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ORIGINAL ARTICLE

A quantitative measure for radiation treatment plan quality

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Summary

Purpose: *To develop and validate an intensity modulated radiation therapy (IMRT) treatment plan quantitative score using QUANTEC dose/volume parameters to assess plan quality.*

Methods: *132 IMRT and volumetric modulated Arc therapy (VMAT) patient plans of various treatment sites were evaluated. The optimized plan's dose volume histogram (DVH) was exported to Velocity for evaluation. The proposed scoring was based on calculating the shortest distance from the QUANTEC objective to the DVH line of each organ. Each plan was normalized against the ideal plan where the organs at risk (OARs) received no dose and hence the distance between the QUANTEC objective and the DVH line was maximized. These normalized scores enabled the comparison of the quality of plans across treatment sites and dosimetrists. The scores were plotted and statistically analyzed to serve as a basis for future research.*

Results: *The score for each treatment site was evaluated and the average percentage scores±SD were found to be 43.5 ± 21.0, 33.3 ± 31.7, 42.6 ± 23.3, 40.2 ± 24.4, 33.5 ± 23.5 for the sites of abdomen, brain, chest, head/neck, and pelvis respectively. Differences in scores between the treatment sites were largely attributed to OAR segmentation and proximity of the OAR to the planning target volume (PTV). Small score differences between dosimetrists were attributed to the number of plans they have completed.*

Conclusion: *This approach allows comparison of patient treatments which will help improve patient care and treatment outcomes. A larger sample of treatment plans is being evaluated to investigate the effect of dosimetrist's experience on plan quality.*

Key words: *DVH, photons, plan evaluation, radiation therapy*

Introduction

Radiation therapy has progressed greatly since the introduction of IMRT [1]. This type of radiotherapy has allowed conventional linear accelerators (LINAC) to deliver higher doses to the tumor by optimizing the positions of individual leaves of the multileaf collimator (MLC) during the treatment. IMRT optimization allows the planner to select the number of beams and their direction and then inversely optimize the dose distribution to maximize the dose to the tumor while sparing the OARs. A rotational aspect of IMRT, known as volumetric modulated radiation therapy (VMAT) [2], has been recently introduced and is being widely used. This technique allows for more degrees of freedom during planning due to the ability to deliver radiation from a full 360 degrees during the treatment. VMAT provides a faster delivery of the treatment and uses fewer Monitor Units (MU) [3].

Both of the aforementioned treatment techniques use inverse planning methods and depend highly on patient anatomy and normal tissue dose/volume constraints during optimization. Such constraints were defined by Emami et al. [4] and later

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refined by QUANTEC [5] to provide a guide for treatment planning. Once a plan has been optimized and calculated, the resulting three-dimensional (3D) dose distribution is evaluated for adequate dose coverage of the PTV. The dose volume constraints are also evaluated for each OAR within the irradiated volume against the objectives requested during the plan optimization. Other checks of the dose distribution normally include the location and magnitude of "hot" and "cold" spots within the PTV. Unfortunately, a DVH does not provide spatial information, making such evaluation insufficient for plan approval by itself [6]. Moreover, it is not enough to simply meet the dose/volume constraints to obtain the best plan. Theoretically, a better plan (more uniform PTV coverage, better OAR sparing, faster delivery, etc.) might exist if a different optimization starting point was selected and it should be the radiation oncology team's interest to always strive for the best possible plan. Often, a number of treatment plans are available for evaluation. The task of evaluating radiation therapy treatment plans qualitatively by examining the DVHs is not easy, especially if plan objectives are partially or even fully met. A quantitative method should be available to score each plan's quality.

In a facility with a large number of clinicians it is necessary for all plans to be created similarly to allow efficient coordination during planning and treatment. Several variables can affect the quality of the plan: patient anatomy, dosimetrist's experience, physician's plan objectives, treatment planning system (TPS) optimization algorithm, patient load, etc. Ideally, a plan quality metric could be used to track plan quality through time to maintain high quality planning.

Table 1. Dose/Volume parameters for the organs at risk in the study [4,5]

Organ	*Volume parameter (%)*	*Dose (Gy)*	*Toxicity (%)*
Brain	Max	<60	<3
Brain stem	Max	<54	<5
Optic nerve / chiasm	Max	<55	<3
Spinal chord	Max	<50	0.2
Cochlea	Mean	<45	<30
Parotid	Mean	<25	<20
Pharynx	Mean	<50	<20
Larynx	Max	<66	<20
Lung	30	<20	
Esophagus	Mean	<35	5-20
Heart	Mean	<26	<15
Liver	Mean	<30-32	<5
	Max	<15	<5
Kidney	Mean	<15-18	<5
	55	<12	<5
	32	<20	<5
	30	<23	<5
	20	<28	<5
Stomach	Max	<45	<7
Small bowel	195 cc	<45	<10
Rectum	50	<50	<15
	35	<60	<15
	25	<65	<15
	20	<70	<15
	15	<75	<15
Bladder	Max	<65	<6
	50	<65	
	35	<70	
	25	<75	
	15	<80	
Penile bulb	Mean	<50	<35

This study was undertaken to address the need to provide a method to assess the quality of a treatment plan based on its DVH, plan objectives and prescribed dose and give the user a representative quantity of the plan's score. In previous studies, a different quality metric was used in which objectives were chosen and weighted based on the importance suggested by the researcher [7]. In this study, objectives were chosen based on clinical need and weighting was not necessary. If this method was adopted in a different clinic it would be simple to change the way objectives are chosen and if weighting is required. The proposed method is intended to be easy to implement and can be broadly used.

Methods

This study analyzed 132 patients with VMAT and IMRT step-and-shoot plans. Sixty one patients were treated with photons of 6 MV energy, whereas 71 patients were treated with 10 MV photon beams. Five different treatment sites were evaluated: abdomen, head and neck, pelvis, chest and brain.

All the plans were optimized using the Philips treatment planning software, Pinnacle® V9.10 (Philips Radiation Oncology Systems, Fitchburg, WI). The collapsed cone convolution superposition (CCCS) algorithm was chosen for dose calculation for all the plans using a dose grid resolution of 0.3 x 0.3 x 0.3 cm [8]. Each patient's optimized 3D dose distribution, CT images and segmented structures were then exported to Velocity® (Varian Medical, Palo Alto, CA) using DICOM protocols.

The dose-volume objectives (DVOs) for each of the treatment sites analyzed were based on the QUANTEC and Emami organ parameters (Table 1). It should be noted that the DVOs described in Table 1 were not necessarily the ones that were used during optimization. These DVOs are chosen for establishing homogeneity in the analysis of the results.

The treatment plans were optimized by 5 dosimetrists, all trained at the same facility. Their years of experience varied from 1 to 25 years: Dosimetrist 1 had one year of experience, dosimetrists 2, 3 and 5 had more than 10 years and dosimetrist 4 had 5 years of experience.

For all exported plans in Velocity®, every OAR DVH was compared against the QUANTEC objectives as shown in Figure 1. Using Equation 1 the distance from the QUANTEC to the intersection of the DVH line was calculated. This distance was used for the calculation of the plan score (Equation 1).

While D represents the QUANTEC objective dose, d is the actual received dose after treatment at the intersection of the DVH line, X is the prescription dose, V is the QUANTEC objective volume (Figure 1) and v is the actual volume percentage receiving dose. All these values were extracted from Velocity®. The data was used to

$$Raw\ Score = \sum_{i=1}^{n} \sqrt{\left(\frac{D_i - d_i}{X}\right)^2 + \left(\frac{V_i - v_i}{100}\right)^2}, \forall\ OAR\ i$$

Equation 1. A distance formula to compare the objective constraint to the actual plan DVH. The raw score is the summation (Σ) of all organ at risk (OAR) scores.

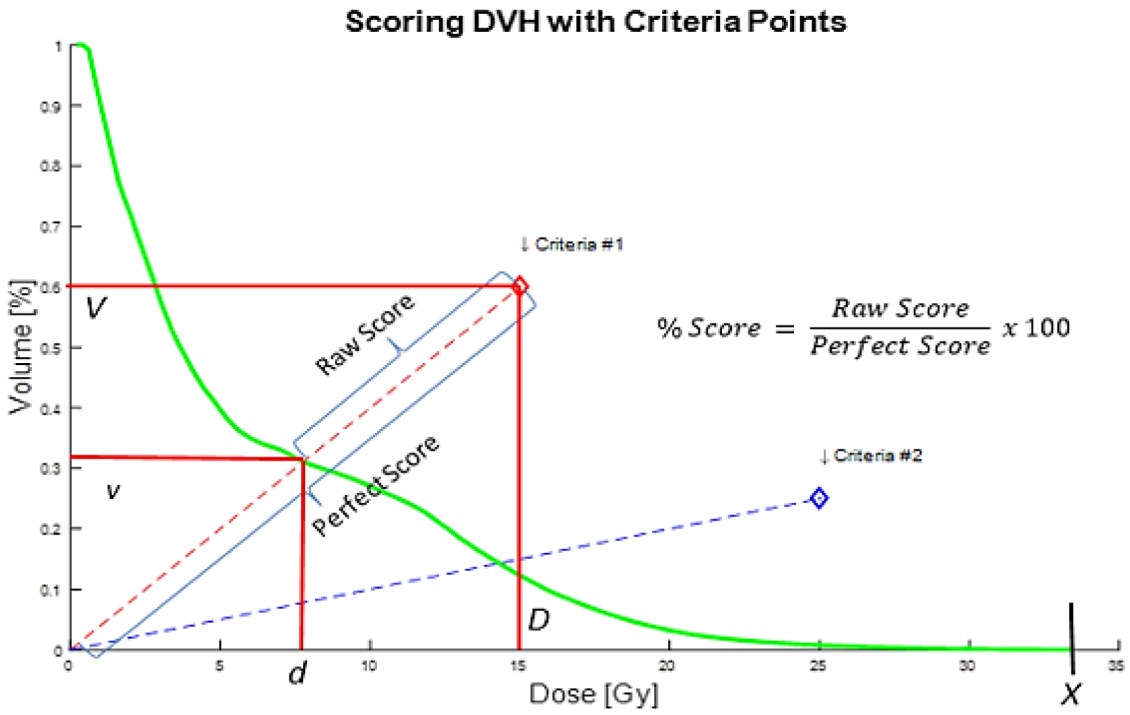

Figure 1. The raw score is represented by the distance from the criteria point to the nearest point on the DVH. The perfect score is the distance from the criteria point to the 0 axis.

calculate the plan score using Equation 1. The total raw scores were added together, giving every met objective (d<D) a positive value and any failed objective (d>D) a negative value. The raw score was then compared to the perfect score which assumes no dose is deposited in the organ being analyzed (*d*= 0). The "perfect scores" were also added together and then compared to the raw score to find a percentage score. This percentage provided a quantitative value for the plan. The normalized scores could then be compared across sites and all patients equally.

The following example demonstrates the steps in calculating the treatment plan score for a patient. The treatment plan structure set and calculated dose distributions exported to Velocity®. Table 2 demonstrates the organization of the data during a calculation. Each OAR dose/volume parameter was analyzed as discussed previously against the DVH and placed in the table for full calculation. The individual score of each OAR was calculated and all were summed together. The same method was followed for the normalized total with the assumption that no dose was received by the tumor. The % score was then found by comparison of those two totals.

Results

The score for each plan was calculated and the average percentage scores±SD per site were 43.5 ± 21.0, 33.3 ± 31.7, 42.6 ± 23.3, 40.2 ± 24.4, 33.5 ± 23.5 for abdomen, brain, chest, head/neck, and pelvis, respectively. All treatment plan scores were evaluated and compared across treatment sites and across dosimetrists. Table 3 shows the breakdown of the percent score analysis done across sites. Figure 2 provides a graphic representation for the comparison across the different sites.

Table 2. Example showing organization of sheet with calculations for each organ at risk

	Prescription 7020 cGy						
OAR	*Plan objectives*		*Optimized DVH points*		*Dose difference*	*Vol difference*	*Score*
	Dose(cGy)	*% Vol*	*Dose (cGy)*	*%Vol*			
Small Intestine	4500	195	3336	139.6	0.17	55.4	0.6
Bladder	6500	Max	7368	0.0	**-0.12**	0.0	**-0.1**
Bladder	6500	50	5152	39.0	0.19	11.0	0.2
Bladder	7000	35	6224	31.1	0.11	3.9	0.1
Bladder	7500	25	7056	23.4	0.06	1.6	0.1
Bladder-CTV Fossa	8000	15	7152	14.8	0.12	0.2	0.1
Rectum	5000	50	4144	41.3	0.12	8.7	0.1
Rectum	6000	35	5024	29.9	0.14	5.2	0.1
Rectum	6500	25	5792	22.4	0.10	2.6	0.1
Rectum	7000	20	6256	17.8	0.11	2.3	0.1
Rectum	7500	15	6656	13.4	0.12	1.6	0.1
Penile bulb	5000	Mean	4352	0.0	0.09	0.0	0.1
Score Total							1.7
Normalized Total							12.0
% Score							14.2

Bold numbers show negative values which signify a failing objective. DVH: dose volume histogram.

Table 3. Five sites were analyzed and the following numbers are the mean, maximum value, minimum value and standard deviation (SD) of the percent scores for abdomen, brain, chest, head and neck (H/N) and pelvis

	Score for each site					
	Abd	*Brain*	*Chest*	*H/N*	*Pelvis*	*All sites*
Mean	43.5	33.3	42.6	40.2	33.5	36.7
Max	75.9	92.2	87.5	80.8	99.6	-
Min	15.3	-3.3	-4.3	-5.1	-2.0	-
SD	21.0	31.7	23.3	24.4	23.5	24.3
Number of plans	8	11	15	30	64	128

The numbers are the corresponding values of each analysis for the percent scores (e.g. 43.5 is the mean for all abdomen plans)

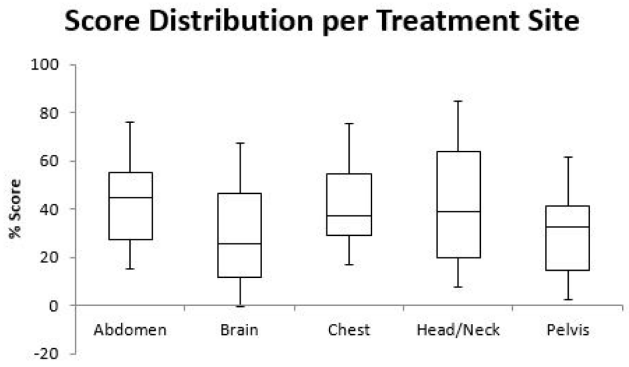

Figure 2. The distribution of scores for all the different sites evaluated.

Table 4. A head/neck patient and a pelvis patient had a treatment plan created by each dosimetrist. It is possible to choose the best plan by choosing the best score within the five created

	Head (%)	*Pelvis* (%)
1	17.1	32.3
2	28.2	32.4
3	18.4	32.5
4	20.5	32.9
5	17.7	15.9

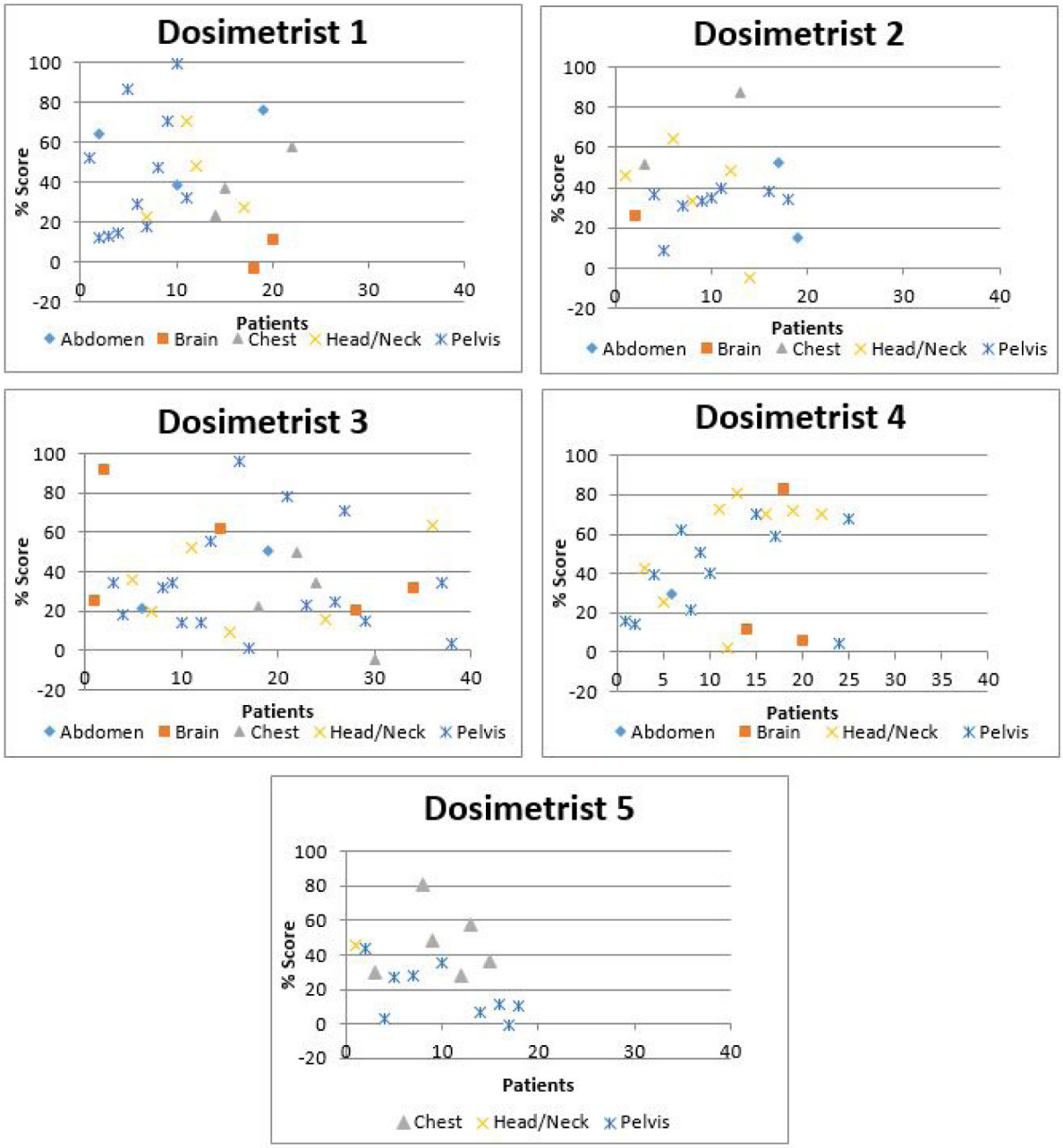

Figure 3. Comparison of the score of each individual patient treatment plan created by the five dosimetrists examined in this study. The variation in the experience of the individual dosimetrists is evident in the number and types of treatment plans they performed.

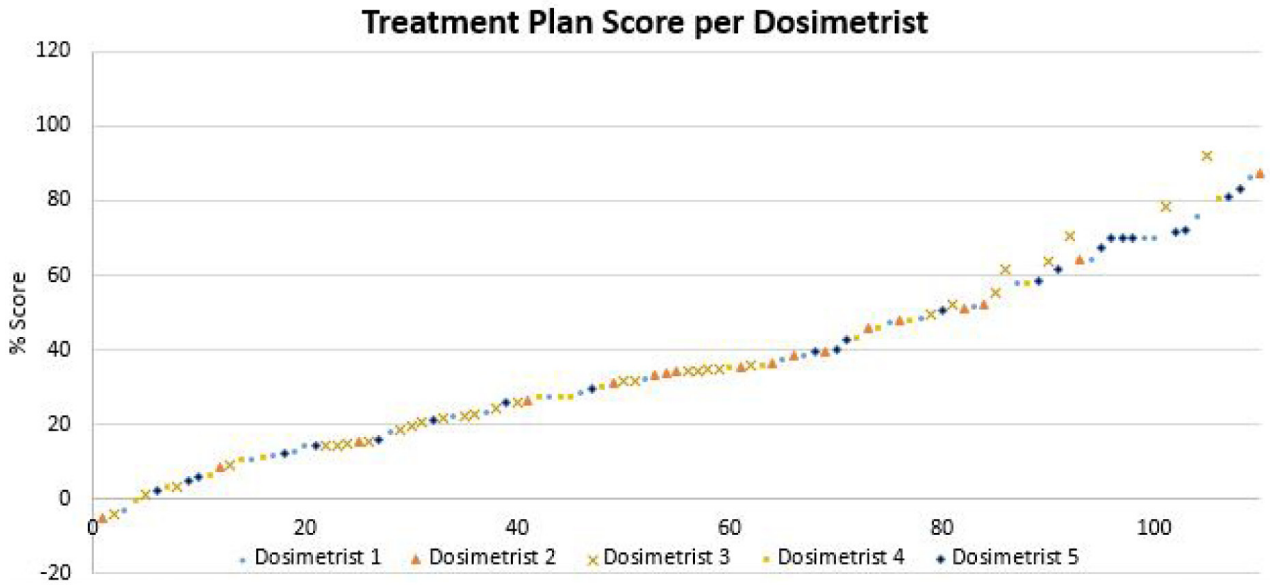

Figure 4. All treatment plan scores obtained in the course of this analysis. Some negative scores can be seen at the bottom of the graph. Negative numbers were possible due to failure to meet OAR objectives.

An analysis of the plan's scores was also performed for each dosimetrist. The results are shown in Figure 3. Each dosimetrist had a different number of data since the experience of each dosimetrist was different and therefore correlated with the number of plans created for this study. The score averages±SD were: 41.1 ± 27.2, 37.5 ± 20.5, 34.9 ± 25.2, 43.9 ± 27.1, and 30.6 for dosimetrists 1, 2, 3, 4 and 5 respectively. The few negative scores observed were due to difficulties in meeting the plan objectives because of anatomical abnormalities in the patient, physician preferences on isodose lines or having to avoid areas of previous radiation. Figure 4 shows all the scores obtained in the course of this analysis.

Discussion

The proposed method of quantifying the radiation therapy treatment plan quality provides a fast and simple way to compare different treatment plans for a given patient, or it can be used for ongoing assessment of the quality of the plans in clinic. Moreover, the suggested method provides proper normalization, which allows comparison of plans independent of treatment site. This study also provides a decision support tool if needed for several plans for the same patient. Throughout the development of this study, 2 patients were chosen (1 head/neck and 1 pelvis) and all 5 dosimetrists were asked to create a plan. The evaluation algorithm was then applied to each variation in order to choose the best plan. Table 4 shows the results of this study.

There are obvious limitations that should be considered such as: (1) the difficulty of the plan at hand; and (2) the ease to meet some of the objectives and not others. These limitations can be removed by weighting certain objectives based on the importance to the treatment plan and adding a factor for the difficulty in achieving dose-volume objectives during the score calculation. This study did not weigh objectives in order to have an all-encompassing method for all plans and weighting objectives would have to be patient plan specific. The proposed method will allow users to easily evaluate plans and produce a quantitative value of reference. It will allow monitoring to encourage hospital and radiotherapy treatment planning improvements, along with improved plan quality and time savings.

Conflict of interests

The authors declare no conflict of interests.

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