Annals of Nuclear Medicine Vol. 17, No. 5, 375–380, 2003

Counting efficiency of a double-well single-plastic scintillation counter to commercially available radionuclides (Tl-201, Tc-99m, I-123, Ga-67, In-111 and I-131)

Kazuo ITOH* and Kimikazu SASAKI**

**Department of Radiology and **Technician's Section of Diagnostic Radiology, JR Sapporo General Hospital*

A new type of well-scintillation counter with a double-well and single-plastic scintillator (DW-counter) was developed to simplify time consuming and cumbersome dilution procedures inherent to *in-vivo* sample measurement. It has the potential to measure many radionuclides which emit a gamma ray or positron. We tested the counting efficiency (CE) of the DW-counter (DCM-200, Aloka Co., Tokyo, Japan) with respect to 6 radionuclides. ***Materials and Methods:*** The outline of DW-counter is altered to a single unit as compared to the prototype, while its basic mechanical constitution was not changed. Six commercially available radionuclides (Tl-201, Tc-99m, I-123, Ga-67, In-111, I-131) were used in this study. For each radionuclide, we prepared two standard solutions containing high (>100 MBq/m*l*) and relatively low radioactivity (10–20 MBq/m*l*). The radioactivity (Bq) of the radionuclide in each sample at time = 0 was measured with a dose calibrator. Afterwards, it was determined from a decay-time with correction by the physical half-life of each radionuclide. Count rate (cps) of each standard sample was measured in each well ten times per sample. The counting efficiency (CE) of the counter for each radionuclide was determined by measured count rate (cps)/standard radioactivity (Bq) × 100 (%). The conversion constant (CC) which predicts standard radioactivity (Bq) from measured count rate (cps) was obtained as a reciprocal value of the CE. ***Results:*** The CE (mean ± SD) in well-A to Tl-201, Tc-99m, I-123, Ga-67, In-111 and I-131 was 5.90 ± 0.285%, 8.56 ± 0.0981%, 8.33 ± 0.344%, 7.77 ± 0.15%, 16.4 ± 0.495% and 10.2 ± 0.139%, respectively. They were significantly different. The coefficient of variation of the measured count rates was less than 1% in radioactive range higher than 10^3 Bq in well-A and 10^6 Bq in well-B. The difference in the CE between well-A and -B ranged from 7.614 × 10^2 (I-131) to 9.395 × 10^2 (Tl). The CC ranged from 6.14 (In) to 17.15 (Tl) in well-A and from 5.05057 × 10^3 (In) to 15.83773 × 10^3 (Tl) in well-B. The CE was not significantly affected by a sample volume from 1 to 4 m*l* in well-A, but showed a slight difference in well-B, which seemed due to a collimation. ***Conclusion:*** The measurement error of the DW-counter was less than 1% and the measured count rate (cps) was exactly converted to the standard radioactivity (Bq) by determined CC. The counter is considered useful in the easy evaluation of *in-vivo* tracer kinetics by avoiding time consuming and cumbersome dilution techniques.

Key words: plastic scintillator, well counter, counting efficiency, *in-vivo* pharmacokinetics

MEASUREMENT of the radioactive concentration of *in-vivo* samples such as blood, plasma and urine is needed for quantifying function in external imaging study using radionuclides. In these procedures, dilution of an injected radioactive tracer is essential. Technical practice is somewhat laborious and requires expertise for accurate measurement. Nonetheless, dilution is considered as a major

Received December 26, 2002, revision accepted April 14, 2003.

For reprint contact: Kazuo Itoh, M.D., Department of Radiology, JR Sapporo General Hospital, Higashi-1, Kita-3, Chuo-ku, Sapporo 060–0033, JAPAN.

E-mail: itohka51@ra2.so-net.ne.jp

source of error even in institutions frequently performing plasma sample clearance.[1] In order to simplify the procedures related to dilution, we have developed a double-well single-plastic scintillation counter (DW-counter) that has a very wide dynamic range of about 10^6 orders for radioactive measurement. We attempted to determine the glomerular filtration rate (GFR) by means of the prototype.[2] The DW-counter was proved to have relevance for the GFR determination using Tc-99m-DTPA. We suggested that the DW-counter can be useful in the simple and accurate determination of the GFR by means of the plasma clearance method following a single injection of Tc-99m-DTPA in routine renography.[3,4]

The instrument has a potentiality to measure radioactivity of all radionuclides which emit a gamma-ray or positron. We used to evaluate counting efficiency of the prototype only to Tc-99m.[2] The commercial product has been improved for the operation and calculation of samples. In the present paper, we evaluated counting efficiency of the new commercial product to commercially available radionuclides: Tl-201 (Tl), Tc-99m (Tc), I-123, Ga-67 (Ga), In-111 (In) and I-131.

Fig. 1 Photograph of a double-well single-plastic scintillation counter (DCM-200, Aloka Co., Tokyo, Japan). Well A is for a sample-tube with a low radioactivity and well B is for a injection syringe with high radioactivity.

MATERIALS AND METHODS

Specifications for the DW-Counter

In comparison with the prototype, the composition of the commercial product (DCM-200, Aloka Co., Tokyo, Japan) was changed to a single unit (Fig. 1). In addition, the mechanical improvement for making the background activity as low as possible and the operation systems for easy setting and counting of samples were developed. However, basic mechanical constitution of the DW-counter was not changed: (1) the first well (well-A) for plasma samples with low radioactivity; (2) the second well (well-B) for counting high radioactivity in a straight needle injection syringe with an attached 3-way cock; (3) the single plastic scintillator (cylindrical, 60 mm in external diameter, 40 mm in internal diameter, 10 mm thick and 100 mm in height); (4) the maximum capacity of 4 m*l* in a sample tube and the full injection syringe up to 5 m*l* (5 m*l* syringe) in well-B; (5) a lead collimator between the two wells; (6) 2 photo-multipliers with a coincidence circuit; (7) no mechanical discrimination against emitted energy.

Radionuclides Studied

Radionuclides used for the study were obtained as commercial preparations (Ga-67 citrate, Tl-201 chloride and

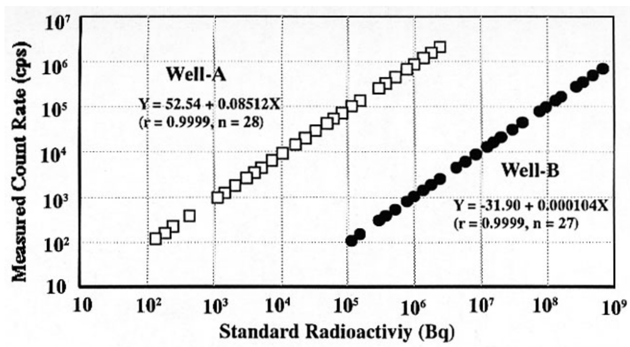

Fig. 2 An example of scatter plots of measured count rates (cps) in both well-A (□) and well-B (●) against standard radioactivity (Bq) of Tc. The regression lines in both wells are linear.

Table 1 Counting efficiency of the counter for 6 radionuclides in well-A and well-B

Radionuclide	Counting efficiency (%)*						A/B ratio** ($\times 10^2$)
	Well-A			Well-B			
	radioactive range	mean	SD	radioactive range	mean ($\times 10^{-3}$)	SD ($\times 10^{-3}$)	
Tl-201	200 Bq–2.1 MBq	5.90	0.285	170 kBq–120 MBq	6.28	0.146	9.395
Tc-99m	130 Bq–2.5 MBq	8.56	0.0981	110 kBq–650 MBq	10.2	0.272	8.392
I-123	500 Bq–1.4 MBq	8.33	0.344	150 kBq–122 MBq	9.8	0.0696	8.50
Ga-67	140 Bq–1.02 MBq	7.77	0.150	80 kBq–104 MBq	9.35	0.12	8.31
In-111	140 Bq–1.01 MBq	16.4	0.495	57 kBq–188 MBq	19.8	0.636	8.283
I-131	135 Bq–1.9 MBq	10.15	0.139	113 kBq–25 MBq	13.33	0.254	7.614

* counting efficiency: (measured count rate (cps)/standard radioactivity (Bq)) × 100 (%)
** A/B ratio: (mean CE in well-A)/(mean CE in well-B)

Tc-99m pertechnetate eluted from the generator and I-131-adosterol which were supplied by Daiichi Radioisotope Laboratory Co., Tokyo, Japan, and In-111 chloride and I-123-BMIPP which were supplied by Medi-Physics Japan, Takarazuka, Japan).

Preparation of Standard Samples for Each Radionuclide
For each radionuclide, we prepared two standard sample solutions containing high (>100 MBq/m*l*) and relatively low radioactivity (10–20 MBq/m*l*) in each. These were sealed in a plastic tube (maximum volume capacity 4.0 m*l*). First, the absolute radioactivity (Bq) of the radionuclide in each standard sample (1 m*l*) at time = 0 was determined by a dose calibrator (ion chamber: IGC-3, Aloka, Japan). Afterwards, it was calculated from decay time with a correction by physical half-life of each radionuclide.[5] The standard sample solution with low radioactivity was prepared for well-A, which is arranged to simulate a regular single-well scintillation counter for plasma samples. The standard sample solution with high radioactivity was prepared for well-B, which is designed specially for counting radioactivity in a straight needle injection syringe with an attached 3-way cock.[2] Each standard sample solution was counted for 1 minute in each well ten times per sample. When the count rate was close to the background activity, the sample was counted for 5 minutes. For I-131 as an example, the measurement was completed in 6 months.

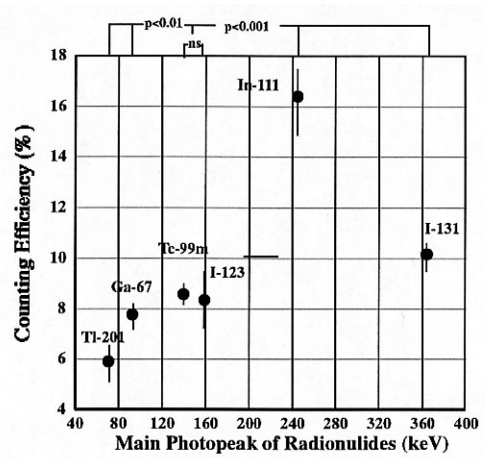

Fig. 3 Relationship between counting efficiency of plastic scintillator against main photopeak energy emitted from 6 radioactive isotopes. The circle indicates the mean and the bar represents the range of 2 SD.

Counting Efficiency and Conversion Constant to Each Radionuclide
The counting efficiency (CE) of the counter to each radionuclide was determined as a ratio (percentage) of the measured count rate (cps) for standard radioactivity (Bq). The conversion constant (CC), which estimates the standard radioactivity from the measured count rate, was determined as the reciprocal value of the arithmetic mean CE.

Effective Volume Capacity in Each Well
The effective volume capacity for counting in each well was tested using Tc-99m. In this experiment, a single standard sample of 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 m*l* in each glass tube (maximum volume capacity 7.0 m*l*) was prepared. They contained radioactivity of about 40 MBq, which was determined with a dose calibrator. Each of them was immediately counted 5 times at the center of a collimator window in well-B. Afterwards when the radioactivity was decreased to a sufficiently low level to be

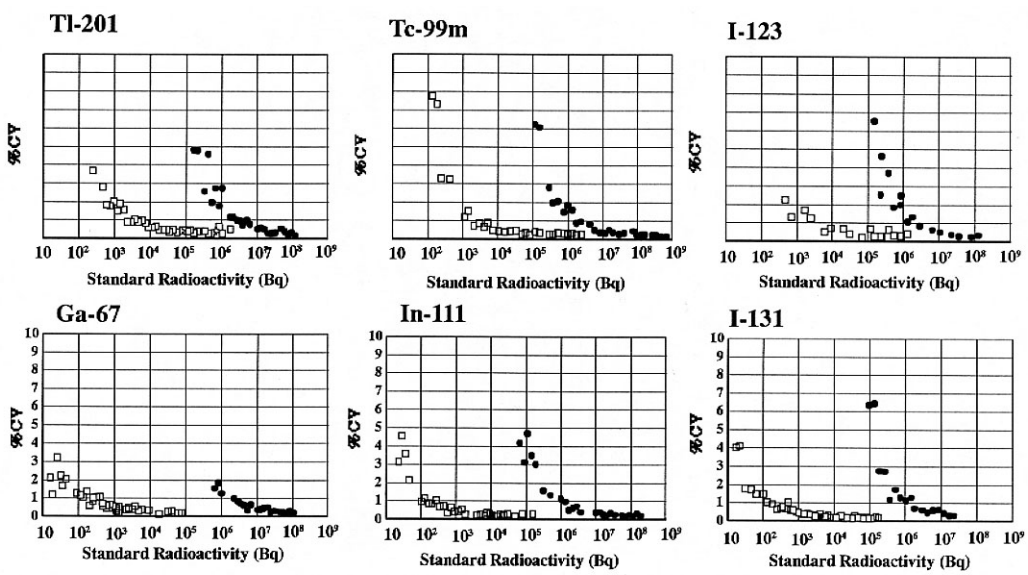

Fig. 4 Scatter plots of the values of the coefficient of variation (CV) of measured count rates against standard radioactivity. The CV exceeds 1% in radioactive range less than about 10^3 Bq in well-A (□) and 10^6 Bq in well-B (●).

Table 2 Coefficient of variation of the measured count rate for 6 radionuclides in well-A and well-B

Radionuclide	Well-A		Well-B	
	radioactive range	mean CV (%)*	radioactive range	mean CV (%)
Tl-201	200 Bq–2.1 MBq	0.860	170 kBq–120 MBq	1.400
	1 kBq–2.1 MBq	0.417	1 MBq–120 MBq	0.557
Tc-99m	130 Bq–2.5 MBq	1.179	110 kBq–650 MBq	1.199
	1 kBq–2.5 MBq	0.478	1 MBq–650 MBq	0.529
I-123	500 Bq–1.4 MBq	0.672	150 kBq–122 MBq	1.821
	1.6 kBq–1.4 MBq	0.536	1.3 MBq–122 MBq	0.609
Ga-67	140 Bq–1.02 MBq	0.962	60 kBq–104 MBq	1.137
	1.1 kBq–1.02 MBq	0.576	1 MBq–104 MBq	0.475
In-111	140 Bq–1.01 MBq	0.843	57 kBq–188 MBq	0.930
	1 kBq–10.1 MBq	0.411	1 MBq–188 MBq	0.410
I-131	115 Bq–1.9 MBq	0.624	68 kBq–25 MBq	1.934
	1 kBq–1.9 MBq	0.624	1 MBq–25 MBq	0.640

*CV: (standard deviation of the estimate/mean of the estimate) × 100%

Table 3 Conversion constant which estimates standard radioactivity from measured count rate in well-A and well-B

Radionuclide	Conversion constant*							
	Well-A				Well-B			
	radioactive range	mean	SD	95% confidence interval	radioactive range	mean (× 10^3)	SD (× 10^3)	95% confidence interval (× 10^3)
Tl-201	1 kBq–2.1 MBq	17.15	0.710	16.82–17.49	1 MBq–120 MBq	15.83773	0.34906	15.64593–16.02953
Tc-99m	1 kBq–2.5 MBq	11.70	0.0764	11.66–11.73	1 MBq–650 MBq	9.71087	0.07437	9.67326–9.74849
I-123	1.6 kBq–1.4 MBq	12.11	0.225	11.98–12.24	1.3 MBq–122 MBq	10.19732	0.09291	10.12727–10.26738
Ga-67	1.1 kBq–1.02 MBq	12.89	0.169	12.82–12.95	1 MBq–104 MBq	10.68859	0.04968	10.66210–10.71507
In-111	1 kBq–10.1 MBq	6.14	0.109	6.10–6.20	1 MBq–188 MBq	5.05057	0.01886	5.04052–5.6063
I-131	1 kBq–1.9 MBq	9.82	0.090	9.79–9.85	1 MBq–25 MBq	7.49983	0.03019	7.47823–7.52143

*conversion constant: standard radioactivity (Bq)/measured count rate (cps)

counted in well-A, the same samples were counted again. The effective volume capacity of the counter for counting in both wells was evaluated with respect to the CE for each volume.

Statistical Analysis

The mean and standard deviation (SD) of the CE for each radionuclide were calculated. The coefficient of variation (CV) of the measured count rate at each measuring point of standard radioactivity was calculated from the standard deviation divided by the mean value of 10 measured count rates of a single sample by 100 (%). The SD and 95% confidence interval of the CC was calculated. The relationship between the standard radioactivity and measured count rate was evaluated by linear correlation and regression analysis. The difference in the CE, CC and effective volume capacity was evaluated and was considered to be significant, when the p-value was less than 0.05.

RESULTS

Counting Efficiency to Each Radionuclide

As an example, Figure 2 shows a scatter plot of measured count rate against standard radioactivity of Tc in well-A and well-B. The measured count rate shows an excellent linear correlation with the standard radioactivity. The counting efficiency (CE) of the counter to each radionuclide was calculated from the relation between the measured count rate (cps) and standard radioactivity (Bq). The highest CE was 16.4 ± 0.495% in In and the lowest CE

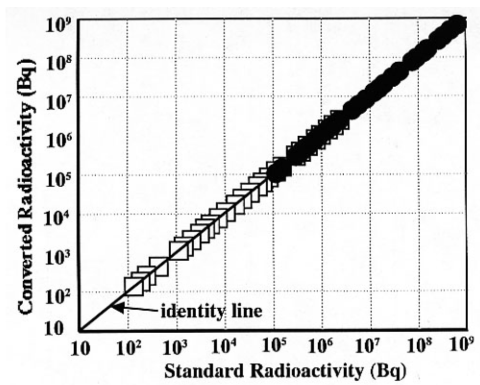

Fig. 5 An example of scatter plots of converted radioactivity against standard radioactivity in well-A (□) and well-B (●) in Tc. The regression line is very closed to the identity line.

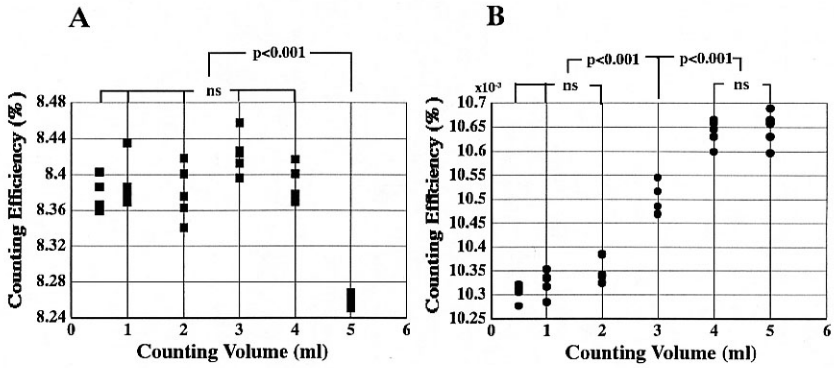

Fig. 6 Scatter plots of the counting efficiency against a sample volume in well-A (A) and well-B (B) using Tc-99m. The counting efficiency for the sample volume of 5 m*l* in well-A is significantly lower than that for another sample volume less than 5 m*l* ($p < 0.05$). In well-B, the counting efficiency for 0.5, 1.0 and 2.0 m*l* is not significantly different in the Student t-test.

was 5.90 ± 0.285% in Tl (Table 1). The CE between Tc and I-123 was not significantly different (Fig. 3). The CEs of 4 other radionuclides were significantly different ($p < 0.01$). These results indicate that the fixed value for each measured radionuclide should be selected when the measured count rate (cps or cpm) is converted to standard radioactivity (Bq).

The CV of the measured count rate to Tc exceeded 1% in radioactive level below 10^3 Bq in well-A and below 10^6 Bq in well-B (Fig. 4). The CV of the counter to 5 other radionuclides was also observed to depend on the measured amount of radioactivity of samples in both wells (Table 2).

Combined Relationship of Measured Radioactivity between 2 Wells

The conversion constant of the counter in each well was determined from relationship between the measured count rates and standard radioactivity in the radioactive range with the CV less than 1% (Table 3). The constant can give standard radioactivity (Bq) from the measured count rate (cps) in each well. Figure 5 shows an example of a scatter plot of the converted radioactivity of measured count rate against the standard radioactivity of Tc in each well. The regression line between the converted radioactivity and the standard radioactivity was very close to the identity line. This result indicates that the dynamic range of the counter widens from 10^3 orders in each well to about 10^6 orders in combined two wells. Five other radionuclides were also confirmed to show the same linear regression as Tc.

Effective Volume Capacity for Counting in Each Well

In well-A, the mean CE for volumes of 0.5 m*l*, 1.0 m*l*, 2.0 m*l*, 3.0 m*l*, 4.0 m*l* and 5.0 m*l* was 8.38%, 8.39%, 8.38%, 8.42%, 8.39% and 8.26%, respectively (Fig. 6). The values of 0.5 m*l* to 4.0 m*l* were not different. In well-B, the mean CE for sample volume of 0.5 m*l*, 1.0 m*l*, 2.0 m*l*, 3.0 m*l*, 4.0 m*l* and 5.0 m*l* was $10.30 \times 10^{-3}\%$, $10.35 \times 10^{-3}\%$, $10.35 \times 10^{-3}\%$, $10.55 \times 10^{-3}\%$, $10.64 \times 10^{-3}\%$ and $10.65 \times 10^{-3}\%$, respectively. Those of 0.5 m*l* to 2.0 m*l* were not significantly different in the t-test. The absolute difference in the mean value of the CE between the volumes 0.5 m*l* and 5.0 m*l* was $0.30 \times 10^{-3}\%$.

DISCUSSION

For testing physical properties of the well-counter such as CE and CV, we considered two methods: 1) single measurement of multiple standard samples which are prepared by dilution of known sample radioactivity (dilution method) and 2) multiple measurements of the single standard sample in which radioactivity is calculated from the physical decay time (decay method). The former is convenient in completing the test within relatively short time. But the results of the estimate may include pitteting error for the preparation of multiple standard samples. The latter method is considered to be better for the evaluation of measurement fluctuation of the counter to the estimates than the former. For this reason, we employed the decay method throughout the present study.

The counting efficiency of the plastic scintillator in well-A of the new instrument ranged from 5.90% for Tl to 16.4% for In (Table 1). The CE for Tc which is the most popular radionuclide in *in-vivo* study was estimated to be 8.56%. As compared to the previous result by the prototype,[2] the CE for Tc was elevated from 6.721% to 8.56% in well-A and from $6.882 \times 10^{-3}\%$ to $1.02 \times 10^{-2}\%$ in well-B. As a result, the relative counting efficiency was altered from 9.80×10^2 to 8.392×10^2. These results are considered to be related to an improvement in the lead cover to decrease the background activity. According to data presented by the company (Aloka Co., Tokyo, Japan), the CE of a commercial NaI-crystal scintillation well-counter for Tc is evaluated to be about 76% with discrimination for the energy range between 80 and 180 keV. Therefore, the

CE of the plastic scintillator used in the DW-counter is about 9-fold lower than that of the standard NaI-detector. The CV of the estimates suggests that the lower limit of sample radioactivity is 10^3 Bq (Table 2, Fig. 4). The effective dynamic range for sample radioactivity in a single well is about 10^3 orders. These physical properties are not considered to be superior to the standard NaI-detector in an *in-vitro* study. In addition, the plastic scintillator is inferior in discriminating the photon energy emitted from radionuclides. This physical property of the plastic scintillator may limit clinical utilization of simultaneous measurement of double tracers with different photopeaks.

In contrast, the counting efficiency of the scintillator for a well-B was arranged to be about 10^3 fold less than that for a well-A. The measured count rates, or converted radioactivity in both wells showed excellent linearity against standard, or absolute radioactivity (Fig. 5). The resulting combined dynamic range of the DW-counter is twice as wide as each well, or 10^6 orders.

For example, the DW-counter can measure the radioactivity from 10^3 Bq to 6.50×10^8 Bq for Tc. These wide dynamic ranges of the DW-counter for radioactivity make it possible to count the injected dose with high radioactivity more than 10^6 Bq and sample radioactivity as low as 10^3 Bq. The DW-counter facilitates direct measurement of injected dose and of radioactive concentration of *in-vivo* samples such as plasma, urine and tissue. These mechanical properties assist simple and easy estimation of *in-vivo* tracer kinetics, because laborious dilution technique is avoided.

The effective volume capacity for counting in well-A should be limited to below 4.0 m*l* (Fig. 6). On the other hand, the absolute difference in the mean CE of the counter between the volumes 0.5 m*l* and 5.0 m*l* in well-B was 3.0×10^{-4}%. This difference in well-B may be explained by the geometric effect of the collimator which has a fan-beam construction. The wide window opening to well-B is collimated at the site of the scintillator using lead. The small volume may result in the narrow window to the scintillator. The window for a large volume may be wider than that for a case of small volume. The volume should be exactly replaced to a height from the bottom to the surface of a sample. The height of injected tracers depends on the size of the syringe used. Therefore, the CC in well-B must be determined exactly from the relationship between the size of the injection syringe and injected volume.

According to a material published by the manufacturer,[5] plastic scintillator technology has been mainly used in the field of high energy physics such as positron emitters. The new counter with a double-well and single-plastic scintillator seems to lead to another application of the plastic scintillator in clinical nuclear medicine using single photon radionuclides. While using a plastic scintillator with its inherently better death time characteristics than a conventional NaI-detector, this advantage is offset by the lower intrinsic efficiency, a factor of about 10, which on the other hand makes the measurement of low activity blood samples more difficult and inaccurate. Therefore, the counter is not suitable to *in-vivo* sample studies which only need a small tracer administered dose less than about 2.0×10^5 Bq. The counter is most effective in carrying out the tracer kinetic study combined with scintigraphy such as the determination of the GFR with Tc-99m-DTPA.[2]

CONCLUSION

The counting efficiency of the DW-counter to Tc is changed from 6.721% to 8.56% as compared to the prototype. The CV is less than 1% over 10^3 Bq in well-A and 10^6 in well-B. Combined dynamic range using 2 wells widens from 10^3 orders to 10^6 orders. Although low intrinsic counting efficiency of the plastic scintillator may limit clinical application to studies with a small tracer administered dose, the counter will assist the simple and easy quantification of *in-vivo* studies such as renal function tests with Tc-99m DTPA and Tc-99m MAG3. The counter is considered also useful in other types of *in-vivo* tracer kinetic studies which are carried out in association with time consuming and cumbersome dilution techniques.

ACKNOWLEDGMENT

The authors thank Mr. Keisuke Oshikiri of Aloka Co., Japan, for his generous comments on the physical properties of commercial products of a NaI(Tl) well counter and a dose calibrator.

REFERENCES

1. Peters AM, Henderson BL, Lui D. Comparison between terminal slope rate constant and "slope/intercept" as measures of glomerular filtration rate using the single-compartment simplification. *Eur J Nucl Med* 2001; 28: 320–326.
2. Itoh K. Determination of glomerular filtration rate by means of newly developed plastic scintillation counter both with and without dilution procedures. *J Nucl Med* 2001; 42: 1484–1488.
3. Levey AS. Use of measurements of GFR to assess the progression of renal disease. *Semin Nephrol* 1989; 9: 370–378.
4. Blaufox MD, Aurell M, Bubeck B, et al. Report of the Radionuclide in Nephrourology Committee on Renal Clearance. *J Nucl Med* 1996; 37: 1883–1890.
5. Browne E, Firstone RB, Shirley VS, edited. *Table of Radioactive Isotopes*, New York; Wiley-Interscience Publication, 1986.
6. Hurlbut CR. Plastic scintillators. A survey. (presented at the American Nuclear Society Winter Meeting, November, 1985), Ohio, USA; BICRON Co., 1985: 1–17.