Journal of Radiotherapy in Practice

Journal of Radiotherapy in Practice (2014)
13, 159–165
doi:10.1017/S1460396913000514

Original Article

Improved visualisation of cervix applicators for magnetic resonance-only-guided brachytherapy planning

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(Received 24th June 2013; revised 18th September 2013; accepted 20th September 2013; first published online 22nd January 2014)

Abstract

Objectives: Current guidelines for image-guided cervical cancer brachytherapy planning recommend both computed tomography (CT) and magnetic resonance imaging (MRI) for adequate visualisation of the applicator and soft tissues, respectively. MRI-only planning would be ideal as it would save time within the patient pathway and avoid the concomitant CT exposures. However, applicator visualisation on MRI is usually achieved using fluid-filled fiducial marker tubes, which can be awkward to use and suffer from unwanted air bubble artefacts. Therefore, a new fiducial-free imaging technique was developed.

Methods: A dual echo time (TE) turbo spin echo sequence was used, at 1·5 T, to provide both T_2-weighted images (100 ms TE) for tissue visualisation and strongly proton density-weighted images (17 ms TE) for improved applicator visualisation. In-house software was used to automatically segment the applicator in the short TE images (using Otsu's method) and transfer the information to the long TE images to provide a single fused dataset.

Results: The method was evaluated successfully using titanium applicators in three patient cases and using a plastic applicator in a tissue-equivalent gel phantom.

Conclusions: The dual-echo technique provides a simple and efficient method for improving the visualisation of brachytherapy applicators in cervical cancer MRI images without the need for marker tubes.

Keywords: applicator; brachytherapy; cervix; dual echo; HDR; IGBT; MR only; MRI; planning; sequence; visualisation

INTRODUCTION

Following guidelines published by GEC-ESTRO,[1,2] we have incorporated magnetic resonance imaging (MRI) into the image-guided brachytherapy (IGBT) planning for the treatment of cervix cancer. This treatment regime consists of the delivery of high-dose rate brachytherapy over three fractions with volumetric guidance provided from both MRI and computed tomography (CT) imaging. These two imaging modalities have their specific advantages in IGBT. The MRI dataset

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provides excellent soft-tissue contrast to enable the organs at risk and high-risk volumes to be contoured. The CT images are particularly good for visualising the applicators because of the high attenuation of the material used. However, unlike external beam radiotherapy, the planning system in brachytherapy does not use CT number in its dosimetric calculations; instead a uniform electron density value is assumed throughout the tissue. These factors, together with the increased radiation exposure of repeated CT scans, mean that it would be desirable to explore the use of MR-only planning in this patient group.

MRI planning scans are performed using a turbo spin echo (TSE)-based imaging sequence with a sufficiently long TE to generate T_2-weighted contrast between the various soft tissues. Initially, we had used MR- and CT-compatible titanium applicators to permit the afterloading of an iridium source. Magnetic susceptibility artefacts arising from the applicator depend on the material used, the direction of the tubes with respect to the main magnetic field and, crucially, the type of imaging sequence used. These artefacts can be managed effectively, and geometric distortion has been shown to be negligible.[3] However, one limitation of the current protocol is the poor visualisation of the applicator owing to it being isointense with the low-signal surrounding anatomy. This arises from the use of MR-compatible materials such as titanium or plastic, which do not exhibit a proton signal. Although the visibility can be very patient specific, often it is the intrauterine (IU) tube that is difficult to distinguish in the high-risk volume. Current practice is to register the MRI dataset with a corresponding CT dataset, in which the definition of the applicator is much clearer. However, the registration centres on the applicator itself and assumes that it can be seen adequately well on MRI, which is often not the case. Furthermore, positional and couch top differences between the CT and MR scanners mean that the success of this registration cannot be easily verified by reference to other anatomical landmarks.

For all these reasons, it would be desirable to move towards MR-only planning, and, as a first step, the issue of poor applicator visualisation needs to be addressed. A few previous studies have described methods of improving the MR visibility of cervix applicators. These applicators typically consist of a separate ring and tandem IU tube assembly. If the tubes have a sufficiently large internal lumen, then a plastic catheter carrying sufficient MR-visible solution can be introduced before imaging, and both saline and copper sulphate-doped water have been used.[4,5] These tubes have been shown to be adequate, although difficult to fill successfully without inadvertently introducing air bubbles. Bubbles must to be avoided to minimise image artefacts and this also has to be verified over the lifetime of the tubes. Some applicators do not have a sufficiently large lumen to accommodate a catheter, and catheters are also a fixed length such that they cannot, on some occasions, be inserted far enough so as to show the first (farthest-most) source dwell position. A further report demonstrated the direct visualisation of the Vienna type of applicator where needle holes, which are located in the ring, may permit bodily fluid to permeate into them.[6] This makes the holes MR-visible and allows the applicator model to be reconstructed from the identification of the hole positions before needle insertion.

This work describes an alternative approach, which involves a simple but effective adaptation to the current MR-imaging protocol to remove the need for the marker tubes and to image the patient within the same allotted scan time. Additional image processing software has then been developed in-house and used to produce a combined dataset, providing the benefits of both soft-tissue contrast and improved delineation of the applicator. Examples of the approach's use are shown with two common types of commercially available applicators.

MATERIALS AND METHODS

All imaging was carried out using a 1·5 T Philips Achieva scanner equipped with a cardiac coil (Philips Healthcare, Eindhoven, the Netherlands). A simple modification to the standard TSE planning sequence was investigated whereby a dual-echo technique was used to provide two images at every slice location with each image

https://doi.org/10.1017/S1460396913000514 Published online by Cambridge University Press

type producing a specific benefit. The first image, acquired with a short TE of 17 ms, was sufficiently proton density-weighted to create a clear intensity difference between the signal-producing soft-tissue and the signal-inert applicator. These images were used to locate the applicator more accurately. The second image was acquired at the previously used TE of >100 ms to provide the characteristic T_2-weighted images required for contouring. By acquiring these multiple images within a dual-echo sequence the scan time is not extended. An additional benefit of the short TE is that the signal void is more representative of the applicator as susceptibility artefacts are reduced. Additional scan parameters were a 3 seconds repetition time, 35 cm field of view, 352×285 matrix interpolated to 0·5 mm in-plane resolution, 2 mm slice thickness with zero gap and an echo train-length of 19.

Image processing software was written in MATLAB (Mathworks, Natick, MA, USA) to identify the hypointensity from the central portion of the short TE image (assumed to be the applicator) using an adaptive histogram threshold. This is an extension of the Otsu algorithm,[7] which assigns image pixel intensities into three bins. Further morphological manipulation was used to clean the selected pixels, and these pixels were then 'burnt in' to the longer echo images to create an overlay of maximum hyperintensity (100% white). The applicator could then easily be identified within the T_2-weighted background image. The dataset was converted into DICOM format using copies of the slice-specific header information from the original acquisition. In this way, the combined benefits of the two image contrasts are used to produce a single image series that can be read into the Flexiplan treatment planning system (Nucletron, Veenendaal, the Netherlands) in the normal way.

Two example types of applicator were used to assess the new imaging methodology. A titanium, Isodose Control applicator (distributed by Nucletron) was imaged in three cervix cancer patients to examine the benefits and assess the efficacy of introducing the technique into clinical practice. All patients were scanned under the hospital's local rules, which had been written after a prior risk assessment had been carried out by the Hospital's MRI Safety Advisor. The local rules prohibited operation of the scanner outside of FDA/CE regulatory safety limits; that is, scanning was not performed in research mode or with unapproved equipment. In addition, patients' clinical management was not affected in any way. A polymer applicator (also distributed by Nucletron) will shortly be introduced for patient treatments within the department. This applicator was imaged in a tissue-equivalent phantom consisting of a 2 L flask containing a radiosensitive gel (Department of Chemistry, the University of York, UK), which had been irradiated so as to simulate the kind of centrally positioned, low signal intensity (i.e., short T_2) region demonstrated in vivo (T_2 contrast being a function of the radiation dose delivered to the gel[8]). The phantom was imaged with the plastic IU applicator tube in situ, using both the routine T_2-weighted sequence and the proposed dual-echo sequence. It was then imaged a third time with a saline-filled line marker tube, as supplied by the vendor, inserted to make a visual comparison between the three scans. The marker tube had an outer diameter of 2·3 mm and an inner diameter of 1·6 mm and was filled with saline solution before imaging.

RESULTS

The following figures illustrate a recent cervix patient example. Figure 1 shows both the first and second echo images, and demonstrates the potential difficulty in distinguishing the applicator from the surrounding, high-risk tissue volume using the normal T_2-weighting. The applicator becomes more conspicuous on the short echo image.

Figure 2 shows a screenshot taken from the Flexiplan treatment planning system. The original images have been processed using the software described, which has turned these into a single combined dataset with the applicator highlighted on the original T_2-weighted image. The catheter in the bladder is also highlighted because of its similar, MR-invisible properties. As the technique picks out anything with very low proton density and/or very short relaxation times, other pixels can be seen that are not

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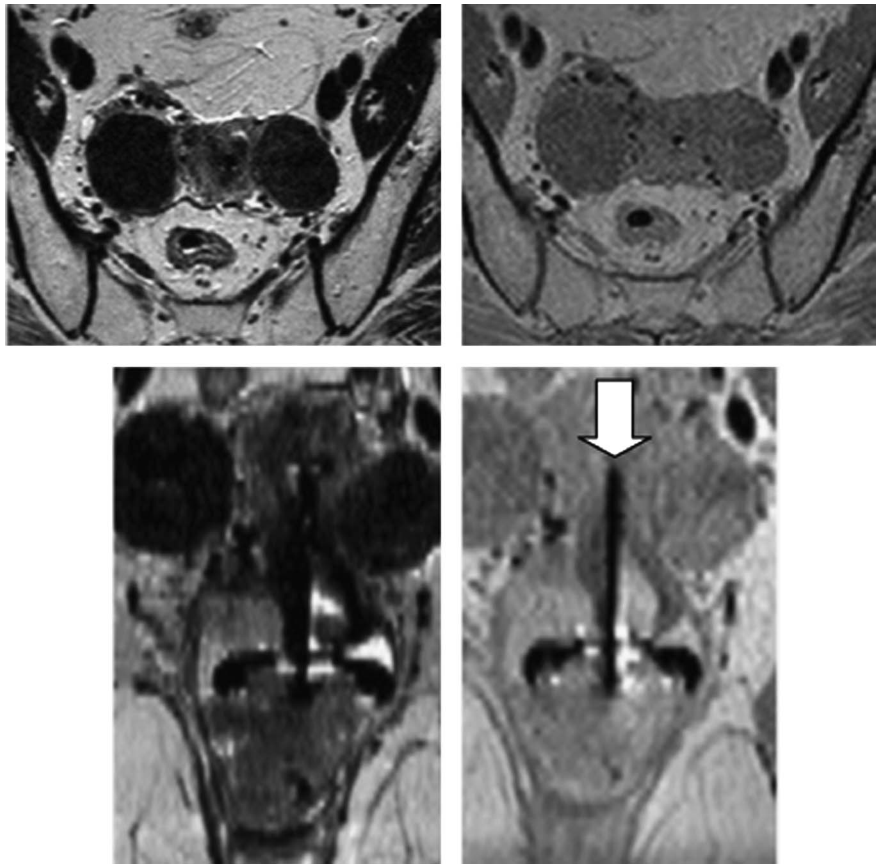

Figure 1. T_2-weighted images (left-hand side) with corresponding short echo time (TE), proton density-weighted images (right-hand side) at the same slice position. The original axial images are shown on the top row, together with the reformatted coronal plane images on the bottom. These images show the difficulty in visualisation of the intrauterine applicator tube using the standard T_2-weighted sequence, and how the use of a short TE improves the contrast (the tip of the applicator shown with a white arrow).

associated with the applicator. However, the planner has the ability to scroll through the images in the dataset in both the original axial plane, and the reformatted coronal and sagittal planes so as to easily interpret the applicator position correctly.

Figure 3 shows images from the gelatine phantom with the plastic IU tube inserted. Figure 3a simulates the difficultly in discriminating the tube, especially in cross-section, from regions where the signal is low on a T_2-weighted image, Figure 3b shows the same image slice on the short-TE image and Figure 3c shows the same image slice on the T_2-weighted image with the marker tube present. The marker tube can be seen but its effectiveness is clearly reliant on maintaining the integrity of fluid signal along the entire length of this tube with different tubes required for different applicator sizes. The benefit of the dual TE method is a direct visualisation of the applicator itself without the need of additional tubes.

DISCUSSION

MRI provides exquisite soft-tissue contrast and is now the recommended gold standard for IGBT planning in the cervix. However, some commercially available applicators are often difficult to distinguish on MRI from hypointense tissue, such as that found in the clinical target volume, owing to the types of materials used to make these applicators safe in the magnetic environment of the scanner. In the case of titanium applicators, this dark intensity is due to the absence of any signal-producing (proton) material. In the case of plastic applicators,

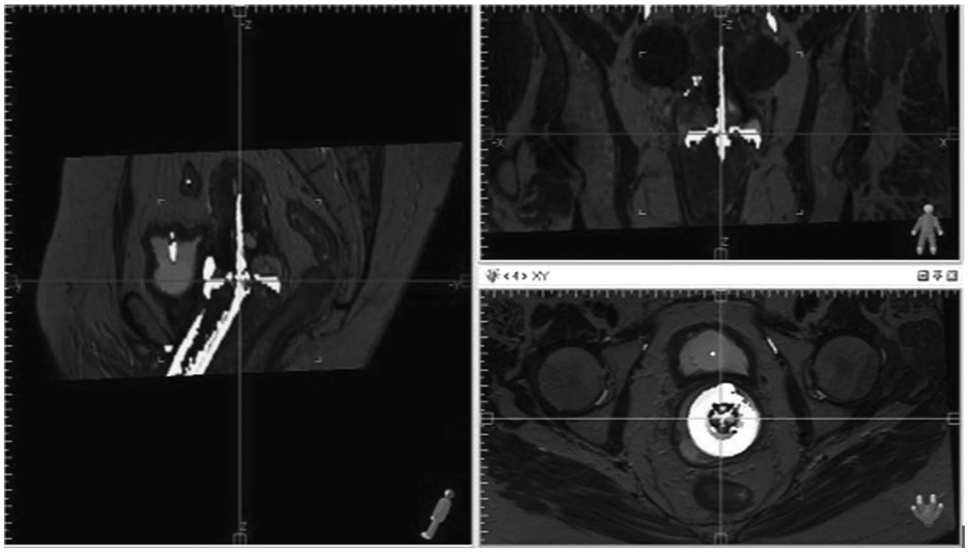

Figure 2. A screenshot showing how the fused applicator location (white pixels) and anatomical data images can be imported successfully into the treatment planning system in DICOM format.

the relaxation time is extremely short so that the signal has rapidly decayed and is not present on conventional image sequences. In an attempt to remedy this problem, applicators with sufficiently large internal dimensions are supplied with an MR-marker, a thin hollow tube that is intended to be filled with fluid so that it appears bright on the MRI. These marker tubes are very difficult to prepare, impractical to use and require regular attention to ensure that they remain uniformly filled. Furthermore, each differently sized applicator requires separately prepared tubes. When marker tubes cannot be used at all, for example, the internal lumen is too small and/or titanium applicators are used, then CT remains the optimum modality for visualising these devices.

We have presented an alternative approach that works equally well with all MR-compatible applicators, irrespective of their construction or composition. This is a simple modification to a widely used imaging protocol that takes advantage of the contrast flexibility offered in MRI sequences. By acquiring a short TE image, the dataset is proton density weighted, which means that the contrast between the tissues becomes similar but significantly different from the applicator that remains hypointense. This approach has been adopted into a dual-echo acquisition such that both required image contrasts can be generated in a single dataset. The efficacy of the technique has further been improved by utilising a relatively simple image-processing step that applies pixel thresholding to first separate and then highlight the applicator on the final planning dataset. Results have shown its efficacy in both titanium and plastic applicators that are currently used in brachtherapy. Importantly, the imaging sequence requires no additional scan time and the software presented can generate the processed DICOM dataset in only a few minutes. This represents a significant time saving within the patient pathway. The T_2-weighted images could be used as the secondary dataset for clinicians to contour the tumour without the applicator overlay if required; these images being inherently registered with the combined dataset used for applicator positioning.

This work presents the improved visualisation of this technique and no attempt has been made to assess spatial accuracy. However, it is important to emphasise that previous studies, by ourselves and others,[3,9] have shown that by using an appropriate sequence (i.e., spin-echo based with a high enough receiver bandwidth) that distortion and artefacts are rendered negligible. In fact, signal de-phasing from susceptibility artefacts, being a function of TE, is even further reduced at the time of the first

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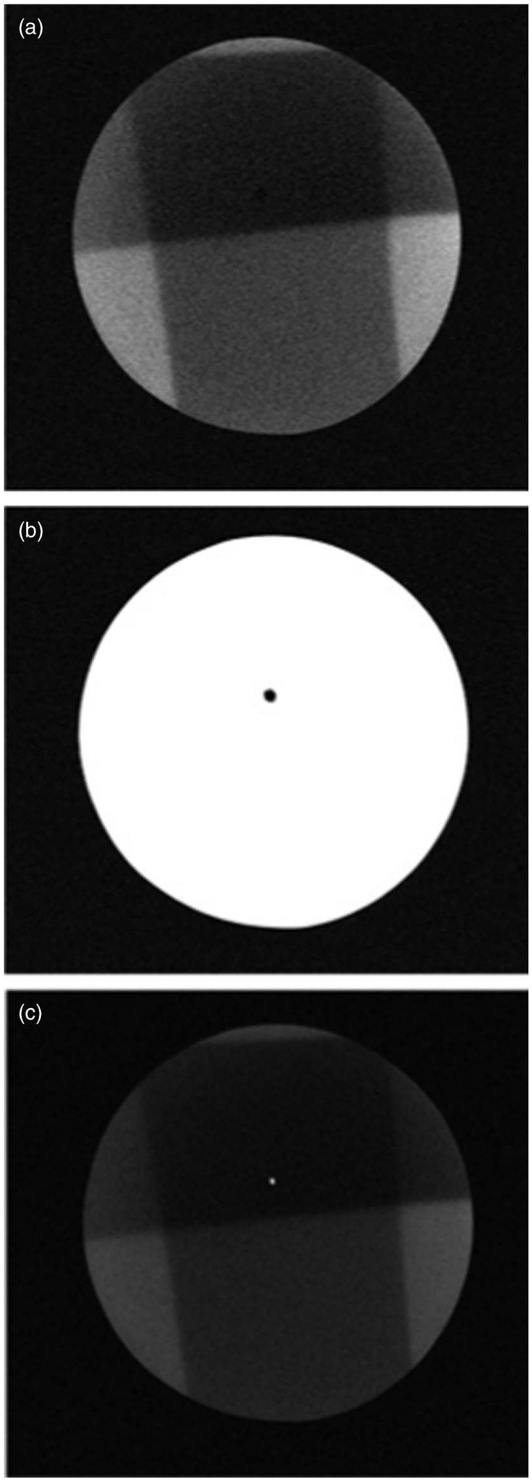

Figure 3. (a) Axial image of the gel phantom with the intrauterine (IU) tube from the plastic applicator in situ, illustrating the difficulty in visualising the plastic applicator in a low signal (short T_2) region. (b) A short echo time image of the same slice location demonstrating the IU tube clearly. (c) A repetition of the scan shown in (a), but with the marker tube inserted.

image, which is used here as the basis for the applicator reconstruction.

In future, there are interesting developments in MRI in terms of ultrashort echo time sequences where the TE can be as short as $<100\,\mu s$.[10] These are currently being explored to image tissues with extremely short T_2 components, for example, cortical bone or cartilage. These sequences with their drastically reduced TEs may also be of benefit in applicator visualisation, either improving the contrast of the first echo in this technique still by imaging the plastic applicator directly.

CONCLUSION

This report describes a simple but effective change in imaging protocol that provides a dataset with the combined advantages of a planning MRI, that is, good soft-tissue contrast, along with the benefit of a CT scan, that is, good applicator conspicuity, into a single MRI acquisition. The technique has been shown to improve the MR visualisation of commercially available applicators and removes the need for the CT acquisition in brachytherapy planning. This technique could be easily adapted for MR-only planning.

Acknowledgements

The authors would like to express their gratitude to the staff at the MRI Department, Castle Hill Hospital, and in particular, Alison Thackeray for her assistance in setting up the scanning protocol used in this study.

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