Physics and Imaging in Radiation Oncology 7 (2018) 58–64

Contents lists available at ScienceDirect

Physics and Imaging in Radiation Oncology

journal homepage: www.elsevier.com/locate/phro

Original Research Article

# Feasibility of magnetic resonance imaging-only rectum radiotherapy with a commercial synthetic computed tomography generation solution

Matteo Maspero[a,b,*], Marcus D. Tyyger[c,a], Rob H.N. Tijssen[a], Peter R. Seevinck[d,b], Martijn P.W. Intven[a], Cornelis A.T. van den Berg[a,b]

[a] Department of Radiotherapy, Universitair Medisch Centrum Utrecht, The Netherlands
[b] Center for Image Sciences, Universitair Medisch Centrum Utrecht, The Netherlands
[c] Leeds Teaching Hospital, Department of Medical Physics and Engineering, Leeds, United Kingdom
[d] Image Science Institute, Universitair Medisch Centrum Utrecht, The Netherlands

ARTICLE INFO

*Keywords:*
MRI
MR
CT
Medical imaging
Dose calculation
MR-only radiotherapy
Position verification
Image-guided radiotherapy
IGRT

ABSTRACT

*Background and purpose:* Synthetic computed tomography (sCT) images enable magnetic resonance (MR)-based dose calculations. This work investigated whether a commercially available sCT generation solution was suitable for accurate dose calculations and position verification on patients with rectal cancer.

*Material and methods:* For twenty rectal cancer patients computed tomography (CT) images were rigidly registered to sCT images. Clinical volumetric modulated arc therapy plans were recalculated on registered CT and sCT images. Dose deviations were determined through gamma and voxelwise analysis. The impact on position verification was investigated by identifying differences in translations and rotation between cone-beam CT (CBCT) to CT and CBCT to sCT registrations.

*Results:* Across twenty patients, within a threshold of 90% of the prescription dose, a gamma analysis (2%, 2 mm) mean pass rate of 95.2 ± 4.0% ( ± 1$\sigma$) and mean dose deviation of −0.3 ± 0.2% of prescription dose were obtained. The mean difference of translations and rotations over ten patients (76 CBCTs) was < 1 mm and < 0.5° in all directions. In the sole posterior-anterior direction a mean systematic shift of 0.7 ± 0.6 mm was found.

*Conclusions:* Accurate MR-based dose calculations using a commercial sCT generation method were clinically feasible for treatment of rectal cancer patients. The accuracy of position verification was clinically acceptable. However, before clinical implementation future investigations will be performed to determine the origin of the systematic shift.

## 1. Introduction

Radiotherapy is an effective treatment modality for rectal cancer patients [1]. In combination with chemotherapy, neoadjuvant radiotherapy prescribing approximately 50 Gy in 1.8–2.0 Gy fractions (long-course radiotherapy) is considered the standard of care for locally advanced rectal cancers when followed by total mesorectal excision (TME) surgery [2]. For non-locally advanced stage III rectal cancer, short-course radiotherapy consisting of neoadjuvant therapy (5 × 5.0 Gy) followed by immediate TME surgery is the standard of care. This short-course radiotherapy scheme showed a reduction in the risk of local recurrence compared to TME surgery alone [3].

For the planning of radiotherapy, magnetic resonance imaging (MRI) demonstrated its superior soft tissue contrast compared to computed tomography (CT) [4]. In the case of rectal cancer, MRI showed prognostic power for staging capabilities [5,6] and reducing the radiotherapy volumes by approximately 20% and inter-observer variability with respect to CT-based delineations [7,8].

Despite these benefits, radiotherapy cannot be planned on MR images alone, as they do not provide the tissue electron density information required for dose calculations [9]. This lead to the adoption of hybrid MRI/CT pathways, which required multimodality image registration [10]. However, such a workflow is susceptible to systematic and random spatial uncertainties originating from registration errors [11,12]. MR-only workflows have been proposed [11] to overcome these uncertainties, as well as, to offer practical and logistical advantages, by reducing: the overall treatment cost [13], workload [14], and patient exposure to ionising radiation [10]. To clinically introduce MR-only

* Corresponding author at: Department of Radiotherapy, Universitair Medisch Centrum Utrecht, Heidelberglaan 1003584 CX, Utrecht, The Netherlands.
*E-mail addresses:* m.maspero@umcutrecht.nl, matteo.maspero.it@gmail.com (M. Maspero).

https://doi.org/10.1016/j.phro.2018.09.002
Received 17 May 2018; Received in revised form 15 September 2018; Accepted 20 September 2018

radiotherapy, MR-based dose calculations and position verification either based on MRI or MRI-derived images should be enabled and evaluated.

Recently, MR-only simulation has been proposed including the generation of synthetic-CT (sCT) images [15] to enable dose calculations and position verification. Investigations into sCT generation mostly focused on brain and prostate cancer patients [16,17], with vendors recently providing certified solutions for prostate cancer radiotherapy [18–20]. Only two publications investigated the feasibility of MR-only radiotherapy calculations for rectal cancer patients [21,22]. These two contributions focused solely on the dosimetric accuracy of MR-based dose calculation without investigating the use of sCT as a reference for position verification.

This study investigated whether one of the commercial solutions certified for prostate cancer patients can also be employed for rectal cancer patients. Notably, this study evaluated the use of sCT images for cone-beam CT (CBCT)-based position verification.

## 2. Materials and methods

### 2.1. Patient data collection

This study was conducted on fifteen male and five female rectal cancer patients that were free from hip implants and who underwent external beam radiotherapy. All patients had previously provided written informed consent regarding the use of their images, in accordance with the Medical Ethical Committee requirements. The patients were diagnosed with intermediate, and high-risk rectal cancer staged T1c-T4. Their mean age was 60 ± 10 years (± 1$\sigma$; range 38–75 years), and their mean body mass index was on average 27 kg/m$^2$ (range 23–39 kg/m$^2$). The patients were treated for neoadjuvant therapy; Three fractionation regimes were adopted: short course treatment delivering 5 × 5.0 Gy (3), and long-course treatment 25 × 2.0 Gy without (14), and with (3) an integrated boost on extra-mesorectal pathological nodes of 25 × 2.4 Gy. Nineteen patients were irradiated with volumetric modulated arc therapy (VMAT) consisting of two coplanar arcs of 10 MV between 50° and 310°. One patient was irradiated with a single 360° VMAT arc. All plan were clinically optimised according to dose prescription to organs reported in the Dutch guidelineshttp://www.oncoline.nl/colorectaalcarcinoom.

Patients' simulations were performed on both CT and MRI between October 2015 and May 2017 at the University Medical Center Utrecht. For all patients, 3T MRI (Ingenia MR-RT, v 5.1.7, Philips Healthcare, The Netherlands) was acquired within 3 h of CT (Brilliance Big Bore, Philips Healthcare, Ohio, USA), with a mean time of 73 min between the two imaging sessions. All patients were asked to drink 200–300 ml of water one hour before the acquisition after emptying their bladder. Patients were positioned on the vendor-provided flat table and using a knee support cushion (lower extremity positioning system, without adjustable FeetSupport, MacroMedics BV, The Netherlands). To facilitate treatment positioning, patients were tattooed at the CT and positioned at the MRI with the aid of a laser system (Dorado3, LAP GmbH Laser Applikationen, Germany).

CT scans were performed with the following parameters: 120 kV, 923 ms exposure time, 121–183 mA tube current, 512 × 512 pixels in-plane matrix, and 3 mm slice thickness. In-plane resolution varied depending on the field of view (FOV) used, with an average pixel size of 1 × 1 mm$^2$ and maximum size of 1.2 × 1.2 mm$^2$. The typical size of the FOV was 50 × 50 × 30 cm$^3$, expressed in terms of anterior-posterior, right-left and superior-inferior directions.

MR images were acquired using anterior and posterior phased array coils (dS Torso and Posterior coils, 28 channels, Philips Healthcare, The Netherlands). To avoid skin contour deformation, two in-house-built bridges supported the anterior coil. For the generation of MR-based sCT images, a dual echo three-dimensional (3D) Cartesian radio-frequency spoiled gradient-recalled echo sequence was acquired with the imaging parameters expressed in Table 1.

**Table 1**
Image parameters of the sequences used for the sCT generation. The terms FOV refers to the field of view, while AP to anterior-posterior.

| Imaging parameters | Value |
|---|---|
| $TE_1/(TE_2)/TR$ [ms] | 1.2/2.5/3.9 |
| Flip Angle [°] | 10 |
| FOV* [cm$^3$] | 55 × 55 × 30 |
| Acquisition Matrix* | 324 × 324 × 120 |
| Reconstruction Matrix* | 512 × 512 × 120 |
| Reconstructed Voxel* [mm$^3$] | 1 × 1 × 2 |
| Bandwidth [Hz/px] | 1072 |
| Readout direction | AP |
| Geometry correction | 3D |
| Acquisition time | 2 min 17 s |

* expressed in terms of anterior-posterior, right-left and superior-inferior directions.

A Dixon [23] reconstruction [24] was performed obtaining in-phase, fat, and water images. Using the acquired MR images, sCTs were generated with a proprietary solution tailored to prostate patients called "Magnetic Resonance for Calculating ATtenuation" (MRCAT, Ingenia MR-RT 5.1.7, rev. 257, Philips Healthcare, Finland). The imaging parameters were locked by the vendor as part of the proprietary solution. The sCT generation occurred directly at the scanner as an integrated reconstruction and employed a model of bone resulting in five bulk-density assigned sCT images. The transverse plane of a CT (a) and sCT (b) for one example patient are shown in Fig. 1.

Delineations were drawn by a radiation oncologist, with target delineations on the MRI composed of T2-weighted turbo spin echo and diffusion-weighted imaging as described in [25] and organs at risk (OARs) delineations on CT. To delineate the structures, MRI was rigidly registered to CT using an in-house developed software [26].

Patients underwent image-guided radiotherapy (IGRT) with pre-treatment position verification on a kV CBCT system integrated into the gantry of linear accelerators (XVI, v 5.0.2b72 Elekta AB, Sweden) with the following imaging parameters: 120 kV, 1175 mAs, 41 × 41 × 26 cm$^3$ FOV, 1 × 1 × 1 mm$^3$ voxel size, detector position was medium, filter F1, counter-clock rotation from −180° to 180° with 0.25 rps gantry speed and 5.5 fps frame rate. Different correction protocols were followed according to the fractionation regime: for five-fraction short-course radiotherapy online correction was performed every fraction, while for 25-fraction long-course radiotherapy the extended non-action level (eNAL) protocol [27] was performed. Set-up errors according to the eNAL protocol were estimated in the first three fractions, followed by imaging every five fractions. All patients expected to undergo five to seven CBCT; for a few patients, the imaging frequency was increased, e.g. based on the amount of inter-fraction motion observed. Set-up corrections were estimated by registering CBCT to the planning CT based on bony anatomy via chamfer matching [28] with six degrees of freedom (DoF) (translation and rotation), which is the local clinical protocol. Registrations with three DoF (translation only) were also performed for completeness. Registrations were estimated within a clipbox including bony pelvic anatomy whilst excluding femoral heads and trochanter minor where possible. The centre of the rotation was assigned as the centre of the planning treatment volume (PTV) or the gross tumour volume (GTV).

### 2.2. sCT evaluation

The clinical suitability of utilising MRCAT as an sCT generation technique for rectal cancer patients was evaluated. CT images were rigidly registered and resampled to the voxel size of sCT images with Elastix v4.7 (Klein et al. 2010) using mutual information and trilinear interpolation as previously reported [19]. The registered CT images were visually inspected. In the following, we use the term $CT_{reg}$ to refer to registered CT images.