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Research Article

Improved Volumetric Modulated Arc Therapy Field Junctions Using *In Silico* Base Plans: Application to Craniospinal Irradiation

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ABSTRACT

Introduction: Field junctions present a major challenge for planning craniospinal irradiation (CSI) using volumetric modulated arc therapy (VMAT). In this study, the feasibility of using *in silico* base dose distributions for planning junctioned VMAT fields for CSI is assessed.

Methods: An in-house computer program was created to generate strategic base plans with controlled linear dose gradients across the junction. The algorithm was generalized to allow user-defined parameters such as number of junctions and junction length. *In silico* base plans were used to optimize junctioned VMAT CSI plans for a pediatric case and an adult case. Throughout optimization, dose to the eyes, kidneys, lungs, heart, and liver were minimized. Final plan quality was evaluated using the percent of planning target volume receiving at least 95% prescription dose ($V_{95\%}$), homogeneity index, and conformity number. Final plan robustness to setup error was evaluated using changes in near-minimum, median, and near-maximum doses defined as the most exposed 98%, 50%, and 2% of the planning target volume ($D_{98\%}$, $D_{50\%}$, $D_{2\%}$) within the junction region before and after setup errors of ±3, ±5, and ±7 mm in the craniocaudal direction.

Results: The program generated ideal *in silico* dose distributions that were compatible with a commercial treatment planning system for use as base doses during VMAT optimization. VMAT plans, that were optimized with the *in silico* base plans, had complementary linear dose profiles across the junction. Final pediatric and adult VMAT CSI plans both had $V_{95\%}$ ≥98.1% and 98.1%, homogeneity index: 0.09 and 0.10, and conformity number: 0.86, 0.84, respectively. In addition, dose to surrounding organs at risk was acceptably low for both cases. For ±3 mm setup errors, small variations in the junction dose were recorded with $\Delta D_{98\%}$ ≤2.3%, $\Delta D_{50\%}$ ≤2.3%, and $\Delta D_{2\%}$ ≤2.8%.

Conclusions: This is the first demonstration of junctioned VMAT field optimization with a controlled linear dose gradient across the junction without the use of any extra planning contours. Planning junctioned VMAT using *in silico* base plans is feasible and capable of generating high-quality plans that are robust to clinically expected setup variations.

RÉSUMÉ

Introduction : Les champs jonctionnels représentent un défi majeur dans la planification de l'irradiation craniospinale (ICS) par arcthérapie volumétrique modulée (VMAT). Dans cette étude, les auteurs évaluent la faisabilité de l'utilisation de distributions de doses de base *in silico* pour la planification des champs jonctionnels pour l'ICS en VMAT.

Méthodologie : Un logiciel maison a été créé afin de produire des plans stratégiques de base avec gradients de dose linéaires contrôlés sur la jonction. L'algorithme a été généré pour accepter des paramètres définis par l'utilisateur, comme le nombre de jonctions et la longueur des jonctions. Les plans de base *in silico* ont été utilisés pour optimiser les plans d'ICS VMAT jonctionnels pour un cas adulte et un cas pédiatrique. Par optimisation, la dose aux yeux, aux reins, au cœur et au foie a été minimisée. La qualité du plan final a été évaluée en utilisant le pourcentage du volume cible de planification (VCP) recevant au moins 95% de la dose prescrite ($V_{95\%}$), l'indice d'homogénéité(IH) et le nombre de conformité (NC). La robustesse du plan final face aux erreurs de mise en place a été évaluée en utilisant les changements par rapport aux doses près du minimum, à la médiane et près du maximum, définies comme les 98%, 50% et 2% les plus exposés du VCP ($D_{98\%}$, $D_{50\%}$, $D_{2\%}$) dans la région de jonction avant et après une erreur de mise en place de ±3, ±5, et ±7 mm en direction craniocaudale.

Résultats : Le programme a généré des distributions de doses *in silico* idéales qui étaient compatibles avec un système commercial de planification de traitement pour utilisation comme doses de base durant l'optimisation VMAT. Les plans de VMAT optimisés avec les plans de base *in silico* présentaient des profils de doses linéaires complémentaires sur la jonction. Les plans de VMAT adulte et pédiatrique finaux présentaient respectivement des valeurs $V_{95\%}$ ≥98,1% et 98,1%, IH: 0,09 et 0,10, et NC: 0,86 et 0,84. De plus, la dose aux organes à risque environnants était acceptable dans les deux cas. Pour une erreur de mise en place de ±3 mm, de faibles variations dans la dose de jonction ont été observées, avec $\Delta D_{98\%}$ ≤2,3%, $\Delta D_{50\%}$ ≤2,3% et $\Delta D_{2\%}$ ≤2,8%.

Conclusions : Il s'agit de la première démonstration de l'optimisation des champs jonctionnels en VMAT avec un gradient de dose

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linéaire contrôlée sur la jonction sans utilisation de contours de planification supplémentaires. La planification de la VMAT sur des champs jonctionnels à l'aide de plans de base *in silico* est faisable et permet de générer des plans de traitement de grande qualité qui résistent aux variations de mise en place attendues en milieu clinique.

Keywords: Inverse plan optimization; Treatment planning

Introduction

Craniospinal irradiation (CSI) is used to treat the entire brain and spinal cord in patients with certain malignant diseases in the central nervous system. CSI is technically challenging because the planning target volume (PTV) is irregular in shape and typically greater than 50-cm long. Field junctions are required because the PTV extends beyond linear accelerator field size limitations. Conventional 3-dimensional conformal CSI techniques consist of lateral opposed fields to treat the brain and 1 or 2 abutting posterior fields to treat the spinal cord [1,2]. Abutting conformal fields are highly sensitive to field matching errors and consequently, dose inhomogeneities are inevitable when they are used. To improve plan robustness to field placement errors, field junctions are shifted (ie, feathered) once per week. In extreme cases, dose inhomogeneities resulting from field match errors may lead to severe toxicities due to overdosing or reduced probability of tumor eradication due to underdosing. Furthermore, conventional CSI techniques do not allow for sparing of organs at risk (OARs) within the treated volume.

The use of junctioned volumetric modulated arc therapy (VMAT) fields has been explored for CSI with several institutions already implementing this modality [3–5]. VMAT is desirable because it offers more homogenous dose distributions to the PTV and improved sparing of surrounding OARs compared to conventional CSI [6–9]. However, careful planning of field junctions (ie, overlap regions) is complicated by the fact that VMAT is inverse-planned using an optimization algorithm [10]. Significant effort has been directed toward junction planning strategies using VMAT. Most initial reports on VMAT CSI demonstrated feasibility of using overlapping VMAT fields to treat long volumes by optimizing a set of overlapping fields concurrently without explicitly controlling the junction dose [3,6–8,11]. This approach is simple but overly relies on the optimization algorithm to achieve a smooth dose across the junction that is robust to field placement error. This approach neglects to maximize final sum plan robustness to field match errors by controlling the junction dose.

Recent VMAT CSI implementations have trended toward prudent planning of a controlled linear dose gradient across the junction to optimize plan robustness [12–14]. Using simple geometry, Strojnik et al mathematically derived that when two fields overlap, each field should contribute complementary linear dose ramps to maximize robustness to field match errors [13]. The concept of controlling the junction dose during optimization was first introduced for intensity modulated radiation therapy (IMRT) [15] and has been applied to VMAT CSI [12,13]. A controlled linear dose gradient across the junction can be achieved by segmenting the PTV within the junction and assigning each segment to gradually decreasing dose objectives. Superior VMAT fields are optimized to deliver prescription dose to PTV superior of the junction while establishing a controlled dose fall off from prescription dose to zero dose across the junction. Subsequently, inferior fields are optimized to deliver prescription to the inferior region and top up the superior plan dose within the junction to full prescription by using the superior plan dose as a base plan. Strojnik et al showed that the dose fall off across the junction becomes more linear and less staircase-like, as the number of PTV segments increases. In an example CSI case, it was found that nine segments were needed to generate a profile that is nearly linear [13]. Unfortunately, as the number of segments increases, planning becomes more cumbersome and error-prone because unique optimization constraints are needed for each segment. This approach becomes prohibitively complex in cases that require more than one junction—such as VMAT CSI for adults. A simple approach for planning junctioned VMAT CSI plans that are robust to field setup error is therefore still needed.

Recently, Traneus et al briefly introduced a universal field matching solution that used an *in silico* ideal base plan dose to guide inverse optimization of junctioned VMAT for CSI [16]. However, to generate acceptable *in silico* base plans, Traneus et al needed to divide the PTV into five segments. Here, the feasibility of a novel implementation of *in silico* ideal base plans that do not require any extra planning contours is assessed. The algorithm used to generate ideal base plans is described, and feasibility is demonstrated for two cases: a two-isocenter, one-junction pediatric CSI case and a three-isocenter, two-junction adult CSI case. For both cases, a junctioned VMAT plan is generated and a thorough dosimetric analysis of plan quality and robustness to field match errors is presented.

Methods

Patient Data

Radiotherapy planning computed tomography data sets from two patients previously treated using conventional CSI in supine position at our clinic were used for this study. A pediatric case of metastatic medulloblastoma treated with 36 Gy over 20 fractions and an adult case of acute myeloid leukemia treated with 23.4 Gy over 13 fractions were used. For both cases, a PTV was generated retrospectively by adding a 5-mm margin to the brain and spinal cord. Contouring and