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Original research article

The effect of beam shape on physical parameters of head and neck simultaneous-integrated boost intensity-modulated radiation therapy

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ABSTRACT

Aim: To evaluate the influence of the beam shape created by X-rays with "flat beams" and without "flattening-filter-free [FFF] beams" a flattening filter, and the isocenter locations for FFF beams on the treatment of a large irradiated volume for tumours.
Background: The increase of dose rate and the decrease of out-of-field dose can be expected for FFF beams and lead to effective and safety radiotherapy. On the other hand, the bell-shaped dose profile is thought to be a factor of negating these advantages.
Materials and methods: Treatment plans for 15 patients with head and neck cancer were created using XiO (Elekta, Stockholm AB, Sweden) in fixed-gantry step-and-shoot delivery under the same dose constraints. Seven fields of FFF beams with 7 MV and flat beams with 6 MV were used with the technique of intensity-modulated radiation therapy (IMRT). We compared the dose homogeneity and conformity of targets and dose constraints for organs as the plan quality and evaluated physical parameters: monitor unit (MU) values, number of segments and their locations from the isocenter in beam's-eye-view.
Results: No significant differences were found in the plan quality. The isocenter locations do not affect the physical parameters for FFF beams. It has been confirmed that the number of segments and MU values were 40% higher with FFF beams than with flat beams ($p < 0.05$).
Conclusion: This study demonstrates flat dose distribution is more suitable for IMRT with large and complex targets.

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1. Background

Advances in radiation therapy have brought about the invention of intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT), a technique that creates a high gradient of dose distribution at the border of a treated volume. They have the advantages over conventional radiation therapy of increasing the target dose while sparing normal tissues. However, they often require an increased treatment time because of the increased modulation level to deliver adequate doses to the complex targets.[1] Most of the X-ray radiation therapy machines used in hospitals have a flattening filter inside its beam line to give flat beam fluence inside the treatment field. The flat dose distribution (hereafter, 'flat beams') is of importance, especially for 3D-CRT, to deliver a uniform dose to the irradiated volume effectively because the dose homogeneity is generally recommended inside the target volume.[2] However, this filter decreases the dose rate, and causes scatter and energy variations away from the central axis, leading to a longer treatment time and non-uniform dose distribution with depth.[3]

Removal of the flattening filter, known as the 'flattening-filter-free' mode (hereafter, 'FFF beams'), has been conducted in the clinical use of radiation therapy. FFF beams generally increase the dose rate by more than approximately a factor of two (depending on the electron energy impinging on the target), decrease the variation in off-axis beam hardening and decrease head scatters by approximately 50% because of the lack of attenuation and scatter caused by the flattening filter. These advantages can be expected to result in shortening of the irradiation time, decreasing field-size-dependent energy variations and decreasing leakage outside of the beam collimation.[3–7] Moreover, studies have shown that these dosimetric properties of FFF beams might improve the dose calculation accuracy. For example, less electron contamination might make modelling in treatment planning easier.[4,8]

FFF beams are expected to be useful for IMRT and VMAT comprising many segments because the profile of FFF beams is thought to be equivalent to that of flat beams in a small field of $4 \times 4\,\text{cm}^2$ and below, depending on beam energies.[9] Moreover, in this situation, higher the dose rate the more it is advantageous for clinical use. Comparative planning studies of FFF beams and flat beams have shown that the plans created by the two beams have equivalent qualities, and that FFF beams can reduce the damage to normal tissues outside the treatment field.[10,11] The treatment time has also been compared, with some studies reporting that the irradiation time, monitor unit (MU) values and number of segments were reduced using FFF beams. Moreover, even if the MUs and numbers of segments increased, the application of FFF beams to IMRT resulted in shorter treatment times for smaller irradiated volumes, as with SBRT and IMRT for prostate cancer.[10,12–14]

However, the use of FFF beams may not be suitable for large targets. For large target volumes, FFF beams are reported to be able to deliver a dose to the target as adequate as with flat beams, although the MU values and number of segments increased.[12,15] This increase is mainly caused by the bell-shaped profile of FFF beams and the delivery of a uniform dose to the target. However, it is unclear whether the advantages of FFF beams are suitable for IMRT with large treatment volumes consisting of complex targets (e.g., simultaneous-integrated boost intensity-modulated radiation therapy [SIB-IMRT]) because more segments and higher MU values may be necessary to deliver uniform doses to the target.

2. Aim

Evaluating the influence of the profile of FFF beams on the plan quality (dose homogeneity and conformity of targets, dose constraints to organs) and physical parameters of IMRT (MU values, number of segments and the distribution of segments in the irradiated field) for large and complex target volumes is essential for the clinical use of FFF beams. Our study investigated the effect of the beam profile on the physical parameters by comparing the treatment plans of head and neck SIB-IMRT created for use with flat and FFF beams. In addition, we assessed the relations between the location of isocenter and physical parameters for FFF beams.

3. Materials and methods

3.1. *Treatment plans*

Treatment plans for 15 patients with head and neck cancer were created using the XiO (version 4.8) treatment planning system (Elekta, Stockholm AB, Sweden) with the superposition algorithm and the segment weight optimization using a dose grid resolution of 2.0 mm in each direction, in fixed-gantry step-and-shoot delivery of the Siemens Artiste (Siemens Healthcare, München, Germany).[16] Minimum segment size, MU values, which are deliverable in the IMRT, were set to $2.0 \times 2.0\,\text{cm}^2$ and 5 MU, respectively. Seven gantry angles were used (0°, 51°, 102°, 153°, 207°, 258° and 309°) for head and neck IMRT. Two kind of treatment plans were created for each patient for retrospective analysis. One is with flat beams and another is with unflat beams. Then we compared parameters obtained by two different plans. The energies of primary electrons are 7 MV for FFF beams and 6 MV for flat beams, the physical characteristics of which are similar with regard to depth-dose curve, energy spectrum and surface dose.[17] This similarity makes it possible to evaluate the effect of beam profile alone.[4]

Applied constraints for organs at risk (OAR) followed the protocol of this institute. The total planning target volume (PTV) for each patient included PTV_{70}, PTV_{63} and PTV_{56}, with the subscripted numbers indicating the prescribed dose in Gy. The isocenter of the treatment plans for SIB-IMRT was set to the center of the total PTV (sum of the volumes of PTV_{70}, PTV_{63} and PTV_{56}) for comparing the treatment plans of both beams, because of the large size of the total PTV and delivering the dose to each PTV effectively. The average location of PTV_{70} in all cases was 6.6 ± 1.9 cm from the isocenter. Moreover, the effect of the isocenter location on physical parameters for FFF beams was also investigated because the suitable location of the isocenter may depend on the shape of beam profiles.

Table 1 shows the dose constraints for OAR and for each PTV. The same dose constraints used in the optimization were applied to the use of each beam type. Statistical differences