In prediction and evaluation of the delivered dose for brachytherapy, the source strength is an essential information. One of the most common ways at present for low-dose-rate source is to measure the strength using a well-type chamber in advance e.g., days before the implantation operation. For tumors in some organs, e.g. prostate, many sources such as tens of $^{125}$I seeds are utilized. An easy measurement which does not consume much time or manpower is required. Among the potential solutions, the measurements during/after the implantation also offer additional assurance to detect the accidental replacement of the sources after the conventional measurement with the well-type ionization chamber. From this viewpoint, the present paper reviews the method utilized currently and related research activities.
1. INTRODUCTION

Brachytherapy is performed for cancers in organs such as prostate, eye, uterine cervix, etc.\textsuperscript{1,2} Similarly to other modality of the radiation therapy, the uncertainty in brachytherapy dose to the patient for all the potential factor origins is aimed at 5\% or less.\textsuperscript{3-5} Dosimetry in brachytherapy has been a topic of many studies\textsuperscript{6-9}. Especially, the effect of shielding by the source capsule has collected attention since it changes the dose distribution inside the tumor and peripheral tissues. Based on the accumulated dosimetry data by experiments\textsuperscript{10-12} and/or calculations\textsuperscript{13,14}, a formalism to calculate doses has been recommended in the American Association of Physicists in Medicine Task Group 43 Updated Protocol (AAPM-TG43U1)\textsuperscript{15} and has been applied in the clinical treatments.

In this formalism, the strengths and the positions of all sources implanted into the patient should be known and utilized for calculating the dose. The AAPM guideline by Task Group 64 (TG64) and related works have pointed out the main cause of the discrepancy between the prescribed and delivered doses is the uncertainty of the source position and tumor geometry such as edema.\textsuperscript{16-23} This discrepancy is tried to be overcome by setting the source positions in the dose calculation geometry consistent with actual positions in the patient. The source position in the patient body is presently measured with computed tomography\textsuperscript{24-27}, film\textsuperscript{28} or ultrasound\textsuperscript{29-31}.

On the other hand, as to the source strength to be used in the dose calculation by the TG43U1 formalism, the TG64 recommends that source strengths should be measured by the users, i.e., medical physicists in clinical facilities.\textsuperscript{16,32} For some cancers, many sources are required to achieve the desired dose distribution throughout the tumor. For example, \textsuperscript{125}I seeds as many as tens to a hundred are used for a low-dose-rate brachytherapy for prostate. In this case, handy and time-saving ways of measuring the source strength are desired. In addition, accidental human error to replace the source assured to have proper strength with that having unintended strength may be an issue. Focusing on this aspect, the present paper reviews the methods of estimating the \textsuperscript{125}I source strengths and related research activities to assure it.

2. Source strength measurement before implantation operation

The strength of brachytherapy source is specified by its air-kerma-strength these days.\textsuperscript{15,16} The strength of \textsuperscript{125}I source is commonly measured before the implantation. The measurement is performed separately for each single source, or for multiple source simultaneously, i.e., in cartridges.\textsuperscript{33} A well-type ionization chamber is quite commonly used for the single source measurement, so called “loose seed assay”.\textsuperscript{34} It has an advantage that the response of the chamber, accordingly the calibration factor, is less dependent on the source position than that of the conventional detector where the source is not surrounded with the detector. This is because the change in the source position leads to increase in solid angle of the detector on one side from the source, while that on the other side decreases. Thus, parts of the change in the chamber response are compensated.

In the TG64 recommendation, the source strength measurement should be performed for at least 10\% of the number of sources, while some of the source models have been reported to have the strength assured enough by the manufacturers.\textsuperscript{35-37} In other words, the strength of 90\% of the sources could potentially not be verified before they are used clinically. Considering this, some facilities measure the strength of more than 10\% of the
sources. According to the well-type chamber size, it takes a few to ten minutes to measure the strength of a source, and the measurements of 100 sources takes a day at most. Also, though the shipment of the sources in the cartridge from the vendor is already sterilized, the sources should be taken away from the cartridge before the measurement and be sterilized again before the implantation. In order to save the load and time consumed for the measurement and sterilization, the measurement is also performed in bulk, i.e., the source strengths are measured while the sources are included in the cartridge. One of the major examples is the autoradiography using the imaging plate. In this case, the measurement for a source can be interfered by the photons from neighboring sources. In order to shield such photons, collimators are often utilized. By combining this method with the well-chamber measurement, the sources are assured to have intended strength. Moreover, this method can be performed for the sterilized sources included in the cartridge, which makes it unnecessary to sterilize the sources after the strength measurement. The detectors to measure the source strength should be calibrated. The well-type chamber should be calibrated at an Accredited Dosimetry Calibration Laboratory with direct traceability to National Institute of Standards and Technology (NIST) in the United States. Otherwise, the sources of which the strength has been calibrated can be obtained from ADCL and they are used to establish the calibration factor for the geometry of the source strength measurement by the users.

3. Related research activities

For the sources, the strength of which is not measured before the implantation, the measurement of the strength during/after the implantation is tried as a backup for quality assurance. This section reviews the research activities for this measurement.

3.1 Measurement during implantation

Methods to estimate the strength of the source during the implantation procedure has been proposed in two modalities as mentioned below. In both cases, similarly to the measurement before the implantation, the source strength measured can be used for intraoperative treatment planning.

An option is to measure the source strength by setting the source stationary in front of a detector. This has been realized by Nucletron Corporation (Stockholm, Sweden) and Tokushima University in Japan, separately. The driving of the source and the measurement is performed automatically. Though this procedure is conducted during the implantation operation, the measurement is, strictly speaking, performed before the source enters the body. In this case, after the source is found to have unintended strength, it can be replaced with the source at correct strength.

The other option is to measure the strength while the source is moving during the implantation. Figure 1 shows the conceptual sketch of this method. This has a difficulty because the speed of the source varies as the source is moved manually during actual implantations. In order to overcome this, its strength is measured at a short time duration so that the measurement will be finished while the source is in a region where 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 a loose source and linked sources. As an in-vitro test, the validity of the proposed method was shown for a source that is manually moved. Consequently, the accuracy was within about
30% when the influence of the shielding effect of additional needles in a typical implantation set-up was not corrected. In this case, the proposed method can also be used to verify that the correct number of sources was implanted in the patient. By accounting for the shielding effect, the accuracy improved up to about several to ten percents. In clinical use, a problem has been found that it is not possible to distinguish $^{125}$I photons from the diagnostic X-ray which is sometimes used during implantation, because it has the component with similar energy to that of $^{125}$I photons. Clinical tests and works to solve this problem are ongoing. On the other hand, the disadvantage of this method is that it is difficult to adjust the strength of the source even if the difference from the prescription is found. When the strength of the source implanted is lower than the prescription, sources would be implanted additionally to compensate for the shortage in dose. However, when the source strength is more than the prescription, it would not be practical to remove the source from the patient surgically. Instead, medical preparation would be available for the potential risk in health by the overdose.

Fig. 1. Conceptual sketch of moving source measurement (a) Geometry (b) Temporal change in measured signal intensity per counting time

3.2. Measurement after implantation

It is tried to measure the source strength after implantation for post-implantation dosimetry. In this case, the measured strength can no longer be used in the intraoperative treatment planning. The related work is a trial to estimate the source position using the scintigraphy. This work focused on the seed migration into the patient body after the implantation. They only estimated the strengths of the sources qualitatively. However, in principle, the source strength can be estimated using the scintigraphy or single photon emission computed tomography (SPECT). The quantitative estimation has been investigated preliminarily for SPECT. The problem in performing this measurement will be low photon energy about 30 keV from $^{125}$I. In this case, the change in the photon energy spectrum in the patient body is not negligible. Then the change in the attenuation coefficient of the photon inside the patient body is not negligible, while it is ignored in conventional scintigraphy and SPECT which uses photons over about 200 keV. Instead of using the variable attenuation coefficient according to the path length of photons inside the body considering the source position, gating of the energy range of the photons to be detected has been tried as a preliminary study. Consequently, proper range of the photon energy was found for a type of detector, for which the attenua-
tion coefficient can be approximated as constant in the body.

A principle which is different from SPECT was also investigated for this purpose. In this investigation, the source position in the body is measured with an established method such as computed tomography. Figure 2 shows the principle of this method. The source strength is set at a tentative value such as the nominal value from the manufacturer, at first. Then the strength is adjusted by means of regression, so that the calculated dose for the source strengths can reproduce experimental dose distribution monitored on the patient body surface after the implantation. This principle was validated for the usage of the glass rod dosimeters. As a result, the difference in the source strength by 4-48% was successfully detected for the phantom which has only two sources inside. The verification of this method is undergoing for the geometry which includes more sources.

This method requires the calculation which precisely predicts the dose. Because the dose monitor is supposed to be performed on the body surface considering the ease for the patient, the dose calculation formalism TG43U1 should not be used. Calculation method for such a dose prediction using a Monte Carlo code has been prepared for $^{125}$I seeds, Oncoseed6711 (GE Healthcare Medi-Physics, Inc., Illinois, US) and STM1251 (Bard, Inc., New Jersey, US), and it is tried to obtain for more source models. The disadvantage of this method is that it takes much time to prepare the dose prediction. However, this method may help the facilities, which do not have enough time or manpower before the implantation but have them after the implantation, to improve the precision of the post-implantation dosimetry.

![Conceptual sketch of source strength estimation by regression of source strength to reproduce dose distribution on patient body surface.](image)

### 3.3. Discussion

The summary of the research activities are listed in Table 1. The advantage of the measurement of the strength during/after the implantation is that users can save the time and load before the implantation. Because the source delivered from the vendor need not be taken out from the cartridge before the implantation for the strength measurement, the sterilization is not required for the source strength measurement. Also, users can detect the accidental human error to replace the source assured to have proper strength with that having unintended strength. On the other hand, the disadvantage is that it is difficult to
adjust the strength of the source even if the discrepancy in strength is found between the prescription and actual usage. In this sense, the measurement before the implantation is the most desirable. However, the measurement during/after implantation is meaningful as an additional quality assurance to detect the accidental replacement mentioned above. The measurement during the implantation has an advantage that the shortage of the source strength can be compensated with implanting the additional sources instantly. On the other hand, the measurement after the implantation by SPECT would be able to determine both the source strength and position. The methods should be selected, considering desired accuracy and time that can be consumed for the quality assurance.

### Table 1. Characteristics of method proposed

<table>
<thead>
<tr>
<th>Temporal relation to implantation operation</th>
<th>Method</th>
<th>Sterilization of source</th>
<th>Clinical use</th>
<th>Number of sources measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>Well-type chamber</td>
<td>Needed</td>
<td>Used</td>
<td>Single</td>
</tr>
<tr>
<td></td>
<td>Film/imaging plate</td>
<td>Not needed</td>
<td>Used</td>
<td>Multiple</td>
</tr>
<tr>
<td>During</td>
<td>Static source measurement</td>
<td>Not needed</td>
<td>Used</td>
<td>Single</td>
</tr>
<tr>
<td></td>
<td>Moving source measurement</td>
<td>Not used</td>
<td>Not used</td>
<td>Multiple</td>
</tr>
<tr>
<td>After</td>
<td>Scintigraphy, SPECT</td>
<td>Not needed</td>
<td>Not used</td>
<td>Multiple</td>
</tr>
<tr>
<td></td>
<td>Regression of source strength</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

4. CONCLUSION

This paper reviewed the research activities of estimating the source strengths, focusing on the $^{125}$I seeds. The measurements were summarized for three usages, i.e., the measurement before/during/after the implantation procedure. From the viewpoint of the manpower of the medical facilities, it is desirable that the statement of the source strength by the manufacturers is accurate enough and they do not need to assure it by the measurement by themselves. However, even if that is achieved, additional assurance by the facilities would support the safety and accuracy in dose of the brachytherapy. In this case, the important issue in developing and selecting the method for clinical use is to focus on the desired precision and accuracy, and on how time- and labor-consuming procedure is acceptable for facilities. The methods reviewed in this paper or combination of them would be examples of the options potentially usable. More practical studies for them and further research for alternative methods are desired.
References


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