An Investigation of Methods for CT Synthesis in MR-only Radiotherapy

In recent years, the interest in using magnetic resonance (MR) imaging in radiotherapy (RT) has increased. This is because MR has a superior soft tissue contrast compared to computed tomography (CT), which makes it a better modality for delineating the target volume (tumor) and possible organs at risk (OARs). In an MR/CT work-flow, independent MR and CT scans are acquired. The target and possible OARs are delineated on the MR and then transferred to CT by aligning the data using a registration. This introduces the risk of systematic registration errors especially in non-rigid body structures, the consequence being a systematic miss of target or increased dose to healthy tissue.

Radiotherapy based on MR as the only modality removes this uncertainty and simplifies the clinical work-flow. However, the information on electron density which is usually contained in the CT must now be derived from the MR. A way to achieve this is to computationally estimate a so-called synthetic CT (sCT) from the MR data, which can then act as a substitute for the CT. This is a challenging task, since no unique relationship between MR and electron density exists.

The goal of this thesis is to develop and investigate the right combination of MR acquisition protocols and computational models for accurate MR-based CT synthesis for use in RT. We investigate different categories of methods for CT synthesis and validate them using clinically relevant quality measures. Specifically, we implement a patch-based multi-atlas method in the brain, which compares favorably to state-of-the-art methods. In our next effort, we substantially improve the speed of the method and apply it in the pelvis, again with promising results. Our final contribution is a voxel-based method, which is developed to be registration-free and broadly applicable. In initial results, the performance of this method is close to the patch-based.

A patch-based pseudo-CT approach for MRI-only radiotherapy in the pelvis

In radiotherapy based only on magnetic resonance imaging (MRI), knowledge about tissue electron densities must be derived from the MRI. This can be achieved by converting the MRI scan to the so-called pseudo-computed tomography
(pCT). An obstacle is that the voxel intensities in conventional MRI scans are not uniquely related to electron density. The authors previously demonstrated that a patch-based method could produce accurate pCTs of the brain using conventional $T_1$-weighted MRI scans. The method was driven mainly by local patch similarities and relied on simple affine registrations between an atlas database of the co-registered MRI/CT scan pairs and the MRI scan to be converted. In this study, the authors investigate the applicability of the patch-based approach in the pelvis. This region is challenging for a method based on local similarities due to the greater inter-patient variation. The authors benchmark the method against a baseline pCT strategy where all voxels inside the body contour are assigned a water-equivalent bulk density. Furthermore, the authors implement a parallelized approximate patch search strategy to speed up the pCT generation time to a more clinically relevant level. The data consisted of CT and $T_1$-weighted MRI scans of 10 prostate patients. pCTs were generated using an approximate patch search algorithm in a leave-one-out fashion and compared with the CT using frequently described metrics such as the voxel-wise mean absolute error (MAE$_{\text{vox}}$) and the deviation in water-equivalent path lengths. Furthermore, the dosimetric accuracy was tested for a volumetric modulated arc therapy plan using dose–volume histogram (DVH) point deviations and $\gamma$-index analysis. The patch-based approach had an average MAE$_{\text{vox}}$ of 54 HU; median deviations of less than 0.4% in relevant DVH points and a $\gamma$-index pass rate of 0.97 using a 1%/1 mm criterion. The patch-based approach showed a significantly better performance than the baseline water pCT in almost all metrics. The approximate patch search strategy was 70x faster than a brute-force search, with an average prediction time of 20.8 min. The authors showed that a patch-based method based on affine registrations and $T_1$-weighted MRI could generate accurate pCTs of the pelvis. The main source of differences between pCT and CT was positional changes of air pockets and body outline.
Computed tomography synthesis from magnetic resonance images in the pelvis using multiple random forests and auto-context features

In radiotherapy treatment planning that is only based on magnetic resonance imaging (MRI), the electron density information usually obtained from computed tomography (CT) must be derived from the MRI by synthesizing a so-called pseudo CT (pCT). This is a non-trivial task since MRI intensities are neither uniquely nor quantitatively related to electron density. Typical approaches involve either a classification or regression model requiring specialized MRI sequences to solve intensity ambiguities, or an atlas-based model necessitating multiple registrations between atlases and subject scans. In this work, we explore a machine learning approach for creating a pCT of the pelvic region from conventional MRI sequences without using atlases. We use a random forest provided with information about local texture, edges and spatial features derived from the MRI. This helps to solve intensity ambiguities. Furthermore, we use the concept of auto-context by sequentially training a number of classification forests to create and improve context features, which are finally used to train a regression forest for pCT prediction. We evaluate the pCT quality in terms of the voxel-wise error and the radiologic accuracy as measured by water-equivalent path lengths. We compare the performance of our method against two baseline pCT strategies, which either set all MRI voxels in the subject equal to the CT value of water, or in addition transfer the bone volume from the real CT. We show an improved performance compared to both baseline pCTs suggesting that our method may be useful for MRI-only radiotherapy.

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Cone beam computed tomography guided treatment delivery and planning verification for magnetic resonance imaging only radiotherapy of the brain

Background. Radiotherapy based on MRI only (MRI-only RT) shows a promising potential for the brain. Much research focuses on creating a pseudo computed tomography (pCT) from MRI for treatment planning while little attention is often paid to the treatment delivery. Here, we investigate if cone beam CT (CBCT) can be used for MRI-only image-guided radiotherapy (IGRT) and for verifying the correctness of the corresponding pCT.

Material and methods. Six patients receiving palliative cranial RT were included in the study. Each patient had three-dimensional (3D) T1W MRI, a CBCT and a CT for reference. Further, a pCT was generated using a patch-based approach. MRI, pCT and CT were placed in the same frame of reference, matched to CBCT and the differences noted. Paired pCT-CT and pCT-CBCT data were created in bins of 10 HU and the absolute difference calculated. The data were converted to relative electron densities (RED) using the CT or a CBCT calibration curve. The latter was either based on a CBCT phantom (phan) or a paired CT-CBCT population (pop) of the five other patients.

Results. Non-significant (NS) differences in the pooled CT-CBCT, MRI-CBCT and pCT-CBCT transformations were noted. The largest deviations from the CT-CBCT reference were <1 mm and 1°. The average median absolute error (MeAE) in HU was 184 ± 34 and 299 ± 34 on average for pCT-CT and pCT-CBCT, respectively, and was significantly different (p <0.01) in each patient. The average MeAE in RED was 0.108 ± 0.025, 0.104 ± 0.011 and 0.099 ± 0.017 for pCT-CT, pCT-CBCT phan (p <0.01 on 2 patients) and pCT-CBCT pop (NS), respectively.

Conclusions. CBCT can be used for patient setup with either MRI or pCT as reference. The correctness of pCT can be verified from CBCT using a population-based calibration curve in the treatment geometry.

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Purpose: In radiotherapy (RT) based on magnetic resonance imaging (MRI) as the only modality, the information on electron density must be derived from the MRI scan by creating a so-called pseudo computed tomography (pCT). This is a nontrivial task, since the voxel-intensities in an MRI scan are not uniquely related to electron density. To solve the task, voxel-based or atlas-based models have typically been used. The voxel-based models require a specialized dual ultrashort echo time MRI sequence for bone visualization and the atlas-based models require deformable registrations of conventional MRI scans. In this study, we investigate the potential of a patch-based method for creating a pCT based on conventional T1-weighted MRI scans without using deformable registrations. We compare this method against two state-of-the-art methods within the voxel-based and atlas-based categories.

Methods: The data consisted of CT and MRI scans of five cranial RT patients. To compare the performance of the different methods, a nested cross validation was done to find optimal model parameters for all the methods. Voxel-wise and geometric evaluations of the pCTs were done. Furthermore, a radiologic evaluation based on water equivalent path lengths was carried out, comparing the upper hemisphere of the head in the pCT and the real CT. Finally, the dosimetric accuracy was tested and compared for a photon treatment plan.

Results: The pCTs produced with the patch-based method had the best voxel-wise, geometric, and radiologic agreement with the real CT, closely followed by the atlas-based method. In terms of the dosimetric accuracy, the patch-based method had average deviations of less than 0.5% in measures related to target coverage.

Conclusions: We showed that a patch-based method could generate an accurate pCT based on conventional T1-weighted MRI sequences and without deformable registrations. In our evaluations, the method performed better than existing voxel-based and atlas-based methods and showed a promising potential for RT of the brain based only on MRI.
A voxel-based investigation for MRI-only radiotherapy of the brain using ultra short echo times

Radiotherapy (RT) based on magnetic resonance imaging (MRI) as the only modality, so-called MRI-only RT, would remove the systematic registration error between MR and computed tomography (CT), and provide co-registered MRI for assessment of treatment response and adaptive RT. Electron densities, however, need to be assigned to the MRI images for dose calculation and patient setup based on digitally reconstructed radiographs (DRRs). Here, we investigate the geometric and dosimetric performance for a number of popular voxel-based methods to generate a so-called pseudo CT (pCT).

Five patients receiving cranial irradiation, each containing a co-registered MRI and CT scan, were included. An ultra short echo time MRI sequence for bone visualization was used. Six methods were investigated for three popular types of voxel-based approaches; (1) threshold-based segmentation, (2) Bayesian segmentation and (3) statistical regression. Each approach contained two methods. Approach 1 used bulk density assignment of MRI voxels into air, soft tissue and bone based on logical masks and the transverse relaxation time T2 of the bone. Approach 2 used similar bulk density assignments with Bayesian statistics including or excluding additional spatial information. Approach 3 used a statistical regression correlating MRI voxels with their corresponding CT voxels. A similar photon and proton treatment plan was generated for a target positioned between the nasal cavity and the brainstem for all patients. The CT agreement with the pCT of each method was quantified and compared with the other methods geometrically and dosimetrically using both a number of reported metrics and introducing some novel metrics.

The best geometrical agreement with CT was obtained with the statistical regression methods which performed significantly better than the threshold and Bayesian segmentation methods (excluding spatial information). All methods agreed significantly better with CT than a reference water MRI comparison. The mean dosimetric deviation for photons and protons compared to the CT was about 2% and highest in the gradient dose region of the brainstem. Both the threshold based method and the statistical regression methods showed the highest dosimetric agreement.

Generation of pCTs using statistical regression seems to be the most promising candidate for MRI-only RT of the brain. Further, the total amount of different tissues needs to be taken into account for dosimetric considerations regardless of their correct geometrical position.

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