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The utilization of MRI in the operating room

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ABSTRACT Online image guidance in the operating room using ultrasound imaging led to the resurgence of prostate brachytherapy in the 1980s. Here we describe the evolution of integrating MRI technology in the brachytherapy suite or operating room. Given the complexity, cost, and inherent safety issues associated with MRI system integration, first steps focused on the computational integration of images rather than systems. This approach has broad appeal given minimal infrastructure costs and efficiencies comparable with standard care workflows. However, many concerns remain regarding accuracy of registration through the course of a brachytherapy procedure. In selected academic institutions, MRI systems have been integrated in or near the brachytherapy suite in varied configurations to improve the precision and quality of treatments. Navigation toolsets specifically adapted to prostate brachytherapy are in development and are reviewed. © 2017 American Brachytherapy Society. Published by Elsevier Inc. All rights reserved.

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Introduction

Interventional MRI (iMRI), a termed coined in the field of interventional radiology, is defined when the images produced by an MRI scanner are used to guide a minimally invasive procedure intraoperatively and/or interactively. iMRI systems have been most widely adopted in the neurosurgical community to guide surgical resection of brain tumors and in interventional radiology departments for guided biopsies and thermal tissue ablations.

In prostate cancer, the first adoption of iMRI has been in guiding prostate biopsies to MRI-defined tumor targets. These approaches and concepts dovetail easily in brachytherapy with the key distinction of a transperineal route of needle entry (compared with transrectal).

Here we describe the evolution of integrating MRI technology in the brachytherapy suite.

MRI images in the OR

Rigid MRI—transrectal ultrasound registration

The rigid registration of previously acquired MRI to intraprocedural transrectal ultrasound (TRUS) has been clinically applied in focal therapy (1) and tumor-targeted dose boosting (2, 3) with only few adjustments to standard-care workflows.

However, MR—TRUS fusion is a very challenging task and is still an active area of research. Several commercial software platforms have been developed to support MR-TRUS—guided biopsy (4). Although the accuracy constraints of targeted biopsies may not be as stringent as they are with brachytherapy planning, the process is essentially the same.

Pioneering work (5) with point-based rigid MRI—TRUS registration acted as a proof of concept, demonstrating that MR images can be brought to the OR with image fusion. This early work used a stepper motor with a stabilized two-dimensional (2D) TRUS probe to acquire ultrasound volumes. Six anatomic common points, the most inferior, superior, anterior, posterior, left, and right points of the prostate were manually identified on both modalities and used for rigid registration.

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This technique can effectively bring prostates acquired from multiple modalities in the same image space, thus accounting for different co-ordinate systems and linear motions and rotations.

However, finding naturally occurring common points between MRI and US can be challenging and poorly reproducible. More commonly, contours of the prostate surface on both US and MRI are visually or computationally aligned using centroid or surface-based matching algorithms. These solutions are highly susceptible to errors introduction by rotation and inaccurate segmentation. It is noteworthy that the accuracy of rigid registration tools for MRI—US registration of the prostate gland has not been well evaluated or documented in the literature. Nonetheless, most commercial brachytherapy navigation and planning systems currently provide tools for rigid multimodality image registration, either manual point-based, contour (surface)-based, or automated mutual information algorithm (6).

Although rigid registration is computationally inexpensive and easy to apply in a clinical workflow, it does not account for prostate deformation which can be caused by the insertion of a TRUS probe or endorectal coil, the insertion of multiple catheters (7), and patient positioning (8), yielding significant elastic deformations that needs to be modeled to ensure accurate brachytherapy treatment. It is also important to address the dynamic nature of the deformation matrix through the course of an implant, whereby a satisfactory registration before catheter insertion can rapidly degrade through the course of a procedure.

Elastic contour-based MRI—TRUS registration

To achieve elastic registration, common anatomic landmarks are rarely used for registration as they can be extremely difficult to identify across multiple modalities and provide only very sparse information. Most techniques now use either image voxels or delineated contours as a basis for registration (Table 1). The usefulness and value of elastic contour-based MRI—TRUS registration was first demonstrated by matching point clouds obtained by manual delineation of both modalities (9). In this work, average 2D target registration errors (TRE) of about 3 mm (up to 8 mm) using the urethra lumen as reference are reported. A more recent approach register signed distance maps with B-spline regularization (21) and produce average TRE of 3.8 mm (up to 7.8 mm). Typical results for this method are presented in Fig. 1 and can be achieved using commercially available tools or shared research-based interfaces (22, 23).

Table 1
MRI-TRUS elastic registration summary

Categories	Rigid	Elastic
Contour based	Point cloud matching (9)	Finite element modeling (10—14) Statistical shape modeling (11—15)
Voxel based	Fiducial points matching (5)	Optimizing mutual information (16) Optimizing modality independent neighborhood descriptors (17, 18)
Hybrid	—	MR contours registered to TRUS voxels using image statistics (19, 20)

TRUS = transrectal ultrasound.

Contour-based approaches are not without issues. Prostate segmentation on TRUS and MRI are prone to interpretation errors. This is especially true when registration is required for dose optimization on volumes acquired after HDR catheter insertion where shadowing artifacts may occur. Even without these added challenges, variations in contour delineation from multiple modalities are well known. Indeed, it has been shown that prostate volumes are overestimated on average by 15% when contoured on computed tomography compared with MR and, similarly, underestimated by 10% on average when delineated on TRUS (24). These segmentation ambiguities, combined with anatomical deformations caused by patient positioning, endorectal coil, TRUS probe, and catheter insertion make precise contour-based fusion especially challenging. In addition, these algorithms must implement proper anatomical constraints; otherwise, any contour pair can be perfectly fitted together regardless of plausibility of the solution.

These challenges can be mitigated in part using finite element model and statistical shape model. Finite element methods were first used to model prostate deformation in the context of MR-to-MR registration acquired with and without an endorectal coil (10, 25). Later, this technique was applied to TRUS to produce statistical shape models based on the simulations of multiple probe insertion angles and pressures (15). These techniques allow nonrigid registration parameters to be constrained to an anatomically plausible search space.

Developing on these approaches, patient-specific statistical shape models based on improved biomechanical finite element models derived from preoperative MR images (11) and even ultrasound elastography (12) have been proposed with reported registration errors of 2.40 and 1.44 mm, respectively. Another technique using finite element modeling, Gaussian mixtures, and statistical shape models were developed to handle contour-based fusion where the ultrasound segmentation was only partial or uncertain (13, 14). Such techniques can be very useful because the mid-gland section is much easier to properly delineate on TRUS imaging than the base and apex. They have reported registration errors of 2.6 mm despite 30% of contours being unavailable or uncertain.

Selected brachytherapy vendors are now offering contour-based elastic registration solutions, but their performance remains to be evaluated critically.