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Non-coplanar trajectories

Non-coplanar trajectories to improve organ at risk sparing in volumetric modulated arc therapy for primary brain tumors

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ABSTRACT

Background and purpose: To evaluate non-coplanar volumetric modulated arc radiotherapy (VMAT) trajectories for organ at risk (OAR) sparing in primary brain tumor radiotherapy.
Materials and methods: Fifteen patients were planned using coplanar VMAT and compared against non-coplanar VMAT plans for three trajectory optimization techniques. A geometric heuristic technique (GH) combined beam scoring and Dijkstra's algorithm to minimize the importance-weighted sum of OAR volumes irradiated. Fluence optimization was used to perform a local search around coplanar and GH trajectories, producing fluence-based local search (FBLS) and FBLS + GH trajectories respectively.
Results: GH, FBLS, and FBLS + GH trajectories reduced doses to the contralateral globe, optic nerve, hippocampus, temporal lobe, and cochlea. However, FBLS increased dose to the ipsilateral lens, optic nerve and globe. Compared to GH, FBLS + GH increased dose to the ipsilateral temporal lobe and hippocampus, contralateral optics, and the brainstem and body. GH and FBLS + GH trajectories reduced bilateral hippocampi normal tissue complication probability ($p = 0.028$ and $p = 0.043$, respectively). All techniques reduced PTV conformity; GH and FBLS + GH trajectories reduced homogeneity but less so for FBLS + GH.
Conclusions: The geometric heuristic technique best spared OARs and reduced normal tissue complication probability, however incorporating fluence information into non-coplanar trajectory optimization maintained PTV homogeneity.

Sparing organs at risk (OAR) in intracranial radiotherapy reduces the risk of side effects that affect quality of life, such as cranial and optic neuropathy, hearing loss, and neurocognitive impairment [1–6]. Using non-coplanar beam orientations has been shown to improve OAR dosimetry in conformal [7], intensity modulated (IMRT) [8], and volumetric modulated arc (VMAT) [9] radiation therapy. However, non-coplanar geometries are fixed during delivery for a given beam, limiting their application to VMAT. New linear accelerators can perform dynamic couch rotation during beam delivery, making possible non-coplanar VMAT trajectories that use more of the 4π space around the patient [10–12] and enabling potential additional reductions in normal tissue complication probability (NTCP).

Early research into the clinical benefit of non-coplanar VMAT mainly focused on planner-defined trajectories [13–15], while recent work has investigated trajectory optimization techniques [10,16–19]. Published optimization techniques have used one of two approaches: geometric heuristics or fluence optimization. Geometric heuristics score individual beam orientations and determine trajectories that minimize the overall score [10,16,17]. Fluence-based techniques identify a smaller group of optimal candidate beam orientations, which are then connected via intermediate paths [18,19]. Geometric heuristics are appealing due to the computational complexity of a full fluence search for a VMAT arc but lack the dosimetric information that can be utilized in fluence optimization.

This paper proposes and evaluates three different trajectory optimization techniques - a geometric heuristic technique and two incorporating fluence optimization - for primary brain tumor radiotherapy using non-coplanar VMAT. We aim to answer three questions:

(1) Does a geometric heuristic technique improve OAR sparing over coplanar VMAT?

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(2) Does a fluence-based local search technique improve OAR sparing over coplanar VMAT?
(3) Is there a synergistic effect if the geometric heuristic and fluence-based local search techniques are combined?

This work quantifies the clinical effect of new techniques for optimizing non-coplanar VMAT and aims to widen the therapeutic window of radiotherapy for primary brain tumors. We demonstrate that a less computationally intense geometric heuristic technique is sufficient to produce high quality plans. Our goal is to facilitate the introduction of non-coplanar VMAT into neuro-oncology clinical practice.

Materials and methods

Patient selection and treatment planning

Fifteen patients treated with radiotherapy for primary brain tumors were planned using VMAT. Mean and standard deviation planning target volume (PTV) size was 336.6 ± 214.1 cc (range 5.5–723.6 cc), with a CTV-PTV margin of 3 mm in all cases. Original PTV prescription doses were 60 Gy in 2 Gy fractions, and 54 Gy or 59.4 Gy in 1.8 Gy fractions. One patient had palliative treatment (30 Gy in 6 Gy fractions) but was replanned to an appropriate radical dose (60 Gy in 2 Gy fractions) for this study. Further information for each patient case is contained in Supplementary Table A1. Coplanar and non-coplanar radiotherapy plans were produced for a 6 MV Elekta Synergy linear accelerator (Elekta AB, Stockholm, Sweden) with Agility multi-leaf collimator [20]. Coplanar VMAT planning used our standard clinical technique of a single arc with 180 control points, however to avoid bias due to the additional degrees of freedom available to non-coplanar methods, dual arc coplanar plans with 360 control points were also produced.

Plans were optimized using an in-house VMAT planning system [21,22] (AutoBeam v5.5a), adapted to import complex couch trajectories [16]. The planning process is summarized here, with the detailed workflow included in Supplementary Fig. A1. AutoBeam performed fluence optimization at each control point before sequencing the fluence maps into deliverable connected VMAT apertures. As sequencing degraded the dose distribution, direct aperture optimization was performed subject to machine limits for VMAT delivery. Further detail on AutoBeam and the optimization techniques used at each stage can be found elsewhere [21,22].

All cases used the same optimization objectives (Supplementary Table A2) to ensure a fair comparison. AutoBeam plans were reconstructed in Pinnacle[3] (Pinnacle[3] v9.8, Philips Medical, Madison, WI) for final dose calculation in line with clinical practice. Dose was prescribed to the PTV mean value and calculated on a $2.5 \times 2.5 \times 2.5\ mm^3$ resolution dose grid using the Adaptive Convolve algorithm.

Trajectory optimization

Three non-coplanar VMAT trajectory optimization techniques were developed in MATLAB (R2010b, The MathWorks, Natick, MA): a geometric heuristic technique (GH), a fluence-based local search technique (FBLS), and the combination of GH and FBLS (FBLS + GH). Organs at risk used in trajectory optimization were the brainstem, globes, optic nerves, optic chiasm, lenses, hippocampi, temporal lobes, cochleae, and the volume of brain excluding the PTV and other OARs. A patient voxel size of $5 \times 5 \times 5\ mm^3$ was used during trajectory optimization. For ray tracing, a beam aperture was defined as the projection of the PTV onto the isocenter plane and rays were cast through the center of $2.5 \times 2.5\ mm^2$ beam elements. A 2 mm margin was applied to the optic nerves, lenses, optic chiasm, and cochleae during trajectory optimization to prevent small OARs being missed in this step.

Geometric heuristic technique

The geometric heuristic technique (Fig. 1(a)) is an extension of the algorithm described in [16]; further detail is provided in Supplementary Fig. A1. Ray tracing was performed through the patient to determine a cost based on OAR geometry for all achievable isocentric beam orientations (Fig. 1(a), step 1). The trajectory optimization was formulated as a graph search problem, with the cost for a given beam orientation being the penalty applied for adding that orientation to the VMAT trajectory, and solved using Dijkstra's least-cost path algorithm [23] (Fig. 1(a), step 2). Single arc trajectories were produced through 358° of gantry rotation, from 179° to 181°, with control points spaced every 2° of gantry or couch rotation. Sections of trajectory with continuous couch rotation but static gantry rotation were allowed, provided the overall trajectory cost was minimized.

For this study the technique was extended to incorporate multiple OARs of different relative importance and prevent large or less important OARs from dominating the cost for a given beam orientation, a limitation of the previous method [16]. The cost, C, for each orientation is given by the sum of the relative volumes of each OAR intersected during ray tracing, weighted by their relative importance (Eq. (1)).

$$C_{c,g} = \sum_{v \in V} i_v \frac{n_v}{N_v} \tag{1}$$

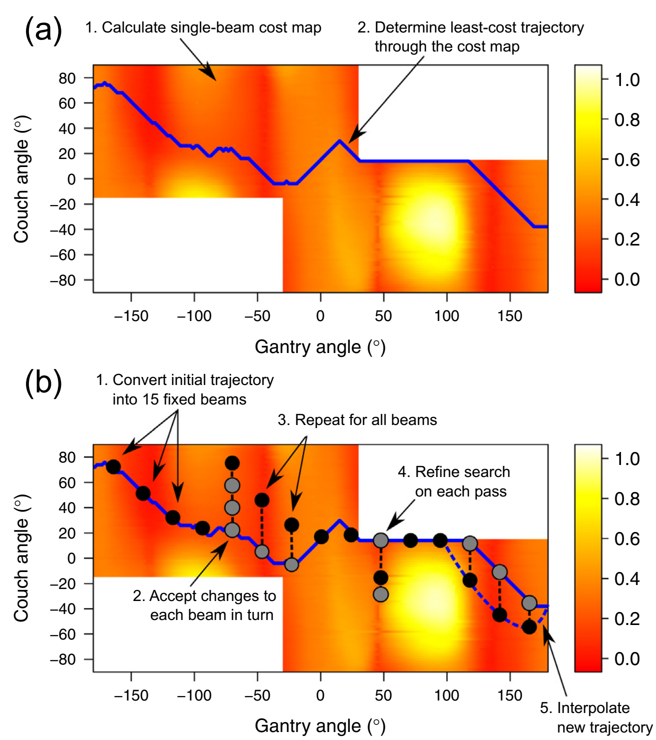

Fig. 1. Non-coplanar trajectory optimization methods for (a) the geometric heuristic technique (GH), and (b) the fluence-based local search (FBLS) algorithm. Followed left to right, (b) shows how the FBLS algorithm updates at each numbered step. As the example shown uses GH as its initial trajectory, (b) would produce a FBLS + GH trajectory. All trajectories are overlaid on the normalized GH cost map. White regions indicate excluded potential collision regions; high cost regions indicate orientations where a beam aperture conforming to the PTV would irradiate multiple or high importance organs at risk. In (b), black and gray circles indicate current and previously considered beam orientations respectively; the dashed line indicates the new trajectory.