Volumetric modulated arc therapy for stereotactic body radiotherapy

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Summary

Intensity modulated radiotherapy (IMRT) is a relatively new approach of radiation dose delivery technique, introduced in the early 1990s. Although it is capable of delivering highly conformal dose distribution, it suffers from several drawbacks, including long treatment times, high integral doses and difficulty in selecting optimal beam orientations. RapidArc™ (Varian Medical Systems), as a form of volumetric modulated arc therapy, is an extension of IMRT which delivers the dose in a 358° gantry rotation. During delivery, an IMRT dose distribution can be generated using varying dose rates, gantry speeds and leaf apertures created using a dynamic multi-leaf collimator. A fast delivery using RapidArc is particularly attractive for stereotactic body radiotherapy (SBRT) treatment which features precise delivery of high radiation dose in only one or few fraction(s). Until 2008, SBRT at our institute was delivered using non-IMRT techniques, consisting of multiple non-coplanar static beams. With the introduction of the new RapidArc approach, it became essential to optimize the treatment planning process, and to evaluate the plan quality.

For many years, SBRT delivery was commonly performed using one of the following three techniques, namely 3-dimensional conformal radiotherapy (3D-CRT), dynamic conformal arc (DCA), and IMRT. In **Chapter 2**, we describe comparative dose distributions and delivery times between RapidArc with other common SBRT delivery techniques for stage I non-small cell lung cancer (NSCLC) measuring < 70 cm^3, which represents the size of tumors commonly treated with this technique. To account for the shortcomings in accuracy of the optimizer calculation algorithm used in an earlier version of the treatment planning software in low density media, RapidArc plans were optimized using planning objectives of 5 – 10% higher than the prescription dose for the planning target volume (PTV). In addition, all plans consisted of at least 2 arcs, where the second arc was optimized by referring to the anisotropic analytical algorithm (AAA) calculated dose distribution of the first arc. The comparative study indicated that RapidArc achieved the highest dose conformity and shortest delivery time. However, it increased the volume of contralateral lung receiving 5 Gy, V_5, when compared to 3D-CRT. In order to limit the dose, high priority optimization objectives were used for the contralateral lung, often in combination with the use of an avoidance sector or partial rotation arc.

Clinical toxicity is uncommon following SBRT for tumors of 70 cm^3 or smaller. **In chapter 3**, we studied early clinical toxicity in patients with large tumors (PTV ranging from 87 – 286 cm^3), following SBRT using RapidArc, and correlated these with different dosimetric parameters. The rates of symptomatic radiation pneumonitis (RP) were higher than those

reported for small tumors (28% vs. <10%). Contralateral lung V_5 was the best predictor as all patients with contralateral lung V_5 > 26% developing RP. Limiting beams coming from contralateral direction can effectively reduce the contralateral lung V_5, but it might also increase the dose to chest wall. The analysis suggested that plans should be prioritized to spare the contralateral lung, while also limiting doses to other organs at risk, also because in-house data show very limited chest wall toxicity for lung SBRT.

For IMRT delivery in mobile tumors, the possibility of interplay between tumor motion and multileaf collimator (MLC) motion is a key concern. During IMRT or RapidArc delivery, both the MLC leaves and tumor are constantly moving, with the interplay effect potentially leading to under- or over-dosage in the PTV. In **Chapter 4**, we evaluated the dosimetric accuracy between delivered and calculated dose distributions and the possible interplay effects of SBRT RapidArc delivery for patients with stage I lung cancer. Film dosimetry confirmed that RapidArc accurately delivered the calculated dose distribution. For most of the clinical plans, the dosimetric impact of the interplay effect can be neglected. Plans with higher modulation in combination with great tumor motion can possible exhibit clear dosimetric errors in a single arc, but the use of 2 arcs delivery per fraction reduces the errors by providing an averaging effect, where the large fraction doses are delivered over at least 33 breathing cycles.

Since its introduction in 2008, the RapidArc planning software has undergone a number of refinements and improvements. **Chapter 5** analyses the accuracy of AAA for a variety of small fields in homogeneous and heterogeneous media, and for RapidArc plans. Two versions of AAA; AAA version 8.6.15 (AAA8) and AAA version 10.0.25 (AAA10), calculated using grid resolutions of 2.5 mm and 1.0 mm were investigated. Both versions performed better in muscle tissue equivalent material than in lung tissue equivalent material. AAA 10 improves the accuracy of dose calculations, and calculation grid of 1.0 mm is superior to using 2.5 mm. Plans consisted of large number of small MLC segments, thus more modulation and numbers of monitor unit (MU), and PTV volume which contains relatively large area of low density tissues are more likely to result in calculation errors. Calculations using 1 mm grid resolution are recommended for these plans, although the calculation times may increase by a factor of 5. During optimization, a highly modulated plan should be avoided by using a suitable upper MU constraint.

The risk of tumor displacement is increased with prolonged treatment times, such as those associated with SBRT, and faster delivery may facilitate treatment accuracy. In most linear accelerators, a flattening filter is inserted within the treatment head to create a flattened beam,

a feature which was necessary to facilitate the forward treatment planning approach used in conventional planning techniques. The introduction of IMRT led to use of an inverse planning approach which accounts for basic beam data by a computerized optimization process. Consequently, flattened beams are no longer needed to facilitate planning. A standard linac operating without a flattening filter can achieve higher output dose rate, and thus, potentially reduce treatment delivery time. **Chapter 6** reports the use of flattening filter free (FFF) beams in RapidArc delivery for SBRT of NSCLC and vertebral metastases. Compared to plans generated using a standard flattened (FF) beam, FFF plans significantly reduce beam delivery times by a factor of up to 2.5, with fraction doses of up to 18 Gy deliverable within 4 minutes. No major dosimetric differences were observed between the 2 techniques and measured FFF plans showed high agreements with calculated dose distributions. These findings suggest that faster delivery using FFF is beneficial for patients as the quality of plans are not compromised.

With a fast treatment delivery using RapidArc and FFF beams, a stringent patient monitoring protocol during beam delivery is required as a great amount of doses can be delivered over a short period of time. Any intra-fraction motions, even sub-millimeters misplacements, over a few seconds may be subjected to large dosimetric errors. **Chapter 7** studies the possible dosimetric impact on spinal cord and target volume caused by intra-fraction shifts for short period of times during the delivery of RapidArc plans for SBRT of vertebral metastases using both FFF and FF beams. For shifts of 1 – 5 mm over 5 – 30 seconds, delivery using FFF beams constantly exhibited larger dosimetric deviations compared to those delivered using a flatten beam. For shifts of 5 mm over 10 seconds, the maximum dose of the spinal cord could increase by more than 50% in a FFF arc, which is a factor of 2 larger than those observed in the corresponding FF arc. This underscores the importance of accurate patient positioning during treatment delivery using a high dose rate FFF beam and any unexpected motions should be corrected quickly.

Chapter 8 discusses the role of volumetric modulated arc therapy in radiotherapy treatment. Many planning studies have compared this technique with other methods, including those modalities such as Tomotherapy and Cyberknife. Although dosimetric differences were not consistent, volumetric modulated arc therapy constantly exhibited superior treatment delivery efficiency. Its clinical implementation in different treatment sites has also triggered discussions on the optimal fields (arcs) arrangement, such as number of arcs, coplanar or non-coplanar beam, full rotational or partial arcs. A better understanding of plans quality, delivery accuracy and toxicity patterns for patients treated using this technique may assist the process of treatment planning. While delivery using FFF beams can further reduce treatment time, the

potential risk associated high dose rate delivery should also been considered such as the possible interplay effect and dosimetric errors caused by sudden shifts. During delivery, a fast reaction time is essential to identify any intrafraction motions and interrupt the treatment to re-align the patient. Finally, future developments will have to emphasize more on the development of fast and precise real-time image guidance system.