Deformable registration and 4D cone-beam CT reconstruction

David Sarrut, Phd.

Introduction

Accounting for organ motion, due to breathing, in lung cancer radiation treatment, is an important challenge[1]. Breathing-induced movement and deformation impair image acquisition (distorted target volume), treatment planning and radiation treatment delivery. Reducing target position uncertainties should result in decreased irradiation of healthy lung areas and should allow tumour dose escalation, potentially leading to better outcome[2]. Several approaches are currently under investigation (breath hold treatment, gating[3]) but all require patient-specific spatio-temporal information about movements and deformations induced by breathing. Ideally, treatment planning should not rely on 3D images only, but also on a patient-specific breathing thorax model, encompassing all mechanical and functional information available. Some data can be obtained from four-dimensional (4D) computed tomography (CT) imaging[4], but 4D images alone are not sufficient and should be associated with new image analysis tools[5]. We describe here a deformable registration method allowing to build a 4D breathing thorax model, and a 4D reconstruction algorithm allowing to build 4D images using Elekta Synergy® XVI.

Image registration for the 4D breathing thorax model

Image registration is a fundamental, widely used medical image analysis process[6, 7]. Its use in the field of radiation therapy is relatively recent and in constant progression[8]. Deformable registration algorithms can be used as motion estimators to automatically propagate 3D organ or target contours to all time-series images. They can also be used to build a 4D model composed of spatio-temporal trajectories of all volume elements in the thorax. Using such a model would make it possible to select the best way of managing organ motion for each patient and provide helpful information for planning real-time tracking and dose delivery.

We have proposed[9, 10] and validated a deformable registration method that can be applied to building a 4D thorax breathing model from a 4D CT image or simulating an artificial 4D CT image, of the thorax during breathing (by registration of two CT scans acquired at inhale and exhale breath holds). Conventional registration is based on the intensity conservation assumption which implies that an image point in the first image has the same intensity in the second image but at a different location. However, lung densities are known to decrease from exhalation to inhalation according to the quantity of inhaled air. Therefore, we decided to adapt the lung density of the first image in order to be closer to the intensity conservation assumption. We called this method A Priori Lung Density Modification (APLDM). Deformable registration is then achieved by optimization of a criterion composed of a similarity measure (squared difference) and a regularization measure (Gaussian) using a steepest gradient descent optimization. The final 4D breathing thorax model is computed in reference to a given phase in the 4D CT by running the deformable registration algorithm between such image and all other phases. Composing the resulting displacement field of each voxel yields a path representing the trajectory of each voxel during the breathing cycle.

Validation

We evaluated the accuracy of the resulting deformation models. The evaluation of motion estimation from 4D CT data relies on the identification and tracking of landmarks by medical experts. Three different experts selected more than 500 landmarks within 4D CT images of the lungs for three patients. Landmark tracking was performed at all time points of the expiration phase. Deforming their locations to another phase in the respiratory cycle allowed to calculate the offset between deformed positions and those specified by the experts, thus serving as a ground truth for evaluating the accuracy of motion models.

The proposed method was estimated to have an accuracy between 1.2 and 3mm, depending on the amplitude of the deformations. It is in the order of the image resolution and comparable to inter-observer variability (1.9mm). The computation time ranged from 2 minutes to 30 minutes, depending on the displacement amplitude and the image resolution (on a conventional PC, Linux).

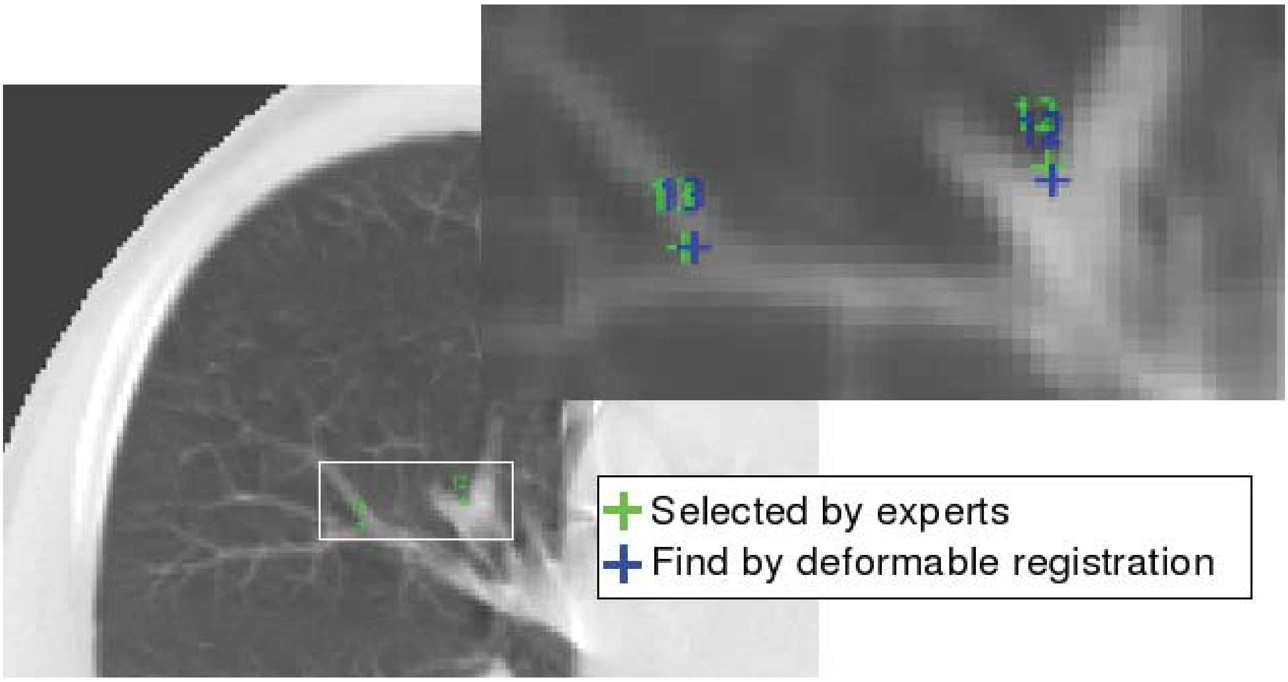

Figure 1: examples of landmarks used for validation of deformable registration.

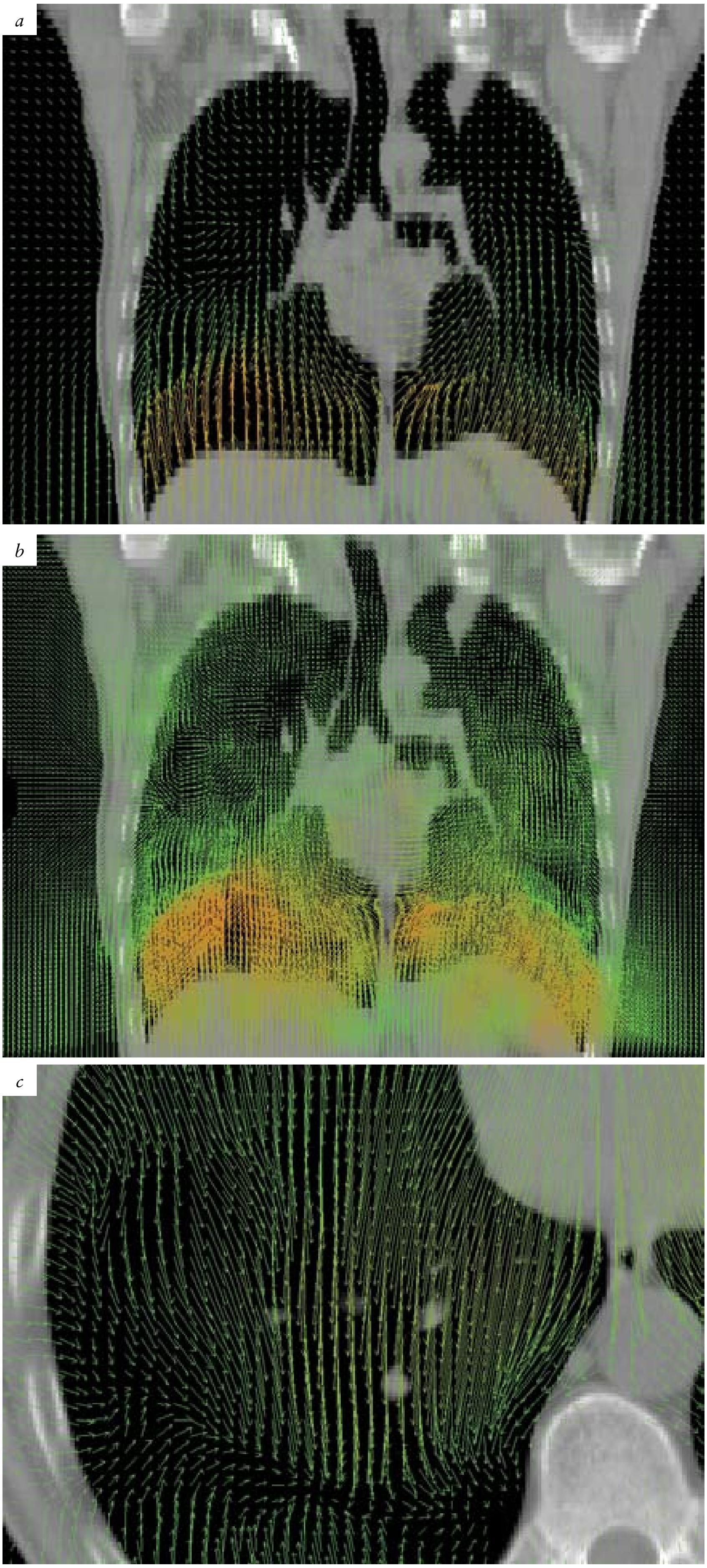

Figure 2: vector field superimposed on CT slices –
a) vector every 3mm,
b) vector every 6mm and
c) vector every 4 mm.

The 4D breathing thorax model is used

– to propagate contours from one phase to the other[11]. Contours are drawn on only one phase of the 4D CT image, then propagated to other phases using the deformation field.
– to define margins according to the breathing pattern of each patient[12]
– to evaluate the distribution of the absorbed dose in moving organs. Dose distribution calculations are performed for every ten phases of the 4D CT using the same treatment planning. The resulting ten dose maps are deformed and merged into a single 4D dose distribution, taking into account the time spent in each phase.
– to motion compensate Elekta XVI VolumeView™ reconstruction (see next section).

Elekta 4D VolumeView™ imaging

Planning patient treatment from a 4D CT image requires controlling the treatment according to 4D information. In the past few years, there has been an increasing interest of the radiation oncology community in cone-beam CT scanners integrated into the gantry of medical linear accelerators, such as Elekta Synergy®. This imaging device enables acquisition of CT images of the patient in treatment position. Unfortunately, as with other CT scanners, the respiratory motion of the patient during acquisition causes artefacts such as blur, streaks and bands. To correct such effects, radiation therapists may use the respiratory-correlated or gated technique, which consists in selecting a subset of the cone-beam projections, on the basis of their position in the respiratory cycle, and to use these projections in a conventional static reconstruction algorithm to obtain an image of a respiratory instant. On the contrary, dynamic reconstruction uses all the projections, but the reconstruction algorithm is modified to compensate for the motion of the thorax. It requires the knowledge of the breathing thorax model during the reconstruction process.

We have compared[13, 14] gated and dynamic CT reconstructions of a moving mechanical phantom obtained from cone-beam projections acquired using Elekta Synergy XVI. We have found that gated reconstruction corrects blur artefacts but yields noisy results. Dynamic reconstruction gives results that are close to the CT image obtained when the platform is fixed.

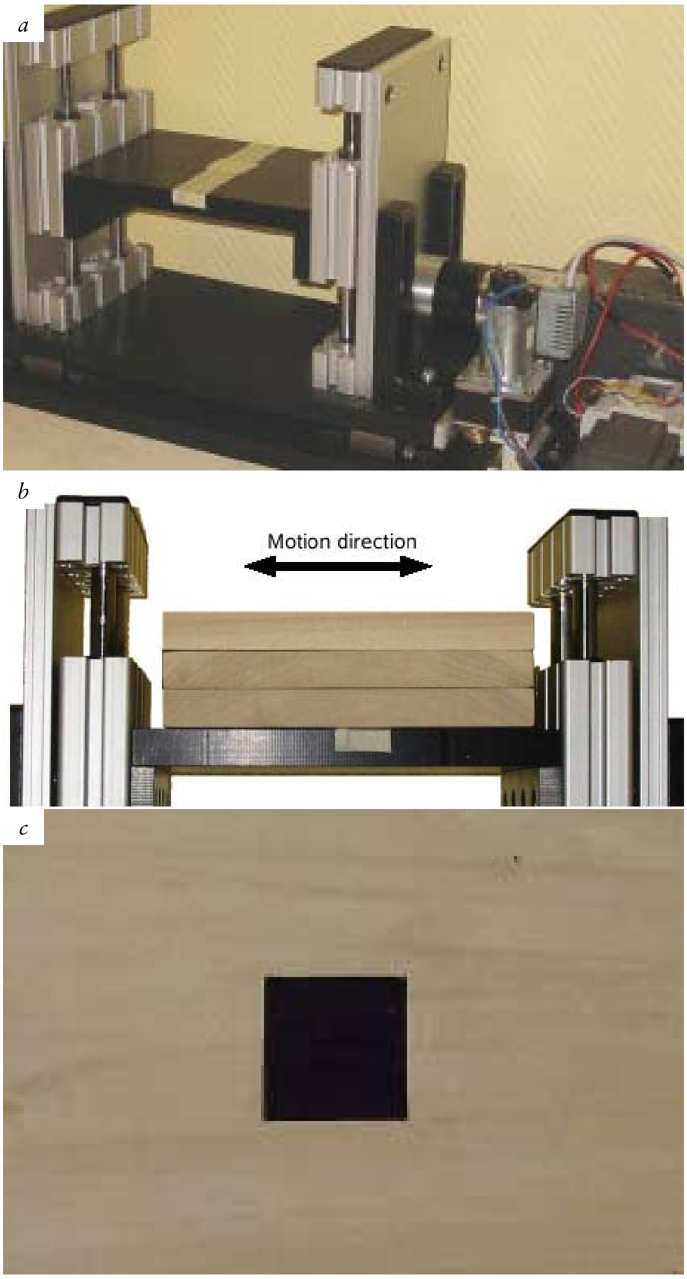

Figure 3: experimental set up composed of –
a) a mobile platform, on top of which is
b) a phantom composed of three wooden slabs with
c) a polyethylene cube inserted in the center of the middle slab.

However, the use of dynamic reconstruction on patient data is much more complicated because it requires accurate knowledge of the 4D motion model (such as the ones presented in the previous section) during the acquisition step[13]. Promising solutions have been proposed in the past to determine such 4D motion models. Our future studies will address the reconstruction of simulated and real patient images with both analytic and algebraic methods.

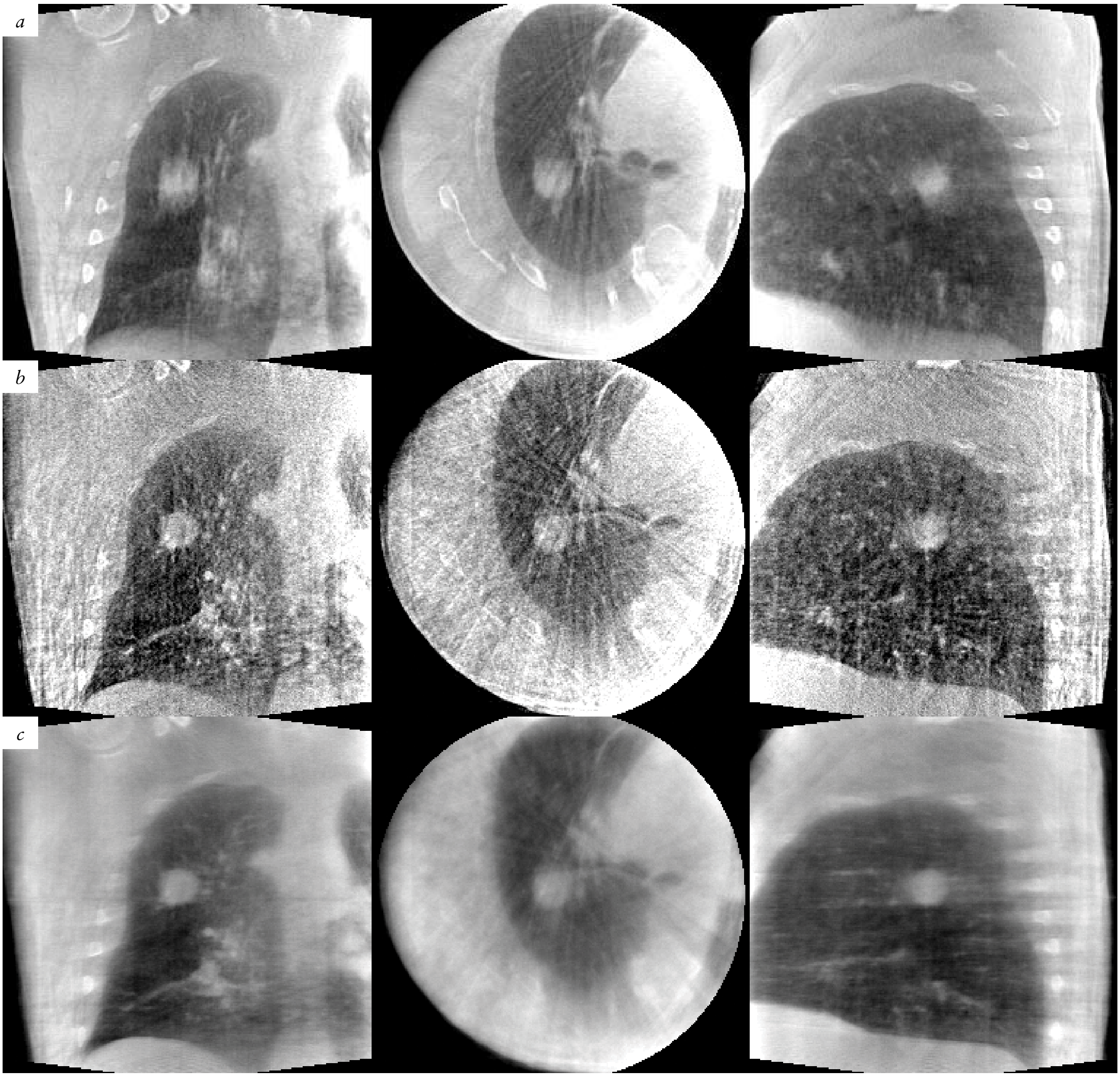

Figure 4:
a) reference blurred 3D CB reconstruction,
b) 4D reconstruction with Feldkamp technique,
c) 4D reconstruction with SART technique.

Conclusion

Deformable registration has increasing applications in radiotherapy. Extensive validation of the numerous existing methods is required before expanding its clinical use. Nevertheless, deformable registration has already become a fundamental image analysis tool for radiotherapy, and will probably be included in all treatment planning systems in the near future.

We have put at the disposal, one of the scientific community a respiratory-correlated 4D CT image of the thorax, along with two point-validated motion models and expert-based validation data. This device is called the popi (point-validated pixel-based) breathing thorax model[15]. We hope this will contribute to the current research on radiotherapy and neighbouring areas.

Acknowledgements

The author wishes to thank all persons which did largely contribute to these works: Chantal Ginestet, Christian Carrie and Patrick Clarysse, all the PhD students: Vlad Boldea, Simon Rit, Myriam Ayadi, Jean-Noel Badel and Jef Vandemeulebroucke and all the other students involved in the project.

References

(1) *M. Goitein. Organ and tumor motion: An overview. Seminars in Radiation Oncology, 14(1):2–9, 2004.*

(2) *CC. Ling, E. Yorke, H. Amols, J. Mechalakos, Y. Erdi, S. Leibel, K. Rosenzweig, and A. Jackson. Editorial : high-tech will improve radiotherapy of NSCLC: a hypothesis waiting to be validated. International Journal of Radiation Oncology Biology Physics, 60(1):3–7, 2004.*

(3) *GS. Mageras and E. Yorke. Deep inspiration breath hold and respiratory gating strategies for reducing organ motion in radiation treatment. Seminars in Radiation Oncology, 14(1):65–75, January 2004.*

(4) *SS. Vedam, PJ. Keall, VR. Kini, H. Mostafavi, HP. Shukla, and R. Mohan. Acquiring a four-dimensional computed tomography dataset using an external respiratory signal. Physics in Medicine and Biology, 48(1):45–62, 2003.*

(5) *PJ. Keall, S. Joshi, SS. Vedam, JV. Siebers, VR. Kini, and R. Mohan. Four-dimensional radiotherapy planning for DMLC-based respiratory motion tracking. Medical physics, 32(4):942–951, 2005.*

(6) *WR. Crum, T. Hartkens, and DL. Hill. Non-rigid image registration: theory and practice. Br J Radiol., 77(2):140–153, 2004.*

(7) *B. Zitova and J. Flusser. Image registration methods: a survey. Image and Vision Computing, 21:977–1000, 2003.*

(8) *D. Sarrut. Deformable registration for image-guided radiation therapy. Zeitschrift fuer Medizinische Physik, 4:285–297, 2006.*

(9) *D. Sarrut, V. Boldea, S. Miguet, and C. Ginestet. Simulation of 4D CT images from deformable registration between inhale and exhale breath-hold CT scans. Medical physics, 33(3):605-617. 2006.*

(10) *D. Sarrut, B. Delhay , PF Villard, V. Boldea, M. Beuve, P. Clarysse. A comparison framework for breathing motion estimation methods from 4D imaging. IEEE Transaction on Medical Imaging. To appear.*

(11) *Boldea, V., Sharp, G.C. , Jiang, S.B. and Sarrut, D. Lung motion modeling with deformable registration: non-linearity and hysteresis estimation and analysis. In XVth International Conference on the Use of Computers in Radiation Therapy (ICCR), Toronto, Canada. 2007.*

(12) *D. Sarrut, V. Boldea, M. Ayadi, JN. Badel, C. Ginestet, and S. Clippe. Non-rigid registration method to assess reproducibility of breath-holding with ABC in lung cancer. International Journal of Radiation Oncology Biology Physics, 61(2):594–607, 2005.*

(13) *Rit, S., Sarrut, D. and Miguet, S. Gated cone-beam CT imaging of the thorax: a reconstruction study. In SPIE Medical Imaging: Physics of Medical Imaging. 2007.*

(14) *Rit, S., Sarrut, D. and Ginestet, C. Comparison of gated and dynamic cone-beam CT reconstruction methods. In XVth International Conference on the Use of Computers in Radiation Therapy (ICCR), Toronto, Canada. 2007.*

(15) *J. Vandemeulebroucke, Sarrut, D. Point-validated Pixel-based Breathing Thorax Model. In XVth International Conference on the Use of Computers in Radiation Therapy (ICCR), Toronto, Canada. 2007.*