A 4DCT Phantom Study of Lung Tumor Volume Variability Under Respiratory Motion

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Purpose

To evaluate the impact of four-dimensional CT (4DCT) reconstruction methods on lung tumor surrogate volume and apparent tissue density under respiratory motion.

Phantoms of diverse sizes, geometries, and materials were imaged, with geometry-derived physical volume as ground truth and static 3DCT as an imaging reference.

Background

- Respiratory motion can alter apparent tumor volume and HU in 4DCT, affecting target delineation for lung SBRT.
- AIP and MIP facilitate motion visualization but do not represent instantaneous tumor anatomy.
- This phantom study uses calculated physical volume and static 3DCT as paired reference standards to separate imaging uncertainty from motion-induced bias.

Fig. 1. Spherical, cylindrical, and truncated-cone lung tumor surrogates (11–61.7 mm in maximum dimension) composed of nylon, rubber, wood, and cork.

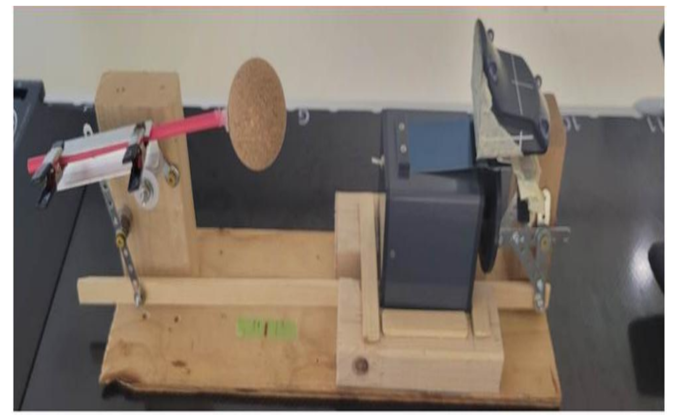

Fig. 2. In-house respiratory motion platform used to drive the phantom surrogates during 4DCT acquisition.

Methods and Materials

Phantoms and Motion Device

- Fifteen spherical, cylindrical, and truncated-cone surrogates (11–61.7 mm) of nylon, rubber, wood, and cork were driven by a prototype in-house respiratory motion platform with partially load-dependent excursion (Figs. 1 and 2).

Physical Measurements

- Precision-caliper dimensions; geometry-derived physical volumes served as the ground truth.

CT Acquisition

- Static 3DCT and respiratory-motion 4DCT images (50% phase, AIP, and MIP) were acquired on a SOMATOM go.Open Pro scanner (Siemens Healthineers) at 120 kVp with 1-mm reconstructed slice thickness (Fig. 3).

Image Segmentation and Analysis

- MIM Maestro v.7.4.2 was used for standardized absolute HU-threshold segmentation; lung window/level settings were used for visualization and contour review.

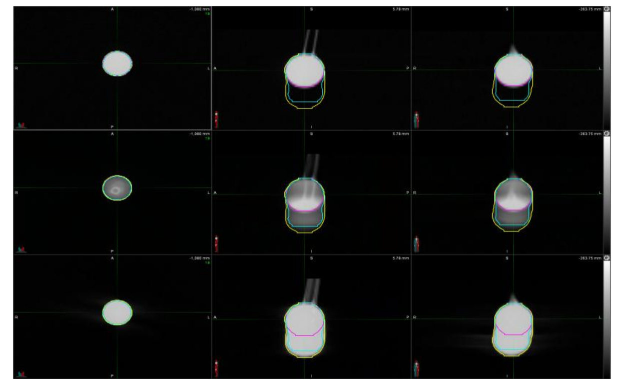

Fig. 3. 50% phase, AIP, and MIP 4D-CT images of a 30-mm nylon sphere. AIP and MIP demonstrate apparent motion-envelope broadening compared with the 50% phase image.

Table 1. Segmented-volume difference from calculated physical volume for static 3DCT and 4DCT reconstructions (n = 15).

Reconstruction	Median volume difference	Range
Static 3DCT	+0.6%	−7.9% to +4.8%
50% phase	+3.2%	−3.0% to +10.7%
AIP	+49.3%	+6.8% to +174.4%
MIP	+86.4%	+39.9% to +293.1%

Note: Large MIP deviations reflect motion-envelope effects influenced by target size and motion amplitude.

Results

- Static 3DCT and 50% phase volumes closely matched calculated physical volumes (Table 1).
- AIP and MIP overestimated volume, especially for smaller targets; bias decreased with target size, most strongly for MIP (Fig. 4).
- Median HU changes versus static 3DCT were −49.5 HU (50% phase), −340.0 HU (AIP), and −517.6 HU (MIP) (Fig. 5), with similar trends across shapes and materials.

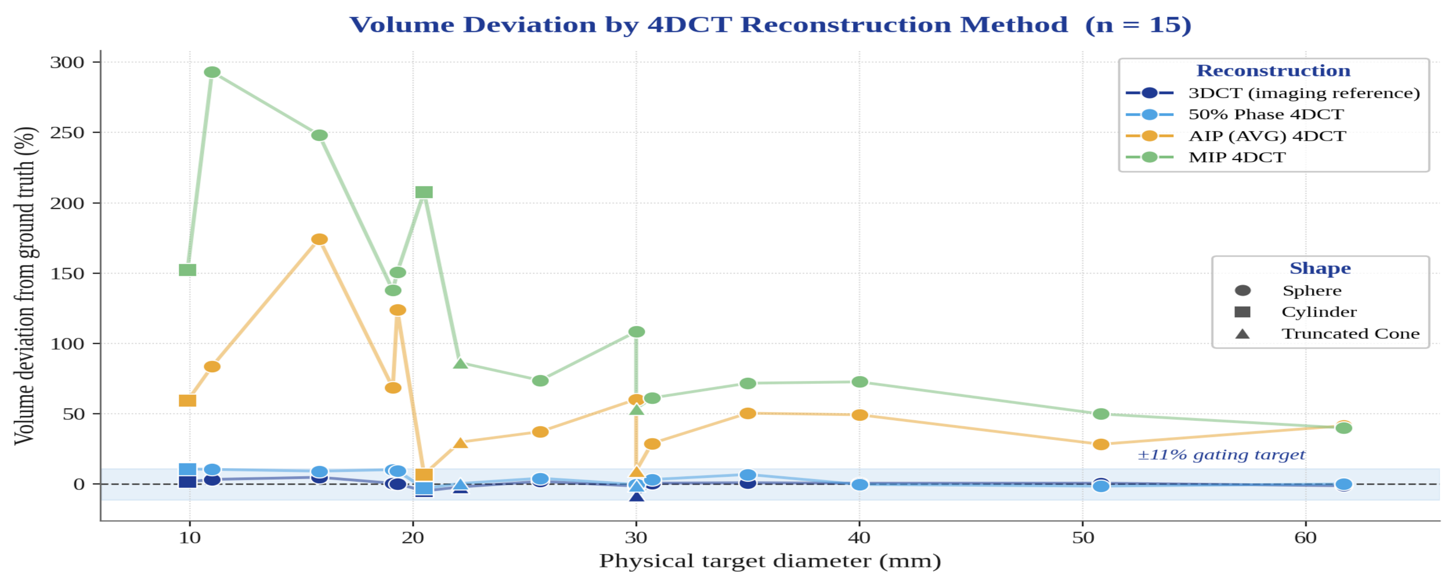

Fig. 4. Volume deviation from calculated physical volume versus target size by reconstruction (n = 15); shaded band, ±11% for 50% phase reference range.

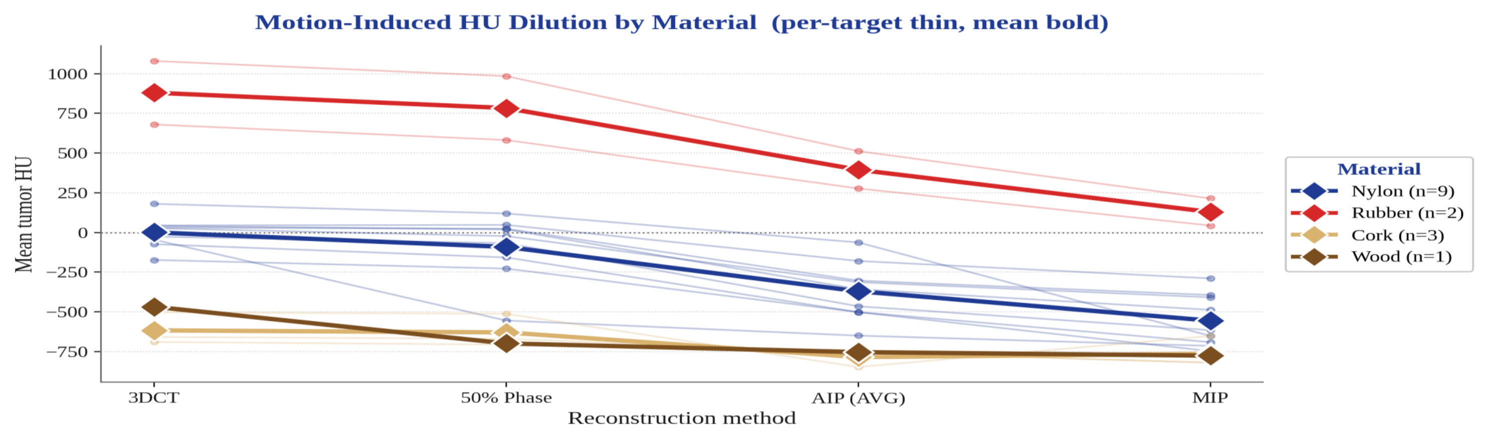

Fig. 5. Mean tumor HU across reconstruction methods, stratified by phantom material (n = 15).

Discussion

- Static 3DCT established the baseline CT and segmentation uncertainty.
- The 50% phase preserved target volume more accurately than AIP or MIP.
- AIP volume enlargement was associated with temporal averaging and contrast loss, whereas MIP represented the respiratory motion envelope rather than instantaneous tumor anatomy.
- Small and low-contrast targets were most susceptible to reconstruction-dependent bias.

Limitations

- Rigid phantoms underwent idealized motion without deformation, hysteresis, or irregular breathing.
- Shape and material groups were unbalanced, and no treatment-planning dosimetry was performed.
- A small internal air cavity in two phantoms lowered their absolute mean HU; reconstruction-relative HU trends were unaffected as the cavity was present across all reconstructions.

Conclusions

- Static 3DCT and 50% phase 4DCT showed the highest volumetric fidelity relative to calculated physical volume.
- AIP and MIP introduced substantial size-dependent volume inflation and apparent HU dilution.
- Phase-resolved or gated imaging may improve target-delineation accuracy and reduce unnecessary treatment-volume expansion in lung SBRT.

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