Treatment of Early Non-Small Cell Lung Cancer, Stage IA, by Image-Guided Robotic Stereotactic Radioablation—CyberKnife

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Objective: To evaluate the efficacy of using image-guided robotic stereotactic radioablation as an alternative treatment modality for patients with surgically resectable, but medically inoperable, T1 N0 M0, stage IA non-small cell lung cancer.

Methods: Between January 2004 and May 2006, 19 patients, 11 women and 8 men ranging in age from 52 to 88 years, with stage IA non-small cell lung cancer were treated. Tumor volume ranged from 1.7 to 13 mL. Total doses ranged from 24 to 60 Gy delivered in 3 fractions. Eleven patients received 60 Gy. Real-time target localization was accomplished by radiographic detection of fiducial marker(s) implanted within the tumor combined with respiratory motion tracking.

Results: All patients tolerated radioablation well with fatigue as the main side effect. Fourteen patients are alive from 1 to 25 months posttreatment. Four patients died: 2 of comorbid disease and 2 of cancer progression (status post 60 and 55.5 Gy). Three patients developed grade I radiation pneumonitis. Two patients have stable disease. In 3 patients, cancer recurred in the planning treatment volume: in 2 patients after treatment with 60 Gy and in 1 patient after treatment with 55.5 Gy. One patient had local control in the target volume but developed metastasis to the ipsilateral hilum. Nine patients had a complete response and show no evidence of disease.

Conclusions: In our early experience, stereotactic radioablation using the CyberKnife system appears to be a safe, minimally invasive, and effective modality for treating early stage lung cancer in patients with medically inoperable disease. Dose escalation and/or increasing the treatment volumes, with the aid of the high conformality of this technique, may help to achieve further improvements in these promising results.

Key Words: extracranial stereotactic radiotherapy, robotic radiotherapy; CyberKnife; non-small cell lung cancer stage IA, image-guided radiotherapy

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Radiation therapy (RT) was the standard of care for medically inoperable non-small cell lung cancer (NSCLC) throughout the past three decades. A minimum dose of 60 Gy has been considered standard on the basis of the results of Radiation Therapy Oncology Group (RTOG) 73-01.[1,2] In this study, after 4 years the survival rate was comparable in all groups (4%–6%). Patients treated with 50 to 60 Gy in whom local tumor control was achieved had a 3-year survival rate of 22% versus a survival rate of 10% if they had intrathoracic failure.[3] Clinical local failures were reduced with higher doses. However, the rate of distant metastasis was 75% to 80% in all groups.[4,5] Hazuka et al[6] reported local tumor progression as the predominant site of failure. Le Chevalier et al[7] suggested that clinical local failure rates of RT ranged from 33% to 52%, and pathologic local failure rates are as high as 85% with doses of 65 Gy. The ability of RT to control local disease is a function of tumor size; it is not unexpected that a dose of 60 Gy, which was intended to treat vocal cord tumors measuring millimeters, is insufficient to control lung tumors measuring several centimeters.[8] This has led to dose intensification strategies from the basic principles advocated by Fletcher [9] who found that doses from 80 to 100 Gy are required to sterilize NSCLC. Dose escalation has been limited by adjacent normal tissue tolerance and the large fields that were commonly used. The RTOG instituted a dose escalation trial in 1983 in an effort to increase local control and survival.[10] Hyperfractionation regimens were used. The best results were seen in patients receiving 69.6 Gy with treatments twice a day for 6 weeks. Three-year survival was 20% in this group.[11]

In a trial from the Netherlands[12], intensified radiation delivery by a concomitant boost technique was used. After a mean follow-up of 14 months, 17 patients (52%) had local tumor control, and 13 patients (39%) developed local recurrence within the treated area. There have been reports of improved survival in patients treated with hyperfractioned radiation compared with standard once-daily radiation.[13]

Three-dimensional conformal radiation therapy was expected to improve the outcome of stage I NSCLC, but this effort did not succeed because of inadequate dose.[14] Blomgren et al in 1995[15] first reported on the successful application of the principles of intracranial stereotactic radio-

therapy (SRT) to extracranial sites, including the lung. Stereotactic radiation delivery offers dose escalation, hypofractionation, and shorter overall treatment times. In these studies 3 to 5 high-dose fractions of 10 to 23 Gy were delivered within 2 weeks to small treatment volumes with a low incidence of serious side effects during follow-up exceeding 3 years.[15–26] Stereotactic body radiotherapy (SBRT) has been reported to be effective with a low risk, especially in controlling T1 and smaller T2 tumors, as long as an adequate dose is used.[27] Timmerman et al[23] published their preliminary results on the use of a modified linear accelerator for medically inoperable stage I NSCLC. In the 37 patients enrolled in the study, 87% responded and a complete response was noted in 27%. Wulf et al[25] similarly found that 92% of their patients with lung cancers had local control and 60% experienced no evidence of systemic progression. McGarry et al,[28] in a phase I study, reported that the maximum tolerated dose was not reached for the T1 stratum at 60 Gy in 3 fractions. The maximum tolerated dose was 72 Gy (3 fractions of 24 Gy) in the T2 group for tumors larger than 5 cm.

Whyte et al[29] were the first to report on the use of image-guided robotic extracranial stereotactic radioablation (IGR-ESR) using the CyberKnife (Accuray, Inc., Sunnyvale, CA) in the treatment of NSCLC. The CyberKnife is a frameless radiosurgical device capable of treating tumors in any part of the body. By incorporating real-time, periodic x-ray imaging of implanted metallic markers (fiducials) within the tumor, accuracy of target localization and dose delivery is achieved.

MATERIALS AND METHODS

Patient Selection

This is a retrospective study of 19 patients with histologically proven NSCLC, using CyberKnife for the delivery of radiation with curative intent. Primary pulmonary tumors, clinically T1 N0 M0, stage IA, were irradiated with total doses of 24 to 60 Gy delivered in 3 fractions over 3 to 8 days prescribed to a planning treatment volume (PTV) enclosing 100% of the gross tumor volume (GTV) plus a 3- to 5-mm margin beyond the GTV to cover microscopic infiltration and motion uncertainties. The prescribed dose was typically to the 60% to 80% isodose line and delivered a heterogeneous higher dose to the center of the tumor. We preferred to use 20 Gy $\times$ 3 fractions whenever possible. However, the total dose depended on tumor size, location, and proximity to vital structures such as the heart, great vessels, major bronchi, spinal cord, esophagus, brachial plexus, and diaphragm. Dose was also determined by etiology, the presence of comorbid disease, and the radiation oncologist's recommendations. See Table 1 for patient and tumor characteristics, dose parameters, and outcomes.

Pretreatment evaluation consisted of a computed tomography (CT) scan of the chest, abdomen, and pelvis; integrated fluorodeoxyglucose (FDG) positron emission tomography (PET) combined in a PET-CT scan with standard uptake value (SUV) reported; and pulmonary function tests, a complete blood count and blood chemistry analysis, and levels of tumor markers such as carcinoembryonic antigen, if applicable. Cancers in eligible patients were clinically T1 N0 M0, stage IA.

All patients selected for this study were determined to have a technically resectable NSCLC but were medically inoperable or refused surgery. They represent a diverse population with varying prognosis. Patients were deemed ineligible for surgery if they lacked adequate respiratory reserve or had cardiac dysfunction or chronic heart disease, pulmonary hypertension, diabetes mellitus with severe end-organ damage, vascular disease, general frailty, or severe cerebral disease. Informed consent was obtained before proceeding with treatment. Because radiation treatment of lesions in the central and hilar regions of the lung may result in atelectasis of large portions of the lung distal to the lesion, lesions within 2 cm of the proximal bronchial tree adjacent to the central chest were not included in this series. Likewise, patients with evidence of mediastinal disease (mediastinal lymph nodes >1 cm and abnormal hilar or mediastinal FDG uptake observed on a PET scan) were not included in the series. Patients who had pleural or pericardial effusions, whether malignant or not, or pneumothorax were excluded. Patients had to be able to lay down on the CT couch and CyberKnife table in a reproducible manner.

We did not exclude patients receiving other forms of antineoplastic therapy such as chemotherapy, biologic therapy, and vaccine therapy. On the contrary, IGR-ESR was targeted to treat the local disease while the patient was evaluated by an oncologist to determine whether systemic therapy was indicated to control spread of the disease. The goal of any combined therapy was to increase survival.

Treatment Planning

Once accepted for treatment, the patients were sent for placement of a gold seed fiducial introduced transthoracically into the tumor under CT guidance using preloaded needles. One patient was referred for bronchoscopic placement of fiducials using an approach recently reported.[30] It has been our experience that once the fiducial is scarred into position in the tumor, displacement relative to the tumor is unlikely. This has not held true when fiducials were placed in normal lung tissue. Although 3 noncollinear markers have typically been used to allow six-dimensional (3 translations and 3 rotations) tumor localization, we adopted an alternative approach that follows the following logic: a lung tumor may deform in shape and thus render the rotation information derived from the implanted fiducial array unreliable. We therefore minimized the number of implanted fiducials, typically to one inside the tumor. An interval of 3 to 7 days between fiducial marker placement and the treatment planning CT scan allowed fiducial markers to stabilize and edema to subside and assured that the fiducial had not migrated.

A planning CT scan was obtained. The patient held his or her breath in full expiration while a thin-slice (1.5-mm contiguous axial slices) CT scan with contrast (125 mL Omnipaque 350) was obtained. Our approach to avoiding critical structures during treatment planning is to divide the lung into a peripheral third, a middle third, and a central (hilar) third. The peripheral third encompasses the least amount of tissue distal from the lesion that is at risk for

TABLE 1. Characteristics of Patients Treated With CyberKnife

Sex	Age	Date	Site	GTV (mL)	Dose (Gy)	Fractions	% Isodose	BED	100% Dose (Gy)	Follow-up (mo)	Death Other (mo)	Death Cancer (mo)	Alive With Disease	Status	Distant Mets
F	88	7/6/2004	LUL	11.0	60	3	70	180	85.71.	21		21		Progression	Yes
F	72	8/5/2004	LUL	1.7	60	3	75	180	80.00	20				CR-NED	
F	80	7/28/2004	LUL	13.0	60	3	65	180	92.31	9		9		Progression	Yes
F	52	10/28/2004	RML	4.4	60	3	60	180	100.00	18				Stable	CNS
F	85	11/8/2004	LUL	11.6	45	3	60	180	75.00	17				CR-NED	
M	73	1/4/2005	LLL	10.7	60	3	61	180	98.36	15				CR-NED	
M	82	1/12/2005	RML	11.8	60	3	83	180	72.28	15				CR-NED	
M	70	1/13/2005	RML	3.2	60	3	80	180	75.00	15			With disease	Partial response	
M	78	3/17/2005	LLL	10.8	60	3	60	180	100.00	6	6			CR-NED	
F	74	3/2/2005	LUL	7.9	55.5	3	80	158	69.38	13				CR-NED	
M	87	1/12/2004	RML	9.3	24	3	63	43	38.09	27	8			CR-NED	
F	79	5/17/2005	RUL	8.1	60	3	68	180	88.24	11				CR-NED	
M	69	5/23/2005	RLL	6.4	60	3	80	180	75.00	11			With disease	Partial response	
F	75	6/28/2005	LUL	5.0	55.5	3	72	158	77.08	10			9 mo recurrence in PTV	Status/post lobectomy	
F	76	8/23/2005	RUL	6.6	55.5	3	75	158	80.00	8				Recurred in PTV	Hilar
F	72	11/9/2005	RUL	9.6	45	3	65	115	69.23	5				Recurred in PTV	Bone
M	63	12/12/2005	RUL	5.9	60	3	85	180	70.58	4				CR-NED	
M	76	1/18/2006	RLL	4.5	48	3	74	158	68.57	3				CR-NED	
F	76	6/15/2005	LUL	11.0	55	3	70		77.14	11				Stable 5/25/06	

Patients are listed by sex, age, date first treated by IGR radiotherapy, location of tumor, GTV in milliliters (a tumor with a diameter of 3 cm = 14.16 mL in volume), dose in Gray, number of fractions, percent isodose line, biological equivalent (BED), 100% dose in Gy, follow-up in months from first treatment, death from comorbid disease other than cancer, death from progression of cancer, alive with disease months from first treatment, and status: CR, complete response; NED, no evidence of disease; recurred in PTV; and distant or regional metastasis (Mets) and location.

LUL, left upper lung; LLL, left lower lung; RUL, right upper lung; RML, right middle lung; RLL, right lower lung; CNS, central nervous system.

atelectasis (parallel system) and so can be treated more aggressively. Treatment of the central or hilar third carries a high risk of damage to major vessels and bronchi and can result in bronchial stenosis, with the ultimate loss of a pulmonary segment or lobe and possibly the entire lung. Other serious complications of central irradiation include fatal hemorrhage. Therefore, in an attempt to limit postradiation hemorrhage or bronchial stenosis, after publication of the RTOG 0236 protocol recommended limits for critical structure tolerance, we followed these recommendations.

Because a single fiducial would not provide global orientation, which is important for accurate dose delivery, stationary bony structures are used for the global setup. A recently introduced skeletal tracking technique called Xsight[31,32] (Accuray, Inc.) is ideal for the purpose of global patient setup. It is noted that even with global patient alignment, a certain degree of local tumor rotation is still inevitable. This can be easily addressed by the added dose margin. Because the linear displacement caused by rotation is mostly tangential, a larger margin was applied to tumors with elongated shape. To ensure an acceptably high dose gradient, 80 to 150 noncoplanar beams (or more) were often required (Fig. 1).

After global setup, the treatment is then carried out while the tumor fiducial is tracked continuously using Synchrony (Accuray, Inc.) as the patient breathes. Synchrony works by tracking the motion of red light-emitting diodes attached to the patient's chest with an array of cameras that sample the location of the diodes 32 times per second. The location of the light-emitting diodes is correlated with the location of the lesion within the lung as determined by a series of orthogonal x-ray images taken at various times during the respiratory cycle. The resulting model is used to move the linac in real time to track the moving lesion while the treatment beam is on. Radiographs taken at regular intervals during treatment allow the model to be validated and updated with small changes in breathing patterns.

Treatment plans were checked by each member of the team, and treatment delivery was scheduled. On the day of treatment, patients received 4.0 mg of dexamethasone 20 minutes before treatment. A typical treatment lasted from 60 to 90 minutes.

Follow-up recommendations included a chest CT scan with contrast and routine physical examination by both the thoracic surgeon and radiation oncologist 1 month posttreatment. In this series, a PET/CT scan was obtained every 3 months after treatment. Local recurrence was diagnosed on the basis of imaging, enlarging lesions not explained by radiation pneumonitis or fibrotic changes, and/or increasing

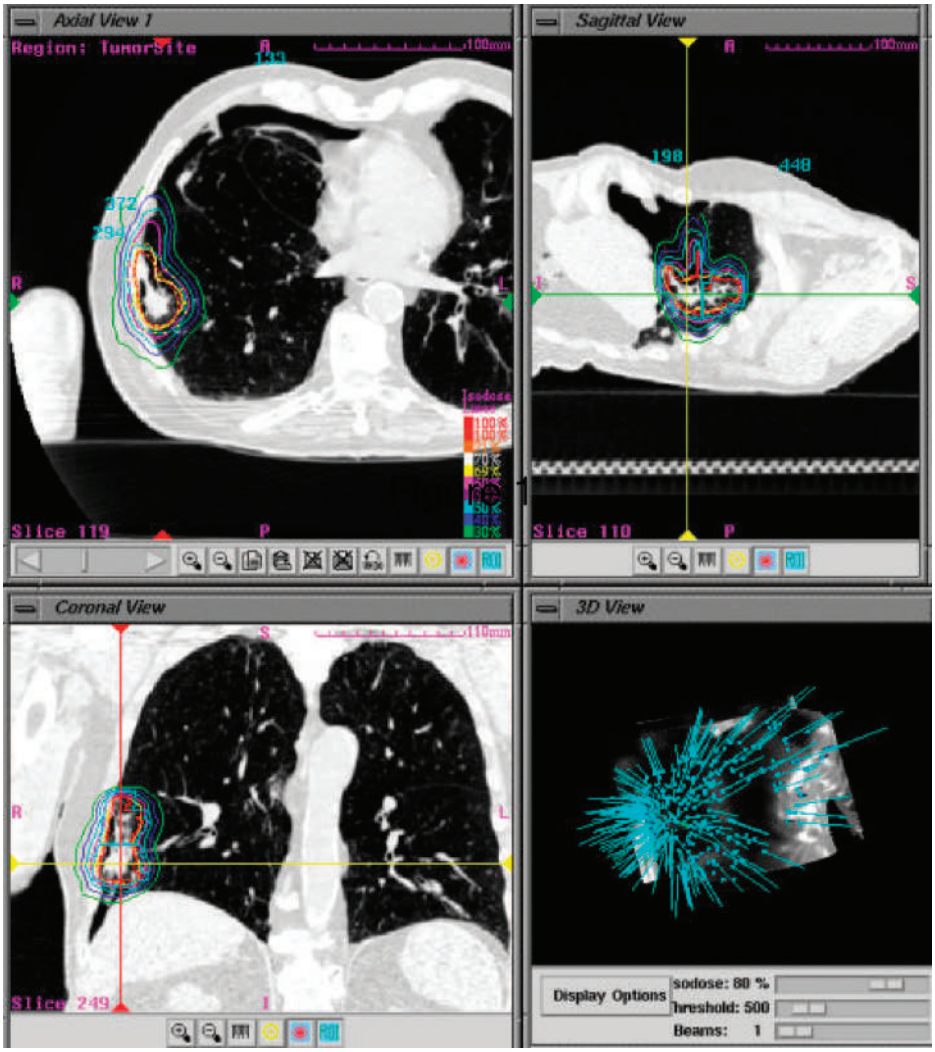

FIGURE 1. Planning for CyberKnife SBRT of stage 1A NSCLC, 20 Gy × 3 fractions to 65% isodose; tumor volume: 13 mL; nonzero beam: 60, V (15 Gy) = 4.6%.

FDG uptake in PET scan. If possible a fine-needle aspiration was obtained to rule out recurrence.

RESULTS

Between March 2004 and May 2006 we treated a total of 19 patients, 8 men and 11 women ranging in age from 52 to 87 years. All patients presented with stage 1A NSCLC and were treated by IGR radiotherapy. Tumor volume ranged from 1.7 to 13 mL. Location was as follows: right upper lobe, 4; right middle lobe, 4; right lower lobe, 2; left upper lobe, 7; and left lower lobe, 2. Dosage ranged from 24 to 60 Gy in 3 fractions (Table 1). Eleven patients received 20 Gy × 3 fractions, to the 60% to 80% isodose line. Biologically effective doses ranged from 43 to 180 Gy in 2 Gy fraction assuming alpha/beta 10.

All patients, even the frail patients, tolerated IGR-ESR well with fatigue as the main side effect. Nine patients had a complete response (lesion no longer present on imaging). All patients showed some local response by either/or a reduction of tumor size and/or reduction of FDG on follow-up PET/CT scans at their first examination at 3 months posttreatment (Fig. 2).

Fourteen patients are alive from 1 to 27 months posttreatment. Four patients died: 2 of comorbid disease and 2 of cancer progression (status post 60 and 55.5 Gy). Three patients developed focal grade I radiation pneumonitis corresponding to the area of PTV. In each of these patients, the first PET/CT scan at 3 months appeared to demonstrate a complete response. However, at 6 to 9 months, they were FDG avid and had a ground-glass appearance corresponding to the PTV, and the radiologist diagnosed recurrent tumors. Two were proven to be recurrent, and one was inflammatory, consistent with radiation pneumonitis. Of these 3 patients in whom the cancer recurred in the PTV, 2 patients treated with 60 Gy had recurrences at 9 and 12 months, both of progressive disease; the third patient had been treated with 55.5 Gy. One recurrence in the PTV demonstrated growth of the tumor from 1.5 to 3 cm, accompanied by increasing SUV at 9 months posttreatment, and this patient underwent a salvage lobectomy. It is of paramount importance to identify those

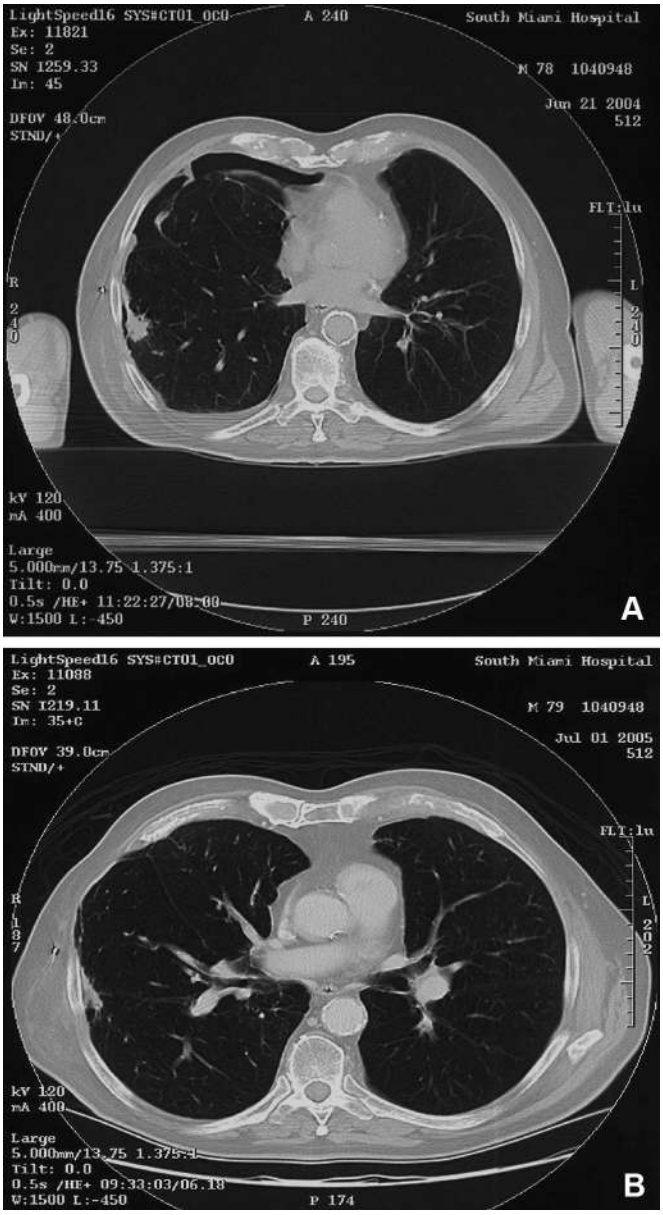

FIGURE 2. (a) Chest CT scans 1 month before CyberKnife treatment and (b) 1 year after treatment.

patients who are most likely to benefit from local control so that they may be treated with curative intent. Nine patients continue to show a complete response, with no evidence of disease.

One patient had a reduction in SUV from 3 to 1.9 and remains stable. One developed a wedge scar in the area of the PTV. One patient treated in August 2005 had an initial response (tumor size was reduced from 2.4 to 1.7 cm and the SUV dropped from 35 to minimal), but at 3 months developed FDG-avid hilar nodes. She received chemotherapy and is alive as of May 2006.

DISCUSSION

Local control is a main step to curing NSCLC because most patients die of local or regional progression of their disease. High-dose, precisely targeted SBRT may be an approach to obtaining local control of NSCLC in patients with inoperable disease or in those who refuse surgery, but its applicability has been limited by difficulties targeting tumors that move with respiration in soft tissue.[33] Several recently published series[21,22,24–26] using SBRT have confirmed that dose escalation can result in enhanced local tumor control with minimal untoward effects if exposure to neighboring normal tissue and other critical structures is limited. Timmerman et al[23] published the results of a phase I dose-escalation protocol in patients treated with SBRT using a stereotactic body frame. Patients received escalating doses ranging from 8 Gy $\times$3 fractions to 23 Gy $\times$3 fractions. Excellent tumor control was obtained at the highest doses without undue effects; dose escalation was ended (at 23 Gy $\times$3 fractions) before a maximum tolerated dose was reached. Regarding the same series, R. C. McGarry (personal communication, 2006) remarked that some late nonsymptomatic signs suggested that they should not go higher in dose. Local recurrence was observed in 6 patients treated with relatively low doses (median 12 Gy $\times$ 3 fractions, up to 18 Gy $\times$ 3 fractions).

Wulf et al[34] reported a series of patients treated with SBRT since 1997 using a range of dose/fractionation regimens, and combined their dose escalation series with previous studies to conclude that a biologically equivalent dose of $\geq$100 Gy, either fractionated or delivered in a single session, produced more robust local control and superior overall and recurrence-free survival than regimens resulting in a biologically equivalent dose of $<$100 Gy.[25,27] At the median follow-up of 24 months, there were 8 failures, all of which were seen in patients who had received a dose $\geq$16 Gy $\times$ 3 fractions. A recently initiated RTOG protocol (0923) takes into account the data on the efficacy of high-dose, hypofractionated treatments, adopting the 20 Gy $\times$ 3 fractions = 60 Gy approach for the treatment of medically inoperable stage I–II NSCLC in patients with lesions with a GTV of no more than 5 cm in the largest dimension and lying outside of the zone of the proximal bronchial tree.

Although these results are encouraging, dose conformity in linac-based SBRT requires extensive immobilization and breathing restriction both during CT simulation and SBRT treatment sessions, and treatment plans include considerable margins to compensate for tumor localization uncertainty. From a purely technical point of view, a new technique such as the CyberKnife can best minimize tumor localization uncertainties, thereby offering better dose escalation.[29]

Tumor cell kill rates vary between 16 and 27 logs to the base of 10 for treatment schedules from 12 Gy $\times$ 4 fractions to 23 Gy $\times$ 3 fractions. The rationale for using the higher end of this scale is based on 2 issues. One is the possible presence of hypoxic or radioresistant cells. The second is the possible presence of microscopic cells beyond the high-dose PTV region.[35,36] Our results of treatment of early NSCLC with small tumor volumes supports the findings of the phase I

study by McGarry et al[28] and the phase II study by Timmerman et al (R.C. McGarry and R. Timmerman, personal communication, 2006). Both found improved local tumor control with higher doses. The maximum tolerated dose for stage IA NSCLC treated by IGR radiotherapy has not been reported. If IGR-ESR radiotherapy is to be used to treat stage IA NSCLC with curative intent to equal surgical resection, higher doses may prove necessary for total tumor ablation. Historically, dose escalation for treatment of NSCLC with 3-D conformal radiation therapy has been proven significant in improving survival.[12,37,38] The dose escalation studies for NSCLC with SBRT should continue until an optimal dose is concluded.

The advantage of IGR-ERS radiotherapy using a dose created by 50 or more noncoplanar beams spread across a wide solid angle is apparent. Although a patient may tolerate a high peripheral dose with far fewer beams, the dose gradient would be far less steep, thereby defeating the reason for using SBRT. This improvement in dose gradient is an important index of comparison for various SBRT techniques. The high-dose gradient beyond the PTV significantly reduces the dose to adjacent normal lung issue,[39] which is essential to avoid grade 3 pneumonitis and to minimize grade 2 pneumonitis.[40–43]

Both SBRT and IGR-ERS radiotherapy result in fewer patients developing radiation pneumonitis posttherapy than RT. In SBRT and IGR-ERS radiotherapy radiation pneumonitis has not been observed to be the limiting factor as the V_{20} for both SBRT and IGR-ERS radiotherapy is significantly lower than that for conventionally fractionated radiotherapy.[44] We chose to measure the V_{15} for 10 primary lesions, each treated to a total dose of 60 Gy; V_{15} varied from 0.8 to a high of 4.6 (Table 2). In our small sample 2 of 3 cases of radiation pneumonitis occurred in the lower lobes and one in an upper lobe. This is similar to the findings of Seppenwoolde and Lebesque,[42] who found that radiation pneumonitis was more frequent in the posterior lower lobes. This toxicity resulted in mild fatigue and required no intervention, even for the elderly frail patient.

Because the dose gradients being used are high, dosimetric miss of microscopic disease beyond the PTV seems more likely to result in failure on the basis of pathologic evidence that show microscopic extension of 1 cm rather than 5 mm. Pathologic studies from Giraud et al[36] support the belief that a PTV of 5 mm beyond the GTV is inadequate. Cheung et al[44] used a 2-cm margin beyond the GTV and showed improved local control. It should be noted that the method used to compensate for respiratory motion in those studies was less precise than the Accuray system. Thus, similar results might be achievable with a somewhat smaller margin.

Use of concurrent chemotherapy has been suggested to cover any malignant cells beyond the treatment area. However, it is unlikely that chemotherapy will result in more than an additional 8% to 10% extra cell kill in addition to the approximately 10 to 11 logs that radiation alone usually delivers. This translates into about 1 log of cell kill, which would probably not significantly improve results compared with the 10- to 11-log cell kill that could be accomplished by inclusion in the radiotherapeutic treatment region. Therefore, it would seem that increasing the PTV would be a better approach.

It should be pointed out that the additional improvement on the precision of dose computation is needed. The current Accuracy's treatment planning system uses simple effective-depth method to correct for tissue heterogeneity. The dose computation accuracy had been evaluated by Monte Carlo simulation.[45] It is well recognized that dose correction due to the drastic difference of lung tissue could result in noticeable difference in the dose computation of the lung tumors, especial for lung tumors with small sizes.

The prognosis of these patients depends on the risk of systemic spread. Spread is inevitable unless local control is obtained. Patients with locally recurrent tumors have incurable disease, and local failure represents a major cause of mortality in patients with NSCLC.[46] This demonstrates the importance of patient selection to identify those who are most likely to benefit from local control and of our selection of PTV[41,43] and dose for treatment of these patients with curative intent.

TABLE 2. V_{15} Values for 10 Primary Lesions

Patient	PTV Volume (mL)	V_{15} (% of total lung volume)
7/6/04	11.0	2.8
8/5/04	1.7	1.1
7/28/04	13.0	4.6
10/28/04	4.4	1.6
11/8/04	12.0	2.9
1/4/05	11.0	1.3
1/12/05	12.0	2.8
1/13/05	3.0	0.8
10/8/04	4.7	1.4
1/12/04	9.3	0.3
Mean	8.5	2.2

V_{15} is the lung volume (outside of PTV) that received 15 Gy or higher. It is related to PTV but is not calculated from PTV. Rather, it is calculated from the DVH of the lung volume (excluding PTV) outlined for each patient. If we are to believe the traditional notion of V_{20}, then 15 Gy (5 Gy × 3 fractions) is a close equivalence for 20 Gy with 2 Gy per fraction. Our V_{15} is then good. We simply assume any lung volume that receives <15 Gy in total would have little or no chance of grade 3 postradiation pneumonitis.

CONCLUSION

The CyberKnife is projected to optimize the technique of body radioablation in NSCLC, providing delivery of radiation with superior precision and flexibility. Our early experience demonstrates the promising efficacy of using this technology as a alternative treatment modality for patients with early-stage NSCLC. The evaluation of our experience and other published studies suggests that this technology may further enhance local control by the following: shortening the treatment time to avoid tumor cell repopulation, improving the accuracy of target volume definition by using multimodality image registration, improving the accuracy of dose computation, further reducing the targeting errors, and delivering higher tumor dose if proven necessary.

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