A 3D isodose manipulation tool for interactive dose shaping

C P Kamerling, P Ziegenhein, H Heinrich and U Oelfke
German Cancer Research Center (DKFZ), Department of Medical Physics in Radiation Oncology, Im Neuenheimer Feld 280, 69120 Heidelberg, Germany
E-mail: c.kamerling@dkfz.de

Abstract. The interactive dose shaping (IDS) planning paradigm aims to perform interactive local dose adaptations of an IMRT plan without compromising already established valuable dose features in real-time. In this work we introduce an interactive 3D isodose manipulation tool which enables local modifications of a dose distribution intuitively by direct manipulation of an isodose surface.

We developed an in-house IMRT TPS framework employing an IDS engine as well as a 3D GUI for dose manipulation and visualization. In our software an initial dose distribution can be interactively modified through an isodose surface manipulation tool by intuitively clicking on an isodose surface. To guide the user interaction, the position of the modification is indicated by a sphere while the mouse cursor hovers the isodose surface. The sphere’s radius controls the locality of the modification. The tool induces a dose modification as a direct change of dose in one or more voxels, which is incrementally obtained by fluence adjustments. A subsequent recovery step identifies voxels with violated dose features and aims to recover their original dose.

We showed a proof of concept study for the proposed tool by adapting the dose distribution of a prostate case (9 beams, coplanar). Single dose modifications take less than 2 seconds on an actual desktop PC.

1. Introduction

Fluence modulation allows intensity modulated radiation therapy (IMRT) to provide a high spatial conformity of the prescribed dose to the tumor volume while minimizing dose in adjacent healthy tissue. Finding a clinically optimal set of fluence intensities typically relies on the iterative optimization of an objective function. This objective function includes pre-segmented volumes of interest and dose constraints which are weighted by penalty factors [1]. The indirect approach of finding the clinically optimal dose distribution suffers from various inherent shortcomings. First, the control of local dose features is limited to segmented volumes of interest, for example making it difficult to remove cold or hot spots. Second, there is no direct mapping between the parameters of the objective function and the resulting dose distribution. Generating a treatment plan may require a tedious loop of manual constraint adaptation and re-optimization. Third, when patient geometry changes between fractions, it is difficult to adapt the initial treatment plan accordingly. In the worst-case the whole optimization process has to be repeated, which depending on the optimization method involves the recalculation of dose-influence data or plan databases.

To overcome these shortcomings we propose a new planning paradigm: interactive dose shaping (IDS). It aims to perform interactive local dose adaptations of a plan without...
compromising already established valuable dose features in real-time. The key operation that facilitates dose shaping is a two-step dose modification and recovery (DMR) strategy. The DMR strategy is triggered by direct interaction with a 3D dose distribution through a graphical user interface (GUI). In this work we introduce an interactive 3D isodose surface manipulation tool which enables local modifications of a dose distribution by sculpting an isodose surface. We show a proof of concept study for a prostate case and compare a plan obtained with our tool to a conventionally optimized treatment plan.

2. Materials & Methods

2.1. Software framework
We developed an in-house IMRT treatment planning system (TPS) framework consisting of a 3D GUI for dose manipulation and visualization (Figure 1). To provide an interactive GUI we required both an intuitive and a responsive graphical representation of patient geometry, beam and fluence setup, dose distribution and quality indicators. To guarantee responsiveness, all our algorithms are optimized for speed and low latency by utilizing various degrees of parallelization. These considerations led to the following technological choices: For 3D graphics we utilized the 3D graphics engine Ogre3D\(^1\). All windows and dialogs were implemented using Qt\(^2\), 2D plots using Qwt\(^3\). The Qt concurrency system was used to ensure a responsive interface, while the computation intensive algorithms run in parallel through OpenMP \(^2\) and AVX\(^4\). All code was programmed in C/C++. Our software supports 3D Vision\(^5\) shutter glasses, which provide the user with optimal depth information. To enable convenient user navigation and manipulation simultaneously, the SpaceNavigator\(^6\) 3D mouse is supported.

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\(^1\) Ogre3D is an open-source multi-platform 3D graphics engine which abstracts over OpenGL (Khronos Group, Beaverton, OR, USA) and Direct3D (Microsoft, Redmond, WA, USA). (www.ogre3d.org)
\(^2\) Qt is a cross-platform application and UI framework by Digia (Helsinki, Finland). (www.qt-project.org)
\(^3\) Qwt is an open-source GUI library (mainly focussing on 2D plotting) based on Qt. (qwt.sourceforge.net)
\(^4\) Advanced Vector Extensions (AVX) is an extension to the x86 instruction set architecture for microprocessors by Intel, Santa Clara, CA, USA. (http://software.intel.com/en-us/avx/)
\(^5\) 3D Vision is a product from NVIDIA, Santa Clara, CA, USA. (www.nvidia.com/object/3d-vision-main.html)
\(^6\) SpaceNavigator is a product from 3Dconnexion, Waltham, MA, USA. (www.3dconnexion.com)
2.2. Interactive dose shaping
The key operation driving IDS is the two-step DMR strategy. The first step, a dose modification, is a direct change of dose in a voxel, selected either directly by the user by GUI interaction or a quality indicator specific algorithm. The fluence adaption will naturally lead to unintended and unwanted dose deviations outside of the selected, local area of modified dose. The subsequent recovery step identifies these voxels and aims to recover their original dose by selecting and modifying a set of fluence amplitudes that does not or only minimally alter the initially achieved dose modification. More information on the DMR strategy can be found in [3].

The local dose modification can be directly imposed by a therapist, by selecting a voxel in our 3D-graphical user interface. The described elemental DMR operation can also be used as building block to achieve more general hierarchical planning goals, such as hot spot removal and whole organ at risk (OAR) sparing. The generalized algorithm for incorporating such planning goals is schematically shown in Figure 2. The first step (1) is the candidate selection of the respective voxels for which the dose will be modified. Subsequently a voxel is chosen (2) from the selection and it’s dose is modified (3). The recovery step (4) reduces the deviations introduced by the modification. When the resulting dose distribution does not satisfy the planning quality (5), the algorithm returns to (1) and the loop is repeated. The DMR operation requires several dose computations, which form the computational bottle neck for IDS. Dose calculation is performed with an adapted ultra-fast pencil algorithm and relies on the inherent locality of the fluence

Figure 2. A schematic overview of the IDS algorithm

Figure 3. Screen coordinates are projected on the 3D isodose surface by casting a ray from the view frustum’s camera origin through the mouse cursor.

Figure 4. Activity diagram for user interaction with the 3D isodose surface manipulation tool.
amplitude changes [4]. The algorithm doesn’t require pre-calculated dose influence data, hence it quickly adapts to changing patient geometries.

2.3. Isodose surface manipulation tool

This section describes the isodose surface manipulation tool we propose. The workflow is shown in the activity diagram in Figure 4. As a first step, the user has to select an isodose value (1) for which he wants to observe an isodose surface. This surface is obtained by a real-time volume extraction algorithm which is based on the original Marching Cubes [5] algorithm. It takes a 3D dose distribution as input and generates a triangulated mesh for a specific isodose value. As second step the user positions a sphere on the isodose surface (2) to alter dose at their intersection. Interaction with a mouse is naturally 2D, however the isodose surface manipulation tool requires 3D interaction. Figure 3 shows the view frustum from the imaginary camera which projects the 3D scene on a 2D screen. Now a ray (indicated by the blue dotted line) is cast from the camera source through the mouse cursor. The first intersecting triangle from the isodose surface is the location where the sphere will be positioned. The radius of the sphere can be set manually to alter the locality of the modification. When the user has found the right sculpting position, he clicks to change the dose (3). This input is then translated to a set of candidate voxels to modify and the IDS algorithm starts (Figure 2). The user is provided with immediate feedback; he can now assess the dose distribution (4) using the 3D dose visualization and quality indicators.

2.4. Proof of concept study: clinical prostate case

We provide a proof of concept study for our isodose surface manipulation tool by applying it to a prostate patient and comparing it to a clinically approved conventionally optimized IMRT plan. Both plans consist of 9 coplanar equidistant beams. The reference plan was planned using the KonRad optimization tool (MRC Systems, Heidelberg, Germany). Starting point of our IDS planning approach was a homogeneous, conformal dose of the target volume at the prescribed dose level that does not account for any dose sparing of OARs. This initial dose distribution was interactively modified using the isodose surface manipulation tool to resemble the reference plan. Before plan comparison, the plan was sequenced.
Figure 6. Four screen-shots from successive planning steps. The therapist used the isodose surface manipulation tool to sculpt the dose in and around the rectum. The fluence maps are shown at the bottom of each screen-shot. The mouse cursor was enlarged for better visibility. A video from the planning process can be found in the Supplementary Data.

3. Results
The dose prescription for the prostate case was 76 Gy to the GTV and 70 Gy to the CTV. The planning goal was rectum sparing while maintaining target coverage. The therapist used the isodose surface manipulation tool to sculpt the dose in and around the rectum. Large radii were chosen for coarse dose changes, small radii for fine dose changes. The whole planning process took 5 minutes on a desktop PC configured with a single Intel i7 processor. Dose was calculated on a clinical voxel resolution of $(2 \text{ mm})^3$. A typical dose shaping request by the tool took less than 2 seconds on the desktop PC and less than 1 second on a workstation configured with two Xeon processors. The generation and visualization of the isodose surface after each dose change took typically 30 ms on the desktop PC and 15 ms on the workstation. Figure 5 shows the dose volume histograms. The IDS plan is represented by the solid curves and the reference plan by the dashed curves. The planning process using our isodose surface manipulation tool was captured on video and can be found in the Supplementary Data. Figure 6 shows four screen-shots from successive planning steps.

4. Discussion
The proof of concept study demonstrates that the use of IDS makes it possible to obtain a plan quality at least similar to conventionally optimized IMRT treatment plans. The high dose region for the rectum is comparable, however the volume receiving less than 40 Gy is clearly smaller.
The target volumes from our IDS plan are slightly better, although the difference between GTV and CTV is not very pronounced. Whereas the reference plan can only be adapted by changing penalty weighting factors, our isodose surface manipulation tool makes it more easy to locally change dose features.

As future work we want to evaluate both the interface and the actual dose shaping tools for a patient collective and incorporate the feedback from clinicians. We want to increase the speed of the dose calculation even further. This enables a larger set of voxels to recover and paves the way for guiding strategies: indicating the user which dose changes are still feasible.

The DMR strategy operates in the fluence domain. Before the IDS dose distribution can be delivered, it has to be sequenced, which may deteriorate the local dose manipulations. Currently, we use an external sequencing algorithm, which is separated from the IDS algorithms. We plan to implement a guiding algorithm, which frequently checks whether the currently shaped dose distribution is still deliverable.

Other groups also make efforts to deal with the disadvantages of conventional IMRT treatment plan optimization as stated in the introduction. One example is automatic planning using a heuristic search based on constraint wish lists [6] or plan databases [7]. Multi-criteria optimization (MCO) [8] makes the exploration of the penalty space feasible, but still suffers from the inability to quickly adapt a plan based on an updated patient geometry. These methods are all computationally intensive and require many conventional optimization loops. Therefore research is done on ultra-fast conventional IMRT plan optimization using various parallelization strategies [9] [10]. The IDS algorithm has the potential to cope with all these drawbacks. Future work will include the implementation of strategies to modify voxels based on changing patient geometries.

5. Conclusion

Technically, interactive dose shaping can be done intuitively and in real-time by 3D isodose surface manipulation, as implemented in our in-house TPS Dynaplan. The quality of the obtained plans still has to be evaluated.

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