to evaluate the effects of global movements of subjects on quantification of MBF and PTF. Our previously validated system was used to detect and correct for the global movements of healthy volunteers, as well as patients who have suffered from severe cardiac dysfunction, during ^{15}O -water PET studies under resting conditions.

METHODS

Subjects

Subjects consisted of 10 healthy volunteers and 3 patients with previous myocardial infarction. The volunteers were all male, 22-32 years of age (mean \pm 1 standard deviation (SD)

25 \pm 3 years). The volunteers had no signs or symptoms of ischemic heart disease. Patients were studied before and after the cell transplantation therapy with autologous myoblast sheets (AMS).^{14,15} Scans were carried out by independent clinical research project, but were included in this study by mutual agreement. Two of the patients were male, the other was female; patients were 43-63 years of age. All patients had left ventricular assist systems (LVASs) at the time of PET study, except for one patient who received LVAS after the first PET and before the second PET studies. The PET studies were carried out 67-104 days (mean \pm SD 82 \pm 19 days) after the implantation of LVASs, and 26-106 days (mean \pm SD 56 \pm 44 days) after AMS transplantation therapy. All subjects gave written informed consent according to a protocol approved by the Ethical Committee and Internal Review Board of Osaka University.

PET Scan

The PET scanner was a HEADTOME-V tomograph (SHIMADZU Corp., Kyoto, Japan).¹⁶ All data were acquired in 2D mode. Reconstructed images were obtained using a filtered back-projection algorithm with a Gaussian filter of 9 mm (full width at half maximum). The matrix and voxel sizes of reconstructed image were 128 \times 128 \times 63 and 2.03 \times 2.03 \times 3.13 mm³, respectively. No scatter correction was applied to the image reconstruction.

Each subject was laid on the bed of the PET camera without any fixation of the body, and scanned at rest. A transmission scan was carried out first for correction of photon attenuation (20 minutes on the healthy volunteers, 10-15 minutes on the patients). A ^{15}O -CO emission scan for blood pool imaging was initiated 8 minutes after inhalation of ^{15}O -CO gas for 2 minutes (3.0-3.2 GBq). The ^{15}O -water dynamic emission scan was then carried out following intravenous administration of ^{15}O -water (1.1 GBq over 40 seconds) into the brachial vein, except for one patient who received the administration via right femoral vein. ^{15}O -water scans were performed for 6 minutes, using 26 dynamic frames consisting of 12 \times 5 s, 8 \times 15 s, and 6 \times 30 s. ^{15}O -water scans were performed only once on eight healthy volunteers; two of the volunteers underwent ^{15}O -water scans twice. Thus, a total of twelve ^{15}O -water scans were carried out on the healthy volunteers. One patient underwent PET scans three times (before and after the implantation of LVAS, and after the cell transplantation therapy); the other two were scanned twice (before and after the cell transplantation therapy). Thus, a total of seven PET studies were carried out on the patients.

Motion Detection and Correction

Subject motion during cardiac ^{15}O -water PET was detected using an optical motion-tracking device, POLARIS (Northern Digital Inc., Canada). This method for motion correction (MC) is based on a rigid body model, and performed on each sinogram of the dynamic frame to correct for inter-scan (IS) and inter-frame (IF) motions, as shown in Figure 1. The correction process was performed automatically, based on

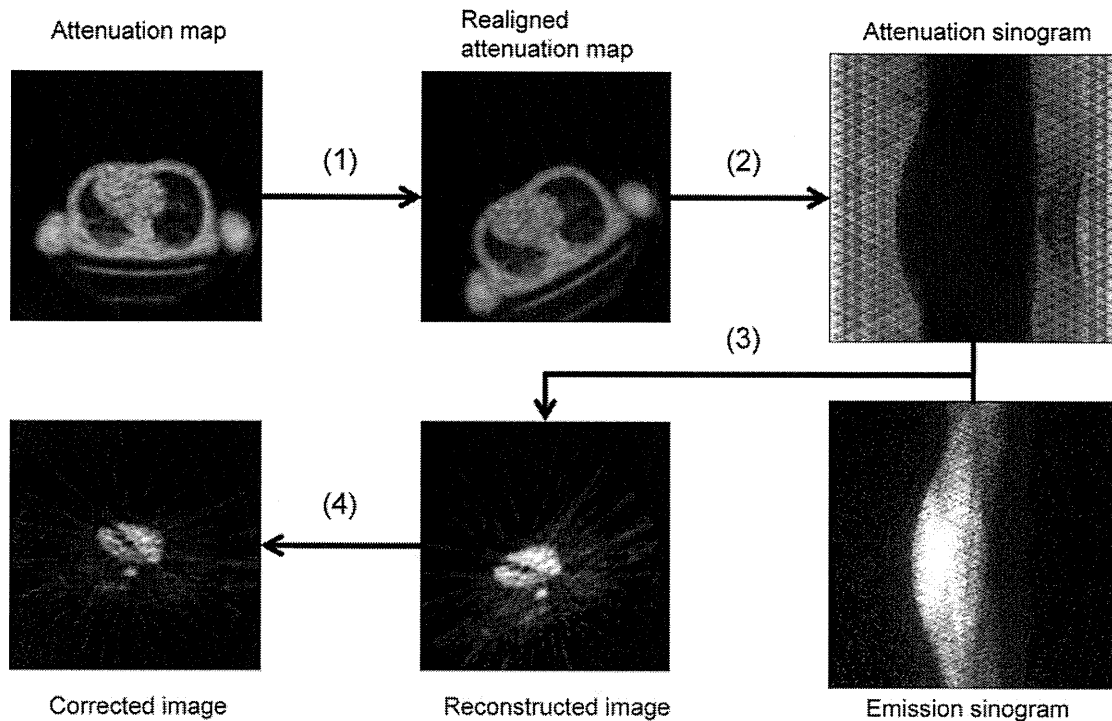


Figure 1. Schematic diagram of the correction for IS and IF motions.

user input consisting of subject locations measured by POLARIS, sinograms, and reconstruction parameters. In this manuscript, the IS motion denotes global motion between transmission and the first frame of ^{15}O -water emission scan; the IF motion, which is in addition to the IS motion, denotes global motion between frames of the ^{15}O -water scan. Methodological details regarding detection and correction of the motions are described in our previous studies.^{13,17,18}

Motion Classification

Global movement during ^{15}O -water scan was characterized as consisting of IS and IF motions. Accordingly, motion was classified as: (1) IS + IF, in which both IS and IF motions were present; (2) IS motion only; (3) IF motion only; and (4) neither type of movement was present (NE). The presence of each IS and IF motion was determined as described below. Using values $t_x(i)$, $t_y(i)$, and $t_z(i)$ to represent translational movement in the x , y , and z , respectively, directions between the transmission and the i th frame of the ^{15}O -water scans, IS motion was considered significant if $\sqrt{t_x(1)^2 + t_y(1)^2 + t_z(1)^2} > 4.0\text{mm}$, where the value of 4.0 mm was the intrinsic spatial resolution of the PET scanner.¹⁶

IF motion was considered to be significant if $\max\{L(i), H(i)\} > 4.0\text{mm}$, where $L(i)$ represents the gradual movement of the subject during the scan, and $H(i)$ denotes the motion between adjacent frames. These two components of the IF motion can be expressed as

$$L(i) = \sqrt{\sum_{w=x,y,z} [t_w(i) - t_w(1)]^2} \quad (1a)$$

$$H(i) = \sqrt{\sum_{w=x,y,z} [t_w(i) - t_w(i-1)]^2} \quad (1b)$$

Motion Effect Evaluation

To evaluate motion effects on perfusion and viability measurements, we estimated regional MBF and PTF values for nine myocardial segments (anterior, lateral, posterior, and septal wall regions at middle and basal levels, as well as apex) with and without MCs, as described in the following section. Percent differences in the estimated values between with and without MCs for the nine myocardial regions were statistically tested using a one-way ANOVA to find myocardial segments sensitive to global movement. The percent differences were employed owing to avoiding difference of physiological states across the subjects. The percent difference was defined by $\% \Delta q(i) = 100 \times |q_w(i) - q_{wo}(i)| / q_{wo}(i)$, where $q_w(i)$ and $q_{wo}(i)$ are MBF or PTF values, respectively, for the i th myocardial segment with and without MCs. Absolute values of MBF and PTF with and without MCs for each group were also assessed using Bland-Altman analysis and a paired 2-tailed t test. In the IS + IF motion group, to assess the effects of IS and IF motions, additional MBF and PTF estimations were performed on the data from ^{15}O -water images corrected for IS motions (IS + IF - IS) and also on data corrected for IF motions (IS + IF - IF). The quantitative values obtained from IS + IF - IS data were considered to be affected by IF

motion; likewise, values obtained from the IS + IF – IF data were considered to be affected by IS motion. The estimated values were compared to those without MCs using a paired 2-tailed *t* test. *P* values <.05 were considered statistically significant. Data was expressed as mean ± 1SD.

MBF and PTF Estimation

Regional MBF and PTF were obtained using the single tissue compartment model with correction for partial volume effects and spillover from the left ventricular cavity (LV)

$$C(t) = \text{MBF} \cdot \text{PTF} \cdot C_a(t) \otimes \exp\left(-\frac{\text{MBF}}{p}t\right) + V_a \cdot C_a(t)$$

where *C*(*t*) represents the segment tissue time-activity curve (TTAC), *C_a*(*t*) represents the arterial time-activity curve, *p* is the partition coefficient of water in the myocardial tissue (0.91 mL/g), and *V_a* is the arterial blood volume and spillover fraction from LV.¹⁹ TTACs were generated for the nine myocardial segments using regions of interest (ROIs) selected within each ¹⁵O-water myocardial image with and without MCs. The myocardial image was obtained by subtraction of the early phase of the dynamic ¹⁵O-water image from the later phase. The midpoint between two phases was determined for each ¹⁵O-water image using the contrast between myocardial regions and LV cavities. To obtain *C_a*(*t*), a ROI was first drawn on a motion-corrected ¹⁵O-CO image, without regard to whether MC had been applied to the ¹⁵O-water image. The recovery coefficient of the LV was calculated from the ROI count on the ¹⁵O-CO image and the blood radioactivity concentration. Second, the ROI was transformed to the ¹⁵O-water image coordinate using a motion matrix that represents misalignment between transmission and the first dynamic frame of the ¹⁵O-water scans. This transformation was made to evaluate motion effects on the ¹⁵O-water scan, excluding effects of misalignment between ¹⁵O-CO and ¹⁵O-water scans. Using the transformed ROI, the LV TAC of the ¹⁵O-water image was calculated. Finally, *C_a*(*t*) was derived using the LV TAC and the overall TTAC was generated from nine myocardial segments according to the previous method.⁶ To demonstrate the influence of IS motion, the ROI-based approach was not used; instead, pixel-by-pixel MBF and PTF values were estimated for a representative normal scan.²⁰ To denoise and smooth these parametric images, MBF and PTF were set to zero in voxels with PTF < 0.3 g/mL or *V_a* > 0.8 mL/mL, and then filtered using a Gaussian filter of 14 mm (full width at half maximum).²¹ For normal scans in the group, improvement of homogeneity between myocardial segments by MC was also evaluated as 100 × (1 – SD_W/SD_{WO}), where SD_W and SD_{WO} were standard deviations of regional values with and without MCs, respectively.

RESULTS

Table 1 shows global movement during ¹⁵O-water scans, categorized by the presence of IS and IF motions. Thirteen scans (7 scans on healthy volunteers and 6

scans on patients) exhibited IS motions greater than 4.0 mm, and 10 scans (5 scans on healthy volunteers and 5 scans on patients) exhibited IF motions greater than 4.0 mm. Among these, 4 scans on healthy volunteers and 5 scans on patients showed both IS and IF motions.

There was no statistically significant difference between the ROI volumes of ¹⁵O-water images with and without MCs for IS, IF, and NE motion groups by paired 2-tailed *t* tests, and between the volumes with and without MCs, IS + IF – IS, and IS + IF – IF motion for IS + IF motion group by a one-way ANOVA.

Table 2 lists MBF and PTF values with and without MCs categorized by the four types of movement that occurred during ¹⁵O-water studies, and average percent differences of MBF and PTF values over nine segments. Among 171 myocardial segments from all subjects, the fitting program failed to provide physiologically meaningful values in two segments (middle and basal septa for a healthy volunteer, in which IS + IF motion was detected) in the absence of MC. Those data were excluded from subsequent analysis. Among MBF values, significant changes by MCs were found in the IS + IF, IS + IF – IF, and IF motion groups: for IS + IF, from 0.845 ± 0.366 to 0.769 ± 0.319 mL/minute/g (*P* < .05); for IS + IF – IF, from 0.845 ± 0.366 to 0.780 ± 0.360 mL/minute/g (*P* < .05); and for IF, from 0.854 ± 0.179 to 1.088 ± 0.154 mL/minute/g (*P* < .01). PTF values in the IS motion group changed significantly from 0.465 ± 0.118 to 0.504 ± 0.087 g/mL (*P* < .05). This significant change is also shown in Figures 2 and 3, as differences between PTF values with and without MCs. In Figure 3, a data point indicated an averaged value for each scan.

Figure 4 illustrates the effect of IS motion of 5.0 mm on MBF and PTF of a normal subject from the IS motion group. The polar maps of normal PTF in Figure 4 demonstrate improvement of homogeneity in anterolateral regions by MC. Improvements of homogeneity of three normal scans in the group were 2.6% ± 26.1% for MBF and 30.9% ± 22.7% for PTF.

Table 1. Characteristics of motion during ¹⁵O-water scans

Motion type	Total (normal) scans	IS motion (mm)	IF motion (mm)
IS + IF	9 (4)	7.7 ± 2.7	11.0 ± 4.0
IS	4 (3)	5.4 ± 1.0	2.8 ± 1.1
IF	1 (1)	2.7	5.1
NE	5 (4)	2.5 ± 0.7	1.4 ± 0.5

Table 2. The summary of MBF and PTF values with and without MCs

Motion type	Without MC	With MC	Percent difference
MBF (mL/minute/g)			
IS + IF	0.845 ± 0.366	$0.769 \pm 0.319^*$	33.8 ± 61.5
IS + IF – IS		0.815 ± 0.341	21.2 ± 38.5
IS + IF – IF		$0.780 \pm 0.360^*$	25.1 ± 41.4
IS	0.855 ± 0.343	0.828 ± 0.259	9.0 ± 8.9
IF	0.854 ± 0.179	$1.088 \pm 0.154^\dagger$	30.2 ± 20.9
NE	0.898 ± 0.233	0.909 ± 0.221	9.7 ± 15.7
PTF (g/mL)			
IS + IF	0.476 ± 0.133	0.469 ± 0.128	13.9 ± 10.9
IS + IF – IS		0.471 ± 0.135	12.3 ± 13.0
IS + IF – IF		0.490 ± 0.119	12.3 ± 10.2
IS	0.465 ± 0.118	$0.504 \pm 0.087^*$	9.0 ± 9.6
IF	0.512 ± 0.067	0.483 ± 0.068	7.1 ± 5.6
NE	0.488 ± 0.095	0.496 ± 0.100	5.1 ± 4.9

IS, Inter-scan; IF, inter-frame.

NE denotes motion ≤ 4.0 mm. IS + IF – IS and IS + IF – IF represent IS + IF motion groups with correction of IS and IF motions, respectively.

* $P < .05$, $^\dagger P < .01$ vs without MC.

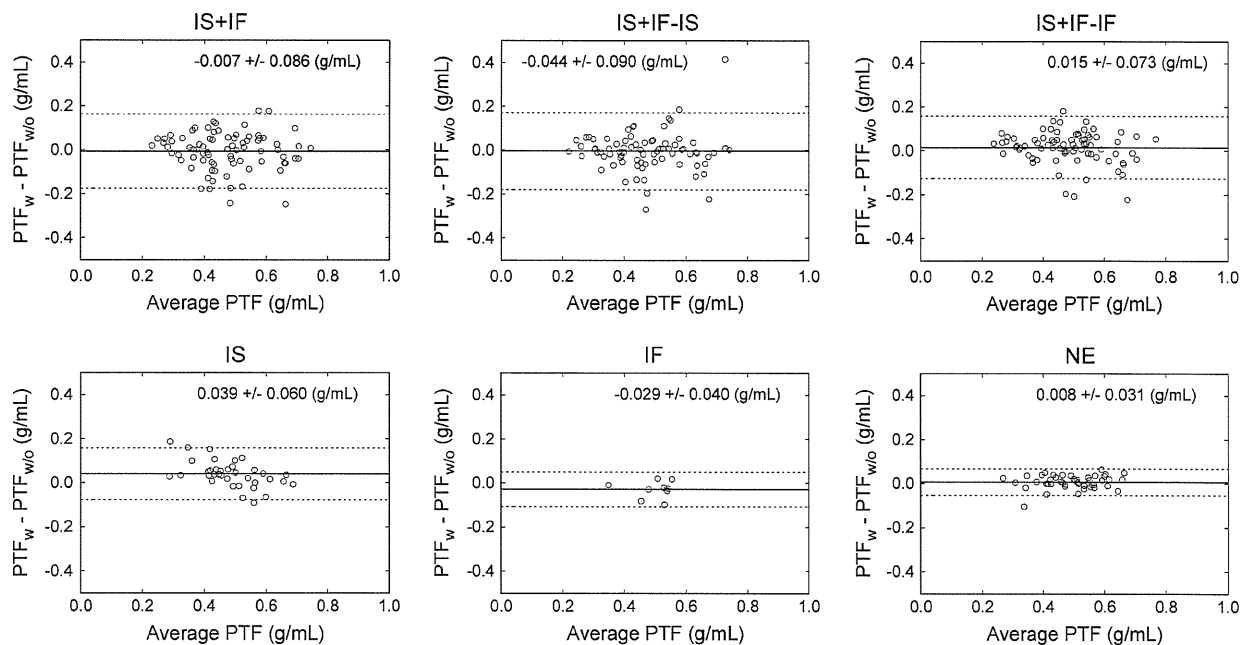


Figure 2. Differences between PTF values with and without the motion corrections. IS, Inter-scan motion; IF, inter-frame motion; NE, no significant motion. IS + IF – IS and IS + IF – IF are groups corrected for IS and IF motion in the IS + IF group, respectively.

Relative variability of regional MBF and PTF values due to global motion are shown in Figures 5 and 6, respectively. For MBF and PTF values in each motion

group including the IS + IF – IS and IS + IF – IF groups, no significant difference between myocardial segments was observed in a one-way ANOVA (IF

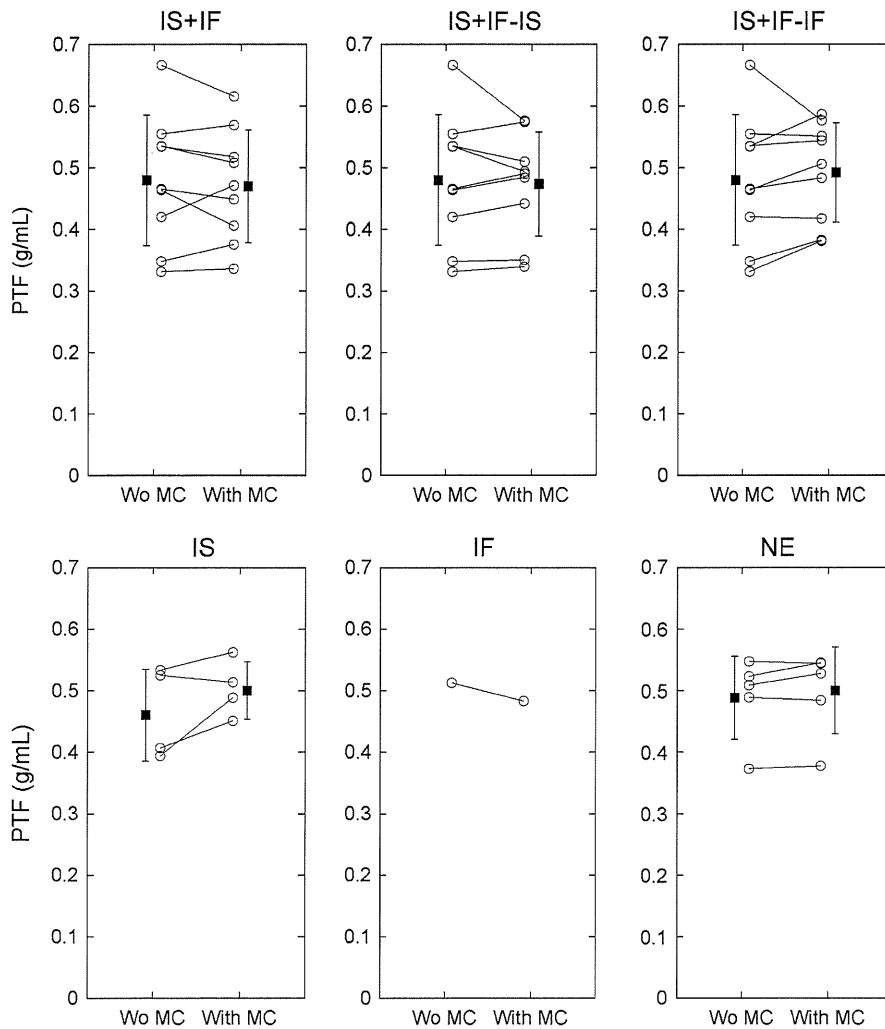


Figure 3. Changes in PTF values in the absolute scale by the MCs. *IS*, Inter-scan motion; *IF*, inter-frame motion; *NE*, no significant motion. *IS + IF - IS* and *IS + IF - IF* are groups corrected for *IS* and *IF* motions in the *IS + IF* group, respectively. A data point indicates an averaged value for each scan.

motion group was excluded from this analysis because one scan was assigned to this group. Data for *IS + IF - IS* and *IS + IF - IF* groups were not shown).

DISCUSSION

In this study, global movements of the subjects during ^{15}O -water PET scans at rest were categorized as *IS* and *IF* motions. *IS* motion involves misalignment relative to the transmission scan, whereas *IF* motions involve changes between the dynamic frames during the ^{15}O -water scan. After categorization, the effects of these motions on MBF and PTF measurements were evaluated. Consequently, it was demonstrated that

MBF values are affected by *IF* motion rather than *IS* motion.

Investigation of regional sensitivity to global movement resulted in no significant difference in regional MBF or PTF. This is because the direction and the magnitude of global movement varied for each subject; under- and over-estimation of MBF and PTF due to the motion could have occurred in any myocardial region. In this study, we utilized a one-way ANOVA to detect segmental differences. Due to small sample sizes, the ANOVA may fail to detect the differences. Correlation between segmental differences and the directions of global motions, especially *IS* motion, effects of which have been reported for misregistration between CT

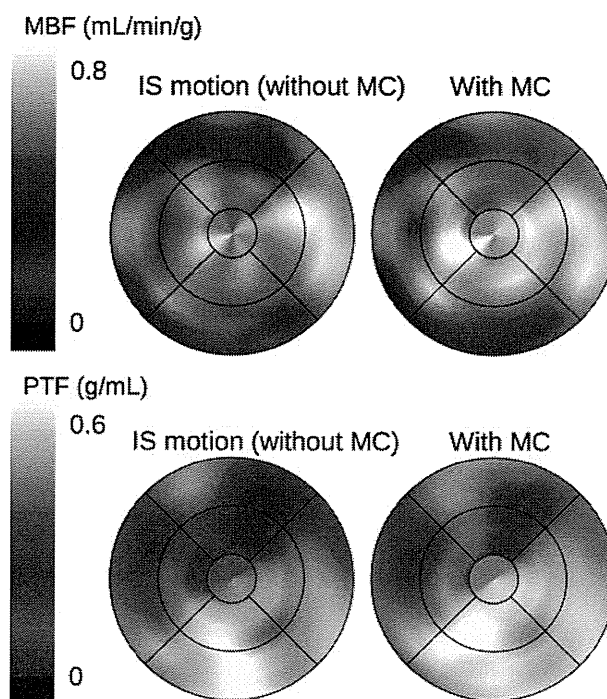


Figure 4. Effect of an IS motion of 5.0 mm on MBF and PTF of a normal subject in IS motion group.

attenuation map and emission image,^{22,23} could be observed in large population study.

MBF values changed significantly upon correction for IF motions in the IF, IS + IF, and IS + IF – IF motion groups. In contrast, correction of IS motion was considered to have little effect, based on the results from the IS + IF – IS and IS motion groups in Table 2. It was further demonstrated that IF motion, but not IS motion, was an important source of error in the MBF measurement. The significant but small changes in MBF of IF, IS + IF, and IS + IF – IF motion groups after MCs could be due to the relatively large number of healthy volunteer scans in each group (1 of 1 scan for IF, 4 of 9 scans for IS + IF, respectively), as shown in Table 1. Suppression of IF motion during the ^{15}O -water scan is needed for accurate MBF measurement. For the IS motion groups, no significant change in MBF values and significant change in PTF values were observed by MCs (Figures 2, 3). For the normal scans in the group, the improvement of regional homogeneity was also observed in PTF rather than MBF. This is because the MBF values obtained using the kinetic model employed in this study were based on a clearance rate assessment of ^{15}O -water rather than the uptake rate of the radiotracer.⁵ This is consistent with the findings of Lubberink et al,²¹ who reported that MBF values do not change even if attenuation correction is omitted; this correction

only caused changes in the absolute scale of TTAC, which then caused changes in PTF values. IS motions were also detected in the IS + IF motion group. For the IS + IF – IS motion group, in which IS motions were corrected, no significant change in PTF values was observed after MCs. This might be because IS and IF motions affected the ^{15}O -water images not subjected to MC in such a way as to cancel out errors in PTF measurements. PTF values were considered to be more affected than MBF values during the wash-in phase. However, in our study, IF motion had little effect on PTF values for the IS + IF – IF and IF groups, as shown in Table 2. The reasons for this discrepancy are follows: (1) to estimate the quantitative values, a nonlinear least squares method with same weights for all data points were applied to the data corrected for the physical decay. This fitting manner could be sensitive to radioactivity concentration in wash-out phase rather than wash-in phase. (2) Over-estimation in TTAC was introduced by contamination of the LV cavity count, using the ROI for TTAC superimposed on dynamic frames. However, the spillover correction could suppress the influence of IF motion. One of the advantages of ^{15}O -water over other cardiac PET tracers is that perfusion and viability measurements can be obtained from a single PET scan with short duration. Because accurate PTF measurement enabled assessment of

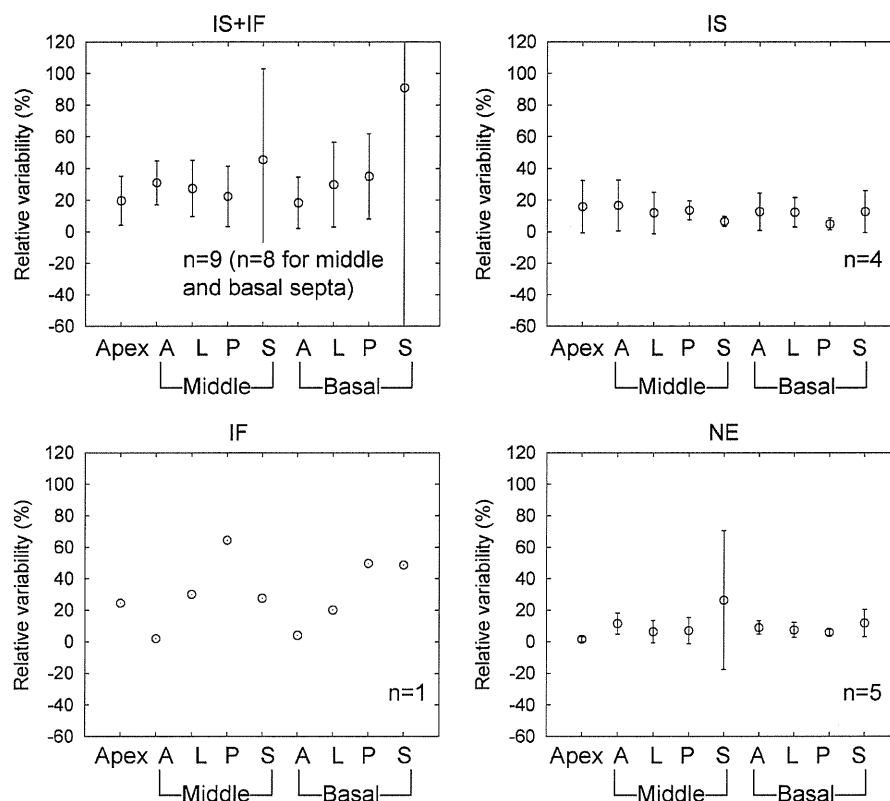


Figure 5. Relative variability of regional MBF due to effects of global motion. *IS*, Inter-scan motion; *IF*, inter-frame motion; *NE* represents no significant motion. *IS + IF* – *IS* and *IS + IF* – *IF* are groups corrected for *IS* and *IF* motion in the *IS + IF* group, respectively.

myocardial viability,⁷⁻¹² correction of *IS* motion, the effect of which was shown as the improvement of regional homogeneity of normal PTF in Figure 4, is considered to be important in the diagnosis of myocardial infarction, or evaluation of effects of cell transplantation therapies.

In this study, we performed ^{15}O -CO scans to determine a recovery coefficient for each subject.^{5,6} ^{15}O -water PET studies without ^{15}O -CO scans have been reported in previous papers^{3,21,24}; in these studies, the recovery coefficient could be fixed, or assumed to have a constant value. Omission of the ^{15}O -CO scan shortened the examination time, and might reduce motion artefacts. However, we considered that the adequacy of using a fixed recovery coefficient is still an unresolved issue in ^{15}O -water PET. We considered that the changes in MBF and PTF resulting from MCs were due to correction for global motion, and not due to variability of myocardial tissue ROIs drawn manually on ^{15}O -water images. We employed nine segmented regions rather than 17-segment AHA standard model for suppressing relatively large noise level of ^{15}O -water data.⁴ In addition, the volumes of the ROIs for each motion

group before and after MCs were almost equal (not statistically significant). Furthermore, lower sensitivity of MBF values to variation in ROI size and shape was demonstrated by Iida et al.⁴ In this study, global motion might have occurred because subjects were scanned without any fixation. Although tight fixation prevents patient motion, such fixation could bring discomfort or pain to the patient; subsequent reaction to such pain could itself induce motion.

One limitation of this study is that all subjects were scanned at rest. When pharmacological or physiological stressors are administered, motion artefacts could be induced, as shown by Naum et al³ in the context of physiological stress conditions. Our finding that MBF was sensitive to *IF* motion rather than *IS* motion was considered to be valid for a stress study; *IF* motion might be source of severe error in MBF and CFR measurements. The rigid body model, which was used in this study, has been promoted for motion compensation not only in brain PET but also in cardiac PET. McCord et al¹ employed the rigid body model to correct for misalignment during the transmission and ^{18}F -fluorodeoxyglucose (^{18}F -FDG) emission scans. Bacharach et al²

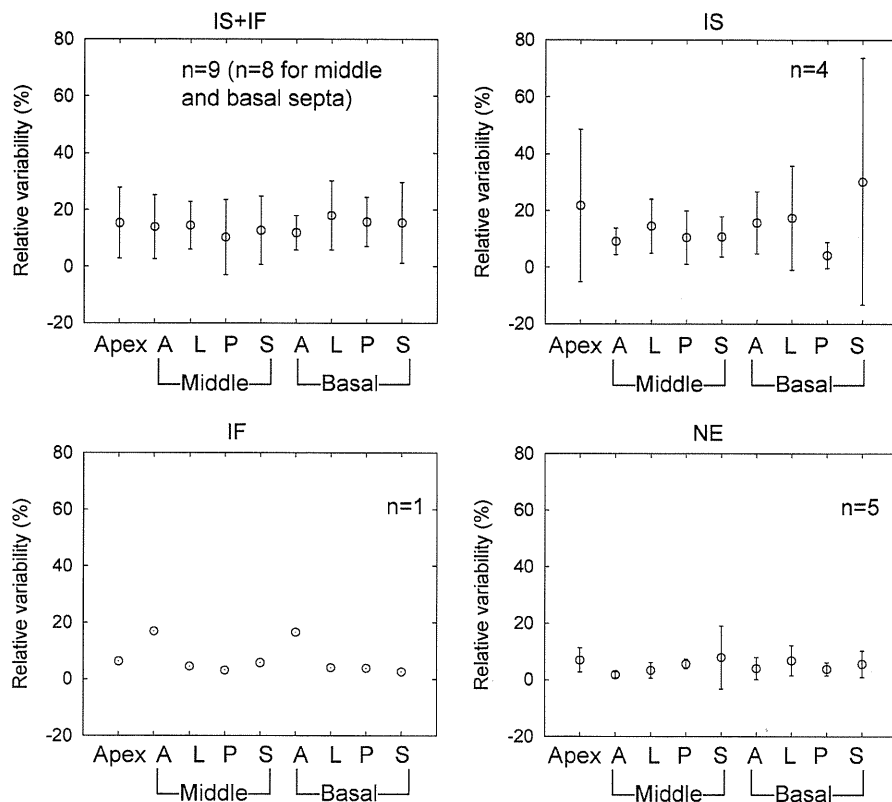


Figure 6. Relative variability of regional PTF due to effects of global motion. *IS*, Inter-scan motion; *IF*, inter-frame motion; *NE* represents no significant motion. *IS + IF - IS* and *IS + IF - IF* are groups corrected for *IS* and *IF* motion in the *IS + IF* group, respectively.

also proposed a registration technique based on the rigid body model for ^{18}F -FDG emission images acquired on different days. The use of the rigid body model is considered to be valid for non-gated cardiac PET images because the images were smoothed spatially due to cardiac wall motion, and also averaged temporally over the duration of the dynamic frames. However, in stress studies, over-correction due to relatively large respiratory motions might be introduced by our system because the subject's motion was estimated by measurement of the location of a target attached on the thoracic surface. With this in mind, further work is necessary to evaluate the contribution of MC in combination with a respiratory gating technique.

The MC system was applied to clinical follow-up studies of the patients who received LVAS and cell transplantation therapy. The aim of this study was to investigate the effects of global movement on quantification of MBF and PTF values in a single ^{15}O -water PET study under resting conditions. Although, we believed that the MC system could contribute to an accurate evaluation of regional perfusion and viability, the effects of LVAS implantation and AMS

transplantation therapy on those patients is beyond the scope of the present study, and will be studied elsewhere.

CONCLUSIONS

This study demonstrated that IF motion during ^{15}O -water scans under resting conditions could be the source of error in MBF measurement. Furthermore, estimated MBF values were less sensitive than PTF values to misalignment between the transmission and the ^{15}O -water emission scans.

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Conflicts of interest

The authors have no conflicts of interest to disclose.

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References

- McCord ME, Bacharach SL, Bonow RO, Dilsizian V, Cuocolo A, Freedman N. Misalignment between PET transmission and emission scans: Its effect on myocardial imaging. *J Nucl Med* 1992;33:1209-14.
- Bacharach SL, Douglas MA, Carson RE, Kalkowski PJ, Freedman NM, Perrone-Filardi P, et al. Three-dimensional registration of cardiac positron emission tomography attenuation scans. *J Nucl Med* 1993;34:311-21.
- Naum A, Laaksonen MS, Tuunanen H, Oikonen Va, Teräs M, Kemppainen J, et al. Motion detection and correction for dynamic (15)O-water myocardial perfusion PET studies. *Eur J Nucl Med Mol Imaging* 2005;32:1378-83.
- Iida H, Kanno I, Takahashi A, Miura S, Murakami M, Takahashi K, et al. Measurement of absolute myocardial blood flow with H215O and dynamic positron-emission tomography. Strategy for quantification in relation to the partial-volume effect. *Circulation* 1988;78:104-15. (Erratum in: *Circulation* 1988;78:1078).
- Iida H, Rhodes CG, de Silva R, Yamamoto Y, Araujo LI, Maseri A, et al. Myocardial tissue fraction-correction for partial volume effects and measure of tissue viability. *J Nucl Med* 1991;32:2169-75.
- Iida H, Rhodes CG, de Silva R, Araujo LI, Bloomfield PM, Lammertsma AA, et al. Use of the left ventricular time-activity curve as a noninvasive input function in dynamic oxygen-15-water positron emission tomography. *J Nucl Med* 1992;33:1669-77.
- Yamamoto Y, de Silva R, Rhodes CG, Araujo LI, Iida H, Rechavia E, et al. A new strategy for the assessment of viable myocardium and regional myocardial blood flow using 15O-water and dynamic positron emission tomography. *Circulation* 1992;86:167-78.
- de Silva R, Yamamoto Y, Rhodes CG, Iida H, Nihoyannopoulos P, Davies GJ, et al. Preoperative prediction of the outcome of coronary revascularization using positron emission tomography. *Circulation* 1992;86:1738-42.
- Iida H, Rhodes CG, Araujo LI, Yamamoto Y, de Silva R, Maseri A, et al. Noninvasive quantification of regional myocardial metabolic rate for oxygen by use of ¹⁵O₂ inhalation and positron emission tomography. Theory, error analysis, and application in humans. *Circulation* 1996;94:792-807.
- Chareonthitawee P, Kaufmann PA, Rimoldi O, Camici PG. Heterogeneity of resting and hyperemic myocardial blood flow in healthy humans. *Cardiovasc Res* 2001;50:151-61.
- Knaapen P, Boellaard R, Götte MJ, van der Weerd AP, Visser CA, Lammertsma AA, et al. The perfusable tissue index: A marker of myocardial viability. *J Nucl Cardiol* 2003;10:684-91.
- Knaapen P, Boellaard R, Götte MJ, Dijkmans PA, van Campen LM, de Cock CC, et al. Perfusible tissue index as a potential marker of fibrosis in patients with idiopathic dilated cardiomyopathy. *J Nucl Med* 2004;45:1299-304.
- Koshino K, Watabe H, Hasegawa S, Hayashi T, Hatazawa J, Iida H. Development of motion correction technique for cardiac 15O-water PET study using an optical motion tracking system. *Ann Nucl Med* 2010;24:1-11.
- Miyagawa S, Matsumiya G, Funatsu T, Yoshitatsu M, Sekiya N, Fukui S, et al. Combined autologous cellular cardiomyoplasty using skeletal myoblasts and bone marrow cells for human ischemic cardiomyopathy with left ventricular assist system implantation: Report of a case. *Surg Today* 2009;39:133-6.
- Miyagawa S, Saito A, Sakaguchi T, Yoshikawa Y, Yamauchi T, Imanishi Y, et al. Impaired myocardial regeneration with skeletal cell sheets—a preclinical trial for tissue-engineered regeneration therapy. *Transplantation* 2010;90:364-72.
- Iida H, Miura S, Kanno I, Ogawa T, Uemura K. A new PET camera for noninvasive quantitation of physiological functional parametric images: HEADTOME-V-Dual. In: Myers R, Cunningham V, Bailey D, editors. *Quantification of brain function using PET*. London: Academic Press; 1996. p. 57-61.
- Watabe H, Sato N, Kondoh Y, Fulton RR, Iida H. Correction of head movement using optical motion tracking system during PET study with rhesus monkey. In: Senda M, Kimura Y, Herscovitch P, editors. *Brain imaging using PET*. London: Academic Press; 2002. p. 1-8.
- Woo SK, Watabe H, Yong C, Kim KM, Choon C, Bloomfield PM, et al. Sinogram-based motion correction of PET images using optical motion tracking system and list-mode data acquisition. *IEEE Trans Nucl Sci* 2004;51:782-8.
- Katoh C, Morita K, Shiga T, Kubo N, Nakada K, Tamaki N, et al. Improvement of algorithm for quantification of regional myocardial blood flow using 15O-water with PET. *J Nucl Med* 2004;45:1908-16.
- Watabe H, Jino H, Kawachi N, Teramoto N, Hayashi T, Ohta Y, et al. Parametric imaging of myocardial blood flow with 15O-water and PET using the basis function method. *J Nucl Med* 2005;46:1219-24.
- Lubberink M, Harms HJ, Halbmeijer R, de Haan S, Knaapen P, Lammertsma AA. Low-dose quantitative myocardial blood flow imaging using 15O-water and PET without attenuation correction. *J Nucl Med* 2010;51:575-80.
- Goetze S, Brown TL, Lavelly WC, Zhang Z, Bengel FM. Attenuation correction in myocardial perfusion SPECT/CT: Effects of misregistration and value of reregistration. *J Nucl Med* 2007;48:1090-5.
- Martinez-Möller A, Souvatzoglou M, Navab N, Schwaiger M, Nekolla SG. Artifacts from misaligned CT in cardiac perfusion PET/CT studies: Frequency, effects, and potential solutions. *J Nucl Med* 2007;48:188-93.
- Nesterov SV, Han C, Mäki M, Kajander S, Naum AG, Helenius H, et al. Myocardial perfusion quantitation with 15O-labelled water PET: High reproducibility of the new cardiac analysis software (Carimas). *Eur J Nucl Med Mol Imaging* 2009;36:1594-602.



Quantification of regional cerebral blood flow in rats using an arteriovenous shunt and micro-PET

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Abstract

Introduction: Measurement of regional cerebral blood flow (rCBF) in rodents can provide knowledge of pathophysiology of the cerebral circulation, but generally requires blood sampling for analysis during positron emission tomography (PET). We therefore tested the feasibility of using an arteriovenous (AV) shunt in rats for less invasive blood analysis.

Methods: Six anesthetized rats received [¹⁵O]H₂O and [¹⁵O]CO PET scans with their femoral artery and vein connected by an AV shunt, the activity within which was measured with a germanium ortho-oxysilicate scintillation detector. The [¹⁵O]H₂O was intravenously injected either at a faster or slower injection rate, while animals were placed either with their head or heart centered in the gantry. The time–activity curve (TAC) from the AV shunt was compared with that from the cardiac ventricle in PET image. The rCBF values were calculated by a nonlinear least-square method using the dispersion-corrected AV-shunt TAC as an input.

Results: The AV-shunt TAC had higher signal-to-noise ratio, but also had delay and dispersion compared with the image-derived TAC. The delay time between the AV-shunt TAC and image-based TAC ranged from 11 to 21 s, while the dispersion was estimated to be ~5 s as a time constant of the dispersion model of exponential function, and both were properly corrected. In a steady-state condition of [¹⁵O]CO PET, the blood activity concentration by AV-shunt TAC was also comparable in height with the image-based TAC corrected for partial volume. Whole-brain CBF values measured by [¹⁵O]H₂O were 0.37±0.04 (mean±S.D.) ml/g/min, partition coefficient was 0.73±0.04 ml/g, and the CBF varied in a linear relationship with partial pressure of carbon dioxide during each scan.

Conclusions: The AV-shunt technique allows less invasive, quantitative and reproducible measurement of rCBF in [¹⁵O]H₂O PET studies in rats than direct blood sampling and radioassay.

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Keywords: Positron emission tomography; Oxygen radioisotopes; Rats; Cerebral blood flow; AV shunt; CO₂

1. Introduction

Regional cerebral blood flow (rCBF) is one of the most frequently used clinically evaluable parameters for characterizing regional hemodynamic and/or functional status of

the brain, and can be noninvasively measured by positron emission tomography (PET) using ¹⁵O-labeled water [1]. The short physical half-life of ¹⁵O (~2 min) also allows repeat measurements of rCBF under different conditions within a relatively short period of time. One of the concerns when measuring rodent rCBF using [¹⁵O]H₂O PET is blood sampling from an artery, which is needed to obtain the arterial input function and calculate rCBF. Owing to the small total volume of blood in rodents, withdrawal of blood

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may alter the physiological conditions of the animals, resulting in instability or bias in the measured rCBF. An image-driven input function in rat PET, which derives time–activity curve (TAC) from a region of interest in the cardiac ventricle, may be a potential solution [2]. However, such image-based data may be compromised by statistical (i.e., count-related) ‘noise’ or biased by the partial volume effect; thus, it is not so simple to estimate arterial input function. Yee et al. recently proposed a model to estimate the input function in rats from the cardiac PET [^{15}O]H $_2$ O image [2], but the model assumed multiple heuristic parameters and is thus difficult to validate.

The arteriovenous (AV)-shunt technique is one of the possible approaches to obtain the input function, and several studies have used this technique using radioactive tracers [3–6]. This technique involves placing a shunt between an artery and vein using a catheter and tube, in which blood activity concentration could be measured by an external detector. The advantages of the AV-shunt technique are high temporal resolution and no loss of blood during the PET study. However, there is concern of potential bias in the arterial input function, for example, due to time delay and dispersion, which may be augmented by a lengthy shunt. In addition, potential unstable flow resulting from blood clotting within the tube has not been well studied.

The aim of this study was to validate the arterial input function obtained by the AV shunt as a reference of image-based one and to quantify the rCBF of rats using [^{15}O]H $_2$ O PET. For this purpose, we first evaluated the stability of blood flow velocity in the AV-shunt line by ultrasonography during the PET scans. Then, we separately performed two scans, one for the heart and the other for the brain, in each animal. The former scan was obtained to validate the shape of arterial input function from the AV shunt, and the latter for calculation of rCBF using the AV-shunt-based TAC. To validate the shape of the AV-shunt-derived blood TAC, the two different methods of injections (faster or slower) were performed. Thereafter, the delay and dispersion of the AV-shunt-based input function were evaluated by comparing with the input function from a region of interest in the left ventricle in the PET images. For the calculation of rCBF, the delay- and dispersion-corrected AV-shunt-derived TAC was used, and we investigated the relationship between the measured rCBF and arterial carbon dioxide partial pressure (pCO $_2$) during each measurement to confirm whether the current system reproduces the known physiological linear relationship between rCBF and pCO $_2$.

2. Material and methods

2.1. Overview of the study

Fig. 1 presents a schematic diagram of our experimental setup. To confirm the stability of the AV shunt during the PET scan, we continuously monitored the blood flow velocity in the AV-shunt line using ultrasonography. For

injection of [^{15}O]H $_2$ O, we tested two injection procedures, namely, faster and slower bolus injection, as shown in Fig. 1C. Fig. 2 shows our experimental protocol for PET scans. A total of three emission scans of [^{15}O]CO for heart, [^{15}O]H $_2$ O for heart and [^{15}O]H $_2$ O for brain were performed in each animal, with additional transmission scans for attenuation correction of 511 keV gamma rays. The cardiac [^{15}O]CO image was used to identify the cardiac ventricle to obtain image-based arterial TACs, while the cardiac [^{15}O]H $_2$ O images were utilized to compare the shape of the arterial input function from the heart and from the AV-shunt line as well as to estimate the dispersion parameter of the input function from the AV shunt. [^{15}O]CO is known to label the red blood cells in the blood, and the specific activity of the supplied [^{15}O]CO was high enough to prevent side effects.

2.2. Animal preparation

Six male Sprague–Dawley rats (6 weeks old) were used in this study. Their body weight ranged from 257 to 319 g (mean±standard deviation, 283±22). The animals were maintained and handled in accordance with the *Guidelines for Proper Conduct of Animal Experiments* (June 1, 2006 Science Council of Japan). The study protocol was approved by the Laboratory Animal Welfare of the National Cardiovascular Center.

We performed all the experiments under deep anesthesia. The anesthesia was induced by intramuscular injection of ketamine (30–50 mg/kg) and xylazine (5–10 mg/kg). A rat was intubated for inhalation of [^{15}O]CO gas and for management of respiration using a respirator (SN-480-7, Shimano, Tokyo, Japan). Two 22-gauge needles were percutaneously inserted into the caudal veins and were attached to 25-cm-long polyethylene tubes for maintenance anesthesia using propofol (20–25 mg/kg/h) and for injection of [^{15}O]H $_2$ O. The right femoral artery was catheterized with a polyethylene tube (PE50, inner diameter of 0.54 mm) for sampling blood for blood gas analysis and for monitoring heart rate and blood pressure using a physiological monitoring device (BSM-2391 Nihon Kohden, Tokyo, Japan). The left femoral artery and vein were also catheterized with PE50 tubes for the AV shunt. The length of the tubes was 55 and 35 cm for the left femoral artery and left femoral vein, respectively, and 10 cm of the ends of the two lines was connected to a thicker polyethylene tube (PE 100, inner diameter of 0.86 mm) to form the AV shunt and to allow passive blood flow dependent on the pressure gradient from artery to vein. The thicker part of the tube was used for monitoring blood flow by the ultrasonographic probe as described below, and a part of the arterial side of the PE50 tube (35–45 cm from the femoral artery) was used for online measurement of activity concentration using a Gd $_2$ SiO $_5$:Ce (GSO) detector (GSO input function monitor system, Molecular Imaging Laboratory, Osaka, Japan) [7]. The GSO detector consists of two pairs of GSO crystals (20 mm×20 mm×12.9 mm for each) with photomultiplier tube

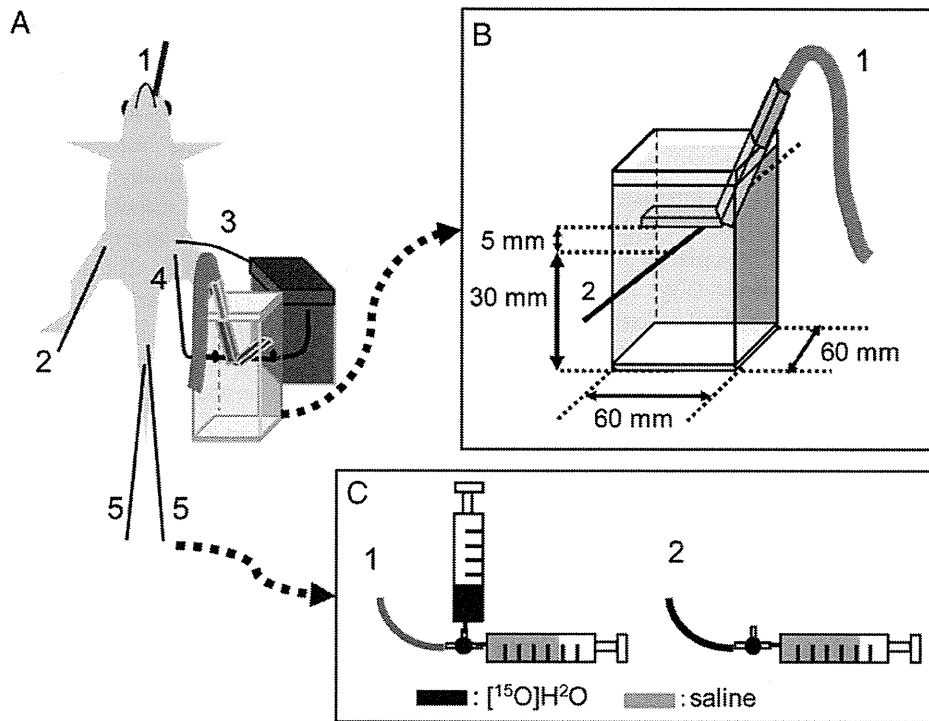


Fig. 1. A schematic diagram of the experimental setup. (A) Animal preparation: intubation for inhalation (1), blood catheter lines in the left femoral artery (3) and vein (4) for AV shunt, and in the right femoral artery (2) for monitoring heart pressure, and in two caudal veins (5), one for injection of $[^{15}\text{O}]\text{H}_2\text{O}$ and the other for infusion of anesthetics. (B) Measurements of blood flow velocity in the AV-shunt line by ultrasonography: the appliance consisted of an echo probe (1) and AV-shunt line (2), and the container was filled with water. The distance between the AV-shunt line and the echo probe was kept at 5 mm. (C) Two injection methods: faster bolus injection (1) and slower bolus injection (2). In the faster bolus injection, a solution of $[^{15}\text{O}]\text{H}_2\text{O}$ (volume of ~ 0.3 ml) in a 1-ml syringe was injected in a period of 15 s into the tail vein, and then the three-way stopcock was turned to the other syringe to flush through 0.7 ml of saline. In the slower bolus injection, $[^{15}\text{O}]\text{H}_2\text{O}$ (~ 0.3 ml) filled the venous catheter line before injection and was flushed through by 0.7 ± 0.1 ml of saline in the syringe over a period of 30 s.

and coincidence circuits. A 2-cm-thick lead is utilized for shielding. The absolute sensitivity for PET tracers is approximately 7%. The total volume in the AV-shunt line was 0.26 ml (as a reference, the total amount of blood per body is ~ 20 ml). The AV-shunt line was coated with heparin to prevent clot formation. Soon after equipment setup, the

animal was fixed in a supine position on the micro-PET imaging bed. A blood sample from the femoral artery was analyzed for pCO_2 using a blood gas analyzer (ABL-500, RADIOMETER, Tokyo, Japan). Body temperature was measured with a probe placed in the rectum, and kept at $36^\circ\text{C} \pm 1^\circ\text{C}$ by using an infrared thermostat.

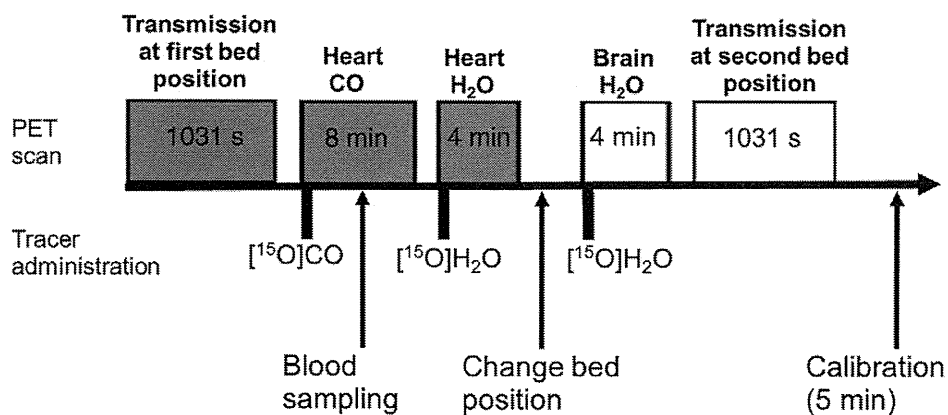


Fig. 2. Experimental protocol. The first three PET scans (gray) were performed for derivation of the cardiac ventricular TAC, while the latter two (white) were performed for brain imaging and the cerebral TAC. The activity concentration of the AV shunt was monitored and recorded to obtain the TAC during the PET scan.

2.3. Measurement of AV-shunt line blood flow velocity by ultrasonography

To confirm that blood constantly flows in the AV-shunt line, we performed measurements of blood flow velocity in three rats using a portable ultrasonographic device (LOGIQ BOOK XP, GE Healthcare UK Ltd., Buckinghamshire, UK) with a probe (i12L-RS, GE Healthcare UK Ltd., Buckinghamshire, UK). The AV-shunt line was placed 30 mm from the bottom of a box filled with water (Fig. 1B), and the distance between the line and the probe was kept at 5 mm. Blood flow velocity (cm/s) was monitored by the ultrasonographic probe during the experiment. The values of blood flow velocity measured by pulse Doppler were recorded twice during each emission scan. The velocity was scaled by the initial value measured before the PET scan of [^{15}O]CO in the heart.

2.4. Injection methods

Intravenous injection of [^{15}O]H₂O was performed in two ways, according to injection rate (faster, $n=3$ or slower, $n=3$) (Fig. 1C). In the faster bolus injection, a solution of [^{15}O]H₂O (59 ± 1.6 MBq, in a volume of ~ 0.3 ml) in a 1-ml syringe was injected in a period of 15 s into the tail vein, and then the three-way stopcock was turned to the other syringe to flush through 0.7 ml of saline. In the slower bolus injection, [^{15}O]H₂O (~ 0.3 ml) filled the venous catheter line before injection and was flushed through by 0.7 ± 0.1 ml of saline in the syringe over a period of 30 s. In both methods, the total injected radioactivity at the time of tracer injection was 68.6 ± 3.3 MBq.

2.5. PET experiments

We used a PET scanner (micro-PET Focus 120, SIEMENS Healthcare USA Inc., Malvern, PA, USA) for imaging activity concentration distribution. This PET scanner is dedicated for small-animal use and has a transaxial field of view (FOV) of 10 cm and an axial FOV of 7.6 cm. The sensitivity and the spatial resolution at the center of the scanner are 7% and 1.18 mm full-width half-maximum, respectively [8]. All PET emission data were acquired in list mode.

For the scan protocol (Fig. 2), the animal was first positioned with its chest (heart) centered in the FOV of the PET scanner to scan the heart. After a transmission scan for a period of 1031 s using a $^{68}\text{Ga}/\text{Ge}$ pinpoint source, an emission scan was initiated immediately after completion of inhalation of [^{15}O]CO (350 ± 20 MBq/min) for 10 s and continued for a period of 8 min. A blood sample was taken from the femoral artery at 4–5 min after starting inhalation of [^{15}O]CO and was radioassayed using a well counter (BeWell, Molecular Imaging Laboratory, Osaka, Japan). After radioactive decay, an emission scan for a period of 4 min was performed immediately after injection of [^{15}O]H₂O by either faster or slower bolus injection. Then, the animal

was repositioned with its head centered in the FOV of the PET scanner for brain scanning, and a 4-min emission scan was performed after injection of [^{15}O]H₂O by either faster or slower bolus injection. The injection method of [^{15}O]H₂O was the same as for the heart scan for each subject. A transmission scan was finally acquired for correction of attenuation. During PET scanning, activity concentration in the AV-shunt line was continuously recorded every second by the GSO detector. After all the PET scans, we removed the AV-shunt line from the animal, filled the line with saline containing [^{15}O]H₂O of known activity concentration measured by the well counter, for cross-calibration of the GSO detector. The well counter was also calibrated to the PET scanner.

PET data, acquired in list mode, were sorted into multiple frames of 3D sinogram data. The emission data for [^{15}O]CO consisted of 31 frames (18 frames \times 10 s, 12 frames \times 20 s, 1 frame \times 60 s), and for [^{15}O]H₂O (in both heart and brain scans), 63 frames (30 frames \times 2 s, 30 frames \times 5 s, 3 frames \times 10 s). All sinogram data were reconstructed by a filtered back projection algorithm (a Ramp filter, cutoff frequency of 0.5 of the Nyquist frequency) with Fourier rebinning and with correction of attenuation using transmission data.

The TACs of arterial blood in the AV shunt were obtained from activity concentration data measured by the GSO detector, corrected for physical decay of ^{15}O and for cross-calibration between the GSO detector and the well counter.

2.6. Determination of image-derived TACs

To derive the image-based TAC, we identified the left ventricular blood pool from multiple PET images and derived time–activity concentration data from the H₂O PET scan [9]. To identify the region of blood pool, we subtracted the summed [^{15}O]CO image from the summed [^{15}O]H₂O image to generate an image that more clearly delineated the border of the myocardium and ventricle (Fig. 3A). A volume of interest (VOI) was defined by manually drawing the border of the ventricle, and the VOI was superimposed on the [^{15}O]H₂O dynamic images to obtain the TAC. As shown in this figure, the initial phase of the [^{15}O]H₂O image showed higher accumulation in the ventricle, while at the later equilibrium phase, the ventricular blood pool became indistinguishable from the myocardium, suggesting more homogenous activity concentration between these compartments at this phase. For the VOI analysis, we used the ASIPro VMimage analysis software (Concorde Micro systems, Knoxville, TN, USA).

2.7. Consistency of input functions obtained from the AV shunt and PET image

To compare the shape of the TACs from the AV-shunt technique and the PET image, we first derived an averaged TAC for each injection method (faster vs. slower) and measurement modality (AV shunt vs. image-derived). Averaging was performed across measurements and animals

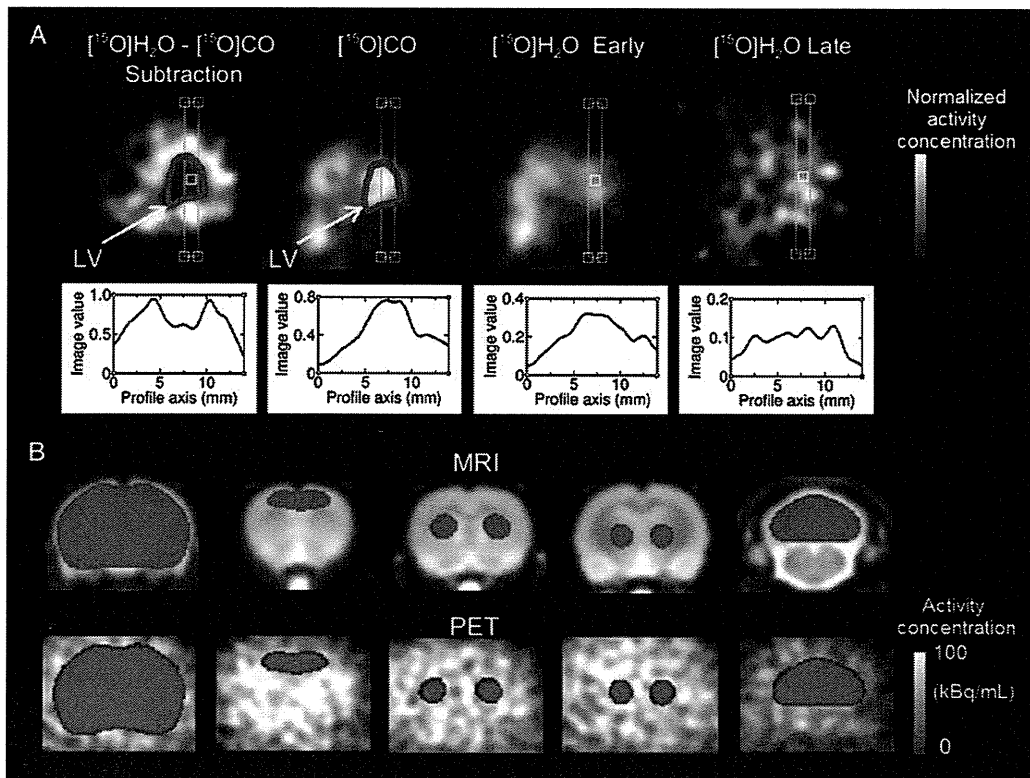


Fig. 3. VOIs. (A) VOI in the cardiac ventricle (delineated by red line). The VOI, delineated manually using the subtraction image of $[^{15}\text{O}]\text{H}_2\text{O}$ minus $[^{15}\text{O}]\text{CO}$ activity concentration (upper left), is transferred to the sum image of $[^{15}\text{O}]\text{CO}$ $[^{15}\text{O}]\text{H}_2\text{O}$ in the early phase (0–30 s) and $[^{15}\text{O}]\text{H}_2\text{O}$ in the late phase (150–180 s). Lower graphs show the profile of activity concentration on the line that is crossing the center of cardiac ventricle (as shown in light blue overlaid on the upper PET image). The image value in the graphs is in units of MBq/ml. Each PET image is shown in a gray color bar in an arbitrary range. (B) The coronal sections of MRI (upper) and PET images (lower) on which cerebral VOIs are overlaid in red. The furthest left section shows the whole-brain VOI. From the second left to right, the distance of each coronal slices was 2, 0, -2.6 and -12.0 mm from the bregma, each depicting the VOIs in the frontal cortex, striatum, thalamus and cerebellum, respectively. Each PET image was obtained by averaging dynamic PET images from 0 to 3 min. The activity concentration shown ranged from 0 to 100 kBq/ml as indicated in the gray color bar.

after normalization of the height and area under the curve. To eliminate variations in administered activity in each measurement, TACs were divided by the area under the curve (from 0 to 180 s). The rising time of each TAC was shifted to time zero by visual inspection. Then, the mean and standard deviation of the TACs were separately determined for each injection method and measurement modality. Finally, averaged TACs were normalized by their peak height and presented in the line chart (in Fig. 4A–B). A pair of AV-shunt and image-based TACs was obtained from the same PET measurement.

Since visual inspection of the shape of the average TAC led us to suspect significant dispersion in AV-shunt TAC as compared with image-based TAC, we investigated whether the dispersion could be corrected before calculating quantitative rCBF [9]. The correction of dispersion can be achieved by an empirical model of dispersion in which dispersion function was expressed in monoexponential function [9]. We estimated a dispersion time constant in this model equation using the “averaged TACs” of AV shunt and image based, since a statistical error in the TAC may affect the estimation of the dispersion. Dispersion time

constants (τ) of 0, 5 and 10 s were used to derive deconvolved TACs from the mean AV-shunt TACs and were plotted against time along with the image-based mean TAC. Among three tested values for τ , we chose the optimal dispersion time constant for the AV-shunt TAC by visually inspecting consistency of the shape of TACs during the initial rising phase (faster: 0–15 s, slower: 0–30 s) between deconvoluted AV-shunt and the image-based TACs. We used a program for deconvolution written in the C programming language.

Then, we compared the “absolute” activity concentration of the TACs of the AV-shunt and image-derived techniques, both obtained simultaneously in the same animal and PET scan. This was primarily for the purpose of determining the adequacy of the calibration and confirming the suitability of the AV-shunt TAC using image-based TAC as a reference. As described previously, the activity concentration of the image-based TAC obtained from cardiac ventricle should reflect the sum of the underestimated activity concentration in the cardiac ventricle and spillover activity from surrounding tissues (cardiac wall tissues). Thus, we estimated the intraventricular blood activity concentration from imaged-

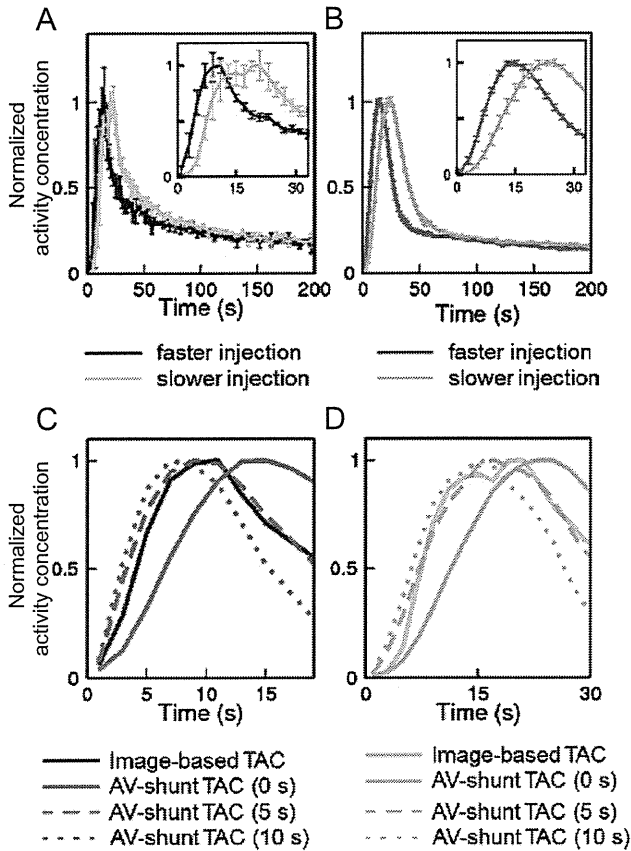


Fig. 4. Comparison of the normalized imaged-based and AV-shunt-derived TACs and of their dispersions. (A) Mean and standard deviation of normalized imaged-based TAC (obtained from the cardiac ventricular VOI) ($n=3$). Dark blue curve, faster injection; light blue curve, slower injection. (B) Mean and standard deviation of normalized AV shunt TAC ($n=3$). Red line, faster injection; orange line, slower injection. In each figure, the error bar indicates standard deviation, and the right upper inset shows the initial rising phase for a period of 30 s. Normalization was performed by scaling using the area under the curve and then the peak of TAC. Note that the standard deviation, particularly in the early rising phase, was much smaller in the AV-shunt TAC as compared with the image-based TAC. (C) Dispersion correction of AV-shunt TAC in faster injection. The blue line indicates the mean TAC obtained from the cardiac ventricle in the PET image, while red lines indicate the TAC of the AV shunt after correction of dispersion with time constants of 0, 5 and 10 s, respectively. (D) Dispersion correction of AV-shunt TAC in slower injection. The light blue line indicates the mean TAC obtained from the cardiac ventricle in the PET image, while orange lines indicate the TAC of the AV after correction of dispersion with time constants of 0, 5 and 10 s. In both faster and slower injection, the dispersion time constant of ~ 5 s appears to be the most optimal among the three for correcting the dispersion of AV-shunt TAC.

based TAC using a one-tissue, one-blood compartmental model of partial volume for the cardiac VOI [10]. The activity concentration in the cardiac ventricular VOI, $C_v(t)$ (Bq/ml), can be expressed by the following equation:

$$C_v(t) = \beta C_a(t) + \gamma \rho C_m(t), \quad (1)$$

where β is a recovery coefficient, γ is the spillover fraction of tissue activity concentration into left ventricle VOI, ρ is

the density of myocardium (g/ml) and C_m the activity concentration of myocardium (Bq/g) [10]. Here, $\beta + \gamma = 1$ if the heart (i.e., the dimensions of the left-ventricular cavity and myocardium) is “large” compared to the spatial resolution of the PET system [10]. The recovery coefficient (β) can be measured by calculating a ratio between mean activity concentration of the cardiac ventricular VOI during steady-state condition in the $[^{15}\text{O}]\text{CO}$ scan (Fig. 3) and actual blood activity concentration sampled during that period, as described previously [11,12]. In addition, under an equilibrium state, the activity concentration of myocardium (C_m) can be estimated by the following equation:

$$C_m = p C_a, \quad (2)$$

where p is a partition coefficient of cardiac tissue (ml/g) and C_a is the activity concentration of $[^{15}\text{O}]\text{H}_2\text{O}$ in blood (Bq/ml); thus, using Eqs. (1) and (2), C_a at an equilibrium state can be estimated from measured C_v by the following equation:

$$C_a = C_v / [\beta + (1 - \beta)\rho p] \quad (3)$$

using known values of ρ and p , 1.04 g/ml and 0.91 ml/g, respectively [10]. Therefore, the comparison of the C_a values estimated from Eq. (3) with the activity concentration of AV shunt at steady state (this should correspond to the blood activity concentration) will mainly indicate the eligibility of the two techniques. Since the equilibrium was achieved at time t from 120 to 180 s after PET scan, the value of C_v was measured from the cardiac ventricular VOI by averaging the activity concentration of $[^{15}\text{O}]\text{H}_2\text{O}$ during the corresponding period, and C_a was estimated from Eq. (3) using the measured value of β . The activity concentration of the AV shunt was obtained from averaged activity concentration during a period of 120–180 s and was compared with the values of C_a predicted from Eq. (3) and the image-based (cardiac ventricular VOI) TAC.

2.8. Regional CBF determination

Cerebral tissue TACs during $[^{15}\text{O}]\text{H}_2\text{O}$ PET scans were obtained from five regions of interest in the brain: frontal cortex, striatum, thalamus, cerebellum and whole brain. A standard T2-weighted magnetic resonance image (MRI) of a rat [13] was automatically realigned to the summed PET image by means of an image registration tool in the FSL software (version 4.1.4) (<http://www.fmrib.ox.ac.uk/fsl/index.html>) [14]. The cross-modal image registration was performed using a cost function of mutual information. The VOI for each brain region was manually drawn on the standard MRI, realigned using an inverted transformation matrix to the PET image and used to obtain the TAC for each VOI (Fig. 3B). The VOI volumes were 1472, 44.0, 22.4, 13.5 and 106 mm³ for the whole brain, frontal cortex, striatum, thalamus and cerebellum, respectively. The rCBF values were determined by using the input function of the

AV-shunt and cerebral TAC data in two steps. In the first step, we determined the time delay of the AV-shunt TAC as compared with cerebral whole-brain TAC by visual inspection. Using the predetermined time delay, the rCBF value for each region was estimated by means of a nonlinear least-square fitting procedure based on a one-tissue compartmental model [1–9,11–15], with unknown parameters of rCBF and partition coefficient p [16–18]. For the cerebral TAC, the initial period of 200 s was used for the fitting. The input function from the AV shunt was corrected for dispersion by deconvolving the original TAC using a single exponential function with a time constant of 5 s, determined based on the previous analysis.

Mathematical manipulations of TAC data and the fitting process to determine CBF were all performed using PyBLD (<http://www.mi.med.osaka-u.ac.jp/pybld/pybld.html>) built upon the Python language.

3. Results

3.1. Measurements of blood flow velocity in the AV-shunt line by ultrasonography

We evaluated the stability of the blood flow velocity in the AV-shunt line by comparing the relative velocity with that measured at a reference time point just before the [^{15}O] CO scan (Fig. 2). The time interval between the reference and the last time point (fourth) was 62 ± 9 min. When scaled by the velocity at the reference point, the relative velocity at the later time ranged from 0.9 to 1.3 (Table 1), and there was no single case in which the flow velocity in the AV-shunt line was systematically biased during the experiments.

3.2. Comparisons of shape of TACs between different methods of injection and input measurement

Fig. 4A–B shows the average and the standard deviation of TACs in which the peak and area under the curve were normalized and averaged for each injection method (faster vs. slower) and measurement method (PET image based vs. AV shunt and GSO based). As predicted, the faster bolus injection showed an earlier rising time and a sharper initial phase of the TACs than after slower injection in both measurement methods. The image-based method provided a much faster and more rapid increase in the normalized

Table 1
Relative velocity of blood in the AV shunt during PET scan

	PET scan		
	Heart [^{15}O]CO	Heart [^{15}O]H $_2\text{O}$	Brain [^{15}O]H $_2\text{O}$
Relative velocity	1.0(0.1)	1.1 (0.1)	1.2 (0.1)

Values were scaled by the initial velocity measured before heart [^{15}O]CO PET scan. Number of observation was $n=6$ for each variable. Values were shown as mean (S.D.). The repeated-measure ANOVA did not show any significant effect of scans.

Table 2
Estimated time delay of AV-shunt TAC as compared with image-based TAC

Injection methods	Estimated delay (s)	
	Between AV-shunt TAC and image-based TAC	Between AV-shunt TAC and whole-brain TAC of cardiac ventricle
Faster injection	11 (9, 12)	9 (7, 11)
Slower injection	20 (18, 21)	17 (16, 18)

Values are shown in median (minimum, maximum) in unit of second. The number of observation was $n=3$ for each injection method. Two-way ANOVA with factors of injection speed (faster vs. slower) and reference TAC (image-based TAC vs. whole-brain TAC) disclosed significant effects of injection speed ($F_{1,8}=89.7, P<.001$) and reference TAC ($F_{1,8}=5.82, P<.05$).

activity and showed a sharper spike shape of the TAC, suggesting less dispersion of the curve shape. However, the standard deviation of the image-based TAC was relatively larger than that of the AV-shunt TAC, suggesting that the image-derived TACs suffer from more statistical noise and/or net detector sensitivity than the AV-shunt method. As also shown in Fig. 4, the AV-shunt-derived TACs were more dispersed than the image-derived converts, particularly in the initial portion of the curves, suggesting that a correction for the dispersion of AV-shunt-derived TACs may be required. The estimated time delays for the AV-shunt-derived versus the image-based TACs are listed in Table 2.

3.3. Dispersion correction of AV-shunt TAC

Fig. 4C shows the effect of dispersion correction on averaged TACs. When corrected by $\tau=5$ s, the shape of the dispersion-corrected mean AV-shunt TAC agreed well with that of the image-derived TAC, as compared with those with corrections of $\tau=0$ and 10 s. We did not estimate the degree of dispersion for each single measurement since the deconvolution performed in the dispersion correction enhances the statistical noise of TAC curves, making it difficult to estimate the size of dispersion. Therefore, we applied the fixed value of $\tau=5$ for correcting the dispersion for each AV-shunt TAC and used them for further analysis since the dispersion constant may be considered almost invariable if the geometry of blood flow paths including arterial architecture and AV-shunt line were the same across measurements.

3.4. Absolute activity concentration in the AV-shunt and image-derived TACs

Fig. 5A shows a comparison of the absolute activity concentration of the TACs obtained from the AV shunt and cardiac PET image in all the test animals. As shown in this figure, at the early phase, the peak of the AV-shunt TAC (red line) was higher than that of image-based TAC (blue line). As shown in Fig. 3A (in the panel second from the right), at the early phase of [^{15}O]H $_2\text{O}$ scan, the activity concentration of the [^{15}O]H $_2\text{O}$ was higher in the center of cardiac ventricle,

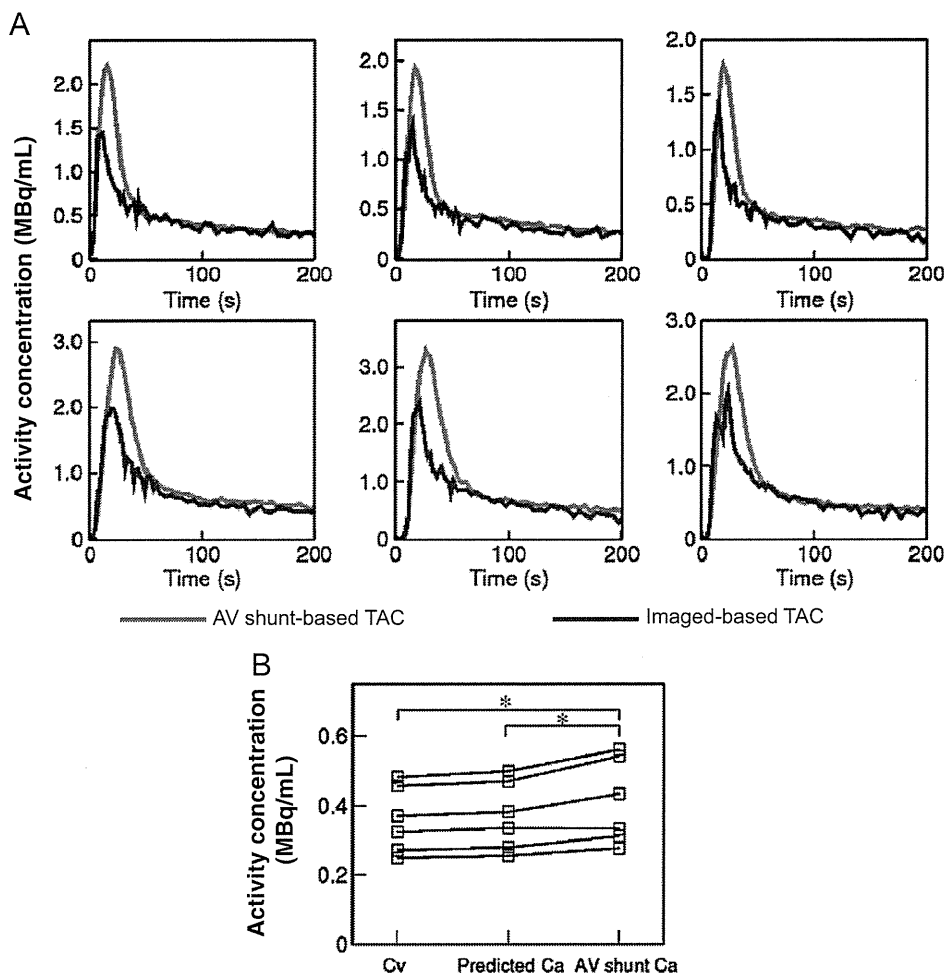


Fig. 5. Image-based and AV-shunt-derived TACs. (A) Absolute activity concentration of the AV-shunt TAC (red) and image-based cardiac ventricular TAC (blue) in all animals. The AV-shunt TAC (red) was corrected for dispersion (a time constant of 5 s), delay and calibration between the GSO detector and PET. Note that the image-based TAC shows almost comparable activity concentration as the AV shunt in the later equilibrium stage (from ~50 to 180 s), while it showed lower peak height of activity concentration in the early phase. (B) Activity concentration measured in the image-based cardiac ventricular VOI (C_v), predicted blood activity concentration (predicted C_a) and measured AV-shunt activity concentration (AV-shunt C_a). * $P < .05$ in paired t test.

suggesting the underestimation of blood activity concentration in the image-based TAC. Actually, the value of β (recovery coefficient for the cardiac VOI) was evaluated to be 0.43 ± 0.05 from the data obtained during [^{15}O]CO scan (Table 3). The underestimation of the peak concentration was $\sim 28.3\% \pm 4.4\%$ by the image-based TAC as compared with AV-shunt TAC. In addition, at the later phase, the activity concentration of image-based TAC was comparable to the height of AV-shunt TAC in all animals (Fig. 5A),

Table 3
Measured and estimated variables from VOI of left ventricle

Variables	Mean \pm S.D.
VOI (μl)	29.0 \pm 0.3
Estimated recovery coefficient of left ventricular VOI (β)	0.43 \pm 0.05

Values were obtained from cardiac PET data with [^{15}O]CO and [^{15}O]H $_2$ O ($n=6$).

suggesting that [^{15}O]H $_2$ O diffused into the cardiac wall tissue and the spatial distribution of the activity extended over a larger region including the myocardial wall as well as the intraventricular cavity (i.e., a region whose dimensions were sufficiently large to minimize the partial volume effect). Consistent with this hypothesis, the count profiles over the late [^{15}O]H $_2$ O images were flatter than those over the early images (Fig. 3A).

The foregoing was corroborated by comparison of the steady-state portions of the AV-shunt-derived TAC and of the imaged-derived curve based on the one-tissue, one-blood compartment model [Eq. (3)]. The averaged blood activity concentration ($120 < t < 180$ s) measured by the AV shunt varied from 0.28 to 0.56 MBq/ml (mean \pm S.D.= 0.41 ± 0.11 MBq/ml). The predicted blood activity from Eq. (3) using the image-based VOI data ranged from 0.25 to 0.50 kBq/ml (0.37 ± 0.09 MBq/ml). Fig. 5B shows a plot of the measured image-based VOI activity concentration (C_v), blood activity

concentration predicted by Eq. (3) (predicted C_a) and AV-shunt blood activity concentration (AV-shunt C_a) in each animal. As shown in this figure, there was significant bias among three measures [repeated analysis of variance (ANOVA), $F_{2,5}=17.9$, $P<.001$]. There was significant differences in blood activity concentration between C_v and AV-shunt C_a and between the predicted C_a and the AV-shunt C_a (post hoc pairwise comparison with correction multiple comparison, $P<.05$). There was a significant linear relationship between predicted C_a and AV-shunt C_a [AV-shunt C_a (MBq)=1.21*predicted C_a (MBq)-4.0×10⁻², $R^2=0.98$, $P<.001$]. This suggests, however, that the bias was relatively small (i.e., only ~20%); the measured activity concentration of AV shunt at the steady state was comparable to and consistent with the blood activity concentration predicted from image-based VOI in the current system of rat heart/micro-PET.

3.5. Quantification of rCBF

The mean and S.D. of rCBF values (in ml/min/g) was 0.37±0.04 in the whole brain, 0.40±0.08 in the frontal cortex, 0.41±0.06 in the striatum, 0.36±0.04 in the thalamus and 0.36±0.05 in the cerebellum (see Table 4 for all the data). The mean and S.D. for partition coefficient (p) in the whole brain was 0.73±0.04 ml/g. No statistically significant difference was observed in rCBF values between faster and slower bolus injections ($P>.05$). Whole-brain rCBF values were plotted against pCO₂ values in all the animals except one, in which we failed to measure the pCO₂ (Fig. 6). As shown in this figure, a linear relationship was obtained between pCO₂ and whole-brain rCBF values [rCBF=0.01×pCO₂+0.06 ($R^2=0.90$, $P<.001$)]. The estimated time delay between whole-brain TAC and AV-shunt TAC is also listed in Table 2; as predicted, the estimated delay was consistently 3–4 s shorter than that between cardiac ventricular TAC and AV-shunt TAC for both injection methods.

4. Discussion

There has been no unbiased measurement method for arterial input function (as well as for blood flow) in rodents PET. The manual sampling may have been a conventional

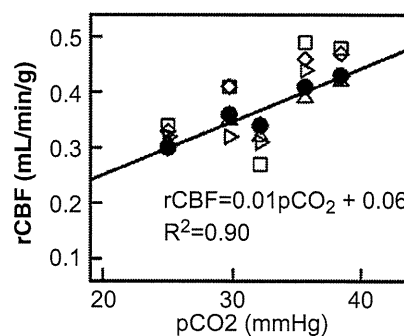


Fig. 6. Correlation between rCBF by brain region and blood pCO₂ using the AV-shunt-derived arterial input function. ●: whole brain, □: frontal cortex, ◇: striatum, Δ: thalamus, ▽: cerebellum.

way of measuring input function, but apparently, it should have substantial bias due to insufficient temporal resolution. Invasiveness of this method makes it difficult for us to fully analyze or understand the actual bias of this system. In this paper, we described an AV-shunt technique for acquiring the arterial input function of [¹⁵O]H₂O during PET acquisition in rats and used an image-based method as a reference of AV-shunt since it has already been used in the past literatures [2,10]. In the ultrasonographic evaluation of the blood flow through the AV shunt, none of the animals showed any evidence of stagnation in the shunt line, which potentially degrades the measurement of blood activity or the shape of AV-shunt TAC. The image-based TAC was obtained using the [¹⁵O]H₂O PET data of the heart chamber based on a method described previously [10]. The results revealed that the count noise, one of the major error sources of activity concentration, was small in the AV-shunt TAC (as compared with image-based TAC) and that the shape of the AV-shunt-based TAC is not attenuated very much and could be properly corrected for time delay and dispersion. In contrast, the image-based method suffered from the partial volume effect even after the model-based correction, and the effect size was varied across time after injection. The PET scan for the brain with the AV shunt provided rCBF values that showed physiologically plausible variation depending on the blood carbon dioxide level. These findings suggest that the AV-shunt technique could be useful for future studies for rCBF measurements. The concept of the current study in

Table 4
rCBF values measured by [¹⁵O]-H₂O PET and AV-shunt technique

Subjects	pCO ₂	rCBF (p)				
		Whole brain	Frontal cortex	Striatum	Thalamus	Cerebellum
1	32.1	0.34 (0.77)	0.27 (0.64)	0.34 (0.86)	0.32 (0.94)	0.31 (0.76)
2	38.4	0.43 (0.80)	0.48 (0.88)	0.47 (0.89)	0.42 (0.86)	0.43 (0.78)
3	35.6	0.41 (0.71)	0.49 (0.80)	0.46 (0.79)	0.39 (0.96)	0.44 (0.72)
4	–	0.37 (0.70)	0.44 (0.77)	0.40 (0.79)	0.37 (0.77)	0.36 (0.66)
5	25.0	0.30 (0.69)	0.34 (0.71)	0.33 (0.73)	0.31 (0.74)	0.32 (0.72)
6	29.7	0.36 (0.69)	0.41 (0.73)	0.41 (0.78)	0.35 (0.80)	0.32 (0.65)

The values of pCO₂ are shown in unit of mmHg, rCBF in ml/g/min and p in ml/g, respectively. We failed to measure the value of pCO₂ of subject 4.

terms of bias and noise in measured arterial inputs is not new in the field of clinical nuclear medicine, but has been rarely taken into account in the field of molecular imaging in small animals. The results provide important messages for researchers who quantify CBF in rodents using PET.

One advantage of the AV-shunt TAC method over the image-based one may be higher temporal resolution and signal-to-noise ratio. As shown in Fig. 4, our approach for the AV-shunt-based TAC clearly detected different shapes of the input function between the faster and slower bolus injections, despite a small difference in the total period for injection. In addition, the figure shows that the error of the mean is also relatively smaller with the AV-shunt technique compared with the image-based one. These findings indicate that the AV-shunt-derived TAC may have less statistical error, mainly due to the high sensitivity of the detector geometry, and thus yield less propagated error associated with the calculated rCBF values than the image-based TAC. The shape of AV-shunt TAC may have been degraded by the dispersion; however, the amount of the dispersion was not too large ($\tau = 5$ s), which was consistent for both injection methods (faster and slower) and was accurately correctable [19]. Iida et al. showed that, in humans, the arterial TAC derived from the radial artery was comparable to the cardiac image-derived TAC if the arterial TAC was corrected for dispersion using a time constant of 4 s [20]. In rats, Weber et al. estimated that the potential dispersion of TAC originating within the shunt tube was in a very small range, but they did not evaluate the actual dispersion time constant needed for correction. Thus, it is notable that our data show that the time constant of dispersion is small enough to properly correct dispersion of AV-shunt TAC in the current rat PET system.

Another notable advantage of the use of AV-shunt-based TAC over the image-based TAC is no necessity for correction of the height of the curve other than calibration for the activity concentration detectors. The activity concentration of cardiac ventricular VOI in the early phase of PET scan consistently showed lower values than those in the AV-shunt TAC, presumably due to predominant spill-out effect rather than spill-in in this early phase. Actually, the current data of [^{15}O]CO scan indicate that this underestimation was ~ 0.43 as a recovery coefficient (Table 3). The steady-state blood activity concentration estimated by AV shunt (AV-shunt C_a) was very close to that predicted from the image-based TAC.

Although we used imaged-based TAC as a reference, after correction for partial volume, it did not fully recover the blood activity concentration of [^{15}O]H $_2$ O, particularly at the early phase of TAC. There was a significant underestimation in the initial phase ($\sim 28\%$) and even in the steady-state period ($\sim 20\%$) (Fig. 5A). The reason for this underestimation may be due to the small size of the heart as compared with the resolution of the current PET scanner, which violates the assumption of the model equation for partial volume (i.e., $\beta + \gamma = 1$). Actually, our [^{15}O]CO results showed small value of recovery coefficient (~ 0.43) for the left-

ventricle ROI, and previous simulation studies also indicated that recovery coefficient of less than 0.65 may result in underestimation of TAC when derived from human left ventricle [10]. Thus, future studies should improve the model to obtain accurate blood TAC from PET image in rat heart.

Other investigators have attempted to derive to a standard input function for small-animal PET study but for a more slowly cleared and localizing tracer, namely, ^{18}F -fluorodeoxyglucose [21]. Because of the fast kinetics of [^{15}O]H $_2$ O, it may be difficult to use the standard input function for this tracer; thus, it requires to be evaluated in detail. In particular, the difference in the delay time of the rising time of TAC should be strictly standardized. In addition, the injection rate of tracer activity concentration should always be standardized, so that an automatic injector that allows a constant infusion of the tracer is recommended. Further, our results suggest that, with careful standardized injections, the use of average small-animal arterial input functions for “fast” tracers such as [^{15}O]H $_2$ O as well as “slower” tracers such as [123I]iodoamphetamine may be valid.

Our motivation to measure blood flow velocity in the AV shunt by ultrasonography was concern for potential occlusion of the line by blood clotting during experiments, which may affect the shape of arterial input curves. Weber et al. showed that there were rare cases of clogging in their AV-shunt method where they did not perform heparinization beforehand and used multiple stopcocks for blood sampling, which may have induced turbulent blood flow and facilitated clot formation [5]. In our case, the AV-shunt line and the animals' blood were both heparinized, and no three-way stopcock was used in the AV-shunt line, thereby avoiding any potential clot inducing of blood flow. The flow velocity inside the tube did not actually decrease within a period of about 1 h during the experiments, suggesting that clot formation was successfully prevented by the current method. On the other hand, there may be potential bleeding when heparin is administered, but none of the test animals in the current study showed such bleeding during the experiments.

There is an extensive literature on the relationship between rCBF and pCO $_2$. Our study showed a significant correlation between rCBF and pCO $_2$; in particular, the slope of the regression line ($\Delta\text{CBF}/\Delta\text{pCO}_2 = 0.01$) was comparable to that obtained in primate animals by Grubb et al. [22]. By an intracarotid injection method using [^{15}O]H $_2$ O tracer and [^{15}O]CO, they showed that the rCBF values of anesthetized monkeys had the following relationship with pCO $_2$: rCBF (ml/g/min) = $0.018 \times \text{pCO}_2$ (mmHg) - 0.17. Other researchers also reported that, in anesthetized monkeys, the value of $\Delta\text{CBF}/\Delta\text{pCO}_2$ was 0.011 [23] and 0.012 [24]. In recent literature, Williams et al. (1992) reported that rCBF measured by a spin-labeling method using MRI had a linear relationship with arterial pCO $_2$ in anesthetized rats and that the value of $\Delta\text{CBF}/\Delta\text{pCO}_2$ was 0.052 [25]. Despite variations in species, anesthetic conditions and measurement methods, our data demonstrating the linear relationship

between rCBF and pCO₂ in rats are consistent with these previous studies.

Our study has several implications for future research in neurophysiology. First, the current method could be used for repeated measurements of quantitative CBF in a single experiment. This could be useful, for example, to evaluate acute hemodynamic changes after pharmacological intervention or during behavioral tasks. It also allows measurement of the cerebral metabolic rate of oxygen utilization, which requires different PET scans using multiple tracers, such as ¹⁵O-labeled water, oxygen and carbon monoxide [26]. Second, the current AV-shunt method could be used for other radiotracers not only for PET but also for single photon emission computed tomography since the GSO detector we used is sensitive to a wide range of photon energies [7]. Third, the current AV-shunt technique can be used in the future to validate more empirical methods of image-based TAC derivation (e.g., Yee et al. [2]) under various possible conditions.

There are several limitations in the AV-shunt technique. First, this method may be technically demanding and particularly difficult when measuring very frequently on different days in the same animal. The catheterized femoral artery and vein were sutured and occluded after the experiment; thus, it is difficult to repeat this study more than twice in the same animal. This could be overcome by using microsurgery to suture the arterial walls without occluding the lumen. Second, the estimation of dispersion may be difficult in each measurement due to the statistical noise in the measured TAC. Therefore, preparation of the AV shunt must be performed in the same manner, particularly in terms of the length and caliber of the shunt tube, site of artery catheter placement and physiological conditions of the animals, which may affect the laminar flow of sampling blood.

5. Conclusions

We confirmed the stability of the AV-shunt technique for measurement of the arterial input function in small animals. The AV-shunt method allowed us to obtain input TAC with less statistical noise than the image-based one and to calculate rCBF using the micro-PET scanner, and proved to be quantitative in identifying physiological changes in rCBF. In contrast, the image-based TAC suffered from the partial volume and could not be fully recovered even after correction particularly during the initial peak phase of input TAC of [¹⁵O]H₂O. The AV-shunt technique could be useful for less invasive measurement of cerebral hemodynamics in small animals than the conventional blood sampling method.

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References

- [1] Kanno I, Iida H, Miura S, Murakami M, Takahashi K, Sasaki H, et al. A system for cerebral blood flow measurement using an H₂¹⁵O autoradiographic method and positron emission tomography. *J Cereb Blood Flow Metab* 1987;7:143–53.
- [2] Yee S, Jerabek PA, Fox PT. Non-invasive quantification of cerebral blood flow for rats by microPET imaging of ¹⁵O labelled water: the application of a cardiac time-activity curve for the tracer arterial input function. *Nucl Med Commun* 2005;26:903–11.
- [3] Matsumoto A, Namon R, Utsunomiya Y, Kogure K, Scheinberg P, Reinmuth OM. The measurement of cerebral blood flow in the rat. *Stroke* 1975;6:630–7.
- [4] Ingvar M, Eriksson L, Rogers GA, Stone-Elander S, Widén L. Rapid feasibility studies of tracers for positron emission tomography: high-resolution PET in small animals with kinetic analysis. *J Cereb Blood Flow Metab* 1991;11:926–31.
- [5] Weber B, Burger C, Biro P, Buck A. A femoral arteriovenous shunt facilitates arterial whole blood sampling in animals. *Eur J Nucl Med Mol Imaging* 2002;29:319–23.
- [6] Weber B, Späth N, Wyss M, Wild D, Burger C, Stanley R, et al. Quantitative cerebral blood flow measurements in the rat using a beta-probe and H₂¹⁵O. *J Cereb Blood Flow Metab* 2003;23:1455–60.
- [7] Kudomi N, Eunjo C, Yamamoto S, Watabe H, Kyeong, Min K, et al. Development of a GSO detector assembly for a continuous blood sampling system. *EEE Trans NuclSci* 2003;50:70–3.
- [8] Kim JS, Lee JS, Im KC, Kim SJ, Kim S, Lee DS, et al. Performance measurement of the microPET focus 120 scanner. *J Nucl Med* 2007;48:1527–35.
- [9] Iida H, Kanno I, Miura S, Murakami M, Takahashi K, Uemura K. Error analysis of a quantitative cerebral blood flow measurement using H₂¹⁵O autoradiography and positron emission tomography, with respect to the dispersion of the input function. *J Cereb Blood Flow Metab* 1986;6:536–45.
- [10] Iida H, Rhodes CG, de Silva R, Araujo LI, Bloomfield PM, Lammertsma AA, et al. Use of the left ventricular time-activity curve as a noninvasive input function in dynamic oxygen-15-water positron emission tomography. *J Nucl Med* 1992;33(9):1669–77.
- [11] Bergmann SR, Fox KA, Rand AL, McElvany KD, Welch MJ, Markham J, et al. Quantification of regional myocardial blood flow in vivo with H₂¹⁵O. *Circulation* 1984;70:724–33.
- [12] Araujo LI, Lammertsma AA, Rhodes CG, McFalls EO, Iida H, Rechavia E, et al. Noninvasive quantification of regional myocardial blood flow in coronary artery disease with oxygen-15-labeled carbon dioxide inhalation and positron emission tomography. *Circulation* 1991;83:875–85.
- [13] Schweinhardt P, Fransson P, Olson L, Spenger C, Andersson JLR. A template for spatial normalisation of MR images of the rat brain. *J Neurosci Methods* 2003;129(2):105–13.
- [14] Smith SM, Jenkinson M, Woolrich MW, Beckmann CF, Behrens TEJ, Johansen-Berg H, et al. Advances in functional and structural MR image analysis and implementation as FSL. *Neuroimage* 23 Suppl 2004;1:S208–19.
- [15] Kety SS, Schmidt CF. The nitrous oxide method for the quantitative determination of cerebral blood flow in man; theory, procedure and normal values. *J Clin Invest* 1948;27:476–83.
- [16] Huang SC, Carson RE, Hoffman EJ, Carson J, MacDonald N, Barrio JR, et al. Quantitative measurement of local cerebral blood flow in humans by positron computed tomography and ¹⁵O-water. *J Cereb Blood Flow Metab* 1983;3:141–53.
- [17] Iida H, Kanno I, Miura S, Murakami M, Takahashi K, Uemura K. A determination of the regional brain/blood partition coefficient of water