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Abstract

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A Comprehensive Analysis of Radiation Modulation in SRS/SBRT Plans: A Single Institution Study of 460 Cases

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Abstract

Objectives:

Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiotherapy (SBRT) plans typically involve high-dose delivery to the target region and a steep dose fall-off outside the target. Achieving these dosimetric goals requires precise radiation modulation, including the use of LINAC motion axes (e.g., MLC leaf travel, gantry rotation) and dose rate variation. Post-hoc analysis has shown that the extent of radiation modulation is correlated with plan-specific dosimetric verification results. Establishing a quantitative guideline for radiation modulation in different planning tasks can aid planners in generating technically consistent plans and prevent outliers with excessively high or low modulation, which may exceed the limitations of modern LINACs and treatment planning systems (TPSs). This study aims to retrospectively evaluate the Radiation Modulation Complexity Score (RMCS) using a library of SRS/SBRT cases treated with Volumetric Modulated Arc Therapy (VMAT) on C-arm LINACs, providing a quantitative guideline for treatment planning.

Methods:

A total of 460 plans from our institution, including 104 SRS plans and 355 SBRT plans, were analyzed. The SBRT treatment sites included liver (n=56), lung (n=57), spine (n=44), pancreas (n=54), prostate (n=104), and bony oligometastasis (n=40). All plans were created using EclipseTM v16.0 TPS (Varian Medical System, Palo Alto, CA). The Radiation Modulation Complexity Score (RMCS) was proposed as a quantitative metric to describe the modulation strength of a plan. RMCS was calculated by assessing the similarity of multi-leaf collimator (MLC)-shaped beam apertures and the travel distances of MLC leaves between adjacent arc control points, weighted by the instantaneous dose rate. Higher RMCS values indicate stronger radiation modulation.
An EclipseTM ESAPI script with a graphic user interface (GUI) was developed to calculate 1) RMCS, 2) total monitor unit (MU) per fraction (MU/cGy), which is recognized as the empirical descriptor of modulation, and 3) the equivalent square of MU-weighted MLC aperture size in cm (FSMLC), in which a smaller value might be desired for stronger radiation modulation. The relationship amongst the three metrics was evaluated using Spearman's rank correlation coefficient. Additionally, results from different treatment sites were compared via the Wilcoxon rank sum test.

Results:

The average Radiation Modulation Complexity Score (RMCS) and [20%, 80%] percentiles, ranked from lowest to highest across all treatment sites, were as follows: lung (0.94; [0.35, 1.37]), pancreas (1.47; [1.23, 1.67]), bony oligometastasis (1.60; [1.24, 1.96]), prostate (1.68; [1.35, 2.02]), liver (1.71; [1.41, 1.92]), spine (1.78; [1.49, 1.99]), and SRS (2.66, [2.02, 3.58]). Statistical significance ($p < 0.01$) was observed in the lowest rank pair (lung vs. pancreas) as well as the highest rank pair (spine vs. SRS). Additionally, significant differences were observed in four non-adjacent rank pairs, including lung vs. bony oligometastasis, pancreas vs. prostate, pancreas vs. liver, and bony oligometastasis vs. spine.
For the empirical modulation descriptor (MU/cGy), the results showed the following ranking: lung (2.26; [1.74, 2.83]), bony oligometastasis (2.61; [2.09, 3.03]), liver (3.19; [2.34, 3.73]), pancreas (3.63, [2.65, 4.67]), spine (3.74; [2.91, 4.23]), prostate (3.81; [3.06, 4.35]), and SRS (4.24, [2.48, 5.2]). The rank order of RMCS was partially consistent with the MU/cGy results, sharing only the same lowest (lung) and highest (SRS) sites. Positive correlations between RMCS and MU/cGy were found for all treatment sites except pancreas, with linear or quadratic relationships. The Spearman correlation coefficients ranged from 0.46 to 0.79 ($p < 0.01$).
Similarly, the FSMLC results are SRS (1.13; [0.8, 1.44]), bony oligometastasis (1.80; [1.12, 2.4]), liver (1.95;

[1.63, 2.3]), lung (2.08; [1.61, 2.48]), spine (2.13; [1.68, 2.47]), prostate (2.25; [1.71, 2.61]), and pancreas (3.18; [2.86, 3.66]). Negative linear correlations between RMCS and FSMLC were found for prostate, pancreas, bony oligometastasis, and spine, with the Spearman correlation coefficients ranged from 0.34 to 0.62 ($p < 0.01$). In terms of MU/cGy - FSMLC relationship, a negative linear correlation was found only in pancreas cases with the Spearman coefficient being 0.45 ($p < 0.01$).

Conclusion(s):

The RMCS results for SRS/SBRT cases provide a valuable metric for assessing radiation modulation in both treatment planning and plan evaluation stages. The developed ESAPI script will be made publicly available, facilitating a multi-institutional consensus study to establish standardized guidelines of radiation modulation in SRS/SBRT plan evaluation.