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Original paper

A novel risk analysis of clinical reference dosimetry based on failure modes and effects analysis

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ABSTRACT

Purpose: The output of a linear accelerator (linac) is one of the most important quality assurance (QA) factors in radiotherapy. However, there is no quantitative rationale for frequency and tolerance. The purpose of this study is to develop a novel risk analysis of clinical reference dosimetry based on failure modes and effects analysis (FMEA).

Methods: Clinical reference dosimetry data and the daily output data of two linacs (Clinac iX and Clinac 6EX) at Hiroshima University Hospital were analyzed. The analysis involved the number of patients per year for five types of fractionations. Risk priority number (RPN) is defined as the product of occurrence (O), severity (S), and detectability (D) in standard FMEA. In addition, we introduced "severity due to output drifting" (mean output change per day) (S') and the number of patients per year for five types of fractionations (W). We calculated the RPN $= O \times S \times D \times S' \times W$ and quantitatively evaluated the risk for clinical reference dosimetry.

Results: Fewer fractions and less output calibration frequency resulted in higher RPN. Since clinical reference dosimetry data has a drift effect, which is missing in human processes, it was essential to use S' in addition to standard FMEA. Moreover, the parameter W was important in evaluating interinstitutional QA for clinical reference dosimetry. The relative risk of Clinac 6EX to Clinac iX was different approximately by twofold.

Conclusions: We developed a novel index that can quantitatively evaluate risk for clinical reference dosimetry of each facility and machines in common on the basis of FMEA.

1. Introduction

External-beam radiotherapy utilizes an electron linear accelerator (linac) for patient treatment using high-energy X-rays. The linac output is controlled by a monitor chamber located in the gantry head. The monitor chamber is a parallel ionization chamber that controls the delivered dose by a monitor unit (MU). In general, the output drifts in one direction because of the changes in response to the monitor chamber. This drifting directly affects the dose delivered to a patient, since the delivered dose is controlled by the MU. The output is evaluated by using a calculated absorbed dose to water with a variety of correction factors, which are defined in guidelines such as Standard Dosimetry 01 of Japan Society of Medical Physics (JSMP2001) [1], American Association of Physicist in Medicine Task Group 51 [2], and International Atomic Energy Agency Technical Reports Series 398 [3]. Measurement failures and resulting wrong correction factors can cause failures in the delivered dose to patients. The International Commission on Radiation Units and Measurements (ICRU) Report 24 reported that a 7–10% change in the dose to the target volume may result in a large change in tumor control probability [4]. Therefore periodic checks of the output are one of the most important quality assurance (QA) tasks. Although academic societies recommend regular output calibrations [1–3], there is no quantitative rationale for the frequency of the periodic checks.

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Recently, failure modes and effects analysis (FMEA) has been introduced in radiation oncology. Risk analyses for radiotherapy processes using the FMEA have been reported, such as AAPM TG-100 [5], lung stereotactic body radiation therapy [6], and high-dose-rate brachytherapy [7]. O'Daniel et al. used FMEA as a useful tool to determine appropriate clinic-specific QA testing frequencies based on TG-142 [8,9]. They evaluated dose errors due to output, laser, optical distance indicator, jaws vs. light field, imaging vs. treatment isocenter, and imaging positioning/repositioning and the failure rate occurring in their clinic and the number of patients affected for head and neck intensity modulated radiation therapy (IMRT). Their study showed that the failure occurrence rate was greatest for the output and laser testing. Our study focused on the risk analysis of output by FMEA with a detailed perspective on clinical reference dosimetry.

Although the recommended value of tolerance and frequency in QA for clinical reference dosimetry has been reported in various guidelines [1–3], its validity has not been quantitatively evaluated. At Hiroshima University Hospital, the clinical reference dosimetry measurement is performed with the same frequency and tolerance for two linacs. In general, since the manpower, measurement devices, and linac output stability are different among facilities, the frequency and the tolerance are decided in each facility [10–13]. Palmer et al. discussed the testing frequency in their survey in the UK [10]. Variation in beam output drift is also quantified by a number of authors [11–13]. Furthermore, the type of radiotherapy varies depending on the purpose of the radiotherapy, such as curative treatment or palliative treatment. This variation provides the difference in the delivered dose per fraction (fr) and the number of fractions. The degree of the dose error depends on the combination of output calibration frequency and number of fractions. For example, when the number of fractions is small, the relative times of the output calibrations for clinical reference dosimetry during the treatment period become small. Once a dose error occurs in the clinical reference dosimetry, it can continue until the next output calibration with clinical reference dosimetry. The dose error directly affects all patients treated during the dose error period. The safety of the output is improved by increasing the output calibration frequency. However, as the need for manpower is proportionate to the frequency of the periodic checks, it is important to check the machine in an appropriate and reasonable frequency that depends on the scale of the facility. In order to determine the appropriate frequency in a quantitative manner, it is important to consider the effects on the patients; these effects have a relationship with a variety of factors described earlier. In this study, we developed a novel risk analysis for the output based on FMEA and investigated its feasibility for clinical applications. This FMEA-based method used the numerical data from daily linac output with fluctuation and drift.

2. Materials and methods

2.1. Clinical reference dosimetry

Clinical reference dosimetry data and the daily output data from 2009 to 2012 at Hiroshima University Hospital were used to develop the FMEA-based risk analysis. The clinical reference dosimetry data of 6-MV X-ray beams from two linacs (Clinac iX and Clinac 6EX; Varian Medical Systems, Palo Alto, CA, USA) were based on the JSMP2001 guideline [1]. The absorbed dose to water at the reference depth was measured by

$$D_r = M_{raw} k_{TP} k_{pol} k_s k_{elec} N_{D,w} k_Q / \mathrm{TMR}\,[\mathrm{Gy}] \quad (1)$$

where M_{raw} is the reading of an electrometer [nC], k_{TP} is the temperature and pressure correction factor, k_{pol} is the polarity effect correction factor, k_s is the ion recombination correction factor, k_{elec} is the calibration factor of electrometer, $N_{D,w}$ [Gy/nC] is the calibration factor for the absorbed dose to water, k_Q is the beam quality conversion factor, and TMR is the tissue-to-maximum ratio. The 6-MV beam was calibrated at d_{max} (the reference depth is d_{max} because of the TMR).

Farmer-type chambers (PTW30013 and PTW30010), electrometers (RAMTEC 1000plus and UNIDOS), and a water phantom were used for the clinical reference dosimetry measurements. These chambers were calibrated every year at secondary standard dosimetry laboratories in Japan, which provided $N_{D,w}$ andk_{elec}. Other correction factors, such as k_{pol} and k_s, were obtained by our own measurements. The factors of TMR were obtained from measurement data collected during commissioning.

A CHECKMATE device (Sun Nuclear, Melbourne, FL, USA) was used for daily output checks. The daily output measured by the device was indicated in percent and that was normalized to the output when a linac output was calibrated. The CHECKMATE measurement values were used to find out the linac output drift.

In addition, the number of patients was used along with the types of fractionations. These types were 48 Gy in 4 fractions for stereotactic body radiation therapy (SBRT), 70 Gy in 35 fractions for definitive radiotherapy, 30 Gy in 10 fractions for palliative radiotherapy, 12 Gy in 2 Gy fractions twice a day for total body irradiation (TBI-A) and 3.6 Gy in1.8 Gy fractions twice a day (TBI-B).

2.2. FMEA and its application to clinical reference dosimetry

FMEA is a method to minimize an incident by analyzing its failure mode. In general, the first step is to list the possible failure modes in a process. Each failure mode is evaluated using risk priority number (RPN), which is calculated as a product of occurrence (*O*), severity (*S*), and detectability (*D*). *O* is the probability of a failure occurring. *S* is the degree of severity of a given failure. *D* is the difficulty of detecting a failure. Each parameter is generally expressed with a ten-point scale. For example, *O*, *S*, and $D = 10$ indicate the most frequent, the most severe, and the most difficult to detect, respectively. A larger RPN indicates a higher risk. The relative evaluation of RPN enables the priority ranking for possible failures.

In this study, the concept of RPN was applied to the clinical reference dosimetry by introducing *O*, *S*, and *D* for the calibration factors described in Sections 2.2.1, 2.2.2, and 2.2.3, respectively. The output drift and radiotherapy type were taken into account by introducing dedicated metrics described in Sections 2.2.4 and 2.2.5, respectively, for estimating the effects of these parameters to the clinical reference dosimetry.

2.2.1. Occurrence (O)

Occurrence in the FMEA framework is defined as the probability that a potential failure will occur. In this study, the occurrence was defined as the probability with which factors such as k_{TP}, k_{pol}, k_s, k_{elec}, $N_{D,w}$, k_Q, and TMR were out of tolerance (Fig. 1). k_{TP} was obtained every clinical reference dosimetry measurement, TMR was obtained from scanning data measured when the Clinac iX and Clinac 6EX were introduced and other factors were obtained every calibration of the reference chamber. The mean, standard deviation (SD), and coefficient of variation (CV) of factors were calculated for the all data taken between 2009 and 2012 (Table 1). The tolerance for each factor was defined by assuming that the factor value followed a Gaussian distribution.

2.2.2. Severity (S)

Severity is generally defined as the degree of resulting severity when a potential failure occurs. In this study, the severity corresponded to the dose error for patients. In addition, the dose error was adjusted to the tolerance applied for the factors in the clinical reference dosimetry. In this way, the severity was defined as the ratio of dose error to total dose. Thus, the dose error is calculated as the dose that was prescribed until the detection of the dose error by using clinical reference dosimetry. For example, supposing that the dose error per 1 fraction is 3%, the prescribed dose is 70 Gy/35 fr, and the output calibration frequency

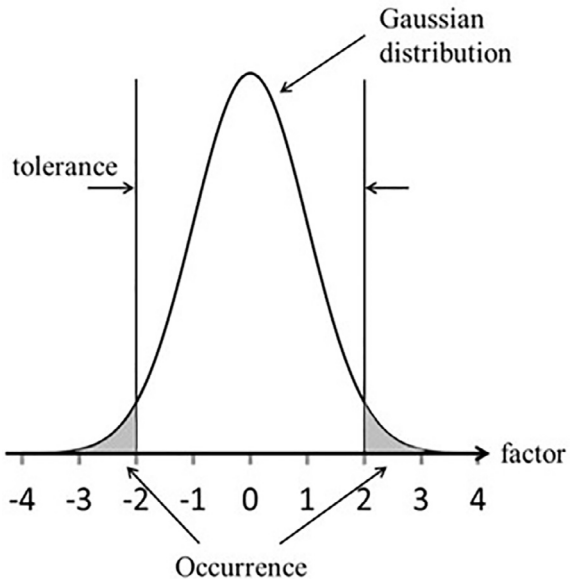

Fig. 1. Distribution of a factor with a given tolerance. Occurrence is defined as the probability that the factor value is out of tolerance.

is 1 time per 4 weeks, the total dose error is 1.2 Gy (= 2 Gy × 0.03 × 20 fr) since the maximum number of fractions of dose error between the clinical reference dosimetries is 20 fractions. The severity in this case is approximately 1.7% (= 2 Gy/70 Gy). It is possible that the dose error is detected in less than 20 fractions, depending on the timing of the treatment start date and the measurement date. Therefore, we defined the severity as the maximum effect. The formula of the severity is

$$\text{Severity}(\%) = \begin{cases} \frac{d\times(t\times 0.01)\times n}{d\times m}\times 100 = \frac{t\times n}{m} & (m > n) \\ t & (m \le n) \end{cases} \quad (2)$$

where t (%) represents the factor's tolerance, d (Gy) represents the absorbed dose per fraction, m (fr) represents the total number of fractions, and the output calibration frequency is defined as once per the number of irradiations "n (fr)".

2.2.3. Detectability (D)

Detectability is the difficulty of the failure detection. Generally, the output calibration is performed regularly; thus, the number of the output calibration during the radiotherapy course varies by the fractionations and the output calibration frequency. We obtained the number of output calibrations during the radiotherapy course by dividing the number of fractions by the frequency of output calibration. The detectability is defined as the reciprocal of the number of output calibrations. The detectability is calculated by

$$\text{Detectability} = 1/(m/n) = n/m \quad (3)$$

Namely, the detectability depends only on m and n. Since the detectability is used for estimating the relative risk, the decrease of the detectability due to the daily output check was assumed to the same among RPNs compared in this study.

2.2.4. Severity by output (S′)

The output of a linac drifts because the response of the monitor chamber changes with time. This phenomenon is linac-specific and may be model-specific, and also dependent on the age of the monitor chamber [11–13]. Dose errors due to the output drift of a linac are accumulated during the course of the treatment. Therefore, a long course treatment is considered to have larger effect by the output drift than that of a short course treatment. The linac stability is an important factor in order to investigate the frequency of the clinical reference dosimetry. Thus, severity due to drift (output change per day) was added to the RPN, and this severity (S') was defined as the accumulated dose error due to drift for the total treatment period. Assuming that mean output drift per day was R (%/day), S' was calculated by

$$S' = \frac{1}{d\cdot m}\{(d\cdot R) + (d\cdot 2R)\cdots+(d\cdot mR)\} = \frac{1}{d\cdot m}\sum_{m=1}^{m}(d\cdot m\cdot R) = R\times\frac{(m+1)}{2}. \quad (4)$$

The daily output data from 2009 to 2013 was used to calculate R of our linacs. The R values were calculated for each period between output adjustments. The mean of R was used in the FMEA analysis.

2.2.5. Number of patients in each radiotherapy type (W)

In practice, radiotherapy types may differ among institutions and linacs. For example, one linac is used for a short course of treatment such as SBRT, whereas another linac is used for a long course of treatment such as head and neck IMRT. Another example is the comparison between a linac used for 50 patients per year and another linac used for 500 patients per year, which produces a difference in severity by a factor of ten.

O'Daniel et al. evaluated the number of patients to perform FMEA for linac QA [8]. Our study also used the number of patients who could be affected by a dose error to calculate the RPN. In addition, the number of patients was analyzed for each radiotherapy type and linac. Since the number of patients and radiotherapy type differ by each linac, the risk for each linac can be evaluated by using this parameter. Thus, the number of patients of each radiotherapy type per year (W) was combined in the RPN. W is obtained by dividing the number of patients of a radiotherapy type by 365 days:

$$W = \frac{a}{365} \quad (5)$$

where a represents the number of patients of a radiotherapy type (Tables 2 and 3).

2.2.6. Calculation of RPN

A standard FMEA method generally employs O, S and D. In this study, the additional parameters S' and W were added to the standard FMEA. $\text{RPN}_{\text{type,factor}}$ was defined as RPN of a correction factor (e.g. k_{TP}, k_{pol}, k_{s}, k_{elec}, $N_{\text{D,w}}$, k_{Q}, and TMR) for a radiotherapy type (see Table 2). $\text{RPN}_{\text{type,factor}}$ was calculated as a product of $O_{\text{type,factor}}$, S_{type} and D_{type} for individual factors for an output calibration frequency and tolerance. RPN_{type} is the mean of $\text{RPN}_{\text{type,factor}}$ for each correction factor, namely,

$$\text{RPN}_{\text{type}} = \frac{1}{7}\sum_{\text{factor}}\text{RPN}_{\text{type,factor}}, \quad (6)$$

Table 1
Correction factors and standard deviation.

	TMR	$N_{\text{D,w}}$	k_{Q}	k_{s}	k_{pol}	k_{elec}	k_{TP}
mean	0.7712	0.0537	0.9922	1.0034	1.0003	1.0000	1.0121
SD	0.00120	0.00040	0.00051	0.00062	0.00059	0.00000	0.00873
CV (%)*	0.160	0.739	0.051	0.062	0.059	0.000	0.863

* CV = SD/mean.

Table 2
Number of patients at Clinac iX. Values in parentheses are the rate of each radiotherapy type in each year (see Section 2.2.5 for details).

Radiotherapy type	Total dose/fraction	Year			
		2009	2010	2011	2012
SBRT	48 Gy/4 fr	12 (0.033)	47 (0.129)	33 (0.09)	32 (0.088)
H&N IMRT	70 Gy/35 fr	13 (0.036)	17 (0.047)	23 (0.063)	19 (0.052)
Palliation	30 Gy/10 fr	21 (0.058)	8 (0.022)	7 (0.019)	3 (0.008)
TBI-A	12 Gy/6 fr/3 days*	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
TBI-B	3.6 Gy/2 fr/day*	5 (0.014)	1 (0.003)	0 (0.0)	0 (0.0)

* Twice-a-day (BID).

and RPN_{type} is the mean of RPN_{type} for each radiotherapy type. In addition, RPN_{type}^{option} is calculated as the product of RPN_{type} and options (S' and/or W) ($RPN_{type}^{S'} = RPN_{type} \times S'$, $RPN_{type}^{S',W} = RPN_{type} \times S' \times W$). In order to observe the drift effect (S') of the output, RPN_{type} and $RPN_{type}^{S'}$ (i.e., RPN without S' and with S') were compared for each radiotherapy type and frequency of output calibration in the case of 1% tolerance and $R = 0.05\%$/day. In the same way, RPN was also calculated for stereotactic radiosurgery (SRS) as other radiotherapy type.

$RPN_{type}^{S',W}$ was adapted for clinical data of Hiroshima University Hospital. In addition, $RPN_{type}^{S',W}$ was switched between the output drift of two linacs to evaluate a risk due to the difference of output drift. $RPN_{type}^{S',W}$ was also calculated in the case that patients were transferred from one linac to another linac because of some linac issues such as downtime.

3. Results

3.1. Frequency of output calibration vs. Tolerance

The RPN_{TBI-B} (3.6 Gy/2 fr/day, BID) was calculated for various tolerances (0.5%, 1.0%, 2.0%, 3.0%, 5.0%) and frequency of output calibration (1/1 fr, 1/5 fr, 1/10 fr, 1/20 fr, 1/30 fr). The result is shown in Fig. 2. A smaller tolerance and a low frequency provide a larger RPN_{TBI-B}. The RPN value is used to evaluate on a relative basis. For example, it was found that the RPN_{TBI-B} (0.5%, 1/1 fr) and the RPN_{TBI-B} (2.0%, 1/10 fr) in Fig. 2 have the same RPN value.

3.2. Effect of output drift

Fig. 3(a) and (b) show RPN_{type} (without S') and $RPN_{type}^{S'}$ (with S'), respectively, for each radiotherapy type and each output calibration frequency (tolerance = 1.0%, $R = 0.05\%$/day). The radiotherapy type with the largest RPN_{type} value among six radiotherapy types including SRS is TBI-B (3.6 Gy/2′fr/day) and SRS (20 Gy/fr), which has the shortest treatment course. On the other hand, the difference of $RPN_{type}^{S'}$ among different radiotherapy types became smaller than RPN_{type} by including the output drift, since radiotherapy types with longer treatment periods had a larger effect due to the accumulation of dose errors. Therefore, this result indicates the importance of the output drifting in the risk evaluation among linacs with different output drift.

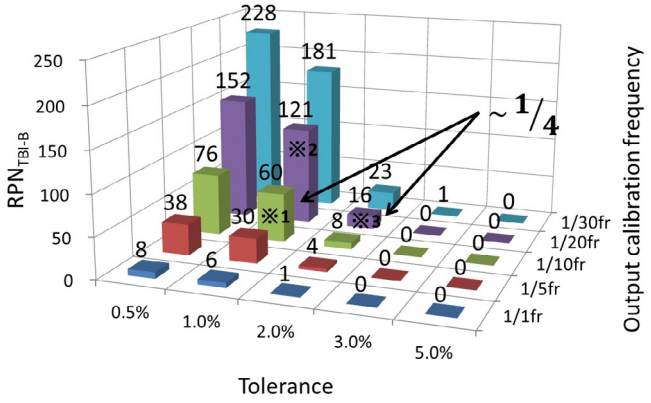

Fig. 2. RPN_{TBI-B} for various output calibration frequencies and tolerances: ※1 Case of 1/10 fr and 1.0% (Hiroshima University Hospital). ※2 Case of 1/20 fr and 1.0% (RPN increased by twofold compared with case ※1). ※3 Case of 1/20 fr and 2.0% (RPN decreased by a factor of four compared with case ※1).

3.3. Output drift per day vs. frequency of output calibration

The mean R of Clinac iX and Clinac 6EX were 0.006%/day and 0.014%/day, respectively. Fig. 4 shows an example of the output drifts (Clinac 6EX). We calculated $RPN_{type}^{S'}$ for the five radiotherapy types and four different types of output drift ($R = 0.006$, 0.0014, 0.02, and 0.05%/day) by the tolerance of 1.0%. The result is shown in Fig. 5. Since $RPN_{type}^{S'}$ depends on the output drift, the larger R provided the larger $RPN_{type}^{S'}$. Thus, adding the output drift to the RPN calculation factors enabled evaluation of the inter-linac or inter-facility risk in a more realistic manner than that without the output drift.

3.4. Adapted novel RPN for clinical data

$RPN_{type}^{S',W}$ for two linacs was calculated by using output drifts and the patient data of Tables 2 or 3. The result is shown in Fig. 6(a). The vertical axis is the RPN value, and the horizontal axis is the radiotherapy type, and the third axis is the year for each linac. These linacs had different output drifts and different numbers of patients for each radiotherapy type. Therefore, there was a difference in RPN between the two linacs. Clinac iX had a large RPN in SBRT, and Clinac 6EX had a

Table 3
Number of patients at Clinac 6EX. Values in parentheses are the rate of each radiotherapy type in each year (see Section 2.2.5 for details).

Radiotherapy type	Total dose/fraction	Year			
		2009	2010	2011	2012
SBRT	48 Gy/4 fr	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
H&N IMRT	70 Gy/35 fr	13 (0.036)	26 (0.071)	35 (0.096)	24 (0.066)
Palliation	30 Gy/10 fr	16 (0.044)	34 (0.093)	27 (0.074)	43 (0.118)
TBI-A	12 Gy/6 fr/3 days*	0 (0.0)	0 (0.0)	0 (0.0)	10 (0.027)
TBI-B	3.6 Gy/2 fr/day*	0 (0.0)	6 (0.016)	6 (0.016)	6 (0.016)

* Twice-a-day (BID).

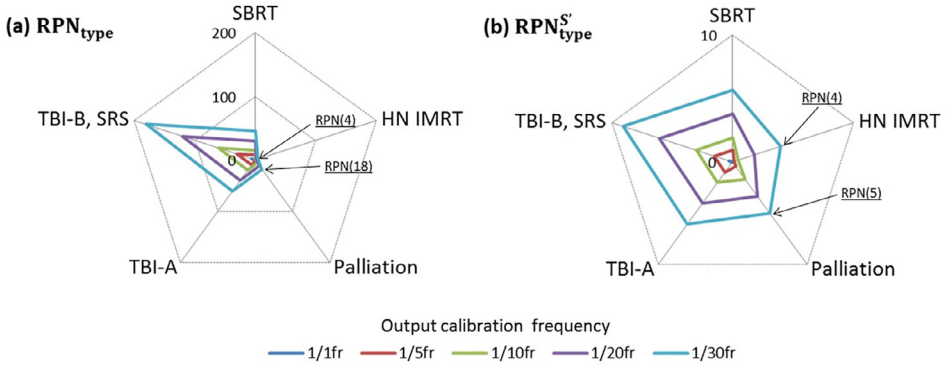

Fig. 3. Comparison of RPN by different output calibration frequency values for five types of radiotherapy: (a) RPN_{type}, (b) $RPN^{S'}_{type}$. Color lines indicate different output calibration frequencies. $RPN^{S'}_{type}$ was greatly affected by the longer treatment period, and the difference of $RPN^{S'}_{type}$ among different radiotherapy types became smaller than RPN_{type}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

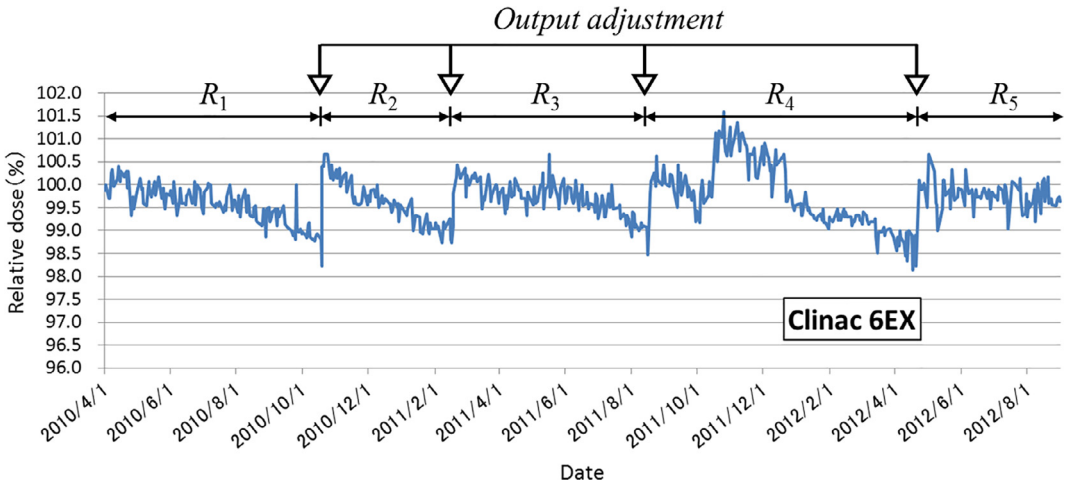

Fig. 4. Daily output measurement data of Clinac 6EX. *R* values were calculated for each period between output adjustments. Then, the mean value of *R* was used in the FMEA analysis. *R* of Clinac 6EX was 0.014%/day.

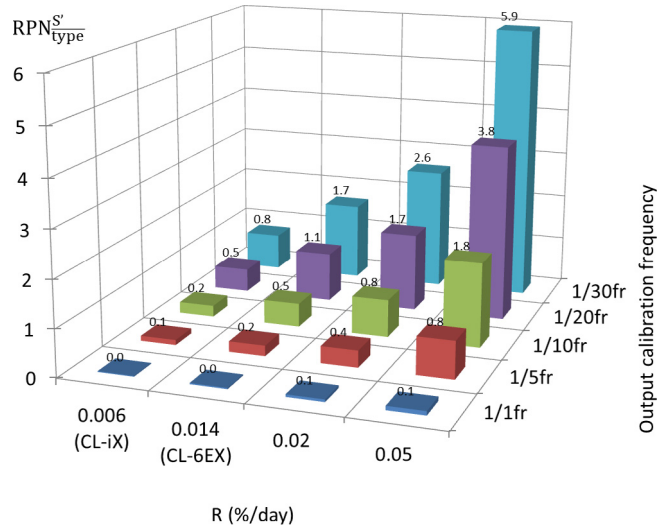

Fig. 5. $RPN^{S'}_{type}$ for linac output drifts and output calibration frequency (tolerance = 1.0%).

large RPN in palliation and TBI-B (Fig. 6(a)). In addition, Fig. 6(b) shows the $RPN^{S',W}_{type}$ switched between the output drift of the two linacs. When comparing Fig. 6(a) and (b), these RPN values were inverted for inter-linacs. Therefore, the result indicated that the effect of the output drifts and the more stable linac was lower risk.

Fig. 6(c) and (d) show $RPN^{S',W}_{type}$ for the case of transferring the patients from Clinac iX to Clinac 6EX, and $RPN^{S',W}_{type}$ for the case of transferring the patients from Clinac 6EX to Clinac iX. The $RPN^{S',W}_{type}$ of each case was clearly different in spite of the same number of patients. In the case of Fig. 6(c), the sums of RPN for the evaluated radiotherapy type were 0.08 (2009), 0.15 (2010), 0.12 (2011), and 0.15 (2012). In the case of Fig. 6(d), the sums of RPN for the evaluated radiotherapy type were 0.04, 0.07, 0.05, and 0.06 for years 2009, 2010, 2011, and 2012, respectively.

4. Discussion

The frequency of output calibration and tolerance vary from clinic to clinic. Fig. 2 shows RPN_{TBI-B} without *S′* and *W* for a combination of tolerance and frequency of output calibration. Since the output of the two linacs at Hiroshima University Hospital is checked once every two weeks (which corresponds to 10 daily fractions) with 1.0% tolerance, the RPN_{TBI-B} of our hospital is approximately 60. This RPN is approximately half that of a linac checked with 1/20 fr (once per month) and 1.0% tolerance. If the tolerance is 2.0% with 1/20 fr, the RPN (=16) is estimated to be smaller than that of our hospital by a factor of approximately four. The method based on FMEA can quantitatively evaluate the relative risk for the combination of tolerance and frequency of output calibration.

In AAPM TG-100, it is recommended to take into account the radiotherapy type and the dose tolerance when the frequency of output calibration is determined [5]. In order to adapt such effects, it is

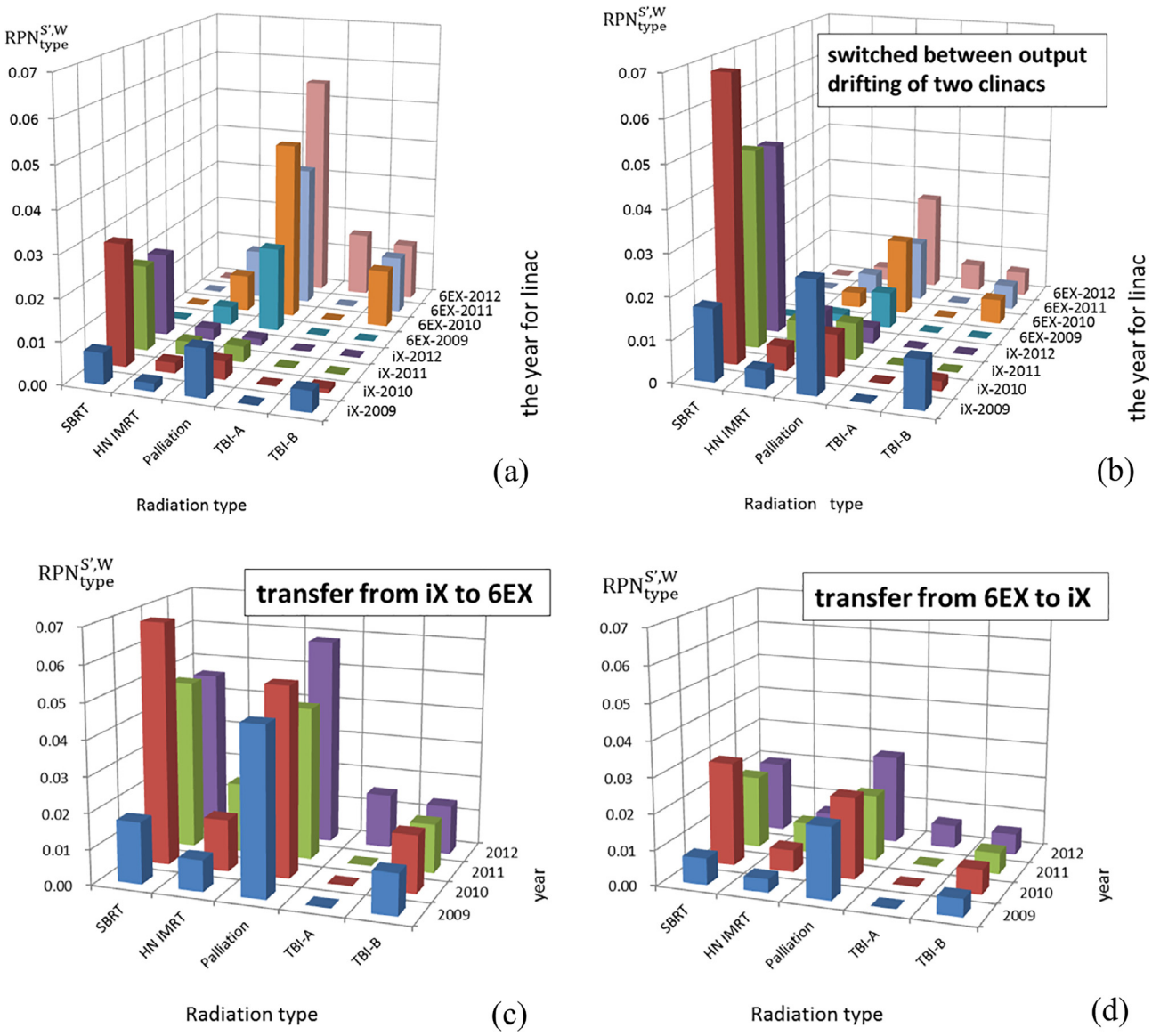

Fig. 6. (a) $RPN_{type}^{S',W}$ with linac output drift. (b) $RPN_{type}^{S',W}$ switched between output drifts of two linacs. (c) $RPN_{type}^{S',W}$ for the case of transferring the patients from Clinac iX to Clinac 6EX. (d) $RPN_{type}^{S',W}$ for the case of transferring the patients from Clinac 6EX to Clinac iX.

necessary to consider the radiotherapy type for each linac to optimize the output calibration frequency of the clinical reference dosimetry. Our study indicated that a short treatment course such as TBI and SRS had a high risk of dose error (Fig. 3(a)), which was similar to the result for AAPM TG-100 [5]. Our study focused on the risk analysis of the physical dose. Thus, the TBI-B and SRS have the same RPN in our method. Note that the tolerance level for each treatment technique (e.g., SRS, SBRT, palliation, etc.) is not taken into account in this method. On the other hand, a long treatment course such as head and neck IMRT increased the risk by taking output drifts into consideration. The larger output drifts provided a larger risk of dose errors for long treatment courses. For example, the ratio of $RPN_{palliation}$ (=18) to $RPN_{HN\ IMRT}$ (=4) was approximately 4.5, whereas the ratio of $RPN_{palliation}^{S'}$ (=5) to $RPN_{HN\ IMRT}^{S'}$ (=4) was approximately 1.25. Thus, the relative risk of the head and neck IMRT with respect to the typical palliation was reduced by a factor of approximately 3.6 by taking the output drifts into account. This result indicates that involving output drifts is important to evaluate the risk of dose errors for the clinical reference dosimetry.

A previous study by Hossain [11] indicated an output drift of 2–4%/year, corresponding to approximately 0.005–0.011%/day. A study by Grattan et al. [13] indicated an output drift of 0.35%/month, corresponding to approximately 0.012%/day over the course of the first 4 years. These output drifts are at the same order as our data, which maximum was 0.014%/day. A stable linac with small output drifts has low risk compared with a linac with large output drifts (Fig. 5). Since the output drift of a linac may be large when a new linac is introduced or a monitor chamber is replaced [13], the frequency of output calibration should be increased at these time periods to reduce the risk. However, it is not always feasible to provide the required manpower when a new linac with large output drifts is installed. In practice, it is important to consider not only the frequency of the clinical reference dosimetry but also to check the malfunction or any other issues of the linac when the output drift is larger than the typical range.

The output calibrations according to clinical reference dosimetry for Clinac iX at Hiroshima University Hospital are performed bi-weekly (1/10 fr). The corresponding $RPN_{type}^{S'}$ is approximately 0.5. According to Fig. 5, in order to ensure that the safety of a linac whose output drifts is 0.02%/day is equal to or more than the safety level of our linac, the output may as well be checked once a week. Thus, the output drift is an

important factor to optimize the frequency of output calibration.

Ford et al. pointed out that underestimation of failure may occur when the failure rate is a very small number, and therefore it is important to evaluate the risk of the failure in context [14]. We also stress that it is important to take into account the number of patients treated at each linac. The maximum value of the sum of RPN each year for Clinac iX and Clinac 6EX are 0.04 and 0.09, respectively (Fig. 6(a)). If two linacs are managed by an equivalent risk, the frequency of output calibration of Clinac 6EX may be increased to the same level as that of Clinac iX. In addition, if the patients treated with one linac are transferred to another linac, $RPN_{type}^{S',W}$ between the cases of Fig. 6(c) and (d) were different approximately by twofold. This result depended on our linacs output drifts. Therefore, in this case, the frequency of output calibration may be optimized by depending on output drift and the number of patients treated.

Recently, the daily check of the parameters other than the dose output (e.g., beam quality, flatness, symmetry, etc.) has become popular. For example, Daily QA 3 device can measure these machine-specific parameters by single irradiation of the beam to the device in morning checks [15]. Park et al. developed a new QA method to conveniently perform comprehensive mechanical QA of linac such as the gantry, collimator, and couch angles, isocentricity, etc. [16]. These improvements would be able to produce opportunities to simultaneously check multiple parameters by simple measurements on daily basis. It may be also useful to utilize our risk analysis method to evaluate the risk of various machine parameters obtained by using the above techniques.

5. Conclusions

We developed a novel risk assessment method for the clinical reference dosimetry based on FMEA that can quantitatively evaluate the risk. It was found that the linac output drifts, the frequency of the output calibration, the treatment course period and the number of patients affect the risk evaluation. The $RPN_{type}^{S',W}$ calculated using these parameters could quantitatively evaluate the relative risk in the clinical reference dosimetry. The $RPN_{type}^{S',W}$ would be one of the utility indexes to consider the frequency of the output calibration. Finally, since the $RPN_{type}^{S',W}$ could be used in any facilities as a common index, it could implement a relative risk assessment of the clinical reference dosimetry among multiple institutions.

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Disclosure of conflicts of interest

All of the authors have no conflicts of interest regarding this work.

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