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# Accuracy and Precision of the 5DCT Protocol

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## ABSTRACT

**Purpose:** To quantify the precision and accuracy of a five-dimensional computed tomography (5DCT) free-breathing simulation approach in a large clinical cohort.

**Methods:** A 5DCT motion model was generated from a subset of 25 free-breathing CT images per patient, parameterized by respiratory amplitude and breathing rate. This model was used to characterize respiratory motion and generate internal target volumes (ITVs). The resulting image datasets were also used for motion-modeling performance quality assurance. Motion-model precision was quantified by calculating the root-mean-square (RMS) of the residual errors between the modeled and observed tissue positions across all available datasets.

Motion model accuracy was evaluated in a subset of 107 patients with clinician-contoured ITVs got which the original 25 CT images were deformed to a reference CT using the motion model, and tumor positions were compared for the 25 scans. A rigid registration was performed within a small region of interest centered on the ITV centroid, with visual verification of registration quality and the offsets used to quantify motion model error.

**Results:** Across 255 patients, the mean median and 90th-percentile residual errors of the motion model were 1.21±0.57 mm and 1.90±0.83 mm, respectively. In the subset of 107 patients evaluated for ITV motion accuracy, the mean RMS and maximum errors were 1.05±0.69 mm and 0.90±1.30 mm, respectively.

Conclusion: In a large clinical cohort, the 5DCT free-breathing motion model demonstrated high-precision and accuracy for most patients and tumor locations within the lungs. These results provide quantitative validation of 5DCT performance and increase confidence in its reliability for respiratory motion characterization and ITV generation. While limitations were observed near the chest wall and in patients with highly irregular breathing, the overall robustness of the approach supports wider clinical implementation of 5DCT as a practical and dependable alternative to conventional 4DCT in thoracic radiation therapy planning.

## KEY POINTS

**Motion Model Tested 255 Patients**

**77 Patients with Lung ITVs**

**Model Residual $90^{th}$ percentile < 6mm**

**Target Accuracy RMS <3.5mm**

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## INTRODUCTION

Our group has developed a process that models human breathing as a function of breathing amplitude and rate[1]. The current process uses 25 fast-helical free-breathing CT scans acquired simultaneous to a breathing surrogate. The surrogate is correlated against the imaged diaphragm dome position such that the amplitude $A$ and rate $\dot{A}$ correspond to the diaphragm craniocaudal position and speed, respectively. The motion model is a linear combination of voxel-specific parameters such that the position of any voxel (specifically within the lungs) is

$$\vec{X} = \vec{X_0} + \vec{\alpha}A + \vec{\beta}\dot{A}$$

$\vec{\alpha}$ and $\vec{\beta}$ describe the motion as functions of breathing depth and rate, corresponding to the motion due to lung filling and hysteresis, respectively, and the model is termed 5DCT to reflect the three spatial coordinates, amplitude and rate. The motion model is used clinically to create a replacement for the commercial 10-phase 4DCT images that represent the motion envelope of the CT session with limited image artifacts and precision and accuracy metrics that allow clinicians to tailor margins according to not only tumor motion, but its measurement uncertainties (Figure 1).

This work is an independent analysis of the 5DCT data for 255 patients using an updated workflow and reports the overall precision of 5DCT for these patients and accuracy for those patients with clinical lung tumor contours

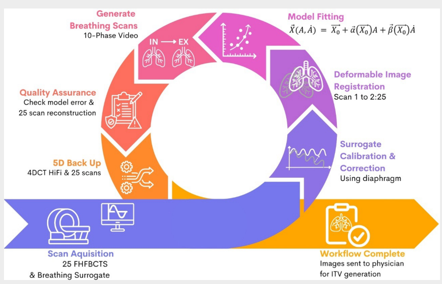


**Fig. 1.** 5DCT clinical workflow describing the steps from image acquisition to the transfer of images for contouring.

## METHODS & MATERIALS

The 5DCT (Figure 1, 5D due to x, y, z, breathing amplitude and rate) begins by acquisition of 25 nominal helical CT scans while monitoring the breathing pattern. The breathing surrogate is calibrated to the diaphragm dome motion to yield the breathing trace as the craniocaudal diaphragm position. deedsBCV[2] registers 24 CT scans to the first CT scan (the reference scan) and the 25 positions of each reference voxel, along with their synchronized breathing amplitude and rate, used to generate the 5D motion model at that location. For this work, the model precision was considered the root-mean square residual of the model fit.

When the CT scan included a lung tumor, the clinical ITV centroid was used to isolate the tumor region and the tumor in the original 25 scans simulated using the model. The actual and simulated tumors were compared by rigidly aligning the simulated and actual tumors and the required shift was considered the motion model error. The accuracy of the shift was validated by eye.

## RESULTS

An analysis of the breathing amplitudes of the patients is shown in Figure 2.

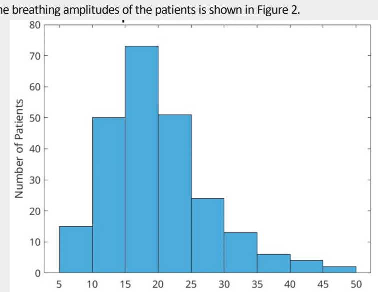


**Fig. 2.** Distribution of breathing amplitudes, defined as the difference between the $95^{th}$ and $5^{th}$ percentile breathing amplitudes.

255 patient scans were analyzed, and Figure 3 shows the $90^{th}$ percentile RMS model errors within the lungs. Figure 4 shows the maximum errors (model accuracy) of the 77 patients with lung tumors. The one patient with >10 mm error had a deep clearing breath during that one scan with an amplitude 3X their nominal breath. When that breath CT was removed, the maximum error for that patient decreased to within the remaining patients.

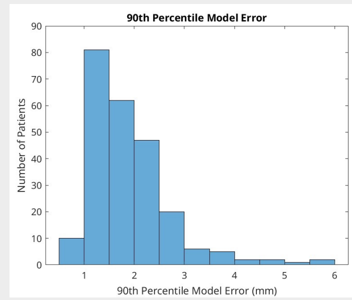


**Fig. 3.** Distribution of the $90^{th}$ percentile model error (RMS of the 25 individual voxel model residuals) within the lung masks.

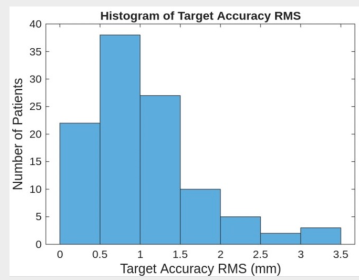


**Fig. 4.** RMS target accuracy calculated as the average RMS within the ITV.

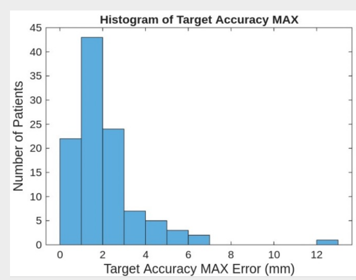


**Fig. 5.** Worst scan target accuracy for the patients with ITVs. The patient with the extreme maximum error also had a deep clearing breath (3X amplitude of the rest of the breaths) and this breath was included in the model. When removed, the error was within the remaining patient distribution.

## DISCUSSION

This analysis showed that the 5DCT model is both precise and accurate with respect to modeling free-breathing lung tissue and tumor motion. The ability to measure and characterize the errors in the 5DCT motion model are one aspect that differentiates it from 4DCT, which has no quantitative feedback to the user.

## CONCLUSIONS

The current implementation of the 5DCT approach provides both accurate and precise motion information that allows the generation of simulated breathing CT scans for treatment planning and gating preparation.

**Future work:** Provide prospective gating for CT acquisition to reduce the number of scans and improve amplitude coverage, improve some of the individual process steps, conduct prospective multi-institutional trial comparing 4D with 5DCT.

## REFERENCES

1.Lauria M, Kim M, O'Connell DP, Lao Y, Miller CR, Naumann L, Boyle P, Raldow A, Lee A, Savjani RR, Moghanaki D, Low DA "A Retrospective Analysis of the First Clinical 5DCT Workflow." Cancers (2025) 17(3):531
2.Heinrich MP, Jenkinson M, Brady M, Schnabel JA "MRF-Based Deformable Registration and Ventilation Estimation of Lung CT." IEEE Transactions on Medical Imaging, 2013; 32(7):1239–1248.

## CONFLICTS

Dr. Low and Dr. Moghanaki are founders of Respirati, a company dedicated to the commercialization of model-based CT.