

# An *in vitro* verification of strength estimation for moving an $^{125}\text{I}$ source during implantation in brachytherapy

Kenichi Tanaka<sup>1,\*</sup>, Tsuyoshi Kajimoto<sup>1</sup>, Takahiro Hayashi<sup>1</sup>, Osamu Asanuma<sup>2</sup>, Masakazu Hori<sup>3</sup>, Ken-ichi Kamo<sup>3</sup>, Iori Sumida<sup>4</sup>, Yutaka Takahashi<sup>4</sup>, Kunihiro Tateoka<sup>3</sup>, Gerard Bengua<sup>5</sup>, Koh-ichi Sakata<sup>3</sup> and Satoru Endo<sup>1</sup>

<sup>1</sup>Quantum Energy Applications, Graduate School of Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

<sup>2</sup>Division of Radiology and Nuclear Medicine, Sapporo Medical University Hospital, South 1, West 17, Chuo-ward, Sapporo, Hokkaido 060-8556, Japan

<sup>3</sup>Department of Radiation Oncology, Graduate School of Medicine, Sapporo Medical University, South 1, West 16, Chuo-ward, Sapporo, Hokkaido 060-8543, Japan

<sup>4</sup>Department of Radiology, Graduate School of Medicine, Osaka University, 2-2 Yamada-oka, Suita, Osaka 565-0871, Japan

<sup>5</sup>Auckland City Hospital, Park Rd, Grafton, Auckland 1142, New Zealand

\*Corresponding author. Quantum Energy Applications, Graduate School of Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan. Tel: +81- 82-424-3739; Fax: +81-82-424-7619; Email: tanakake@hiroshima-u.ac.jp

(Received 4 September 2017; revised 8 December 2017; editorial decision 28 February 2018)

## ABSTRACT

This study aims to demonstrate the feasibility of a method for estimating the strength of a moving brachytherapy source during implantation in a patient. Experiments were performed under the same conditions as in the actual treatment, except for one point that the source was not implanted into a patient. The brachytherapy source selected for this study was  $^{125}\text{I}$  with an air kerma strength of 0.332 U ( $\mu\text{Gy m}^2\text{h}^{-1}$ ), and the detector used was a plastic scintillator with dimensions of 10 cm  $\times$  5 cm  $\times$  5 cm. A calibration factor to convert the counting rate of the detector to the source strength was measured and then the accuracy of the proposed method was investigated for a manually driven source. The accuracy was found to be under 10% when the shielding effect of additional needles for implantation at other positions was corrected, and about 30% when the shielding was not corrected. Even without shielding correction, the proposed method can detect dead/dropped source, implantation of a source with the wrong strength, and a mistake in the number of the sources implanted. Furthermore, when the correction was applied, the achieved accuracy came close to within 7% required to find the Oncoseed 6711 ( $^{125}\text{I}$  seed with unintended strength among the commercially supplied values of 0.392, 0.462 and 0.533 U).

**Keywords:** brachytherapy;  $^{125}\text{I}$ ; source strength; moving source; verification

## INTRODUCTION

Dosimetry in low-energy brachytherapy has been the topic of many studies [1–5], particularly the effect of shielding by the source capsule, which changes the dose distribution inside the tumor and peripheral tissues. Based on the accumulated data, a formalism for calculating doses has been recommended in the American Association of Physicists in Medicine Task Group 43 Updated Protocol (AAPM-TG43U1) [6] and has been applied in clinical treatments. In this formalism, the strengths of all implanted sources should be known in advance of implantation.

The AAPM published a guideline by Task Group 64 (TG64) recommending that source strengths should be measured by the users, i.e. medical physicists [7, 8]. However, according to the TG64 recommendation, source strength measurement should be performed for at least 10% of the sources. In other words, the strength of 90% of the sources at most can potentially not be verified before they are used clinically.

A method for estimating the strength of a source while it is being implanted has been proposed as a backup for quality assurance [9]. The method for estimating the moving-source strength is briefly

described here, and is described in detail in other publications [9, 10]. Source strength measurement has been shown to be difficult during actual implantations because the speed of the source varies, as the source is moved manually. Irrespective of the source speed, its strength is measured over a short time interval and should be started and finished while the source is in a region in which the efficiency of the detector is almost constant.

The feasibility of the proposed method has been verified experimentally using a clinical source moving at different constant speeds for both a loose source [9] and linked sources [10]. In the present study, the validity of the proposed method was investigated for a source that was manually driven. The experiments were performed under the same conditions as in the actual treatment for prostate cancer using  $^{125}\text{I}$  seed, except for one point—wherein the source was not implanted into the patient. The present study served as an *in vitro* test in advance of a clinical trial. The accuracy of the source strength was estimated. Through this, we investigated the purposes for which the proposed method can be used.

## MATERIALS AND METHODS

In the present study, an  $^{125}\text{I}$  source with known strength was moved manually in the same geometry as during an actual treatment. The source strength was estimated using the proposed method while the source was moving.

The source used in this work was the  $^{125}\text{I}$  seed (Oncoseed 6711, GE Healthcare Medi-Physics, Inc., Arlington Heights, IL). The air kerma strength of the source was found to be  $0.332 \pm 0.08$  U, as measured by a well-type ionization chamber (HDR1000 Plus, Standard Imaging, Inc., Middleton, WI). Here, U denotes the unit combination  $\mu\text{Gy m}^2 \text{h}^{-1}$ , as defined in TG43U1 [6]. The chamber used was calibrated at the University of Wisconsin, a member of the Accredited Dosimetry Calibration Laboratory Program [6].

The experimental set-up is shown in Fig. 1. This is the same conditions as in the actual treatment, except for one point—that the source is not implanted into the patient but moved only inside the needle (#918,201, Bard, Inc., Murray Hill, NJ) by an applicator and a push rod (200-TPV, Mick Radio-Nuclear Instruments, Inc., Mount Vernon, NY). The detector used in the measurements was a plastic scintillator (G-tech, Inc., Saitama, Japan). The detector system consists of a scintillator (EJ200, Eljen Technology, Inc., Sweetwater, TX) with dimensions of  $10\text{ cm} \times 5\text{ cm} \times 5\text{ cm}$ , and a photomultiplier tube (H7416, Hamamatsu Photonics, Inc., Shizuoka, Japan). Since the detector and jig were designed not to interfere with the other materials, the detector and jig can be utilized not only in the present study but also during actual treatment. In the present study, the detector was set as close to the source path as possible in order to obtain more data for better statistics and was fixed by a jig. The detector was 1 cm away from the template in the  $y$ -direction, as shown in Fig. 1a. In the  $z$ -direction, the center of the 10 cm-long detector was set aligned along the center of the 6 cm-long hole region of the template, i.e. the line 3.5 in Fig. 1b. The template has holes with 0.5 cm pitch. In the  $x$ -direction, the clearance between the applicator and template in the actual implantation is often  $\sim 3$  cm to several centimeters. In order to set

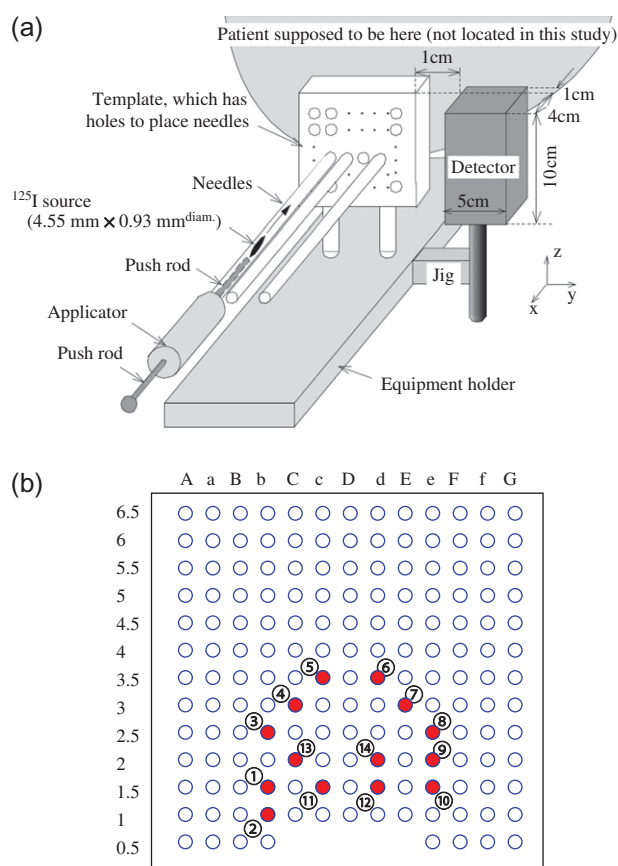


Fig. 1. Experimental set-up: (a) overview; and (b) needle position on template. The figure is not to scale.

the center of the 3 cm-long clearance to be at the same  $x$ -position as the center of the detector that was 5 cm long, the detector was set as shown in Fig. 1a. The signal from the photomultiplier tube was analyzed with a preamplifier (5607, Clear Pulse, Inc., Tokyo, Japan), an amplifier (4467A Clear Pulse, Inc.), and a single-channel analyzer (1150, Clear Pulse, Inc.), in that sequence. The threshold of the single-channel analyzer was set to  $\sim 6$  keV of the photon energy in order to include the photons from  $^{125}\text{I}$  with an energy range between 27.2 keV and 35.5 keV and to reduce the signal from the electric noise and background radiation. The signal was finally counted by a scaler (3340, Clear Pulse, Inc.).

The calibration factor (U/cps) was measured for all the needle positions on the template in Fig. 1. The source was not moved during this measurement. The source was set at the same  $x$ -position as the center of the detector. Only one needle, which contained the source, was used. Measurements of 1-s duration were performed 10 times.

Using the obtained calibration factor, the strength of the source moving in the needles was measured and its accuracy was investigated. As a simulation of an actual implantation, 14 needles were set as shown in Fig. 1b, which is the same configuration as in the actual treatment. The source was then moved inside a needle in the order

following the numbered sequence in Fig. 1b. Each needle was removed after the source had passed through it. Since the source was moved manually using the applicator, the speed of the source was not constant. From the stroke of the push rod at ~20 cm and the duration of the source movement, which was 1–2 s, the speed of the source was estimated to be ~10–20 cm/s. This measurement was conducted three times. The counting time and analysis are described later, together with the measured value.

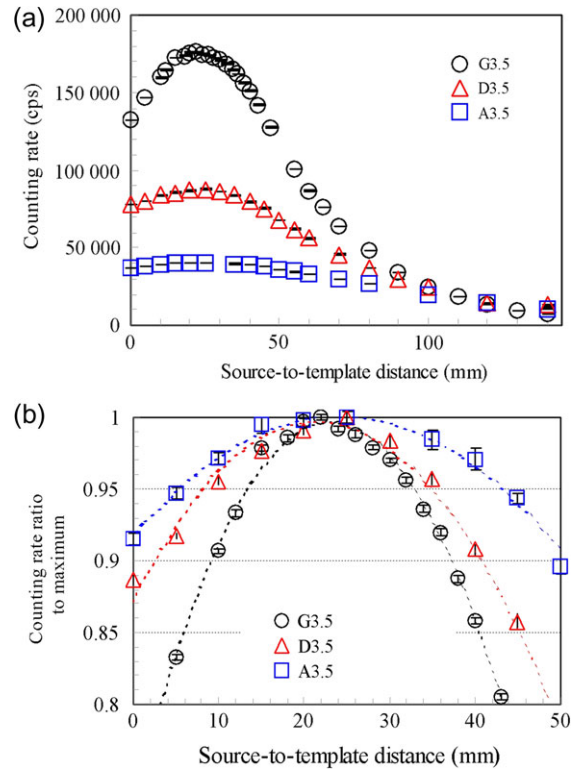
**RESULTS**

The dependence of the detector counting rate on the source-to-template distance is shown in Fig. 2 for a static source at three needle positions. The error bars indicate the standard deviation for 10 measurements. The counting rate of the background signal was  $251 \pm 12$  cps, and this was subtracted from measured values. The readings at three needle positions reached their maximum at 25 mm source-to-template distance. In order to compare the relative change in the counting rate, the data in Fig. 2a were normalized at 25 mm and are shown in Fig. 2b. In Fig 2b, the change in the counting rate was ~5% at positions of ~15–35 mm (20 mm length) for G3.5, and 5–45 mm (40 mm length) for A3.5. Similarly, the length of the region in which the change in the counting rate was ~10% was ~30 to 50 mm. These lengths are comparable to those in the previous study [9]. The previous study showed the uncertainty from a source speed variation of 2–20 cm/s was within 2.3% for a counting time of 50 ms [9]. In this study, the source speed was assumed to be 10–20 cm/s. Thus, the counting time in the moving source measurement was set at 50 ms. In this case, the source moved by 0.5 to 1 cm during the counting time, which allowed the measurement to be performed while the source was in the region where the detector response did not change much, i.e. within 5–10%.

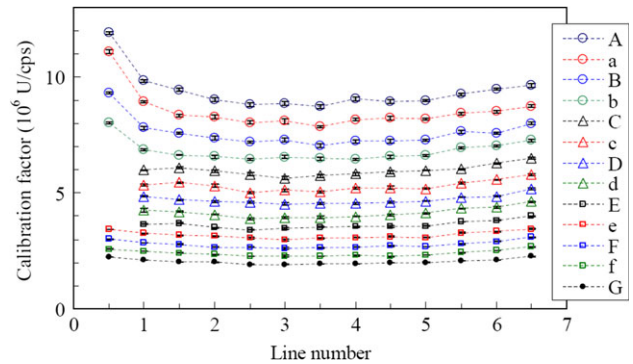
The detector response at all the needle positions on the template was measured for the source-to-template distance of 25 mm. The calibration factor (U/cps) obtained under these conditions is shown in Fig. 3. This data was used in estimating the strength of the moving source.

An example of measured counts for a moving source is shown in Fig. 4 at needle position #1 in Fig. 1b. The measurements were performed as three individual runs. For each run, the maximum count was used to estimate the source strength, assuming that the source reached the position with a high detector response when the maximum count in each run was obtained.

As a measure of the accuracy of the proposed method, the ratio of the source strength estimated in the moving source measurement to the strength obtained with the well-type chamber was computed and is shown in Fig. 5a. The plotted data are the average and standard deviation of three runs. The needle positions correspond to those in Fig. 1b. All needles were initially placed in the template and removed after the source had passed through them, i.e. 14 needles were present during the measurement for the first needle position, and only 1 needle was left during the measurement for the 14th needle. The shielding effect of the needles other than the one used for implanting a source results in a general underestimation of the source strength. In order to correct for this shielding effect, its



**Fig. 2. Dependence of counting rate on source position: (a) raw data, and (b) relative distribution normalized at 25 mm, where the counting rate reaches its maximum. Dashed lines are visual guides.**



**Fig. 3. Calibration factor obtained from static source measurements dependent on the needle position on the template. Lines are visual guides.**

influence in the detected signal is estimated by a 1-s measurement with the static source in the needle. The results of these measurements are shown in Fig. 6. As the number of additional needles increased, the detector response decreased. The data in Fig. 6 was then used to account for the shielding effect of the additional needles set on the template for the moving source measurement. The

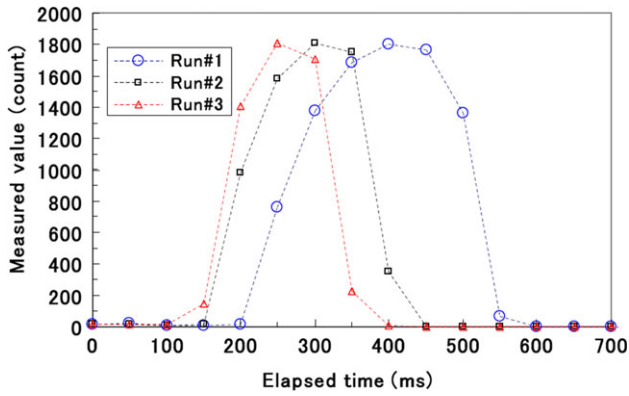


Fig. 4. Measured counts at needle Position b1.5 for counting time of 50 ms. Lines are visual guides.

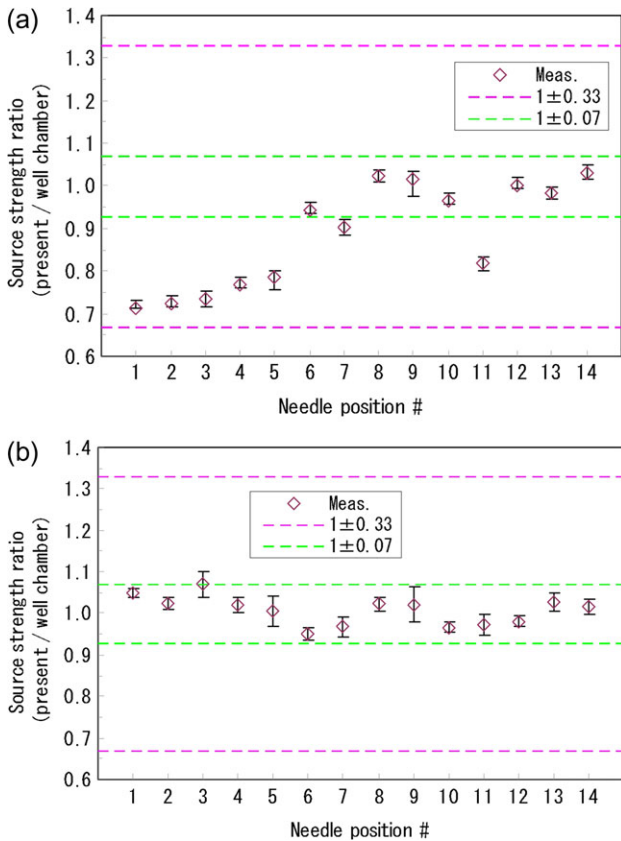


Fig. 5. Ratio of estimated source strength of a moving source to the measured strength by a well-type chamber (a) without and (b) with the shielding correction to account for the presence of additional needles.

data shown in Fig. 5b are the corresponding data from Fig. 5a with the shielding corrections applied. The moving source measurement agreed with the well-type chamber measurement within several percent to 10%.

## DISCUSSION

The proposed method of estimating the strength of a moving source during implantation will be useful in the situations mentioned below. The required accuracy in each of these potential applications is likewise mentioned.

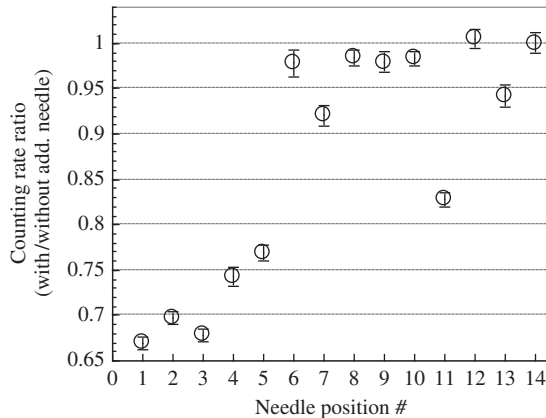
- (i) An equally precise alternative to the measurement method provided by the manufacturer and at a comparable accuracy of within 7%.
- (ii) A way of identifying accidental replacements of sources with those having strengths among the currently supplied strengths of 0.392, 0.462 and 0.533 U. They differ by 15% or more. The accuracy of the proposed method,  $a$ , should satisfy  $1 + a < 1.15(1 - a)$ . The solution of this equation is 0.0698. Thus, the tolerance for the accuracy for this application is 7%.
- (iii) A method of confirming that only one source is being driven at a time by the applicator. Only one source is supposed to be driven by pushing the ‘push rod’ (of the applicator in Fig. 1). Thus, accidental simultaneous implantations of two or more sources should be distinguished from one-source implantation. The required accuracy for this method is 33%, similarly to the consideration in (ii).
- (iv) As a means of recognizing the accidental replacement of sources with those which have decayed after being kept in the storage box in the clinical facility for a long time. The accuracy of 33%, comparable with (iii), is acceptable for the purpose of finding sources with strengths of 50% or less of their initial values, i.e. the sources that have been kept for longer time than the half-life after the strength calibration by users at the facility.
- (v) As a way of identifying dead seeds, which have very low or unusable activity, or to identify the ‘dropped’ source that is being removed from the patient when the applicator push rod is pulled out after source has been implanted successfully. This can be performed as long as the detector responds more than the fluctuation of the background signal.

The tolerance levels of the accuracies required in each application mentioned above are shown in Fig. 5. For applications (i), (ii) and (iii), (iv), these are  $1.00 \pm 0.07$  and  $1.00 \pm 0.33$ , respectively. As for (ii), when sources with different strengths are available in the future, the tolerance level will be different. For application (v), the fluctuation of the background signal corresponds to 0.0003, which is out of the range of the  $y$ -axis in Fig. 5. From Fig. 5b, when the influence of the shielding by the additional needles has been successfully corrected, the accuracy was within 7% except for a few points. In this case, the proposed method is therefore suitable for all the applications (i)–(v), depending on the condition of the implantation and assuming that the correction factor for the shielding effect was evaluated in advance of the implantation. This can be accomplished as long as the sources are implanted following the preplan. In those implantations, the correction factor can be measured for all the geometries depending on the preplan, in advance of the implantation.



On the other hand, for intra-operative planning when the arrangement of the potential additional needles differs from the pre-plan, it is not practical to prepare the shielding correction factor for all the combinations of the additional needle arrangements. In that case, the source strength estimation undertaken during the implantation using the proposed method would have an accuracy of within ~30%, as shown in Fig. 5a. The proposed method would then be limited to applications (iii)–(v). However, in that case, the proposed method could be used to detect a dead/dropped source, implantation of a source with wrong strengths, and a mistake in the number of sources implanted, which are the issues in clinical implantations. Furthermore, the accuracy could be improved by measuring the correction factor after the implantation is finished. By doing so, the proposed method could then be applied to (i) and (ii) as described above. This is potentially useful in the post implantation dosimetry. Currently, there is no way of performing post implantation dosimetry that modifies the estimated dose by changing the source strength based on the value measured for the sources actually implanted. Only ideas and feasibility in principle for such applications have been suggested for single-photon-emission computed tomography (SPECT) [11] and the glass rod dosimeter [12].

A possible way of improving the accuracy shown in Fig. 5a is to categorize the combination of the needle arrangements into practical number of groups, depending on the desired application and corresponding accuracy. In an implantation for which the number of combinations of the needle arrangement is not too many to measure, it will be practical to prepare the shielding correction factors for all the required cases and to accomplish the intra-operative estimation of the source strength. Potentially, applicable examples of such an implantation is the peripheral loading where the



**Fig. 6. Ratio of counting rates for a condition in which additional needles were present to those for a condition in which the additional needles were not on the template. Additional needles refer to the needles placed on the template to prepare for the implantation. For example, in the measurement for the needle Position #1, the remaining 13 additional needles are set on the template at Positions from #2 through #14.**

peripheral needles (#1 through #10 in Fig. 1b) are not placed while loading through the inner needles (#11 through #14) and vice versa.

The calibration factors shown in Fig. 3 and the shielding correction factors in Fig. 6 will change on each day due to fluctuation in the detector response. A practical way of compensating that will be to measure the calibration factor at a few needle positions where the error in positioning the needle is small, such as A3.5, and to set the relative relationships of the calibration factors between the needle positions, as well as the shielding correction factors, to the values obtained in the reference measurements that are performed periodically.

## CONCLUSION

The validity of the proposed method for measuring the strength of the source during the implantation using short-time counting was investigated for a source that was manually moved. The experiments were performed under the same conditions as the actual treatment, except for one point—that the source was not implanted into a patient or a phantom but moved only inside the needle. Regarding this point, the present study served as an *in vitro* test in advance of a clinical trial.

The source strength was estimated successfully using the method described in this study. The accuracy was ~30% when the influence of the shielding effect of additional needles in the implantation set-up was not corrected. In this case, the proposed method can be used to detect a dead/dropped source, implantation of a source with wrong strengths, and a mistake in the number of sources implanted, which are the issues in the clinical implantations. By accounting for the shielding effect, the accuracy improved up to about several per cent to 10%, which is close to the accuracy required for finding a  $^{125}\text{I}$  seed with unintended strength among the commercially available strengths of 0.392, 0.462 and 0.533 U. Through this work, it has been confirmed that correcting for the shielding effect created by additional needles is an important factor in improving the accuracy of a measured source strength.

In practice, the calibration factor for converting the counting rate of the detector to the source strength should be measured in advance. Moreover, the accuracy of the strength estimation should be checked periodically using a source with a known strength, as shown in the present study.

## ACKNOWLEDGEMENTS

The authors express their sincere appreciation to Mr Seisuke Noguchi and the staff at Innovation Plaza in Hiroshima University, and Mr Yoshiyuki Kanazawa and the staff in the workshop at Sapporo Medical University, Japan for their support in the investigations.

## CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

## FUNDING

Part of the present study was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science under Grant No. 21791203, and grants from the Japan

Science and Technology Agency [Grant Nos AS221Z02563F and HWY2012-1-314].

#### REFERENCES

1. Nath R, Anderson L-L, Luxton G et al. Dosimetry of interstitial brachytherapy sources: recommendations of the AAPM Radiation Therapy Committee Task Group No. 43. *Med Phys* 1995;22:209–34.
2. Saitoh J, Ohno T, Sakurai H et al. High-dose-rate interstitial brachytherapy with computed tomography-based treatment planning for patients with locally advanced uterine cervical carcinoma. *J Radiat Res* 2011;52:490–5.
3. Jarusevicius L, Inciura A, Juozaityte E et al. Comparison of implant quality between loose and intra-operatively linked iodine-125 seeds in prostate cancer brachytherapy. *J Radiat Res* 2012;53:439–46.
4. Ohno T, Noda S, Okonogi N et al. In-room computed tomography-based brachytherapy for uterine cervical cancer: results of a 5-year retrospective study. *J Radiat Res* 2016;53:1–9.
5. Tanaka K, Tateoka K, Asanuma O et al. A dosimetry study of the Oncoseed 6711 using glass rod dosimeters and EGSS Monte Carlo code in a geometry lacking radiation equilibrium scatter conditions. *Med Phys* 2011;38:3069–76.
6. Rivard M-J, Coursey B-M, DeWerd L-A et al. Update of AAPM Task Group No. 43 Report: a revised AAPM protocol for brachytherapy dose calculations. *Med Phys* 2004;31:633–74.
7. Yu Y, Anderson L-L, Li Z et al. Permanent prostate seed implant brachytherapy: report of the American Association of Physicists in Medicine Task Group No. 64. *Med Phys* 1999;26:2054–76.
8. Butler WM, Bice W-S Jr, DeWerd L-A et al. Third-party brachytherapy source calibrations and physicist responsibilities: report of the AAPM Low Energy Brachytherapy Source Calibration Working Group. *Med Phys* 2008;35:3860–5.
9. Tanaka K, Tateoka K, Asanuma O et al. Measurement of the strength of iodine-125 seed moving at unknown speed during implantation in brachytherapy. *J Radiat Res* 2014;55:162–167.
10. Tanaka K, Endo S, Tateoka K et al. Strength estimation of a moving  $^{125}\text{I}$  source during implantation in brachytherapy: application to linked sources. *J Radiat Res* 2014;55:608–12.
11. Tanaka K, Tateoka K, Asanuma O et al. Fundamental study on evaluating source strength for brachytherapy using SPECT. *Jpn J Med Phys* 2012;32:192–3 (in Japanese).
12. Tanaka K, Tateoka K, Asanuma O et al. A dosimetry method for low dose rate brachytherapy by EGSS combined with regression to reflect source strength shortage. *J Radiat Res* 2014;55:1146–52.