

A magnetic resonance imaging-based workflow for planning radiation therapy for prostate cancer

Peter B Greer, Jason A Dowling, Jonathon A Lambert, Jurgen Fripp, Joel Parker, James W Denham, Chris Wratten, Anne Capp and Olivier Salvado

In Australia, prostate cancer is, after skin cancer, the most common cancer diagnosed, and it is second only to lung cancer as a cause of cancer-related deaths.¹⁻⁴ In 2005, prostate cancer was the most prevalent cancer for Australian men, accounting for over 29% of all cancer diagnoses.²

A major clinical treatment for prostate cancer is external-beam radiation therapy (EBRT). Computed tomography (CT) scans are used to provide the required electron density information for radiation therapy dose planning. However, magnetic resonance imaging (MRI) gives superior soft-tissue contrast for visualising the prostate and determining target volume. Here, we describe the development of an efficient, alternative planning method using MRI only for both organ delineation and dose calculation; “pseudo-CT scans” created from the MRI scans are used for dose planning.

Standard treatment planning for EBRT

In EBRT for prostate cancer, high-energy x-ray beams from multiple directions deposit energy (dose) within the tumour (prostate) to destroy cancer cells. The standard process for EBRT treatment planning is shown in Box 1(A). The first step is patient imaging (a CT scan sometimes combined with MRI). The treatment targets (the prostate and sometimes the seminal vesicles) and important normal tissues (the rectum, bladder, and femoral heads) are then manually defined from the scans (Box 2). Modern radiotherapy machines offer improved treatment accuracy through better visualisation and the correction of errors in patient setup, making target delineation the most significant uncertainty in radiotherapy planning.

In standard treatment planning, if MRI is used for visualising the prostate, then the scans from MRI and CT are aligned to transfer the structure contours defined by MRI to the CT scans for accurate dose calculation. The defined prostate volume is then expanded to become the larger, planning target volume for treatment. This allows for uncertainties in delineation and patient setup, and for prostate movement. The next step is the use of computer planning tools to determine the directions, strengths and shapes of the treatment beams used to deliver the prescribed dose to the defined target, while minimising the dose to normal tissues. Finally, the patient is carefully positioned and the treatment is delivered. The optimal way to align the patient for treatment is to use small implanted fiducial markers in the prostate. These are visible under x-ray imaging and show the precise position of the prostate within the body. Image guidance is used to align the treatment target each day for the entire radiotherapy course.

CT v MRI for radiation therapy planning

CT scans are acquired using low-energy x-ray beams. An image is created, with each pixel value assigned a CT number. This number can be easily related by a calibration process to the density of electrons within the tissues. The CT scan converted to electron densities can then be used to calculate the dose to be delivered to a

ABSTRACT

- Dose planning for prostate radiation therapy is performed using computed tomography (CT) scans that provide the electron density information needed for individual patients' radiation dose calculations.
- For visualising the prostate and determining the target volume for radiation treatment, magnetic resonance imaging (MRI) gives vastly superior soft-tissue contrast. However, currently, MRI scans cannot be used for dose planning, as they do not provide the electron density information.
- We aimed to develop an alternative and efficient MRI-only image-based workflow, enabling both organ delineation and dose planning to be performed using MRI, with “pseudo-CT scans” generated from MRI scans supplying the information for dose planning.
- The feasibility of implementing MRI-based prostate radiation therapy planning is being investigated through collaboration between the clinical and medical physics group at the Calvary Mater Newcastle Hospital/University of Newcastle and the biomedical imaging processing group at the CSIRO (Commonwealth Scientific and Industrial Research Organisation) Australian e-Health Research Centre.
- Results comparing Hounsfield units calculated from CT scans and from MRI-based pseudo-CT scans for 39 patients showed very similar average values for the prostate, bladder, bones and rectum, confirming that pseudo-CT scans can replace CT scans for accurate radiation dose calculations.
- MRI-based radiotherapy planning can also be used for tumours in other locations, such as head and neck, and breast cancers.

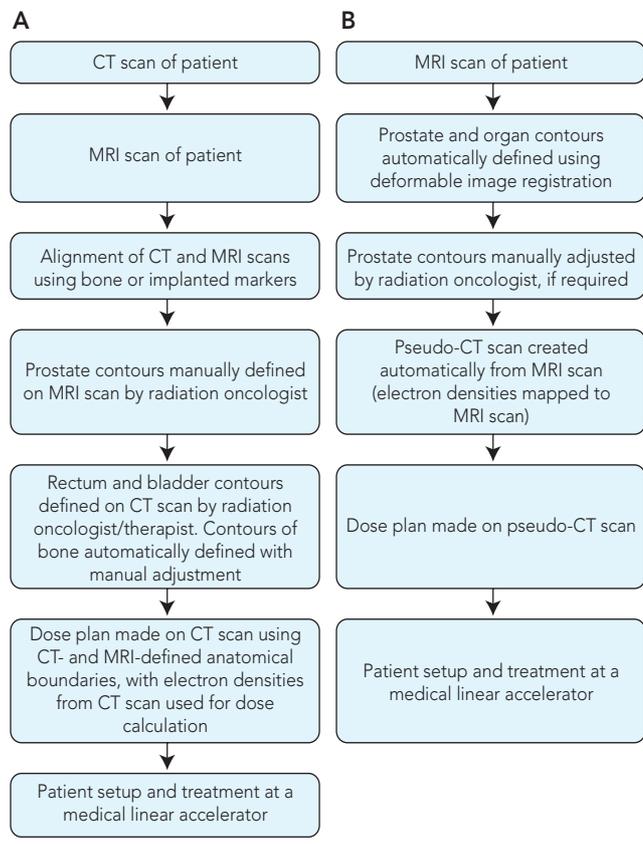
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patient from a radiotherapy x-ray beam. Energy is deposited in tissues mainly by the Compton scattering process. The likelihood of dose deposition depends on local electron densities; hence, this information is obtained from CT scans to calculate radiation dose.

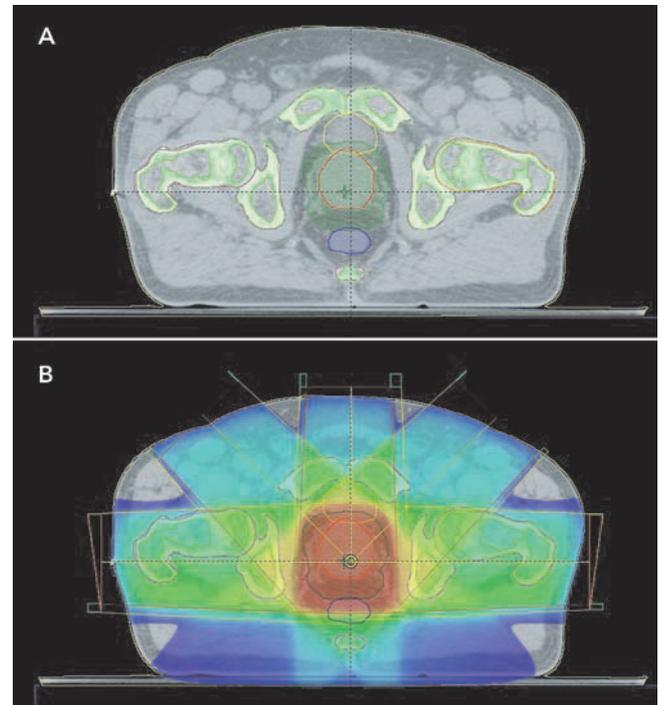
MRI scans are acquired by a completely different physical process, which is related to the magnetic properties of tissues within the body. Tissues with slightly different magnetic properties (eg, because of their water content) will give different MRI values. This means that MRI scans cannot be calibrated to electron density. MRI scans must be manually aligned to CT scans to accurately transfer the contour of the organ or tissue delineated on the MRI scan, and then dose calculation can be performed using the CT scan.

MRI scans have vastly superior soft-tissue contrast compared with CT scans, with better visualisation and more accurate delineation of the border of the prostate. Prostate borders delineated on MRI scans show greater consistency between radiation oncologists,^{5,6} and prostate size is smaller than that determined by CT

1 (A) Steps in the conventional prostate radiotherapy workflow with computed tomography (CT) and magnetic resonance imaging (MRI); and (B) the proposed new radiotherapy workflow based on MRI only



2 Conventional computed tomography scans for delineating the prostate and surrounding normal tissues, and calculating radiation dose



A: Manually defined contours of the prostate (red), bladder (yellow), rectum (blue) and bone (light green/magenta). The dark green contour is the expansion of the prostate (planning target volume), which becomes the treatment target.

B: Dose plan showing the arrangement of the radiation fields (straight yellow lines) — two lateral, one anterior, and two anterior oblique beams — and the dose deposited from these beams is shown by the colourwash, with red being the higher dose and blue the lower dose. ◆

scan.⁷ Using MRI, the size of the extra margins to be added to account for delineation uncertainties is reduced, and less normal tissue is irradiated, thus reducing treatment toxicity.

A proposed new workflow for prostate radiation therapy planning using MRI scans only is shown in Box 1(B). The prostate and organs would be automatically defined on a high-contrast MRI scan using computer segmentation (organ delineation) algorithms. These algorithms use an “average” MRI scan that has been created from a set of patient MRI scans, commonly known as an “atlas”. This atlas is deformably “warped” (registered) to the patient’s MRI scan until all the tissues line up with the patient’s MRI scan. As the organ boundaries are known in the MRI atlas, these boundaries are also warped onto the patient’s MRI scan and hence the patient’s organ boundaries are determined.

The automatically defined prostate borders would then be inspected and adjusted if necessary by the radiation oncologist. Automatic delineation of organs minimises interobserver variation and uncertainty. To calculate dose, a pseudo-CT scan would be created automatically from the MRI scan, with electron densities mapped to the tissues by means of a CT electron densities atlas that corresponds exactly with the MRI atlas. As the deformation for the MRI atlas to the patient’s MRI scan is known, the same deformation will work for the CT electron densities atlas. The result is a pseudo-CT scan with electron densities mapped to the patient’s MRI scan.

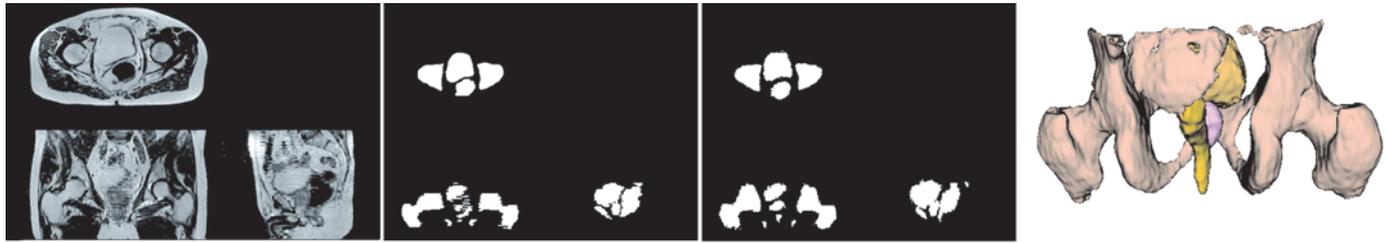
Patients and feasibility study design

The feasibility of this MRI-based workflow is being investigated through a collaborative project between the clinical and medical physics group at the Calvary Mater Newcastle Hospital/University of Newcastle and the biomedical imaging processing group at the CSIRO (Commonwealth Scientific and Industrial Research Organisation) Australian e-Health Research Centre.

Thirty-nine patients undergoing prostate radiotherapy have had whole pelvic T2-weighted MRI scans, in addition to standard small-field-of-view MRI scans and conventional radiation therapy CT scans. The contours of the bladder, rectum, bone and prostate were manually delineated on each MRI and CT dataset.

Probabilistic atlas-based organ segmentation methods were developed to automatically segment the organs of interest (prostate, rectum, bladder, and femoral heads) from the MRI scans. After the scans were preprocessed (including correction of intensity inhomogeneity⁸ and patient movement artefacts⁹), the images and manually defined contours for each patient were combined into a single reference atlas by image registration methods. This atlas can then be warped onto the MRI scans of a new patient, automatically contouring the organs of interest (Box 3). A match-

3 Automatic magnetic resonance image (MRI) segmentation results



A: Axial, coronal and sagittal views of the MRI scan of the pelvic region of one patient.

B: Expert organ contours manually delineated from the scan in A (bones, bladder, rectum and prostate).

C: Automatic organ contours of same patient derived from the automatic segmentation method using a probabilistic MRI "atlas".

D: A surface rendering of the organs in the MRI "atlas" used to perform the automatic segmentation.

4 Comparison of the mean (SD) Hounsfield units (HUs) of the patients' original computed tomography (CT) scans and the pseudo-CT scans

Organ	Mean HU (SD) (n = 39)		P†
	CT scan	Pseudo-CT scan*	
Rectum	-54 (4)	-54 (143)	> 0.9
Bladder	9 (0)	9 (6)	> 0.9
Bone	339 (10)	340 (85)	> 0.9
Prostate	42 (1)	42 (25)	> 0.9

* The larger SD for the pseudo-CT scans is due to the greater number of CT scans used to generate the pseudo-CT atlas. † Two-tailed t test.

observed ($P > 0.09$). The mean ratios (SDs) of physical path length and water equivalent path length for the left lateral beams were 1.068 (0.02) and 1.089 (0.02) ($P < 0.001$), and for the right lateral beams were 1.074 (0.02) and 1.084 (0.03) ($P = 0.09$). These results indicate that pseudo-CT scan HU values approximate CT scan HU values well, particularly for bone. A significant difference observed for the left lateral beams is not enough to result in dose-calculation differences.

Conclusion

Atlas-based segmentation methods provide the ability to automatically define anatomy on MRI scans of the pelvis, as well as to map electron densities to MRI scans for radiotherapy dose planning. This project combines the expertise of a major radiation therapy and medical physics clinical research group with the computer algorithm and software development expertise of the CSIRO's Australian e-Health Research Centre. The work is ongoing and currently involves further validation of the pseudo-CT scan and automatically defined contours against standard CT scan-based treatment planning, and the automatic identification of fiducial markers from MRI.

We have demonstrated the feasibility of MRI-based radiotherapy, and the results of this work can be applied to cancers in other locations, such as breast or head and neck cancers.

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Competing interests

None identified.

Author details

Peter B Greer, PhD, Medical Physicist in Charge of Research^{1,2}
 Jason A Dowling, PhD, Research Scientist³
 Jonathon A Lambert, BSc(Hons), PhD Student²

ing CT atlas enables the automatic estimation of electron densities from MRI scans by the same method.

The differences between the original CT scan and the MRI-based pseudo-CT scans for each of the 39 patients were validated by two methods.

- First, for each patient and each organ of interest, a comparison was made between the Hounsfield units (HUs) (a quantitative measure of electron density needed to calculate radiation attenuation) of the pseudo-CT scan and the HUs of the original CT scan.
- Second, for each patient, a ratio was calculated between the lateral treatment beam physical path length (distance from the skin to the tumour dose calculation point) and the water equivalent path length (distance from the skin to the same calculation point) on both the CT and pseudo-CT scans.

Another important part of the new workflow process is the production of customised software that has been written and validated (i) for information transfer from the Varian Eclipse and Philips Pinnacle treatment planning systems at Calvary Mater Newcastle (Digital Imaging and Communications in Medicine – Radiotherapy [DICOM-RT] and Radiation Therapy Oncology Group [RTOG]),¹⁰ and (ii) for transfer of automatically defined contours and pseudo-CT images back into each system for dose planning.

Results

As shown in Box 4, for the main organs of interest for the 39 patients, HU values of the generated pseudo-CT scans and the original CT scans were very similar, with no significant differences

Jurgen Fripp, PhD, Research Scientist³

Joel Parker, BAppSc(MedRadScRadTherap), Research Radiation Therapist¹

James W Denham, MD, FRCR, FRANZCR, Radiation Oncologist^{1,2}

Chris Wratten, MB BS, FRANZCR, Radiation Oncologist^{1,2}

Anne Capp, FRANZCR, FRCR, MMed(ClinEpi), Radiation Oncologist^{1,2}

Olivier Salvado, PhD, Group Leader³

1 Calvary Mater Newcastle Hospital, Newcastle, NSW.

2 University of Newcastle, Newcastle, NSW.

3 Biomedical Imaging, Australian e-Health Research Centre, CSIRO ICT Centre, Brisbane, QLD.

Correspondence: jason.dowling@csiro.au

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