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Towards more realistic 4DCT(MRI) numerical lung phantoms

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Purpose: Numerical 4D phantoms are a valuable tool for simulations and developments in 4D radiotherapy and image guidance. We present an upgrade of the 4DCT(MRI) lung phantoms, integrating realistic respiratory ribcage motion and further enhancing the lung density representation throughout the breathing cycle.

Methods: Synthetic 4DCTs, referred to as 4DCT(MRI)s, are based on density information of reference CTs combined with motion from multiple-breathing-cycle 4DMRIs. First, the motion of the lungs and ribcage was independently extracted from 4DMRIs using deformable image registration (DIR). After establishing inter-subject correspondence between the CT and MRI anatomy through the DIR of binary masks of the lungs and ribcage, the 4DMRI motion was applied to the corresponding locations in the CT. The resulting deformation vector fields (DVF) was further post-processed to preserve sliding organ motion along the chest wall. Lastly, lung densities were scaled according to the Jacobian determinant of the DVFs, which represents local lung volume changes. The new workflow was validated using four clinical 4DCTs and compared to the old workflow (without ribcage motion and density scaling). For this purpose, synthetic 4DCTs (referred to as 4DCT(CT)s), were generated using the motion from the 4DCTs themselves. 4DCT(CT)s were created using the old and new workflow and compared to the original 4DCTs in terms of mean lung density and through pencil beam scanned (PBS) proton 4D dose calculations.

Results: The newly implemented lung density scaling resulted in a reduction of the maximum difference in mean lung HU from 45 HU to 12 HU between the 4DCTs and the corresponding old and new 4DCT(CT)s, respectively. Comparison of 4D dose distributions of PBS plans calculated on the new 4DCT(CT)s and 4DCTs resulted in very high 2%/2mm gamma pass rates (>97%), which were on average 1.4% higher than for the old 4DCT(CT)s.

Conclusion: The 4DCT(MRI) workflow was successfully improved and the resulting 4DCT(MRI) lung phantoms demonstrate realistic respiratory ribcage motion with sliding organ motion along the chest wall and a more accurate representation of respiratory induced lung density changes.

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