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Original article

Fast and robust adaptation of organs-at-risk delineations from planning scans to match daily anatomy in pre-treatment scans for online-adaptive radiotherapy of abdominal tumors

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ABSTRACT

Purpose: To validate a novel deformable image registration (DIR) method for online adaptation of planning organ-at-risk (OAR) delineations to match daily anatomy during hypo-fractionated RT of abdominal tumors.

Materials and methods: For 20 liver cancer patients, planning OAR delineations were adapted to daily anatomy using the DIR on corresponding repeat CTs. The DIR's accuracy was evaluated for the entire cohort by comparing adapted and expert-drawn OAR delineations using geometric (Dice Similarity Coefficient (DSC), Modified Hausdorff Distance (MHD) and Mean Surface Error (MSE)) and dosimetric (D_{max} and D_{mean}) measures.

Results: For all OARs, DIR achieved average DSC, MHD and MSE of 86%, 2.1 mm, and 1.7 mm, respectively, within 20 s for each repeat CT. Compared to the baseline (translations), the average improvements ranged from 2% (in heart) to 24% (in spinal cord) in DSC, and 25% (in heart) to 44% (in right kidney) in MHD and MSE. Furthermore, differences in dose statistics (D_{max}, D_{mean} and $D_{2\%}$) using delineations from an expert and the proposed DIR were found to be statistically insignificant ($p > 0.01$).

Conclusion: The validated DIR showed potential for online-adaptive radiotherapy of abdominal tumors as it achieved considerably high geometric and dosimetric correspondences with the expert-drawn OAR delineations, albeit in a fraction of time required by experts.

Recent studies demonstrated that re-planning based on daily acquired computed tomography (CT) scans can improve dose delivery in stereotactic body radiotherapy (SBRT) of liver and pancreatic tumors [1–5]. Online-adaptive SBRT, including online re-planning or verification of computed dose statistics of organs-at-risk (OARs), is being increasingly employed in radiotherapy as well as proton therapy centers with the use of in-room CT-on-rails or MR imaging. Such a setup, however, requires accurate and fast delineations of the relevant organs [1,6]. Manual delineation of OARs in a repeat CT is tedious and time-consuming, and is therefore not suitable for online adaptive strategies, where time is a major limiting factor. Automatic OAR delineation using deformable image registration (DIR) has the potential to obtain adapted delineations from the planning CT within a permissible time-frame [1,7].

DIR of abdominal organs has proven to be particularly challenging due to large day-to-day deformations and moderate soft-tissue contrast in CT images [8]. As a result, sparse literature exists on the application of DIR algorithms, especially, for abdominal radiotherapy. Brock et al. [9] assessed the accuracy of multiple DIR algorithms on data from different anatomical sites including abdomen. Liu et al. [10] evaluated a free-form DIR algorithm based on calculus of variations [11] using a physical deformable abdominal phantom. Hoffman et al. [12] tested a commercially available DIR tool, Velocity AI (Velocity Medical Systems, Atlanta, GA), on abdominal CTs of 5 patients. Most of the proposed methods demonstrated an overall improvement in accuracy, but also showed significantly high errors. In addition, the validation was performed either on phantoms [10] or limited clinical data [9,12], thus lacking sufficient evidence for their application in a clinical setting.

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The aim of this study is to comprehensively evaluate a fast DIR method for online-adaptive radiotherapy of abdominal tumors, especially with in-room CT on rails as the imaging device. The proposed DIR method enables fast and efficient adaptation of OAR delineations from planning to repeat CT scans. By adopting a multi-resolution scheme, it avoids local minima and achieves fast convergence. As the entire process is also unsupervised, it has the potential for online automated application. Compared to the existing studies, we evaluated it with the clinical data from a sufficiently large patient group of 20 liver cancer patients. The proposed DIR was validated by comparing automatically obtained delineations with the expert drawn gold-standard delineations.

Materials and methods

Patient characteristics and CT acquisition

20 patients (Table 1), diagnosed with liver metastases or hepatocellular carcinoma (HCC) and previously treated with liver SBRT, were included in this retrospective study. The planning CT image acquisition and fractionated treatments involved the positioning of patients in a stereotactic body frame (SBF) (Elekta Instrument AB, Sweden) with abdominal compression to reduce respiratory-induced tumor motion. The tumor and surrounding OARs were delineated in the large planning CTs (including lungs) that were enhanced with contrast in only 7 patients. For rest of the patients, only short (spanning only liver) planning CTs were acquired with contrast. The tumor delineation from such short CTs were transported to the larger non-contrast planning CTs that were used for OAR delineations. Only large planning CTs were used in this study. On each treatment day, prior to dose delivery, a contrast-enhanced CT scan was acquired to establish the position of the tumor in the SBF. This position was used to calculate the setup correction vector for the alignment of the tumor and the treatment beams. The dataset of each patient was acquired using Siemens SOMATOM Sensation Open CT scanner (Erlangen, Germany), and included 1 planning CT and 3 or 6 repeat CT scans with slices of 512×512 pixels, thickness of 2.5 mm and in-plane pixel size of 0.98–1.27 mm.

Table 1
Patient characteristics ($N = 20$).

Gender	
Female	7
Male	13
Age (years)	
Mean ± Standard deviation	65.9 ± 11.3
Median	65
Patient diagnosis	
Liver Metastases (Liver Mets)	17
Hepatocellular carcinoma (HCC)	3
Patients with contrast agent in	
Planning CT	7
Repeat CTs	20
Patients with	
3 treatment fractions	16
6 treatment fractions	4

Gold-standard OAR delineations

Only those OARs that had dose limiting constraints in our institute's treatment protocol were included in this study. Consequently, duodenum (partial small bowel), esophagus, heart, kidneys, liver, spinal cord, and stomach constituted the OAR set that was delineated *de novo* in each repeat CT by one of the observers in the 3-member expert panel. Prior to their acceptance as gold-standard, OAR delineations were extensively reviewed and modified (if required) by the panel to ensure a reliable anatomical representation. Manual delineations of esophagus, stomach and duodenum proved to be the most challenging, primarily due to the ambiguities related to their junctions. To investigate the effect of junction uncertainties on the accuracy measurements, we created another OAR i.e., ESD (Esophagus–Stomach–Duodenum), by combining the existing delineations of these organs.

OAR adaptation in repeat CTs

Translation, rigid alignment and the proposed DIR (Accuray Incorporated, Sunnyvale, CA, USA) were used to automatically adapt OAR delineations from the planning to the repeat CTs (Fig. 1). Translation for each OAR was obtained by utilizing the clinical setup correction required for the alignment of the tumor and treatment beams. Rigid alignment, i.e. an alignment including rotations and translations, was also evaluated [13–15]. Consequently, for each pair of planning and repeat CTs, we obtained 3 different transformation fields corresponding to translation, rigid alignment and the proposed DIR. Such fields, when applied to the planning delineations, resulted in automatically segmented or DIR-adapted OARs in the repeat CTs. The subsequent section provides more detail on the proposed DIR method.

Proposed DIR method

A novel multi-organ and intensity based DIR method was evaluated. A multi-organ method allows simultaneous deformation of multiple organs instead of using an organ specific deformation method. The DIR software evaluated is a standalone version of

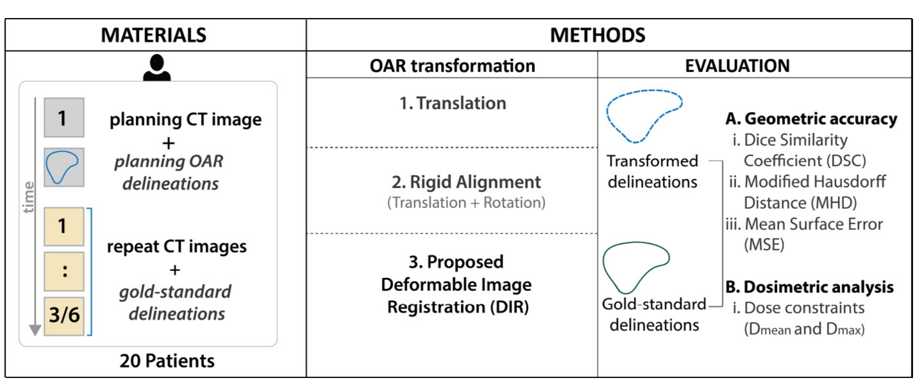

Fig. 1. A schematic illustration of materials and methods. The material column shows the composition of patient data and corresponding delineations. The method column presents the different OAR transformation methods used in this study along with the evaluation strategy that illustrates how the transformed (or automatically adapted) and gold-standard delineations were compared using geometric and dosimetric measures.

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