OC-0058

A novel 4DCT technique for breathing motion modeling

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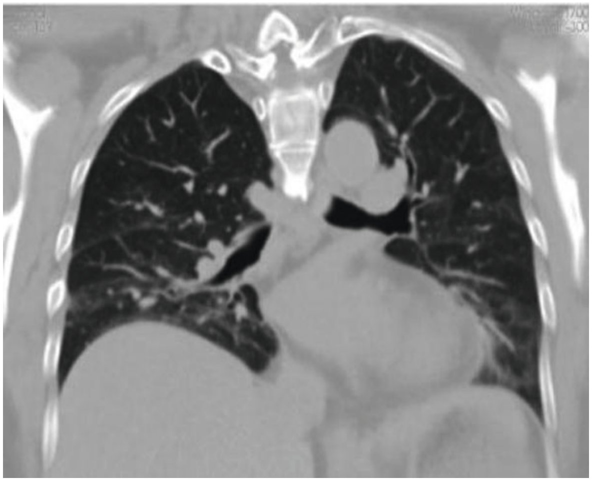
Purpose/Objective: To develop a novel method for 4DCT data acquisition that avoids the pitfalls of existing methods, including abutment discontinuities, management of irregular breathing, and high dose.

Materials and Methods: The proposed 4DCT method uses simultaneous breathing surrogate measurement (pneumatic bellows around the abdomen) and standard fast helical scanning to acquire the breathing-correlated CT scans. The CT scanner is operated in standard helical mode using a pitch of 1, the fastest rotation rate (<0.3s), low mAs (40mAs) and covering the lungs. The scans acquisition is repeated 25 times, switching scanning directions between successive acquisitions. The scans take roughly ¼ of the breathing cycle to acquire, so no image corresponds to any specific breathing phase. Instead, each CT slice is correlated with a specific time and therefore phase. We use deformable image registration to determine the locations of tissues in the 25 scans. The registration maps indicate the tissue motion as a function of the measured breathing phase. We utilize the 5D breathing motion model, which correlates motion to the breathing amplitude (surrogate voltage) and its derivative. The motion model is used to determine the motion paths taken by the tissues during respiration. Because all of the images are coregistered, they are deformed to a single reference image geometry and averaged, reducing the statistical image noise. The motion model allows that aggregate image to be deformed to a user-specified breathing phase.

Results:



Because the images were acquired during quiet respiration and with rapid helical scanning, the images were motion artefact free and the coregistration accuracy was better than 1 mm. The figure shows an example of a reconstruction of an exhalation image. Note that there are no obvious motion or abutment artefacts typical of commercial 4DCT techniques. This technique has allowed us to measure the breathing motion model so that the correspondence of the model to the deformed tissues is 0.4 mm ± 0.6 mm.

Conclusions: The proposed 4DCT acquisition and analysis technique promises to improve the clinical and research applications of breathing motion management, producing artefact-free images and the ability to generate low-noise images at arbitrary breathing phases. Determination of breathing motion model parameters is greatly improved with the proposed technique and we are developing it into a replacement for the current clinical 4DCT protocols.

OC-0059

Motion compensated Digital Tomosynthesis using an a priori motion model

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Purpose/Objective: Gantry mounted kV imaging systems allow inline Digital Tomosynthesis (DTS) to monitor intrafraction motion during VMAT delivery.[1] Respiratory motion in the thorax and upper abdominal region, however, blurs DTS images, potentially compromising monitoring accuracy. Motion compensated (MC) DTS has the potential to mitigate such motion artifacts. The purpose of this study was therefore to implement MC-DTS and evaluate the registration accuracy for normal and MC DTS.

Materials and Methods: An a-priori motion model (4D deformation-vector-field (DVF)) was calculated from the 4D planning CT which was forced to be zero on average to ensure a MC-DTS with each organ in its time averaged mean position. During DTS reconstruction, the respiratory phase was calculated for each projection image, the corresponding DVF extracted from the motion model and applied to deform the back-projection to the Mid-Position geometry.

To evaluate MC DTS, both static and moving scans were made of the dynamic thorax phantom (CIRS, Norfolk, Virginia, USA). The motion pattern was sin^6 with a peak-to-peak (pp) amplitude of 2 cm in the CC direction and a 1 cm pp sinus in the AP direction. Scans were acquired over an arc of 360°, with overlapping 30° DTS reconstructions every 10°.

Both conventional and MC-DTS images were registered to the corresponding 30 degree static DTS using correlation ratio as a cost function. The registration only optimized 2D translations in the imaging beam's eye view based on a 3D-rectangular region of interest defined around the spherical phantom insert in the static reference scan.

Results: Visual inspection shows that the motion blur is strongly reduced using MC-DTS (figure 1). The translations found for the DTS were CC -2.30 ± 1.29 mm, LR 0.12 ± 0.54 mm and AP -0.21 ± 1.06 mm (mean ± 1 SD). For the MC-DTS the translations were CC -0.02 ± 0.20 mm, LR 0.09 ± 0.33 mm and AP -0.01 ± 0.21 mm. The translational difference was significant for the CC (p<0.001) but not for the AP/LR direction. For two gantry angles registration outliers were removed from the analysis.

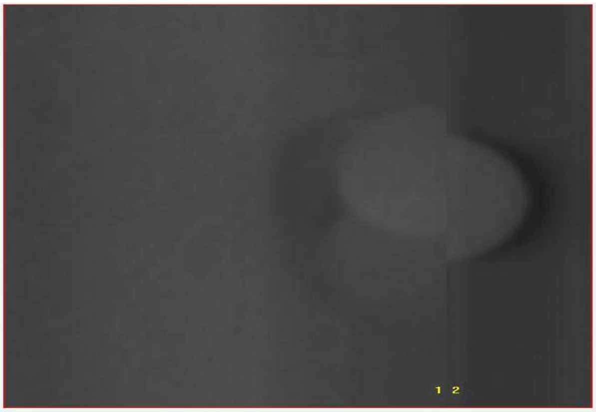

Figure 1: A conventional DTS (1) and motion compensated DTS (2) image of 30 degree of the phantom in the imaging beam's eye view. Motion blur in both CC and AP direction is minimized in MC-DTS.

Conclusions: Motion compensation considerably reduced motion blur in DTS images and improved registration with static reference DTS images allowing more accurate DTS guidance and intra-fraction monitoring concurrent with VMAT delivery.

[1] M. van Herk et al., On-line digital tomosynthesis for patient stability monitoring during VMAT delivery for SBRT of lung cancer, ESTRO 2012

OC-0060

Workflow automation for ultrafast kilovoltage-megavoltage cone-beam CT for image guided radiotherapy

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Purpose/Objective: Combined kilovoltage-megavoltage cone-beam CT (kV-MV CBCT) enables CBCT imaging of lung tumors during breath-hold. We established synchronized kV-MV imaging based on a 90° angle interval for kV and MV projections that are acquired simultaneously within 15 seconds, which roughly corresponds to one breath-hold phase in most patients. The previous workflow that was already established to provide proof-of-principle included extensive manual interaction and was therefore not feasible for a potential clinical application.This abstract presents a novel concept for a fully automatic setup that has been established recently.

Materials and Methods: In accordance with the vendor a clinical treatment unit (Elekta Synergy) was modified with dedicated hardware (in-house development) which allows simultaneous and synchronized kV-MV imaging. This hardware can be activated by a key switch to enable kV-MV mode. An application program was developed which communicates with the various Linac components over a proprietary port. The software coordinates the online kV-MV imaging system tasks: It manages the readout of the MV-detector using the XIS library (Perkin Elmer) and captures the angular gantry position for each projection online. Gain, offset and defect pixel corrections are applied on the acquired raw MV data. MV detector shift is corrected based on measured flexmap data. For the kV contribution, conventional XVI cone-beam projections are acquired. After appropriate greyscale normalization, MV and kV data are then used to reconstruct a 3D-dataset with a CUDA-accelerated FDK algorithm. After conversion into the compatible *.SCAN* data format, the combined kV-MV reconstruction volume is imported into the XVI system to enable patient positioning based on information provided by the reference volume, e.g. planning CT.

Results: Figure 1 provides a schematic of the system. Duration of the automated workflow is roughly 10 times faster than the workflow without automation, not including additional Linac preparation for kV-MV mode in the latter case. A detailed time comparison of each step is given in table 1. No error-prone manual entering of Linac settings has to be done anymore. The handling of the procedure is now stable and requires only minimal training.

Figure 1

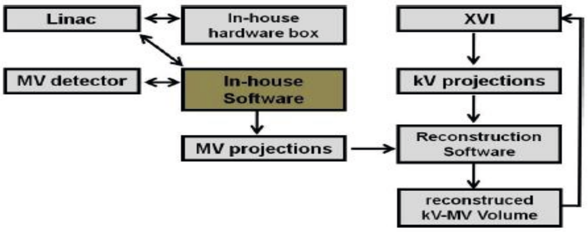
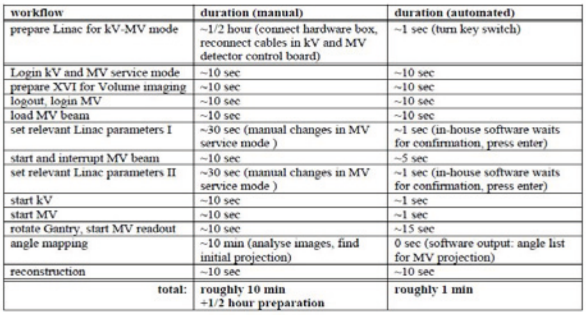


Table 1



workflow	duration (manual)	duration (automated)
prepare Linac for kV-MV mode	~1/2 hour (connect hardware box, reconnect cables in kV and MV detector control board)	~1 sec (turn key switch)
Login kV and MV service mode	~10 sec	~10 sec
prepare XVI for Volume imaging	~10 sec	~10 sec
logout, login MV	~10 sec	~10 sec
load MV beam	~10 sec	~10 sec
set relevant Linac parameters I	~30 sec (manual changes in MV service mode)	~1 sec (in-house software waits for confirmation, press enter)
start and interrupt MV beam	~10 sec	~5 sec
set relevant Linac parameters II	~30 sec (manual changes in MV service mode)	~1 sec (in-house software waits for confirmation, press enter)
start kV	~10 sec	~1 sec
start MV	~10 sec	~1 sec
rotate Gantry, start MV readout	~10 sec	~15 sec
angle mapping	~10 min (analyse images, find initial projection)	0 sec (software output: angle list for MV projection)
reconstruction	~10 sec	~10 sec
total:	**roughly 10 min +1/2 hour preparation**	**roughly 1 min**

Conclusions: The kV-MV CBCT acquisition workflow is now almost entirely automatic, based on interaction with all relevant Linac components over a single proprietary port, minimizing human interaction with the system. This is a prerequisite for safe clinical operation. At the moment the procedure only works in research mode. Risk analysis and documentation, which are the basis for clinical operation as an in-house medical device development, are currently in progress.

OC-0061

Validation of three deformable image registration algorithms using the TEST method

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Purpose/Objective: Deformable image registration (DIR) is an important tool in radiotherapy for contour propagation and for estimating the actual given dose in adaptive radiotherapy (ART). Presently used methods to quantify DIR accuracy provide information about image regions with high contrast (e.g. anatomical landmarks). However, in ART it is important to know the deformation accuracy in the entire irradiated volume. Therefore, we developed the TEST method that quantifies the DIR accuracy both in high and low contrast regions in the image.

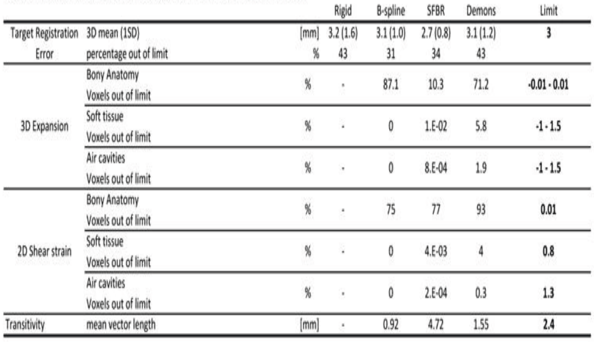
The objective of the current study was to assess three frequently used DIR algorithms with regard to the deformation from planning CT (pCT) to repeat CT (rCT) or from pCT to cone-beam CT (CBCT) in patients treated for head and neck cancer.

Materials and Methods: The study population was composed of 10 head and neck cancer patients. For the purpose of this study, we used as well pCT and rCT as pCT and CBCT. The pCT was deformed to the rCT or CBCT, which were acquired in the last week of radiotherapy. Three different DIR-algorithms were compared: the Fast Symmetric Demons (Demons) and the Salient Feature Based Registration (SFBR), both implemented in Pinnacle Research 9.100 and the B-Spline from the ITK library, implemented in the Elastix toolbox 4.4. For all deformations the TEST parameters were determined. TEST is an abbreviation for: Target registration error, Expansion and Shear strain of the deformation vector field, and Transitivity. Anatomically plausible limits have been set for expansion and shear strain. The transitivity gives the lower bound of the error of the deformation per voxel.

Results: For the deformations from pCT to rCT, the target registration error showed minor variation between the different algorithms, as shown in table 1. However, the expansion and shear strain of the DVF showed a larger difference. Where the Demons algorithm exceeded the limits on almost all aspects, e.g.5,8% soft tissue voxels are out of limit for the expansion, the B-Spline and the SFBR both stayed within the limits for soft tissue and air cavities. The expansion and shear strain in the bony anatomy exceeded the limits for all algorithms. The average transitivity exceeded the limit for SFBR, while it remained within limits for B-Spline and Demons.

The results of deforming the pCT to the CBCT gives the SFBR algorithm as the most promising algorithm.

Table 1: Overview of the accuracy of deformations with the B-spline, Salient Feature Based Registration (SFBR) and Demons algorithm from the planning CT to a repeat CT for ten different patients. The proposed limits for clinical use are indicated.



			Rigid	B-spline	SFBR	Demons	Limit
Target Registration Error	3D mean (1SD)	[mm]	3.2 (1.6)	3.1 (1.0)	2.7 (0.8)	3.1 (1.2)	**3**
	percentage out of limit	%	43	31	34	43	
3D Expansion	Bony Anatomy Voxels out of limit	%	-	87.1	10.3	71.2	**-0.01 - 0.01**
	Soft tissue Voxels out of limit	%	-	0	1.E-02	5.8	**-1 - 1.5**
	Air cavities Voxels out of limit	%	-	0	8.E-04	1.9	**-1 - 1.5**
2D Shear strain	Bony Anatomy Voxels out of limit	%	-	75	77	93	**0.01**
	Soft tissue Voxels out of limit	%	-	0	4.E-03	4	**0.8**
	Air cavities Voxels out of limit	%	-	0	2.E-04	0.3	**1.3**
Transitivity	mean vector length	[mm]	-	0.92	4.72	1.55	**2.4**

Conclusions: Using the TEST method the accuracy of three different DIR algorithms could be quantified and compared in all image voxels (both in high and low contrast image regions). The B-spline algorithm gave the most accurate results for pCT to rCT deformations, while the SFBR algorithm performed best for pCT to CBCT deformations.

OC-0062

Imaging dose assessment for intrafraction motion management in ion beam therapy

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Purpose/Objective: Image guidance is crucial for assuring a safe and accurate delivery in particle therapy and advanced photon radiotherapy. However, kV based imaging systems for treatment planning, position verification and intrafraction motion management lead to an additional dose burden for the patient. An investigation of the imaging dose for various organs at risk (OARs) caused by different imaging protocols for lung was performed at a conventional radiotherapy department (CRD) and an ion beam center (IBC).

Materials and Methods: Imaging dose was measured utilizing thermoluminescent dosimeters (TLDs) in an Alderson Rando phantom with the isocenter in the sinister lung of the phantom. Two sets of TLD-100 chips (3x3x1 mm^3; sensitivity within ±3 %) were chosen. Measurements were performed for 25 selected points on the skin or within OARs (in each point 3TLDs). For calibration 5 TLDs were irradiated in a Co-60 beam and 6 TLDs were used to account for background irradiation. Measurements were performed for:

CRD:

- Elekta XVI planar kV: 120 kV, AP and LR, 5 mAs per image, S20F0
- ExacTrac planar kV:120 kV, right posterior oblique and left posterior oblique projections, each with 160 mA, 160 ms