A comparison of planned radiotherapy dose distributions calculated by Monte Carlo with variation of technique, statistical uncertainty and voxel size on resulting gamma pass rates.

Kurt W. Van Delinder, M.Sc, M.Sc[a]

[a] *Karmanos Cancer Center, Wayne State University, School of Medicine Department of Radiation Oncology, 4100 John R St, Detroit, MI 48201, USA.*

Abstract

Background: The gamma analysis index (γ) is the most commonly used method to compare a calculated and measured dose distribution. A caveat to the clinical use of γ is that the formalism does have a sensitivity to noise present in either distribution. Monte Carlo (MC) based dose calculation methods are widely accepted as the most accurate method to calculate a resulting patient dose distribution from a radiation therapy treatment plan [6]. However, noise is inherently present as random errors or statistical uncertainty within all MC based dose calculation methods and is inversely proportional to the dose calculation time [7]. A research experiment performed by Van Delinder et al. investigated the effect of decreasing voxel size and increasing statistical uncertainty for a Monte Carlo based dose calculation method using 10 clinical head and neck (H&N) IMRT treatment plans. The experimental result was a definitive increase in γ passing rates with combined decrease in voxel size [10]. In order to further clinical information regarding this phenomenon, a large comprehensive study is required using multiple treatment techniques, a different treatment site, and using a different type of radiation measurement device.

Methods/Design: A study consisting of (n_{total} = 30) thirty total prostate cancer radiation therapy plans comprised of (n_1 = 10) ten VMAT plans, (n_2 = 10) ten IMRT plans and (n_3 = 10) ten 3DCRT plans. All treatment plans consisting of three different treatment techniques are to be delivered with a total dose of 79.2 Gy prescribed to the PTV at a rate of 1.8 Gy in 44 fractions. 3DCRT will be delivered using 6 fields, IMRT delivered as 7 fields and VMAT consists of 2 arcs (CCW from 1^o to 359^o with a collimator angle of 170^o and CW from 359^o to 1^o with a collimator angle of 190^o). All three treatment techniques will be calculated using 6 and 10 MV energy to allow an intra-study comparison between energies. All QA plans will then be calculated with varied statistical uncertainty from 0.5%, 1%, 2%, 3%, 4% and 5%. The voxel sizes will also be varied from 3mm, 2mm and 1mm for each of the statistical uncertainty percentages. All treatment plans will be measured using ArcCHECK radiation dose measurement device and the γ will be applied within SNC Machine. Both 3%/3mm and 2%/2mm will be implemented for γ criteria for all of the treatment plans.

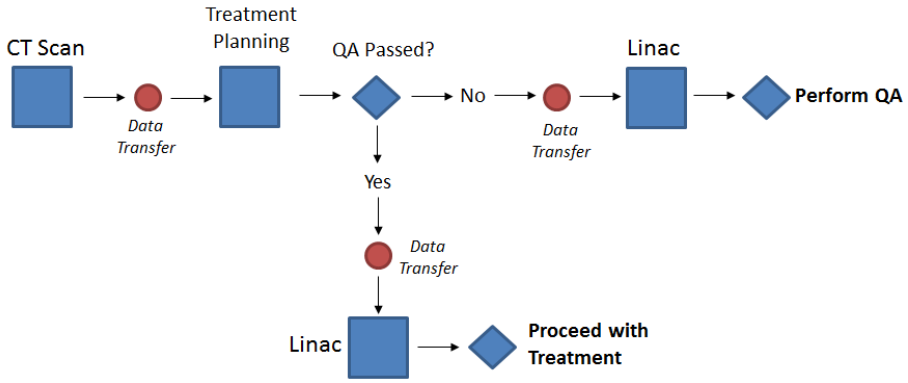
Discussion: The necessity for a comprehensive research experiment investigating the effects of statistical uncertainty and voxel size amongst multiple treatment techniques with additional variations is required to guarantee safe quality assurance with routine use of Monte Carlo dose calculation methods.

This experimental design acts as a contrasting research experiment when combined with prior literature allowing the clinician the ability to use the direct results and develop clinical recommendations for IMRT QA involving the use of Monte Carlo based dose calculations.

Background

The medical discipline of radiation oncology is rapidly evolving in both the implementation of health care technology and in the development of novel clinical treatment techniques. Therapeutic radiation treatments have undergone many stages of great advancement within only a short number of increasing years. Long gone are the days in which a medical practitioner could personally administer a radiation based treatment and be able to discern the accuracy of the delivered setup [1]. Linac delivered treatments now use many individual synchronized component movements, consisting of: dynamic multileaf collimators (MLCs), gantry rotation, collimator rotation, and variation of radiation output. These dynamic linac movements are used to satisfy the creation of advanced delivery techniques first planned within a radiation treatment planning software (TPS). A radiation therapy plan first starting from an initial computed tomography (CT) scan sent to a treatment planning work-station then to a clinical accelerator relies heavily on the integrity of the computerized data transfer. To minimize the possibility of a catastrophic mistreatment from occurring, the final produced radiation therapy treatment plan must be administered on a dosimetric device or phantom and formally documented prior to the first therapeutic patient treatment [2].

Figure 1. Flowchart for Radiation Oncology IMRT QA.



Due to the common use of intensity modulated radiation therapy techniques employed within radiation oncology, this quality assurance task is simply called intensity modulated radiation therapy quality assurance (IMRT QA). IMRT QA consists of re-calculating a treatment plan within a TPS on a computer replicated measurement device and then administering the radiation based treatment plan via a linear accelerator on a physical measurement device. The radiation dose calculated within the treatment plan is then directly compared to the measured radiation dose via a mathematical formalism called the gamma analysis index (γ) [3]. The application of the γ for radiation oncology IMRT QA requires the user to select three main input criteria for the formalism to be calculated: whether the measured or

calculated distribution will be used as the reference or evaluated plan, the percent dose difference, and the distance-to-agreement (DTA). Both the percent dose difference and the distance-to-agreement are put into the algorithm and if the γ is calculated to be ≤ 1 for greater than 90% of all points considered, then the plan would be deemed acceptable for treatment [3,4,5]. Task Group 119 produced by The American Association of Physicists in Medicine (AAPM) produced by Ezzell et al. determined a threshold of 90% points passing and a preference of 3% percent dose difference and 3mm distance to agreement for clinical practice [5].

The gamma analysis index (γ) is the most commonly used method to compare a calculated and measured dose distribution. A caveat to the clinical use of γ is that the formalism does have sensitivities first mentioned in a publication by DA Low and JF Dempsey, entitled 'Evaluation of the gamma dose distribution comparison method'. Three sensitivities were stated, including: whether the calculated or measured dose distribution was selected as the reference, regions of high dose gradients, and if noise is present in either the measured or calculated dose distribution. The sensitivity to noise in either the measured or calculated distribution is clinically esoteric because noise is inherently present in many different radiation dose measurement devices and can also be verified within clinically implemented dose calculation methods [4].

As a result from many prior experimental research projects, Monte Carlo (MC) based dose calculation methods are widely accepted as the most accurate method to calculate a resulting patient dose distribution from a radiation therapy treatment plan [6]. However, noise is inherently present as random errors or statistical uncertainty within all MC based dose calculation methods and is inversely proportional to the dose calculation time [7]. The calculation time can be relatable to the user input values of statistical uncertainty and voxel size [8]. Smaller input values of statistical uncertainty and voxel size are desirable but clinically impracticable due to an excessively long calculation time. The user must select input values that satisfy the accuracy of the treatment plan's dose calculation as a trade-off with plan calculation time. Noise will be inherently present to some extent for each and every Monte Carlo based dose calculation [7].

The effect of sensitivity of noise on γ has been investigated using different methods within prior research publications. A publication authored by Huang et al. investigated the effect of noise and image resolution applicable to a noisy measurement device being film and the result on passing γ values. A result was a definitive increase in passing γ values for both an increase in resolution and increase in noise for a 3%/3mm γ criteria [9]. A research experiment performed by Van Delinder et al. investigated the effect of decreasing voxel size and increasing statistical uncertainty for a Monte Carlo based dose calculation method using 10 clinical head and neck (H&N) IMRT treatment plans. The experimental result was a definitive increase in γ pass rates with combined decrease in voxel size [10].

The experimental result of increased γ pass rates with increasing statistical uncertainty and voxel size calls for a parallel study investigating these two criteria over a broader application of radiation therapy based treatment conditions. The prior study demonstrating with 10 standard clinical IMRT H&N treatment plans and the result of increased pass rates requires that a future additional study should

implement a treatment site different than H&N [10]. This will allow clinicians to contrast γ pass rates between subsequent treatment sites and approximate a relative magnitude for other treatment regions which currently lack a comprehensive study. Also, selecting a treatment site which can be treated by multiple techniques, for example: three-dimensional conformal radiation therapy (3DCRT), intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT). This would provide the clinician with valuable information that can be extrapolated into making informative clinical decisions [11]. As a result of the input criteria being selected in order to minimize the time of the calculation; values for each dose calculation time with variation of input metrics should be tabulated and presented within this scientific experiment.

Due to the experimental success that Monte Carlo based dose calculation methods have had with the accuracy of calculating radiation treatment plan dose; it's fair to assume that in the future, this system will be the most commonly implemented method utilized within clinical practice [12]. A verified sensitivity between this dose calculation method and the algorithm used within IMRT QA requires that a more comprehensive experimental research project be performed to investigate the magnitude of this phenomenon over a different treatment site using multiple treatment techniques.

Methods

A) Radiation Therapy Treatment Planning

To accurately investigate the effects of this phenomenon a total of (n_{total} = 30) thirty prostate cancer treatment plans will be utilized, comprised of (n_1 = 10) ten VMAT plans, (n_2 = 10) ten IMRT plans and (n_3 = 10) ten 3DCRT plans.

Table 1. Prostate cancer radiotherapy dose prescription [13].

Prescription Dose (Gy)	Minimum PTV Dose ≥ 98% PTV.	Minimum CTV Dose ≥ 100% CTV.	Maximum PTV Dose ≤ 2% of PTV (No variation).	Maximum PTV Dose ≤ 2% of PTV (Minor variation).	Maximum PTV Dose ≤ 2% of PTV (Major variation).
79.2Gy: 1.8Gy in 44 fractions.	79.2 Gy	79.2 Gy	84.7 Gy	87.1 Gy	> 87.1 Gy

All treatment plans consisting of three different treatment techniques are to be delivered with a total dose of 79.2 Gy prescribed to the PTV at a rate of 1.8 Gy in 44 fractions. 3DCRT will be delivered as a 6 field technique, IMRT delivered with 7 fields and VMAT using 2 arcs (CCW from 1^{o} to 359^{o} with a collimator angle of 170^{o} and CW from 359^{o} to 1^{o} with a collimator angle of 190^{o}). All three treatment techniques will be calculated using 6 and 10 MV energy to allow an intra-study comparison between energies. All three treatment plan constraints are motivated by 'RTOG 126: A phase III study on 3DCRT/IMRT prostate cancer' and 'Quantitative Analysis of Normal Tissue Effects in the Clinic (QUANTEC)' [13, 14].

Table 2. Prostate cancer radiotherapy dose constraints [13].

Organ Limit	No more than 15% V receives dose that exceeds	No more than 25% V receives dose that exceeds	No more than 35% V receives dose that exceeds	No more than 50% V receives dose that exceeds
Bladder Constraint	80 Gy	75 Gy	70 Gy	65 Gy
Rectum Constraint	75 Gy	70 Gy	65 Gy	60 Gy
Femoral Head	50 Gy	45 Gy	40 Gy	30 Gy
Penile Bulb	Mean dose ≤ 52.5 Gy.			

All treatment plans are to be calculated within Monaco treatment planning software, first using the initial finite size pencil beam (FSPB) algorithm followed by the (XVMC) X-ray Voxel Monte Carlo dose calculation calculated with a 1% statistical uncertainty and 1mm voxel size [15]. For each of the treatment plans, QA plans are to be generated and replicated on a setup reproducing ArcCHECK dosimetry device. All QA plans will then be calculated with varied statistical uncertainty from 0.5%, 1%, 2%, 3%, 4% and 5%. The voxel sizes will be varied from 3mm, 2mm and 1mm for each of the statistical uncertainty percentages. All QA plans with variation of statistical uncertainty and voxel size will then be administered on a linear accelerator and measured by a radiation measurement device.

B) Radiation Dose Measurement

The requirements for a radiation dose measurement device include the capability to measure a radiation dose distribution from all three techniques and also approximate as a measurement device with negligible inherent noise within a measurement. ArcCHECK, a very popular commercial diode based measurement device produced by Sun Nuclear satisfies both of these criteria [16-19]. ArcCHECK is a cylindrical water-equivalent phantom with a three-dimensional array of 1386 diode detectors [17]. A common limitation for many different radiation measurement devices is the inability to accurately measure VMAT based treatment plans. ArcCHECK was primarily designed for this reason. Another great reason for the selection of ArcCHECK is due to the software suite provided with the product which allows many useful tools to directly apply computational analysis and analyze the measurement data.

C) Gamma Analysis Index

For all γ comparisons, the measurement profiles are to be selected as the reference profile. The recommended γ criteria based on TG 119 and clinical practice is 3%/3mm. For this experimental research project, both the 3%/3mm and 2%/2mm criteria will be employed for all γ applications. The γ criteria is to be calculated using a local percent dose difference (%) and with a threshold of 10. The comparisons will be performed within a Sun Nuclear software suite called SNC Machine [20].

Discussion

The necessity for a comprehensive experimental project investigating the effects of statistical uncertainty and voxel size amongst multiple treatment techniques with additional variations is required to guarantee safe quality assurance with routine use of Monte Carlo dose calculation methods. Van Delinder et al. with a focus on 10 clinical head & neck radiation therapy plans was able to demonstrate an average increase of 0.7% in γ pass rates going from 0.5% to 5% statistical uncertainty at a voxel size of 1mm for a 3%/3mm γ criteria [10]. As a result from this single study, there are still many questions regarding the magnitude that this phenomenon would have if switched to a different technique using different treatment circumstances. As the prior study was performed only on head and neck treatment cases, a change in treatment site should be performed to compare the resulting effect. Radiation oncology is not limited to IMRT and employs the use of many different techniques which have yet to be studied. 3DCRT requires less complexity than an IMRT designed treatment plan while VMAT requires considerably more [21-23]. As Monte Carlo based dose calculation methods are rapidly increasing in clinical use and will soon be the standard format in performing treatment plan dose calculations. The design of this study can directly answer many key questions on the effects of statistical uncertainty and voxel size on γ pass rates. This experimental design acts as a contrasting research experiment when combined with prior literature allowing the clinician the ability to use the direct results and develop clinical recommendations for IMRT QA involving the use of Monte Carlo based dose calculations.

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