Journal of Radiation Research, Vol. 62, No. 1, 2021, pp. 58–66
doi: 10.1093/jrr/rraa088
Advance Access Publication: 19 October 2020

Radiation protection in radiological imaging: a survey of imaging modalities used in Japanese institutions for verifying applicator placements in high-dose-rate brachytherapy

Hiroyuki Okamoto[1,*], Satoshi Kito[2,3,4], Naoki Tohyama[5], Shunsuke Yonai[6], Ryu Kawamorita[7], Masaru Nakamura[8], Takahiro Fujimoto[9], Syoji Tani[10], Akihiro Yomoda[11], Toru Isobe[12], Hiroshi Furukawa[13], Kikuo Kotaka[14], Jun Itami[15], Hitoshi Ikushima[16], Takushi Dokiya[17] and Yoshiyuki Shioyama[18]

[1]Department of Medical Physics, National Cancer Center Hospital, 5-1-1 Tsukiji, Chuo-ku Tokyo, 104-0045, Japan
[2]Department of Radiotherapy, Tokyo Metropolitan Bokutoh Hospital, 4-23-15 Koutoubashi, Sumida-ku Tokyo, 130-8575, Japan
[3]Department of Radiotherapy, Tokyo Metropolitan Cancer and Infectious Diseases Center Komagome Hospital, 3-18 Honkomagome, Bunkyo-ku Tokyo, 113-8677, Japan
[4]Division of Medical Physics, Department of Information Technology and Medical Engineering, Human Health Sciences, Graduate School of Medicine, Kyoto University 53 Shogoin-Kawaharacho, Sakyo-ku Kyoto, Kyoto, 606-8507, Japan
[5]Division of Medical Physics,Tokyo Bay Advanced Imaging & Radiation Oncology Makuhari Clinic, 1-17 Toyosuna, Mihama-ku Chiba, Chiba, 261-0024, Japan
[6]Department of Accelerator and Medical Physics, National Institute of Radiological Sciences, National Institutes for Quantum and Radiological Science and Technology, 4-9-1 Anagawa, Inage-ku Chiba, Chiba, 263-8555, Japan
[7]Department of Radiation Oncology, Tane General Hospital, 1-12-21 Kujyouminami, Nishi-ku Osaka, Osaka, 550-0025, Japan
[8]Department of Radiology, Aichi Medical University Hospital, 1-1 Yazakokarimata, Nagakute, Aichi, 480-1195, Japan
[9]Division of Clinical Radiology Service, Kyoto University Hospital, 54 Shogoin-Kawaharacho, Sakyo-ku Kyoto, Kyoto, 606-8507, Japan
[10]Department of Medical Technology, Osaka General Medical Center, 3-1-56 Bandaihigashi, Sumiyoshi-ku Osaka, Osaka, 558-8558, Japan
[11]Technical Section, Medical Equipment Business, Chiyoda Technol Corporation, 1-7 Yushima, Bunkyo-ku Tokyo, 101-0021, Japan
[12]Oncology Product Marketing Manager, Elekta K.K, 3-9-1 Shibaura, Minato-ku Tokyo, 108-0023, Japan
[13]Japan Medical Imaging and Radiological Systems Industries Association, 2-2-23 Koraku, Bunkyo-ku, Tokyo, 112-0004, Japan
[14]Nuclear Safety Technology Center, 5-1-3-101 Hakusan, Bunkyo-ku, Tokyo, 112-8604, Japan
[15]Department of Radiation Oncology, National Cancer Center Hospital, 5-1-1 Tsukiji, Chuo-ku Tokyo, 104-0045 Japan
[16]Department of Therapeutic Radiology, Institute of Biomedical Sciences, Tokushima University Graduate School, 3-18-15 Kuramoto-cho, Tokushima, Tokushima, 770-8503, Japan
[17]Department of Radiology, Kyoundo Hospital, 1-8 Kandasurugadai, Chiyoda-ku Tokyo, 101-0062, Japan
[18]Department of Clinical Radiology, Graduate School of Medical Sciences, Kyushu University, 3-1-1 Maidashi, Higashi-ku Fukuoka, Fukuoka, 812-8582, Japan
*Corresponding author. Department of Medical Physics, National Cancer Center Hospital, 5-1-1 Tsukiji, Chuo-ku Tokyo, 104-0045, Japan.
Tel: +81(3) 3542-2511; Fax: +81(3)3545-3567; Email/Fax: hiokamot@ncc.go.jp
(Received 3 June 2020; revised 2 August 2020; editorial decision 23 August 2020)

ABSTRACT

Institutional imaging protocols for the verification of brachytherapy applicator placements were investigated in a survey study of domestic radiotherapy institutions. The survey form designed by a free on-line survey system was distributed via the mailing-list system of the Japanese Society for Radiation Oncology. Survey data of 75 institutions between August 2019 and October 2019 were collected. The imaging modalities used were dependent on resources available to the institutions. The displacement of a brachytherapy applicator results in significant dosimetric impact. It is essential to verify applicator placements using imaging modalities before treatment. Various imaging modalities used in institutions included a computed tomography (CT) scanner, an angiography X-ray system, a multi-purpose X-ray system and a radiotherapy simulator. The median total exposure time in overall treatment sessions was ≤75 s for gynecological and prostate cancers. Some institutions used fluoroscopy to monitor the brachytherapy source

movement. Institutional countermeasures for reducing unwanted imaging dose included minimizing the image area, changing the imaging orientation, reducing the imaging frequency and optimizing the imaging conditions. It is worth noting that half of the institutions did not confirm imaging dose regularly. This study reported on the usage of imaging modalities for brachytherapy in Japan. More caution should be applied with interstitial brachytherapy with many catheters that can lead to potentially substantial increments in imaging doses for monitoring the actual brachytherapy source using fluoroscopy. It is necessary to share imaging techniques, standardize imaging protocols and quality assurance/quality control among institutions, and imaging dose guidelines for optimization of imaging doses delivered in radiotherapy should be developed.

Keywords: imaging dose; brachytherapy; IGBT; displacement; fluoroscopy

INTRODUCTION

Radiological imaging in radiotherapy is widely used for multiple purposes, including the assessment of the extent of a disease, conducting radiotherapy used for treatment planning, and verifying and correcting patient setup before radiotherapy. In brachytherapy, applicator placements or brachytherapy source location can be confirmed using imaging modalities. However, recently, there has been growing interest in radiological protection in medicine [1–8], and imaging dose management should be considered, even for radiotherapy [9–11]. The guidelines related to imaging dose management are well organized, and the caution advised in several guidelines for imaging dose management in medicine is to prevent excessive imaging doses to patients. For instance, IEC60601-2-44 [12] requires the display of computed tomography (CT) dose metrics such as the volume CT dose index ($CTDI_{vol}$) and dose length product (DLP) [4, 13] as proof of mechanical performance.

In Japan, regulations on the medical radiation safety management system took effect from April 2020, and a statement to domestic radiotherapy institutions [14] was issued by the Ministry of Health, Labour, and Welfare of the Japanese government. According to their notification, imaging dose management, along with the reduction of unnecessary imaging doses using the principle of as low as reasonably achievable (ALARA), must be conducted. These imaging modality regulations focus on imaging doses that are potentially higher than that of a typical X-ray imaging systems. These were identified based on the categories of imaging modalities in the package insert. Examples of imaging systems that may be in these categories included the systems used for portable analog-angiography, portable digital-angiography, stationary analog-angiography, stationary analog-angiography, angiography-computed tomography (CT), CT scanner, single photon emission computed tomography (SPECT)-CT and positron emission tomography (PET)-CT.

Fig. 1 shows a radiographic image and CT images for the verification of applicator placements before treatment for the same patient. A radiation oncologist relies on using X-ray imaging to verify applicator position or brachytherapy source location before treatment using the above image modalities. The imaging doses delivered to brachytherapy patients remains unclear, and they might vary widely due to variations in institutional imaging protocols, image conditions and imaging modalities. This study aimed to conduct a survey study in domestic radiotherapy institutions to assess institutional imaging protocols and imaging doses in fluoroscopy, which potentially result in higher imaging doses for the verification of brachytherapy applicator placements or brachytherapy source locations in high dose rate (HDR) brachytherapy. To the best of our knowledge, this is the first report with extensive investigations on imaging dose management in HDR brachytherapy.

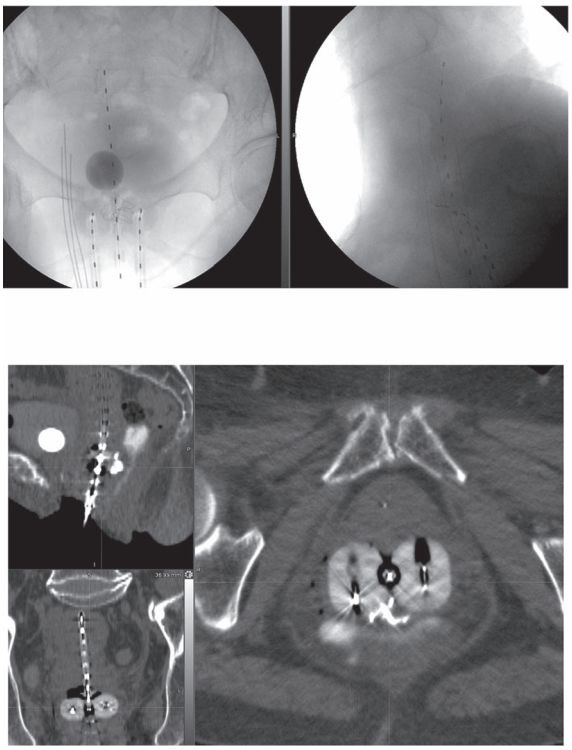

Fig. 1. (a) Radiography and (b) CT-images for the verification of applicator placements.

MATERIALS AND METHODS

Survey design

The Radiotherapy Imaging Dose Management Subcommittee (RIDMS) was established as part of the medical safety committee of the Japanese Society for Radiation Oncology (JASTRO). The RIDMS was composed of some JASTRO committee members and radiotherapy safety management specialists, including radiation oncologists, medical physicists and radiotherapy technologists. The concept and questionnaires in this survey had been discussed among members of the RIDMS since 2019. The survey form, designed by a free on-line survey system (google forms), was distributed via the mailing-list system of JASTRO. The survey study focused on domestic radiotherapy institutions.

Table 1. Summary of the questions used in this survey study

#	Question
1.	Institution
2.	Respondent
3.	HDR RALS
4.	The vendor of image modalities for verification of applicator placements, including other purposes such as confirmation of gas in the rectum
5.	Categories of your image modalities in the package insert
6.	Institutional countermeasures to reduce imaging dose
7.	Methods to record imaging conditions
8.	Display of imaging dose ($CTDI_{vol}$, DLP) on CT scanners
9.	$CTDI_{vol}$ (mGy) and DLP (mGy·cm) in LDR prostate, HDR breast, HDR gynecology and HDR prostate brachytherapy for the five most recent patients
10.	Images transferable to PACS
	Intracavitary brachytherapy in gynecological cancer
11.	Select your verification timing of applicator placements using the above image modalities (multiple choice allowed) (a) Before treatment (b) After treatment (c) During treatment (d) Others
12.	Typical image conditions such as kV and mAs
13.	Prescribed dose (X Gy in Y fractions)
14.	The frequency for each item in question #11 (multiple choice allowed)
15.	Exposure time in fluoroscopy for each item in question #11 (multiple choice allowed)
	Combined intracavitary with interstitial brachytherapy in gynecological cancer
	#16–20 are the same questions as #11–15
	Interstitial brachytherapy in prostate cancer
	#21–25 are the same questions as #11–15

Table 1 summaries the questionnaires in this survey. The treatments performed were intracavitary brachytherapy, a combination of intracavitary and interstitial brachytherapy for gynecological cancer, and interstitial brachytherapy for prostate cancer. These are represented with the symbols, G_{IC}, G_{COMB}, and P_{INT}, respectively, in this study. Concerning the survey on $CTDI_{vol}$ and DLP, the investigated techniques were low dose rate (LDR) prostate, HDR breast, HDR gynecology and HDR prostate brachytherapy.

Analysis

Survey data of 75 institutions between August 2019 and October 2019 were collected. The survey response rate was ∼50% by a total of 152 institutions owning a remote afterloading system (RALS). Two institutions did not have a RALS. Thus, the total number of data for analysis was 73. These were analyzed by H.O. and some members of the RIDMS. All circle graphs in this paper are expressed as percentages of institution numbers, with an indication of the total number of institutions also given in the figures.

RESULTS

The vendors of the RALS were Elekta (Stockholm, Sweden), Varian Medical Systems (Palo Alto, CA, USA) and Eckert & Ziegler BEBIG GmbH (Berlin, Germany), and the numbers of institutions using these vendors were 62, 3 and 8, respectively. Table 2 summarizes the prescribed doses for G_{IC}, G_{COMB} and P_{INT} in the 73 institutions analyzed. The median prescribed dose was 24 Gy in 4 fractions for gynecological cancer and 18 Gy in 2 fractions for prostate cancer. Institutions that performed G_{IC}, G_{COMB} and P_{INT} were 70, 20 and 13 in number, respectively. Fig. 2 shows the verification timing of applicator placements and the monitoring of a ^{192}Ir or ^{60}Co source movement using imaging modalities. The imaging modalities used for this purpose were dependent on the resources available to each institution, such as a CT scanner, an angiographic X-ray system or a multi-purpose X-ray system etc., as seen in Table 3. Almost all institutions used a CT scanner, an angiography X-ray system and a multi-purpose X-ray system for the purpose. Almost all institutions verified applicator placements before treatment, irrespective of variations in treatment sites. The verification timing of 'During treatment' involves two methods: radiography and fluoroscopy. Institutions using the two methods were almost equal in number: The number of institutions using radiography and fluoroscopy in G_{IC} was 7 and 6, respectively. The number of those in G_{comb} was 3 and 4, respectively. The fraction of the other component (36%) in P_{INT} was more than that of gynecological cancer. This was because some institutions used ultrasonic diagnostic equipment instead of radiation equipment specialized for checking the presence of gas in the rectum. Table 4 shows the median and maximum total exposure times in fluoroscopy in the overall treatment sessions. The observed median imaging exposure time during treatment was

Table 2. Median (minimum–maximum) prescribed dose and fractions for G_{IC}, G_{COMB} and P_{INT}

Site	G_{IC}	G_{COMB}	P_{INT}
Fractional dose (Gy)	6 (4–6.5)	6 (5–7)	9 (6.5–15)
Fractions	4 (3–6)	4 (2–7)	2 (1–7)
Prescribed dose (Gy)	24 (12–30)	24 (12–42)	18 (15–49)

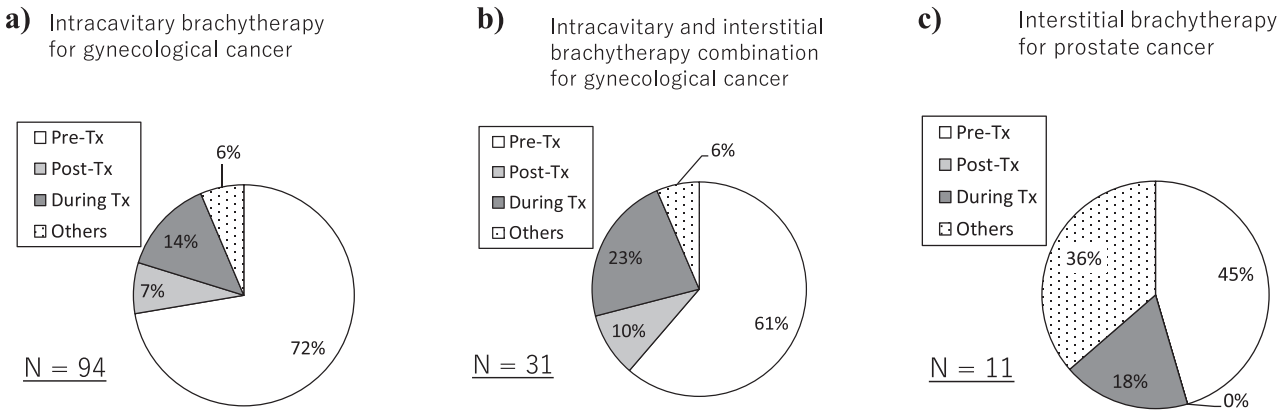

Fig. 2. Verification timing of applicator placements using imaging modalities for (a) G_{IC}, (b) G_{COMB} and (c) P_{INT}. Imaging modalities are summarized in Table 3.

highest. The maximum fluoroscopy exposure time during treatment was 420 s in P_{INT} for one institution. Fig. 3a shows institutional policies for reducing unwanted imaging dose to the patient. The most frequent countermeasure (74%) was to minimize the imaging area. The second most frequent countermeasure was the optimization of imaging conditions such as tube voltage (kV) and tube current (mA) (changing imaging conditions from the standard parameters). One institution used an iterative reconstruction for this purpose. As shown in Fig. 3b, various methods to record imaging dose in the radiology information system (RIS) were investigated: automatic recording to RIS, manually recording to RIS, use of spreadsheet applications such as Microsoft Excel, and manual recording on paper. Institutions that were unable to export imaging dose, recorded image conditions such as kV and mA instead of recording imaging dose. Approximately 60% of institutions had a system capable of recording imaging dose. As shown in Figs. 3c and d, almost all of the institutions have CT scanners capable of displaying imaging dose and exporting CT images to picture archiving and communication systems (PACS). Fig. 3e shows the frequency of checking imaging dose for fluoroscopic apparatus. It is worth noting that almost half of institutions regularly did not confirm imaging dose, and only 15% of institutions confirmed it regularly. Fig. 4 shows the boxplots for the $CTDI_{vol}$ and DLP from the mean values of the five most recent patients in each institution for LDR prostate, HDR breast, HDR gynecology and HDR prostate brachytherapies; fewer variations of the median $CTDI_{vol}$ for these were observed. However, greater deviations of the $CTDI_{vol}$ and DLP at each treatment site were observed, and the maximum-to-minimum ratios of the $CTDI_{vol}$ among institutions for those were 2.9, 1.4, 19.4 and 2.4, respectively. Similarity, the DLP ratios were 3.5, 3.0, 3.0 and 36, respectively. The DLP also demonstrated more substantial variations among institutions.

DISCUSSION

In external radiotherapy, we can verify patient setup using an on-line kV imaging system equipped with a linac. In brachytherapy, the therapeutic region cannot be physically confirmed by the dedicated device. Therefore, applicators or catheters should be firmly fixed during the treatment process. In addition, the brachytherapy source has a steep dose gradient, and dosimetric impact due to source positional changes can be influenced significantly [15]. Kirisits *et al.* reviewed clinical uncertainties in brachytherapy [16], and the overall brachytherapy uncertainties could be categorized by source strength, treatment planning, medium dosimetric corrections, dose delivery including registration of applicator geometry to anatomy, and interfraction/intrafraction changes between imaging and dose delivery. Notably, the greatest uncertainty was interfraction/intrafraction changes in all components. For instance, uncertainties in the HDR ^{192}Ir source for intracavitary and image-guided cervical cancer were 2, 3,1, 4 and 11%, for source strength, treatment planning, medium dosimetric corrections, dose delivery including registration of applicator geometry to anatomy, and interfraction/intrafraction changes, respectively, with interfraction/intrafraction uncertainty being the greatest. To effectively reduce applicator displacements, not only the fixation of applicators but also the immobilization of the patient's legs and hips was essential [17]. It was also reported that by using a hover patient transport system, the percentage of fractions with applicator displacements >5 mm could be reduced from 22.7 to 7.4% [18]. Shindel *et al.* investigated the dosimetric impact by displacement of tandem and ovoids. They concluded that a $\pm$ 3 mm applicator displacement could cause a dosimetric change of $\geq$10% [19]. Takenaka *et al.* investigated displacements of catheters in interstitial HDR brachytherapy for the prostate, and the mean displacement distances were 4.3, 4.6 and 5.8 mm at 21, 45 and 69 h after initial planning CT [20]. Iijima *et al.* also investigated dosimetric changes due

Table 3. Imaging modalities for the verification of applicator placements

Imaging modality	*n*
CT scanner	22
Angiography X-ray system	20
Multi-purpose X-ray system	15
Radiotherapy simulator	7
Computed tomographic angiography X-ray system	2
Others (including unidentified)	7

Table 4. Median (Med) and maximum (Max) total exposure times in fluoroscopy in the overall treatment sessions

	G_{IC}			G_{COMB}			P_{INT}		
	n	Max	Med	*n*	Max	Med	*n*	Max	Med
Before treatment	51	600	36	10	180	75	3	60	10
After treatment	3	120	6	1	9	9		*NA*	
During treatment	5	180	70	4	300	155	2	420	360

n = Number of institutions, NA = the number of institutions was zero.

to inter-fractional variations in a strut-adjusted volume implant (SAVI) for accelerated partial breast irradiation. The dose constraints met the criterion of every fraction for nine patients and the dosimetric impact was small [21].

As shown in Fig. 2, a general verification of applicator placements was done before the treatments were performed. In cases where the imaging system for this purpose was a CT scanner, the obtained CT images could be used for treatment planning. Some institutions confirmed applicator placement during treatment using fluoroscopy. Nose *et al.* developed a modified C-arm fluoroscopic verification of an HDR ^{192}Ir source position, and two positional errors were detected among 2031 treatment sessions for 370 patients [22]. Furthermore, recently they tried to use a commercial flat-panel detector fluoroscope without modification of the imaging properties; they were able to visibly locate an actual source with sufficient image quality [23]. However, when imaging an actual brachytherapy source, halation on images generally occurs due to scattering from the brachytherapy source to a detector, making it difficult to image in some cases. In such a case, the adjustment of gain or the distance from the brachytherapy source in the X-ray imaging system should be addressed. However, the adjustment of gain is generally not applicable because it is impossible for users to only adjust the gain in general X-ray imaging systems. In interstitial brachytherapy with many catheters or higher fractional dose, irradiation time is consequently longer. In such cases, fluoroscopic examination time becomes longer when monitoring the overall movement of the brachytherapy source, potentially leading to skin injuries [24]. To avoid this, the RIDMS recommends that institutions should check the brachytherapy source instantaneously or use a dummy source instead of an actual source to prevent harmful radiation exposure in patients. The dose rate in fluoroscopy is dependent on equipment, geometries and image conditions such as kV and mA. A typical entrance dose rate of 20 mGy/min was reported by AAPM task group 75 [9]. Under the assumption that the entrance dose rate was 20 mGy/min, the total imaging doses for fluoroscopic examination in G_{IC}, G_{COMB} and P_{INT} were roughly estimated from Table 4. The imaging dose contributed by the CT scanner was not considered, because the $CTDI_{vol}$ metric does not represent the actual patient dose [25, 26]. The median total imaging doses in the overall G_{IC}, G_{COMB} and P_{INT} treatment sessions were 13, 40 and 12 mGy, respectively. This was estimated by considering the frequency of verification of applicator placement and exposure time in fluoroscopy (Fig. 2 and Table 4). The corresponding fractions of the imaging doses relative to the institutional prescribed doses for G_{IC}, G_{COMB} and P_{INT} were 0.2, 0.2 and 0.1%, respectively. The corresponding maximum imaging doses were 200, 100 and 20 mGy, respectively, and the corresponding fractions were 0.8, 0.6 and 0.1%, which were less than the recommended threshold of 5% for the therapeutic target dose recommended by the AAPM task group 180 [11]. Moreover, this survey did not focus on head and neck and bronchial cancers, which is a limitation of the study. For such sites, frequent utilization of fluoroscopy is possible.

The imaging conditions, such as geometry, exposure time and shielding, should be considered. For instance, the imaging dose dramatically changes with distance from an X-ray tube according to an inverse square law. It is essential to keep sufficient distance between an X-ray tube and a patient. Additionally, minimizing the distance between a flat panel detector and a patient is also effective. Institutional policies for the reduction of unwanted imaging doses were evaluated. As shown in Fig. 3a, a generally utilized method of achieving this was minimizing the imaging area. The CT scout is essential to determine the minimal scan area. In brachytherapy, CT imaging of the whole lung, which is a common protocol in external radiotherapy for

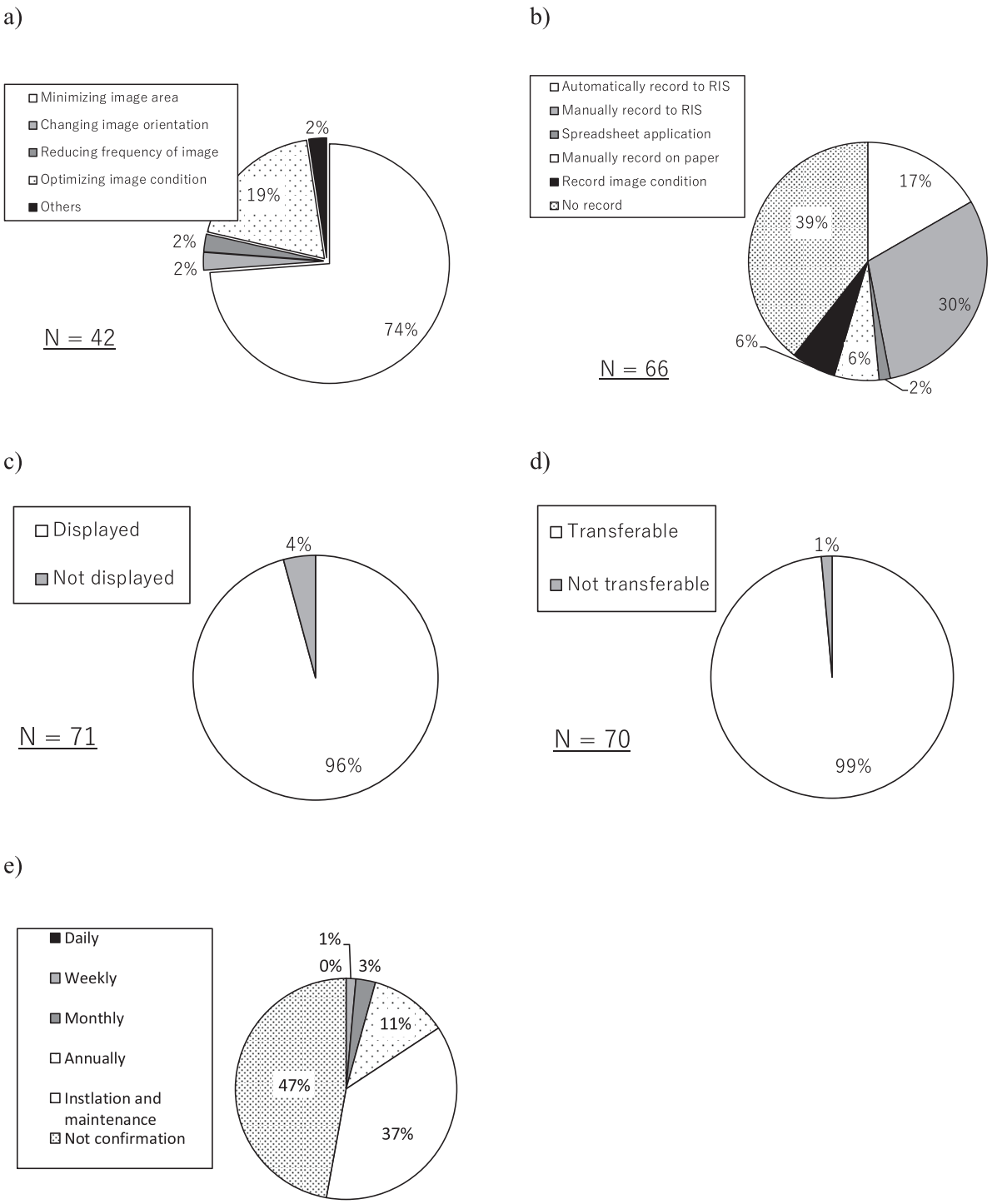

Fig. 3. (a) Institutional policies to reduce imaging dose. (b) Methods to record imaging dose. (c) Institutional ability to display imaging dose in CT scans. (d) Institutional abilities to transfer CT images to PACS. (e) Frequency of checking imaging dose for fluoroscopic apparatus.

evaluating parameters such as V_{20Gy}, might not be necessary, because the brachytherapy source provides an extremely high dose only near the source. Therefore, as shown in Fig. 4, the institutional DLP in HDR breast brachytherapy was the lowest despite the small number of institutions. The optimization of imaging conditions is mainly performed through the application of automatic exposure control

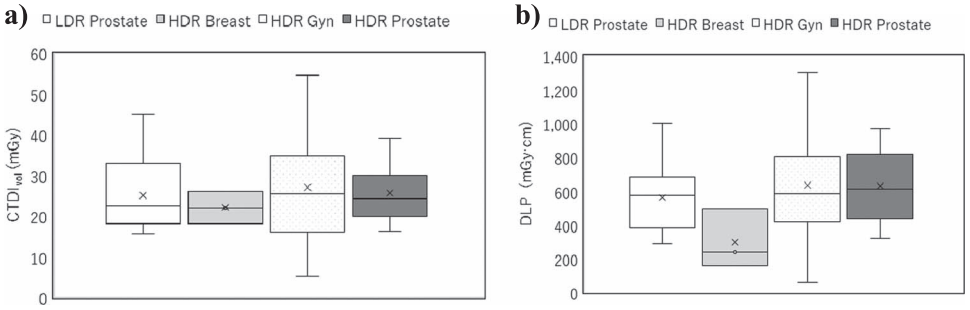

Fig. 4. The CT dose metrics, (a) CTDIvol (mGy) and (b) DLP (mGy·cm) for the five most recent patients in each institution for LDR prostate, HDR breast, HDR gynecology and HDR prostate brachytherapy. The symbol (×) signifies the mean value.

(AEC). Imaging dose is proportional to the product of tube current and exposure time. Recently, it was shown that AEC application may be used for individual patients in CT and X-ray imaging systems. For instance, the implementation of AEC for adjusting tube current achieved a 27–40% dose reduction in a phantom study [27]. A novel image reconstruction approach to reduce imaging dose has been developed, and iterative reconstruction and deep learning image reconstruction without the deterioration of image quality are anticipated [28–31]. Our survey demonstrated two major issues. Fig. 3b shows the examination of institutional methods to record imaging doses in RIS. Approximately 60% of all institutions had a system capable of recording, including manual paper recording. However, ∼40% of all institutions did not record imaging doses. This is a major problem in terms of radiation protection in radiological imaging, and should be addressed. Institutions should manually record imaging conditions on paper, even if institutional imaging modalities cannot provide or display imaging doses. Additionally, Fig. 3e shows the results of the survey on checks for imaging doses for the fluoroscopic apparatus in periodic institutional quality assurance/quality control (QA/QC) programs. It was revealed that half of the institutions in Japan did not confirm imaging doses regularly. Standardized and adequate environments and resources for measuring kV imaging dose thus remain too limited. The RIDMS recommends that a typical ionization chamber should be provided to monitor the stability of the exposure level from baseline (at commissioning) in fluoroscopy.

CT dose assessment for individual patients should consider CT radiation dose and patient size. However, it is not practical to directly measure the absorbed dose to the organs of interest. Therefore, physical or mathematical representations of patients were developed as anthropomorphic phantoms. Utilizing such phantoms provided the effective doses based on measurements or Monte Carlo calculations. Recently, there have been several methodologies to estimate the effective dose: by comparing effective dose with DLP, the coefficient k was obtained to convert DLP to an effective dose for a standard-sized patient [32, 33]. In addition, the AAPM evaluated size-specific doses with the corrections based on the size of the patient [34, 35]. Moreover, the CT organ dose estimation tool, the ImPACT, allows the selection of a specific scan range and reports patient dose based on Monte Carlo methods [36]. Similarly, a web-based CT dose calculator, WAZA-ARI [37, 38], can be utilized, and it provides effective doses based on the Japanese adult male phantom (JM phantom) using the particle and heavy ion transport code system (PHITS). It should be noted that the results determined for standard phantoms should not be applied to the examination of individual patients for dose assessment.

As shown in Fig. 4, fewer variations in the median $CTDI_{vol}$ were observed. In general, the $CTDI_{vol}$ is dependent on scan conditions such as tube voltage, tube current, collimator size, gantry rotation time, pitch and bowtie filter. In contrast, filters and the reconstruction kernel are less influential. The $CTDI_{vol}$ provides only a coarse indication of patient exposure, although it can be used with dose coefficients from mathematical modelling to estimate organ and effective doses for specific scanning techniques [4]. In addition, $CTDI_{vol}$ is used to compare machine performance, such as radiation output, among CT scanners.

According to ICRP 135 [8], the $CTDI_{vol}$ and DLP can be used for the setting of diagnostic reference levels (DRLs), allowing the management of imaging doses in medical X-ray imaging and diagnostic nuclear medicine procedures. The DRLs are regarded as a commonly and easily measured parameter. A large domestic survey by Matsunaga *et al.* [39] reported that the tube currents associated with imaging doses in Japanese institutions were higher than those in other countries. By comparing DRLs, institutions can evaluate their situation and have a chance to improve and optimize medical imaging protocols.

As our survey study demonstrated, institutions rely on medical imaging to ensure safety in radiotherapy, and medical imaging plays an important role in radiotherapy. The ICRP mentioned that DRLs are not intended for use in radiotherapy but they should be considered for imaging for treatment planning, treatment rehearsal and patient set-up verification in radiotherapy [8]. The AAPM recommends that the imaging dose should be <5% of the prescribed therapeutic dose, and the ALARA principle should be applied in clinical practice. For minimizing radiation exposure in radiotherapy, not only staff's mindset should be changed, but also education regarding radiation protection in radiological imaging protection and skillful imaging techniques are essential in radiotherapy. Furthermore, based on the survey results, it is necessary to share imaging techniques, standardize imaging protocols and QA/QC programs among institutions, and develop imaging dose guidelines for the optimization of imaging doses delivered in radiotherapy.

CONCLUSION

The displacement of a brachytherapy applicator results in significant dosimetric impact. It is essential to verify applicator placements using

appropriate imaging modalities. This study evaluated institutional imaging protocols in brachytherapy. More caution should be applied in interstitial brachytherapy with many catheters, which can potentially lead to substantial increments in imaging dose for monitoring an actual brachytherapy source during treatment using fluoroscopy. Approximately 40% of all institutions did not record imaging dose. This is a major problem in terms of radiation protection in radiological imaging protection. Institutions should manually record imaging conditions on paper, even if institutional imaging modalities cannot provide or display imaging doses. Based on the survey results, it is necessary to share imaging techniques, standardized imaging protocols and QA/QC programs among institutions, and imaging dose guidelines for the optimization of imaging doses delivered in radiotherapy should be developed.

ACKNOWLEDGMENTS

The authors would like to thank Chiyoda Technol Corporation, Varian Medical Systems, Inc., Euro Medi Tech, Inc. for technical support of the survey study. We would like to appreciate all radiotherapy institutions in Japan for cooperating this survey study.

FUNDING

This research is partially supported by the Japanese Society for Radiation Oncology (JASTRO).

CONFLICT OF INTEREST

None declared.

REFERENCES

1. UNSCEAR. *Sources and Effects of Ionizing Radiation. Volume I: Sources*. United Nations, New York: United Nations Scientific Committee on the Effects of Atomic Radiation2000 Report to the General Assembly, with Scientific Annexes, 2000.
2. ICRP. The 1990 recommendations of the international commission on radiological protection. ICRP publication 60. *Ann ICRP* 1991;21:1–201.
3. ICRP. Radiological protection and safety in medicine. ICRP publication 73. *Ann ICRP* 1997;24:1207–9.
4. ICRP. Managing patient dose in computed tomography. ICRP publication 87. *Ann ICRP* 2000;30:1–45.
5. ICRP. Radiation and your patient: A guide for medical practitioners. ICRP supporting guidance 2. *Ann ICRP* 2001;31:5–31.
6. ICRP. The 2007 recommendations of the international commission on radiological protection. ICRP publication 103. *Ann ICRP* 2007;37:1–332.
7. ICRP. Radiological protection in medicine. ICRP publication 105. *Ann ICRP* 2007;37:1–63.
8. ICRP. Diagnostic reference levels in medical imaging. ICRP publication 135. *Ann ICRP* 2017;46:1–144.
9. Murphy MJ, Balter J, Balter S et al. The management of imaging dose during image-guided radiotherapy: Report of the AAPM task group 75. *Med Phys* 2007;34:4041–63.
10. Ding GX, Munro P. Radiation exposure to patients from image guidance procedures and techniques to reduce the imaging dose. *Radiother Oncol* 2013;108:91–8.
11. Ding GX, Alaei P, Curran B et al. Image guidance doses delivered during radiotherapy: Quantification, management, and reduction: Report of the AAPM therapy physics committee task group 180. *Med Phys* 2018;45:e84–99.
12. IEC 60601-2-44 Medical electrical equipment - Part 2-44: Particular requirements for the basic safety and essential performance of X-ray equipment for computed tomography 3rd Ed, 2009. 02. 25.
13. Dixon RL, Anderson JA, Bakalyar DM. *Comprehensive methodology for the evaluation of radiation dose in x-ray computed tomography, AAPM Task Group 111, Report of AAPM Task Group 111: The Future of CT Dosimetry*. College Park, Maryland: AAPM, 2010.
14. JASTRO, *Japanese Society for Radiation Oncology*, (Japanese document) https://www.jastro.or.jp/medicalpersonnel/notification/0312_7.pdf (1 Aug 2020, date last accessed)).
15. Okamoto H, Aikawa A, Wakita A et al. Dose error from deviation of dwell time and source position for high dose-rate 192Ir in remote afterloading system. *J Radiat Res* 2014;55:780–7.
16. Kirisits C, Rivard MJ, Baltas D et al. Review of clinical brachytherapy uncertainties: Analysis guidelines of GEC-ESTRO and the AAPM. *Radiother Oncol* 2014;110:199–212.
17. Pham HT, Chen Y, Rouby E et al. Changes in high-dose-rate tandem and ovoid applicator positions during treatment in an unfixed brachytherapy system. *Radiology* 1998;206:525–31.
18. Andrew M, Kim Y, Ginader T et al. Reduction of applicator displacement in MR/CT-guided cervical cancer HDR brachytherapy by the use of patient hover transport system. *J Contemp Brachytherapy* 2018;10:85–90.
19. Schindel J, Zhang W, Bhatia SK et al. Dosimetric impacts of applicator displacements and applicator reconstruction-uncertainties on 3D image-guided brachytherapy for cervical cancer. *J Contemp Brachytherapy* 2013;5:250–7.
20. Takenaka T, Yoshida K, Ueda M et al. Assessment of daily needle applicator displacement during high-dose-rate interstitial brachytherapy for prostate cancer using daily CT examinations. *J Radiat Res* 2012;53:469–74.
21. Iijima K, Okamoto H, Takahashi K et al. Inter-fractional variations in the dosimetric parameters of accelerated partial breast irradiation using a strut-adjusted volume implant. *J Radiat Res* 2020;61:123–33.
22. Nose T, Chatani M, Otani Y et al. Real-time verification of a high-dose-rate iridium 192 source position using a modified C-arm fluoroscope. *Int J Radiat Oncol Biol Phys* 2017;97:858–65.
23. Nose T, Masui K, Takenaka T et al. An easy and novel method for safer brachytherapy: Real-time fluoroscopic verification of high-dose-rate 192Ir source position using a flat-panel detector. *J Radiat Res* 2019;60:412–5.
24. Shope TB. Radiation-induced skin injuries from fluoroscopy. *Radiographics* 1996;16:1195–9.
25. Bauhs JA, Vrieze TJ, Primak AN et al. CT dosimetry: Comparison of measurement techniques and devices. *Radiographics* 2008;28:245–53.
26. Zhang D, Cagnon CH, Villablanca JP et al. Estimating peak skin and eye lens dose from Neuroperfusion examinations: Use of

Monte Carlo based simulations and comparisons to CTDIvol, AAPM report no. 111, and ImPACT dosimetry tool values. *Med Phys* 2013;40:091901.
27. Lechel U, Becker C, Langenfeld-Jäger G et al. Dose reduction by automatic exposure control in multidetector computed tomography: Comparison between measurement and calculation. *Comparative Study Eur Radiol* 2009;19:1027–34.
28. Chen H, Zhang Y, Zhang W. Low-dose CT via convolutional neural network. *Biomed Opt Express* 2017;8:679–94.
29. Bao P, Sun H, Wang Z et al. Convolutional sparse coding for compressed sensing CT reconstruction. *IEEE Trans Med Imaging* 2019;38:2607–19.
30. Yamada Y, Jinzaki M, Hosokawa T et al. Dose reduction in chest CT: Comparison of the adaptive iterative dose reduction 3D, adaptive iterative dose reduction, and filtered back projection reconstruction techniques. *Eur J Radiol* 2012;81: 4185–95.
31. Singh R, Digumarthy SR, Muse VV et al. Image quality and lesion detection on deep learning reconstruction and iterative reconstruction of Submillisievert chest and abdominal CT. *AJR Am J Roentgenol* 2020;214:566–73.
32. Jessen KA, Shrimpton PC, Geleijns J et al. Dosimetry for optimisation of patient protection in computed tomography. *Appl Radiat Isot* 1999;50:165–72.
33. International Commission on Radiobiological Protection. ICRP publication 102: Managing patient dose in multi-detector computed tomography (MDCT). *Ann ICRP* 2007;37: (International Commission on Radiological Protection).
34. Waszczuk LA, Guziński M, Czarnecka A et al. Size-specific dose estimates for evaluation of individual patient dose in CT protocol for renal colic. *AJR Am J Roentgenol* 2015;205:100–5.
35. Boone JM, Strauss KJ, Cody DD et al. *Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations: report of AAPM Task Group 204*. American Association of Physicists in Medicine (AAPM).
36. impactscan.org | ctdosimetry.xls - ImPACT's CT dosimetry tool. Impactscan.org, http://www.ImPACTscan.org (1 Aug 2020, date last accessed).
37. Ban N, Takahashi F, Sato K et al. Development of a web-based CT dose calculator: WAZA-ARI. *Radiat Prot Dosimetry* 2011;147:333–7.
38. Takahashi F, Sato K, Endo A et al. Numerical analysis of organ doses delivered during computed tomography examinations using Japanese adult phantoms with the WAZA-ARI dosimetry system. *Health Phys* 2015;109:104–12.
39. Matsunaga Y, Kawaguchi A, Kobayashi K. Effective radiation doses of CT examinations in Japan: A nationwide questionnaire-based study. *Br J Radiol* 2016;89:20150671.