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Interactive dose shaping: development and evaluation of a novel treatment planning software application

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Fluence modulation allows intensity modulated radiation therapy (IMRT) to provide a high spatial conformity of the prescribed dose to the target volume, while minimising dose to adjacent normal 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 (VOIs) and dose constraints which are weighted by penalty factors. 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-optimisation. Third, when patient geometry changes between fractions it is difficult to adapt the initial treatment plan accordingly. In the worst case the whole optimisation process has to be repeated, which depending on the optimisation method involves the recalculation of dose-influence data or plan databases.

To overcome these shortcomings, a new planning paradigm was proposed: 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. This strategy is triggered by direct interaction with a dose distribution through a graphical user interface (GUI).

The first step of the DMR strategy, a dose modification, is a direct change of dose in a voxel, selected either directly by the user through GUI interaction or a quality indicator specific algorithm. The fluence adaptation will naturally lead to unintended and unwanted dose deviations outside 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. The elemental DMR operation can also be used as building block to achieve more general planning goals. 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-beam algorithm and relies on the inherent locality of the fluence amplitude changes. The algorithm does not require pre-calculated dose influence data, hence it quickly adapts to changing patient geometry.

The IMRT research treatment planning system (TPS) Dynaplan was implemented exclusively for this work. Dynaplan is a software prototype, consisting of a 3D GUI for dose manipulation and visualisation, including a 2D and 3D interface which hosts a slice view, VOI visualisation, beam's eye view, volume rendering, quality indicators and graph plotting. The software development process was presented in terms of functional and non-functional requirements, third party libraries, peripheral hardware support, acceleration strategies, logical, and physical design. To guarantee responsiveness, all algorithms were optimised for speed and low latency by utilising various degrees of parallelisation. 3D graphics were based on the extension of the 3D graphics engine Ogre3D. All windows, dialogues and other widgets were implemented using Qt, 2D plots using Qwt. The Qt concurrency system was utilised to ensure a responsive interface, while the computation intensive algorithms run in parallel through Open Multi-Processing (OpenMP) and Advanced Vector eXtensions (AVX). For some algorithms, for which latency is of little importance, Compute Unified Device Architecture (CUDA) implementations were realised. All code was programmed in C++. Dynaplan supports 3D Vision shutter glasses, which provide the user with optimal depth information. To enable convenient user navigation and manipulation simultaneously, the SpaceNavigator 3D mouse is supported. From a usability perspective, intuitive interaction was discussed for all implemented widgets, as the dose shaping tools should be used from novice to expert users. To support further development, design choices which relate to maintainability were discussed.

Three dose shaping tools were implemented in Dynaplan: (1) The most straight-forward IDS tool is the dose grid manipulation tool. Using this tool, the user can select a voxel in a dose grid and subsequently request a dose increase or decrease. (2) The isodose curve manipulation aims at interactive dose shaping by direct interaction with isodose lines. (3) In addition to conventional 2D presentation, dose can be visualised in 3D space by rendering of isodose surfaces. The isodose surface manipulation tool is designed to enable sculpting of such a surface. To guide the user interaction, the position of the modification is indicated by a spherical sculpting element, while the mouse cursor hovers the isodose surface. To support dose shaping, several other tools were developed and implemented: the target coverage tool, an undo/redo stack, functionality to save dose states, and a direct fluence manipulation tool.

A DMR evaluation was performed to illustrate the key concept driving IDS. Several scripted dose changes were requested for an artificial phantom patient geometry, consisting of a C-shaped target volume, partly surrounding a spherical organ at risk (OAR). The respective OAR voxels received a dose decrease request. This successfully resulted in a steep dose gradient around the OAR, while the recovery process was able to maintain acceptable target coverage. The response times of the implemented visualisation entities were assessed. During dose shaping, the interface can be updated with a frame-rate of more than 10 Hz. When dose shaping is idle, a frame-rate of more than 20 Hz is achieved. A step-by-step visual assessment was performed to show the working principle of each IDS tool. Each dose shaping request could be performed in less than a second.

The proposed IDS tools were utilised to create a treatment plan for six clinical patients with an adeno-carcinoma of the prostate. The obtained IDS treatment plans were compared to conventionally optimised clinically approved plans. Moreover, case studies for two more complex intra-cranial cases were performed. Both studies have shown promising results. It was technically possible to utilise the software prototype to generate treatment plans for patient geometries with a moderate amount of target volumes and OARs in 15-45 minutes. The plans could compete with the clinically approved reference plans. However, as treatment planning was performed by one of the Dynaplan developers, and not by clinical staff, it cannot yet be concluded that IDS is clinically feasible, as this would require a planning study incorporating clinical therapists. The second intra-cranial case study has shown the major shortcoming of the current recovery algorithm, to select the right set of voxel adaptations, for geometries with many competing OARs. Also, the relatively high integral dose needs to be considered for future improvements of Dynaplan.

The recovery algorithm has to be improved for complex patient geometries, which should be accompanied by a further speed-up for the IDS dose calculation. The IDS tools have to be assessed in a usability study involving multiple clinical therapists. The DMR operation has to be extended, so that it can be guaranteed that a treatment plan is derivable. The tools can then be assessed in a clinical treatment planning study. The generalised DMR algorithm allows for the development of other IDS tools. A guiding algorithm should advice the user which tool has to be utilised for a specific planning goal and where dose changes are still feasible. Future work also includes the application of IDS for adaptive radiation therapy (ART).

In conclusion, this work has shown that real-time treatment planning utilising IDS is technically feasible. The proposed improvements have the potential to bring IDS closer to the clinic.