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간세포암의 정위적 체부 방사선 치료에서 적합한 치료 방침 선택에 관한 연구

최서희 · 우중렬 · 성진실
연세대학교 의과대학 방사선종양학교실

Selection of Proper Modality in Stereotactic Body Radiation Therapy for Hepatocellular Carcinoma

Seo hee Choi, Joong Yeol Woo, Jinsil Seong
Department of Radiation Oncology, Yonsei University College of Medicine, Seoul, Korea

Background/Aims: As the optimal stereotactic body radiation therapy (SBRT) modality for hepatocellular carcinoma (HCC) has not been confirmed, we aimed herein to provide a practical guideline by our retrospective review.
Methods: Thirty-nine patients with primary HCC who underwent liver SBRT via 3 modalities (helical tomotherapy [HT]: 22, volumetric modulated arc therapy [VMAT]: 13, Cyberknife: 4) at our institution between July 2014 and July 2015 were included. Modalities were compared with regard to dose conformity index (CI), homogeneity index (HI), clinical results, and patient compliance.
Results: VMAT SBRT had favorable conformity (CI: 0.7±0.2), homogeneity (HI: 1.1±0.0), and shortest treatment time (100.2±26.1 seconds). HT SBRT yielded good dosimetric outcomes, especially in conformity (CI: 1.0±0.2). Although the Cyberknife SBRT synchrony system allowed real-time tumor targeting, the treatment time was longest (3,015.0±447.3 seconds), invasive pre-treatment procedures were required, and the HI (1.3±0.0) was lowest.
Conclusions: All 3 modalities yielded competent dosimetric planning parameters. VMAT SBRT was most appropriate for tumors with residual lipiodol or patients with poor conditions. HT SBRT is available for multiple or irregular targets. Cyberknife SBRT is recommended for carefully selected patients and tumors indicated for sono-guided fiducial insertion.
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Keywords: Radiotherapy; Hepatocellular carcinoma; Volumetric-Modulated Arc Therapy; Helical tomotherapy

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INTRODUCTION

Resection, ablation, and liver transplantation are the available curative options for hepatocellular carcinoma (HCC), according to many clinical practice guidelines. However, only 10–20% of patients with HCC have resectable tumors[1,2]; here, potentially curative options such as radiofrequency ablation (RFA), transarterial chemoembolization (TACE), transarterial chemoinfusion (TACI), or radiotherapy should be consid-

Corresponding author : Jinsil Seong
Department of Radiation Oncology, Yonsei Cancer Center, Yonsei University College of Medicine, 50-1 Yonsei-ro, Seodaemun-gu, Seoul 03722, Korea
Tel. +82-2-2228-8095, Fax. +82-2-2227-7823
E-mail; jsseong@yuhs.ac

ered for locoregional tumor control rather than other systemic therapies or supportive care. In particular, radiotherapy is one of effective locoregional therapies. Although radiotherapy is not a standard treatment in the Barcelona Clinic Liver Cancer (BCLC) staging system,[3,4] the National Comprehensive Cancer Network (NCCN) guideline, a major pillar of oncologic practice, recommends radiotherapy as a preferred option.[5]

Radiotherapy has recently gained popularity because of substantial local antitumor effects.[6] In particular, stereotactic body radiotherapy (SBRT) has become an important option for selected patients ineligible for RFA or TACE who have unresectable hepatic lesions measuring <5 cm and good liver function.[7,8] Accumulating evidence indicates that SBRT may be effective for hepatic tumors, with a satisfactory local control rate and tolerable toxicity profiles in both retrospective[9-16] and prospective[17-20] settings. Recently, local control rates of 80–100% have been demonstrated with SBRT using volumetric modulated arc therapy (VMAT) or Cyberknife.[11,12,14,16,19] Our institution is the first to study SBRT using helical tomotherapy (HT) for hepatic tumors and has achieved good response rates since 2006.

SBRT utilizes sophisticated treatment planning, special patient immobilization devices, and precise image guidance to deliver high radiation doses to tumors in 1–5 fractions. SBRT can be performed using 3-dimensional conformal radiotherapy techniques (3D-CRTs) or intensity modulated radiation therapy (IMRT) with VMAT, HT, or Cyberknife. Each modality has been studied regarding SBRT competence and is considered effective, with strengths and weaknesses. Many studies compared performances of various SBRT modalities from clinical and dosimetric viewpoints.[21,22] However, such comparison studies have been limited in HCC. In current HCC clinical practice, SBRT is mainly used as salvage treatment after RFA or TACE failure, rather than primary treatment; HCC-specific clinical consideration is thus required.

Our institution makes available several precise radiotherapy systems, including HT, VMAT, and Cyberknife. Although these modalities have been proven effective for liver tumor SBRT, there is a growing need to select optimal modalities depending on clinical situations. Herein, we aimed to provide a practical guideline regarding the optimal modality in a certain situation retrospectively based on our experiences with dosimetric parameters, clinical applications, and patient compliance.

METHODS

1. Patient data

Thirty-nine patients with primary HCC treated via liver SBRT in our institution between July 2014 and July 2015 were selected as follows: HT SBRT, 22 patients (T group); VMAT SBRT, 13 (V group); Cyberknife SBRT, 4 patients (C group). Patients' characteristics are shown in Table 1.

All patients had Child–Pugh scores of A or B (≤7). Only 1 patient had lung metastasis; no others had extrahepatic metastasis. All but 1 patient had no vascular tumor thrombosis. Most patients (n=37, 95%) received other treatment before SBRT and were referred to our department for salvage treatment even after several treatment sessions. Twenty T group patients who received initial curative radiotherapy for newly diagnosed HCC experienced TACE or TACI failure. Twelve V group patients (except 1 with postoperative S1 recurrence) received SBRT after TACE or TACI failure. At the time of SBRT, residual lipiodol was detected via cone-beam computerized tomography (CT) in 55% (n=12) of T group, 77% (n=10) of V group, and 25% (n=1) of C group patients. Regarding tumor location, 36% (n=14) of tumors were located in S8 (S8 [n=14, 36%] > S4 [n=8, 21%] > S7 [n=7, 18%] > S1 [n=6, 15%]). Few tumors were located in S2 (n=1, 3%), S3 (n=2, 5%), or S6 (n=0) (Table 2).

2. Treatment planning

All patients underwent planning CT (slice thickness = 3-mm) while immobilized in the supine position with a respiration control device. To correct respiration-related deformation and rotation of the normal liver and tumor, all patients underwent 4-dimensional (4D)-CT scans (SOMATOM Sensation; Siemens, Munich, Germany), in which CT data were acquired synchronously with a respiratory signal. For SBRT

Table 1. Patients' characteristics

Characteristics	HT (n=22) (n, %)	VMAT (n=13) (n, %)	Cyberknife (n=4) (n, %)
Age (years)	Median 64 (42-86)	Median 63 (47-75)	Median 59.5 (54-72)
Sex			
Male	16 (73)	12 (92)	2 (50)
Female	6 (27)	1 (8)	2 (50)
ECOG			
0	16 (73)	4 (31)	1 (25)
1	6 (27)	9 (69)	3 (75)
2	0 (0)	0 (0)	0 (0)
Underlying liver disease			
HBV	13 (59)	8 (62)	3 (75)
HCV	5 (23)	3 (23)	1 (25)
Alcohol-related	1 (4)	2 (15)	0 (0)
None	3 (14)	0 (0)	0 (0)
CTP score			
5	20 (91)	9 (69)	3 (75)
6	2 (9)	3 (23)	0 (0)
7	0 (0)	1 (8)	1 (25)
UICC stage			
I	1 (4)	0 (0)	0 (0)
II	8 (36)	4 (31)	1 (25)
III	12 (55)	7 (54)	2 (50)
IVA	1 (5)	2 (15)	0 (0)
IVB	0 (0)	0 (0)	1 (25)
Tumor location			
S1	3	3	
S2			1
S3	1		1
S4	4	3	1
S5	1		
S6			
S7	6	1	
S8	7	6	1
Maximum tumor diameter (cm)	Median 2.1 (0.7-4.8)	Median 1.2 (0.3-4.8)	Median 2.6 (1.3-5.5)
Tumor vascular thrombosis			
Yes	0 (0)	1 (8)	0 (0)
No	22 (100)	12 (92)	4 (100)
Extrahepatic metastasis			
Yes	0 (0)	0 (0)	1 (25)
No	22 (100)	13 (100)	3 (75)
Previous treatments			
None	2	0	0
Surgery	4	3	0
TACE/TACI	20	12	4
RFA	1	2	2
Sorafenib	0	0	1
Chemotherapy	4	0	1
Radiotherapy aim			
Definitive	2 (9)	0 (0)	0 (0)
Salvage	20 (91)	13 (100)	4 (100)

Values are presented as n (%) unless otherwise indicated.
HT, helical tomotherapy; VMAT, volumetric-modulated arc therapy; ECOG, Eastern Cooperative Oncology Group; HBV, hepatitis B virus; HCV, hepatitis C virus; CTP, Child–Pugh score; UICC, Union for International Cancer Control; TACE, transarterial chemoembolization; TACI, transarterial chemoinfusion; RFA, radiofrequency ablation.

using HT or VMAT, a customized Vac-Lock™ (CIVCO, Coralville, IA, USA) was used for patient immobilization; an abdominal compressor was used to maintain shallow breathing during treatment. Occasionally, moderate deep-inspiration breath holding with an active breathing control (ABC) device replaced the abdominal compressor (applicable only with VMAT SBRT). In Cyberknife SBRT, the customized Vac-Lock™ was used alone because of long treatment time; breathing synchronization with fiducial tracking was used.

A radiation oncologist with expertise in liver tumors contoured gross tumor volumes (GTVs) on each slice after fusing CT images with dynamic CT and magnetic resonance (MR) images. GTV contours were superimposed using 4D-CT series to generate the internal target volume (ITV); the clinical target volume (CTV) was defined as ITV + 5–7 mm. No additional margin was added for a planning target volume (PTV). Patients were prescribed 56 Gy for PTV and 60 Gy for ITV in 4 fractions (≥95% coverage). Cyberknife SBRT did not use an ITV; only 60 Gy in 4 fractions was prescribed for a single target (PTV). All patients rested for 1 day after every 4 consecutive treatment fractions. Normal structures and organs at risk (OARs), including remaining normal liver, stomach, duodenum, bowel, kidney, and spinal cord, were also contoured. Dose constraints were defined according to the

Table 2. Comparison of dosimetric factors

Characteristics	HT (n=22)	VMAT (n=13)	Cyberknife (n = 4)	*P*-value
ITV volume (mL)	36.0±22.8	37.3±35.5	43.3±33.3	0.720
PTV volume (mL)	87.6±39.2	85.8±69.7	79.0±54.0	0.601
Remained normal liver volume (mL)	1,309.1±274.6	1240.9±185.5	1,183.6±489.6	0.718
PTV $D_{99\%}$ (Gy)	52.4±5.5	52.5±5.0	50.7±7.1	0.536
PTV $D_{95\%}$ (Gy)	54.5±3.2	55.3±1.7	53.8±6.8	0.872
PTV $D_{90\%}$ (Gy)	55.9±2.4	56.4±1.1	55.8±6.6	0.959
CI	1.0±0.2	0.7±0.2	0.8±0.2	0.097
nCI	1.3±0.4	1.4±0.6	1.4±0.4	0.234
HI	1.1±0.0	1.1±0.0	1.3±0.0	0.002
Remained normal liver D_{mean} (Gy)	10.5±2.0	10.3±2.6	10.0±3.6	0.989
Stomach $D_{0.03cc}$ (Gy)	12.7±6.2	12.4±3.9	12.5±7.8	0.967
Stomach D_{2cc} (Gy)	10.8±5.3	10.2±3.5	10.1±6.3	0.934
Duodenum $D_{0.03cc}$ (Gy)	6.6±6.9	5.3±4.4	7.2±7.0	0.778
Duodenum D_{2cc} (Gy)	4.2±4.9	2.9±2.8	5.4±6.3	0.848
MU	4,338.8±548.9	3,223.8±838.7	8,627.3±3,349.3	<0.0001
Treatment time (sec)	656.6±73.7	100.2±26.1	3,015.0±447.3	<0.0001

Values are presented as mean ± SD unless otherwise indicated.
HT, helical tomotherapy; VMAT, volumetric-modulated arc therapy; ITV, internal target volume; PTV, planning target volume; CI, conformity index; HI, homogeneity index; MU, monitor unit.

AAPM Task Group report 101: i) ≥700 mL of remaining normal liver should receive ≤15 Gy; ii) maximum dose (D_{max}) to bowel, duodenum, and stomach, <24 Gy; iii) D_{max} to spinal cord, <18 Gy; iv) ≥67% of each kidney should receive <15 Gy, and V_{15} should be <35%.[23]

In T group, planning CT images and all contours were transferred to a Tomotherapy Treatment Planning System (Accuray, Sunnyvale, CA, USA), enabling inverse helical IMRT treatment planning at 6 MV. Beamlet calculation parameters were: field width, 5 cm; pitch, 0.123; fine resolution mode.

In V group, an Elekta VERSA accelerator with 10-MV flattening filter free photons was used to plan treatment for planning CT and all contours. Raystation (RaySearch Laboratories, Stockholm, Sweden) was used for VMAT planning. A 1-arc arrangement was used to adapt the locations of tumor and normal tissues. Some arc portions were blocked to minimize doses to normal structures.

In C group, planning CT images and all contours were transferred to the MultiPlan CyberKnife treatment planning system (Accuray). The Synchrony system (Accuray) was used for real-time tumor targeting and Cyberknife planning. Several light-emitting diodes (LEDs) were placed on the patient's chest wall and tracked by wall-mounted cameras in the treatment room. Throughout the procedure, Synchrony motion-tracking software correlated external body surface movement with internal tumor fiducial movement to follow and adjust for tumor motion. At our institution, <3 sets of internal fiducial data were entered before treatment.

On each treatment day, all patients underwent on-board mega-voltage CT (MVCT) or kilo-voltage CT (kVCT) for image-guidance (MVCT in HT SBRT; kVCT in VMAT or Cyberknife SBRT) before each fraction. Whole-liver MVCT/kVCTs were registered with planning kVCT, while ensuring exact matching of tumor-containing hepatic segments.

3. Dosimetric evaluation parameters

Each plan PTV was compared regarding dose conformity and homogeneity. Conformity evaluation used the compo-

nents of corresponding target volume coverage by the prescribed dose ($D_{99\%}$, $D_{95\%}$, $D_{90\%}$ for PTV) and conformity index (CI). CI and homogeneity index (HI) were defined as follows[24]:

$$CI = V_{RI}/TV,\ HI = I_{max}/RI,$$

where V_{RI} is the prescribed dose volume for PTV, TV is the total PTV, I_{max} is the maximum dose, and RI is the prescribed dose for PTV. We also calculated a normalized conformity index (nCI) to more accurately analyze conformity in each plan.[25]

$$nCI = (V_{RI}/TV) * (100/PTV\ V_{RI}),$$

where PTV V_{RI} is the percentage of PTV covered by the prescribed isodose line.

OARs were analyzed using mean doses (D_{mean}) or doses to 0.03 cc and 2 cc ($D_{0.03cc}$, D_{2cc}, respectively).

4. Statistical analysis

The benefit for each treatment group was assessed separately. Data from all plans were compared with the non-parametric Kruskal–Wallis test and Mann–Whitney test (SPSS 15.0; SPSS Inc., Chicago, IL, USA). Statistical significance was set at a P value ≤ 0.05.

RESULTS

1. Target coverage, conformity, and heterogeneity

The average ITVs (GTVs in group 3) were 36.0 mL, 37.3 mL, and 43.3 mL in T group, V group, and C group, respectively. The corresponding average PTVs were 87.6 mL, 85.8 mL, and 79.0 mL, respectively. There were no statistically significant differences among modalities in the maximum tumor diameter, ITV, PTV, and remaining normal liver volume. No statistically significant differences were found in the PTV $D_{99\%}$, $D_{95\%}$, and $D_{90\%}$ (P=0.462, 0.834, and 0.953, respectively).

In a conformity analysis, CI was better with HT than with Cyberknife (P=0.048) and VMAT (P=0.130). Cyberknife had the worst nCI, although this difference was not significant (P=0.097). The respective average CI and nCI were 1.0 and 1.3 with HT, 0.7 and 1.4 with VMAT, and 0.8 and 1.4 with Cyberknife. Cyberknife had a significantly worse HI (mean 1.3, range 1.30–1.37) than other plans (P=0.001). The VMAT and HT plan HIs did not significantly differ (Table 2).

2. Organ-at-risk dose sparing

All plans achieved our institution's dose constraints for critical organs. Stomach and duodenum $D_{0.03cc}$ and D_{2cc} and remaining normal liver D_{mean} did not significantly differ among modalities (Table 2).

3. Patient model plan comparison

For dosimetric comparison of modalities, we performed 4 different radiotherapy plans for 1 patient: Cyberknife, HT, and VMAT with ABC or abdominal compressor (Fig. 1). A 59-year-old male with cT3N0M0-stage disease received 60 Gy SBRT/4 fractions for residual tumor after TACE. All conformal and homogenous SBRT plans achieved OAR constraints. With Cyberknife, a high-dose region ($\geq$70 Gy) exceeding the prescribed dose (60 Gy) was observed. Superior homogeneity

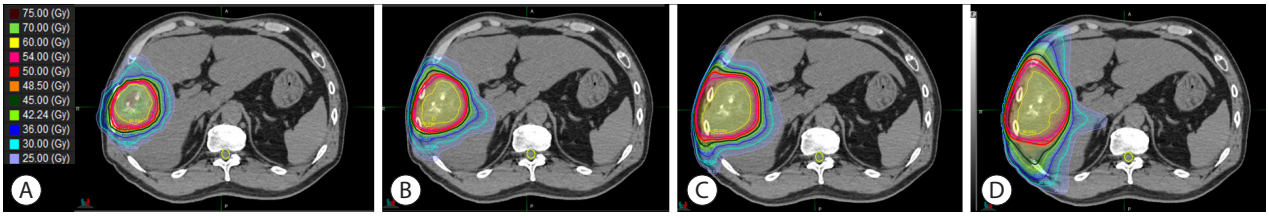

Figure 1. Dose distributions in the axial plane with (A) cyberknife, (B) volumetric modulated arc therapy (VMAT) using active breathing control, (C) helical tomotherapy, and (D) conventional VMAT using abdominal compressor during the same computed tomography session (1 patient).

and conformity were achieved with VMAT, and a more conformal plan and small PTV margin were available when using ABC. PTV coverage and conformity were superior with HT vs. other plans. To summarize this dosimetric comparison, i) PTV coverage: HT > VMAT = VMAT using ABC > Cyberknife, ii) OAR dose: Cyberknife > HT > VMAT = VMAT using ABC, iii) Conformity: HT > VMAT using ABC > VMAT > Cyberknife, and iv) Homogeneity: VMAT = VMAT using ABC = HT > Cyberknife. Additional dosimetric data are available in Supplementary Table 1.

4. Monitor unit and delivery time

The average total monitor unit (MU) values were 4472.0, 3161.7, and 8083.5 for HT, VMAT, and Cyberknife, respectively. Compared to HT (P<0.0001) or Cyberknife (P=0.002), VMAT yielded a significantly reduced MU. Mean treatment delivery times (beam-on times) were 698.6, 93, and 3030 seconds in the T, V, and C groups, respectively. Compared to HT (P<0.0001) or Cyberknife (P=0.001), VMAT required the shortest beam-on time.

5. Clinical benefit

Thirty-six of 39 patients had a previous TACE/TACI history involving radioopaque lipiodol deposition in the tumor area that might act as a good internal fiducial marker. For VMAT and Cyberknife, high-resolution kVCT was acquired immediately before treatment, and well-traced residual lipiodol increased the ease, speed, and accuracy of treatment setup. However, lipiodols could not be visualized or traced as an internal marker using MVCT in HT SBRT. The recurrence-free survival rates from the start date of radiotherapy were 92% and 89% at 1-year and 2-year, respectively. The overall survival rates from the start date of radiotherapy were 95% and 80% at 1-year and 2-year, respectively. There was no radiation-toxicity until last follow-up.

6. Patient compliance

For each modality, we analyzed compliance with treatment time, need for hospital admission or any invasive procedure, and treatment period (Table 3). Cyberknife SBRT required the longest time at 50–60 minutes, whereas VMAT SBRT only required 1–2 minutes; HT SBRT had an intermediate time. Regarding hospital admission or invasive procedures, Cyberknife SBRT required an invasive pre-treatment procedure to insert external fiducials; accordingly, patients were admitted and observed for ≥1 day to monitor for acute complications. HT or VMAT SBRT did not require complex procedures. Because VMAT could use kVCT with residual lipiodol as an internal marker, neither fiducial markers nor a long preparation time were required. However, ABC system application reduced compliance because patients required intensive training in regular breathing over a long period, thus increasing the total treatment time. The total treatment time including kVCT and preperation before breath holding was approximately 10–15 minutes. Prior to Cyberknife SBRT, an approximately 3-week treatment period was needed because an interval of ≥1 week after fiducial insertion was needed before planning CT to prevent any possible dislocation. HT and VMAT required only a 2-week preparation.

Table 3. Comparison of patient compliance

Characteristics	HT	VMAT	Cyberknife
Treatment time (per 1 fraction, min)	8-15	1-2*	50-60
Need for admission to hospital			Necessary
Need for any invasive procedure			Necessary
Treatment period (weeks)	2	2	3

HT, helical tomotherapy; VMAT, volumetric arc-modulated treatment.
*Only in cases without an active breathing control device for respiration control.

DISCUSSION

Herein, we compared three different SBRT modalities to determine the appropriate choice for HCC. VMAT SBRT required the shortest treatment time and could exploit residual lipiodol as an internal fiducial. HT SBRT had a favorable dosimetric outcome and the best conformity. Although Cyberknife SBRT could utilize a synchrony system for real-time

tumor targeting, it required the longest treatment time and invasive pretreatment procedures, thus causing the worst compliance, and was possible only in a few selected patients.

Since its development to treat intracranial malignancies, SBRT has been extended to treat extracranial malignancies. SBRT for liver tumors was introduced in the early 1990s.[26] Liver SBRT is cumbersome because it requires accurate patient repositioning, target localization, and control of breathing-related motion and confers a toxicity risk of small bowel including duodenum. Technological advances have allowed radiation delivery to small liver tumors while reducing the risk of normal organ toxicities. Currently, most studies of SBRT are retrospective, involving small cohorts with different histological types and high local control rates (70–90% at 1–2 years).[9-16] Several studies noted dose-response relationships for liver SBRT,[20,27,28] and recent prospective series demonstrated favorable outcomes.[17-20] In most series with a salvage aim, inclusion of large tumors or heavily pretreated patients with repeated recurrences greatly worsened the outcomes. In a naïve series, however, SBRT yielded 3-year local control rate of 92% and a 3-year overall survival rate of 73%, comparable to outcomes following surgery or percutaneous ablation.[29] SBRT, however, is not yet the "standard of choice" in guidelines for early-stage HCC because previous phase III trials lacked comparisons with other local therapies.

Currently, SBRT is indicated as a second or salvage option when other options, including TACE and RFA, are not applicable, rather than a first option.[7,8] In our study, all but 2 patients received salvage SBRT after other treatments failed. This unique situation requires clinical consideration. Tumors in the liver dome are not indicated for RFA, given the difficulty of sono-guided tumor targeting under a poor sonographic visual field. Post-RFA failures are also frequent in the S1 region, especially the porta hepatis because of the high risk of complication or multivascular tumor supply. For the same reasons, fiducial insertion would be difficult in these tumors, and Cyberknife SBRT is not a good option. In our study, C group tumors were located in S2, S3, S4, or S7/8 (not liver dome). In V and T groups, 13 tumors (V group: 6/13, T group: 7/22) were located in S8, and 6 (V group: 3/13, T group: 3/22) were in S1. Cyberknife SBRT could not easily be performed as initially planned even in 4 selected C group tumors; although we attempted to insert at least 3 functional fiducials, successful fiducial geometry was achieved in only 2 patients. As an experienced interventional radiologist performed fiducial insertion, Cyberknife SBRT should be considered only in highly selected tumors available for exact fiducial insertion after a multidisciplinary approach. This limitation did not exist for VMAT or HT SBRT. Furthermore, radio-opaque lipiodol can be used as an internal fiducial tumor marker advantageously during VMAT SBRT.

Although SBRT using 3D-CRT incorporates multiple beams with coplanar and noncoplanar arrangements, inverse optimized IMRT plans were found to be dosimetrically superior to 3D-CRT at the expense of increased beam utilization and treatment time.[30] Treatment with VMAT, an IMRT delivery modality, can be completed in <2 minutes with a gantry continuously rotating around patients and variable instantaneous dose rate, MLC leaf positions, and gantry rotational speed for dose distribution optimization; this shorter overall treatment time improves patient compliance and feasibility of breathing-holding maneuvers (e.g., ABC).[31-33] High-resolution kVCT could also correct possible interfractional VMAT errors. Several reports involving diverse diseases have demonstrated the superiority of VMAT SBRT after dosimetric intermodality comparisons. Qui et al.[22] demonstrated some advantages of VMAT-based SBRT over conventional IMRT-based SBRT for liver tumors, including substantially reduced delivery time (22.2%) and concomitantly reduced total MU required for delivery (29.2%). Kannarunimit et al.[21] compared 3 SBRT techniques (robotic radiosurgery, VMAT, and HT) and suggested guidelines for central lung lesion treatment. All techniques provided similar coverage and conformity, with subtle differences according to the PTV-OAR overlap degree or PTV size. However, to our knowledge, no study has compared VMAT with modern techniques, including Cyberknife or HT, for primary HCC.

Our study has some limitation, such as the small sample size for each modality and the imbalanced patient numbers among modalities related to the timing of device introduction in our institution. Second, although our experiences with VMAT and HT were sufficient, our experience with Cyberknife remains

incomplete. Third, dosimetric comparison might have been limited by the failure to compare different plans for the same patients. However, liver tumors that satisfy criteria for SBRT are nearly identical in shape, size, or target location. Thus, our dosimetric comparisons were reasonable, as confirmed by our additional dosimetric analysis of 4 plans for a single patient (Fig. 1). Our data were obtained at a single institution with the same experienced clinician and dosimetrist.

In conclusion, all 3 modalities yielded competent dosimetric planning. For salvage SBRT after TACE failure (the majority of SBRT indications), VMAT can suitably use residual lipiodol as an internal fiducial and yielded the best patient compliance with the short treatment time. HT SBRT can be considered for multiple or irregular targets. Cyberknife SBRT can be recommended for highly selected patients with good performance and availability of sono-guided fiducial insertion. Our results facilitate optimal modality selection for liver SBRT depending on clinical situations. We believe this is the first study to compare 3 different SBRT modalities for HCC and to suggest valuable modality selection guidelines.

SUPPLEMENTARY MATERIAL

Supplementary data including one figure can be found with this article online https://doi.org/10.17998/jlc.17.1.45.t001.

Conflicts of Interest

The authors have no conflicts to disclose.

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