Application of Fast Inverse Dose Optimization to Intensity Modulated Proton Therapy

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INTRODUCTION

- Optimization of intensity modulated proton therapy (IMPT) treatment plans is computationally demanding to perform.
- This is a result of the repeated dose and objective function calculations perform during optimization.
- Recent GPU/CPU parallelization has helped improve the computational efficiency of these calculations considerably, but further acceleration is still welcome.

Question: Could modifying the objective function used in treatment optimization also improve the optimization speed?

METHOD

Proposal: Use the quadratic Fast Inverse Dose Optimization (FIDO) objective function [1]:

$$f(\vec{\tau}) = p_{ptv}\sum_{x\in PTV}\left(\sum_i \mathbf{d}_{xi}\tau_i - d_{pres}(x)\right)^2 + \sum_{x\in OAR} p_{oar}(x)\sum_i \mathbf{d}_{xi}^2\tau_i^2$$

Note: spatially varying d_{pres} and p_{oar} are used to enforce non-quadratic objectives (e.g. min, max, dose-volume)

Motivation for this: Through Taylor Series expansion, this objective function and its derivatives can be condensed to:

$$\begin{bmatrix} f \\ \nabla f \end{bmatrix} = \begin{bmatrix} \vec{\tau}^T \\ \mathbf{I} \end{bmatrix}\left(\boldsymbol{\alpha}\vec{\tau} - \vec{\beta}\right) + \begin{bmatrix} f_0 - \vec{\tau}^T\vec{\beta} \\ 0 \end{bmatrix}$$

Advantages of this matrix equation:

1. Yields both the value and the derivatives simultaneously.
2. Number of operations performed when computing the matrix equation is often orders of magnitude smaller than computing the conventional objective function value alone.

Evaluation:

- A planning study was performed on 15 patient datasets.
- MFO IMPT treatment plans were optimized in MATLAB using the modified and unmodified objective functions.
- Same planning objectives were used in both optimizations.
- Plan quality and optimization performance was compared.

RESULTS

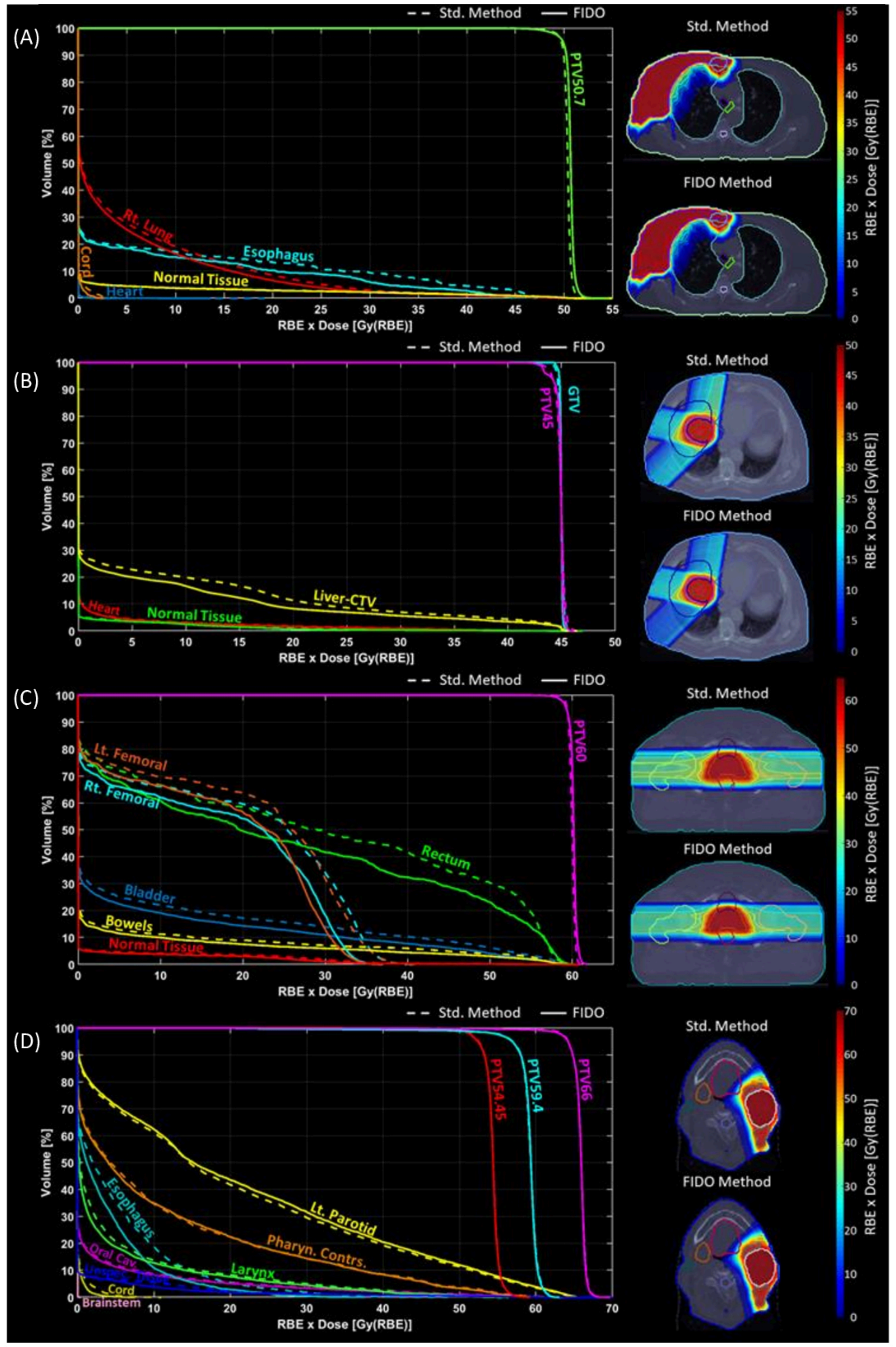

Fig 1. DVH and dose distributions of standard (dashed) & FIDO (solid) optimized plans.
(A) Advanced breast plan. (B) Liver plan (C) Simple prostate plan (D) Ipsilateral head-and-neck plan

Description	# of Beams	# of Spots	Non-zero dose matrix, $d_{x,i}$, elements [x10^6]	Optimization Time (# of Iterations)		Speed Enhancement
				Standard Method	FIDO	
TG 119 Phantom	1	2,463	5.0	24.2s (181)	0.4s (29)	69.1
Simple Prostate	2	3,916	18.9	23.5s (76)	0.5s (4)	47.0
Advanced Prostate	3	18,376	70.3	74.8s (206)	14.4s (85)	5.2
Advanced Breast	2	26,597	65.8	240.0s (540)	41.5s (181)	5.8
Bronchus	3	9,536	31.0	99.9s (404)	2.9s (49)	34.3
Liver	3	5,668	19.3	21.4s (40)	0.8s (11)	27.8
Bilateral HN	5	19,397	40.2	25.0s (96)	9.6s (29)	2.6
Rt. Temporal Lobe	3	9,704	21.7	93.3s (435)	4.3s (104)	21.7
Pancreas	3	26,877	103.7	157.9s (274)	50.6s (35)	3.1
Esophagus	3	24,455	72.5	135.6s (291)	22.6s (75)	6.0
Vagina	4	25,209	97.3	56.0s (107)	51.5s (69)	1.1
Bladder	3	42,509	183.7	172.2s (189)	76.2s (40)	2.3
Ipsilateral HN	3	14,421	34.4	71.4s (146)	9.0s (111)	7.9
Lt Lung	2	1,059	2.7	52.8s (218)	1.3s (122)	39.7
Lt Arm Sarcoma	2	13,026	29.2	27.5s (39)	5.8s (80)	4.7

Table 1. Summary of the 15 optimization problems and each optimization algorithm's performance.

DISCUSSION

- On average (standard deviation), the FIDO algorithm enhance the optimization speed by 18.6 (20.7) fold, taking 19.4s (23.9s) over 68 (48) iterations to converge to a solution while the conventional algorithm took 85.0s (65.7s) over 216 (149) iterations to converge its solution.
- Plans of similar or better quality were obtained with the FIDO algorithm.
- Further speed enhancement could be achieved with GPU/CPU parallelization.

Future Work: Apply algorithm to robust and multi-criteria optimization, GPU/CPU parallelization.

ACKNOWLEDGEMENTS & REFERENCE

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[1] MacFarlane M, Hoover D, Wong E, Goldman P, Battista JJ, Chen JZ. A fast inverse direct aperture optimization algorithm for intensity-modulated radiation therapy. Med. Phys., 46: 1127-1139. doi:10.1002/mp.13368