A hybrid 4D cone beam CT reconstruction algorithm for highly under-sampled projections from the 1-minute cone beam scan

Introduction  Respiratory motion is the main problem in lung/upper-abdominal radiotherapy. Due to the variations of respiratory motion (e.g., magnitude, baseline, period and regularity) and tumor shrinkage between planning and treatment sessions, high-quality 4D image guidance is needed.

While 4D cone beam CT (CBCT) has been developed to provide respiratory-phase resolved images for treatment guidance, its clinical use is limited for the following reasons: 1) Current 4D-CBCT needs long scan protocol. This inherent problem elevates the imaging dose and impedes clinical workflow. Moreover, even with a scan of 4-min (very long from a clinical point of view), the image quality is still inferior to that of a standard 1-min 3D-CBCT of static anatomies, let alone CT; 2) The intensity of 4D-CBCT is susceptible to scatter contamination. The potential truncation may further degrade image quality.

Innovation/Impact 1) Our method integrates patient-specific CT information and reconstructs 4D-CBCT via motion vector domain by solving an optimization problem, which is fundamentally different from conventional reconstruction approaches via image intensity domain.

2) An iteratively performed forward-backward splitting (FBS) method is invented to split the original reconstruction problem into separated reconstruction and deformable registration problems. By performing FBS, it achieves a fusion of both the right geometrical information from measured CBCT projections and correct intensity values from the planning CT, and hence yields a high quality 4D-CBCT image, even with highly sparse projections from a 1-min CBCT scan.

3) Our method is capable of reconstructing high-quality 4D-CBCT images with combined intensity and geometry accuracy. This is very important for precise tumor targeting, accurate dose calculation and deformable registration in lung/upper-abdominal radiotherapy, particularly under the context of a) The increasingly used hyper-fractionation or stereotactic body radio-surgery, where the high fractional dose makes it less forgiving to targeting error; b) the next generation of radiation treatment, i.e., adaptive radiation therapy (ART), where accurate dose calculation/escalation and deformable registration relies on high quality in-room image with accurate HU values.

Methods 1) Reconstruction model. A prior CT or one phase of the 4DCT \( f_p(x) \) is firstly aligned via rigid registration with the average 3DCBCT FDK image obtained using projections at all phases. For the image of the 4DCBCT at phase \( i \), denoted as \( f_i(x) \), there exists a displacement vector field \( v_i(x) \) that deforms \( f_p(x) \) as \( f_i(x) = f_p(x + v_i(x)) \). Denote the x-ray projection matrix for phase \( i \) as \( P_i \) and the corresponding measured projections as \( g_i \). We propose to restore \( v_i(x) \) by solving an optimization problem ensuring the solution fidelity to measurements and its smoothness as:

\[
v_i = \arg \min_{v_i} E[v_i] = \arg \min_{v_i} \frac{1}{2} \| P_i f_p(x + v_i(x)) - g_i \|_2^2 + \frac{\lambda}{2} \| \nabla v_i \|_2^2, \tag{1}
\]

Once the vector field \( v_i(x) \) is determined, \( f_i(x) \) can be obtained by deforming \( f_p(x) \) via \( v_i(x) \).

Compared with conventional reconstruction algorithms calculating voxel intensities, this model reflects the essential physics behind 4DCBCT, i.e., the anatomy changes are physical deformation rather than intensity variation. It has the following advantages: 1) the inherent temporal correlation between 4DCBCT images at successive phases is implicitly considered in our model, because images at different phases reconstructed in Eq. (1) are deformed from the same prior image via smooth vectors fields. 2) this model permits the inclusion of physically realistic constraints. 3) The solution is deformed from a high-quality prior CT image, prohibiting streak artifacts, incorrect HU values and truncation problems from the results. 4) The resulting vector-field information facilitates dose deformation and accumulation.

2) Forward-backward splitting (FBS) algorithm. For the non-convex problem in Eq. (1), it is always a concern regarding the solution optimality. To maximally mitigate this problem we have developed an

\[
s = f_i^{(k)} - F(P f_i^{(k)} - g), \tag{A1}
\]
\[
v_i = \arg \min_{v_i} \frac{1}{2} \| s - f_p(x + v_i(x)) \|_2^2 + \frac{\lambda}{2} \| \nabla v_i \|_2^2, \tag{A2}
\]
\[
f_i^{(k+1)}(x) = f_p(x + v_i(x)). \tag{A3}
\]
innovative forward-backward splitting (FBS) method with steps shown in Table 1. In A1, $s$ is an intermediate variable, $F$ is the FDK operator in a CBCT reconstruction problem. It can be seen that $s$ contains the geometrical information from cone beam measured projections via FDK algorithm, which serves the guidance for the subsequent deformable registrations (Eqs. A2 and A3). A1-A3 steps are iteratively performed. In each cycle, the prior image $f_p$ is deformed to match $s$. The whole process gradually leads to a fusion of both right anatomy information from $s$ and correct intensity values from $f_p$. All the key components, including $f$(FDK), $P$(forward projection), and deformable registration are implemented on GPU.

Key results We have first tested our algorithm on a motion phantom where a ball attached to a rod moves along SI direction during a 1-min CBCT scan. Fig. 1 summarizes the results. While the 3D-CBCT image shows blurring artifacts and FDK reconstructed 4D-CBCT suffers from the streaking artifacts, our method yields the 4D-CBCT image with superior image quality and correct HU values. To validate the anatomical geometry accuracy, the ground truth ball center location along the SI direction is compared to that measured from our results. Satisfactory agreements (0.364mm average and 0.504mm maximum error) can be observed.

The algorithm is also tested in three patient cases under 4-min scans. The projections corresponding to a 1-min scan are sparsely extracted from the whole dataset. A typical result is shown in Fig. 2. We can see that for the 1-min data, FDK result shows severe under-sampling streaks and truncation artifacts. While increasing scan time from 1 min to 4 min improves image quality, it is still inferior to our method from 1-min scan in terms of HU value accuracy and the truncation issue. Note that compared with 4-min 4D-CBCT image, the anatomy in our method is quite accurate, see, e.g., the small structures around the tumor in sagittal view, as well as the tumor shapes and locations in coronal view (Fig. 5 (e)-(f)).