The POPI-model, a point-validated pixel-based breathing thorax model

Jef Vandemeulebroucke David Sarrut Patrick Clarysse

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Abstract

We wish to put at the disposal of the scientific community a real patient 4D CT image, two corresponding point-validated motion models and the used expert-based validation data. We also propose to host third-party 4D images, motion models or validation data on the same dedicated website (http://www.creatis.insa-lyon.fr/rio/popi-model). We feel that availability of such ready-to-use data could constitute a welcome complement to the widely used analytical phantoms, providing additional evaluation of novel techniques in the field of radiotherapy and related areas (motion estimation, 4D dosimetry, emission tomography imaging, image reconstruction). The provided pixel-based breathing thorax model represents a higher degree of reality than common geometry-based models, both in terms of anatomy and respiratory motion. In addition they contain all limitations that can be expected from real 4D CT acquisitions onto which for example a treatment plan is based. For example heart motion is not taking into account during acquisition, resolution is fixed and limited and there is the presence of noise and possibly even artifacts. While preliminary evaluation on synthetic phantoms remains useful, final testing on real patient data is imperative for medical applications. In the future we hope to expand this initiative to a repository of own and third-party 4D CT images, validation data and motion models. Accuracy of own and sent in motion models will be estimated through the available expert-based validation data. We will also provide additional data, such as segmentations and stoichiometric calibration of Hounsfield units, that should facilitate the use of the data in certain areas of research.

Introduction

Goal

We wish to put at the disposal of the scientific community a respiratory-correlated four-dimensional (4D) CT image of the thorax, along with 2 corresponding point-validated motion models and expert-based validation data. We hope this will contribute to the current research on radiotherapy and neighboring areas as we feel there is a genuine need for such resources. We also offer the possibility of hosting third party 4D CT images of the thorax, motion models or validation data; thus allowing participants to contribute in building up a breathing thorax standard based on real patient data.

Backround

Simulation is a powerful tool for characterizing, evaluating, and optimizing medical imaging systems. An important aspect of simulation is to have a realistic computerized phantom or model of the human anatomy. For instance, for a given medical imaging device, artificial images can be generated using the computerized patient model according to different acquisition parameters, allowing the acquisition process to be optimized. This forms the basis of simulation techniques. Besides wanting the used model to be as realistic as possible, it is vital to have it thoroughly validated in order to serve as reliable reference during simulation.

The fabrication of realistic models is an area of research on it's own. Earlier work can be divided into two main categories: pixel-based and geometry-based models. Pixel-based phantoms [26] are usually based on patient data, and are thus limited to a particular anatomy, so that study of the effects of anatomical variations is limited. Also, they are fixed to a specific resolution and generation of the phantom at other resolutions requires interpolation which induces error. Geometry-based phantoms [24], on the other hand, allow for anatomical variation and generation at multiple resolutions. They can be made reasonably realistic, but will not be as realistic as pixel-based phantoms. They carry the advantage that exact ray-tracing calculations can be performed using these phantoms, which explains their popularity in fields such as reconstruction. An example is the FORBILD phantom[1] which was designed to provide semi-anthropomorphic cone-beam data for CT examinations of the thorax and has been successfully used for that purpose [10, 11].

Realism can be added to geometry-based phantoms by fitting mathematically defined surface elements to actual patient data [1]. The need for 4D (3D+t) studies has led several authors to incorporate simulated heart and/or respiratory motion [16, 8] in their phantom. A well-known 4D phantom, which can be considered as hybrid between the realism of pixel-based phantoms and the flexibility of geometry-based phantoms, is the four-dimensional NURBS-based cardiac-torso (NCAT) phantom [20]. Although initially developed for use in nuclear medicine imaging research, it has been expanded for use in CT imaging [21] and applied successfully in both areas [25, 7]. Organs are modeled using non-uniform rational B-splines (NURBS), as used in computer graphics [13], and fitted to real patient data. Cardiac and respiratory motion are simulated by applying time-dependent translations to the control points defining the NURBS surface of each organ.

Motivation

We wish to complement these popular geometry-based models by providing a point-validated pixel-based breathing thorax model (popi-model) based on a real 4D CT acquisition. Even though the NCAT phantom has valuable properties which make it convenient to use in simulation techniques, we feel

[1] http://www.imp.uni-erlangen.de/forbild/english/results/thorax/thorax.htm

there are some important arguments in favour of using a model based on real patient data for final evaluation of developed techniques.

The NCAT phantom is built up using analytically defined surfaces that represent the internal organs, ribs and spine. To make their representation more accurate, they were fitted to real patient data. However, the phantom remains a simplified, artificial version of the human thorax that can only approximate anatomical reality. Our model is based on a real patient acquisition, immediately providing this anatomical complexity. In addition it is subject to the same limitations as a common CT image available in current clinical facilities, providing it with characteristics that make it a suitable for use as a practical testing reference: the resolution is fixed and cannot be changed without interpolation and there is the presence of noise and possibly even artifacts which can change the behavior of certain algorithms.

A similar difference between the both models, is the way they represent motion. While respiratory motion is simulated in the case of the NCAT phantom, our model is based on a respiratory-correlated 4D acquisition providing several frames of an actual respiration cycle. Motion between these time frames is estimated through deformable registration. Considering the complexity of the breathing motion, this constitutes a valuable advantage in our opinion. Contrary to the NCAT phantom, heart motion is not taken into account in our model and the heart is therefor represented by a blurred area. Again this is similar to current practice in radiotherapy.

The main advantage to using analytical computerized patient models in simulation studies is that the exact anatomy and physiological functions of the phantom are known, thus providing a gold standard from which to evaluate and improve medical imaging devices and image processing or reconstruction techniques. When working with a model based on real patient data, validation is difficult and requires considerable additional effort. The presence of fiducial markers during image acquisition can provide precise references against which the accuracy of developed motion models can be measured. In absence of such markers, anatomical landmarks identified by experts in all 3D CT images can provide such a measurement [18]. It is through this expert-based validation data that our provided model is validated. The fact that obtaining this expert-based validation is time-consuming, constitutes an additional reason why we feel it is important to put it at the disposal of the community.

The model provided can be used for a variety of applications. Research on motion estimation aims at automatically mapping voxels across 2 or more images with altered configuration. A priori defined references are required to estimate the achieved accuracy. 4D dosimetry research pursues the determination of a treatment plan that results in a dose distribution as close as possible to the physicians prescription, this while taking into account subject movement due to breathing activity. Hence, simulations on real patient data can provide important complementary information to what is obtained through phantom simulations [4, 9, 12]. In order to study the physiological characteristics of the respiration movement and obtain ventilation images, 4D CT images and accompanying motion models are considered a valuable source of information [3]. On board Cone-beam CT imaging (CBCT) has become available in radiotherapy clinics to help identify the target position for treatment. However, due to the relatively slow gantry rotation during acquisition of the CBCT projection data, the patient's respiratory motion causes serious blurring, doubling, streaking and distortion in the reconstructed images. Studies on respiration correlated reconstruction techniques [15, 22] could benefit from the proposed model, allowing to simulate different acquisition conditions with realistic data. Another approach to improve image quality consists of motion compensated reconstruction techniques where a patient-specific motion model is incorporated during reconstruction [16, 5]. In this area it is usually assumed that the motion model is known. CBCT data can be simulated and the provided motion model can be used for such purposes. In Emission Tomography imaging the correction of respiratory motion is currently a hot topic as well. Motion models and/or gated CT images can be used to derive information about the motion observed. Similarly, dynamic PET data can be simulated from the provided model and the information about the subject's motion can be incorporated during reconstruction to perform a motion correction [14, 6].

Data

Image and Scanner Properties

The anonymised respiration-correlated 4D CT image provided consists of 10 3D CT images sampling the entire respiratory cycle. The 3D images are made up of 90-110 slices with a slice thickness spacing of 3mm. Each slice is a 2D image with size 512x512 with an isotropic in-plane resolution of 1.05 mm. The cathode tension is 120kV. All images were acquired using the Philips Brilliance CT Big Bore Oncology configuration. This machine can measure up to 16 slices in one full gantry rotation in only 0,44s. 4D imaging is supported through the Bellows system which consists of a belt strapped around the thorax. Measuring the movement of this belt provides an external signal for synchronization to the phase of the breathing cycle.

Motion Models

Two models are provided: one parametric and another non-parametric. Both were obtained following the Lagrangian approach where the observation of a material point is considered throughout the set of 3D images. This is contrary to the Eulerian approach where a geometrical space is considered, through which material objects move. In practice this means that motion is estimated with respect to a reference space given by one of the 3D CT image. Vector fields deforming this reference state to the remaining 3D CT images are provided, as well as the inverse deformation fields. Deformation fields between two arbitrary states can be easily obtained by composition of the 2 corresponding vector fields. Both motion models only contain estimates for the respiration motion, no cardiac motion was taken into account.

The non-parametric model relies on deformable registration between two 3D CT images. It was implemented using a modified version of the demons algorithm [23], while applying a Gaussian regularization between iterations. A detailed description of the method can be found in [18]. The parametric model is based on non-linear parametric registration. The deformation model is a free form deformation [17] based on hierarchical multi-scale parametric representation using B-spline basis functions. A detailed description can be found in [2]. Both motion models were computed with a resolution of 2.5x2.5x2.5mm. However, there are provided with the same resolution as the CT images (trilinearly interpolated) as well for the sake of convenience.

Validation Data

Landmarks defined by experts in all of the 3D CT images that make out a 4D CT image are provided. Deforming their locations to another phase in the respiratory cycle allows us to calculate the offset between their deformed positions and those specified by the experts, thus serving as a ground truth for verifying motion models. The procedure for obtaining the landmarks is similar to the one described in details in [18]. The precision of the two motion models has been thoroughly evaluated on similar CT images [19]. The non-parametric model is estimated to have an accuracy between 1.2 and 3mm depending on the amplitude of the deformations. For the parametric method similar estimates between 1.4 and 2.7mm were obtained. The dedicated website will contain the estimated precision of both models on the provided images obtained through the provided expert-based validation data.

Web Organization

On the website http://www.creatis.insa-lyon.fr/rio/popi-model all information is presented concerning this initiative. A complete description is given on the used formats for representing the downloadable data. Specifications can be found on how to proceed to downloading, and a explanation clarifies how others can participate to this initiative.

Conclusion

We propose to put at the disposal of the scientific community a 4D CT image, 2 point-validated motion models and expert-based validation data. This dataset can be considered as a point-validated pixel-based breathing thorax model (popi-model) ready to use in research on radiotherapy and related areas. Built up from a real 4D CT acquisition, it constitutes a realistic representation of human anatomy and breathing motion. By being subjected to the same acquisition process applied during normal radiotherapeutic treatment planning, it incorporates the same level of limitations and can provide a realistic practical testing standard. In our opinion the use of the model is limited mainly for the following reasons. Since it is based on one patient, it is limited to a specific anatomy and breathing pattern. Eventhough the image was acquired on a currently state of the art scanner, we estimate these scanners will improve rapidly and will be able to provide higher quality images soon. As mentioned before, cardiac motion is not taken into account in this model.

Perspectives

The website may be used as a repository for 4D CT images, motion models and corresponding validation data. The accuracy of the provided models will be mentioned in the form of the average and standard deviation of distances between identified and deformed landmarks. This can provide a comparison for the accuracy of own developed motion models. It can also serve as an indicator for the error induced by the motion model when used for other means. We may provide additional data that should facilitate the usage of the model in certain research areas. This additional data includes but is not limited to: the signal of the bellows-system used for the 4D acquisition, manual segmentations by experts of the GTV, automatic segmentations of the patient/thorax/lungs and stoichiometric calibration of Hounsfield units for the purpose of Monte-Carlo simulations. When made available, the dedicated website will contain the description for this data.

References

[1] C. P. Bradley, A. J. Pullan, and P. J. Hunter. Geometric modeling of the human torso using cubic hermite elements. *Ann Biomed Eng*, 25(1):96–111, 1997.

[2] B. Delhay, P. Clarysse, C. Pera, and I.E. Magnin. A spatio-temporal deformation model for dense motion estimation in periodic cardiac image sequences. In *From Statistical Atlases to Personalized Models: Understanding Complex Diseases in Populations and Individuals, Satellite Workshop MICCAI 2006*, pages in–press, Copenhagen, Denmark, October 2006.

[3] T. Guerrero, K. Sanders, E. Castillo, Y. Zhang, L. Bidaut, T. Pan, and R. Komaki. Dynamic ventilation imaging from four-dimensional computed tomography. *Phys Med Biol*, 51(4):777–791, Feb 2006.

[4] E. Heath and J. Seuntjens. A direct voxel tracking method for four-dimensional monte carlo dose calculations in deforming anatomy. *Med Phys*, 33(2):434–445, Feb 2006.

[5] T. Li, E. Schreibmann, Y. Yang, and L. Xing. Motion correction for improved target localization with on-board cone-beam computed tomography. *Phys Med Biol*, 51(2):253–267, Jan 2006.

[6] T. Li, B. Thorndyke, E. Schreibmann, Y.Yang, and L. Xing. Model-based image reconstruction for four-dimensional PET. *Med Phys*, 33(5):1288–1298, May 2006.

[7] R. Manjeshwar, Xiaodong Tao, E. Asma, and K. Thielemans. Motion compensated image reconstruction of respiratory gated PET/CT. In *Biomedical Imaging: Macro to Nano, 2006. 3rd IEEE International Symposium on*, pages 674–677, 6-9 April 2006.

[8] R. Manzke, P. Koken, and M. Grass. Extended cardiac reconstruction with large area detectors: a simulation study. In *Nuclear Science Symposium Conference Record, 2004 IEEE*, volume 6, pages 3514–3518Vol.6, 16-22 Oct. 2004.

[9] M.Rosu, I. J. Chetty, J. M. Balter, M. L. Kessler, D. L McShan, and R. K. Ten Haken. Dose reconstruction in deforming lung anatomy: dose grid size effects and clinical implications. *Med Phys*, 32(8):2487–2495, Aug 2005.

[10] F. Noo, M. Defrise, and H. Kudo. General reconstruction theory for multislice X-ray computed tomography with a gantry tilt. *Medical Imaging, IEEE Transactions on*, 23(9):1109–1116, Sept. 2004.

[11] J. D. Pack, F. Noo, and H. Kudo. Investigation of saddle trajectories for cardiac CT imaging in cone-beam geometry. *Phys Med Biol*, 49(11):2317–2336, Jun 2004.

[12] H. Paganetti. Four-dimensional monte carlo simulation of time-dependent geometries. *Phys Med Biol*, 49(6):N75–97, March 2004.

[13] L. Piegl. On NURBS: a survey. *Computer Graphics and Applications, IEEE*, 11(1):55–71, Jan. 1991.

[14] M. Reyes, G. Malandain, P. M. Koulibaly, M. A. Gonzlez Ballester, and J. Darcourt. Respiratory motion correction in emission tomography image reconstruction. *Med Image Comput Comput Assist Interv Int Conf Med Image Comput Comput Assist Interv*, 8(Pt 2):369–376, 2005.

[15] S. Rit, D. Sarrut, and C. Ginestet. Respiratory signal extraction for 4D CT imaging of the thorax from cone-beam CT projections. *Med Image Comput Comput Assist Interv Int Conf Med Image Comput Comput Assist Interv*, 8(Pt 1):556–563, 2005.

[16] S. Rit, D. Sarrut, and S. Miguet. Gated cone-beam CT imaging of the thorax: a reconstruction study. In *SPIE Medical Imaging*, Accepted to appear in 2007.

[17] D. Rueckert, L. I. Sonoda, C. Hayes, D. L. Hill, M. O. Leach, and D. J. Hawkes. Nonrigid registration using free-form deformations: application to breast MR images. *IEEE Trans Med Imaging*, 18(8):712–721, Aug 1999.

[18] D. Sarrut, V. Boldea, S. Miguet, and C. Ginestet. Simulation of four-dimensional CT images from deformable registration between inhale and exhale breath-hold CT scans. *Med Phys*, 33(3):605–617, Mar 2006.

[19] D. Sarrut, B. Delhay, V. Boldea, P. F. Villard, M. Beuve, and P. Clarysse. A comparison framework for breathing motion estimation methods from 4D imaging. *Submitted to IEEE Transactions on Medical Imaging*, 2007.

[20] W.P. Segars. *Development and Application of the New Dynamic NURBS-based Cardiac-Torso (NCAT) Phantom*. PhD thesis, The University of North Carolina at Chapel Hill, 2001.

[21] W.P. Segars, B.M.W. Tsui, E.C. Frey, and E.K. Fishman. Extension of the 4D NCAT phantom to dynamic X-ray CT simulation. In *Nuclear Science Symposium Conference Record, 2003 IEEE*, volume 5, pages 3195–3199Vol.5, 19-25 Oct. 2003.

[22] J.J. Sonke, L. Zijp, P. Remeijer, and M. van Herk. Respiratory correlated cone beam CT. *Med Phys*, 32(4):1176–1186, Apr 2005.

[23] J. P. Thirion. Image matching as a diffusion process: an analogy with maxwell's demons. *Med Image Anal*, 2(3):243–260, Sep 1998.

[24] B. M. Tsui, J. A. Terry, and G. T. Gullberg. Evaluation of cardiac cone-beam single photon emission computed tomography using observer performance experiments and receiver operating characteristic analysis. *Invest Radiol*, 28(12):1101–1112, Dec 1993.

[25] B.M.W. Tsui, Y. Du, W.P. Segars, X. Zhao, S. Sayeram, and E.C. Frey. Fast monte carlo simulation method for medium- and high-energy SPECT. In *Nuclear Science Symposium Conference Record, 2002 IEEE*, volume 2, page 1263vol.2, 10-16 Nov. 2002.

[26] I. G. Zubal, C. R. Harrell, E. O. Smith, Z. Rattner, G. Gindi, and P. B. Hoffer. Computerized three-dimensional segmented human anatomy. *Med Phys*, 21(2):299–302, Feb 1994.