# The Dosimetric Effects of Photon Energy on the Quality of Volumetric Modulated Arc Therapy for Lung Stereotactic Body Radiation Therapy

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**Abstract:** *Purpose:* There is little published data on the optimal energy to use to minimize doses to Organs at Risk (OARs), while maintaining adequate Planning Target Volume (PTV) coverage in lung volumetric-modulated arc therapy (VMAT) stereotactic body radiation therapy (SBRT).

*Methods:* 35 lung lesions in 33 patients were treated at our institution by VMAT SBRT. Dosimetric plans using 6-Megavoltage (6-MV) and 10-Megavoltage (10-MV) energies were generated for each lesion. The median dose was 5000cGy delivered over 3-5 daily fractions. Various dosimetric parameters were recorded for both the 6-MV and 10-MV plans and the patients were stratified according to the tumor to chest wall distance (TCW), the tumor location (central versus peripheral), patient anterior-posterior (AP) diameter, and the diameter of an equivalent sphere encompassing the patient's body over the distance of the PTV (ESD).

*Results:* There was a statistically significant difference between 6-MV and 10-MV with respect to the sum lung dose, which favored 6-MV plans ($p=0.04$). For those stratified by TCW, there was a difference in conformity index (CI) for patients with peripheral tumors ($p=0.04$). For the group stratified by AP separation, there was a difference in mean sum lung dose favoring 6-MV ($p=0.01$). In the group stratified by ESD, there were statistically significant (SS) differences in the volume of lung receiving at least 13Gy (V13), mean sum lung dose, and CI, all favoring 6-MV plans ($p=0.05$, $p<0.01$, and $p<0.01$). For the cohort overall, and within each subgroup, there was a SS difference in the total number of monitor units (MUs), which consistently favored planning with 10-MV.

*Conclusion:* With the exception of thinner patients, for which 6-MV plans was superior with respect to OARs and conformity index, 10-MV should be considered for use in lung VMAT SBRT. 10-MV plans consistently resulted in fewer total MUs. Fewer MUs results in shorter treatment times, with the potential for improved target accuracy due to less intrafractional tumor motion.

**Keywords:** Stereotactic body radiation therapy, Lung cancer, Volumetric-modulated arc therapy, Physics, intensity modulated radiation therapy.

## INTRODUCTION

Lung cancer is the leading cause of cancer-related mortality in the United States and worldwide [1]. About 80% of all lung cancers are non-small cell lung cancer (NSCLC). Of these, approximately 15-20% are diagnosed at an early stage [2]. With the increasing use of CT for lung cancer screening, there is an expected increase in the proportion of patients diagnosed with Stage I disease [3]. For operable candidates, surgery is the treatment of choice and yields 5-year overall survival rates of 60-70%. Primary radiation therapy utilizing stereotactic body radiation therapy (SBRT) has emerged as the curative intent approach for patients who are unable to undergo or who refuse surgery [4].

SBRT delivers a very high dose of radiation per fraction to a limited-sized target over a short period of time. This technique has proven to be more effective than standard fractionation techniques for patients with early stage lung cancer with control rates of 90% and greater [5-12]. SBRT, however, requires a high degree of accuracy in treatment planning and delivery in order to achieve this degree of efficacy. SBRT treatments on a standard Linac can be delivered either utilizing an intensity-modulated radiotherapy (IMRT) technique or via volumetric-modulated arc therapy (VMAT). IMRT involves 5 or more fixed fields that can be varied only with respect to the position of the multileaf collimators while the beam is on. VMAT, on the other hand, allows for full gantry rotation around a 360 degree arc, with variation of the dose rate, speed of gantry angle rotation, and position of the multileaf collimators. VMAT offers several advantages over IMRT which include decreased number of monitor units, shorter treatment time, decreased skin dose, and a lower mean lung dose [13-15].

While a promising treatment modality with proven efficacy in managing early stage lung cancer, delivery

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of VMAT SBRT to lung lesions presents a number of dosimetric challenges due to the loss of lateral scatter equilibrium as the radiation beam crosses the tissue-air interface. Selecting the appropriate photon energy to use in treatment planning is one of these challenges. Studies have shown that using higher energy photon beams results in the under-dosing of tumors secondary to the loss of build-up as the beam enters the target from the low-density lung [16]. Loss of lateral scatter is even more pronounced with small field dosimetry, which is required for SBRT, further complicating the choice of beam energy. As a result, low energy beams in the range of 4-10MV have been recommended by national and international agencies [17] and are being used in prospectively designed trials [5, 6, 8, 10-12]. The disadvantage of using such low energies is inferior coverage of the entire target resulting from the poorer penetrating ability of the lower energy beam.

The present study undertook to investigate whether there is an optimal energy within the lower range of energies used in radiation therapy that should be selected when using VMAT SBRT in the treatment of lung tumors. In particular, we compared dosimetric data for 6-MV versus 10-MV energies. We further sought to uncover subsets of patients in which selection of a particular energy would result in more optimal treatment plans.

## MATERIALS AND METHODS

33 consecutive patients with a total of 35 lung lesions treated by VMAT SBRT at our institution were included in this study with IRB approval. All but one patient were treated for primary lung cancer. The remaining patient was treated for oligometastatic sarcoma after refusing other therapies.

Each patient underwent computed tomographic (CT) simulation in the supine position using a BlueBAG™ BodyFIX Vacuum Cushion by Elekta. 4D-CT scans were obtained for each patient to assess tumor motion throughout the breathing cycle. Each tumor was contoured on the planning CT which was then fused with the 4D-CT to create an internal target volume (ITV) in order to account for tumor motion during the respiratory cycle. A 3mm margin was then added to the ITV to create the planning target volume (PTV). Treatments were delivered in 3-5 daily fractions, with a median total dose of 5000cGy. All patients were treated with either 6MV or 10MV photon beams on a Varian Clinac iX Linear Accelerator. Daily cone-beam computed tomographic (CBCT) scans were taken to ensure patient set-up accuracy.

Dosimetric plans using both 6-MV and 10-MV energies were generated for each lesion and all plans were identically optimized. Dose was calculated using Varian Eclipse AAA (Anisotropic Analytical Algorithm) convolution-superposition photon-beam dose computation algorithm (version 8.6), with heterogeneity corrections applied. All plans utilized the VMAT technique and were coplanar. The organ at risk (OAR) constraints used for optimization were obtained from Radiation Therapy Oncology Group (RTOG) protocol 0236. Dosimetric parameters including isocenter, number of arcs, and degree of arc rotation were identical for the 6-MV and 10-MV plans for each patient. Each plan was normalized such that 95% of the PTV received 100% of the prescribed dose.

### Dosimetric Parameters Used for Analysis

Dose-volumetric parameters analyzed for comparison included the following: the maximum dose to the PTV (PTVmax), the maximum dose to the spinal cord (Cord Dmax), the mean dose to the sum lung, the lung V13, the conformity index (CI), the gradient measure (GM), integral dose, and the total number of monitor units (MUs).

The PTVmax was defined as the highest dose within the PTV recorded as a percentage of the total dose. The closer the PTVmax to 100%, the more homogeneous the dose delivered to the target volume. The Cord Dmax was recorded as the highest dose in cGy anywhere within the cord. The sum lung included the volume of both lungs minus the Gross Tumor Volume (GTV). The mean dose to the sum lung was obtained from Eclipse as the average dose in cGy delivered to this structure. The lung V13 was defined as the volume of the sum lung receiving 13Gy or more. The lower the values of the Cord Dmax, the mean lung dose, and the lung V13, the more favorable the plan.

The CI was calculated as the volume enclosed by the prescription isodose surface divided by the target volume. The closer the value to unity, the more optimal the plan, with a value less than one indicating underdosage of the PTV and a value greater than one indicating potential toxicity to surrounding healthy tissue. The GM was defined as the difference between the equivalent sphere radius of the prescription and the half-prescription isodoses with a smaller value indicating a sharper dose fall-off and, therefore, a more optimal plan [18]. Figure **1** shows the isodose curves including the 50% isodose lines for the 6-MV and 10-MV plans generated for a patient with a peripheral tumor. The normal tissue integral dose was calculated as the product of the mean dose to the volume of the

body over the length of the PTV (excluding the PTV), and the volume of that region (again excluding the volume of the PTV), with units of Liter-Gray (L-Gy). The total number of MUs were also recorded for each plan with a smaller value indicating a more optimal plan given the shorter beam on time.

### Sub-Group Analysis

The above parameters were compared for the 6-MV and 10-MV plans using 2-tailed sign tests for both the entire cohort and within certain subsets of patients. These subsets included patients stratified into two groups depending on tumor location, distance from the chest wall, anterior-posterior (AP) separation and patient diameter as shown in Table **1**.

Patients stratified by tumor location were divided into those with central tumors and peripheral tumors. Central tumors were defined as those lying within 2 cm in all directions around the proximal bronchial tree as delineated in RTOG 0236[5], while peripheral tumors were those not meeting this definition. Patients stratified by distance from the chest wall were divided into those with PTVs including a portion of or abutting the chest wall (0cm), and those that neither encompassed nor abutted the chest wall (>0cm).

The AP separation was measured across the central axis of the patient at the isocenter. The median AP diameter for our cohort of patients was 22cm. Patients stratified according to this parameter were therefore divided into those with a separation less than or equal to 22 cm (≤22cm) and those with a separation greater than 22 cm (>22cm). Finally, patient diameter was defined as the diameter of an equivalent sphere encompassing the patient's body over the distance of the PTV. This parameter was chosen to serve as another means of measuring the volume of tissue being traversed by the radiation beams in reaching the target volume. It was included in addition to AP separation because in VMAT plans, as opposed to IMRT plans, radiation beams enter the patient from anywhere along a 360 degree arc. The volume of tissue traversed anywhere along this 360 degree arc is, therefore, of relevance. The median patient diameter for our group of patients was 18cm. Patients stratified according to the patient diameter were thus divided into those with an equivalent diameter less than or equal to 18cm (≤18cm) or those with an equivalent diameter greater than 18cm (>18cm).

### Statistical Analysis

Statistical analysis was performed using Microsoft Excel 2007 and STATA Statistical Software, version 13.1. Two-sided T-tests were used to determine

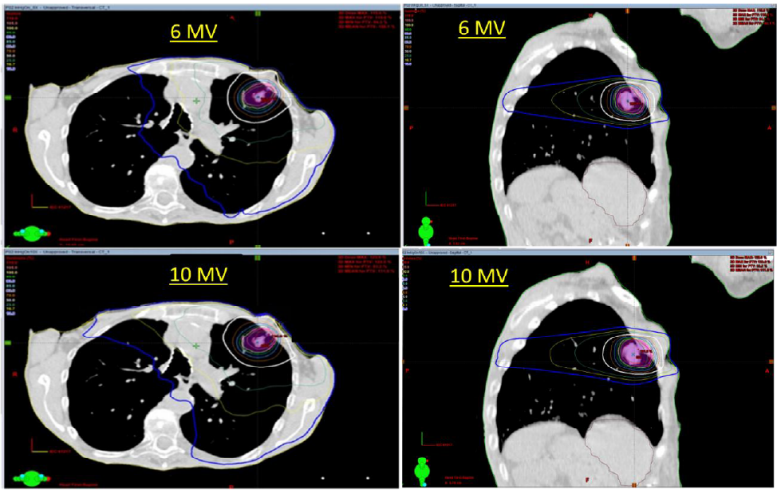


**Figure 1:** Axial and Saggital images of isodose curves for a patient with a peripheral lesion. The 95% ISL is shown in pink and the 50% is shown in white. Abbreviations: ISL, isodose level.

**Table 1: Number of Patients Within Each Subgroup**

| | Tumor Location | | Distance from Chest Wall | | AP Separation | | Peripheral Volume | |
|---|---|---|---|---|---|---|---|---|
| | Central | Peripheral | 0 cm | > 0 cm | ≤ 22cm | > 22cm | ≤ 18cm | >18cm |
| Number of Patients | 9 | 26 | 10 | 25 | 18 | 17 | 18 | 17 |

**Abbreviations:** AP, anterior-posterior.

**Table 2a: Mean, Median, and Range for each Dosimetric Parameter for 6-MV Plans is shown in this Table**

| 6-MV | PTVmax (%) | Cord Dmax (cGy) | Lung V13 (cc) | Mean Sum Lung Dose (cGy) | Conformity Index | Gradient Measure | Integral Dose | Total MUs |
|---|---|---|---|---|---|---|---|---|
| Mean | 118 | 23 | 231 | 221 | 1.18 | 1.41 | 3.90 | 2892 |
| Median | 116 | 20 | 216 | 194 | 1.16 | 1.44 | 3.73 | 2425 |
| Range | 106-134 | 8-61 | 0-487 | 26-429 | 0.76-1.50 | 1.05-1.95 | 2.98-5.74 | 1596-6233 |

**Abbreviations:** MV, mega-voltage; PTVmax, maximum dose to the planning target volume; Cord Dmax, maximum cord dose; Lung V13, volume of lung receiving at least 13Gy; MU, monitor units.

**Table 2b: Mean, Median, and Range for each Dosimetric Parameter for 10-MV Plans is shown in this Table**

| 10-MV | PTVmax (%) | Cord Dmax (cGy) | Lung V13 (cc) | Mean Sum Lung Dose (cGy) | Conformity Index | Gradient Measure | Integral Dose (L-Gy) | Total MUs |
|---|---|---|---|---|---|---|---|---|
| Mean | 118 | 25 | 235 | 228 | 1.24 | 1.49 | 4.06 | 2732 |
| Median | 116 | 22 | 214 | 202 | 1.20 | 1.47 | 3.88 | 2213 |
| Range | 102-195 | 7-66 | 0-479 | 24-471 | 0.76-1.50 | 1.09-2.27 | 2.96-5.79 | 1353-8626 |

**Abbreviations:** MV, mega-voltage; PTVmax, maximum dose to the planning target volume; Cord Dmax, maximum cord dose; Lung V13, volume of lung receiving at least 13Gy; MU, monitor units.

statistical significance. A p-value less than or equal to 0.05 was considered statistically significant (SS).

## RESULTS

There were no SS differences between the 6 MV and the 10 MV plans among any of the parameters tested, except for the mean lung dose and the total MUs. The difference in the mean lung dose favored the 6-MV plans (194 cGy vs 201 cGy, p = 0.04), while the total number of MUs favored the 10-MV plans (2425 MU vs 2213 MU, p<0.01). The mean, median, and range for the various parameters are shown in Table **2A** and **2B**. The data for the overall cohort is shown in Table **3**.

**Table 3: Dose-Volumetric Comparison of the Mean Value of each Parameter for the 6-MV and 10-MV Plans for the Cohort Overall. A p-value of 0.05 or Less was Considered Significant and is Indicated with an Asterisk**

| | Cohort Overall | | |
|---|---|---|---|
| **Energy (MV)** | **6-MV** | **10-MV** | **p-value** |
| PTVmax (cGy) | 116 | 116 | 0.31 |
| Cord Dmax (cGy) | 20 | 22 | 0.61 |
| Lung V13 (cc) | 216 | 214 | 0.30 |
| Mean Sum Lung Dose (cGy) | 194 | 202 | 0.04* |
| Conformity Index | 1.16 | 1.2 | 0.06 |
| Gradient Measure | 1.44 | 1.47 | 0.11 |
| Integral Dose (L-Gy) | 3.73 | 3.88 | 0.99 |
| Total MUs | 2425 | 2213 | <0.01* |

**Abbreviations:** MV, mega-voltage; PTVmax, maximum dose to the planning target volume; Cord Dmax, maximum cord dose; Lung V13, volume of lung receiving at least 13Gy; MU, monitor units.

Table **4** shows our results for lesions stratified according to location within the lung. Among patients with centrally located tumors, the only parameter that was SS was the total number of MUs, which favored the 10 MV plans (3180 MU vs 2166 MU, p=0.04). Among those with peripherally located tumors, the CI and the total number of MUs were SS different between the 6-MV and 10-MV plans. The CI favored the 6-MV plans (1.19 vs 1.23, p=0.04) , while the total number of MUs favored the 10-MV plans (2383 vs 2245, p<0.01).

Table **5** shows patients stratified according to the distance from the chest wall. The total number of MUs was the only variable showing a SS difference among those with PTVs with a distance of 0 cm from the chest wall and those with a PTV farther than 0 cm from the chest wall, again favoring the 10-MV plans (p<0.01).

Stratification according to AP diameter is shown in Table **6**. There was a SS difference in mean lung dose and total number of MUs for patients with a diameter less than or equal to 22 cm. Within this subset of patients, the mean lung dose favored the 6-MV plans (178 vs 189, p=0.01), while the total number of MUs favored the 10-MV plans (2425 vs 2276, p=0.02). For patients with a total separation greater than 22 cm, the

**Table 4: Dose-Volumetric Comparison of the Mean Value of each Parameter for the 6-MV and 10-MV Plans in Patients Stratified by Location within the Lung, Central or Peripheral. A p-value of 0.05 or Less was Considered Significant and is Indicated with an Asterisk**

| | Site | | | | | |
|---|---|---|---|---|---|---|
| **Subgroup** | **Central** | | | **Peripheral** | | |
| Energy (MV) | 6 | 10 | p-value | 6 | 10 | p-value |
| PTVmax (cGy) | 120 | 117 | 0.99 | 116 | 115 | 0.33 |
| Cord Dmax (cGy) | 27 | 23 | 0.18 | 19 | 20 | 0.99 |
| Lung V13 (cc) | 242 | 237 | 0.73 | 190 | 200 | 0.42 |
| Mean Sum Lung Dose (cGy) | 221 | 216 | 0.51 | 193 | 202 | 0.06 |
| Conformity Index | 1.09 | 1.13 | 0.99 | 1.19 | 1.23 | 0.04* |
| Gradient Measure | 1.58 | 1.68 | 0.99 | 1.43 | 1.43 | 0.11 |
| Integral Dose (L-Gy) | 4.12 | 4.32 | 0.73 | 3.73 | 3.77 | 0.85 |
| Total MUs | 3180 | 2166 | 0.04* | 2383 | 2245 | < 0.01* |

**Table 5: Dose-Volumetric Comparison of the Mean Value of each Parameter for the 6-MV and 10-MV Plans in Patients Stratified by Distance from the Chest Wall. A Value of 0cm Indicates that the Lesion was Abutting, or Including a Portion of, the Chest Wall. A p-value of 0.05 or Less was Considered Significant and is Indicated with an Asterisk**

| | Distance from Chest Wall (cm) | | | | | |
|---|---|---|---|---|---|---|
| **Subgroup** | **0** | | | **>0** | | |
| Energy (MV) | 6 | 10 | P- value | 6 | 10 | P- value |
| PTVmax (cGy) | 116 | 116 | 0.42 | 118 | 116 | 0.75 |
| Cord Dmax (cGy) | 20 | 23 | 0.84 | 20 | 19 | 0.75 |
| Lung V13 (cc) | 242 | 243 | 0.31 | 157 | 158 | 0.99 |
| Mean Sum Lung Dose (cGy) | 221 | 202 | 0.09 | 158 | 185 | 0.34 |
| Conformity Index | 1.16 | 1.2 | 0.15 | 1.15 | 1.18 | 0.34 |
| Gradient Measure | 1.44 | 1.47 | 0.21 | 1.35 | 1.43 | 0.51 |
| Integral Dose (L-Gy) | 3.72 | 3.70 | 0.42 | 4.07 | 4.48 | 0.18 |
| Total MUs | 2425 | 2276 | < 0.01* | 2455 | 2067 | 0.02* |

**Table 6: Dose-Volumetric Comparison of the Mean Value of each Parameter for the 6-MV and 10-MV Plans in Patients Stratified by AP Separation Measured in Centimeters. A p-value of 0.05 or Less was Considered Significant and is Indicated with an Asterisk**

| | AP Separation (cm) | | | | | |
|---|---|---|---|---|---|---|
| **Subgroup** | **≤22** | | | **>22** | | |
| Energy (MV) | 6 | 10 | P- value | 6 | 10 | P- value |
| PTVmax (cGy) | 119 | 116 | 0.99 | 116 | 115 | 0.26 |
| Cord Dmax (cGy) | 20 | 22 | 0.99 | 20 | 22 | 0.50 |
| Lung V13 (cc) | 169.8 | 180.1 | 0.3013 | 266.7 | 275.6 | 0.81 |
| Mean Sum Lung Dose (cGy) | 178 | 189 | 0.01* | 258 | 260 | 0.65 |
| Conformity Index | 1.24 | 1.33 | 0.12 | 1.12 | 1.13 | 0.36 |
| Gradient Measure | 1.41 | 1.39 | 0.12 | 1.44 | 1.49 | 0.63 |
| Integral Dose (L-Gy) | 3.84 | 4.06 | 0.61 | 3.72 | 3.82 | 0.82 |
| Total MUs | 2425 | 2276 | 0.01* | 2393 | 2166 | < 0.01* |

**Abbreviations:** AP, anterior-posterior.

total number of MUs was different between the 6-MV and 10-MV plans, favoring 10-MV (2393 vs 2166, p<0.01).

As shown in Table **7**, there were a number of parameters with SS differences between the 6-MV and the 10-MV plans among patients with a patient diameter less than or equal to 18 cm. The CI (1.23 vs 1.3, p<0.01), mean lung dose (178 vs 192, p<0.01), and lung V13 (157 vs 173, p=0.05) all favored the 6-MV plans. The total number of MUs, on the other hand, favored the 10-MV plans (2523 vs 2468, p<0.01). Among patients with a patient diameter greater than 18cm, the only SS difference between the 6-MV and 10-MV plans was in the total number of MUs, favoring the 10-MV plans (2354 vs 2147, p<0.01).

## DISCUSSION

To our knowledge, this is the first study that analyzes the effect of beam energy on VMAT treatment planning within the low energy range currently recommended for use in lung SBRT. Previous studies have focused on the effect of using a high versus a low beam energy, primary 6-MV versus 18-MV, for the treatment of lung tumors using a variety of different treatment techniques, including 3D-conformal treatment planning and static IMRT [19-22]. Studies such as these contributed to the recommendation that low energy photon beams, ≤ 10-MV, be used in treatment planning for lung lesions. However, little is known about the optimal energy to use within this range and whether or not there are any parameters that would guide the selection of one energy over another. Specifically, data are lacking in the choice of energy selection in VMAT treatment planning where beamlets delivering the dose to the target are able to do so over a 360-degree arc, therefore traversing a distinct volume of body tissue and air.

With the exception of the mean sum lung dose, which was slightly higher for 10-MV plans, planning with 6-MV did not prove to be superior for the cohort overall. This is in accordance with the findings of the study by Weiss *et al*, who compared planning with 6MV versus 18MV in lung IMRT and concluded that higher photon energies should not be excluded a priori in all patients [20]. The only subgroup of patients for which planning with 6-MV over 10-MV consistently showed a benefit in more than one parameter, and could thus be said to offer a more optimal plan, is among patients with a patient diameter less than or equal to 18cm. Among this group of patients, planning with the lower energy resulted in a lower mean sum lung dose, a lower lung V13, and a superior conformity index.

10-MV plans, however, consistently demonstrated superiority with respect to the total number of monitor units needed to deliver the prescribed dose to the target volume. In fact, the difference in magnitude between the total number of MUs for 6-MV versus 10-MV plans was close to ten percent for each subgroup, in favor of 10-MV. For any tumor that was not abutting or invading the chest wall, planning with 6-MV required twenty-percent more monitor units to deliver the same dose to the same target as compared to 10-MV. The difference in monitor units was especially pronounced for central lesions where the total number of MUs for the 10-MV plans was two-thirds that of the 6-MV plans.

The total number of MUs is always expected to increase with decreasing energy and this increase should be taken into consideration when selecting the optimal treatment plan. The percent depth dose, PDD, increases at higher energies. Given that the total

**Table 7: Dose-Volumetric Comparison of the Mean Value of each Parameter for the 6-MV and 10-MV Plans in Patients Stratified by Peripheral Volume Measured in Cubic Centimeter. A p-value of 0.05 or Less was Considered Significant and is Indicated with an Asterisk**

| | Patient Diameter (cm) | | | | | |
|---|---|---|---|---|---|---|
| **Subgroup** | **≤18** | | | **>18** | | |
| Energy (MV) | 6 | 10 | P- value | 6 | 10 | P- value |
| PTVmax (cGy) | 119 | 117 | 0.24 | 116 | 115 | 0.99 |
| Cord Dmax (cGy) | 18 | 20 | 0.99 | 22 | 24 | 0.33 |
| Lung V13 (cc) | 157 | 173 | 0.05* | 292 | 297 | 0.80 |
| Mean Sum Lung Dose (cGy) | 178 | 192 | <0.01* | 301 | 297 | 0.99 |
| Conformity Index | 1.23 | 1.30 | <0.01* | 1.13 | 1.11 | 0.99 |
| Gradient Measure | 1.32 | 1.32 | 0.81 | 1.48 | 1.64 | 0.06 |
| Integral Dose (L-Gy) | 3.95 | 3.94 | 0.63 | 3.68 | 3.88 | 0.63 |
| Total MUs | 2523 | 2468 | <0.01* | 2354 | 2147 | < 0.01* |

number of MUs is equal to the dose divided by the product of the PDD (in addition to a number of other correction factors), we would expect the total number of MUs to decrease as the PDD increases [23]. Therefore, lower energy photon beams result in a higher number of MUs to deliver the same dose as compared to higher energy beams.

Increasing the total number of monitor units results in a longer treatment time which, in turn, allows for greater intrafractional tumor motion. The movement of lung lesions during targeted radiation therapy has been well studied [24-28]. As suggested by Seppendwoolde *et al*, this motion is not strictly due to tumor motion resulting from the respiratory cycle, but is also driven by gravity, changes in muscle tone, and changes in patient position [28]. While the use of immobilization devices, intrafractional tumor tracking, and breath-hold techniques are all utilized to minimize tumor motion during treatment, some degree of motion is inevitable and is more likely to occur during a longer treatment. Indeed, in their study assessing the importance of CBCT for tumor localization during lung SBRT, Purdie *et al* note a significant change in tumor position with prolonged treatment sessions [29].

Minimizing tumor motion is particularly important for SBRT treatments in which a very high dose is delivered in a small number of fractions to a small target volume. In their paper on the effects of intrafraction tumor motion on dosimetric data for lung SBRT, Zhao *et al* demonstrated a deviation of up to 14% in the dose delivered to 95% of the PTV even with the use of respiratory gating [30]. The addition of a margin to the GTV to create a PTV, or the creation of an ITV in cases where tumor tracking is not available, allows some room for error with respect to tumor motion. However, due to the very high dose per fraction and the sensitivity of adjacent healthy lung to radiation, this margin must be kept small, potentially allowing for underdosing of the tumor. In addition to the dosimetric consequences of a prolonged treatment time, a longer treatment is inconvenient for both the patient and the treating facility.

Longer treatment times also results in longer beam on time. An increase in beam-on time results in increased leakage from the head of the machine and increased scatter from the collimators and flattening filter, which theoretically results in increased integral dose to the patient. Increased integral dose to the patient, in turn, may result in an increased risk of secondary malignancies as a result of therapeutic radiotherapy [31-33]. Our study, however, failed to show any differences in integral dose for 6-MV versus 10-MV plans. This may be because of the averaging effect resulting from the dose being spread out among several beamlets as is the case in VMAT treatments.

While selecting 10-MV for lung SBRT clearly results in fewer MUs and therefore shorter treatment times, there are disadvantages to selecting this energy over 6-MV which should be considered. One of the consequences of using 10-MV is the production of neutrons, which are more biologically damaging than photons or electrons [34]. However, neutron contamination begins at 10-MV and is very low, or even negligible, at this photon energy [35]. Another disadvantage of 10-MV over 6-MV is in the increased uncertainty of the dose calculations at higher energies. This is especially true for calculations at tissue interfaces for small fields, as are used in lung SBRT [36]. With the exception of Monte Carlo, treatment planning algorithms are less accurate in those regions, resulting in a degree of uncertainty with respect to the dose delivered [37]. In order to reduce this uncertainty, small field dosimetry using scanning diodes was used during the commissioning tests of our Linac.

While this study was retrospective and included a small sample size, it sheds some light on the ongoing debate regarding the optimal energy to use for lung VMAT SBRT where dose delivery to the target is challenging on account of the lung-tissue interface.

## CONCLUSION

Our study shows that, with the exception of thinner patients with a diameter ≤ 18cm, for which 6-MV plans proved superior with respect to OARs and conformity index, 10-MV should be strongly considered for use in lung VMAT SBRT. We showed that plans using 10-MV had a statistically lower number of MUs as compared to 6-MV plans which would result in a shorter treatment time, with the potential for improved target accuracy due to less intrafractional tumor motion.

## CONFLICT OF INTEREST

The authors have no conflicts to disclose.

## ABBREVIATIONS

**OARs =** Organs at Risk

**PTV =** Planning Target Volume

**VMAT =** Volumetric-Modulated Arc Therapy

**SBRT =** Stereotactic Body Radiation Therapy

**6-MV =** 6-Megavoltage

**10-MV =** 10-Megavoltage

**AP =** Anterior-Posterior

**TCW =** Tumor to Chest Wall distance

**ESD =** Equivalent Sphere Diameter

**CI =** Conformity Index

**SS =** Statistically Significant

**Lung V13 =** Volume of Lung receiving at least 13Gy

**MU =** Monitor Unit

**NSCLC =** Non-Small Cell Lung Cancer

**MRT =** Intensity Modulated Radiation Therapy

**CT =** Computerized Tomography

**ITV =** Internal Target Volume

**GTV =** Gross Tumor Volume

**CBCT =** Cone-Beam Computerized Tomography

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