$PixelPrint^{4D}$: A 3D Printing Method for Fabricating Patient-specific Deformable Pulmonary CT Phantoms

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Hypothesis:
Respiratory motion has a significant impact on clinical workflows in diagnostic imaging and radiation therapy. Technologies such as motion artifact reduction and tumor tracking have been developed to compensate for its effect. To assess these technologies, respiratory motion phantoms (RMPs) are required as preclinical testing environments, for instance, in computed tomography (CT). However, previous CT RMPs are highly simplified and do not exhibit realistic tissue structures or deformation patterns. This work presents $PixelPrint^{4D}$, a 3D printing method for fabricating lifelike, patient-specific deformable lung phantoms for CT imaging.

Methods:
The right lung of a radiation therapy patient 4DCT was 3D printed in the end inhalation phase with a flexible thermoplastic polyurethane (TPU) material. The printed infill ratio was adjusted on a voxel-by-voxel basis in the phantom to mimic the varying attenuations in the patient's lung. The phantom was compressed in the superior-inferior, and anterior-posterior directions, and then scanned at different compression levels matched to the respiratory phases of the reference 4DCT. Deformable image registration was performed to obtain deformation vector fields and Jacobian maps for both the patient and phantom datasets. Finally, attenuations, motion vectors, and Jacobians of the phantom images were compared to those of the patient.

Results:
The attenuation profiles measured in the phantom images demonstrated a close correlation to those of the patient images, with a mean absolute error of ~20 HU. The deformation vectors in the phantom demonstrated mean tumor motion errors $\leqslant 0.7 \pm 0.6$ mm in each orthogonal direction. The background lung parenchyma in the phantom and patient both exhibited a trend of decreasing Jacobian values and increasing attenuation during lung compression. The relationship between Jacobian and attenuation was roughly linear in both the patient and phantom, with analysis of covariance indicating no significant difference ($p = 0.83$) between the phantom and patient.

Discussion and Conclusions:
The deformable lung phantom developed in this study exhibits realistic lung structures and deformation characteristics, indicating potential for advancing more lifelike respiratory motion phantoms. These will aid the development and assessment of various respiratory motion compensation technologies in CT imaging applications.

References:

1. Im, J. Y., et al. (2025). "PixelPrint4D: A 3D Printing Method of Fabricating Patient-Specific Deformable CT Phantoms for Respiratory Motion Applications." Investigative Radiology: 10.1097/RLI.0000000000001182.

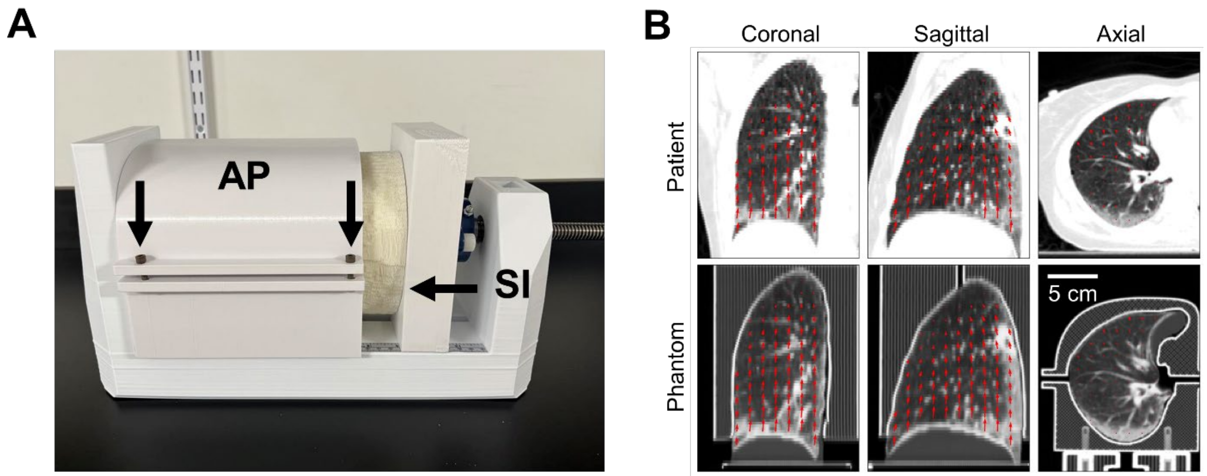

Figure 1. (A) Completed *PixelPrint^{4D}* lung phantom inserted into compression device. Arrow indicates direction of compression for superior/inferior (SI) and anterior/posterior (AP) compression. (B) Deformation vector fields (DVFs) at end exhale displayed as a field of arrows overlaid on the patient and phantom CT images. (WL: -500, WW: 1000).

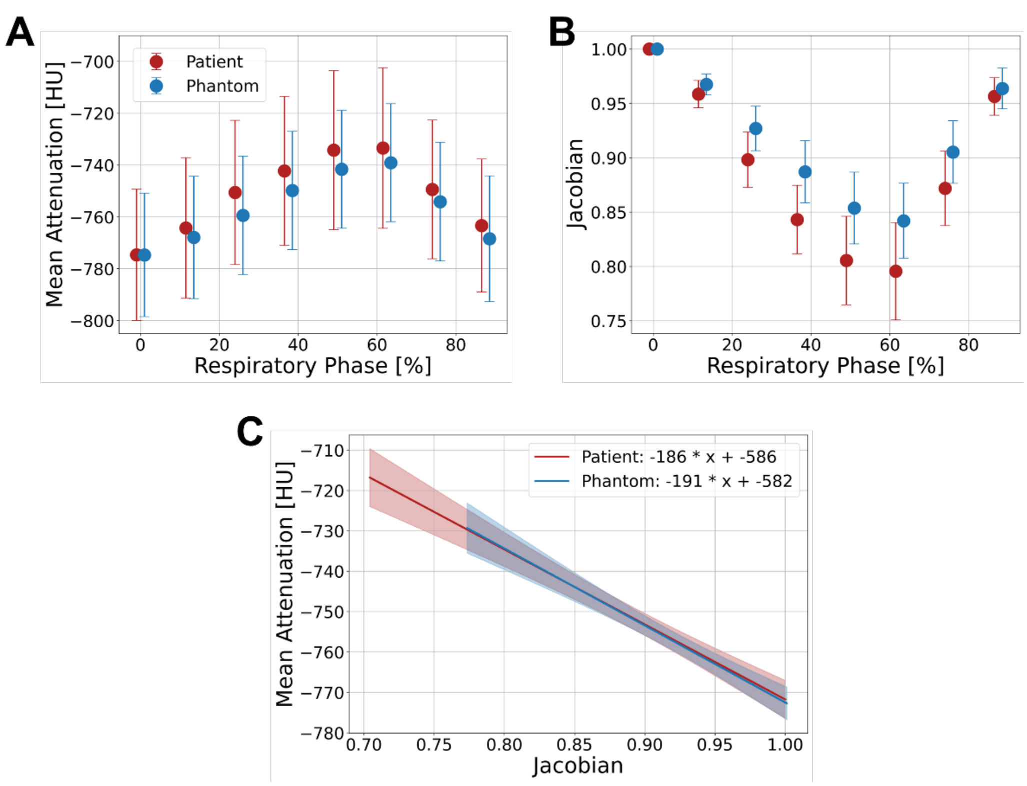

Figure 2. (A) Mean attenuation and (B) Mean Jacobian values representing volumetric changes measured in the background lung parenchyma across different phases in the patient and matched phantom compression scans, with data points displaced in the x-axis between the patient and phantom datasets to improve visibility. (C) The linear regression relating attenuation and Jacobian in the patient and phantom, along with the 95% confidence interval indicated with the shaded regions.