An automated dose tracking system for adaptive radiation therapy

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ABSTRACT

Background and objective: The implementation of adaptive radiation therapy (ART) into routine clinical practice is technically challenging and requires significant resources to perform and validate each process step. The objective of this report is to identify the key components of ART, to illustrate how a specific automated procedure improves efficiency, and to facilitate the routine clinical application of ART.

Methods: Data was used from patient images, exported from a clinical database and converted to an intermediate format for point-wise dose tracking and accumulation. The process was automated using in-house developed software containing three modularized components: an ART engine, user interactive tools, and integration tools. The ART engine conducts computing tasks using the following modules: data importing, image pre-processing, dose mapping, dose accumulation, and reporting. In addition, custom graphical user interfaces (GUIs) were developed to allow user interaction with select processes such as deformable image registration (DIR). A commercial scripting application programming interface was used to incorporate automated dose calculation for application in routine treatment planning. Each module was considered an independent program, written in C++ or C#, running in a distributed Windows environment, scheduled and monitored by integration tools.

Results: The automated tracking system was retrospectively evaluated for 20 patients with prostate cancer and 96 patients with head and neck cancer, under institutional review board (IRB) approval. In addition, the system was evaluated prospectively using 4 patients with head and neck cancer. Altogether 780 prostate dose fractions and 2586 head and neck cancer dose fractions went processed, including DIR and dose mapping. On average, daily cumulative dose was computed in 3 h and the manual work was limited to 13 min per case with approximately 10% of cases requiring an additional 10 min for image registration refinement.

Conclusions: An efficient and convenient dose tracking system for ART in the clinical setting is presented. The software and automated processes were rigorously evaluated and validated using patient image datasets. Automation of the various procedures has improved efficiency significantly, allowing for the routine clinical application of ART for improving radiation therapy effectiveness.

1. Introduction

In adaptive radiation therapy (ART), improvements in treatment plan (re-planning) are made during the course of a multi-fraction schedule based on the delivered dose during initial fractions [1]. About 40 percent of the head&neck plans were adapted through re-planning in our clinic. Critical steps in the implementation of ART involve the estimation of the radiation dose received by the patient for each treatment fraction and the assessment of the estimated dose. Daily cone-beam computed tomography (CBCT) imaging provides volumetric information of the patient position, tumor and normal organs immediately prior to each treatment fraction. This affords a practical means to assess the patient position and movement of the tumor and critical, normal structures including dose limiting normal tissues defined in the initial treatment plan [2].

The re-planning process begins by estimating variations in dose distributions typically from dose volume histograms (DVH's). Three steps are involved. First, the plan is simulated from the daily CBCT image dataset to calculate the estimated actual delivered daily dose for the given treatment fraction. Second, structures of interest are delineated to obtain daily DVHs to provide dose metrics for the tumor and organs-at-risk (OARs) from which oncologists can evaluate treatment plan effectiveness. Third, the doses to the

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therapeutic target and OARs are modified, if necessary, to meet the dose constraints in the original treatment plan, or to afford further improvement in plan quality, if possible. Practical execution of the various tasks for ART in clinical practice is not trivial for several reasons. For instance, the process for a physician to manually delineate the target and surrounding normal tissue structures is cumbersome, typically taking hours even for a skilled clinician. This becomes a procedural challenge given the number of individual fractions (i.e. 35–40) comprising a complete treatment, and given that each fraction requires the full set of structures to be delineated. The limited image quality of daily CBCT places practical constraints on the ability to manually delineate structures as well as estimate actual daily doses. Furthermore, even though the daily organ dose is available through the above steps, in the absence of accurate point-to-point correspondence between the CBCT datasets at each fraction, it is not possible to accurately estimate the cumulative dose at each voxel within the image dataset, an obvious limitation.

One solution is to use DIR to establish point correspondence. DIR can also be used to transfer structure contours from one image to another through a deformation vector field (DVF) so that structures only need to be delineated once. There is a clinical need for such a tool in fractionated radiation therapy. Practically speaking, however, DIR in general is challenging due to the unknown individual biomechanics and potentially large organ deformation between treatments.

There remains debate as to the appropriateness of deforming dose along with DIR, especially under conditions where the tumor and/or surrounding normal organs undergo mass changes [3–5]. We believe that: (1) when inter-fraction motion is small, the DIR can be accurate in local regions; (2) when automated DIR produces visually large errors; user interaction can greatly improve the accuracy [6]. Thus, the DIR quality needs to be sensibly and frequently monitored while appropriate tools need to be implemented for uncertainty detection and correction. Currently there are several commercial software and open source projects dedicated to DIR. Although commercial software solutions provide sophisticated evaluation tools and fast calculation, they currently lack sufficient robustness to handle difficult cases such as prostate registration as well as patient specific optimization [7,8]. Alternatively, open source projects with similar functions are being developed. Despite their flexibility and accuracy, these research endeavors are not tailored to the clinical environment; it takes great effort and resources to upgrade them based on rigorous quality assurance, based on extensive, independent tests for accuracy/robustness and their ability to fit into a complex and heavily regulated hospital IT structure [9]. In addition, many existing solutions lack automation and scripting capabilities. One cost effective solution explored in this report is a custom system to fulfill clinical needs that address efficiency and accuracy at the same time. Lei et al. [10] outlined the critical computational components required for implementation of ART. Each component is investigated separately so as to identify the steps that can be safely automated to achieve maximum efficiency. The work presented herein represents the first step toward this goal, providing the following:

(a) Demonstration of the clinical use of DIR for daily dose calculation and accumulation, which has been validated and applied to clinical data sets.
(b) Presentation of a highly integrated and automated software system for medical physicists and physicians to perform ART with accurate dose tracking based on daily CBCT image datasets. Our goal is for readers to be able to implement a similar custom system at their respective institutions using available resources, and the ideas presented.

It is important to note that re-planning, another major component of ART, is outside of the scope of the current paper. This article is organized as follows: Section 2 describes our system in detail; Section 3 illustrates an example case and evaluates utility; Section 4 discusses the limitations of the current system, and Section 5 presents conclusions and future work.

2. Methods and materials

Daily dose calculation and dose accumulation are the 2 major steps necessary to track radiation dose during adaptive radiation therapy [10]. We use a modularized design to ensure the flexibility of different dose calculation and accumulation modules catered for different clinics, and we store all data in a separate database/workspace to minimize the occupation of the clinical database. To automate the modules, a major software component enables free flow of data between modules, including the clinical TPS. Another key required design feature is a distributed computing architecture to enable various modules to run on different servers within an intranet while sharing data. This allows scalability of the system to facilitate dose tracking for multiple patients, simultaneously. Our design shares a lot of similarities with the Google file system [11].

2.1. Data acquisition and representation

The following input data are needed to initiate the calculation: CT image, radiotherapy structure (RT structure) set, and CBCT image. A patient simulation CT (SimCT) is obtained before any treatment planning or re-planning on which the target and normal tissues are contoured by a physician. At each treatment fraction, CBCT image datasets are acquired to provide daily patient information for accurate target localization. These data are initially stored in the TPS before being exported to the ART engine using a DICOM database daemon and a file daemon provided by the vendor. The exported DICOM files are converted to intermediate formats. DICOM images and dose grids are converted into meta image format (.mhd+raw); the DICOM structures are resampled and stored as binary mask images while DICOM plan files are converted to text format. The converted input data are stored in intranet-shared folders, i.e., ART database, in a Windows file server for easy access and credential control. Program workspaces containing results in intermediate formats also reside in these shared folders. Related images and structures are converted back to DICOM using DCMTK [12] before being imported into the TPS for dose calculations. Lock files are used for synchronization between processes of the same module. The intermediate files are relatively small and allow for the direct use of versatile software tools without frequent data conversions.

2.2. Software system architecture

The software system was designed to accomplish the following tasks:

(1) Perform required data processing and calculation for dose tracking.
(2) Provide end users with interactive tools to i) make corrections in the case of problematic data and ii) conduct proper quality assurance (QA) tasks.
(3) Minimize the time between tasks due to delayed user feedback.

To these ends, a software package was developed containing three distinct components: ART engine, user interactive tools, and integration tools. Fig. 1 shows the relationship between different components, the important points of which are discussed in detail below.