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Original paper

Modalities and techniques used for stereotactic radiotherapy, intensity-modulated radiotherapy, and image-guided radiotherapy: A 2018 survey by the Japan Society of Medical Physics

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ABSTRACT

Over the last several decades, there have been great advances in radiotherapy with the development of new technologies and modalities, and radiotherapy trends have changed rapidly. To comprehend the current state of radiotherapy in Japan, the QA/QC 2016–2017 Committee of the Japan Society of Medical Physics set up an intensity-modulated radiotherapy/image-guided radiotherapy (IMRT/IGRT) working group and performed a Web-based survey to show the current status of radiotherapy in Japan. The Web-based questionnaire, developed using Google Forms, contained 42 items: 7 on stereotactic radiotherapy implementation, 4 on IMRT, 24 on IGRT, and 7 on respiratory motion management. The survey was conducted from 17 January to 9 March of 2018; in total, 335 institutions provided data. The results show that volumetric modulated arc therapy was used at a level comparable to that of static gantry IMRT. For IGRT, machine-integrated computed tomography (CT), including kilovoltage or megavoltage cone-beam CT and megavoltage CT, was used at many institutions in conjunction with target-based image registration. For respiratory motion management, breath holding was the most commonly used technique. Our hope is that multi-institutional surveys such as this one will be conducted periodically to elucidate the current status of radiotherapy and emerging developments in this field. If our questionnaire was distributed worldwide, in the same format, then global trends in radiotherapy could be better understood.

1. Introduction

Over the last few decades, radiotherapy technologies have advanced greatly. For brain metastases, single-fraction stereotactic radiosurgery and fractionated stereotactic radiotherapy (SRT) have shown excellent local control [1]. Stereotactic body radiotherapy (SBRT) treatments for extracranial tumors, such as those of the lungs, liver, and prostate, have also demonstrated good clinical outcomes [2,3]. Intensity-modulated radiotherapy (IMRT) provides the means to deliver a precise radiation dose, thus minimizing the amount of radiation delivered to the surrounding healthy tissue; such precision has also enabled dose escalation and hypo-fractionation [4,5]. Volumetric modulated arc therapy (VMAT) offers a significantly reduced treatment time, with excellent dose distribution comparable to those of static gantry IMRT [6,7]. Image-guided radiotherapy (IGRT) devices have improved target localization accuracy, which has resulted in reductions of the target margin and the dose delivered to healthy tissues [8–10]. Some organs, such as the lungs, liver, and pancreas, move with respiratory motion, resulting in the need for additional margins to ensure proper coverage [11,12]; here, the dose delivered to healthy tissues can be reduced by

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respiratory-gating [13], respiratory tracking [14], and breath-holding [15,16] techniques.

As various technologies and modalities have been developed, trends in radiotherapy have changed rapidly in Asia [17–19]. To comprehend the current state of radiotherapy in Japan, the QA/QC 2016–2017 Committee of the Japan Society of Medical Physics set up an IMRT/IGRT working group and performed a web-based survey to determine the current status of radiotherapy. Here, we report the results of this survey.

2. Materials and methods

The web-based questionnaire was developed using Google Forms (Google LLC, Mountain View, CA, USA). The questionnaire was announced by e-mail and website postings. Data were collected from the chief medical physicist or radiotherapy technologist of each participating institution. The questionnaire contained 42 items: 7 on SRT, including its availability, techniques, modalities, and the treatment planning system (TPS) used; 4 on IMRT, including its availability, techniques, modalities, and the TPS used; 24 on IGRT, including the modalities and reference structures used for image registration for various treatment sites; and 7 on respiratory motion management, including its implementation, the devices used to collect respiratory signals, techniques, devices controlling patient respiration, and the lesions treated. The questions, which take approximately 15 min to answer, are listed in Supplementary Tables 1 and 2. The survey was conducted from January 17 to March 9, 2018. A unified data set was used in cases where multiple responses were collected from the same institution. The collected data were analyzed using a Microsoft Excel spreadsheet (Microsoft Corp., Redmond, WA, USA) and JMP Pro software (ver. 14.0; SAS Institute, Cary, NC, USA).

3. Results

In total, 335 institutions provided data for the survey. Table 1 summarizes the implementation status of SRT, IMRT, IGRT, and motion management, listed by regions of Japan. SRT and IMRT were conducted at 77% and 66% of the surveyed institutions, respectively. In total, 64% of the institutions conducted both SRT and IMRT, and 97% of those using IMRT also conducted SRT. When classifying the institutions into three categories, those using SRT accounted for 96%, 74% and 71% of all university, public, and private hospitals, respectively. Institutions using IMRT included 93%, 59% and 58% of all university, public, and private hospitals, respectively. IGRT and respiratory motion management were used at 91% and 67% of the surveyed institutions, respectively. An especially large number of survey responses were received from institutions in Kanto, Chubu, and Kansai regions; notably, these institutions were more likely to conduct IMRT compared with those in other regions.

Table 2 shows the instruments used for SRT. Linear accelerators (linacs) equipped with a multileaf collimator (MLC) of 5–10-mm leaf width were used most widely. For brain SRT, linacs with < 5-mm MLC width were also employed at many institutions. Stereotactic cones and external MLC attachments were also applied, indicating that brain SRT requires more conformal dose distributions. Table 3 shows the techniques used for brain SRT and SBRT. A conformal arc and three-dimensional conformal radiotherapy (3D-CRT) were the most widely used techniques for brain and extracranial SRT, respectively. VMAT was also used at 71 and 58 institutions for brain and extracranial SRT, respectively. Table 3 also shows the various IMRT techniques used. In total, 137 institutions used VMAT; this was the most commonly used technique. Static gantry IMRT, including static MLC (SMLC) and dynamic MLC (DMLC), was used at 135 institutions, which was nearly the same number of institutions that used VMAT.

Table 4 shows the IGRT instruments used for SRT for different lesion

Table 2
Instruments used for SRT.

Instrument	Brain	Extracranial
Linac (MLC leaf width: < 5 mm)	64	71
Linac (MLC leaf width: 5–10 mm)	72	132
Linac (MLC leaf width: > 10 mm)	4	32
Linac with cone	36	0
Linac with MLC attachment	26	0
TomoTherapy	20	11
CyberKnife	19	17
GammaKnife	12	0
Total	253 [208]	263 [243]

Values in square brackets are the number of institutions that answered this question.
Instrument manufacturers: TomoTherapy; Accuray, Inc., Sunnyvale, CA, USA; CyberKnife; Accuray; GammaKnife; Elekta, Stockholm, Sweden.
Abbreviation: MLC, multi-leaf collimator.
Note: Multiple selection was allowed.

Table 3
Techniques used for brain SRT, SBRT and IMRT.

Techniques	Brain SRT	SBRT	IMRT
Conformal arc	104	29	–
3D-CRT	79	194	–
VMAT	71	58	137
Static IMRT	27	19	135*
TomoTherapy	12	9	27
Other	14	3	17
Total	307 [207]	312 [243]	316 [217]

Values in square brackets are the number of institutions that answered this question.
Abbreviations: 3D-CRT, three-dimensional conformal radiotherapy; VMAT, volumetric modulated arc therapy.
*Included 86 dynamic multi-leaf collimator and 49 static multi-leaf collimator techniques.
Note: Multiple selection was allowed.

Table 1
Number of institutions conducting SRT, IMRT, IGRT, and respiratory management, by region.

Region	SRT		IMRT		IGRT		Motion		All modalities	
Hokkaido	11	(65%)	6	(35%)	14	(82%)	6	(35%)	17	[5%]
Tohoku	22	(71%)	16	(52%)	28	(90%)	21	(68%)	31	[9%]
Kanto	67	(85%)	63	(80%)	75	(95%)	54	(68%)	79	[24%]
Chubu	52	(84%)	43	(69%)	57	(92%)	49	(79%)	62	[19%]
Kinki	50	(74%)	47	(69%)	61	(90%)	44	(65%)	68	[20%]
Chugoku/Shikoku	27	(77%)	20	(57%)	32	(91%)	21	(60%)	35	[10%]
Kyushu/Okinawa	30	(70%)	25	(58%)	39	(91%)	28	(65%)	43	[13%]
Total	259	[77%]	220	[66%]	306	[91%]	223	[67%]	335	[100%]

Values in parentheses and square brackets represent the percentages for each individual region and for all institutions, respectively.
Abbreviations: SRT, stereotactic radiotherapy; IMRT, intensity-modulated radiotherapy; IGRT, image-guided radiotherapy; Motion, respiratory motion management.

Table 4
IGRT instruments used for SRT.

Instrument	Brain		Lung		Liver		Prostate	
Integrated CT	100	(47%)	183	(75%)	103	(70%)	29	(56%)
2D imaging	52	(24%)	37	(15%)	28	(19%)	14	(27%)
In-room CT	4	(2%)	12	(5%)	8	(5%)	4	(8%)
ET/CK/RTRT	44	(20%)	6	(2%)	7	(5%)	5	(10%)
Other	3	(1%)	5	(2%)	1	(1%)	0	(0%)
None	12	(6%)	0	(0%)	0	(0%)	0	(0%)
Total	215	[64%]	243	[73%]	147	[44%]	52	[16%]

Values in parentheses and square brackets represent the percentages among institutions treating a particular site and all institutions, respectively.
Abbreviations: CT, computed tomography; ET, ExacTrac (BrainLAB, Munich, Germany); CK, CyberKnife (Accuray); RTRT, real-time tumor-tracking radiation therapy including SyncTraX (Shimadzu Corp., Kyoto, Japan).

types. For all treatment sites, machine-integrated computed tomography (CT), including kilovoltage cone-beam CT (kV-CBCT), megavoltage CT (MVCT) and megavoltage cone-beam CT (MV-CBCT), was the most commonly used technique. Especially for lung and liver SRT, integrated CT was used at ≥70% of institutions conducting SRT. Among all 335 institutions, 64% and 73% conducted brain SRT and lung SBRT, respectively.

Table 5 shows the reference structures used for IGRT. This was relevant only to SBRT, as most institutions commonly conduct bone-based image registration for brain SRT. For lung SRT, 81% of institutions determined the treatment position based on the target. For liver tumors, although the target was the most common reference for IGRT, 33% of institutions used markers, including gold fiducial markers and contrast agents such as Lipiodol. Many institutions stated that the entire liver organ was considered for image registration. For prostate cancer, approximately half of the institutions using SRT conducted target-based image registration, whereas one quarter used markers and the remaining one quarter used bone-based image registration.

Table 6 shows the IGRT devices used for IMRT. For all lesions, integrated CT was the most commonly used modality. The proportion of institutions conducting IMRT for brain, head and neck (H&N), prostate, and pelvic cancer was 53%, 55%, 76%, and 69%, respectively. Table 7 shows the reference structures used for IGRT during IMRT treatment. For H&N and pelvic regions, more than half of institutions registered images based on bone structures. For the other lesions, target volume was the most commonly used image registration reference.

We also conducted a cross-tabulation analysis of IGRT instruments used in the treatment of each lesion type against the reference structure used for IGRT. Fig. 1 shows that target-based image registration using integrated CT was the modality most frequently applied for SRT. The percentage of institutions using this modality was 69%, 39%, and 56% for lung, liver, and prostate SRT, respectively. Fig. 2 shows the IMRT results. For the pelvic region, bone-based registration using 2D imaging was the most frequently used method (38%). Target-based registration with integrated CT was the most frequently used modality for H&N (33%), lung (61%), liver (48%), pancreas (59%) and localized prostate (56%) IMRT, although bone-based registration was also used for H&N IMRT with integrated CT (25%) and 2D imaging (29%) modalities.

Table 5
IGRT reference structures used for SRT.

Reference	Lung		Liver		Prostate	
Target	197	(81%)	68	(46%)	27	(52%)
Markers	8	(3%)	48	(33%)	12	(23%)
Bone	36	(15%)	21	(14%)	13	(25%)
Other	2	(1%)	10	(7%)	0	(0%)
Total	243	[73%]	147	[44%]	52	[16%]

Values in parentheses and square brackets represent the percentages among institutions treating a particular site and all institutions, respectively.

Table 8 shows the techniques used for respiratory motion management during irradiation. Breath holding was the most commonly used technique, with 1.5-fold as many institutions using this technique compared to respiratory gating. Abdominal compression was also used at many institutions.

4. Discussion

In this study, we investigated the current status of radiotherapy in Japan using a web-based survey. Although many surveys have been carried out in other countries, our survey was more comprehensive due to its inclusion of detailed questions regarding advanced radiotherapy technologies, and the large number of institutions surveyed. The SRT and IMRT modalities were available at 77% and 66% of the surveyed institutions, respectively (Table 1). As of July 2017, there were 278 IMRT-certified institutions in Japan, indicating that approximately 79% of institutions conducting IMRT replied to our questionnaire [20]. According to an October 2017 survey conducted by the Ministry of Health, Labor and Welfare [21], the number of institutions conducting radiotherapy in Japan in that year was 846. Thus, we estimate that IMRT is used by approximately 34% of all institutions in Japan. Although the number of patients eligible for IMRT will be larger than that of SRT, more institutions were conducting SRT. Two studies conducted in 2010 reported that IMRT was available in 87.5% of the institutions surveyed in Canada [22] and 76% of those in the United Kingdom [23]. A survey in New Zealand reported that IMRT/VMAT and SRT/SBRT were available in 100% (seven institutions) and 86% (six of seven institutions) of institutions, respectively [24]. Our data show that the number of institutions conducting IMRT was not uniformly distributed over Japan; differences by region will have been attributable to insufficient human resources and linac configurations. In Japan, the level of certification required to use IMRT is higher than that required for SRT, and is difficult to attain, especially in non-metropolitan areas. In a Canadian survey, the most commonly cited barriers to the implementation of IMRT were recruitment and/or training of skilled personnel [22]. A survey in Korea conducted in 2018 reported that the availability of IMRT and SRT was higher in metropolitan areas than in non-metropolitan areas [17]. In this study, most university hospitals conducted both SRT and IMRT. The ratios of use of these advanced techniques were similar between public and private hospitals, indicating that regional differences were more correlated with implementation of SRT and IMRT.

Supplementary Table 3 summarizes the number of institutions that used a TPS for brain SRT, SBRT, and IMRT [18]. For brain SRT, the BrainLAB TPS (Brainlab AG, Munich, Germany) typically includes iPLAN, BrainSCAN, and Elements. For SBRT and IMRT, the Varian Eclipse TPS (Varian Medical Systems, Palo Alto, CA, USA) was used in many institutions. As shown in Table 4, VMAT was used with comparable frequency to static gantry IMRT. Similarly, a web-based survey in Germany performed in 2014 showed that the most frequently used IMRT technology was VMAT (58.4%) [25]. It is reported that moving targets, such as those associated with lung and liver tumors, show motion effects according to the interplay of respiratory organ motion with dynamic beam delivery when IMRT is used [26]. Thus, 3D-CRT has been the most widely used technique for lung SBRT. Some studies have reported that the motion effects of VMAT are smaller those of static gantry IMRT [27–29]. It is expected that over the next several years, VMAT will be used for SRT by many institutions in which 3D-CRT was traditionally applied.

Over the course of the last decade, many old treatment instruments have been replaced by modern machines equipped with CT imaging for IGRT. Table 1 shows that 91% of the institutions surveyed in this study used IGRT. Supplementary Table 5 summarizes the IGRT instruments used. In total, 279 institutions used integrated CT, whereas 286 used kV-2D and MV-2D imaging. This indicates that most linacs are equipped with an integrated CT device for IGRT as standard. In our survey, 270

Table 6
IGRT instruments used for IMRT.

Instrument	Brain		H&N		Breast		Lung		Liver		Pancreas		Prostate		Pelvis	
Integrated CT	84	(47%)	108	(59%)	23	(58%)	75	(72%)	55	(75%)	51	(72%)	172	(68%)	115	(50%)
2D imaging	48	(27%)	55	(30%)	10	(25%)	18	(17%)	13	(18%)	13	(18%)	56	(22%)	90	(39%)
In-room CT	2	(1%)	2	(1%)	1	(3%)	3	(3%)	2	(3%)	2	(3%)	7	(3%)	5	(2%)
ET/CK/RTRT	41	(23%)	13	(7%)	3	(8%)	5	(5%)	2	(3%)	4	(6%)	15	(6%)	21	(9%)
Other	2	(1%)	4	(2%)	0	(0%)	3	(3%)	1	(1%)	1	(1%)	3	(1%)	1	(0%)
None	0	(0%)	2	(1%)	3	(8%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)
Total	177	[53%]	184	[55%]	40	[12%]	104	[31%]	73	[22%]	71	[21%]	253	[76%]	232	[69%]

Values in parentheses and square brackets represent the percentages among institutions treating a particular site and all institutions, respectively.
Abbreviations: H&N, head and neck; CT, computed tomography; ET, ExacTrac (BrainLAB); CK, CyberKnife (Accuray); RTRT, real-time tumor-tracking radiation therapy including SyncTraX (Shimadzu Corp.).

Table 7
IGRT reference structures used for IMRT.

Reference	H&N		Lung		Liver		Pancreas		Prostate		Pelvis	
Target	64	(35%)	72	(69%)	41	(56%)	45	(63%)	152	(60%)	51	(22%)
Markers	0	(0%)	1	(1%)	11	(15%)	4	(6%)	30	(12%)	1	(0%)
Bone	118	(64%)	28	(27%)	16	(22%)	21	(30%)	68	(27%)	178	(77%)
Other	2	(1%)	3	(3%)	5	(7%)	1	(1%)	3	(1%)	2	(1%)
Total	184	[55%]	104	[31%]	73	[22%]	71	[21%]	253	[76%]	232	[69%]

Values in parentheses and square brackets represent the percentages among institutions treating a particular site and all institutions, respectively.

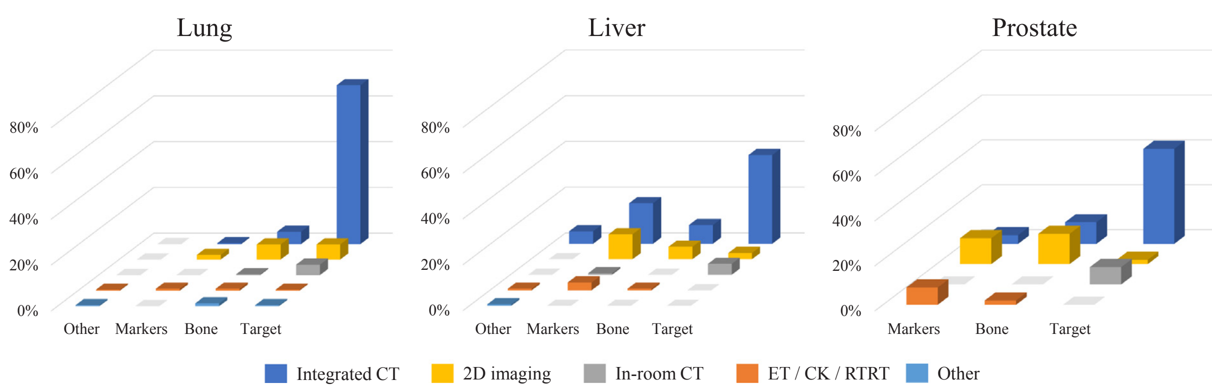

Fig. 1. Cross-tabulation analysis of image-guided radiotherapy (IGRT) devices used for stereotactic radiotherapy against the reference structure for image registration in IGRT. Abbreviations: CT, computed tomography; ET, ExacTrac (BrainLAB); CK, CyberKnife (Accuray); RTRT, real-time tumor-tracking radiation therapy including SyncTraX (Shimadzu Corp.).

institutions (80.6%) reported using volumetric IGRT devices, including kV-CBCT, MVCT, MV-CBCT, and in-room CT. In 2009, similar surveys of physicians in the United States (US) reported that 93.5% used IGRT, although this decreased to 82.3% when MV portal imaging was excluded [30]. In another US survey of physicians conducted in 2014, 95% reported using IGRT, with 92% indicating that they had access to volumetric imaging modalities [31]. In a 2015 Australian survey, all respondents regularly used IGRT, and 97% of them used kV-CBCT [18]. The current status of radiotherapy in Japan appears similar to that of the US a decade ago. Several studies have shown that IGRT significantly decreased rectal and bladder toxicity in prostate radiotherapy [8,10,32,33]. A phase 3 clinical trial of prostate radiotherapy also showed that daily IGRT significantly decreased the risks of biochemical recurrence and rectal toxicity compared with weekly IGRT [9]. Most of the institutions that we surveyed used CT imaging in combination with target-based image registrations with the exception of H&N and pelvic IMRT cases, as shown in Figs. 1 and 2; many institutions used 2D imaging for these two lesions instead, probably because the positions of the neck and pelvic lymph node are well correlated with those of bone structures. However, CT imaging can also be used for H&N, as deformations of the spine and shoulder joint often make registration difficult. In the pelvic region, CT imaging facilitates monitoring of bladder and rectum filling. The National Comprehensive Cancer Network (NCCN) guidelines for prostate cancer (ver. 2.2019) suggested that hypo-fractionated IMRT techniques can be considered as alternatives to conventionally fractionated regimens when clinically indicated [34]. The guidelines also state that IGRT is essential, with either 3D-CRT or IMRT, for target margin reduction and treatment accuracy. Although the availability of IMRT and IGRT techniques did not show a uniform distribution throughout all regions of Japan, the use of such advanced technologies is as important with respect to treatment efficacy as the prescribed dose. There are many technical guidelines for IMRT, SRT, IGRT and motion management [35–38] that could aid in the implementation of these techniques.

For respiratory motion management, the majority of the institutions that we surveyed were using the breath-holding technique [39] rather than respiratory gating. Abches (APEX Medical Inc., Tokyo, Japan) was the second-most widely used instrument for acquisition of the respiratory-gating signal (Supplementary Table 6), and the most commonly used device for controlling patient respiration (Supplementary Table 7). Recently, new technologies, such as VMAT and flattening filter-free beams, have achieved treatment success within a short period. These technologies are better-suited to the breath-holding technique compared to respiratory-gated irradiation, which requires

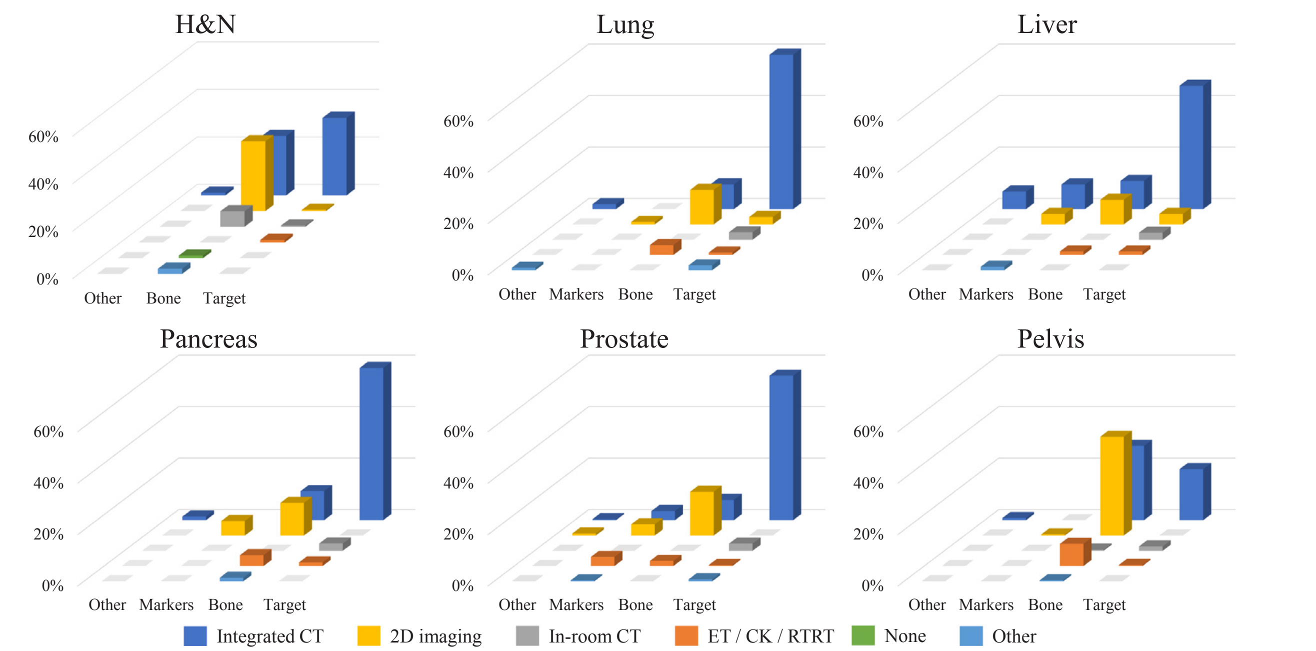

Fig. 2. Cross-tabulation analysis of IGRT instruments used for IMRT against the reference structure for image registration in IGRT. Abbreviations: H&N, head and neck; CT, computed tomography; ET, ExacTrac (BrainLAB); CK, CyberKnife (Accuray); RTRT, real-time tumor-tracking radiation therapy including SyncTraX (Shimadzu Corp.).

Table 8
Techniques used for respiratory motion management.

Technique	N
Breath holding	121
Abdominal compression	114
Respiratory gating	82
Respiratory tracking	20
RTRT	9
Total	346 [221]

The value in square brackets is the number of institutions that answered this question.
Abbreviation: RTRT, real-time tumor-tracking radiation therapy including SyncTraX (Shimadzu Corp.).
Note: Multiple selection was allowed.

longer treatment times [40]. Respiratory motion management has been used for treating various organs, such as the pancreas, stomach, and biliary tract, as shown in Supplementary Table 8. With improvements in dose delivery, target identification, and motion management of the abovementioned techniques, conformal dose delivery has become possible. Such advanced technologies have also enabled dose escalations and hypo-fractionation, although careful attention is required in cases involving critical organs.

5. Conclusion

This survey showed the current status of radiotherapy in Japan, in terms of the instruments used for SRT, IMRT, IGRT and motion management. The VMAT technique is now used with comparable frequency to static gantry IMRT. Regarding IGRT, machine-integrated CT systems were used at many institutions, in conjunction with target-based image registration. The respiratory motion management data indicated that the breath-holding technique was the most commonly used technique. To assess the current status of radiotherapy and highlight emerging developments in the field, additional multi-institutional surveys should be conducted on a periodic basis. If our questionnaire was distributed globally, in the same format, then global trends in radiotherapy could be better understood.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejmp.2019.07.009.

References

[1] Yamamoto M, Serizawa T, Shuto T, Akabane A, Higuchi Y, Kawagishi J, et al. Stereotactic radiosurgery for patients with multiple brain metastases (JLGK0901): a multi-institutional prospective observational study. Lancet Oncol 2014;15:387–95. https://doi.org/10.1016/s1470-2045(14)70061-0.

[2] Chi A, Liao Z, Nguyen NP, Xu J, Stea B, Komaki R. Systemic review of the patterns of failure following stereotactic body radiation therapy in early-stage non-small-cell lung cancer: clinical implications. Radiother Oncol 2010;94:1–11. https://doi.org/10.1016/j.radonc.2009.12.008.

[3] Boike TP, Lotan Y, Cho LC, Brindle J, DeRose P, Xie XJ, et al. Phase I dose-escalation study of stereotactic body radiation therapy for low- and intermediate-risk prostate cancer. J Clin Oncol 2011;29:2020–6. https://doi.org/10.1200/jco.2010.31.4377.

[4] Wortel RC, Incrocci L, Pos FJ, Lebesque JV, Witte MG, van der Heide UA, et al. Acute toxicity after image-guided intensity modulated radiation therapy compared to 3D conformal radiation therapy in prostate cancer patients. Int J Radiat Oncol Biol Phys 2015;91:737–44. https://doi.org/10.1016/j.ijrobp.2014.12.017.

[5] Abu-Gheida I, Reddy CA, Kotecha R, Weller MA, Shah C, Kupelian PA, et al. Ten-year outcomes of moderately hypofractionated (70 Gy in 28 fractions) intensity modulated radiotherapy for localized prostate cancer. Int J Radiat Oncol Biol Phys 2019. https://doi.org/10.1016/j.ijrobp.2019.01.091.

[6] Otto K. Volumetric modulated arc therapy: IMRT in a single gantry arc. Med Phys 2008;35:310–7. https://doi.org/10.1118/1.2818738.

[7] Verbakel WF, Senan S, Cuijpers JP, Slotman BJ, Lagerwaard FJ. Rapid delivery of

stereotactic radiotherapy for peripheral lung tumors using volumetric intensity-modulated arcs. Radiother Oncol 2009;93:122–4. https://doi.org/10.1016/j.radonc.2009.05.020.

[8] Zelefsky MJ, Kollmeier M, Cox B, Fidaleo A, Sperling D, Pei X, et al. Improved clinical outcomes with high-dose image guided radiotherapy compared with non-IGRT for the treatment of clinically localized prostate cancer. Int J Radiat Oncol Biol Phys 2012;84:125–9. https://doi.org/10.1016/j.ijrobp.2011.11.047.

[9] de Crevoisier R, Bayar MA, Pommier P, Muracciole X, Pene F, Dudouet P, et al. Daily versus weekly prostate cancer image-guided radiotherapy: phase 3 multicenter randomized trial. Int J Radiat Oncol Biol Phys 2018. https://doi.org/10.1016/j.ijrobp.2018.07.2006.

[10] Kok D, Gill S, Bressel M, Byrne K, Kron T, Fox C, et al. Late toxicity and biochemical control in 554 prostate cancer patients treated with and without dose escalated image guided radiotherapy. Radiother Oncol 2013;107:140–6. https://doi.org/10.1016/j.radonc.2013.04.007.

[11] Wolthaus JW, Sonke JJ, van Herk M, Belderbos JS, Rossi MM, Lebesque JV, et al. Comparison of different strategies to use four-dimensional computed tomography in treatment planning for lung cancer patients. Int J Radiat Oncol Biol Phys 2008;70:1229–38. https://doi.org/10.1016/j.ijrobp.2007.11.042.

[12] Akino Y, Oh RJ, Masai N, Shiomi H, Inoue T. Evaluation of potential internal target volume of liver tumors using cine-MRI. Med Phys 2014;41:111704https://doi.org/10.1118/1.4896821.

[13] Underberg RW, Lagerwaard FJ, Slotman BJ, Cuijpers JP, Senan S. Benefit of respiration-gated stereotactic radiotherapy for stage I lung cancer: an analysis of 4DCT datasets. Int J Radiat Oncol Biol Phys 2005;62:554–60. https://doi.org/10.1016/j.ijrobp.2005.01.032.

[14] Hoogeman M, Prevost JB, Nuyttens J, Poll J, Levendag P, Heijmen B. Clinical accuracy of the respiratory tumor tracking system of the cyberknife: assessment by analysis of log files. Int J Radiat Oncol Biol Phys 2009;74:297–303. https://doi.org/10.1016/j.ijrobp.2008.12.041.

[15] Hanley J, Debois MM, Mah D, Mageras GS, Raben A, Rosenzweig K, et al. Deep inspiration breath-hold technique for lung tumors: the potential value of target immobilization and reduced lung density in dose escalation. Int J Radiat Oncol Biol Phys 1999;45:603–11.

[16] Onishi H, Kawakami H, Marino K, Komiyama T, Kuriyama K, Araya M, et al. A simple respiratory indicator for irradiation during voluntary breath holding: a one-touch device without electronic materials. Radiology 2010;255:917–23. https://doi.org/10.1148/radiol.10090890.

[17] Rim CH, Lee J, Kim WC, Yang D, Yoon WS, Koom WS, et al. A survey of radiation therapy utilization in Korea from 2010 to 2016: focusing on use of intensity-modulated radiation therapy. J Korean Med Sci 2018;33:e67https://doi.org/10.3346/jkms.2018.33.e67.

[18] Batumalai V, Holloway LC, Kumar S, Dundas K, Jameson MG, Vinod SK, et al. Survey of image-guided radiotherapy use in Australia. J Med Imaging Radiat Oncol 2017;61:394–401. https://doi.org/10.1111/1754-9485.12556.

[19] Kron T, Healy B, Ng KH. Surveying trends in radiation oncology medical physics in the Asia Pacific Region. Phys Med 2016;32:883–8. https://doi.org/10.1016/j.ejmp.2016.06.001.

[20] Ministry of Health, Labour and Welfare, Report of 401th Meeting, 2017. https://www.mhlw.go.jp/stf/shingi2/0000212500_00011.html (accessed 06.03.19).

[21] Ministry of Health, Labour and Welfare, Survey in 2017, 2017. https://www.mhlw.go.jp/toukei/saikin/hw/iryosd/17/index.html (accessed 06.03.19).

[22] AlDuhaiby EZ, Breen S, Bissonnette JP, Sharpe M, Mayhew L, Tyldesley S, et al. A national survey of the availability of intensity-modulated radiation therapy and stereotactic radiosurgery in Canada. Radiat Oncol 2012;7:18. https://doi.org/10.1186/1748-717x-7-18.

[23] Mayles WP. Survey of the availability and use of advanced radiotherapy technology in the UK. Clin Oncol (R Coll Radiol) 2010;22:636–42. https://doi.org/10.1016/j.clon.2010.06.014.

[24] Padayachee J, Loh J, Tiong A, Lao L. National survey on image-guided radiotherapy practice in New Zealand. J Med Imaging Radiat Oncol 2018;62:262–9. https://doi.org/10.1111/1754-9485.12682.

[25] Frenzel T, Krull A. The use of IMRT in Germany. Strahlenther Onkol 2015;191:821–6. https://doi.org/10.1007/s00066-015-0832-4.

[26] Jiang SB, Pope C, Al Jarrah KM, Kung JH, Bortfeld T, Chen GT. An experimental investigation on intra-fractional organ motion effects in lung IMRT treatments. Phys Med Biol 2003;48:1773–84.

[27] Stambaugh C, Nelms BE, Dilling T, Stevens C, Latifi K, Zhang G, et al. Experimentally studied dynamic dose interplay does not meaningfully affect target dose in VMAT SBRT lung treatments. Med Phys 2013;40:091710https://doi.org/10.1118/1.4818255.

[28] Rao M, Wu J, Cao D, Wong T, Mehta V, Shepard D, et al. Dosimetric impact of breathing motion in lung stereotactic body radiotherapy treatment using intensity modulated radiotherapy and volumetric modulated arc therapy [corrected]. Int J Radiat Oncol Biol Phys 2012;83:e251–6. https://doi.org/10.1016/j.ijrobp.2011.12.001.

[29] Ong C, Verbakel WF, Cuijpers JP, Slotman BJ, Senan S. Dosimetric impact of interplay effect on RapidArc lung stereotactic treatment delivery. Int J Radiat Oncol Biol Phys 2011;79:305–11. https://doi.org/10.1016/j.ijrobp.2010.02.059.

[30] Simpson DR, Lawson JD, Nath SK, Rose BS, Mundt AJ, Mell LK. A survey of image-guided radiation therapy use in the United States. Cancer 2010;116:3953–60. https://doi.org/10.1002/cncr.25129.

[31] Nabavizadeh N, Elliott DA, Chen Y, Kusano AS, Mitin T, Thomas Jr CR, et al. Image guided radiation therapy (IGRT) practice patterns and IGRT's impact on workflow and treatment planning: results from a national survey of American Society for Radiation Oncology members. Int J Radiat Oncol Biol Phys 2016;94:850–7. https://doi.org/10.1016/j.ijrobp.2015.09.035.

[32] Valeriani M, Bracci S, Osti MF, Falco T, Agolli L, De Sanctis V, et al. Intermediate-risk prostate cancer patients treated with androgen deprivation therapy and a hypofractionated radiation regimen with or without image guided radiotherapy. Radiat Oncol 2013;8:137. https://doi.org/10.1186/1748-717x-8-137.

[33] Sveistrup J, af Rosenschold PM, Deasy JO, Oh JH, Pommer T, Petersen PM, et al. Improvement in toxicity in high risk prostate cancer patients treated with image-guided intensity-modulated radiotherapy compared to 3D conformal radiotherapy without daily image guidance. Radiat Oncol 2014;9:44. https://doi.org/10.1186/1748-717x-9-44.

[34] Mohler JL, Antonarakis ES, Armstrong AJ, D'Amico AV, Davis BJ, Dorff T, et al. Prostate cancer, version 2.2019. J Natl Compr Canc Netw 2019;17:479–505. https://doi.org/10.6004/jnccn.2019.0023.

[35] Mizowaki T, Hatano K, Hiraoka M. Surveillance on interfacility differences in dose-prescription policy of intensity-modulated radiation therapy plans for prostate cancer. J Radiat Res 2012;53:608–14. https://doi.org/10.1093/jrr/rrs016.

[36] Mancosu P, Nisbet A, Jornet N. Editorial: the role of medical physics in lung SBRT. Phys Med 2018;45:205–6. https://doi.org/10.1016/j.ejmp.2018.01.001.

[37] Caillet V, Booth JT, Keall P. IGRT and motion management during lung SBRT delivery. Phys Med 2017;44:113–22. https://doi.org/10.1016/j.ejmp.2017.06.006.

[38] Matsuo Y, Onishi H, Nakagawa K, Nakamura M, Ariji T, Kumazaki Y, et al. Guidelines for respiratory motion management in radiation therapy. J Radiat Res 2013;54:561–8. https://doi.org/10.1093/jrr/rrs122.

[39] Boda-Heggemann J, Knopf AC, Simeonova-Chergou A, Wertz H, Stieler F, Jahnke A, et al. Deep inspiration breath hold-based radiation therapy: a clinical review. Int J Radiat Oncol Biol Phys 2016;94:478–92. https://doi.org/10.1016/j.ijrobp.2015.11.049.

[40] Boda-Heggemann J, Mai S, Fleckenstein J, Siebenlist K, Simeonova A, Ehmann M, et al. Flattening-filter-free intensity modulated breath-hold image-guided SABR (Stereotactic ABlative Radiotherapy) can be applied in a 15-min treatment slot. Radiother Oncol 2013;109:505–9. https://doi.org/10.1016/j.radonc.2013.09.014.