Experimental verification of the planned dose perturbation algorithm in an anthropomorphic phantom

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Abstract. 3DVH software is capable of generating a volumetric patient VMAT dose by applying a volumetric perturbation algorithm based on comparing measurement-guided dose reconstruction and TPS calculated dose to a cylindrical phantom. The primary purpose of this paper is to validate this dose reconstruction method on an anthropomorphic heterogeneous thoracic phantom by direct comparison to independent measurements. Reconstructed “patient” doses compare well with the independent dose profile measurements in the unit-density target inside a thoracic phantom lung. The largest differences are observed in lung and are associated with the highly modulated plan with narrow (few mm) MLC openings. Such a plan is instructive as a stress test of the algorithm but is not likely to be clinically encountered in lung. This residual disagreement underscores the fact that 3DVH is not designed to correct the errors related to the TPS dose calculations in the low-density media.

1. Introduction
Historically, the most frequently employed method for practical dosimetric QA in highly conformal radiation therapy, such as IMRT and VMAT, has been comparison of the calculated and measured dose in a phantom. Ideally, the dose should be measured with high resolution throughout the entire phantom volume. But even then it is not trivial to correlate the detected dose-errors in a phantom to the clinically relevant dose deviations in the patient. A software package called 3DVH (Sun Nuclear Corp., USA) attempts to bridge this gap by employing a planned dose perturbation algorithm to estimate the dose deliverable to the patient from the phantom measurement. A full density absolute 3D dose in a phantom can be reconstructed from the relatively sparse detector data if the shape of the dose profiles is known a priori. In 3DVH software, this is achieved by an independent calculation by a convolution/superposition method of the relative dose distribution, which is then converted to absolute dose based on the measured point doses. The ratio of the actual to TPS dose for any voxel in the patient is about the same as the ratio of the reconstructed and TPS dose in the phantom, for the corresponding voxel in relation to the isocenter. This was successfully demonstrated in homogeneous phantoms representing a patient for IMRT [1] and VMAT [2]. While this approach is fairly intuitive for a homogeneous “patient”, it is less obvious when a substantial heterogeneity is present. Hence we set out to specifically validate the 3DVH method in a heterogeneous anthropomorphic thoracic phantom with an SBRT target suspended in the lung material.
2. Methods

2.1. The phantom
The novel detector insert was designed in this work for the commercial IMRT Thorax Phantom (CIRS Inc., USA). The design pursued a dual goal of accomplishing measurements necessary for this work but also of creating a phantom useful for periodic end-to-end testing of the SBRT delivery chain. The phantom is made of unit-density tissue equivalent plastic with 0.21 g/cm³ lung inserts (Figure 1). The right lung can accommodate an 8.5 cm diameter cylindrical lung density insert.

One version of the insert contains a 4 cm diameter spherical Plastic Water target with a cavity for an ion chamber in the center. The other version (5) is overall geometrically equivalent but has a removable two-piece (3 and 4 in Figure 1) target insert designed to accommodate orthogonal linear arrays of optically stimulated luminescent dosimeters (OSLD) known as nanoDots (Landauer Inc., USA). The dosimeters are 5 mm apart in the target and 4.1 mm in the lung.

2.2. OSLD calibration
The OSLDs were calibrated individually. The average angular correction was determined by exposing the nanoDots to an open 360° arc irradiation in the Thoracic phantom. The angular corrections are separate for the nanodots parallel to the transverse plane (“edge on”) and two other cardinal planes (“standard orientation”).

2.3. Treatment planning
We used 5 VMAT plans for measurements in lung. The first two were optimized to deliver 200 cGy to a 2 and 7 cm diameter targets centered inside the Plastic Water sphere. The next three plans were not created anew but rather copied from our previous work on the homogeneous phantom [2]. They were modeled after some of TG-119 plans [3], including the most challenging C-shape one.

2.4. Dose reconstruction and comparison
3D dose matrix in the patient (Thorax Phantom) was reconstructed from the measurements in the ARCCHECK (Sun Nuclear) diode array phantom using 3DVH software v. 2.2. For the ion chamber point dose measurements, the Thorax Phantom was squared on the room lasers and aligned on the lung target by CBCT. The doses in the middle of the spherical target were extracted from both the initial TPS calculation and 3DVH dose reconstruction on the Thorax Phantom.

By using the dosimetric insert in three different orientations for each plan, two nanoDot profiles in each of the cardinal directions (SI, AP, LR) were acquired and averaged. The individual nanoDot doses were compared to the TPS and 3DVH by composite % dose-difference (local)/DTA analysis. The data were further subdivided for the measurement points inside the unit density sphere and in the
lung. In addition, the nanoDot doses in the center of the target were compared to the ion chamber measurements.

3. Results and discussion

3.1. OSLD angular dependence
The average angular corrections for the “edge-on” and standard irradiation geometries were 1.020±0.008 (1SD) and 1.008±0.004, respectively. The first value is 1.5% lower than reported by Kerns et al [5] and almost splits the difference between the values obtained in that work and by Jursinic [6]. The second value has no direct counterpart in the cited work but our numerical integration of the figure 5 curve in [5] yields the value of 1.022, again 1.4% different from our result. The values may not be really different as the 1SD error bars overlap.

3.2. 3D dose comparison – TPS vs. 3DVH
The 3DVH reconstructed patient dose is generally close to the TPS calculations. This means that in these cases, the TPS dose does not need to be perturbed much. The lowest γ-analysis passing rate among the 5 plans ranged from 98.3% for the most lenient 3%(global)/3mm thresholds to 90.9% for the most stringent 2%(local)/2mm combination. The lowest passing rates were always associated with the C-shape plan, with disagreement primarily localized in the low dose central area corresponding to the avoidance structure.

3.3. Point dose comparison – ion chamber
The ion chamber measurements for the most part agree well with both 3DVH and the TPS (Table 1), with the notable exception of the C-shape plan, where the isocenter is in the low dose (avoidance) region. It must be mentioned that all percentage errors here are normalized locally. If normalized globally as in the TG-119 report [3], the % error values for the C-shape would be about ¼ of that presented in Table 1. For this plan, 3DVH substantially reduced the difference from the measured value compared to the TPS.

3.4. Dose profiles in lung - nanodots
The ratio of the average nanoDot dose from the two innermost detector positions to the ion chamber was 0.999±0.015 (1SD, range 0.976-1.013), thus validation our overall OSLD correction methodology.

The composite analysis passing rates for all 5 VMAT plans in the lung are given in Table 1, while dose profiles in the SI and LR directions are presented in for the 4 cases in Figure 2. The AP profiles are included in the numerical analysis but omitted from the figures for clarity. Overall, for the 4 plans that do not include the C-shape, the results of the 3%/3mm composite analyses are similar between the TPS and 3DVH. In the unit density target, 3DVH provides very good agreement (100% of the points) while the TPS agrees with the measured profiles for 93% of the points in the worst case scenario. The lower passing rates in the lung are associated with the plans where there is no sharp dose gradient (7 cm target and HN). In those plans, the TPS errors in the heterogeneous media are not hidden in the distance to agreement analysis. However the difference between 3DVH and measurement in the low gradient region in lung never exceeded 3.9%. The last case in the lung – the C-shape– shows a persistent area of disagreement between the TPS and 3DVH in the low dose area (central avoidance structure). In the water-equivalent target 3DVH reconstruction agrees well with the measured dose, unlike the TPS. However the disagreement between the measured dose and 3DVH in lung remains substantial (up to 14% normalized locally), although smaller than with the TPS (up to 28%).

4. Conclusions
3DVH measurement-guided VMAT dose reconstruction compared favorably with the independent measurements in the unit density mass inside the lung volume of the thoracic phantom. Composite
analysis with 3% (local)/3mm thresholds yielded 100% agreement for 4 VMAT plans, and 96% passing rate for the last, exceedingly complex one. Dosimetric agreement in lung is slightly worse, reflecting the fact that by design 3DVH does not attempt to correct the errors related to the TPS dose calculations in the low-density media. The largest errors are associated with the highly modulated plan, which is useful as a stress test of the algorithm. These errors are primarily localized in the low-dose region corresponding to a central avoidance structure where it has lung density. Such a combination is rather unlikely in a patient.

Table 1: Percent difference in point doses on the Thorax Phantom: measurement-guided dose reconstruction (3DVH) and TPS vs. the ion chamber (IC), and composite analysis passing rates overall (All), in the unit density central sphere (Water), and Lung. Local % dose-error normalization is used.

|          | 3DVH – IC (%) | Composite analysis pass rate 3%/3mm (%) | TPS – IC (%) | Composite analysis pass rate 3%/3mm (%) |
|----------|---------------|-----------------------------------------|--------------|-----------------------------------------|
|          | All | Water | Lung | All | Water | Lung |
| 2 cm     | 0.0  | 100   | 100  | 100 | 96   | 94   |
| 7 cm     | -0.2 | 93    | 100  | 83  | -0.1 | 98   | 100  | 94   |
| H&N      | 1.0  | 93    | 100  | 83  | -1.8 | 88   | 93   | 78   |
| Multi-Target | -1.9 | 100  | 100  | 100 | -1.6 | 98   | 100  | 94   |
| C-shape  | 4.9  | 85    | 96   | 72  | -12.5| 59   | 48   | 72   |
| Bone     | 1.5  | 2.6   |      |     |      |      |      |      |

Figure 2: AP (left axes) and SI (right axes) dose profiles for 7-cm target (A), Mock Head and Neck (B), Multi-Target (C), and C-shape (D) VMAT plans. Pinnacle calculations (TPS), 3DVH measurement-guided reconstruction (3DVH) and independent measurements (OSLD + ion chamber in the center) are compared. The left and right scales are slightly different to separate the profiles for better visualization. Otherwise AP and SI profiles would intersect at zero distance from the center.

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6. References
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