Improving Respiration-Gated IMRT Delivery Efficiency by Dual-Gating at Inhale and Exhale: Treatment Planning Formalism

Innovation/Impact: We propose a novel delivery method for intensity modulated radiation therapy (IMRT) that significantly reduces treatment delivery times by delivering dose during both inhale and exhale windows. We developed an inverse treatment planning method for developing inhale and exhale IMRT fluence maps that produce a final dose (the summed inhale and exhale doses) that meets clinical requirements.

Introduction: Respiratory motion presents a significant challenge for the treatment of thoracic and abdominal tumors, and respiratory-gated radiotherapy is a widely-employed means of treating tumors that undergo significant motion during breathing. However, gating reduces the duty cycle and can significantly extend delivery. Protracted treatment time increases the likelihood of several potential deleterious effects, including: deviations between the planned and delivered dose distributions resulting from postural shifts during delivery, decreased clinical work-flow, and increased patient discomfort.

To reduce the total delivery time, a dual-gated intensity modulated radiation therapy (DG-IMRT) technique is proposed to deliver radiation at both inhale and exhale gating windows. This method can either take advantage of the natural pauses that occur at peak-inspiration and end-exhalation during free breathing or use respiratory coaching [1] to achieve brief breath holds at both inhale and exhale. A schematic illustration of dual-gated delivery is shown alongside conventional gating in Figure 1 for a free-breathing respiratory trace. To a large extent, DG-IMRT provides the advantages of 4D radiation therapy (4DRT) [2, 3], e.g., improving delivery efficiency without compromising dose conformality, while avoiding the technical barriers associated with MLC [4, 5] and couch tracking [6]. Toward the realization of the proposed treatment scheme, we formulate and present a treatment planning method for designing DG-IMRT plans.

Inverse Treatment Planning for Dual-Gating: DG-IMRT consists of two individual IMRT plans to be alternately delivered during inhale and exhale gating windows as presented in Figure 1. The aim of DG-IMRT planning is to find the inhale and exhale fluence maps that produce the optimal cumulative dose distribution. As opposed to optimizing inhale and exhale plans as decoupled systems, DG-IMRT treatment planning simultaneously optimizes the accumulated dose to identify optimal inhale and exhale IMRT beamlet weights, \( w_i \) and \( w_e \), to produce a dose distribution that most closely matches the prescribed dose to the tumor target while limiting the dose to critical structures. The problem is mathematically defined as

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\begin{align*}
\text{minimize} & \quad \sum_s \lambda_s \left[ |A v w_e|_s + |R(A v w_i)|_s - D_s \right] \\
\text{subject to} & \quad 0 \leq w_i \leq w_{\text{max}} \\
& \quad 0 \leq w_e \leq w_{\text{max}} \\
& \quad D_{\text{min}} \leq (|A v w_e|_s + |R(A v w_i)|_s) \leq D_{\text{max}},
\end{align*}
\]

(1)

where desired, minimum, and maximum doses (\( D_s, D_{\text{min}}, \) and \( D_{\text{max}} \)) are prescribed for each structure of interest, \( s \), and \( [\cdot]_s \) denotes the vector of dose values at voxels within \( s \). For critical structures, \( D_{\text{min}}, \) and \( D_{\text{max}}, \) are zero. The beamlet intensities are non-negative and limited by \( w_{\text{max}} \), resulting in a constrained optimization problem. A relative importance weight, \( r_s, \) is defined for each of the structures and \( \lambda_s = \frac{1}{r_s M_s} \).

Optimizing Equation 1, requires applying the registration, \( R \), to the inhale dose at each step of the optimization. To facilitate computation, we incorporate this deformation into the inhale dose matrix to enable direct computation of the inhale dose mapped to the exhale anatomy, \( R(d_i) = R(A_i w_i) = A_e w_i \). The inhale dose at the \( j \)th voxel within the inhale geometry is \( [d_i]_j = [A_i]_j w_i \) where \([A_i]_j \) is the \( j \)th row of the inhale dose matrix. The registration \( R \) provides a function, \( f \), that maps a subset of voxels, \( j \), to a particular voxel, \( k \) in the exhale geometry. This mapping can be applied to the inhale dose matrix, so that for each voxel, \( k \), in the exhale geometry, the inhale dose at that voxel is \( |R(d_i)|_k = f([A_i])_k w_i = ([A_i])_k w_i \), where the \( k \)th row of the mapped inhale matrix, \( A_i \), is composed of the function \( f \) applied to the \( j \) rows of \( A_i \). The accumulated dose distribution on the exhale anatomy is \( d_{DG} = A_i w_i + A_e w_e \), avoiding repeatedly mapping the inhale dose distribution onto the exhale geometry.

The proposed DG-IMRT planning method was evaluated using a QuasarTM Multi-Purpose Body Phantom (Modus Medical Devices Inc., London, Ontario) undergoing 1, 2, and 3 cm of translational motion in the superior/inferior (SI) direction, and retrospectively applied to a lung cancer patient case with approximately 1.5 cm tumor motion in the SI direction. The does distributions of the DG-IMRT and conventional exhale-gated plans were compared quantitatively.
Results: Dual- and single-gated exhale dose distributions and DVHs are shown in panels Figure 2 and the DVHs. With a 2.7 Gy increase in minimum PTV dose and 4.6 Gy decrease in maximum PTV dose, the dual-gated plan has improved PTV dose homogeneity as compared to the single-gated plan. The DG-IMRT plan also exhibits lower maximum doses to the ipsilateral lung, but slightly higher maximum doses to the contralateral lung, heart, and spinal cord. These results demonstrate the ability of the proposed DG-IMRT planning method to produce dose distributions that meet the clinical requirements.

Conclusion: DG-IMRT leverages the natural respiratory pauses at peak-of-inhale and end-of-exhale, which comprise comparatively stable and reproducible portions of the respiratory cycle. In doing so, DG-IMRT improves treatment efficiency. Relative to tracking techniques, DG-IMRT may be more accurate because it avoids irradiation during more unpredictable portions of respiration. The strategy may also prove more clinically feasible because it obviates the need for real-time MLC- or couch-based tracking.

DG-IMRT treatment enhancement under a free breathing scenario without coaching guidance and/or intervention is proportional to the window durations around peak inhale and end exhale over the full respiratory cycle duration. Analysis of free breathing behavior has demonstrated that patient’s typically spend more time in the exhale window than the inhale window in the absence of coaching [7–9]. In the presence of free-breathing, a nearly two-fold improvement in DG-IMRT delivery efficiency enhancement is expected. With instructed breathing and/or visual and audio coaching, a short breath-hold at both inhale and exhale can be utilized by most patients to increase the proportion of time spent at both peak inhalation and end exhalation in order to improve DG-IMRT-enabled delivery efficiency gains beyond double.