3DVH™ AND TISSUE HETEROGENEITIES:

PDP Accuracy in the Presence of Significant Tissue Density Variation

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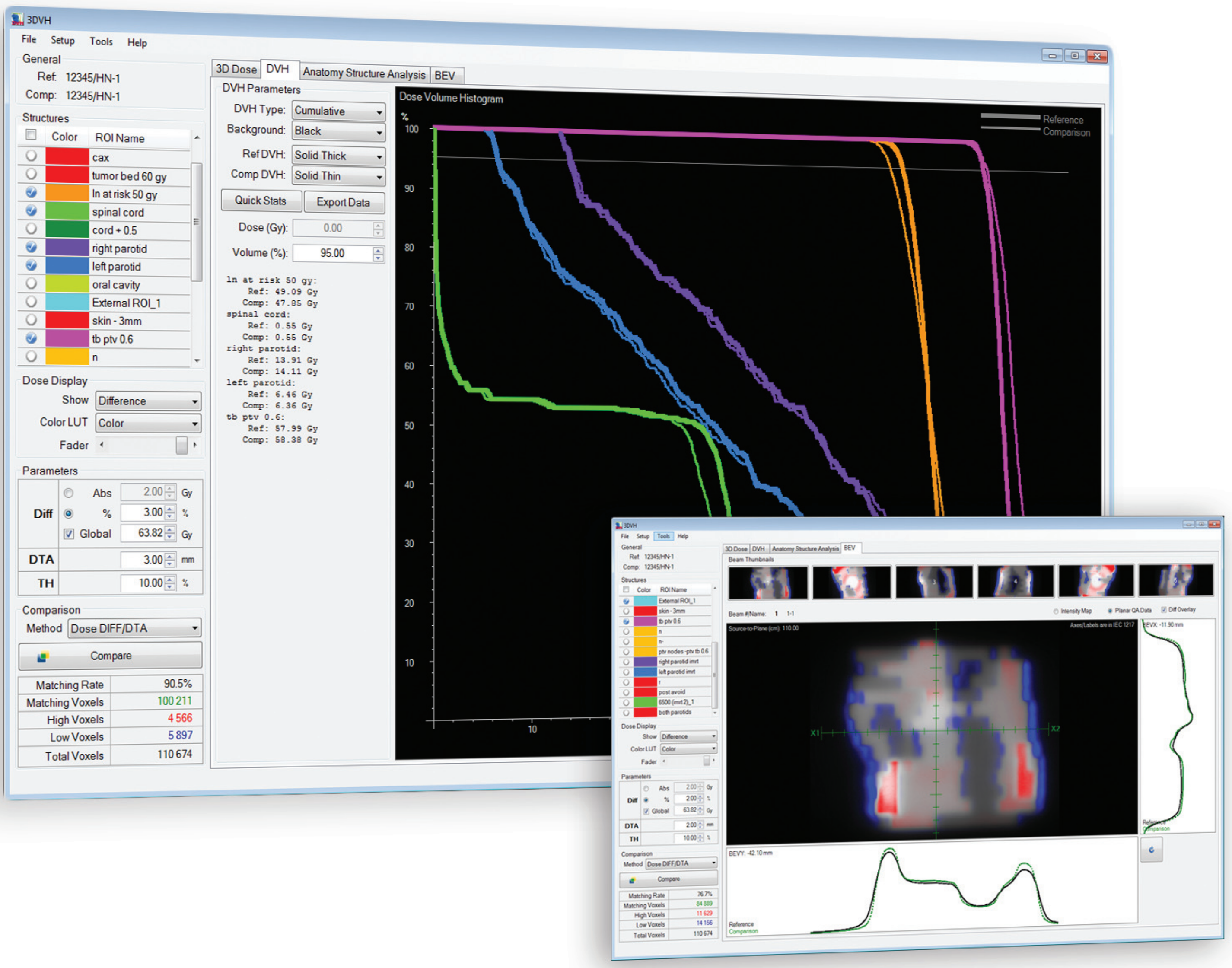

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introduction ▶▶▶

3DVH utilizes the Planned Dose Perturbation (PDP) algorithm to accurately estimate dose-to-patient and patient DVH using conventional planar IMRT QA data as inputs. The goal is to produce clinically-relevant metrics to replace conventional metrics that are limited in both sensitivity and specificity.[1,2] The presence of significant tissue heterogeneities and their effect on PDP accuracy is a consideration given that: input dose planes are a single depth in a homogeneous QA phantom, and CT image sets are not required for the PDP calculation. It is the intent of this technical note to clarify how PDP is very accurate for patient volumes that have significant tissue heterogeneity.

Remapping of CT-based tissue-heterogeneities is not required for 3DVH because 3D dose voxel modification can be accomplished with great accuracy by knowing the patient geometry (surface, internal regions-of-interest), and the beam geometries relative to the patient model. Depth-dependence is built into PDP (in addition to other variables, such as the effects of beam energy, linac, and MLC model). The goal of PDP is not to correct for heterogeneities if the TPS has not, because a properly commissioned modern TPS dose algorithm will account for this.[7] TPS errors (e.g. beam modeling, failure in a specific patient plan, etc.) or delivery errors (e.g. MLC errors, file corruption, output errors, etc.) that are measured in conventional IMRT QA, are used by PDP to estimate the impact to the patient dose/DVH. The inherent heterogeneity corrections by the TPS will be preserved and the dose voxels will be modified correctly.

Any and all QA systems should be verified with rigor[8] over many permutations of plans and patient types. Accuracy testing of PDP has been discussed[9], however the focus of this technical note is to illustrate the high performance level of PDP in the presence of large tissue heterogeneities.

What's the difference?

QA systems that use pencil beam algorithms[3] try to predict beam incident fluence based on measurements, and then continue to 3D dose with a calculation by an independent dose algorithm. While this strategy does produce a dose-to-patient estimation for comparison to the original treatment plan, the dependence on another dose algorithm introduces new sources of variation and potential error, in addition to the need to model and maintain the beam model similar to what is required by a TPS. If the dose algorithm in the QA system is inferior to the TPS, it may negate the validity as a “virtual measurement”. For example, any QA system built on a pencil beam dose calculation to the heterogeneous patient[3] will suffer from well-known deficiencies in accuracy in the presence of common tissue heterogeneities.[4,5,6]

materials and methods ▶▶▶

Lung IMRT Plan

In order to analyze PDP's accuracy in predicting IMRT dose in the presence of tissue heterogeneities, a previously described method[8] that allows analysis of full density 3D grids is employed; with an emphasis on the large tissue heterogeneities of a lung IMRT plan (Figure 1). An “error-free” plan/beam is used to calculate per beam IMRT Planar Dose files (dose to a flat phantom, one depth) that serve as “simulated measurements”. Then, errors are introduced to the plan via the beam model, to emulate an imperfect calculation or delivery, and both the 3D patient dose and the per-beam QA dose planes are calculated (“error-induced”). Therefore, the error-free and error-induced IMRT QA dose planes represent the simulated IMRT QA measurements and calculations, respectively; these are the inputs into the PDP algorithm, along with the imperfect error-induced 3D patient dose.

PDP is performed, and the resulting PDP-corrected patient dose/DVH can then be compared to the error-free patient dose/DVH, which was calculated by the error-free beams. These comparisons quantify the ability of PDP to predict the correct dose in the presence of heterogeneities using patient dose differences and DVH differences as comparison measures.

The induced errors in this study's example are extreme, with an average IMRT QA of 3%/3mm DTA passing rate of 53.9%. These large errors were used to demonstrate that PDP is accurate and effective; even in extreme cases of dose error and tissue heterogeneities. The locations and degrees of the induced errors per beam are illustrated in Figure 2.

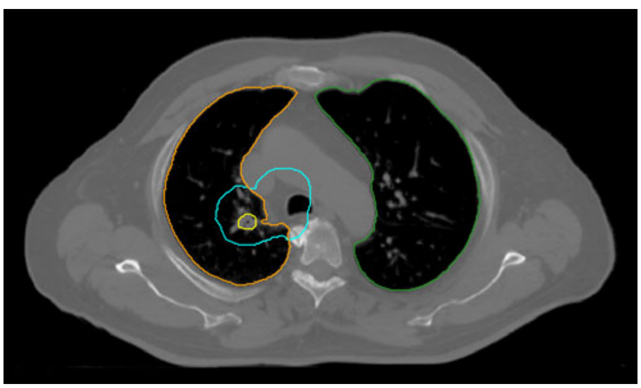

Figure 1 - Methods, 7-field lung IMRT
Lung heterogeneities evident in axial planning CT images.

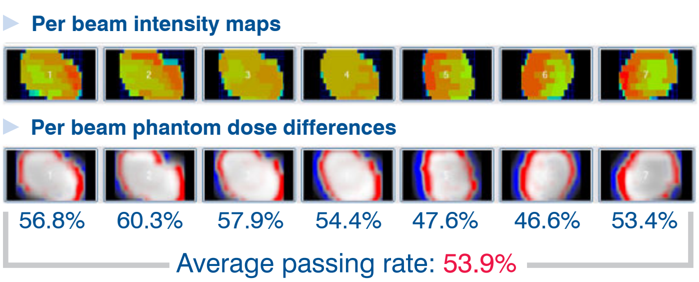

Figure 2 - Methods, 7-field lung IMRT
In this example, there were very large degrees of errors induced to be corrected for by PDP. This was to illustrate that PDP works even for extreme errors and in the presence of tissue heterogeneities. The patterns of errors per beam are shown in the middle row, and the conventional IMRT QA results for each of the seven beams in the lung plan are show in the bottom row.

Single Beam on Heterogeneous Phantom

Two step-and-shoot IMRT beams are designed with three segments each and with segment sizes and exposure levels as defined in Figure 3. These beams have dose level differences in the outer outline (B2 > B1) and the middle outline (B1 > B2), with the center outline roughly equal in MU delivered. The heterogeneous phantom has three large slabs of density: the first goes from 0 to 5 cm deep and is water-equivalent, the second goes from 5 cm to 15 cm deep and has 30% of water's density, and the final slab starts at 15 cm and is again-water equivalent. This design allows the performance of PDP to be assessed for regions of high- and low-dose errors, and through significant volumes of low-density material.

In this example, B1 is used as the delivered/actual beam and B2 as the planned beam. The B1 and B2 planar QA results are then calculated in a homogeneous flat QA phantom as per conventional IMRT QA methods. The PDP algorithm estimates the "patient" (heterogeneous phantom) delivered dose, using only the B2 planned dose and the planar QA pairs. Next, comparison of the B2 plan to: 1) the PDP-modeled B1 plan, and 2) to the actual B1 plan, is performed to prove that both comparisons yield equivalent results. Additionally, a comparison of the PDP-modeled B1 plan to the actual B1 plan is performed to directly quantify the accuracy of the PDP algorithm.

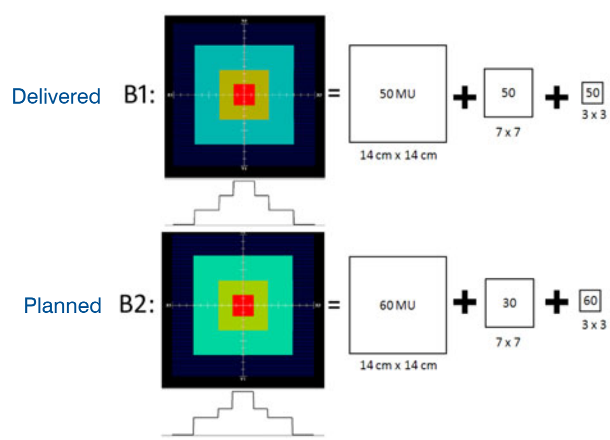

Figure 3 - Methods, Single beam/heterogeneous phantom
Two step-and-shoot IMRT beams used for the single beam plans on a heterogeneous phantom.

Lung IMRT Plan

The dose errors induced to this treatment plan were large, as evident in Figure 2. However, when PDP corrects the error-induced patient dose to yield a new dose estimate, this PDP estimate accurately reproduces the error-free patient dose which was calculated for comparison purposes only, and not used or referenced at all by the PDP algorithm. This is illustrated in Figures 4 through 6.

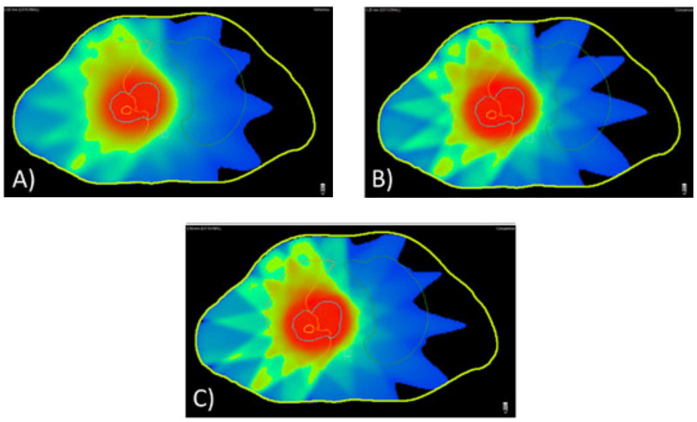

Figure 4 - Results, 7-field lung IMRT
Axial dose plane in the presence of tissue heterogeneities for a seven-beam IMRT plan: A) Error-induced dose; B) PDP-corrected dose; and C) Error-free dose (i.e. "answer key"). Note how the PDP dose (B) closely models the error-free dose (C), despite the large induced errors and the large tissue heterogeneities.

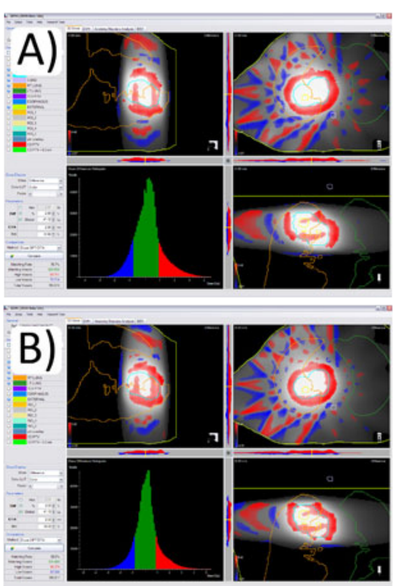

Figure 5 - Results, 7-field lung IMRT
Dose differences of the seven-beam IMRT plan on representative sagittal, axial, and coronal dose planes: A) Error-induced vs. PDP-corrected; and B) Error-induced vs. Error-free. Note how panels (A) and (B) are similar, including the passing rate of 78.7% (A) 80.5% (B), meaning the analysis of planned dose vs. PDP estimated dose is substantially equivalent to the planned dose vs. the error-free dose. In other words, PDP is working to estimate the real dose to the patient, but only using conventional phantom-QA planes as inputs.

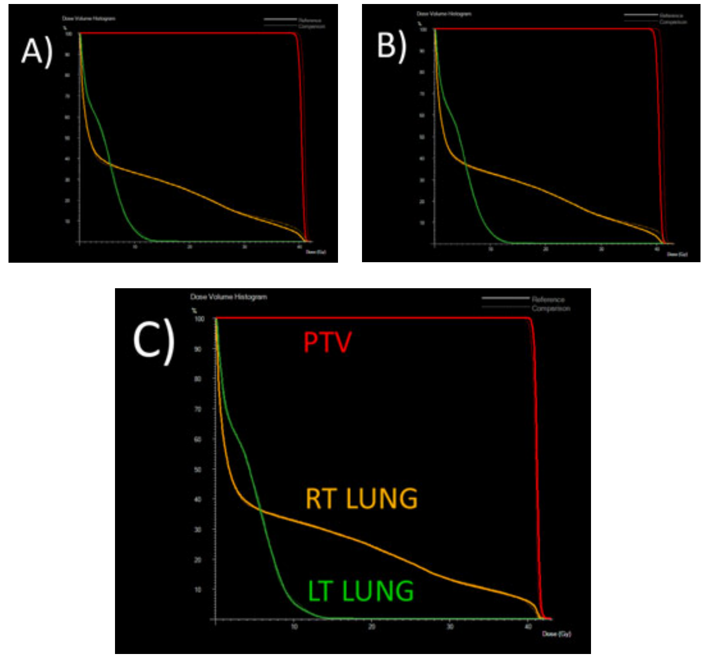

Figure 6 - Results, 7-field lung IMRT
DVH graphics of the seven-beam IMRT plan: A) Error-induced (solid) vs. PDP-corrected (dashed); B) Error-induced (solid) vs. Error-free (dashed); and C) Error-free (solid) vs. PDP-corrected (dashed). Note how panels (A) and (B) show the same DVH differences, while panel (C) shows very little difference between the curves, meaning that the PDP-corrected dose is predicting the error-free dose with great accuracy, despite: 1) large induced errors and 2) large tissue heterogeneities.

In Figure 4 and 6, the PDP dose resembles the error-free dose even though there were considerable volumes of low-density lung in this patient. Furthermore, if PDP is to be used to compare vs. the original treatment plan, PDP would yield similar comparisons to the original (error-induced) dose as the true (error-free) dose would. Figure 5 shows that this is true, as the comparison matching rates are 78.7% and 80.5% for the PDP vs. Error-induced and the Error-free vs. Error-induced, respectively*.

Finally, because the patient DVH curves are the common plan evaluation method, the expectation is that the PDP DVHs will be very similar to the actual (error-free) DVHs. Figure 6, shows that for both lungs and for the PTV, the PDP DVHs overlap the actual DVHs (panel C). Figure 6, panels A and B, illustrate that using PDP DVHs to compare with the original plan will yield analysis similar to if the actual dose to the static patient was known.

* Comparison criteria: 2%/2mm DTA, Global % Difference, 10% Lower Threshold

Single Beam on Heterogeneous Phantom

Figure 7 shows an axial view of the three dose volumes: B2 (Planned), PDP-modeled B1, and actual B1. The effects of the different levels of MU per segment are evident in this figure, as is the effect of the large volume of low-density material (from 5 to 15 cm deep) where the dose is scattering further than in the initial 5 cm of water-equivalent density. From this figure, the PDP-modeled B1 dose and the actual B1 dose look qualitatively similar.

Figure 8 shows axial view of dose difference analyses. In this figure, the PDP-modeled B1 dose (calculating by perturbing the 3D B2 dose using the PDP algorithm) generates almost identical comparisons to B2 as does the actual B1 dose compared to B2. Furthermore, the PDP-modeled B1 dose matches the actual B1 dose with a 100.0% matching rate at 2%/2mm, absolute dose, using 10% lower dose threshold. This PDP estimation was achieved in a phantom that had a 10 cm thick volume of low density material (0.30 density, relative to water).

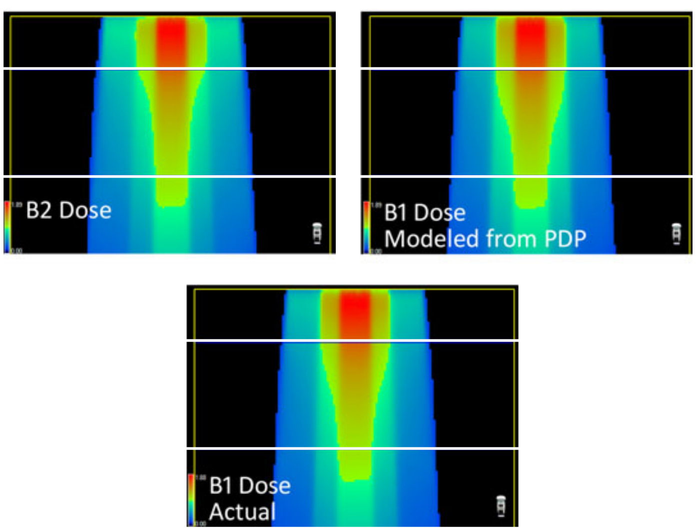

Figure 7 - Results, Single beam/heterogeneous phantom
The middle white region is 0.30 density relative to water, and this is qualitatively obvious from the wider spread in dose in that region. Shown here are: Left panel) B2 dose; Middle panel) B1 Dose modeled using the PDP algorithm, perturbing the B2 dose according to B1 and B2 planar QA files; and, Right panel) B1 dose, actual.

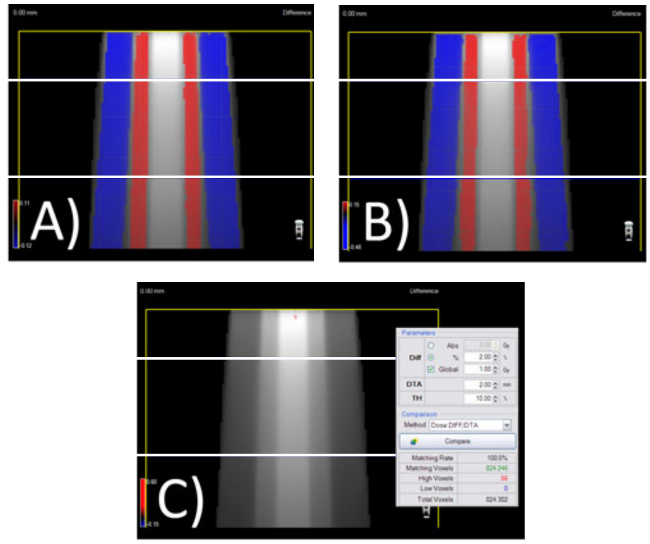

Figure 8 - Results, Single beam/heterogeneous phantom
Panel A) PDP-modeled B1 dose vs. B2 planned dose; Panel B) Actual B1 dose vs. B2 dose; Panel C) PDP-modeled B1 dose vs. Actual B1 dose. Panels A and B are similar to each other, and Panel C shows the PDP-modeled B1 dose matching the actual B1 dose with 100.0% of the points passing 2%/2mm, absolute dose difference, 10% lower threshold of analysis. This confirms PDP is perturbing (correcting) the dose accurately in the presence of large heterogeneous volumes.

discussions and conclusions ▶▶▶

3DVH's PDP algorithm can produce very accurate patient dose/DVH estimates even in the presence of extreme tissue heterogeneities, as evidenced in the lung patient IMRT and the heterogeneous phantom. This was also substantiated (with a lesser degree of heterogeneities) by the Head/Neck examples published previously, which also had regions of low and high-density.[9]

PDP assumes and requires that the TPS dose algorithm accounts for tissue heterogeneities in the original treatment plan. Modern algorithms – such as collapsed cone convolution (Pinnacle TPS, Philips Radiation Oncology Systems), AAA (Eclipse TPS, Varian), Superposition (XiO, CMS-Elekta), and Monte Carlo (various TPS) – all estimate dose in volumes of heterogeneous density. Unlike other QA systems that also aim to predict the dose in the patient geometry, PDP does not introduce new sources of error and variation by requiring an independent dose algorithm that calculates dose as a TPS would; rather, PDP estimates patient dose in 3D only as needed, based on high resolution dose-to-phantom data.

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