Three imaging techniques for treatment of moving organs

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Abstract

Taking into account organ motion in lung cancer radiation treatment is a challenge. Movement and deformation lead to issues according to image acquisition, treatment planning and radiation delivery [1,2]. Motion management in radiation therapy is composed of several steps : motion limitation (contention, breath-holding, coached breathing, gated radiation delivery), residual motion quantification (intra and inter-fraction), residual motion management (adapted dosimetry) and treatment delivery control (QA). Image acquisition, image processing and image analysis are the key components of motion management. In this abstract, we will review three promising imaging techniques. First, **breath-hold** technique, when tolerated by the patient, is a simple but efficient method to limit the motion, both during image acquisition and radiation delivery. Second, **4D CT images** acquisition is a very promising technique to bring new quantifiable spatio-temporal information on moving organs, allowing free-breathing, gated radiation delivery. Third, **deformable image registration** will become a key tool to model motion and deformation. All these techniques allow to plan new strategies (including 4D temporal information) to perform the treatment.

1 Motion reduction by breath-holding

When it is possible, using apnea during image acquisition and radiation treatment is a common way to reduce motion [3,4,5,6,7,8,9,10,11,12,13,10,14,15,16,17,18,19,20,21,22,23,24]. Breath is generally held at (medium) deep inspiration (mDIBH), which increases the lung volume and consequently decreases the mass of irradiated lung. It can be implemented in a passive (patient holds his breath on instruction) or active way (with Active Breathing Control device [23]). *Intra-breath-hold* motion (which are the residual movements that could possibly occurring *during* a breath hold) was studied by Dawson [6,18] with videotaped fluoroscopy and almost no motion of the diaphragm or fiducial markers was observed. However, these techniques do not totally eliminate motion. Mean *intra-fraction* motions (that occur between two breath holds, without patient repositioning) were estimated between 1 and 2.5 mm with active breath hold [6,10,9,18]. *Inter-fraction* reproducibility (patients left the room after each breath-hold) range from 1.0mm [22] to 6.6mm [18], and has been reviewed in [3].

Breath-hold is a very effective way to limit organ motion (both during planning image acquisition and treatment). It requires that the patient understands and tolerate the procedure. Evaluation of breath-hold reproducibility (both intra and inter fraction) and quantification of residual internal displacements (that vary with each patient's respiratory capacity) is still under investigation.

2 4D thorax images acquisition

4D CT imaging [25] can be defined as the acquisition of a sequence of 3D CT image sets over consecutive segments of a breathing cycle. 4D acquisition is limited by the speed of the detectors and the gantry, and by the amount of delivered dose. Most of principal works [26,27,28,29,30,31,25,32,33,34,35,36] [37,38,39,40,41,42,43,44,45,46,47,48,46,49,50,51,52,53,54,55] use a respiratory signal during data acquisition. Such signal is then used to sort data corresponding to a same range of respiratory signal. 3D images are then reconstructed from these datasets. A respiratory signal $f(t)$ represent the periodic spatial position of the thorax in the breathing cycle and is considered as a surrogate to internal motion measurement. It should ideally have the following properties. When $f(t_1) = f(t_2)$, internal spatial configuration should be (almost) equivalent. It should be a continuous function (smooth deformation). All of current studies consider f as a 1D signal ($f : \mathbb{R} \mapsto \mathbb{R}^n$, with $n = 1$) although this is not required. Three different types of systems have been used :

- External signal (tracking surface motion) : RPM, video. RPM (Real-Time Position Management from Varian) is the most used [29,39,34,37,36,50,27,32] [45,56]. It records in real-time (1/30 sec.) the vertical motion of abdominal surface using markers (infrared reflecting dot) and a CCD camera. Intra-fraction reproducibility and correlation with internal motion are not fully assessed [5,50,57,58].
- Internal signal : image-based tracking by image processing techniques [43,31]. It ideally requires no other techniques than image processing but is still in the early stages of development.
- Lung volume : a spirometer signal records internal air content within the lung [28,47] according to time. It seems to exist a strong correlation with internal-object motion [28]. However drift correction are needed.

Respiratory signal is then used to sort acquired data into bins having (approximately) a certain coherence. Each method requires some level of reproducibility from cycle to cycle [29] and are under investigation. Audio or visual coaching seems to be a interesting way to reduce breathing irregularities [59]. Breathing cycle is typically split into 8-10 phases.

Several CT acquisition modes were used. *Cine mode* refers to a technique which acquires repeated axial CT images for a specified period of time, at each table position. In *helical* mode, the table advance continuously during rotation (at a constant speed). [30] compares this two modes and found cine mode to be faster and more dose efficient. Single-row detectors are very inefficient for 4D acquisition while multi-row detectors (2, 4, 8 or 16 slices-CT have been used) allow to acquire more data in a single gantry rotation. *Cone-Beam* geometry use area of detectors (i.e. flat-panel). Works on dedicated 4D CT (256-slices) are in progress [44,49].

All authors noticed that the link between the signal and internal motion could change from day to day. Studied are in progress to combine abdominal (surfacic) and tidal volume signal. Choice of parameters involves a trade off between dose, temporal resolutions and the presence of artifacts.

Ref.	**Acqui. (nb of slices)**	**Synchro.**
[26,43,31,51]	Slow Cone-Beam	image-based
[48,52,53]	Fast Cone-Beam	sinogram-based
[28,47]	Cine (16/4)	Digital spirometer
[29,39,34,37,36,50]	Cine (8/4/1)	RPM
[27,32,45,56]	Helical (16/1)	RPM
[44,49]	Dedicated CT (256 slices)	

Table 1
Examples of 4D acquisitions

3 Deformable registration

Registration is the process of determining a mapping T between the coordinates in one image space and those in another, $T(\mathbf{x}) = \mathbf{x}'$, $\mathbf{x} \in \mathbb{R}^n, \mathbf{x}' \in \mathbb{R}^m$ (with n, m the images dimensions). When the mapping is not constraint to be affine ($T(\mathbf{x}) = A\mathbf{x} + b$), it is considered as a deformable (or non-linear) registration.

There are a lot of registration methods [60,61] (we only cite here some example references). In dense deformation methods, T is described with a dense field of displacement vectors (i.e. for each voxel) : optical-flow like method [62,63] or inspired from continuum mecanics [64] (elastic or fluid regularization). There are also parameterized transformation (T is constraint to belong to a class of transformation) such as thin-plate spline [65,66,67] or free-form-deformation with B-spline [68,69,70]. Methods can be features-based (transformation is computed on features points, curves or surface) or voxel-based (according to voxel intensities). Hybrids methods are also studied [71]. Methods are still being researched and developed.

Deformable registration was used for example studying prostate [72,73,74,75], or liver deformation [76]. Several works used deformation registration to map exhale to inhale breath-hold CT images [77,78,67,79,80,81] in order to study amplitude motion. Several authors also used deformation registration between phases of 4D CT images [27,41] in order to study trajectories. Works are in progress in order to compare 4D CT images and 4D model build, by deformation registration, from 2 exhale/inhale CT image [82]. With the advance of 4D images, deformation registration methods will become more and more used, for example in order to help segmentation (contours) propagation between each phases.

4 Conclusion

In this abstract, we briefly reviewed three techniques (breath-holding, 4DCT acquisition and deformable registration), which are probably becoming more and more used in clinical practice. Taking into account organ motion in lung cancer radiation treatment is a challenge which is largely based on imaging techniques. Whatever the technique, the acquisition of quantitative information on motion is required in order to adapt the strategy for each specific patient (according to its clinical situation and his tolerance).

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