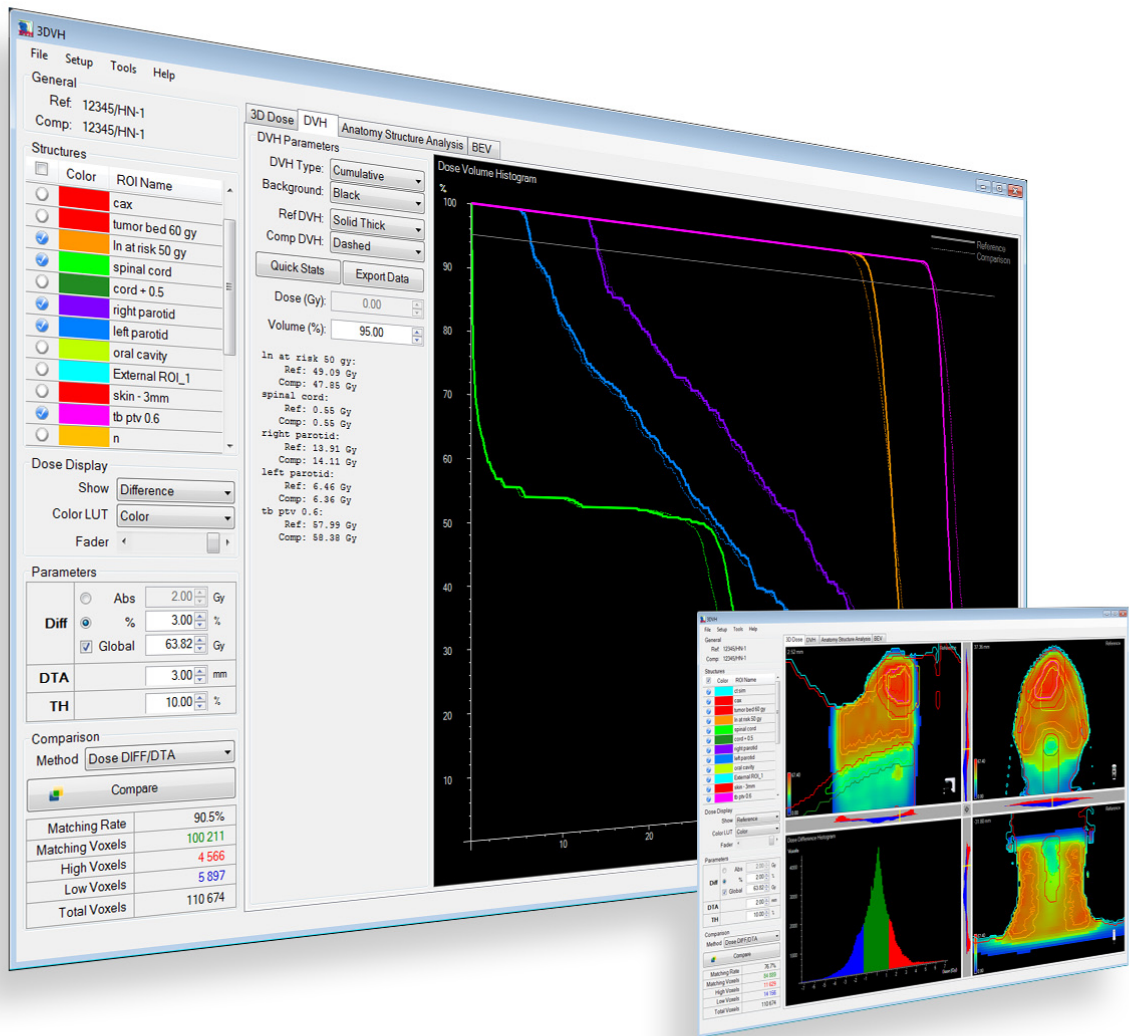


3DVH™:

On The Accuracy Of The
Planned Dose Perturbation Algorithm



Your Most Valuable QA and Dosimetry Tools

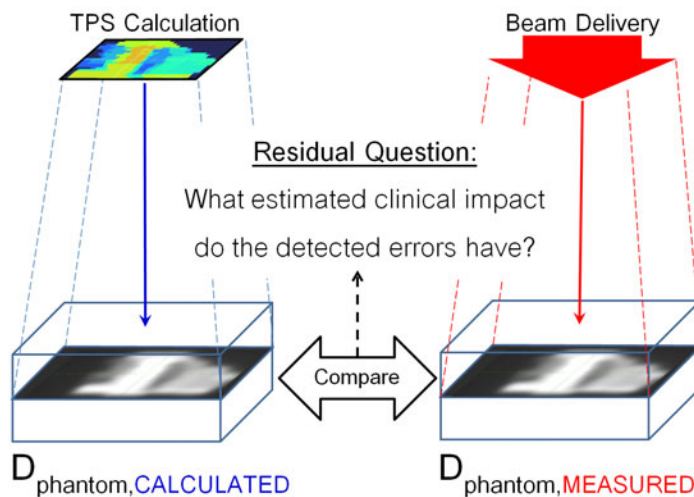
*Patent Pending

State-of-the-art IMRT QA of static gantry IMRT consists of beam-by-beam analysis of planar dose in a phantom, comparing measured vs. calculated absolute dose (Figure 1). This method, assuming usage of a detector array of sufficiently small detectors to avoid volume averaging, has proven to be sensitive in detecting errors in both the calculation and/or the delivery system^{1,2}.

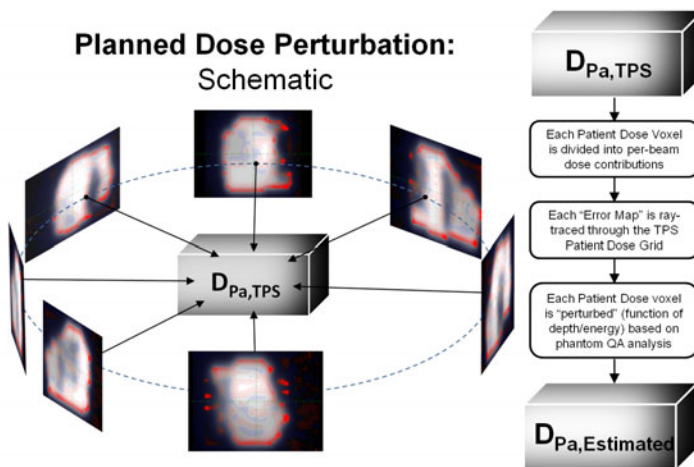
However, suggested action levels for IMRT QA have largely been based on what accuracy is achievable³⁻⁵ without proving whether what is achievable provides the necessary specificity to detect clinically relevant dose errors, per patient plan. There has been a call for correlative studies⁶ to determine the specificity of IMRT QA and a recent study has proven that conventional IMRT QA, though sensitive at detecting errors during commissioning, has almost no predictive power in detecting per-patient dose errors of clinical significance⁷. 3DVH is the solution.

The Sun Nuclear 3DVH™ solution uses conventional IMRT QA data (based on dose-to-phantom) to accurately predict the impact on patient dose and DVH. 3DVH processes this data from a phantom-based geometry to a heterogeneous patient dose-based geometry using a patent pending algorithm called “Planned Dose Perturbation” (PDP™) described at high level in Figure 2. PDP avoids the uncertainty and overhead of a duplicate dose calculation engine (which by itself can introduce new errors), and instead “perturbs” the patient planned dose to account for known errors measured in the conventional per beam QA.

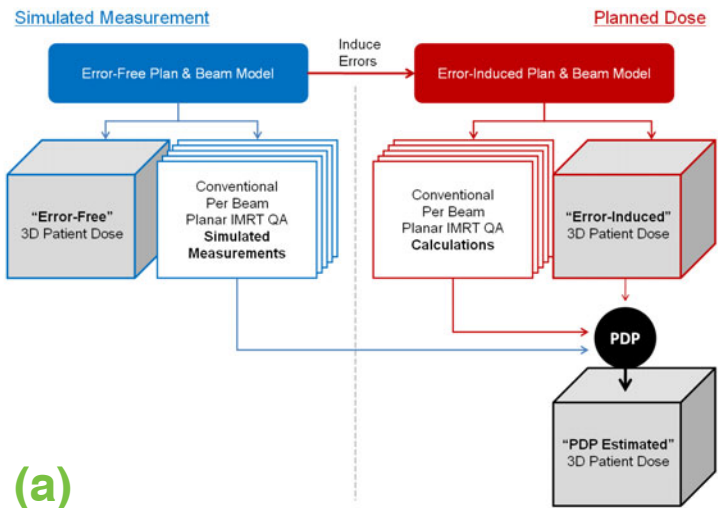
In a modern 3DVH-enabled clinic, the same QA measurements are made, but the analysis metrics are now clinically relevant. 3DVH analysis metrics include patient DVH changes, patient dose analysis per patient region of interest (ROI), and other patient dose-specific endpoints of interest to the user. 3DVH patient dose estimations must be very accurate to accomplish this. It is the purpose of this white paper to show some of the evidence of the accuracy of 3DVH and PDP.



▶ **Figure 1 -** Schematic of conventional IMRT QA.

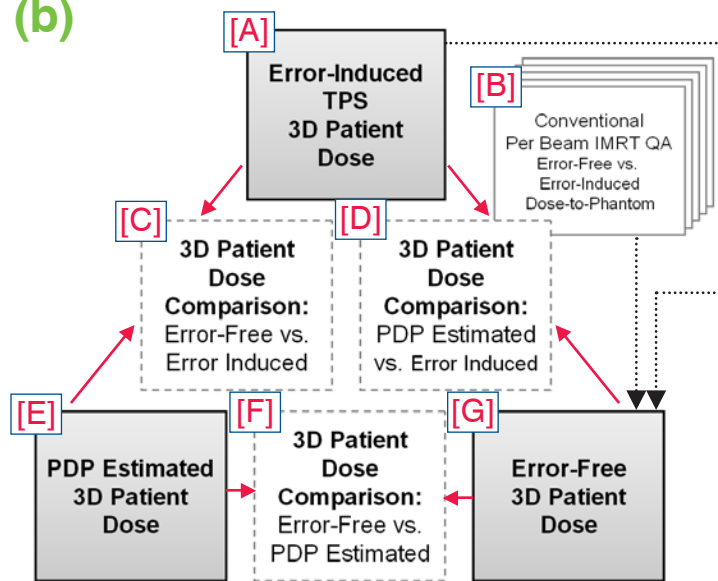


▶ **Figure 2 -** High level description of the PDP algorithm. (patent pending)



(a)

(b)



▶ General Strategy

Verifying the accuracy of a complex 3D patient dose can be challenging, as a full density 3D dose measurement clearly cannot be made in a true patient. A common strategy employed to verify TPS dose algorithms is to calculate dose in phantoms where the dose can be measured in a subset of the points, allowing measured vs. calculation comparisons. This same strategy can be used in verifying PDP, but with the following limitations: 1) the “patient” for which the original plan is created must be a simple phantom rather than a true patient; 2) in any 3D dose measurement, the number of points that can be verified with measurement is limited; and 3) in order to verify DVH and real clinical metrics (mean dose, max dose, D95, etc.), you need full density “measurements” and real anatomy.

Therefore, a more thorough and stringent method to verify PDP accuracy is used here. An “Error Free” plan/beam model is used to create a “correct” patient 3D dose and the associated per beam IMRT planar QA files (which in this case will represent “simulated measurements” to a flat phantom). Then, the plan and/or beam models have various errors induced to emulate an imperfect plan. (NOTE: Errors are really differences between the error free and the actual treatment plan, and can represent differences due to either TPS imperfections or delivery errors.) Now, the error free and error-induced IMRT QA planar dose files represent the simulated IMRT QA measurements and calculations, respectively; these are the inputs into the PDP algorithm, along with the error-induced 3D patient dose.

The resulting 3D PDP estimated dose can be compared against the error free 3D patient dose in order to quantify PDP accuracy. Figure 3 shows a schematic of this method.

▶ Figure 3 - Methods

PDP accuracy test strategy. Panel (a) illustrates how error free and error-induced plans/beam models are used to create test files. Panel (b) shows the analysis strategy for PDP accuracy: if PDP is accurate, then analysis results from the panel [C] comparison will be very similar to results from the panel [D] comparison. More importantly, panel [F] comparisons (Error Free vs. PDP) will result in almost all points passing (i.e. the same) and the DVHs from [E] will overlap those from [G].

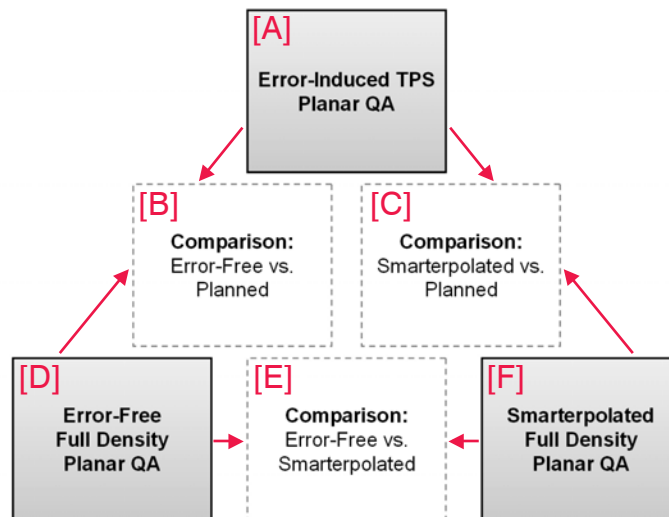
Note: The error-induced represents the TPS Dose

► Verification of Smarterpolation high density restoration

The PDP algorithm requires as input the pairs of measured vs. calculated planar QA (absolute dose planes to flat phantom). For film and EPIDose™, the input measured planes are both high resolution (small detectors, no volume averaging) and high density (full density array, no spaces in between detectors). However, for MapCHECK and MapCHECK 2, the high resolution diodes have spaces in between and are thus not full density. Because PDP requires full density planar dose input, a method called “Smarterpolation” was developed to accurately create full density array data from the MapCHECK diodes. Simple interpolation is not sufficient, instead, the a priori knowledge of dose gradients (from the TPS files) is used to “smartly” increase the dose density. All diode measurements stay exactly as acquired, but the slopes and gradients in between are filled in using information acquired from the TPS. Smarterpolation can be compared to a technique called “compressed sensing” that is also used in imaging applications⁹.

Smarterpolation therefore needs to be tested apart from the general PDP algorithm. This is done by taking full density, error-free dose planes and sampling them down to MapCHECK density to create MapCHECK-equivalent measurements.

Then, with no knowledge of the original full density plane, the sampled data is “smarterpolated” to estimate the full density plane, which can then be compared to the original full density plane to verify the performance of Smarterpolation. Figure 4 illustrates the test strategy for Smarterpolation.



► **Figure 4 - Methods**
 Smarterpolation test strategy. If Smarterpolation is accurate, then analysis results from the panel [B] comparison will be very similar to results from the panel [C] comparison. More importantly, panel [E] comparisons (Error Free vs. Smarterpolation) will result in almost all points passing in a comparison of [D] and [F].

► PDP Testing: Clinical IMRT Plans

Many tests have been run, all with excellent results and seven representative tests are documented here. Five of the tests are head/neck IMRT plans, and two are prostate plans. Multiple linacs are modeled (Varian and Elekta), and plans have at least five beams per plan. The degree and the types of errors induced are shown in Table 1.

Following Figure 3, moderate to large errors are induced into each plan to create the TPS planned dose. The error-induced plan is used to create the Planar IMRT QA calculation and is analyzed vs. the Planar IMRT QA Error Free measurement. These per-beam IMRT QA planes are input into the PDP algorithm with the error-induced 3D patient plan, and PDP estimates the actual 3D dose. The actual dose is compared to the error free dose with full 3D dose voxel analysis (2%/2mm with 10% lower dose threshold for analysis and global % normalization, normalized to the prescription dose of the plan). In addition, to ensure that the per-ROI doses are correct, the mean and the max dose per ROI are compared for the PDP dose vs. the Error Free Dose.

results ►►►

► PDP Testing: Clinical IMRT Plans

The results of seven PDP accuracy tests for clinical IMRT plans are summarized in Table 1. In all seven 3D patient plans, the PDP dose corrects the errant TPS dose and achieves greater than 99% of dose points passing 2%/2mm compared to the error free plan (global normalization, 10% lower threshold). In addition, the mean and max doses per ROI were all within 1% (PDP vs. Error Free). Examples of the test strategy, with screen capture results, are shown in Figures 5-7. Notice how the PDP Dose vs. Error-Induced Dose analysis looks almost identical to the Error Free Dose vs. Error-Induced Dose analysis.

► PDP Testing - “Stress Test” IMRT Plans

The strategy is the same as the clinical plans, however the errors induced are very large, thus a “stress test” of the PDP algorithm. In Table 2, the plans are summarized. Six are single-beam plans, and one is a 3-beam plan. All plans are to a rectangular phantom (which represents the patient). The plan denoted P1 is a three-segment IMRT beam with concentric square segments of sizes: 14, 7, and 3 cm and MU per segment of: 50, 50, and 50. The plan denoted P2 is a three-segment IMRT beam with concentric square segments of sizes: 13, 8, and 2 cm and MU per segment of: 50, 50, and 50. The plan denoted P3 is a three-segment IMRT beam with concentric square segments of sizes: 14, 7, and 3 cm and MU per segment of: 60, 30, and 60. All permutations of errors (substituting one beam for another) are tested, resulting in six tests. Then, a 3-beam plan with beams at both lateral directions along with AP, each with similar extreme errors, is tested.

► PDP Testing: “StressTest” IMRT Plans

The results of seven PDP accuracy tests for the “stress test” IMRT Plans are summarized in Table 1. In all seven 3D plans, the PDP dose corrects the errant TPS dose and achieves greater than 96% of dose points passing 2%/2mm compared to the error free plan (global normalization, 10% lower threshold). In addition, the mean doses per ROI were all within 1% (PDP vs. Error Free) and the max dose per ROI error ranges was -0.31% to 2.08% (PDP vs. Error Free). This accuracy of PDP is despite the fact that the induced errors in these tests were very large, corresponding to conventional IMRT QA passing rates ranging from 8.6% to 56.5%. An example of this test strategy, with screen capture results, is shown in Figure 8. Notice how the PDP Dose vs. Error-Induced Dose analysis looks almost identical to the Error Free Dose vs. Error-Induced Dose analysis.

► **Table 1 - Results**

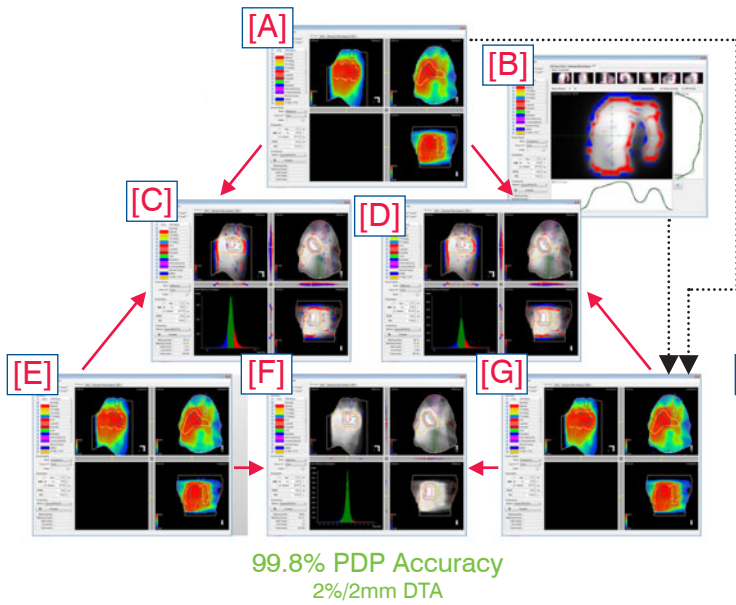
PDP Accuracy for estimating the correct dose for clinical IMRT plans. Even though the degree of induced errors is large (down to 47% conventional IMRT QA pass rate), PDP estimates the dose extremely well. All PDP estimates vs. the error free plan have passing rates of greater than 99% (full volumetric analysis at 2%/2mm, absolute dose). The PDP predictions of mean and max dose to critical volumes (ROIs) all have errors of less than 1.00%.

Plan	Induced Error	Degree of Induced Errors Results of Conventional IMRT QA Results (Averaged over all beams in plan) 2%/2mm DTA (Planar)	PDP Accuracy		
			PDP Patient Dose vs. Error Free Patient Dose 2%/2mm DTA (3D)	PDP Patient Dose vs. Error Free Patient Dose Average ROI Mean Dose Errors	PDP Patient Dose vs. Error Free Patient Dose Average ROI Max Dose Errors
Head/Neck 1 6-field, Elekta	TPS dose calculation has very shallow gradients, causing errors in: peaks, valleys, and edges	57.1%	99.9%	0.41%	-0.58%
Head/Neck 2 7-field, Varian 120	TPS dose calculation has very shallow gradients, causing errors in: peaks, valleys, and edges	64.8%	99.8%	0.41%	-0.06%
Prostate 1 5-field, Elekta	TPS dose calculation has very shallow gradients, causing errors in: peaks, valleys, and edges	54.5%	99.5%	-0.43%	0.24%
Prostate 2 5-field, Elekta	TPS dose calculation has too-sharp gradients, causing errors in: peaks, valleys, and edges	47.0%	99.1%	0.09%	-0.24%
Head/Neck 3 7-field, Varian 120	MLC Transmission modeled too high (2X) in the TPS (also emulates delivered transmission too low)	99.4%	100.0%	-0.06%	-0.06%
Head/Neck 4 7-field, Varian 120	MLC Transmission modeled too low (0.5X) in the TPS (also emulates delivered transmission too high)	99.4%	100.0%	0.07%	0.04%
Head/Neck 5 7-field, Varian 120	Penumbra semi-shallow in the TPS model; delivered dose sharper	85.0%	100.0%	-0.03%	-0.14%

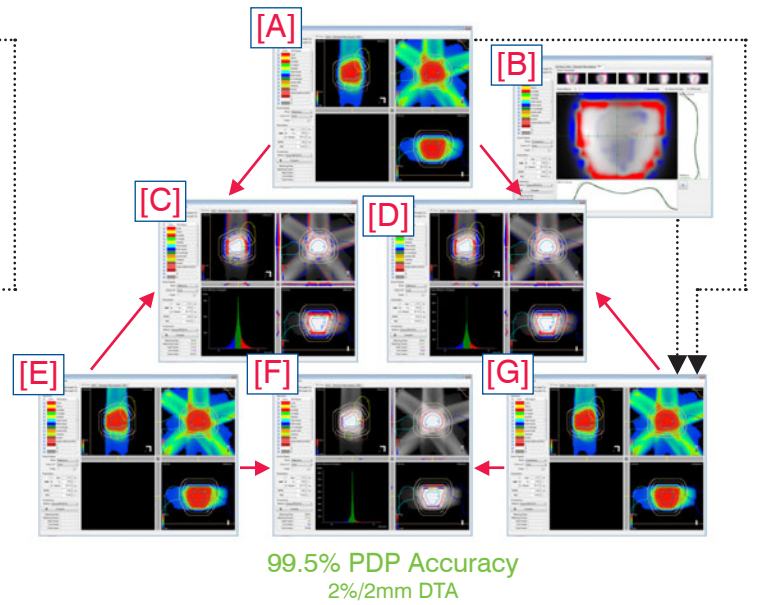
► **Table 2 - Results**

PDP Accuracy for estimating the correct dose for “stress test” IMRT plans with gross errors introduced. The degree of induced errors is very large (8.6 – 56.5% conventional IMRT QA pass rate), and still PDP estimates the dose extremely well. All PDP estimates vs. the error free plan have passing rates of greater than 96% (full volumetric analysis at 2%/2mm, absolute dose). The PDP predictions of mean dose to critical volumes (ROIs) all have errors of less than 1.00%, and the errors in max dose to ROIs range from -0.31% to 2.08%.

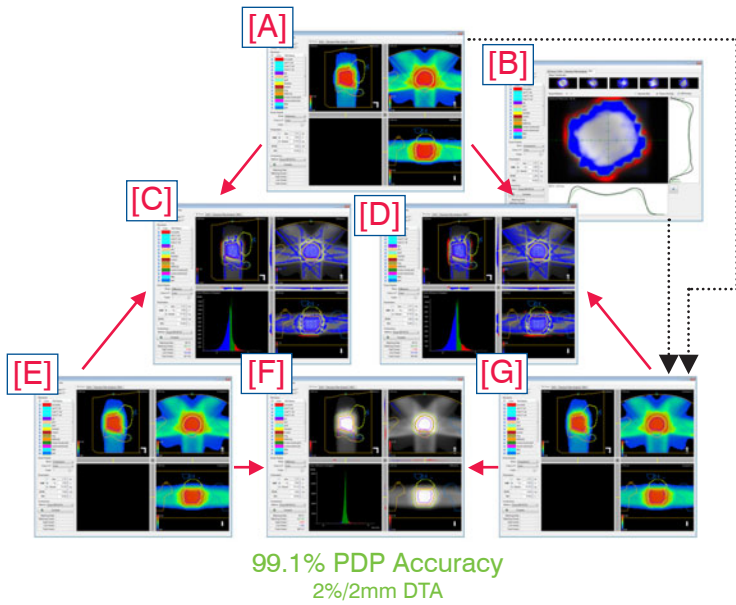
Plan	Induced Error	Degree of Induced Errors Results of Conventional IMRT QA Results (Averaged over all beams in plan) 2%/2mm DTA (Planar)	PDP Accuracy		
			PDP Patient Dose vs. Error Free Patient Dose 2%/2mm DTA (3D)	PDP Patient Dose vs. Error Free Patient Dose Average ROI Mean Dose Errors	PDP Patient Dose vs. Error Free Patient Dose Average ROI Max Dose Errors
Single Beam P1	P1 to P2: 3-segment IMRT field with segment sizes and MU per segment changed	47.7%	98.4%	0.16%	-0.31%
Single Beam P1	P1 to P3: 3-segment IMRT field with segment sizes and MU per segment changed	28.6%	100%	0.00%	-0.05%
Single Beam P2	P2 to P1: 3-segment IMRT field with segment sizes and MU per segment changed	56.5%	96.9%	-0.43%	2.08%
Single Beam P2	P2 to P3: 3-segment IMRT field with segment sizes and MU per segment changed	12.7%	96.1%	-0.49%	1.87%
Single Beam P3	P3 to P1: 3-segment IMRT field with segment sizes and MU per segment changed	31.9%	99.1%	0.00%	0.05%
Single Beam P3	P3 to P2: 3-segment IMRT field with segment sizes and MU per segment changed	8.6%	98.6%	0.19%	-0.26%
Three Beams Orthogonal	P1 to P2: 3-segment IMRT field with segment sizes and MU per segment changed for each beam	47.7%	99.2%	-0.10%	-0.06%



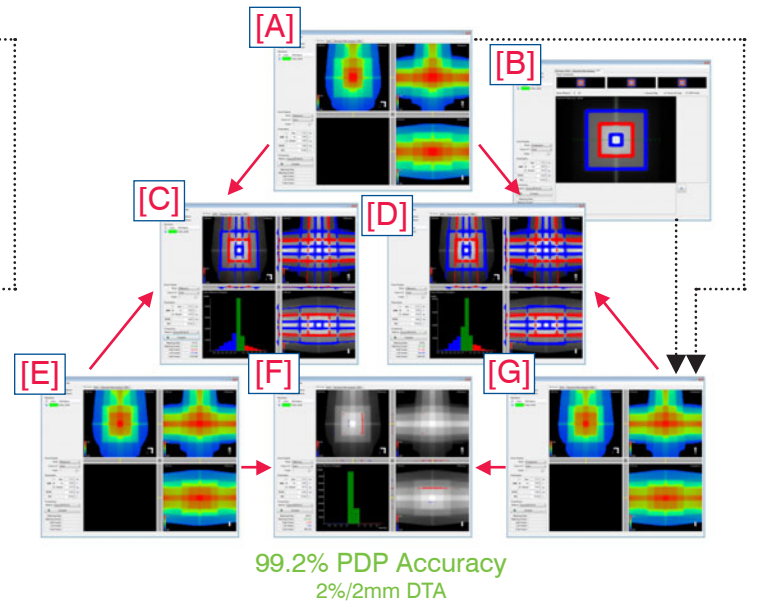
► **Figure 5 - Results**
Screen captures and results for Head/Neck2 test, following the schematic of Figure 3.



► **Figure 6 - Results**
Screen captures and results for Prostate1 test, following the schematic of Figure 3.



► **Figure 7 - Results**
Screen captures and results for Prostate2 test, following the schematic of Figure 3.

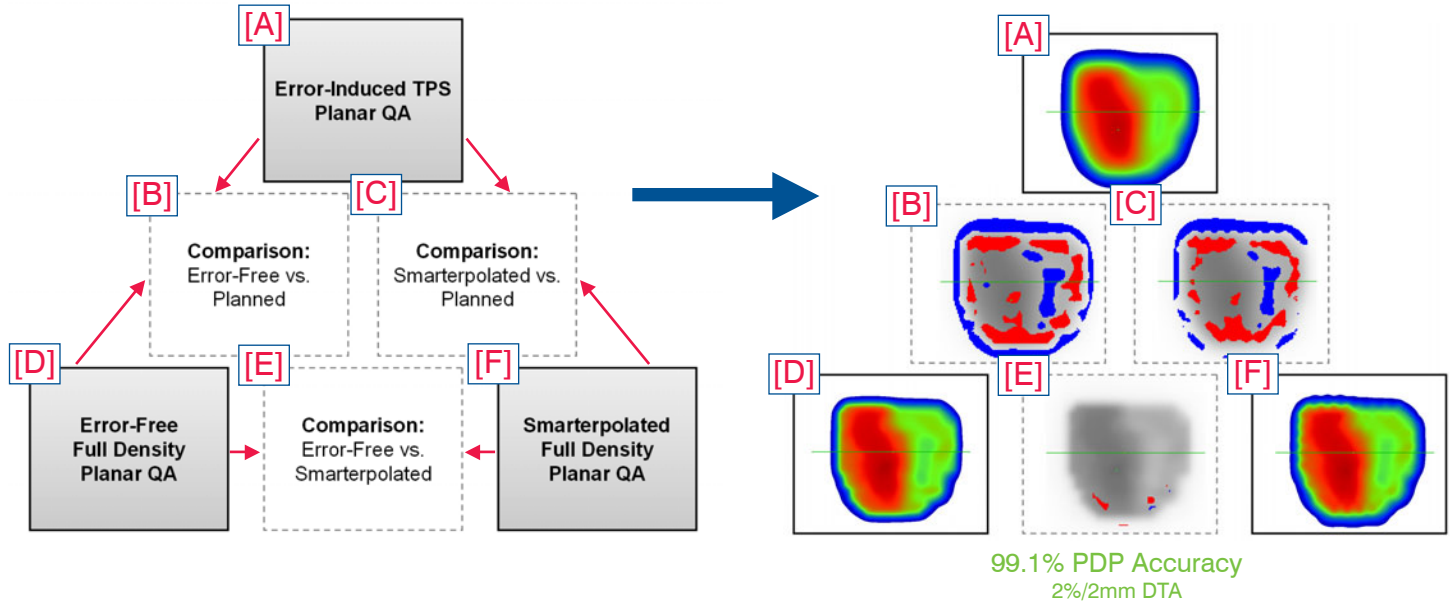


► **Figure 8 - Results**
Screen captures and results for the 3-field stress test, following the schematic of Figure 3.

► Verification of Smarterpolation high-density restoration

Figures 9 and 10 show examples of how Smarterpolation takes a low density MapCHECK array and creates an accurate high density array. Figure 9 illustrates how a Smarterpolated planar QA field is almost identical to a full

density diode array, though derived only from the sparser density diode array. Figure 10 shows 1D profiles, and again the effectiveness of Smarterpolation at restoring data density accurately.



► **Figure 9 - Results**

A low density MapCHECK (not shown) is extracted from a “full density error free” dose plane (lower left) and then Smarterpolated to a high density prediction (lower right). The Error Free vs. Smarterpolation comparison shows a 99.1% passing rate (2%/2mm) when compared, showing Smarterpolation is very effective at creating accurate density of data.

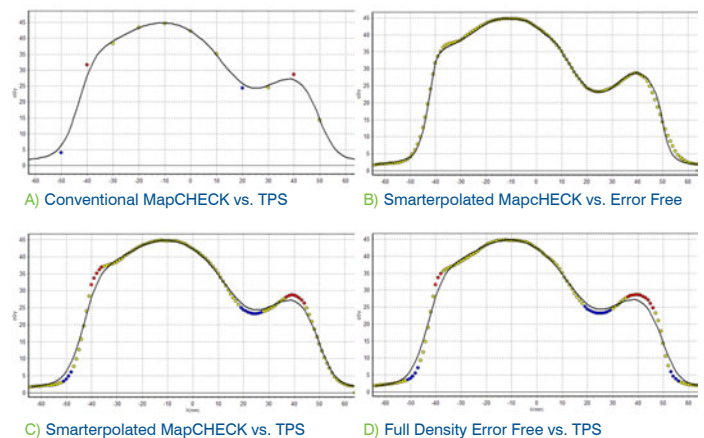
Note: The full density standard was not known during Smarterpolation, and was only used as a standard for comparison.

► **Figure 10 - Results**

Smarterpolation profiles:

- A) Conventional MapCHECK profile vs. TPS
- B) Smarterpolated MapCHECK vs. full density Error Free
- C) Smarterpolated MapCHECK vs. TPS
- D) Full density Error Free vs. TPS

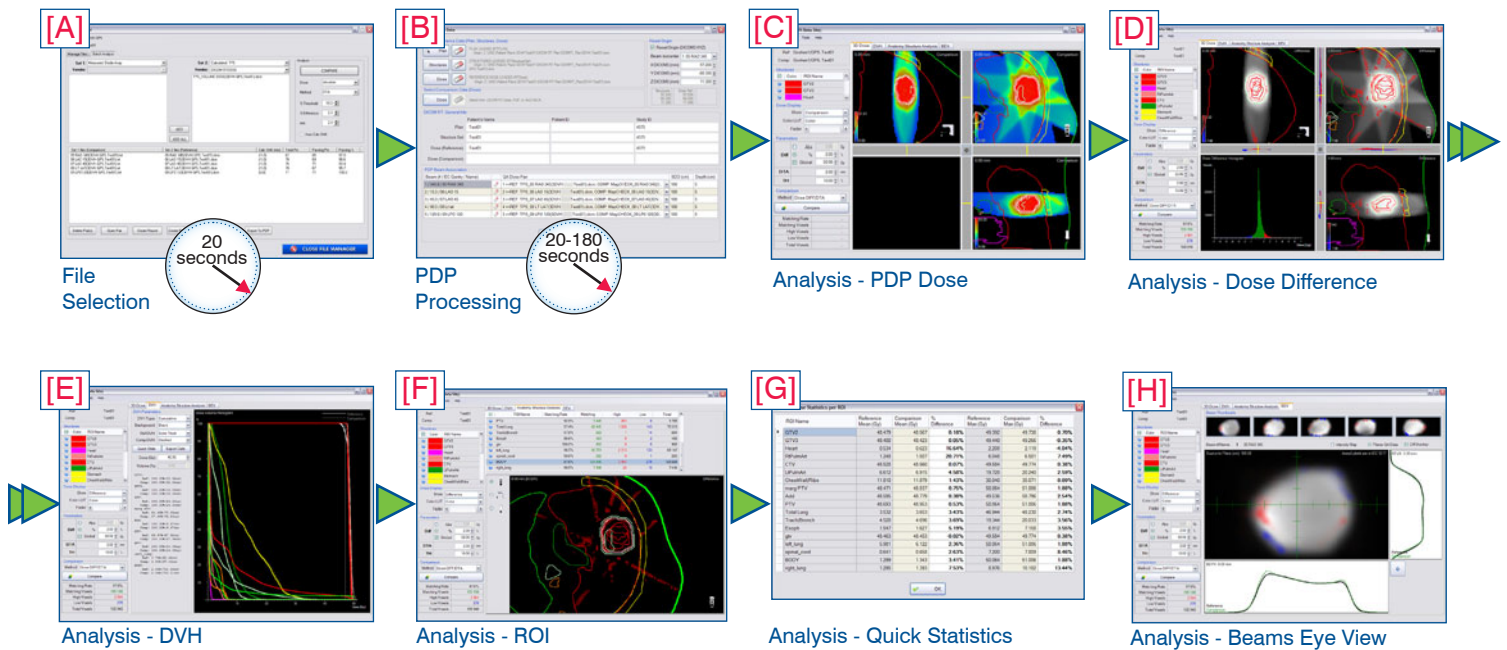
Note the similarity between panels C and D, and the excellent agreement of the two profiles in Panel B.



▶ Workflow of a clinical case

Clearly, in true clinical usage, the “error free” patient dose is never known. The purpose of 3DVH and PDP is to estimate that dose by correcting TPS patient dose based on conventional IMRT QA data input. In Figure 11, the workflow of a clinical case is illustrated.

- 1 ▶ The conventional IMRT QA measurements vs. calculations are processed using the Batch Analysis feature of MapCHECK software to create the file required for PDP processing.
- 2 ▶ The patient DICOM RT files (Plan, Structure Set, and Dose) are processed with the PDP file in order to estimate the revised patient dose.
- 3 ▶ The revised patient dose, which has the effect of the IMRT QA differences factored into it, is compared to the original TPS dose by: dose difference, DVH changes, dose analysis per ROI, ROI “quick stats” and by beam’s-eye-view images. All of these analysis tools are included in 3DVH.



▶ **Figure 11 - Workflow**

3DVH requires the same data as conventional IMRT QA plus the patient DICOM RT files (plan, structure set, and dose). These are processed by PDP (Panels A and B) into an estimated patient dose for comparison with the TPS planned dose via: 3D dose analysis, DVH, analysis per ROI, ROI “quick stats”, and even BEV analysis of the conventional IMRT QA dose errors (Panels C through H).

* Time estimates based on a 2.4+ GHz dual processor; times vary with total dose volume size.

▶ Conclusions

For static-gantry IMRT plans, 3DVH proves to be extremely accurate at predicting patient dose and DVH impact given the conventional IMRT QA phantom dose planes. A 3rd party dose calculation algorithm is not necessary, and instead the perturbation algorithm called “PDP” is used to correct the original patient dose based on phantom measurements. A method called Smarterpolation allows

diode array planes to be converted to full density planes, as required by 3DVH/PDP. The 3DVH PDP calculations take only 20-200 seconds for modern PC’s, scaling primarily with the patient dose volume (number of voxels). 3DVH allows clinicians to make IMRT QA decisions based on clinically relevant patient dose and DVH metrics.

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