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Survey on utilization of flattening filter-free photon beams in Japan

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ABSTRACT

To understand the current state of flattening filter-free (FFF) beam implementation in C-arm linear accelerators (LINAC) in Japan, the quality assurance (QA)/quality control (QC) 2018–2019 Committee of the Japan Society of Medical Physics (JSMP) conducted a 37-question survey, designed to investigate facility information and specifications regarding FFF beam adoption and usage. The survey comprised six sections: facility information, devices, clinical usage, standard calibration protocols, modeling for treatment planning (TPS) systems and commissioning and QA/QC. A web-based questionnaire was developed. Responses were collected between 18 June and 18 September 2019. Of the 846 institutions implementing external radiotherapy, 323 replied. Of these institutions, 92 had adopted FFF beams and 66 had treated patients using them. FFF beams were used in stereotactic radiation therapy (SRT) for almost all disease sites, especially for the lungs using 6 MV and liver using 10 MV in 51 and 32 institutions, respectively. The number of institutions using FFF beams for treatment increased yearly, from eight before 2015 to 60 in 2018. Farmer-type ionization chambers were used as the standard calibration protocol in 66 (72%) institutions. In 73 (80%) institutions, the beam-quality conversion factor for FFF beams was calculated from $TPR_{20,10}$, via the same protocol used for beams with flattening filter (WFF). Commissioning, periodic QA and patient-specific QA for FFF beams also followed the procedures used for WFF beams. FFF beams were primarily used in high-volume centers for SRT. In most institutions, measurement and QA was conducted via the procedures used for WFF beams.

Keywords: survey; flattening filter-free (FFF) beams; utilization for treatment; measurement protocols

INTRODUCTION

In recent years, modern linear accelerators (LINACs) have been designed to implement a flattening filter-free (FFF) mode. This mode increases the dose rate by a factor of 2–4 through removal of the flattening filter, instead of generating a uniform dose distribution [1].

The characteristics of FFF beams (e.g. the conical beam profile, high dose rate [i.e. high dose per pulse] and softer photon spectrum) are distinct from those of beams with a flattening filter (WFF). However, uniform dose distribution is not always necessary in treatments using intensity-modulated radiation therapy (IMRT) or small fields [2,3]. The utility of FFF beams has been investigated for several tumor sites, including the lung, brain, prostate and breast [4–8]. In particular, a high dose rate is beneficial in stereotactic radiation therapy (SRT), which is delivered in a short time. Compared to WFF beams, the short beam-on time of FFF beams improves the feasibility of breath-hold or respiratory-gated treatments (for tumors under respiratory motion) [9].

Another characteristic of FFF beams distinct from WFF beams is the special consideration required when measuring the applied correction factor for the beam-quality conversion (k_Q), volume-averaging correction and ion-recombination factors [10]. The user must adapt the factors calculated for FFF beams or introduce additional factors to compensate for the differences from WFF beams.

In Japan, general guidelines for the clinical use and measurement protocols of FFF beams have not been formulated. It is unclear how many institutions have installed FFF beams, which tumor sites are being treated, how the absolute and relative dose distributions are measured and how quality is controlled. The objective of this study is to assess the current usage of FFF beams in Japan. To the best of our knowledge, very little literature has been published regarding FFF beam utilization surveys in Japan or other countries. To understand the current state of FFF beam adoption, the quality assurance (QA)/quality control (QC) 2018–2019 Committee of the Japan Society of Medical Physics (JSMP) conducted a follow-up survey to previous surveys conducted on the state of radiotherapy in Japan [11,12]. Modern LINACs in which the flattening filters have been removed since the beginning of development (e.g. TomoTherapy [Accuray Inc., Sunnyvale, CA, USA], CyberKnife [Accuray Inc.] and Halcyon [Varian Medical Systems Inc., Palo Alto, CA, USA]) were excluded from this survey.

MATERIALS AND METHODS

A 37-question survey (shown in the Supplementary Table) was designed to collect facility information and specifications regarding FFF beam adoption and usage. The survey consisted of six topic sections, including four questions on facility information, five on devices, 10 on clinical usage, nine on standard calibration protocols, five on modeling for treatment planning systems (TPS) and four on commissioning and QA/QC. In this report, we collectively group the Infinity, Access and Synergy (Elekta Instrument AB, Stockholm, Sweden) LINACs as 'other Elekta LINACs.' Non-users were asked their reasons for not using FFF beams in treatment. The web-based questionnaire was developed using Google Forms (Google LLC, Mountain View, CA, USA). The survey was announced through a website post and e-mails were sent out with a link to the online survey. The responses were submitted by a medical physicist or radiotherapy technologist at each institution between 18 June and 18 September 2019. We confirmed the responses with panelists when multiple responses were collected from an institution and found to be inconsistent.

RESULTS

Devices

Of the 323 institutions that responded, 92 (28%) had adopted FFF beams. Thus, we received responses from 38% of the 846 institutions implementing external radiation therapy in Japan [13]. Table 1 summarizes the number of institutions that have adopted FFF beams in terms of the institution category and total number of LINACs. Numerous cancer centers (Category 1) and university hospitals (Category 2) operate several LINACs. The percentages of institution types that have adopted FFF beams were 65%, 48%, 11%, 21% and 24% for Categories 1 to 5, respectively. Table 2 shows the number of LINACs that have implemented FFF beams in terms of model and energy. The number of LINACs were 54 (49%), 27 (24%), 13 (12%), 17 (15%) and 0 (0%) for TrueBeam (Varian Medical Systems Inc.), TrueBeam STx (Varian Medical Systems Inc.), Versa HD (Elekta Instrument AB, Stockholm, Sweden), other Elekta LINACs and Artiste (Siemens AG, Erlangen, Germany), respectively. The energies of the implemented FFF beams were 6 MV only, 10 MV only and both energies for five (4%), 0 (0%) and 106 (96%) LINACs, respectively. Fig. 1 shows the $TPR_{20,10}$ of FFF beams from each LINAC model. The $TPR_{20,10}$ (average ± standard deviation) of the 6 MV beams were 0.632 ± 0.002, 0.632 ± 0.002, 0.677 ± 0.003 and 0.679 ± 0.002 for TrueBeam, TrueBeam STx, Versa HD and other Elekta LINACs, respectively. The $TPR_{20,10}$ of 10 MV beams were 0.706 ± 0.003, 0.706 ± 0.002, 0.723 ± 0.004 and 0.722 ± 0.006 for TrueBeam, TrueBeam STx, Versa HD and other Elekta LINACs, respectively. Despite identical nominal energies, differences in $TPR_{20,10}$ were observed between different manufacturers at both energies.

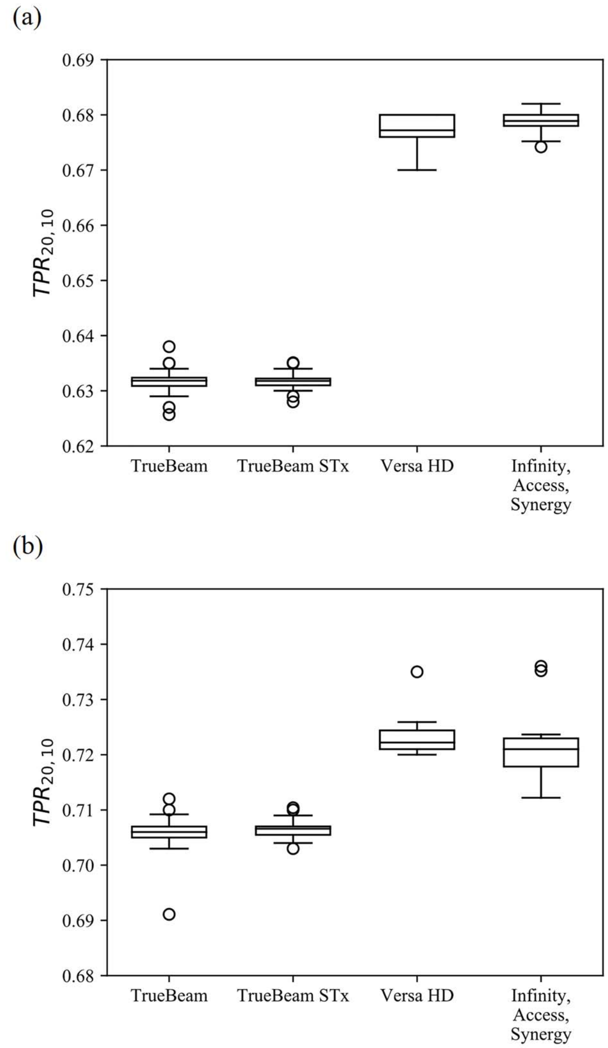

Fig. 1. ***$TPR_{20,10}$*** **of FFF beams in each LINAC model for (a) 6 MV and (b) 10 MV.**

Table 1. Number of institutions that adopted FFF beams with respect to institution category and total number of LINACs

	Institution category	Total number of LINACs								Adopted	Not adopted
		1		2		3–5		6+			
		Adopted	Not Adopted	Adopted	Not Adopted	Adopted	Not Adopted	Adopted	Not Adopted		
1	Cancer centers	0	1	2	2	8	2	1	1	11 (65%)	6
2	University hospitals	8	6	14	19	7	6	0	0	29 (48%)	31
3	National hospital organizations and public hospitals	1	15	0	2	1	0	0	0	2 (11%)	17
4	Red Cross, labor, public welfare, social welfare corporation, public interest incorporated association, corporation and mutual association hospitals	22	96	10	22	0	2	0	0	32 (21%)	120
5	Private, medical corporation, medical association and other hospitals	9	43	5	12	4	2	0	0	18 (24%)	57
	Total	40	161	31	57	20	12	1	1	92 (28%)	231

Values in parentheses represent the percentage for each category.

Table 2. Number of LINACs implementing FFF beams with respect to model and energy

LINAC model	6 MV only	10 MV only	Both	Total
TrueBeam	2	0	52	54 (49%)
TrueBeam STx	1	0	26	27 (24%)
Versa HD	0	0	13	13 (12%)
Infinity, Access, Synergy	2	0	15	17 (15%)
Artiste	0	0	0	0 (0%)
Total	5 (5%)	0 (0%)	106 (95%)	111

Values in parentheses represent the percentage for each energy or LINAC model.

Information on clinical use

Of the 92 institutions that have adopted FFF beams, 66 (73%) had treated patients using FFF beams by the investigation date. Fig. 2 shows the number of patients treated using FFF beams in 2018, divided by all patients treated in 2018. When the number of patients increased, the percentage of institutions that used FFF beams also increased. Recently, the number of institutions using FFF beam treatments has increased. The number that started using FFF beams for treatment before 2015, in 2015, in 2016, in 2017 and in 2018 were eight, nine, 10, 14 and 19, respectively. Meanwhile, 26 institutions with FFF beam technology did not apply it in treatment; reasons for this were given in the survey and they include incomplete commissioning, lack of suitable cases, undecided measurement protocols and 'other' in 14 (54%), 13 (50%), 11 (42%) and two (8%) institutions, respectively.

Multiple criteria for the adoption of FFF beams were considered in 55 institutions (89%). The treatment sites, prescription dose per fraction, field size, irradiation technique and treatment time were considered in 45 (73%), 40 (65%), 40 (65%), 38 (61%) and four (6%) institutions, respectively. Fig. 3 shows the beams used in SRT for each treatment site; most institutions used FFF beams at both energies in SRT, except for prostate treatment. In particular, the lung and liver were treated using FFF beams of 6 MV and 10 MV in most institutions, respectively. Different respiratory motion-management protocols to those of WFF beams were used for FFF beams in 39 (54%) institutions. Among these institutions, breath-holding, respiratory gating, abdominal compression and 'no management' were adopted in 17 (43%), 10 (25%), six (15%) and six (15%) institutions, respectively.

Standard calibration protocol

For the standard FFF beam calibration protocols, 66 (72%) institutions used the Farmer-type ionization chamber (sensitive volume: ~0.6 cm^3). The mini-ionization chamber (sensitive volume: ~0.1 cm^3) was used in 22 (20%) institutions, and the ionization chamber (sensitive volume: ~0.3 cm^3) was used in two (2%) institutions. No institutions used a micro-ionization chamber (sensitive

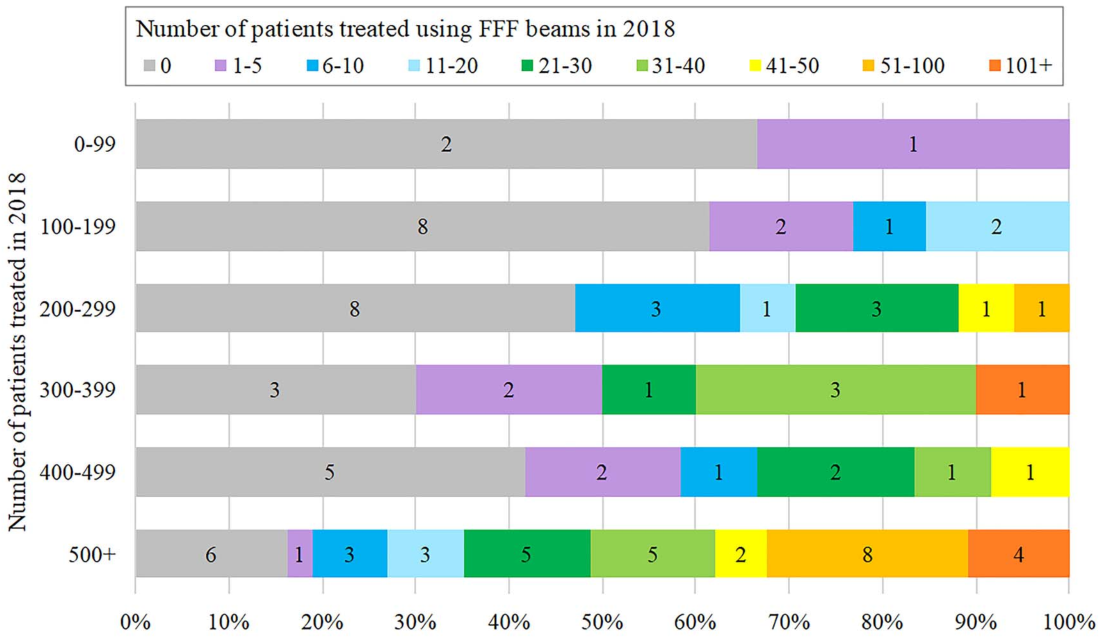

Fig. 2. Number of patients treated using FFF beams in 2018, divided by all patients treated in 2018. The values in the horizontal bar graph represent the number of institutions.

volume: ~0.01 cm^3). Of the institutions using Farmer-type ionization chambers, the volume-averaging correction factor was 'validated', 'not validated' and 'under consideration' in 41 (62%), 21 (32%) and four (6%) institutions, respectively. Of 41 institutions, 26 (63%) adopted this factor for dose calculation. Table 3 groups the institutions according to their method for validating this factor for chambers used in each institution, not only for Farmer-type ionization chambers. Among 44 institutions that performed validation for each chamber, the factor calculation was conducted by using the TPS; using the formula found in the Technical Reports Series No. 483 (TRS483), published by the International Atomic Energy Agency (IAEA) and American Association of Physicists in Medicine (AAPM) [14]; comparing to a small detector; and using the dose distribution in 28 (64%), 13 (30%), nine (20%) and seven (16%) institutions, respectively. Fig. 4 shows the volume-averaging correction factor for Farmer-type ionization chamber from each LINAC model. The volume-averaging correction factor (average ± standard deviation) of the 6 MV beams were 1.004 ± 0.001, 1.003 ± 0.001, 1.003 ± 0.001 and 1.005 ± 0.002 for TrueBeam, TrueBeam STx, Versa HD and other Elekta LINACs, respectively. The volume-averaging correction factor of 10 MV beams were 1.007 ± 0.001, 1.007 ± 0.001, 1.006 ± 0.001 and 1.005 ± 0.003 for TrueBeam, TrueBeam STx, Versa HD and other Elekta LINACs, respectively.

In addition to the volume-averaging correction factor, a k_Q protocol is required to obtain the absolute FFF beam dose. Table 4 shows the number of institutions grouped according to the validation method for k_Q. Fifty-three (58%) institutions calculated k_Q for FFF beams using the WFF-beam protocol, without validation. Among the other institutions, 20 (22%) calculated k_Q using the WFF-beam protocol with validation, nine (19%) calculated it using different protocols, and

Table 3. Validation method for volume averaging correction factor of FFF beams

Method	N
Calculated using TPS	28 (64%)
Calculated using TRS483 formula	13 (30%)
Compared to small detector	9 (20%)
Calculated from dose distribution	7 (16%)

Multiple choices allowed.
Values in parentheses represent the percentage for each method.

nine (10%) were still under consideration. Among the institutions that validated k_Q or used different protocols, the number that adapted collection factors for the stopping-power ratio [15–17]; calculated k_Q from TRS483 [14]; calculated k_Q from Task Group Report No. 51 and its addendum (TG51), published by the AAPM (protocol based on *%dd*(10)x) [18,19]; and applied other methods were 22 (76%), 9 (31%), 5 (17%) and 1 (3%), respectively.

Modeling for TPS

The measured and representative beam data [20] were used to calculate the TPS patient dose in 76 (83%) and 12 (13%) institutions, respectively. Table 5 shows the detectors used for measuring the percentage depth dose (PDD) and off-center ratio (OCR) in FFF beams. Ionization chambers (sensitive volume: ~0.1 cm^3) were the most commonly used detector for PDD and OCR in 72 (82%) and 67 (76%) institutions, respectively. Multiple detectors for PDD and OCR were used in 36 (41%) and 34 (38%) institutions, respectively. Table 6 shows the correction factors used for PDD and OCR. Most institutions

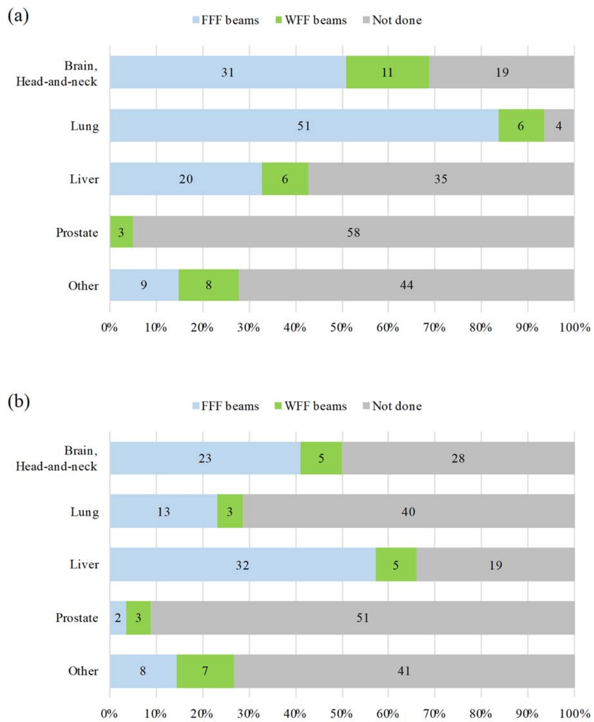

Fig. 3. Beams selected for SRT at each disease site with (a) 6 MV and (b) 10 MV energies. The values in the horizontal bar graph represent the number of institutions.

Table 4. Validation method for k_Q of FFF beams

Method	N
Adopted correction factor for the stopping-power ratio*	22 (76%)
Calculated from TRS483	9 (31%)
Calculated from TG51	5 (17%)
Other	1 (3%)

Multiple choices allowed.
Values in parentheses represent the percentage for each method.
*The first option means that factor was adopted to k_Q calculated from WFF-beam protocol to correct the stopping-power ratio.

did not adopt correction factors for PDD (87%) and OCR (89%). The ion-recombination correction factor and volume-averaging correction factor were adopted in 10 (9%) and two (2%) institutions for PDD and seven (8%) and two (2%) institutions for OCR, respectively.

Commissioning and QA/QC

During FFF beam commissioning, all institutions adopted the protocols used for WFF beams. Moreover, 74 (84%) institutions did not implement specific QA protocols for FFF beams, three (3%) implemented specific QA protocols and 13 (13%) were still under consideration. Table 7 shows the methods used in patient-specific QA for IMRT and conventional radiotherapy. No large differences in IMRT method were observed between FFF and WFF beams. In contrast,

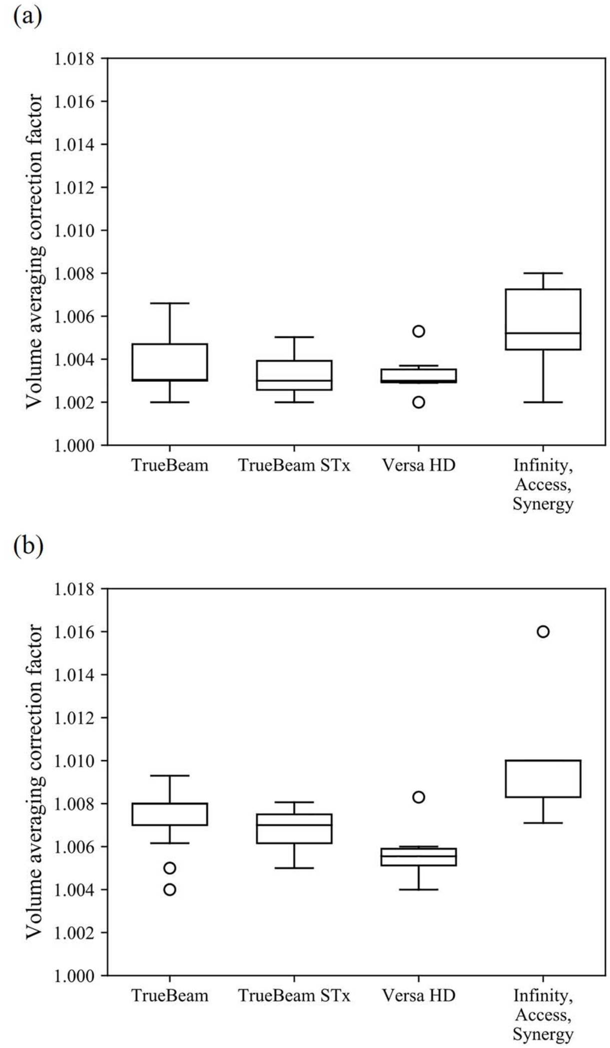

Fig. 4. Volume-averaging correction factor with respect to LINAC model for (a) 6 MV and (b) 10 MV FFF beams for Farmer-type ionization chamber.

Table 5. Detector used in PDD and OCR measurement

Detector	PDD	OCR
Ionization chamber (0.1 cm^3)	72 (82%)	67 (76%)
Ionization chamber (0.01 cm^3)	34 (39%)	35 (40%)
Diode	14 (16%)	20 (23%)
Ionization chamber (0.3 cm^3)	7 (8%)	6 (7%)
Diamond	6 (7%)	5 (6%)
Ionization chamber (0.6 cm^3)	3 (3%)	2 (2%)
Other	0 (0%)	2 (2%)

Multiple choices allowed.
Values in parentheses represent the percentage for each detector.

Table 6. Adoption status of correction factors for PDD and OCR

Correction factor	PDD	OCR
No correction	76 (87%)	75 (89%)
Ion recombination	10 (9%)	7 (8%)
Volume averaging	2 (2%)	2 (2%)

Multiple choices allowed.
Values in parentheses represent the percentage for each correction factor.

for conventional radiotherapy, more institutions applied measurement-based techniques (instead of recalculations using another system) for FFF beams compared to WFF beams.

DISCUSSION

The objective of this study is to assess the current usage of FFF beams in Japan. This is the first survey to be conducted to this end. FFF beams are currently being used by 28% of the respondents. Most institutions first adopted FFF beams when their old LINACs would be replaced by new ones. Therefore, the adoption of FFF beams is greater in institutions such as high-volume centers possessing multiple LINACs. In the coming years, the adoption of FFF beams will most likely increase in Japan as old LINACs are progressively replaced.

TrueBeam and TrueBeam STx employ identical components and geometries in the head of the LINAC, upstream from the multi-leaf collimator. Thus, in this study, both machines having the same $TPR_{20,10}$ value. In the Varian LINAC, the electrons for the WFF beams are used to create FFF beams of the same nominal energy. Therefore, the FFF beams have a lower energy than the WFF beams, owing to the absence of beam hardening from the flattening filter [21]. In contrast, the energy spectra of the Elekta LINAC are tuned to have similar penetrations for both WFF and FFF beams; therefore, the $TPR_{20,10}$ values obtained with or without a flattening filter are similar [22,23]. As a result, the $TPR_{20,10}$ value of the Elekta LINAC exceeds that of the Varian LINAC, despite the fact that the LINACs have the same nominal energy. In Fig. 1, slightly higher data of $TPR_{20,10}$ about 0.735 for 10 MV was observed in Elekta LINACs. It would be explained by that tuning of the energy spectra. Kragl *et al.* reported that the $TPR_{20,10}$ of the 10 MV in their Elakta LINAC were 0.714 and 0.735 for FFF (not tuned) and WFF beams, respectively [1]. If FFF beams was tuned to have similar penetrations for WFF beams, the $TPR_{20,10}$ for FFF beams would be about 0.735.

Of the 92 institutions that have adopted FFF beams, 60 (65%) used them to treat patients in 2018. However, between these institutions, large differences were observed in the number of patients treated using FFF beams. In Japan, the use of FFF beams has not been discussed in radiation therapy treatment guidelines. Therefore, the utilization of FFF beams depends heavily on the treatment policy applied in each institution. We listed five options for using FFF beams. Most institutions considered the treatment site. Furthermore, multiple criteria (excluding treatment time) were considered in 55 (89%) institutions.

FFF beams have previously been investigated primarily in terms of the delivery time and dosimetry for various treatment sites [1–9,24]. In particular, Vassiliev *et al.* showed that a shorter delivery time increases the feasibility of breath-hold treatment and the efficiency of respiratory-gated treatment for lung SRT [9]. In this survey, we investigated the selection of beams with or without a flattening filter in SRT for various disease sites. Excluding the prostate (which was treated with SRT in only a few institutions), most institutions used FFF beams in SRT for all disease sites. Of these institutions, most selected 6 MV FFF beams, especially for the lungs. After adopting FFF beams, the institutions would begin using respiratory motion-management protocols, such as breath-hold or respiratory gating.

Twenty-six (28%) institutions had not used FFF beams as of the investigation date. Of these institutions, incomplete commissioning, absence of suitable patients, undecided measurement protocols and 'other' reasons were selected in 14 (54%), 13 (50%), 11 (42%) and two (8%) institutions, respectively. Furthermore, no guidelines are available for FFF beam measurement in Japan; therefore, the protocols for measuring absolute doses depend on the decisions taken at each institution.

In Japan, the standard calibration protocol for WFF beams is based on TRS398 [25], which was established by JSMP in 2012 [26]. By following this protocol, the absolute-dose-to-water can be measured, to ensure traceability to national standards. Farmer-type ionization chambers (sensitive volume: $\sim$0.6 cm^3) are recommended for the standard calibration of WFF beams in this protocol. Meanwhile, the significant radial non-uniformity of FFF beams can affect volume averaging within the ionization chamber volume [14,19]. Therefore, the user might underestimate the dose on the central axis when using a large-volume Farmer-type ionization chamber without correction. TG51 (from AAPM) recommends that the chamber used for measuring FFF beams should have a short sensitive volume [19]. Recently, new ionization chambers (e.g. Exradin A26, which has a short sensitive volume), have become commercially available [27]. However, Farmer-type ionization chambers are used for measuring FFF beams in most institutions in Japan. We deduced several reasons for this: the k_Q values for new ionization chambers are not listed in the protocol yet, institutions must purchase another chamber if they lack adequate chambers, or the institutions have only water tank or solid phantoms trimmed for Farmer-type ionization chambers. No large differences in volume-averaging correction factor were observed between the LINAC models for Farmer-type ionization chambers. In the Elekta LINACs, slight differences were observed between the Versa HD and other Elekta LINACs at 10 MV; however, the number of data points (six for Versa HD and five for other Elekta LINACs) was insufficient to draw a firm conclusion.

A standard calibration protocol (e.g. TRS483 or TG51) calculates k_Q from beam-quality indices such as $TPR_{20,10}$ or $\%dd(10)_x$ [14,19]. Using the $TPR_{20,10}$ value for FFF beams to calculate k_Q from tables (based on WFF-beam data) results in different relationships between the $TPR_{20,10}$ and stopping-power ratio compared to WFF-beam values [15–17]. Therefore, Xiong *et al.* suggested that it is necessary to decrease the value of k_Q by approximately about 0.5%; this corresponds to a change in the stopping-power ratio in the above case [15]. Moreover, in TRS483, k_Q is specified for both FFF and WFF beams [14]. Meanwhile, the differences are acceptable in the relationship between

Table 7. Method used for patient-specific QA of IMRT and conventional radiotherapy

	IMRT		Conventional	
Method	FFF beams	WFF beams	FFF beams	WFF beams
Measurement (ionization chamber)	39 (85%)	37 (80%)	24 (45%)	15 (28%)
Measurement (film)	23 (50%)	20 (43%)	9 (17%)	5 (9%)
Measurement (array detector)	41 (89%)	43 (93%)	14 (26%)	8 (15%)
Recalculation using another system	6 (13%)	4 (9%)	36 (68%)	44 (83%)
Log-file analysis	6 (13%)	5 (11%)	3 (6%)	3 (6%)
Not performed	0 (0%)	0 (0%)	1 (2%)	1 (2%)

Multiple choices allowed.
Values in parentheses represent the percentage for each method.

%dd(10)x and the stopping-power ratio for beams with and without a flattening filter [15]. In our protocol, k_Q was calculated using $TPR_{20,10}$; therefore, we must consider the differences in the relationships. However, in more than half of the institutions, the k_Q for FFF beams was calculated using the WFF-beam protocol, with no validation.

The dose per pulse of FFF beams exceeds that of WFF beams; therefore, the ion-recombination correction factor varies with the off-axis position and scanning measurement depth in the ionization chamber [28–33]. We investigated the detector used for measuring PDD and OCR and the adoption status of ionization chamber correction factors. Most institutions employed a standard detector for profile measurements such as an ionization chamber (sensitive volume: ~0.1 cm^3) without adopting correction factors. To compensate for ion-recombination in the profile measurements, several methodologies were proposed in previous reports; however, they remain in the research stage [34,35].

Regarding the commissioning and periodic QA of FFF beams, most institutions reused the WFF-beam protocols; most of these procedures (e.g. output constancy, beam profile constancy and symmetry change with respect to a baseline) can be adapted for FFF beams [36]. In addition to these procedures, the use of the unflatness, slope and peak position has been proposed by Fogliata *et al.* [37,38]. In our survey, one institution responded that they used such procedures for FFF beam QA.

Recently, numerous software applications and detectors have been used to verify the patient dose. For IMRT, most institutions performed a secondary independent dose verification; this was conducted via measurement-based techniques, using an ionization chamber or array detector with or without a flattening filter. Our survey indicated the same trends as a survey of QA practices in the USA and Canada [39]. Meanwhile, for conventional radiotherapy, most institutions performed recalculations using another system, with or without a flattening filter; however, differences were identified in the percentages of institutions doing so. Measurement-based techniques were more popular for FFF beams than for WFF beams. There is a possibility that the secondary independent dose verification software installed at these institutions does not support FFF beams.

This study has several important limitations. We received responses from ~38% of institutions implementing LINACs in Japan. It is possible that non-users of FFF beams were less likely to respond, which would lead to an overestimation of the true prevalence of FFF beam use. There were no questions that assessed the use of FFF beams in detail. Therefore, further investigations are required for each category.

CONCLUSION

This study reports upon trends of FFF beam utilization in Japan. FFF beams were primarily used to perform SRT in high-volume centers. In most institutions, measurement and QA followed the procedures used for WFF beams. To standardize absolute-dose-to-water measurements, new guidelines that cover the volume-averaging correction and k_Q procedures are required. In the future, FFF technology will be rapidly adopted in Japan. It is possible that the status of FFF beam adoption will change; therefore, periodic surveys are needed.

SUPPPLEMENTARY DATA

Supplementary data is available at *RADRES Journal* online.

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CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

PRESENTATION AT A CONFERENCE

The 119th Scientific Meeting of the Japan Society of Medical Physics.

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