

**PhD Thesis title:** 'Magnetic resonance imaging –based radiation therapy'

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**ABSTRACT:** Magnetic resonance imaging (MRI) is increasingly applied for external radiotherapy target delineation owing to the superior soft tissue contrast in MR images compared to that in computed tomography (CT) images. CT image has remained as a standard reference for other parts of radiotherapy treatment planning (RTP) workflow; dose calculation and image guidance, due to the restrictive features of MR images for these tasks; such as lack of explicit relation between MR signals and electron densities. Consequently, currently widely used practice of RTP workflow necessitates imaging with two modalities that is time-consuming, resource-intensive, increases RTP uncertainty by requisite image co-registration, and exposes patients' healthy tissues to the additional ionizing radiation applied in CT. The ultimate goal of this work was to introduce a RTP workflow for prostate cancer patients that relies solely on MRI-based RTP images throughout the process.

Scanner-specific intensity values of T1/T2\*-weighted in-phase MR images and Hounsfield units (HUs) of CT images in the male pelvis were analyzed. The results were utilized to generate a dual model conversion technique transforming the MRI data into pseudo-HUs by separate conversion models within and outside of bone segment. The technique was implemented by constructing pseudo-CTs for 15 prostate cancer patients. Feasibility of the obtained images for RTP was evaluated by comparisons against the standard CTs. Dose distributions were analyzed with volumetric-modulated arc therapy calculated by Monte Carlo algorithm and with intensity-modulated radiotherapy calculated by anisotropic analytical algorithm. Feasibility of MRI-based reference images for image guidance was investigated for patient position verification with X-ray based localization images. The potential susceptibility-induced bone outline shift in MR images and the effect of different bone parts to the absorbed dose were quantified with a dedicated fresh bone phantom.

Figure 1 shows an example of the obtained heterogeneous pseudo-CT images. The local soft- and bony tissue presentation uncertainties in the pseudo-CTs were on average 11 HUs and 99 HUs, respectively. The prostate dose level differences between those in pseudo-CTs and those in CTs were ranging from -1.0% to 0.8%. The percentages of dose points in the body passing the 1 mm & 1% 2D gamma index criteria between the images ranged from 79% to 100%. The maximum dose distribution inconsistency behind the bones was 1.3% measured for a single 6 MV radiation field. The bone outlines in the MR images were correctly illustrated within a 1 mm-pixel size, but each 1 mm-sized systematic error in bone segmentation resulted in roughly 0.4% change to the prostate dose level in the pseudo-CTs. The

SDs of differences between cone-beam CT (CBCT)-to-pseudo and CBCT-to-CT automatic registrations were  $\leq 1.0$  mm &  $\leq 0.7^\circ$ . The SDs of differences between pseudo-digitally reconstructed radiograph (DRR)- and CT-DRR-based manual registrations with planar localization were  $\leq 1.0$  mm (kV) &  $\leq 1.7$  mm (MV).

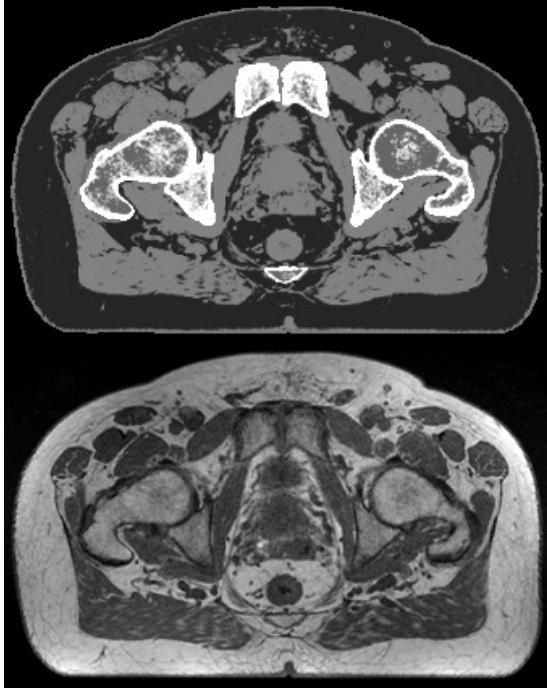


Figure 1. An example pseudo-CT image (left) of prostate cancer patient obtained by the introduced dual model HU conversion technique transforming the intensity values of a T1/T2\*-weighted in-phase MR image (right) to pseudo-HUs.

This work shows that it is possible to construct heterogeneous pseudo-CTs of the pelvis by transforming intensity values of a single MR image into pseudo-HUs, and that by adopting these images for dose calculation and image guidance the entire MRI-based RTP workflow of prostate cancer patients can be conducted accurately according to required standards of modern radiotherapy thus demonstrating a possibility to omit CT imaging from the RTP workflow. The MRI-based RTP workflow for prostate cancer patients has been introduced in Helsinki University Central Hospital Cancer Center.

#### References to author publications that relate specifically to the dissertation:

- I **J. Korhonen**, M. Kapanen, J. Keyriläinen, T. Seppälä, L. Tuomikoski, and M. Tenhunen; *"Absorbed doses behind bones with MR image-based dose calculations for radiotherapy treatment planning,"* Med. Phys. 40(011701), 1-10 (2013).
- II **J. Korhonen**, M. Kapanen, J. Keyriläinen, T. Seppälä, and M. Tenhunen; *"A dual model HU conversion from MRI intensity values within and outside of bone segment for MRI-based radiotherapy treatment planning of prostate cancer,"* Med. Phys. 41(011704), 1-13 (2014).

- III **J. Korhonen**, M. Kapanen, J. Keyriläinen, T. Seppälä, L. Tuomikoski, and M. Tenhunen; *"Influence of MRI-based bone outline definition errors on external radiotherapy dose calculation accuracy in heterogeneous pseudo-CT images of prostate cancer patients;"* Acta Oncol. 53(8), 1100-1106 (2014).
- IV **J. Korhonen**, M. Kapanen, J.-J. Sonke, L. Wee, E. Salli, J. Keyriläinen, T. Seppälä, and M. Tenhunen; *"Feasibility of MRI-based reference images for image-guided radiotherapy in the pelvis with either cone-beam computed tomography or planar localization images,"*Acta Oncol 2015; 54(6):889-95.