Original paper

Multi-institutional comparison of computer-based independent dose calculation for intensity modulated radiation therapy and volumetric modulated arc therapy

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ABSTRACT

Purpose: No multi-institutional studies of computer-based independent dose calculation have addressed the discrepancies among radiotherapy treatment planning systems (TPSs) and the verification programs for intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT). We conducted a multi-institutional study to investigate whether ± 5% is a reasonable action level for independent dose calculation for IMRT/VMAT.

Methods: In total, 477 IMRT/VMAT plans for prostate or head and neck (H&N) malignancies were retrospectively analyzed using a modified Clarkson-based commercial verification program. The doses from the TPSs and verification programs were compared using the mean ± 1 standard deviation (SD).

Results: In the TPS-calculated dose comparisons for prostate and H&N malignancies, the sliding window (SW) technique ($-2.5 \pm 1.8\%$ and $-5.3 \pm 2.6\%$) showed greater negative systematic differences than the step-and-shoot (S&S) technique ($-0.3 \pm 2.2\%$ and $-0.8 \pm 2.2\%$). The VMAT dose differences for prostate and H&N malignancies were $0.9 \pm 1.8\%$ and $1.1 \pm 3.3\%$, respectively. The SDs were larger for the H&N plans than for the prostate plans in both IMRT and VMAT. Such plans including more out-of-field control points showed greater systematic differences and SDs.

Conclusions: This study will help individual institutions to establish an action level for agreement between primary calculations and verification for IMRT/VMAT. A local dose difference of ± 5% at a point within the planning target volume (above − 350 HU) may be a reasonable action level.

1. Introduction

Intensity modulated radiation therapy (IMRT) has been widely used in external beam radiation therapy at several anatomical sites. Volumetric modulated arc therapy (VMAT) is also gaining popularity because of its rapid delivery of highly conformal dose distributions. This is accomplished using complex modulation of the beam intensity of each field [1].

Some reports have described adverse dose-delivery events for both simple and complex treatment plans [2–6]. An incident that occurred in 2005 involved IMRT treatment using dynamic motion of a multileaf collimator (MLC) [7]. Most reported incidents may have been avoided if pretreatment measurement verification had been conducted, such as that using ionization chambers, film, and online two- or three-

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dimensional detectors [8]. A departmental process for measurement verification is therefore recommended for complex treatment plans. Independent dose calculation is also useful for secondary plan checks. Clarkson-based dose calculation is a conventional method of independent dose calculation [9] and is still commonly used worldwide. Independent dose calculation is generally performed for conventional treatment plans generated by an on-site radiotherapy treatment planning system (TPS) as a secondary check. Actual dose measurements are common for IMRT/VMAT, although they may be time-consuming and labor-intensive [10,11]. IMRT/VMAT has also been used in palliative radiotherapy such as for whole-brain radiotherapy with hippocampal avoidance, multiple brain metastases, and spine metastasis [12–14], in which the time between planning computed tomography (CT) acquisition and the first treatment fraction is as short as possible. Thus, efficiency is an important factor of IMRT/VMAT quality assurance (QA). The number of IMRT/VMAT procedures performed is likely to continue increasing, and dose measurements may begin to obstruct the clinical workflow.

Independent dose calculation may provide simple and efficient QA by using patients' CT image data to verify the dose inside the patient's body before treatment. Sun et al. [15] reported that an independent dose calculation-based method can be performed in an average of 32 min, which is much more efficient than the measurement-based QA approach. Recent studies have shown that independent dose calculation can now be performed using the trajectory log files, an approach that includes the expected and actual information on MLC location, gantry position, and monitor unit (MUs). This phantom-less QA approach allows the possibility of checking the prescription dose or dose distribution in the patient's body accompanied by verification of deliverability [16,17]. However, only a few verification programs are able to take the log files into account when estimating deliverability. Therefore, independent dose calculation using a patient's CT image data without the log files is still a more effective QA tool for IMRT/VMAT when accompanied by measurement verification of the safety of deliverability.

The number of commercially available verification programs using the Clarkson method for the IMRT/VMAT dose is increasing [18–20], and they are now entering clinical use. The American Association of Physicists in Medicine Task Group 114 (AAPM TG-114) has recommended that the disagreement between the primary TPS and secondary verification program should not exceed ± 5% [21]. However, this does not cover IMRT/VMAT. Several published studies have demonstrated that ± 5% is a reasonable limit using in-house verification programs for IMRT [22–24]. Additionally, in other studies, dose calculation was performed with a commercial verification program for IMRT/VMAT [2,25,26], and comparisons were made between the TPS and the verification program using homogeneous phantoms. Sun et al. [15] stated that such a phantom measurement verification would not be able to account for tissue inhomogeneities in patients. Kuppusamy et al. [27] performed a study comparing an in-house program with a commercial verification program that took heterogeneity corrections for VMAT into account. In their report, they concluded that a commercial verification program using a modified Clarkson method can be used for independent dose calculation of VMAT plans with isocenters above − 350 HU. However, each of these studies was performed in a single institution.

No multi-institutional studies of independent dose calculation have addressed the discrepancies between TPS doses and program-calculated doses for IMRT/VMAT. Multi-institutional studies have recently been conducted to evaluate the dosimetric consistency among different institutions and to identify problems [28,29]. Moreover, a multi-institutional study would be helpful to determine the departmental action levels of independent dose calculation because the results would incorporate different patient characteristics, different treatment planning techniques, different dose–volume constraints, and different physical settings for the MLC, allowing consensus values for action levels to be derived [30].

In the present study, we performed the first multi-institutional comparisons of independent dose calculation verification in IMRT/VMAT and evaluated the discrepancies between the TPS doses and the program-calculated doses. We investigated whether ± 5% is an achievable action level for local dose discrepancies at a point within the planning target volume (PTV) (above − 350 HU) for independent dose calculation with heterogeneity corrections for IMRT/VMAT across multiple institutions. We employed a commercial verification program using a modified Clarkson method to calculate doses for inhomogeneous tissues according to patient CT images. First, on-site TPS doses and verification program-calculated doses incorporating information from patients' CT image data were compared in an anatomic region as recommended by Kuppusamy et al. [27]. Additionally, the measured dose and the TPS-calculated dose were compared at each institution to evaluate the accuracy of the TPS before the multi-institutional study.

2. Methods

2.1. Computer-based verification program

Simple MU Analysis Ver1.3.13 (Triangle Products, Chiba, Japan) was used as the verification program. This program computes the dose according to a modified Clarkson method, accounting for dosimetric leaf gap (DLG) and MLC transmission. For comparison between the primary TPS and secondary verification program, we exported Digital Imaging and Communications in Medicine (DICOM) files, including RT-Dose, RT-Plan, RT-Structure, and CT image data, from the TPS to the verification program. Additionally, the couch structure models (Cavity, Surface, Rail) generated by the TPS were exported as DICOM-RT files. The CT values in the planning were assigned to the structures of the couch structure models.

The calibration curve for the relative electron density values and CT values were obtained from the TPS. The program uses CT image data to compute the radiation path length from the surface to an arbitrary (reference) point for each control point. All of the control points were used in the calculations. The MLC aperture shape was simultaneously modeled by referring to the information from a DICOM-RT plan file. Dose calculation was performed using a modified Clarkson method considering MLC transmission and DLG. DLG was used as the MLC offset to move the planned position for each MLC leaf to the dosimetric-considered position. However, a limitation of this verification program is that smooth falloff of the MLC penumbra cannot be considered.

The dose $D_{total}(ref)$ to be delivered to the reference point *ref* was calculated as follows:

$$D_{total}(ref) = \sum_{i=1}^{n} [D(d_i, s_{eff,i}) + D^{MT}(d_i, c_i)] \tag{1}$$

where n is the number of control points in the MLC sequence; $D(d_i, s_{eff,i})$ is the dose to be delivered without consideration of the MLC transmission for an MLC aperture defined as equivalent to the square field size of $s_{eff,i}$ at a depth of d_i at the control point i; and $D^{MT}(d_i, c_i)$ is the dose to be delivered from only the MLC transmission for a field size using XY Jaws: c_i at a depth of d_i at the control point i.

$D(d_i, s_{eff,i})$ was calculated as follows

$$D(d_i, s_{eff,i}) = MU_i \times D_r(d_r, 10 \times 10) \times TMR(d_i, s_{eff,i}) \times S_c(c_i) \times S_p(s_{eff,i})$$
$$\times A_0(r_i) \times G_i \tag{2}$$

where MU_i is the number of MUs at the control point i, $D_r(d_r, 10 \times 10)$ calibrates the dose per MU at dmax, and $TMR(d_i, s_{eff,i})$ is the tissue maximum ratio for an MLC aperture defined as the equivalent square field size of $s_{eff,i}$ at a depth of d_i at the control point i. $S_c(c_i)$ is the collimator scatter factor for a field size using XY Jaws: c_i at the control point i. S_c was measured by an ionization chamber attached with a cylindrical water-equivalent phantom. $S_p(s_{eff,i})$ is the phantom scatter