Original Article

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Comparison of IMRT and VMAT Techniques in Spine Stereotactic Radiosurgery with International Spine Radiosurgery Consortium Consensus Guidelines

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Stereotactic body radiation therapy (SBRT) is increasingly used to treat spinal metastases. To achieve the highest steep dose gradients and conformal dose distributions of target tumors, intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) techniques are essential to spine radiosurgery. The purpose of the study was to qualitatively compare IMRT and VMAT techniques with International Spine Radiosurgery Consortium (ISRC) contoured consensus guidelines for target volume definition. Planning target volume (PTV) was categorized as T_B, T_{BPT} and T_{ST} depending on sectors involved; T_B (vertebral body only), T_{BPT} (vertebral body+ pedicle+transverse process), and T_{ST} (spinous process+transverse process). Three patients treated for spinal tumor in the cervical, thoracic, and lumbar region were selected. Each tumor was contoured by the definition from the ISRC guideline. Maximum spinal cord dose were 12.46 Gy, 12.17 Gy and 11.36 Gy for T_B, T_{BPT} and T_{ST} sites, and 11.81 Gy, 12.19 Gy and 11.99 Gy for the IMRT, RA1 and RA2 techniques, respectively. Average fall-off dose distance from 90% to 50% isodose line for T_B, T_{BPT}, and T_{ST} sites were 3.5 mm, 3.3 mm and 3.9 mm and 3.7 mm, 3.7 mm and 3.3 mm for the IMRT, RA1 and RA2 techniques, respectively. For the most complicated target T_{BPT} sites in the cervical, thoracic and lumbar regions, the conformity index of the IMRT, RA1 and RA2 is 0.621, 0.761 and 0.817 and 0.755, 0.796 and 0.824 for rDHI. Both IMRT and VMAT techniques delivered high conformal dose distributions in spine stereotactic radiosurgery. However, if the target volume includes the vertebral body, pedicle, and transverse process, IMRT planning resulted in insufficient conformity index, compared to VMAT planning. Nevertheless, IMRT technique was more effective in reducing the maximum spinal cord dose compared to RA1 and RA2 techniques at most sites.

Key Words: Stereotactic body radiation therapy (SBRT), International Spine Radiosurgery Consortium (ISRC), Intensity-modulated radiation therapy (IMRT), Volumetric-modulated arc therapy (VMAT)

INTRODUCTION

Stereotactic body radiation therapy (SBRT) is increasingly used to treat metastatic spine diseases.[1-3] SBRT requires a steep dose gradient with image guide systems, including ExacTrac (BrainLAB, Feldkirchen, Germany) and cone beam computed tomography (CBCT; Varian Medical System, CA, USA).[4-9] To achieve the highest steep dose gradients and conformal dose distributions with a small margin for the planning target volume (PTV),[10] intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) techniques are essential. Several authors already reported that there are differences between IMRT and VMAT for various sites, such as the brain,[11-14] head and neck,[15-17] esophagus,[18] lung[19-21] and prostate.[22-25] However, this comparison have not been reported for spinal metastatic diseases.

The International Spine Radiosurgery Consortium (ISRC) has recently proposed guidelines for target volume definition of spinal metastases.[26] The guideline for spine metastases clas-

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sified a vertebral bone into 6 sectors; vertebral body, left pedicle, left transverse process, spinous process, right transverse process, and right pedicle in the cervical, thoracic and the lumbar region respectively. According to number of sectors involved for a given vertebral body, the extent of clinical target volume (CTV) around the spinal cord can vary substantially, resulting in different dosimetric parameters across radiation treatment plans.

Thus, we have compared the effectiveness of IMRT and VMAT in sparing the spinal cord using the ISRC contoured consensus guidelines for target volume definition.

MATERIALS AND METHODS

Three patients treated with spinal tumor of cervical, thoracic, or lumbar region at our institution were selected for this study. As Ryu et al.[27] concluded that partial volume tolerance of spinal cord is at least 10 Gy to 10% of the spinal cord volume (defined as 6 mm above and below the spine radiosurgery target), Computed Tomography (CT) images were acquired with a slice thickness of 2 mm. Each case was retrospectively re-planned to compare dosimetric characteristics between IMRT and RapidARC techniques with prescription of an 18 (Gy) single fraction at 6 MV photon energies.

Novalis Tx (Varian Medical Systems, CA, USA and BrainLAB, Feldkirchen, Germany) linear accelerator system with HD-120 MLC (High Definition Multi Leaf Collimator, 64 inner leaves with 2.5 mm and 56 outer leaves with 5 mm) was used to compare the dosimetric difference of the IMRT and VMAT techniques. Also, the eclipse® (8.6 Platform, Varian Medical System, CA, USA) was used as the radiation treatment planning (RTP) system, to achieve the objective of radiation therapy which the dose to deliver the maximum dose to the target tumor and the minimum dose to the critical organs.[28] To perform the VMAT, the RapidARC® (Varian Medical System, CA, USA) with a progressive resolution optimizer (PRO) 8.6.15 version was used in this study.

1. Contouring of the PTV

Gross target volume (GTV) included the complete extent of the gross metastatic tumor, all epidural and para-spinal components of tumor, and abnormal marrow signal suspicious for microscopic invasion from all available clinical information and imaging modalities, including MRI, CT, and functional imaging studies such as positron emission tomography CT. Planning target volume (PTV) was not added to GTV for additional margin. Spinal cord and organs at risk (OAR) were contoured by 6 mm above and below the target volume supposed by the Ryu et al.[27]

PTV was categorized to T_B, T_{BPT} and T_{ST} depending on the ISRC defined sectors involved; T_B (vertebral body only), T_{BPT} (vertebral body+pedicle+transverse process), and T_{ST} (spinous process+transverse process).

Table 1 shows volume of planning target volume and spinal cord volume according to the locations and parts of target tumors. The mean volume was 12.6 cm^3 for PTV and 1.3 cm^3 for partial spinal cord with ISRC contoured consensus guidelines.

2. IMRT planning

All of the plans for IMRT technique in this study were composed of fixed-gantry 7 fields with angles of 105°, 130°, 155°, 180°, 205°, 230° and 255°, with a collimator angle of 45°. Radiation treatment delivery method was selected for the sliding window. The dose-volume constraints for the tumor in the IMRT optimization were 18.30 Gy for the upper constraint

Table 1. PTV and spinal cord volume according to the locations of the tumor contoured by ISRC consensus guidelines for the target volume.

Case no.	Spine	Tumor location	Volume (cm^3)	
			PTV	Spinal cord
#1	Cervical	B	3.3	1.2
#2		BPT	6.6	1.2
#3		ST	1.4	1.1
#4	Thoracic	B	13.6	1.4
#5		BPT	12.7	1.2
#6		ST	11.4	1.2
#7	Lumbar	B	24.9	1.5
#8		BPT	18.9	1.2
#9		ST	20.9	1.4
Average (range)	Cervical Thoracic Lumbar	B/BPT/ST	12.6 (1.4∼24.9)	1.3 (1.1∼1.5)

B: vertebral body, BPT: vertebral body+pedicle+transverse process, ST: spinous process+transverse process.

with 0% and 17.70 Gy for the lower constraint with 100% for the optimization priority of the 250. Also, dose constraints for the spinal cord were 9 Gy with 5% and 13 Gy with 0% for the optimization priority of the 200 and 100, respectively. The normal tissue objective to deliver the highly steep gradient dose to target volume was values of 200 with a 0.5 fall-off between the start dose of the 100% and the end dose of the 50%. The maximum iteration of calculations was limited to 500 times to compare the difference between IMRT and VMAT. The anisotropic analytical algorithm (AAA)[29] was used for dose calculations in the treatment planning system. A grid size of 2.5 mm and inhomogeneity correction were used for calculations. To compare the differences in dose between IMRT and RapidARC technique, the prescription to target was normalized to 95% coverage of the target volume.

3. ARC planning

ARC plans were generated by a single arc (RA1) that composed of gantry angles of $181^o \sim 179^o$ in clockwise direction with a collimator angle of 45^o and by double arcs (RA2) composed of gantry angles of $181^o \sim 179^o$ in clockwise and of 179^o~181^o in counter-clockwise directions with collimator angles of 45^o and 315^o, respectively. The constraints of MLC optimization for arc planning were used for the synchronized value of IMRT planning to compare the two treatment modalities under the same conditions. AAA algorithms with a grid size of 2.5 mm were selected for dose calculations.

4. Evaluation

Dose volume histogram (DVH) was evaluated for the target volume and normal organs. The 3D dose max (%), spinal cord max (cGy), spinal cord V10 (%), and distance from 90% to 50% isodose line (mm) were qualitatively compared among the three plans (IMRT, RA1, and RA2) at the cervical, thoracic, and lumbar regions. The conformity index (CI=Conformation Number (CN)) was used to assess the quality of target coverage in the respective regions. Van't Riet et al.[30] was defined as

$$CI = \frac{TV_{RI}}{TV} \times \frac{TV_{RI}}{V_{RI}};$$

Where TV_{RI}=target volume covered by the reference isodose,
V_{RI}=volume of the reference isodose, and
TV=target volume (in this study, reference isodose used for 95%).

The dose homogeneity index (DHI) was used to investigate the uniformity of target tumor. M. Oliver et al.[31] described the radical dose homogeneity index (rDHI) and moderate homogeneity index (mDHI):

$$rDHI = \frac{D_{\min}}{D_{\max}},$$

Where D_{min}=minimum dose to the target volume and
D_{max}=maximum dose to the target volume.

$$mDHI = \frac{D_{\geq 95\%}}{D_{\geq 5\%}},$$

Where $D_{\geq 95\%}$=dose to 95% of the target volume and
$D_{\geq 5\%}$=dose to 5% of the target volume.

RESULTS AND DISCUSSION

Fig. 1 illustrates the dose distributions with IMRT, RA1 and RA2 techniques for the T_{BPT} case (vertebral body, left-pedicle, and transverse process) in the thoracic region. The red lines outline the PTV for the tumor target in one patient and green and white lines represent 95% and 50% isodose lines of the prescribed dose in the tumor. In comparing the discrepancy between the 50% isodose lines, dose distributions seems to be more rounded for RapidARC technique than for the IMRT, in the region adjacent to tumor.

Generally, the plans to treat the patient for the IMRT or VMAT techniques were conducted for the several optimizations with artificial structure to reduce the hot spot and cold spot. However, to minimize the difference according to the optimizations between the IMRT and VMAT techniques in this study, the calculation for the optimizations was performed once in a case.

The DVH for the IMRT, RA1 and RA2 techniques for the T_{BPT} tumor case in the thoracic region are illustrated in Fig. 2. Panel (a) shows the overall DVH of the PTV, and normal tissues includes the left-right kidney and spinal cord. Panel (b) and (c) indicate magnified DVH in the shoulder and tail re-

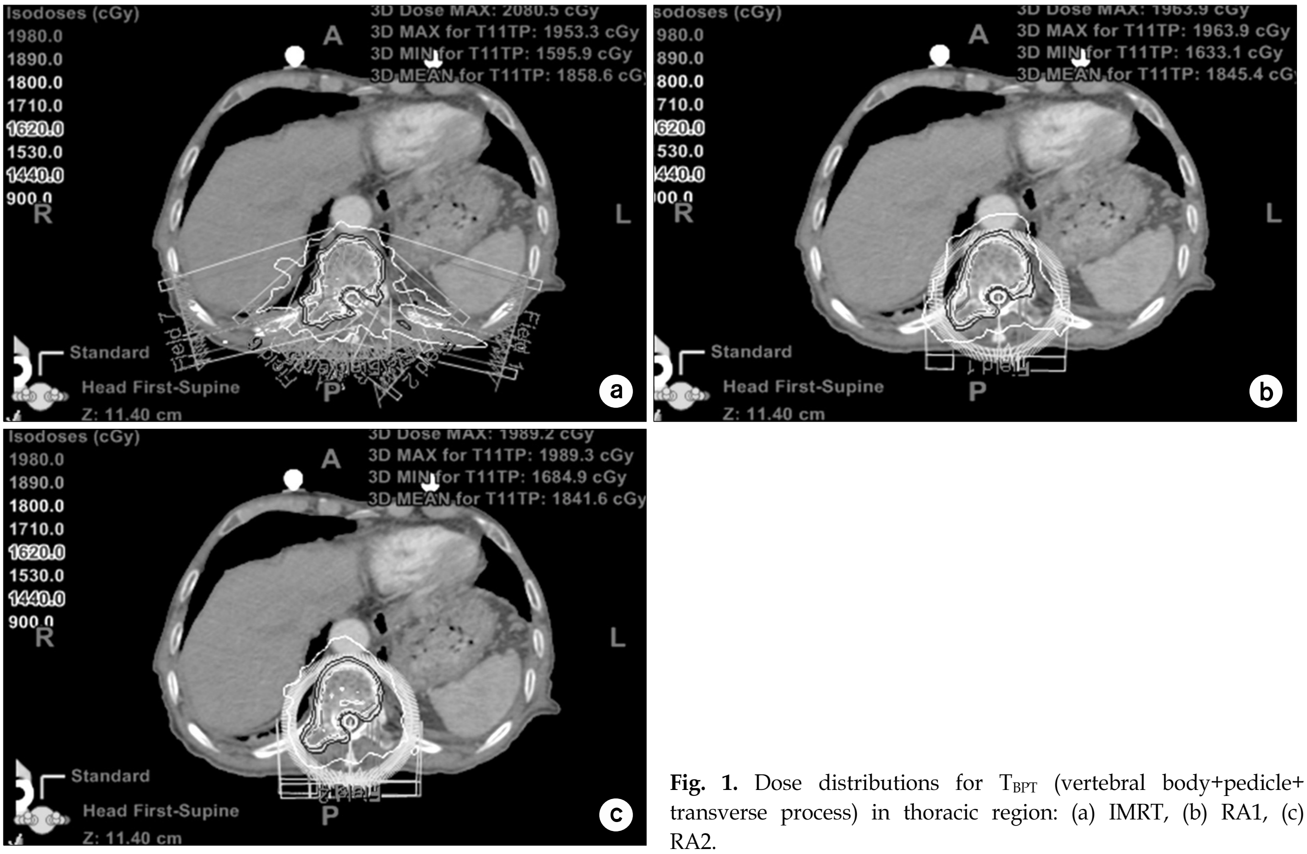


Fig. 1. Dose distributions for T_{BPT} (vertebral body+pedicle+ transverse process) in thoracic region: (a) IMRT, (b) RA1, (c) RA2.

gions of PTV, respectively. In these magnified views, dose coverage and more conformal dose distributions for the tumor are better for RA1 and RA2 than for IMRT.

3D dose max (%) in the cervical, thoracic and lumbar regions are shown in Fig. 3. The 3D dose max in T_B, T_{BPT} and T_{ST} regions were 109.1%, 110.6% and 109.1% for the RA1 technique and 108.5%, 110.7% and 108.5% for the RA2 technique, respectively. On the other hand, the respective values were 107.8%, 118.3%, and 110.0% for IMRT. The highest 3D dose max was 125.4% for T_{BPT} in the cervical region with IMRT technique because of the limited 7 field (105°, 130°, 155°, 180°, 205°, 230° and 255°) of the fixed gantry to deliver the dose to the tumor, while VMAT was delivered via all of the angles for gantry ($181^{\circ} \sim 179^{\circ}$: clockwise, $179^{\circ} \sim 181^{\circ}$: counter clockwise).

Fig. 4 shows the maximum spinal cord dose in T_B, T_{BPT} and T_{ST} sites. The 2010 American Association of Physicists in Medicine (AAPM) Task Group No. 101 Report[1] recommended 14 Gy as the max point dose, 0.35 cc for the max critical volume above threshold of 10 Gy for the spinal cord tolerance in a single fraction. The maximum spinal cord dose was 12.46 Gy, 12.17 Gy and 11.36 Gy for the T_B, T_{BPT} and T_{ST} sites, and 11.81 Gy, 12.19 Gy and 11.99 Gy for IMRT, RA1, and RA2, respectively. T_{ST} had the lowest maximum dose in the spinal cord compared to the maximum dose for the T_B with a difference of 1.1 Gy. This discrepancy was expected to be due to a posterior beam arrangement. Also, IMRT technique was the most effective in reducing the maximum spinal cord dose compared to RA1 and RA2 techniques at most sites. Wu et al.[6] evaluated feasibility of using volumetric arc-modulated treatment for spine stereotactic body radiotherapy with static intensity-modulated treatment. Wu et al.'s results for the spinal cord sparing were in good agreement with our study.

The V10 (%) partial volume tolerance for spinal cord was shown in Fig. 5. Ryu et al. suggested constraints dose of below the 10% with partial spinal cord receiving more than 10 Gy. The partial volume tolerance of spinal cord for all of the techniques were satisfactory at below 10%. IMRT and RA2

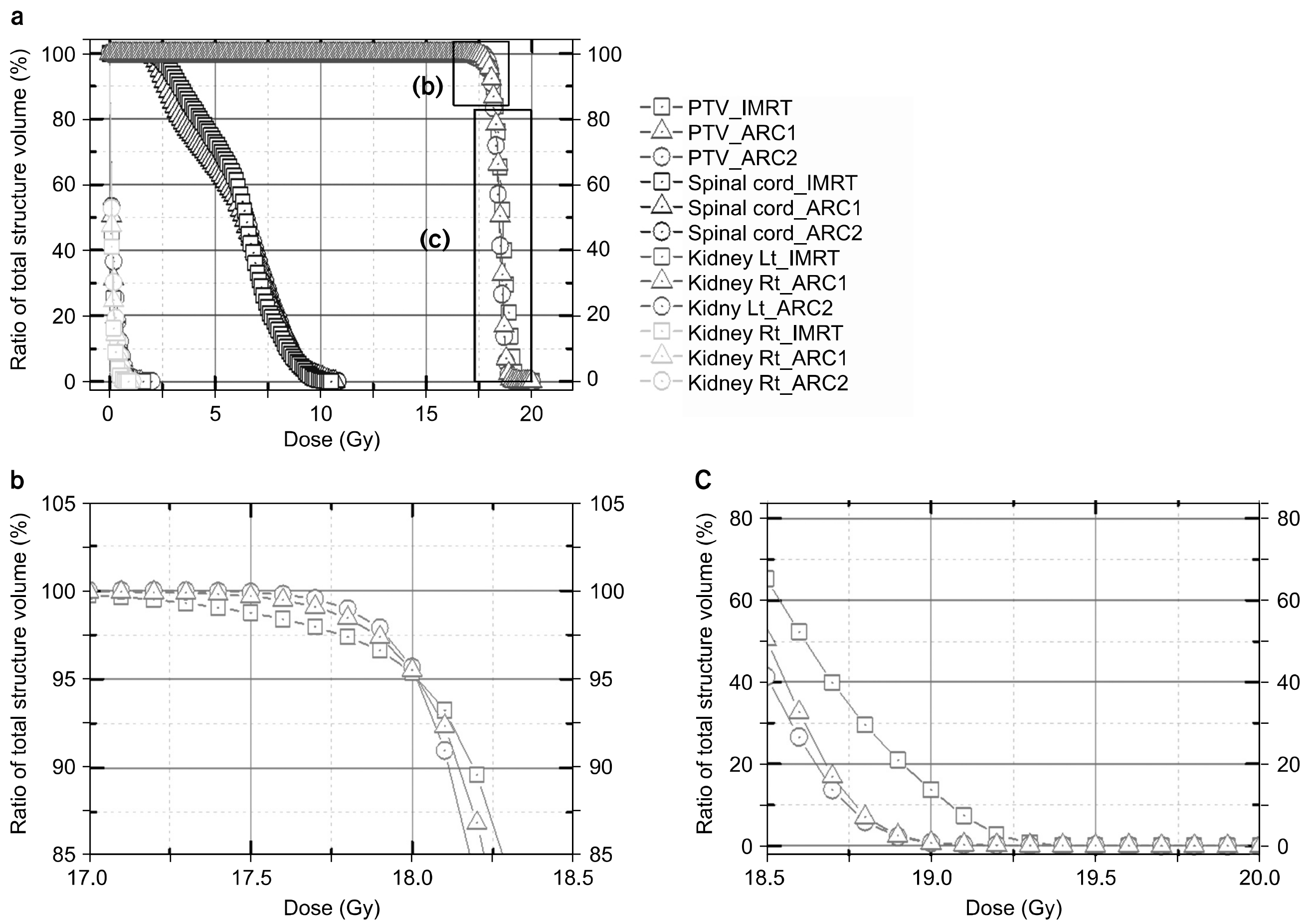
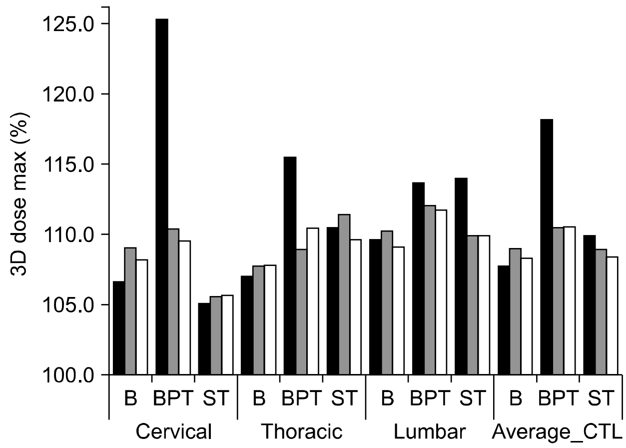
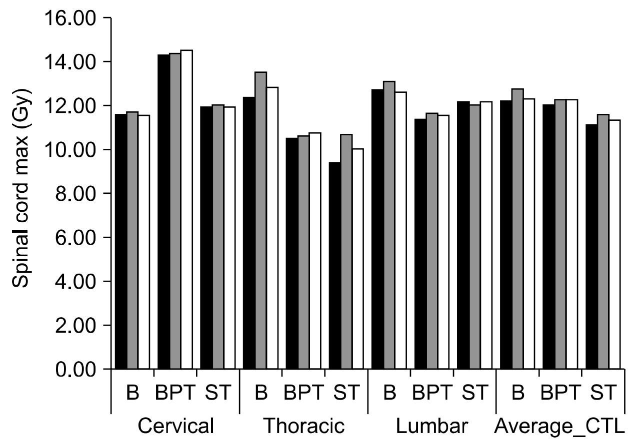


Fig. 2. Dose volume histogram (DVH) for IMRT, RA1, and RA2 techniques in the thoracic region. (a) Overall DVH of PTV and normal tissues, (b) Magnified DVH in shoulder regions of PTV, (c) Magnified DVH in tail regions of PTV.



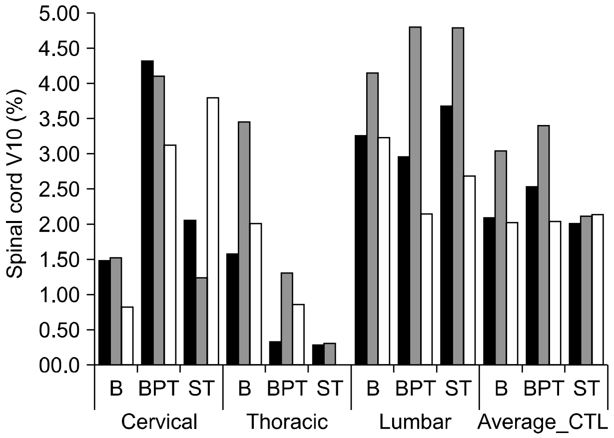
	Cervical B	Cervical BPT	Cervical ST	Thoracic B	Thoracic BPT	Thoracic ST	Lumbar B	Lumbar BPT	Lumbar ST	Average_CTL B	Average_CTL BPT	Average_CTL ST
IMRT	106.7	125.4	105.2	107.1	115.6	110.6	109.7	113.8	114.1	107.8	118.3	110.0
RA1	109.1	110.6	105.8	107.8	109.1	111.5	110.3	112.2	110.1	109.1	110.6	109.1
RA2	108.3	109.7	105.8	107.9	110.5	109.7	109.2	111.8	110.1	108.5	110.7	108.5

Fig. 3. The 3D dose max (%) for T_B, T_{BPT} and T_{ST} in cervical, thoracic and lumbar sites.



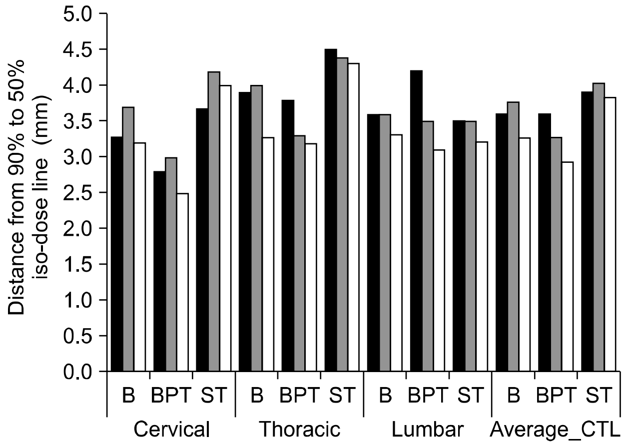
	Cervical B	Cervical BPT	Cervical ST	Thoracic B	Thoracic BPT	Thoracic ST	Lumbar B	Lumbar BPT	Lumbar ST	Average_CTL B	Average_CTL BPT	Average_CTL ST
IMRT	11.61	14.29	11.94	12.40	10.45	9.36	12.78	11.35	12.15	12.26	12.03	11.15
RA1	11.71	14.39	12.00	13.53	10.65	10.68	13.08	11.66	12.05	12.77	12.23	11.58
RA2	11.52	14.51	11.97	12.82	10.71	9.96	12.69	11.58	12.14	12.34	12.26	11.35

Fig. 4. The spinal cord max (Gy) dose for T_B, T_{BPT} and T_{ST} in cervical, thoracic and lumbar sites.



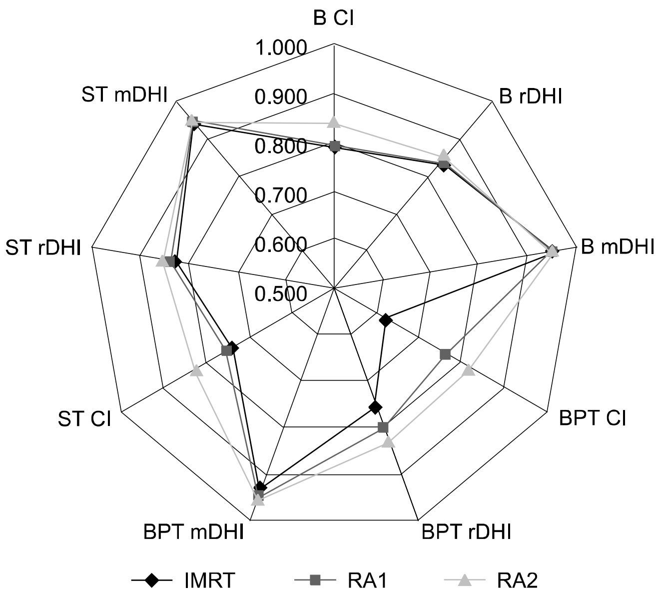
	B	BPT	ST	B	BPT	ST	B	BPT	ST	B	BPT	ST
IMRT	1.51	4.33	2.09	1.59	0.33	0.31	3.25	2.97	3.69	2.12	2.54	2.03
RA1	1.54	4.11	1.23	3.47	1.32	0.32	4.17	4.82	4.81	3.06	3.42	2.12
RA2	0.83	3.14	3.80	2.03	0.88	0.00	3.24	2.15	2.70	2.03	2.06	2.17

Fig. 5. Spinal cord V10% (receiving more than 10 Gy) for T_B, T_{BPT} and T_{ST} in cervical, thoracic and lumbar sites



	B	BPT	ST	B	BPT	ST	B	BPT	ST	B	BPT	ST
IMRT	3.3	2.8	3.7	3.9	3.8	4.5	3.6	4.2	3.5	3.6	3.6	3.9
RA1	3.7	3.0	4.2	4.0	3.3	4.4	3.6	3.5	3.5	3.8	3.3	4.0
RA2	3.2	2.5	4.0	3.3	3.2	4.3	3.3	3.1	3.2	3.3	2.9	3.8

Fig. 6. The distance from 90% to 50% isodose line (mm) for T_B, T_{BPT} and T_{ST} in cervical, thoracic and lumbar sites



Technique	B			BPT			ST			Average_CTL		
	CI	rDHI	mDHI	CI	rDHI	mDHI	CI	rDHI	mDHI	CI	rDHI	mDHI
IMRT	0.787	0.838	0.953	0.621	0.755	0.934	0.733	0.825	0.936	0.714	0.806	0.941
RA1	0.795	0.843	0.954	0.761	0.796	0.949	0.753	0.842	0.950	0.770	0.827	0.951
RA2	0.845	0.860	0.955	0.817	0.824	0.953	0.817	0.850	0.953	0.827	0.845	0.953

Fig. 7. Conformity index&homogeneity index for T_B, T_{BPT} and T_{ST} in cervical, thoracic and lumbar sites. CI: conformity index, rDHI: radical dose homogeneity index, mDHI: moderate dose homogeneity index.

techniques were highly efficient in reducing V10 (%) of the partial volume tolerance. Increasing the number of the arc made, while sparing the critical organs near the target volume from spinal cord V10 (%), results of the RA1 and RA2 techniques.

Fig. 6 indicates the distance from 90% to 50% isodose line (mm) in T_B, T_{BPT} and T_{ST} sites. Ryu et al.[27] reported an average dose fall-off from 90% to 50% isodose lines at the spinal cord in single-dose radiosurgery was 5.24 mm ± 0.92 mm. Similarly, fall-off dose distance (mm) from 90% to 50% isodose line for T_B, T_{BPT} and T_{ST} sites were 3.6 mm, 3.6 mm and 3.9 mm for IMRT; 3.8 mm, 3.3 mm and 4.0 mm for RA1; and, 3.3 mm 2.9 mm and 3.8 mm for RA2 technique, respectively. The worst fall-off dose occurred with the combination of RA1 technique and TST site, and this was related to the positional relations between target and normal organs, RA2 is more advantageous for steep dose gradient in the spinal cord. In particular, T_{BPT} surrounded by most of angle around the critical organ was more prominent in the difference of RA2 and IMRT.

The conformity index and homogeneity index are shown in Fig. 7. The difference in these indices was most notable for T_{BPT} between IMRT and VMAT. In the T_{BPT} sites for cervical, thoracic and lumbar regions, the conformity index of the IMRT, RA1 and RA2 is 0.621, 0.761 and 0.817, and 0.755, 0.796 and 0.824 for the rDHI, and 0.934, 0.949 and 0.953 for the mDHI, respectively. For conformity and homogeneity, RA2 was the most advantageous. When a tumor is adjacent to critical organs in all of the angles (i.e. T_{BPT} site), RA2 is more preferable in terms of conformity and homogeneity in tumor dose distribution.

CONCLUSION

In this study, we qualitatively compared the quality of plans using IMRT and VMAT techniques in spine stereotactic radiosurgery with 18 Gy single fraction. Both IMRT and VMAT techniques deliver high conformal dose distributions to tumor distributions of T_B, T_{BPT} and T_{ST}, while satisfying the tolerance of spinal cord specified in the AAPM TG-101 report and partial volume tolerance reported by Ryu et al. However, if the target volume includes the vertebral body, pedicle, and transverse process; plan quality in IMRT inferior to the VMAT in terms of CI. Nevertheless, IMRT was most effective in reducing the maximum spinal cord dose, when compared to VMAT.

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International Spine Radiosurgery Consortium Consensus Guidelines에 따른 Spine Stereotactic Radiosurgery에서 IMRT와 VMAT의 비교연구

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정위적 체부 방사선치료(Stereotactic Body Radiation Therapy, SBRT)는 척추 전이암을 치료하는데 있어서 점점 증가하고 있다. 표적 종양의 급격한 선량 변화와 등선량 분포를 얻기 위해서, 세기조절방사선치료(Intensity-modulated radiation therapy, IMRT)와 체적변조회전치료(Volumetric-modulated arc therapy, VMAT)는 척추 방사선수술에 있어서 필수적인 치료기법이다. 이 연구의 목적은 표적 종양을 위한 International Spine Radiosurgery (ISRC) Consortium의 consensus guideline으로 그려진 표적에 있어서 IMRT와 VMAT의 치료기법을 질적으로 비교하고자 한다. 경부, 흉부, 요추 부위에 종양치료를 받은 3명의 환자를 선택 하였다. 표적 종양은 ISRC의 consensus guideline을 바탕으로 정의 하였다. T_B는 vertebral body만 포함하였고, T_{BPT}는 vertebral body, pedicle, transverse process를 포함하였다. 그리고 TST는 spinous process와 transverse process를 포함하여 그렸다. Maximum spinal cord선량은 T_B, T_{BPT}, T_{ST}에서 각각 12.46 Gy, 12.17 Gy, 11.36 Gy였고, IMRT, RA1, RA2에서 각각 11.81 Gy, 12.19 Gy, 11.99 Gy였다. 평균 감소(90%∼50%) 선량 거리 (mm)는 T_B, T_{BPT}, T_{ST}에서 각각 3.5 mm, 3.3 mm, 3.9 mm였고, IMRT, RA1, RA2에서 각각 3.7 mm, 3.7 mm, 3.3 mm였다. 가장 복잡한 T_{BPT}의 경우에서 IMRT, RA1, RA2의 conformity index는 각각 0.621, 0.761, 0.817 이었고, rDHI는 0.755, 0.796, 0.824 였다. IMRT와 VMAT 모두 척추 정위적 방사선수술에서 표적 종양에 급격한 선량 변화와 등선량 분포를 전달하였다. 그러나 표적 종양이 vertebral body, pedicle, transverse process를 포함한다면, IMRT 치료기법은 VMAT 치료기법과 비교해서 conformity index 측면에서 불충분하였다. 그럼에도 불구하고, IMRT 치료기법은 RA1, RA2와 비교해서 대부분의 영역에서 maximum spinal cord 선량을 줄이는데 더 효과적이었다.

중심단어: 정위적 체부 방사선치료, International Spine Radiosurgery Consortium (ISRC), 세기조절방사선치료, 체적변조회전치료