A Method to Generate CT Scanner-Independent Synthetic Internal Target Volumes for a Dynamic Thorax Phantom with an Embedded Target: Single Waveform, Fixed-Period Motion

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Innovation: The development of a scanner-independent quality assurance (QA) framework that establishes a mathematically defined ground-truth internal target volume (ITV) within image space. Using a synthetic CT based on the geometry of a dynamic thorax phantom, respiratory motion is modeled analytically and embedded directly into the dataset to generate a motion-resolved synthetic ITV. These synthetic structures are registered to user-acquired scans using embedded fiducial markers, enabling direct volumetric and geometric comparison. This approach replaces inferred agreement with a reproducible, physics-based reference for validating 4DCT volume reconstruction.

INTRODUCTION

4DCT QA has relied on scanning dynamic phantoms, which are programmed to simulate tumor motion. The accuracy of motion capture is then assessed by comparing the reconstructed image data to the known phantom motion. Because reconstructed ITVs exist in image space while phantom motion exists in physical space, evaluation is limited to indirect analytical approximations. No independent gold standard has existed to quantify the accuracy of 4DCT volume reconstruction, that is, until now.

METHODS AND MATERIALS

- Geometry of a commercially available dynamic thorax phantom was modeled in Python to generate a synthetic CT volume.
- Known respiratory motion profiles were programmed into synthetic dataset, and a spherical target was embedded and repositioned across respiratory phases.
- The ITVs were generated on a slice-by-slice basis from the phase-specific positions.
- All structures were saved as RTSTRUCT DICOM files.
- Fiducial markers were embedded in synthetic CT to enable rigid registration with user-acquired phantom scans in Velocity AI.
- Using Python, comparison between acquired and synthetic ITVs was performed using metrics such as volume difference, Dice Similarity Coefficient, Jaccard Index, and Hausdorff distance.

RESULTS

- Figure 1 shows a three-dimensional view of the acquired and synthetic internal target volumes for each of the nine motion profiles. The purpose of this figure is simply to demonstrate that the volumes agree well visually across all cases.
- Figure 2 lists the volumes, in cc, for synthetic ITVs, acquired ITVs, and analytical volume approximations calculated using Eq (1) and Eq (2).
- Figure 3 and 4 further illustrates the volume differences across six comparison scenarios. The largest discrepancy occurred for comparisons involving the Eq (1) approximation. The maximum deviation was observed between the acquired and Eq (1) volumes and between the synthetic and Eq (1) volumes, with a difference of 2.0 cc (23%). Eq (2) proved to give the superior approximation with a maximum deviation of 0.31 cc (3.9%).
- Figure 5 shows geometric agreement across all synthetic versus acquired ITVs, Dice similarity coefficients ranged from 0.95-0.97, Jaccard indices ranged from 0.90-0.93, and precision and recall values were all above 0.90.
- Figure 6 presents mean surface and Hausdorff distances. MSD ranged from 0.16-0.33 and HD95 were less than 1.56 mm, demonstrating sub-voxel spatial agreement for all motion excursions.

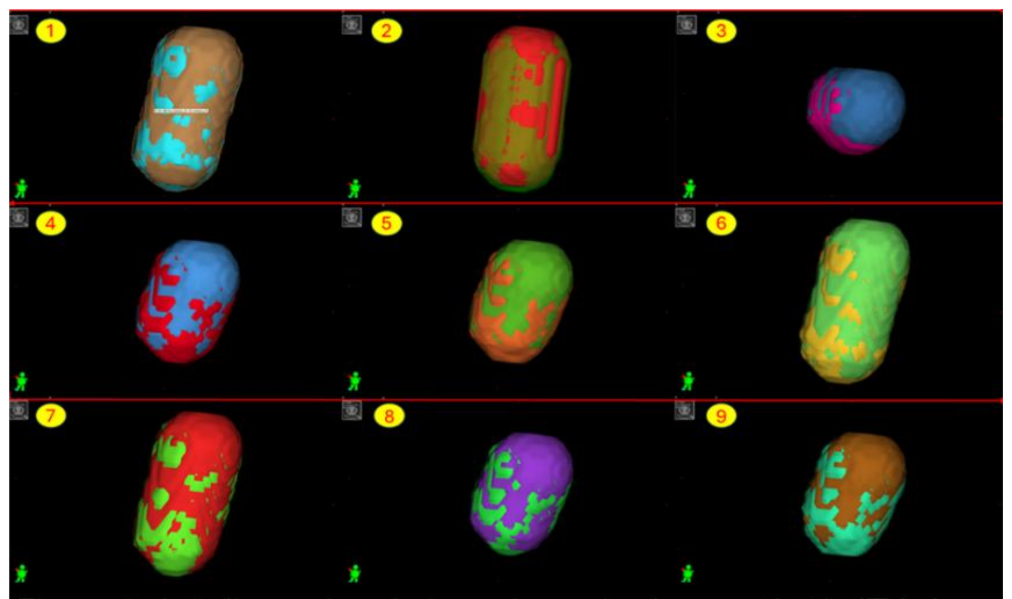
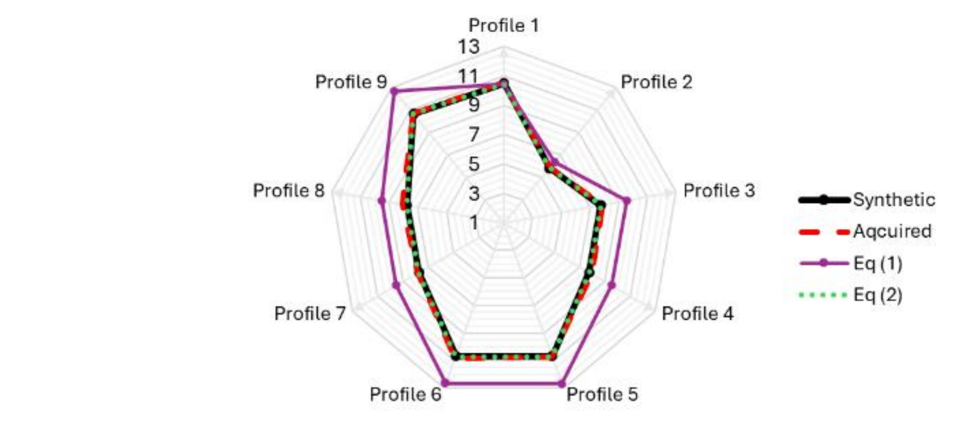


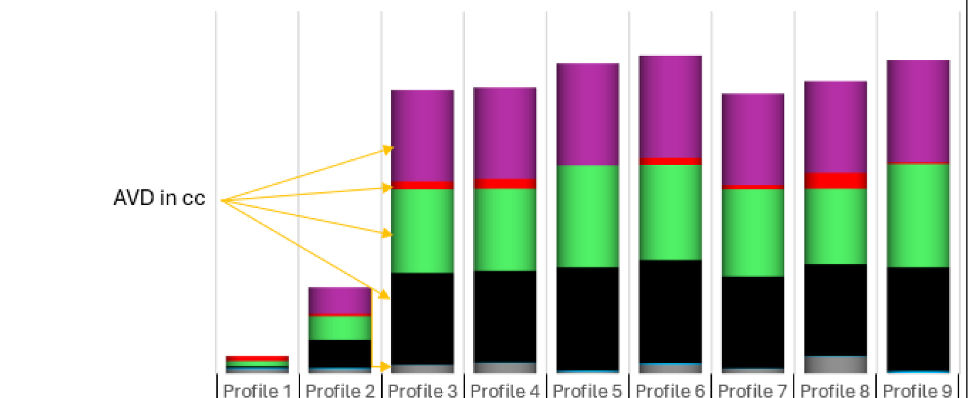
Figure 1. A 3-dimensional view of acquired vs synthetic ITVs for motion profile 1-9.

Figure 2. Volume in cc of ITVs Generated from 4 Methods: Synthetic, Acquired, Equation (1), and Equation (3)



	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8	Profile 9
Synthetic	10.498	5.847	7.746	7.746	10.669	10.669	7.745	7.745	10.658
Aqcuired	10.575	5.931	7.911	7.944	10.7	10.835	7.839	8.07	10.668
Eq (1)	10.472	6.388	9.529	9.529	12.671	12.671	9.529	9.529	12.671
Eq (2)	10.472	5.881	7.757	7.757	10.696	10.696	7.757	7.757	10.696

Figure 3. AVD in cc of 6 sets: Synthetic vs Acquired, Eq (1), and Eq (2), Acquired vs Eq (1) and Eq (3), and Eq (1) vs Eq (3)



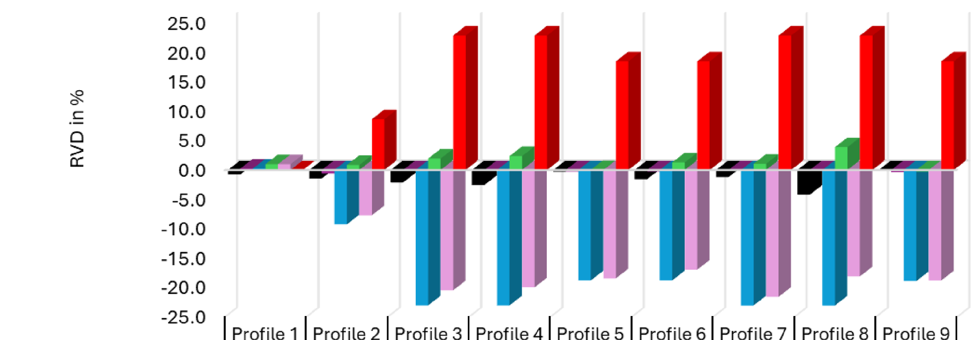
	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8	Profile 9
Eq (1) vs Eq (2)	0.000	0.510	1.770	1.770	1.980	1.980	1.770	1.770	1.980
Aquired vs Eq (2)	0.100	0.050	0.150	0.190	0.000	0.140	0.080	0.310	0.030
Aqcuired vs Eq (1)	0.100	0.460	1.620	1.590	1.970	1.840	1.690	1.460	2.000
Synthetic vs Eq (1)	0.030	0.540	1.780	1.780	2.000	2.000	1.780	1.780	2.010
Synthetic vs Eq (2)	0.030	0.030	0.010	0.010	0.030	0.030	0.010	0.010	0.040
Synthetic vs Acquired	0.080	0.080	0.160	0.200	0.030	0.170	0.090	0.330	0.010

$$ITV_{ph} = \frac{4\pi r^3}{3} + \pi r^2 (L_{LR} + L_{AP} + L_{IS}), \qquad \text{Eq (1)}$$

where r is the radius of the target and L is the excursion distance in the anterior-posterior (AP), left-right (LR), and inferior-superior (IS) directions

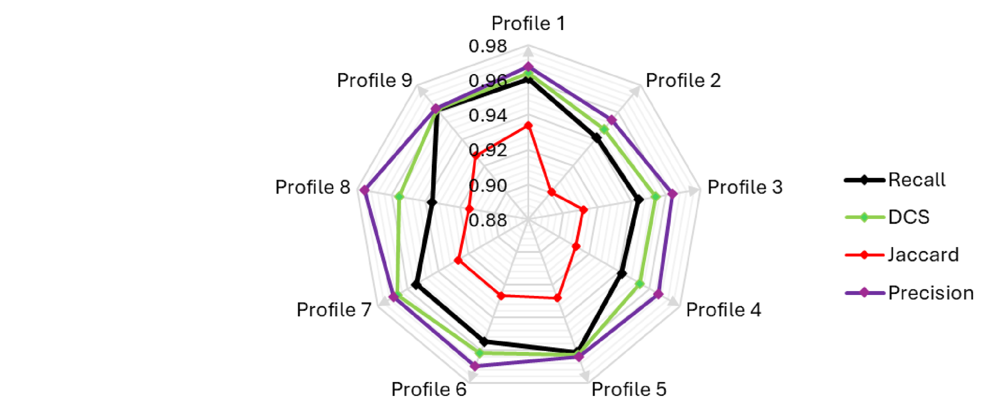
$$V = \frac{4\pi r^3}{3} + \pi r^2 \left(\sqrt{L_{LR}^2 + L_{AP}^2 + L_{IS}^2}\right). \qquad \text{Eq (2)}$$

Figure 4. RVD in % of 6 sets: Synthetic vs Acquired, Eq (1), and Eq (2), Acquired vs Eq (1) and Eq (3), and Eq (1) vs Eq (3)



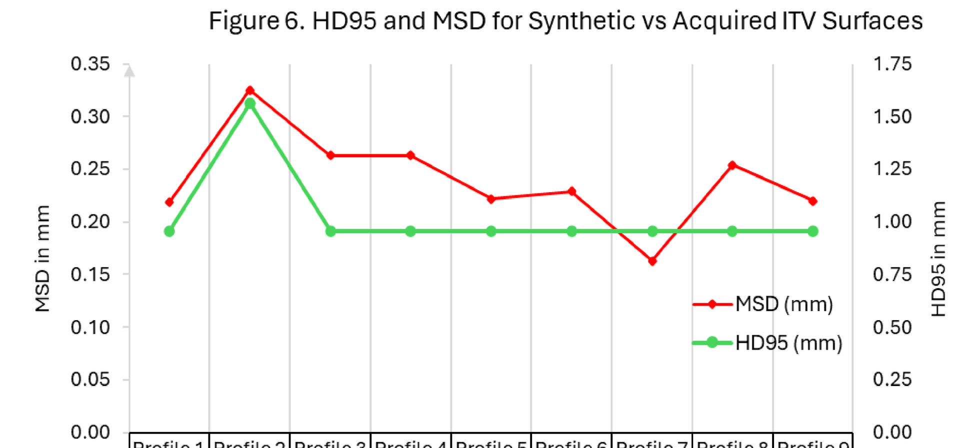
	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8	Profile 9
Synthetic vs Acquired	-0.733	-1.437	-2.130	-2.556	-0.291	-1.556	-1.214	-4.196	-0.094
Synthetic vs Eq (2)	0.248	-0.581	-0.142	-0.142	-0.253	-0.253	-0.155	-0.155	-0.357
Synthetic vs Eq (1)	0.248	-9.253	-23.018	-23.018	-18.765	-18.765	-23.034	-23.034	-18.887
Aqcuired vs Eq (2)	0.974	0.843	1.947	2.354	0.037	1.283	1.046	3.879	-0.262
Aquired vs Eq (1)	0.974	-7.705	-20.453	-19.952	-18.421	-16.945	-21.559	-18.079	-18.776
Eq (1) vs Eq (2)	0.000	8.621	22.844	22.844	18.465	18.465	22.844	22.844	18.465

Figure 5. DCS, Jaccard Index, Precision, and Recall for Synthetic vs Acquired ITVs



	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8	Profile 9
Recall	0.960	0.941	0.944	0.942	0.961	0.955	0.955	0.936	0.962
DCS	0.964	0.948	0.954	0.954	0.963	0.962	0.967	0.956	0.962
Jaccard	0.934	0.900	0.912	0.911	0.928	0.927	0.927	0.915	0.927
Precision	0.968	0.954	0.964	0.966	0.964	0.969	0.969	0.976	0.963

Figure 6. HD95 and MSD for Synthetic vs Acquired ITV Surfaces



	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8	Profile 9
MSD (mm)	0.219	0.325	0.263	0.263	0.222	0.229	0.163	0.254	0.220
HD95 (mm)	0.954	1.562	0.954	0.954	0.954	0.954	0.954	0.954	0.954

CONCLUSIONS

This framework establishes a scanner-independent ground truth for 4DCT ITV validation, enabling objective, reproducible assessment of volumetric and geometric reconstruction accuracy.

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