# CHAPTER 5

# DOSIMETRIC COMPARISON OF THE MONO- AND DUAL-ISOCENTRIC VMAT TECHNIQUE FOR SPINAL SBRT

In this chapter, planning characteristics of spinal stereotactic body radiotherapy (SBRT) using mono-and dual-isocentric volumetrically modulated arc therapy (VMAT) techniques have been studied. The dosimetric indices were compared between different beam arrangement techniques for spinal SBRT planning, including spinal cord avoidance, planning target volume (PTV) dose coverage, conformity, homogeneity, and gradient index. An introduction to the topic, the methodology used in the measurements, the formulas used in the calculations, the results, and conclusions are discussed below.

## 5.1 INTRODUCTION

Stereotactic body radiotherapy (SBRT) is increasingly being used in radiotherapy to treat patients with spinal metastasis as well as primary malignancies. It can relieve pain more rapidly than conventional methods and may effectively improve patients' quality of life and neurological function (Jin et al., 2009). The growing use of SBRT for spinal lesions is due to its ability to ablate tumours by delivering very high doses of radiation precisely inside the tumour while sparing nearby critical organs (Schipani et al., 2012). The effective implementation of this treatment modality necessitates advancements in treatment planning techniques, optimization procedures, and delivery efficiency. Furthermore, modern image guided radiotherapy (IGRT) and immobilization devices are essential for ensuring patient setup accuracy and reproducibility.

The length of treatment delivery time is considered an important factor in spinal SBRT treatment because rapid dose delivery reduces setup errors and thus improves target conformity. Similarly, the total duration from developing a treatment plan to the start of radiotherapy is critical in determining the quality of life of patients with spinal metastasis. These factors must be considered when deciding on a treatment technique for spinal SBRT. SBRT from a standard linear accelerator (LINAC) can be performed using techniques such as three-dimensional conformal radiotherapy (3DCRT), intensity modulated radiation therapy (IMRT), or RapidArc therapy, also known as volumetrically modulated arc therapy (VMAT).

3DCRT employs forward planning to shape the beam aperture to match the size of the planning target volume (PTV) at each gantry angle using a multileaf collimator (MLC). The conformality of beam apertures to PTV is dependent on leaf width and target margin. However, the dose delivery to the PTV in this technique is restricted by spinal cord tolerance doses (Lee et al., 2019). An IMRT or VMAT technique generates intensity-modulated dose distribution by employing inverse planning algorithms, which has the added benefit of rapid dose falloff at target boundaries and minimal exposure to critical organs, particularly the spinal cord (Shiu et al., 2003; Timmerman et al., 2007; Timmerman et al., 2008; Benedict et al., 2010; Sahgal et al., 2012).

The selection of treatment techniques for patients with spinal SBRT should be performed in an optimized way. Radiotherapy, for example, is required as soon as possible in the treatment of spinal cord compression syndrome of non-contiguous vertebral bodies. As a result, common techniques such as single isocentric IMRT or VMAT may not be the best choice in this case, but rather double isocentric techniques may be more appropriate. The VMAT SBRT is an important modality that can be used to treat small contiguous and non-contiguous spinal tumours. For spine tumours, this can be planned by using a co-planar arc on an axial plane with a single or multiple isocenters.

Traditionally, all of these SBRT techniques used flattening filter (FF) photon beams for treatment planning, which has a significant dose rate limitation. However, newly developed flattening filter-free (FFF) photon beams have overcome this barrier by achieving 2-4 times higher dose rates than FF beams (Sharma, 2011; Dobler et al., 2016). As a result, using an FFF beam can significantly shorten the treatment time of these techniques. The faster dose delivery may reduce treatment setup errors, which improves dose conformality to PTV while minimising doses to surrounding organs (Foote et al., 2011; Li et al., 2012).

To obtain an efficient SBRT plan with high accuracy, the appropriate treatment technique must be chosen based on the severity, location, and size of the tumour. The purpose of this study was to compare the mono- and dual-isocentric VMAT techniques for SBRT with non-contiguous spinal targets using FFF beams. Based on the characteristics of the individual case and target size, plans from each technique were generated on sample PTVs within a phantom model. The study assumes that plans from each technique will be able to meet the Radiation Therapy Oncology Group (RTOG) 0631 protocol's criteria. Finally, the appropriate treatment technique was determined by comparing differences in dosimetric indices such as PTV dose conformity, monitor units (MUs), dose to critical organs, dose fall-off, and dose spillage.

## 5.2 MATERIALS AND METHODS

This study is a dosimetric analysis of sample PTVs of various sizes designed at different locations of vertebrae in an anthropomorphic RANDO man phantom. Computed tomography (CT) images of the phantom were used for treatment planning. The Eclipse treatment planning system (Eclipse TPS, Varian Medical Systems, Inc., Palo Alto, CA, USA) was used to delineate different sizes of PTVs.

### 5.2.1 Tumor demographics

Two major sections of the spine, namely the thoracic and lumbar spines, were chosen for target delineation. A total of 8 targets were contoured, with four PTVs per section of spine. These PTVs are a set of four distinct tumours, each with one contiguous and three non-contiguous spine metastases.

### 5.2.2 Tumor and organ delineation

"PTV-I" of each spinal section was delineated on two contiguous vertebral bodies; "PTV-II" of each spinal section was delineated on two non-contiguous vertebral bodies separated by a segment; "PTV-III" of each spinal section was delineated on two non-contiguous vertebral bodies separated by two segments; and "PTV-IV" of each spinal section was delineated on two non-contiguous vertebral bodies. The PTVs were delineated with no additional margin for presumed microscopic extension. The PTVs were contoured using the International Spine Radiosurgery Consortium consensus guidelines (Cox et al., 2012). The CT image fusion of a RANDO phantom with an identical-size anonymous patient was performed to replace the phantom's soft tissue material with a suitable organ. The spinal cord and other organs were contoured in the registered image of the phantom to reflect the average size of organs reported in the previous literature (Ko et al., 2004). The sizes of the 8 PTVs (n = 8) per location of the spine (thoracic or lumbar) are shown in Table 5.1.

**Table 5.1** The size of the eight PTVs (n = 8) per location of the spine (thoracic or lumbar) used in this study.

| PTV# | Location | Volume (cc) |
|---|---|---|
| 1 | T8–9 | 41.81 |
| 2 | T8–10 | 41.74 |
| 3 | T8–11 | 43.62 |
| 4 | T8–12 | 48.98 |
| 5 | L1–2 | 81.30 |
| 6 | L1–3 | 81.53 |
| 7 | L1–4 | 75.99 |
| 8 | L1–5 | 81.28 |

PTV, planning target volume

### 5.2.3 Treatment planning techniques

A 6-MV FFF photon beam with a high dose rate of 1400 MU/min from a True Beam linear accelerator (Varian Medical Systems, Inc., Palo Alto, CA, USA) was used for treatment planning on Eclipse Treatment Planning System (Eclipse TPS, version 13.6). Beam apertures were created using Varian Millennium 120-leaf multileaf collimators (MLCs). The Acuros XB (dose-to-medium) algorithm was used with a grid resolution of 2.5 for radiation dose calculations. Thirty-two mono- and dual-isocentric VMAT plans were generated using four different beam arrangement techniques (mono isocentric (MI) and dual isocentric (DI) for each PTV). For MI, a single isocenter was placed on the geometric centre of a PTV, while two isocenters were placed on two separate segments of a PTV for DI. The VMAT plans were iteratively optimised using inverse planning algorithms to obtain an optimal dose volume histogram (DVH) that met the RTOG dosimetric criteria. The four different beam arrangement techniques of VMAT are as follows:

*2-Arcs MI:* Two full coplanar arcs delivered the dose over a 358° counter-clockwise (CCW) and clockwise (CW) gantry rotation with a couch angle set to 0°.

The collimator angle was set at 0° or 90° to prevent interleaf leakage doses beyond the PTV and to reduce the jaw opening area twice as much as other collimator angles.

*3-Arcs MI:* Three full coplanar arcs delivered the dose over a 358° CCW, CW, and CCW gantry rotation to avoid the spinal cord, with 1 arc (CCW) with the collimator at 90° and 2 arcs (CW) with the collimator at 0°. The couch has the same settings as the 2-Arcs MI plans.

*4-Arcs DI:* The four DI arcs were planned with two arcs for each isocentre at the same setting as two MI arcs.

*6-Arcs DI:* The six DI arcs were planned with three arcs for each isocentre at the same setting as three MI arcs.

### 5.2.4 Planning consideration and analysis

The plans were designed to meet the planning objective established by RTOG 0631. In summary, the protocol-recommended planning recommendations were as follows: The beam apertures were normally adjusted to shape the PTV with no additional margin. However, depending on the technique, a beam aperture margin of 2-3 mm was provided beyond the PTV to ensure adequate PTV dose coverage, and this margin was further reduced to 0-1 mm in the spinal cord area to meet spinal cord dose constraints. The treatment plan was optimal when the prescribed dose covered at least 90% of the PTV (16 Gy in a single fraction). Table 5.2 shows the single fraction dose constraints (to a point or volume) for several critical organs, such as the spinal cord, cauda equina, oesophagus, and kidneys. The dosimetric indices listed in Table 5.3 were used to analyse the outcomes of each spinal SBRT plan.

**Table 5.2** Plan acceptance criteria of tumor and critical organs for single fraction spinal SBRT.

| **ROI*** | **RTOG 0631 criteria*** |
|---|---|
| Tumor | V16Gy > 90% |
| Spinal cord | V10Gy < 10%,<br>D0.03cc < 14 Gy |
| Cauda equine | V10Gy < 12 %,<br>D0.03cc < 16 Gy |

*ROI, region of interest; RTOG, radiation therapy oncology group

**Table 5.3** Mathematical definition of plan quality metrics studied.

| **Dosimetric Index** | **Definition*** |
|---|---|
| Conformity index | $CI = PTV_{PD}/(PTV \times PIV)$. |
| Homogeneity index | $HI = (D_{2\%}-D_{98\%})/D_{50\%}$. |
| Gradient index | $GI = V_{50PD}/PIV$. |

*CI, conformity index; $PTV_{PD}$, PTV (planning target volume) receiving at least the prescribed dose (PD); HI, homogeneity index; Dx%, minimal dose to the x% highest irradiated target volume; $V_{50PD}$, volume receiving 50% of the PD.

## 5.2.5 Statistical analysis

The spinal SBRT plans generated by the four planning techniques were statistically compared. The dosimetric indices of the plans of different techniques, as well as the algorithms, were statistically compared using the Wilcoxon signed rank test (also known as the paired difference test), which is a non-parametric test used to compare two related samples to assess whether the mean of their populations differs. This test was based on the probability value (p), and if the calculated p-value was less than 0.05 ($p < 0.05$), the difference between the individual pairs of data columns was considered significant.

## 5.3 RESULTS

A total of thirty-two VMAT plans were generated, which comprise eight for each beam arrangement and one for each lumbar and thoracic target. All four techniques were able to deliver conformal SBRT plans (delivering the prescription dose to 90% of the PTV) while meeting the RTOG 0631 dose constraints. $D_{95\%}$ results for 2-Arcs MI, 3-Arcs MI, 4-Arcs DI, and 6-Arcs DI were on average 97.29 ± 0.32%, 97.26 ± 0.20%, 98.14 ± 0.30% and 98.12 ± 0.23% of the prescription dose, respectively. The results of the mean dosimetric indices for the 2-Arcs MI, 3-Arcs MI, 4-Arcs DI, and 6-Arcs DI VMAT plans of all spinal PTVs are summarized in Table 5.4. The dose distributions and DVH of the four different VMAT techniques (2-Arcs MI, 3-Arcs MI, 4-Arcs DI, and 6-Arcs DI) for thoracic PTV#4 and lumbar PTV#8 are shown in Figure 5.1, 5.2, 5.3, and 5.4, respectively. The GI, CI, HI, $V_{10Gy}$, maximum spinal cord dose of 0.03 cc ($D_{0.03cc}$), and MUs for lumbar and thoracic PTVs are shown in Figs. 5.5, 5.6, 5.7, 5.8, 5.9, and 5.10, respectively.

**Table 5.4** Summary of mean dosimetric indices

| Organ | Parameter | VMAT techniques | | | |
|---|---|---|---|---|---|
| | | 2Arcs-MI | 3Arcs-MI | 4Arcs-DI | 6Arcs-DI |
| PTV | CI | 1.04 ± 0.02 | 1.05 ± 0.02 | 1.06 ± 0.02 | 1.06 ± 0.01 |
| | GI | 4.00 ± 0.11 | 4.02 ± 0.15 | 3.97 ± 0.19 | 3.99 ± 0.21 |
| | HI | 0.11 ± 0.01 | 0.11 ± 0.01 | 0.09 ± 0.01 | 0.09 ± 0.01 |
| | $D_{2\%}$ | 103.85 ± 0.31 | 103.76 ± 0.51 | 103.11 ± 0.23 | 103.03 ± 0.28 |
| | $D_{98\%}$ | 92.52 ± 1.12 | 92.63 ± 1.06 | 94.32 ± 0.51 | 94.12 ± 0.96 |
| | $D_{50\%}$ | 102.38 ± 0.27 | 102.37 ± 0.39 | 101.36 ± 0.15 | 101.21 ± 0.49 |
| | $D_{95\%}$ | 97.29 ± 0.32 | 97.26 ± 0.20 | 98.14 ± 0.30 | 98.12 ± 0.23 |
| | MUs | 4356 ± 468 | 4512 ± 508 | 4255 ± 247 | 4286 ± 307 |
| Spinal cord/ Cauda equina | $V_{10\ Gy}$ | 3.54 ± 1.66 | 3.43 ± 1.54 | 1.22 ± 1.04 | 1.35 ± 1.09 |
| | $D_{0.03\ cc}$ | 10.95 ± 0.38 | 10.85 ± 0.34 | 10.28 ± 0.58 | 10.30 ± 0.55 |

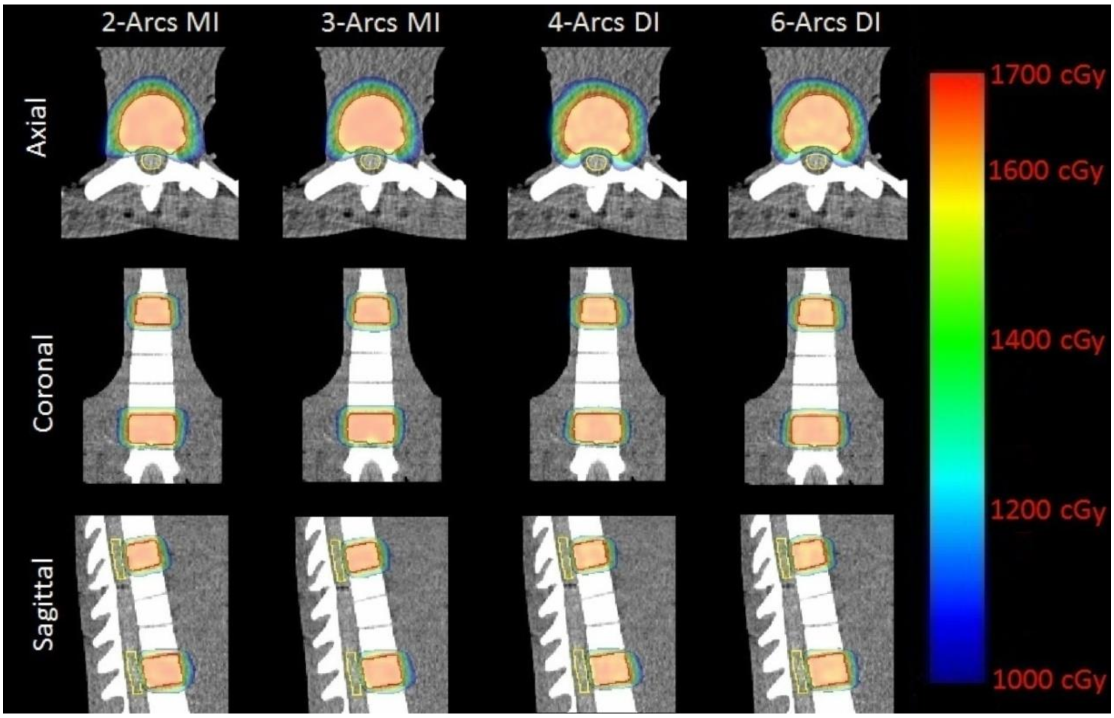

**Figure 5.1** Dose distribution of the four different beam arrangement VMAT techniques for thoracic PTV#4.

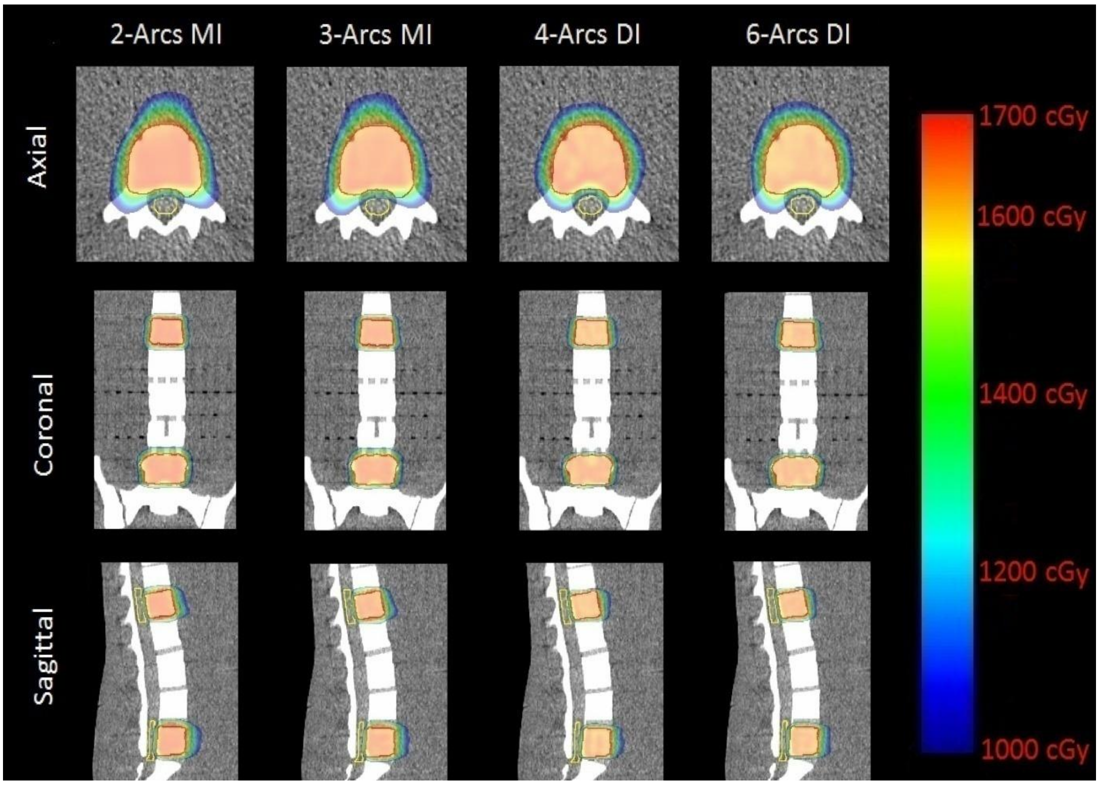

**Figure 5.2** Dose distribution of the four different beam arrangement VMAT techniques for lumbar PTV#8.

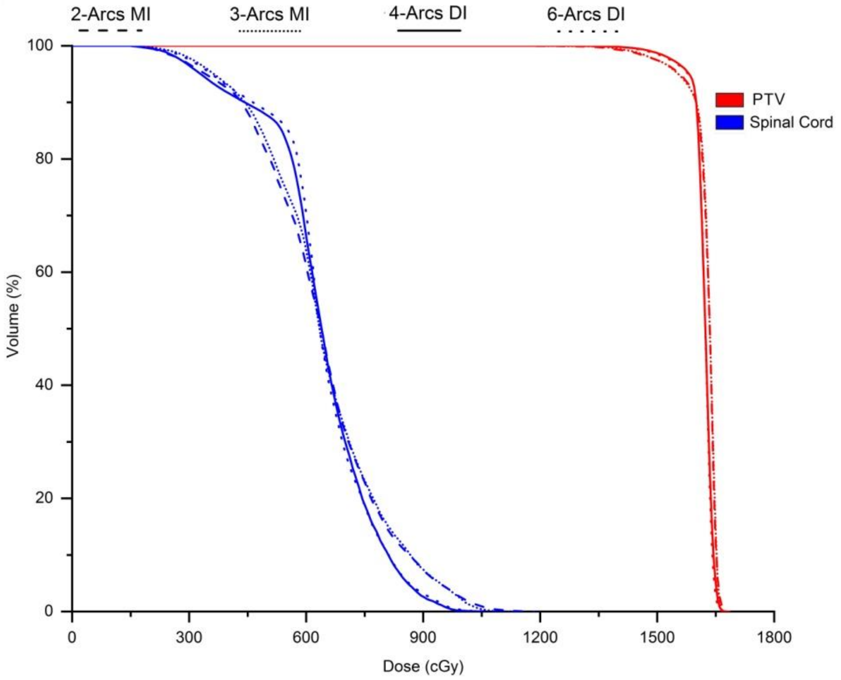

**Figure 5.3** Dose volume histogram (DVH) of the four different beam arrangement VMAT techniques for thoracic PTV#4

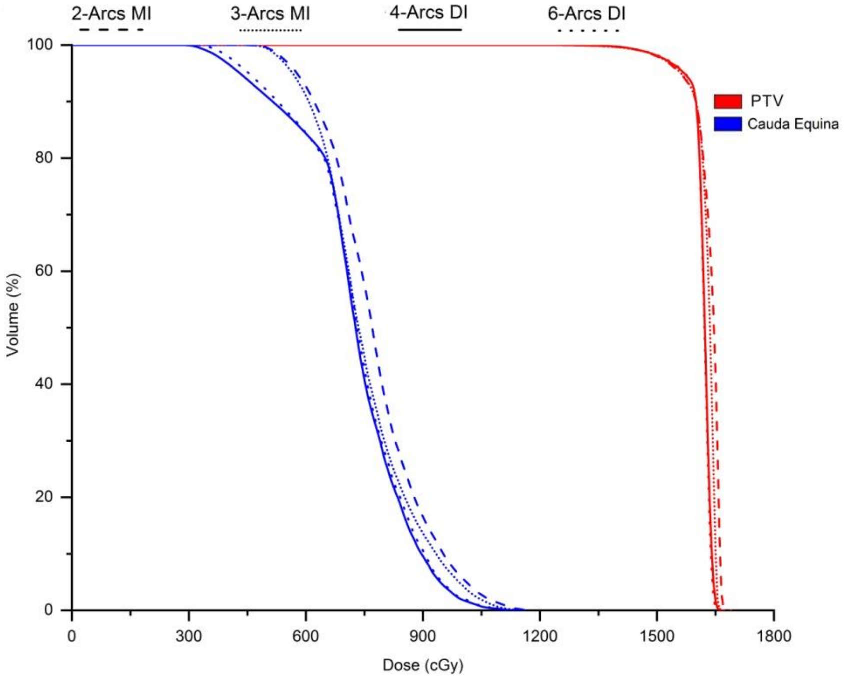

**Figure 5.4** Dose volume histogram (DVH) of the four different beam arrangement VMAT techniques for lumbar PTV#8

### 5.3.1 Gradient index

The GI was 4.00 ± 0.11, 4.02 ± 0.15, 3.97 ± 0.19, 3.99 ± 0.21 for 2-Arcs MI, 3-Arcs MI, 4-Arcs DI, and 6-Arcs DI, respectively. The mean value of GI improved with 4-Arcs DI. The results of the 6-Arcs DI were comparable to the 4-Arcs DI and slightly better than the 3-Arcs MI. GI showed greater variability between 4-Arcs DI and 3-Arcs MI but less variability between 6-Arcs DI and 2-Arcs MI. The Wilcoxon test showed no significant differences (p > 0.05) between the different beam arrangements.

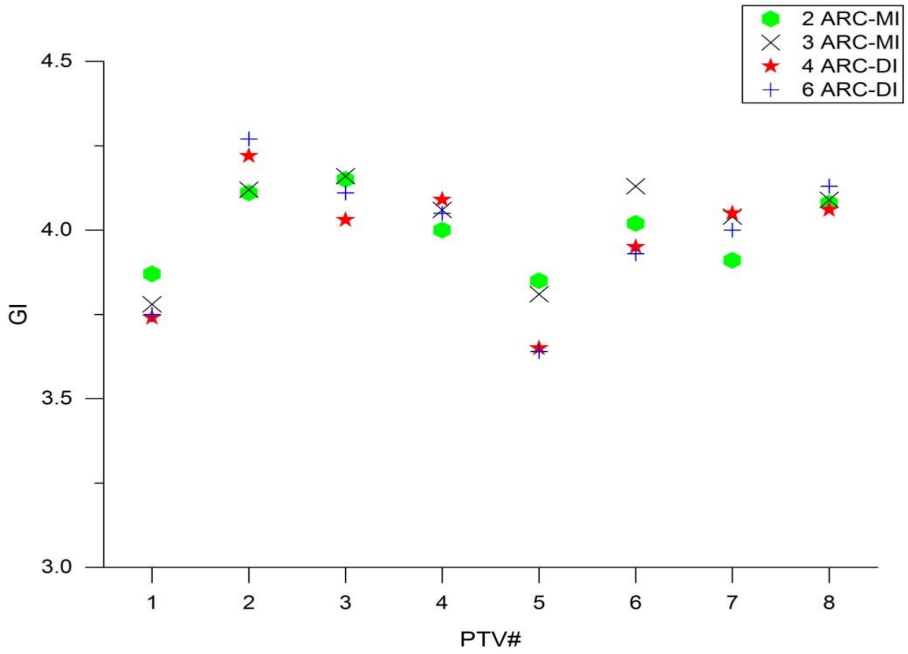

**Figure 5.5** Gradient index (GI) for the four different beam arrangement VMAT techniques

### 5.3.2 Conformity index

The CI was 1.04 ± 0.02, 1.05 ± 0.02, 1.06 ± 0.02, and 1.06 ± 0.01 for 2-Arcs MI, 3-Arcs MI, 4-Arcs DI, and 6-Arcs DI, respectively. CI remains almost the same for all beam arrangements. The 2-Arcs MI showed the highest conformity. The Wilcoxon test showed no significant differences (p > 0.05) between the different beam arrangements.

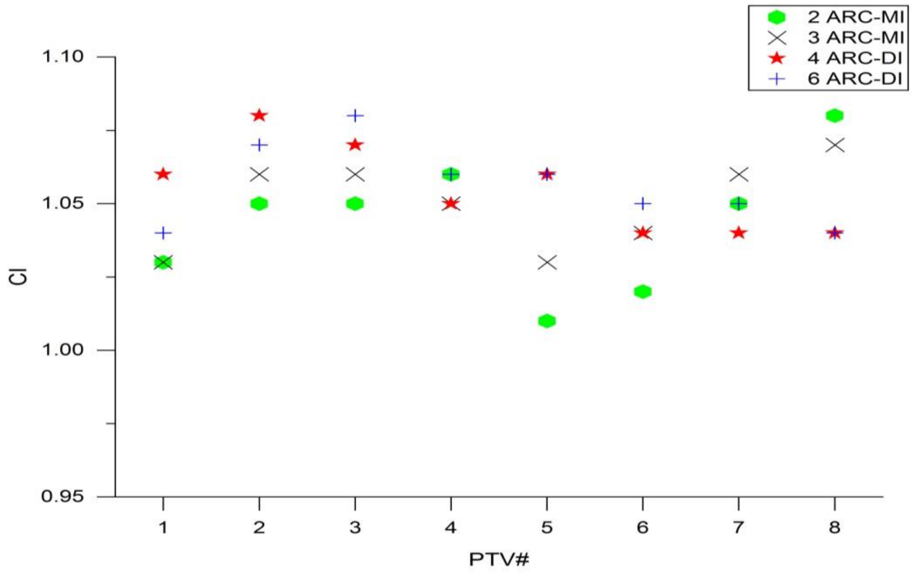

**Figure 5.6** Conformity index (CI) for the four different beam arrangement VMAT techniques

### 5.3.3 Homogienity index

The HI was 0.11 ± 0.01, 0.11 ± 0.01, 0.09 ± 0.01, and 0.09 ± 0.01 for 2-Arcs MI, 3-Arcs MI, 4-Arcs DI, and 6-Arcs DI, respectively. The mean value of HI improved more with DI than with MI techniques. The 2-Arcs MI and 3-Arcs MI were significantly less homogeneous than the 6-Arcs DI ($p < 0.05$) and 4-Arcs DI ($p < 0.05$).

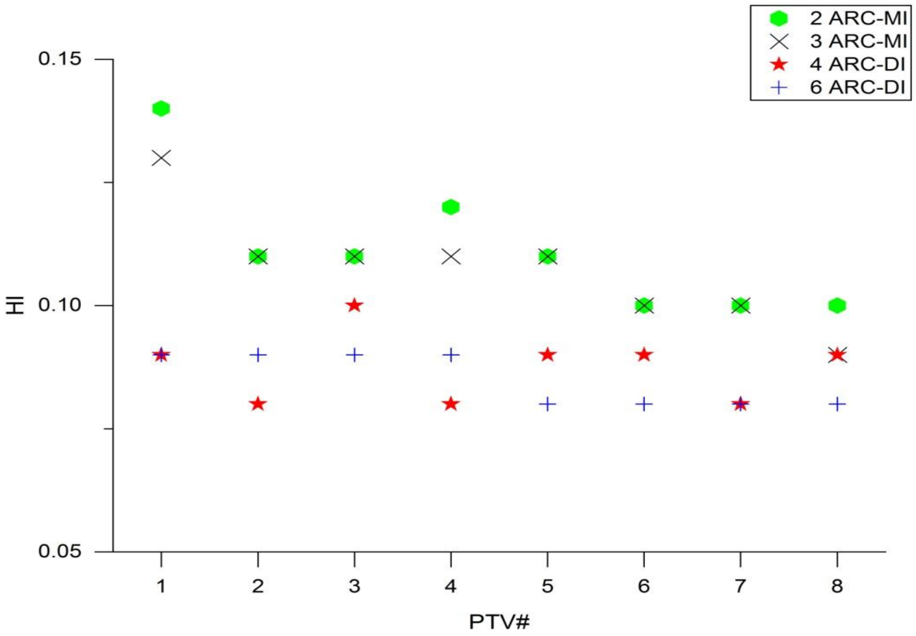

**Figure 5.7** Homogeneity index (HI) for the four different beam arrangement VMAT techniques

### 5.3.4 Organ at risk

All four beam arrangements met the organs at risk (OARs) dose constraints. $V_{10Gy}$ and $D_{0.03cc}$ showed the most variability between 2-Arcs MI and 4-Arcs DI techniques. This can be seen in Table 2, where the $V_{10Gy}$ and $D_{0.03cc}$ were 3.54 ± 1.66% and 10.95 ± 0.38 Gy for 2-Arcs MI, respectively, while only 1.22 ± 1.04% and 10.28 ± 0.58 Gy for 4-Arcs DI. Both 6-Arcs DI and 4-Arcs DI had lower spinal cord doses and sharper dose falloff than the other beam arrangement techniques. As illustrated in Figs. 5, 8, and 9, 4-Arc DI achieved the lowest overall cord doses and also produced the sharpest dose falloff, as indicated by the GI. The Wilcoxon test for $V_{10Gy}$ and $D_{0.03cc}$ (spinal cord/cauda equina) showed significant differences between the MI and DI techniques ($p < 0.05$).

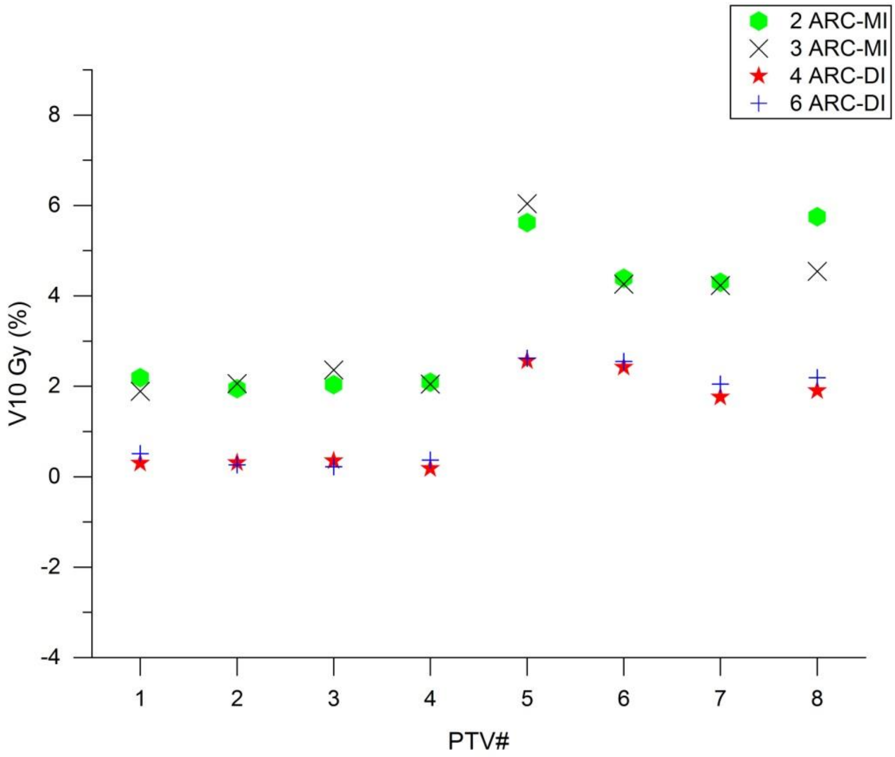

**Figure 5.8** Volume of partial cord receiving 10 Gy ($V_{10\ Gy}$) for the four different beam arrangement VMAT techniques

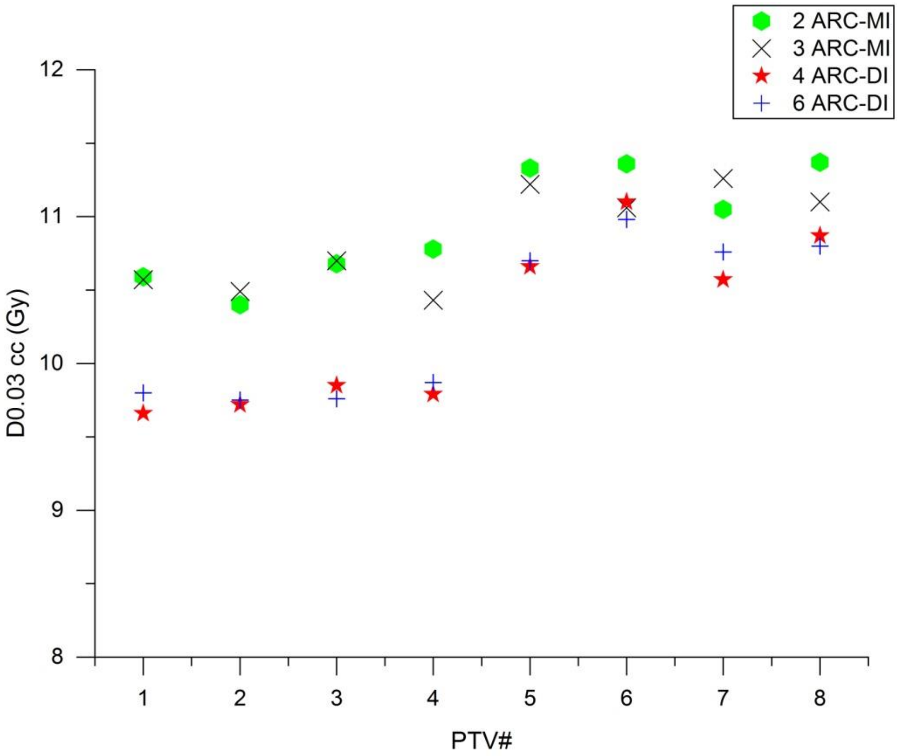

**Figure 5.9** Maximum dose to 0.03 cc partial cord for the four different beam arrangement VMAT techniques

### 5.3.5 MUs and Treatment Time

The MUs were 4356 ± 468, 4512 ± 508, 4255 ± 247, and 4286 ± 307 for 2-Arcs MI, 3-Arcs MI, 4-Arcs DI, and 6-Arcs DI, respectively. MUs for MI techniques were higher than for DI techniques. The 4-Arcs DI showed the lowest MUs for treating a tumor, while it was the highest for the 3-Arcs DI. The Wilcoxon test for MUs between the MI and DI techniques also indicated significant differences ($p < 0.05$). Although the MUs for DI techniques are lower than those for MI, treatment time can vary greatly depending on the beam arrangement techniques used. On average, the MI techniques can deliver treatment faster than the DI techniques.

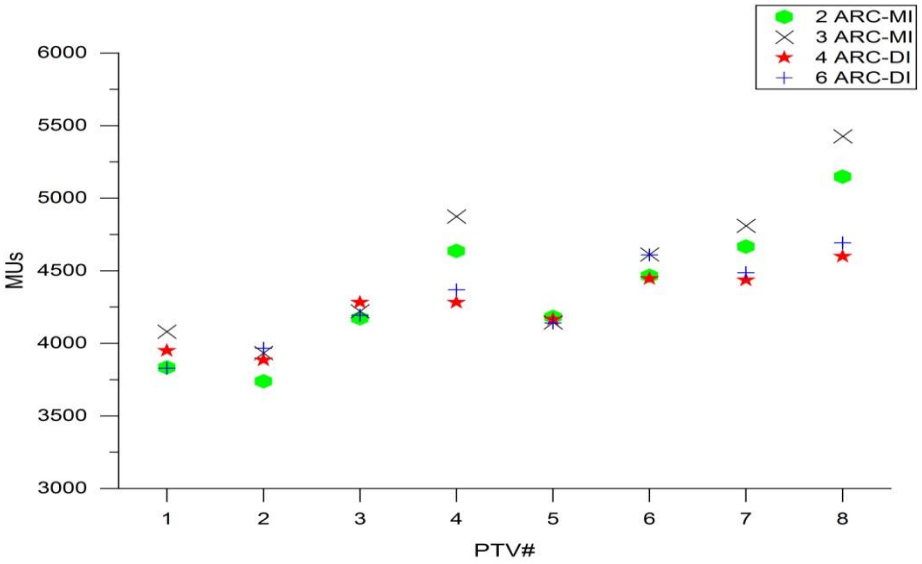

**Figure 5.10** Monitor units (MUs) for the four different beam arrangement VMAT techniques

## 5.4 DISCUSSION

The purpose of this study was to evaluate the planning characteristics of spinal SBRT using mono- and dual-isocentric VMAT techniques. Dosimetric indices such as spinal cord avoidance, PTV dose coverage, conformity, homogeneity, and gradient index were compared between different beam arrangement techniques for spinal SBRT planning. The 4-Arcs DI VMAT plans demonstrated a significant improvement in target coverage, spinal cord dose, and delivery efficacy, providing a significant benefit to spinal SBRT. The 4-arcs DI had better overall dosimetric results, which could be attributed to the use of a greater number of possible volumetric arcs with the dual isocentre (Clark et al., 2010). The 6-Arcs DI yielded comparable results to the 4-Arcs DI.

The DI beam arrangement reduces the possibility of interleaf MLC leakage while also improving HI efficiency for non-contiguous spinal lesions. The greater number of arcs increases the possibility of dose optimization as well as the efficiency of reducing GI. When compared to MI, DI has a lower gradient index and is more effective at precisely administering doses to each tumour for far-distance non-contiguous spinal lesions. The study discovered that when non-contiguous spinal lesions are widely spaced, it may be more effective to use 4-Arc DI to generate a better HI and GI, whereas 2-Acrs SI was beneficial for closely spaced lesions. In addition, the use of more arcs with dual isocenters reduced $V_{10Gy}$, $D_{0.03cc}$ and MUs.

The treatment plans generated using the 2-Arcs MI technique produced results that were only loosely comparable to those obtained using the 6-Arcs DI technique. In comparison to DI, MI planning was relatively simple and convenient in practise, except that it increases the possibility of interleaf MLC leakage for non-contiguous spinal lesions. Furthermore, the MI technique required less treatment delivery time, resulting in less treatment setup errors. These results are better than the data reported previously (Nalichowski et al., 2017; Zach et al., 2016).

Patient treatment time is another important clinical consideration in the administration of spinal SBRT. When compared to the DI VMAT technique, the MUs required for treatment delivery were higher with the MI VMAT technique. Despite the requirement for more MUs in MI plans, we found that treatment times were shorter than those for DI. The average beam-on time for MI VMAT plans was 3.2 minutes, compared to 6.1 minutes for DI VMAT plans. In reality, effective treatment times for DI plans using dual isocentres are slightly longer due to the therapist's need to load a greater number of arcs as well as reposition the couch during treatment. Prolonged treatment times for patients with spinal metastases receiving palliative radiation can result in significantly more pain and discomfort, as well as additional patient movement and missed treatments. The use of a single isocentre in MI VMAT allows for slightly faster treatments without compromising target coverage or OAR sparing, but it also increases the possibility of interleaf MLC leakage for non-contiguous spinal lesions, which is not the case with a dual isocentre. Nalichowski et al. reported beam-on times for single-fraction radiosurgery to spinal lesions ranging from 4.4 minutes with FFF VMAT to 58.1 minutes with Cyber-Knife in a recent study (Nalichowski et al., 2017).

Rapid advancement in the field of medical physics and radiation oncology requires the highest priority in terms of safety before implementing new technology. In spinal SBRT, the tumor is adjacent to the spinal cord, so it is extremely important to minimize the dose to OARs while maintaining the ability to deliver an adequate dose to the target. As administration of very high doses per fraction in SBRT treatment decreases the margin of error compared to conventional fractionation. A small inaccuracy in the reproducibility of the patient setup during actual treatment delivery can have serious and significant consequences that could far outweigh the differences between four different beam arrangements. Therefore, it is important to assess the relative ability of MI and DI VMAT approaches for accurate treatment delivery in order to establish whether one has a meaningful advantage over the other for a particular spinal SBRT treatment. When avoiding the spinal cord for non-contiguous spinal SBRT, the DI technique can be preferred. On the other hand, the MI technique can be used when the patient is in poor general condition and needs a shorter treatment.

The results of point dose measurement using ion chambers were within 3.6% of the dose predicted by the TPS. Both MI and DI had median local gamma pass rates better than 98% at 3%/3 mm for the treatment plans measured with portal dosimetry. However, the lowest with DI were 96.9% and 95.6% for T and L spine plans, respectively; the lowest with MI were 97.5% and 96.5%. The differences in QA results between the MI and DI plans were not statistically significant, despite the fact that the MI plans had fewer control points than the DI plans. The portal dosimetry system that uses EPID provides a very simple and time-efficient approach for both MI and DI plans, as the QA plan is delivered to the portal imager in air, i.e. without a phantom, and images are acquired. On the other hand, the phantom-based verification devices require significant setup time, particularly when verifying DI plans because dose deliveries for each isocentre require the shifting of either the couch or the phantom (Nicolini et al., 2013; Matsumoto et al., 2013).

## 5.5 CONCLUSIONS

In the present study, we have investigated the feasibility of both DI and MI VMAT techniques for non-contiguous spinal SBRT. All four beam arrangements tested were capable of delivering treatment plans that met the RTOG 0631 dose constraints. However, certain beam arrangements performed better than others depending on the tumor shapes, locations, and treatment goals. According to the findings of the study, DI has higher plan quality than MI for treating non-contiguous spine SBRT, achieving adequate tumor coverage, comparable delivery accuracy, better homogeneity, and a lower dose to the spinal cord. 4-Arcs DI had the sharpest dose falloff and achieved the lowest overall spinal cord doses at the expense of twice the treatment time as 2Arcs-MI. These findings could help in deciding which beam arrangements for VMAT are optimal for treating non-contiguous spine tumors.