Journal of
Nuclear Medicine & Radiation Therapy

Wu et al., J Nucl Med Radiat Ther 2012, S:3
DOI: 10.4172/2155-9619.S3-002

Research Article Open Access

A Preliminary Study of Reconstructing Four-Dimensional CT Image Sets by Limited Phase-Specific CT Scans and Image Registration

Xingen Wu[1]*, Warren D. D'Souza[2] and Cedric X Yu[2]

[1]Department of Radiation Oncology, University of Alabama at Birmingham, USA
[2]Department of Radiation Oncology, University of Maryland School of Medicine, Baltimore, USA

Abstract

A 3D block searching image registration algorithm was used to reconstruct 4D CT image sets from limited two or three phase-specific CT scans. A modified first-aid thorax phantom was used to verify the algorithm by acquiring ten known-phase (0°, 20°, 40°, 60°, 80°, 100°, 120°, 140°, 160° and 180°) image sets simulating breath-holding lung with an inflatable balloon. Two methods were used to reconstruct 4D image sets: two-phase approach and three-phase approach. The former only used two extreme phases: end-of-exhalation (0° phase) and end-of-inhalation (180° phase). The three-phase approach adds an intermediate phase. The average overlapping ratio for the two-phase approach is 95.3% with its range between 93.2% and 97.5%. For the three-phase approach, the average overlapping ratio is 97.3 with its range between 95.6% and 98.4%. Except the extreme top, the maximum 2D contour deviation was 3 mm for the two-phase approach and 1 mm for the three-phase approach respectively. A clinical lung patient case was also used to test the algorithm. There were total three phase-specific CT scans (0°, 90°, and 180°) and the middle phase (90° phase) was used to verify the accuracy of the reconstructed middle phase. The overlapping ratio is 98.5% and the maximum contour deviation is 1.5 mm. With this approach, it is feasible to reconstruct 4D image sets with limited phase-specific, breath-holding CT scan on a single-slice CT scanner in an acceptable accuracy range.

Keywords: Breath hold; 4D CT; Image registration; Gating

Introduction

Respiratory-induced motion can cause artifacts on free-breathing planning CT images for lung cancer patients. Tumor motion can also lead to suboptimal treatment from a patient-customized plan. There are many approaches to manage respiratory-related motion problems, including phase or amplitude gating and breath-hold techniques (active and passive) [1-5]. Although breath-hold techniques are effective in immobilizing treatment target of lung cancer patients, they are often uncomfortable for patients with compromised pulmonary capacity. Some of these patients are often unable to perform within reasonable scan time. Their discomfort of breath-holds during CT simulation may be alleviated by phase-triggering (or gating) CT scanner. Some commercial products have been used in clinic, like Varian Real-Time Position Management (RPM) system [6] (Varian Medical Systems, Palo Alto, CA) and the Active Breathing Control (ABC) system [7] (Elekta Oncology Systems, Norcross, GA). 4D imaging has been demonstrated by retrospectively sorting helical data sets from single [8-10] or multi-slice [11-13] CT scanners according to their time stamp. It is easy for multiple-slice CT scanners to associate respiration phases with the recorded respiratory signals [14]. However, some clinics do not have these advance multiple-slice CT scanners, especially those in developing countries. It is relative hard for single-slice CT scanners to scan so many phases. In this study we propose a new approach to reconstructing 4D CT data sets from a limited number of phase-specific CT scans on a Picker PQ 5000 (Philips/Marconi Medical Systems, Cleveland, OH) single-slice CT scanner with an image registration algorithm.

Materials and Methods

3d Block searching image registration algorithm

The 3D block searching method is a coarse-to-fine direct image registration approach [15-17]. The target image volume was divided into multiple non-overlapping blocks of voxels. There are total two levels of iterations: the resolution of the images increase at the outer level to transfer the current estimation of displacement field into the next higher resolution. At the inner level, the estimation of displacement filed can be improved through a local search. For example, a typical dimension of image volume is 512 x 512 x 128 voxels. The image resolution can be 32 x 32 x 32, 64 x 64 x 64 and 128 x 128 x 64 voxels. For each image resolution, a local correlation search was conducted by a small block (typical dimension from 2 x 2 x 2 voxels to 4 x 4 x 4 voxels). All the voxels in this small block can be shifted to maximize its correlation scores with the corresponding block in the target image volume. The searching usually is limited within its neighborhood (about 2 to 3 voxels). The displacement found on the low (coarse) resolution can be used in the next finer resolution through linear interpolation to match the new image and block dimension. The advantage of this searching strategy is that it can avoid local minima in regional searching and speed up the convergence because the searching starts with an initial starting point from the previous search. The cost function to be minimized consists of two parts: the similarity measurement part and the smoothing part for regulation purpose. The first part is used to find two best matching regional blocks and the second part is to preserve the continuity of tissues due to limited elasticity it has. The cost function can be defined as:

$$E = \sum_{i,j,k}\left[A(i,j,k)+\phi)-B(i,j,k)\right]^2+\alpha\left[\left(\frac{\partial^2\phi}{\partial x^2}\right)+\left(\frac{\partial^2\phi}{\partial y^2}\right)+\left(\frac{\partial^2\phi}{\partial z^2}\right)\right] \quad (1)$$

Where (i,j,k) is the voxel of block A in the moving volume and block

***Corresponding author:** Xingen Wu, Department of Radiation Oncology, University of Alabama at Birmingham, AL 35249, USA, E-mail: xnwu@uabmc.edu

Received March 07, 2012; **Accepted** April 12, 2012; **Published** April 16, 2012

Citation: Wu X, D'Souza WD, Yu CX (2012) A Preliminary Study of Reconstructing Four-Dimensional CT Image Sets by Limited Phase-Specific CT Scans and Image Registration. J Nucl Med Radiat Ther S3:002. doi:10.4172/2155-9619.S3-002

Citation: Wu X, D'Souza WD, Yu CX (2012) A Preliminary Study of Reconstructing Four-Dimensional CT Image Sets by Limited Phase-Specific CT Scans and Image Registration. J Nucl Med Radiat Ther S3:002. doi:10.4172/2155-9619.S3-002

B in the target volume respectively. If the displacement vector ϕ can be set arbitrarily, the similarity (first part of the above equation on the right side) can be close to zero by moving a similar-intensity voxel in the moving image set. The resultant image can be very 'noisy' and useless. The second part on the right side is a Laplacian operator to enforce 'smoothing' on the resultant image set through minimization. This effect is similar to the elasticity enforcement for the imaging tissue. The weighting factor α is used to balance the two terms and its value reflects the emphasis (importance) of the 'smoothing' or 'regulation'. A larger value of α can be used for suppressing noise in the CT image sets and for less elastic (motion) tissue. Our selection of this weighting factor is a trial-and-error procedure. Its range is between 0 and 100 [16].

A modified respiration phantom

A modified T1Man CPR training phantom (First Aid Products, CA) was used to simulate respiratory-induced motion. A cavity was cut in the thoracic region of the phantom to accommodate an inflatable latex balloon to simulate human's lung. The balloon was connected to a plastic tube via an adaptor (Figure 1) while the tube was connected to an air pump driven by an oscillating piston. The piston is connected and driven by a direct-current motor (Figure 1a). A dial was attached on the oscillator to indicate phases of a simulated respiration cycle (Figure 1b). The motor can stop at any specific phase or smoothly transmit to other respiration phases. Since the air balloon is a closed system, it can keep the shape and volume at a specific phase during CT scanning. There were 10 total CT scans acquired with the balloon volume at different phases of 'breathing': 0°, 20°, 40°, 60°, 80°, 100°, 120°, 140°, 160°, and 180° by using a single-slice Picker PQ5000 CT scanner. The 0° and 180° phases are two extreme positions in a simulated respiration cycle: end-of-exhalation and end-of-inhalation respectively. In the two-phase approach, they can be used to reconstruct the rest intermediate phases through the 3D block searching image registration. In the three-phase approach, a third middle phase (80°) is used to reconstruct the rest phases. The reconstructed image sets were then compared with their corresponding phase-known image sets. There are total 46 CT slices for each phase.

In the two-phase approach, the 0° phase was used as the target image set and the 180° phase was used as the moving image set. As part of the registration process, the 160° phase was first reconstructed. This new reconstructed phase was then used as the new source and was registered to the same target (0°phase). This procedure was repeated until all the other six phases (including 120°, 100°, 80°, 60°, 40° and 20°) were reconstructed.

In the three phases approach, the middle phase (80°) was first used as the target and it was registered by 180° phase in the first stage. Four middle phases (160°, 140°, 120° and 100°) were reconstructed. In the second stage the 80° phase used as moving object was registered to the 0° phase (target). Three phases (60°, 40° and 20°) were reconstructed.

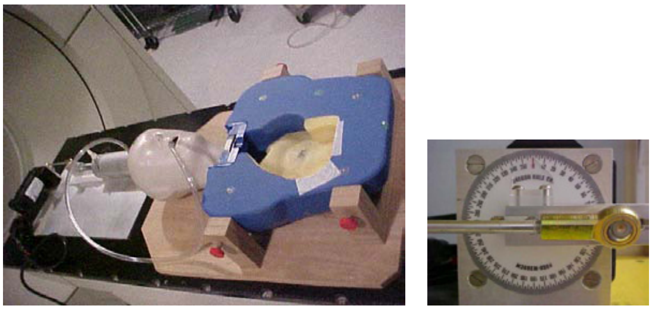
A clinical case

CT images of three phases (0°, 90° and 180°) were acquired from a lung cancer patient. The breath-holding technique was carried out with an active breathing control (Aktina Inc., Congers, New York). The ABC system is a spirometer-based system which monitors the volume of air in-and-out of the patient. Before the formal scan, the patient underwent a training session to familiarize himself/herself with the monitoring system. After training, the patient was able to maintain breath-holding about 12 seconds each time. The pre-selected phase signal was synchronized with beam-on time of our spiral CT scanner.

Results

The phantom case

In the two-phase approach (Figure 2a), the reconstructed volumes of different phases (green) were overlapped on the original CT volumes (gray). The average overlapping ratio (defined as percentage of overlapping volume to the target volume) is 95.3% with a range between 93.2% and 97.5%. In the three-phase approach (Figure 2b), the average overlapping ratio is 97.3 with its range between 95.6% and 98.4%. The overlapping ratios are improved in the three-phase situation. The centroid movement of lung mass was calculated (Figure 3) in order to trace their motion. The two motion trajectories of the reconstructed lung volumes are compared with the centroid movement of the original lung volume (the red trajectory). In the case of two-phase approach (the blue trajectory), the maximum differences in *X*, *Y* and *Z* direction are 1.1 mm, 2.8 mm and 4.8 mm respectively. In the three-phase approach (the black trajectory), the maximum differences in *X*, *Y* and *Z* directions were 1.0 mm, 1.6 mm and 0.0 mm. The three-phase approach achieves better agreement than the two-phase approach due to the fact that the middle phase (the 80° phase) was used as constraint in image registration and with less deformation between the moving and the target**.** The 2D contours on the reconstructed volumes were also calculated and compared with the original contours. The maximum deviations were 3 mm and 1 mm (except the extreme top) for the two-phase and three-phase approaches respectively.



(a) (b)

Figure 1: A modified first-aid thorax phantom (a) and a phase-indicated mater (b).

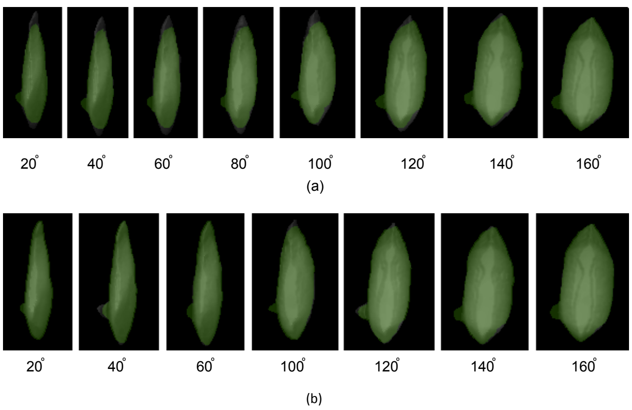


Figure 2: Overlapping of the reconstructed (green) and the original volumes (gray) of different phases for two-phase approach (a) and three-phase approach (b).

The clinical case

Only three phase (0º, 90º, and 180º) CT scans were obtained in order to reduce the scanning time. The two extreme phases (0º and 180º) were used to reconstruct three intermediate phases: 45º, 90º and 135º. The original 90º phase was used to compare the reconstructed 90º phase. Figure 4 shows the three reconstructed phases (45º, 90º and 135º) with the original two phases (0º and 180º) viewed from the direction of the lung apex. Figure 5 shows the overlapping between the reconstructed 90º phase (green) and the original 90º phase. The overlapping ratio is 98.5%. The contour deviation was also calculated and the maximum deviation is 1.5 mm.

Conclusion

A 3D block searching image registration method was used to reconstruct 4D CT image sets through specific two- or three-phase CT scans. Our phantom study shows the three-phase approach is better than the two-phase approach. Our clinical case also shows that two CT scans (0º phase and 180º phase) can be used to reconstruct other intermediate phases (45º, 90º and 135º). For those hospitals with only single-slice traditional CT scanners, this approach provides an alternative way to reconstruct 4D CT sets within acceptable accuracy range and makes it possible to do 4D treatments for cancer patients.

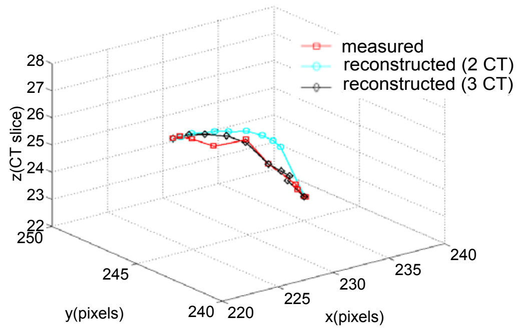


Figure 3: Motion trajectories of two-phase approach (blue) and three-phase approach (black) compared with the original measured trajectory (red).

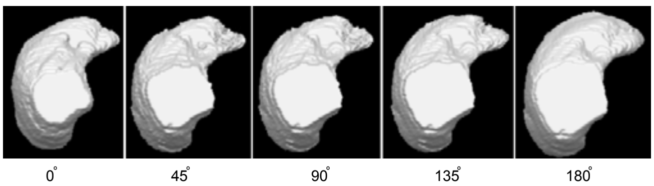


Figure 4: Three reconstructed intermediate phases (45º, 90º, 135º) and two original phases (0º and 180º) viewed from the tip of the lung.

Figure 5: Overlapping of the reconstructed 90º phase (green) with the original 90º phase (gray).

References

1. Sager O, Beyzadeoglu M, Dincoglan F, Oysul K, Kahya YE, et al. (2012) Evaluation of active breathing control-moderate deep inspiration breath-hold in definitive non-small cell lung cancer radiotherapy, Neoplasma 59: 333-340.
2. Hanley J, Debois MM, Mah D, Mageras GS, Raben A, et al. (1999) Deep inspiration breath-hold technique for lung tumors: The potential value of target immobilization and reduced lung density in dose escalation. Int J Radiat Oncol Biol Phys 45: 603-611.
3. Rosenzweig KE, Hanley J, Mah D, Mageras G, Hunt M, et al. (2000) The deep inspiration breath-hold technique in the treatment of inoperable non-small-cell lung cancer. Int J Radiat Oncol Biol Phys 48: 81-87.
4. Wong JW, Sharpe MB, Jaffray DA, Kini VR, Robertson JM, et al. (1999) The use of active breathing control (ABC) to reduce margin for breathing motion. Int J Radiat Oncol Biol Phys 44: 911-919.
5. Stromberg JS, Sharpe MB, Kim LH, Kini VR, Jaffray DA, et al. (2000) Active breathing control (ABC) for Hodgkin's disease: reduction in normal tissue irradiation with deep inspiration and implications for treatment. Int J Radiat Oncol Biol Phys 48: 797-806.
6. Dawson LA, Brock KK, Kazanjian S, Fitch D, McGinn CJ, et al. (2001) The reproducibility of organ position using active breathing control (ABC) during liver radiotherapy. Int J Radiat Oncol Biol Phys 51: 1410-1421.
7. Shen S, Duan J, Fiveash JB, Brezovich IA, Plant BA, et al. (2003) Validation of target volume and position in respiratory gated CT planning and treatment. Med Phys 30: 3196-3205.
8. D'Souza WD, Kwok Y, Deyoung C, Zacharapoulos N, Pepelea M, et al. (2005) Gated CT imaging using a free-breathing respiration signal from flow-volume spirometry. Med Phys 32: 3641-3649.
9. Ford EC, Mageras GS, Yorke E, Ling CC (2003) Respiration-correlated spiral CT: a method of measuring respiratory-induced anatomic motion for radiation treatment planning. Med Phys 30: 88-97.
10. Vedam SS, Keall PJ, Kini VR, Mostafavi H, Shukla HP, et al. (2003) Acquiring a four-dimensional computed tomography dataset using an external respiratory signal. Phys Med Biol 48: 45-62.
11. Underberg RW, Lagerwaard FJ, Cuijpers JP, Slotman BJ, van Sörnsen de Koste JR, et al. (2004) Four-dimensional CT scans for treatment planning in stereotactic radiotherapy for stage I lung cancer. Int J Radiat Oncol Biol Phys 60: 1283-1290.
12. Low DA, Nystrom M, Kalinin E, Parikh P, Dempsey JF, et al. (2003) A method for the reconstruction of four-dimensional synchronized CT scans acquired during free breathing. Med Phys 30: 1254-1263.
13. Keall PJ, Starkschall G, Shukla H, Forster KM, Ortiz V, et al. (2004) Acquiring 4D thoracic CT scans using a multislice helical method. Phys Med Biol 49: 2053-2067.
14. Pan T, Lee TY, Rietzel E, Chen GT (2004) 4D-CT imaging of a volume influenced by respiratory motion on multi-slice CT. Med Phys 31: 333-340.
15. Seppenwoolde Y, Shirato H, Kitamura K, Shimizu S, van Herk M, et al. (2002) Precise and real-time measurement of 3D tumor motion in lung due to breathing and heartbeat, measured during radiotherapy. Int J Radiat Oncol Biol Phys 53: 822-834.
16. Clarenz U, Droske M, Henn S, Rumpf M, Witsch K (2006) Computational methods for nonlinear image registration: Mathematical Models for Registration and Applications to Medical Imaging Mathematics in Industry. Springer 10: 81-101.
17. Kjems U, Philipsen PA, Hansen LK, Chen CT, Anderson JR (1996) A nonlinear 3D MRI Brain CO-registration Method: Proceedings of the Interdisciplinary Inversion Workshop 4 Lyngby 1996 Methodology and Applications in Geophysics Astronomy Geodesy and Physics, 1996. Denmark.