Quantitative MR Imaging Assessment of Prostate Gland Deformation before and during MR Imaging–guided Brachytherapy

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Rationale and Objectives. The authors performed this study to document the deformations that occur between pretreatment magnetic resonance (MR) imaging and intraoperative MR imaging during brachytherapy.

Materials and Methods. MR images obtained at 1.5 and 0.5 T in 10 patients with prostate cancer were analyzed for changes in the shape and substructure of the prostate. Three-dimensional models of the prostate were obtained. The authors measured anteroposterior dimension; total gland, peripheral zone, and central gland volumes; transverse dimension; and superoinferior height.

Results. Gland deformations were seen at visual inspection of the three-dimensional models. The anteroposterior dimension of the total gland, central gland, and peripheral zone increased from 1.5- to 0.5-T imaging (median dimension, 4.9, 1.5, and 1.8 mm, respectively), and the increase was greatest in the peripheral zone (P < .05, all comparisons). There was a decrease in the transverse dimension from 1.5- to 0.5-T imaging (median, 4.5 mm; P < .005). The total gland volume and the superoinferior height did not show a statistically significant change.

Conclusion. There were significant deformations in the shape of the prostate, especially in the peripheral zone, between the two imaging studies. The likely causes of the shape change are differences in rectal filling (endorectal coil used in 1.5-T studies vs obturator in 0.5-T studies) and/or changes in patient position (supine vs lithotomy). These findings suggest that pretreatment images alone may not be reliable for accurate therapy planning. It may be useful to integrate pre- and intraoperative data.

Key Words. Magnetic resonance (MR), guidance; magnetic resonance (MR), treatment planning; prostate, MR; prostate, neoplasms.

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Recent results from the National Cancer Data Base suggest that the use of radiation implants (brachytherapy) to treat localized prostate carcinoma has increased substantially (1). Transrectal ultrasound (US) is the primary imaging choice for intraoperative guidance during brachytherapy. Recently, magnetic resonance (MR) imaging has been introduced for intraoperative guidance and planning (2,3). MR imaging provides superior spatial resolution and higher soft-tissue contrast than do other imaging modalities. In particular, the substructure of the prostate and the anatomic position of adjacent tissues (eg, rectum, bladder, and urethra) can be defined.

There are discrepancies between the preoperative and intraoperative images in both prostate brachytherapy and external beam radiation delivery. This disagreement is
explained by the positional changes of the prostate gland (4). Haken et al (5) reported that the prostate gland can move up to 2 cm, with an average of 0.5-cm motion, along the anteroposterior (AP) and superoinferior dimensions but less along the right-left axis. Others have reported that the prostate gland may rotate around the AP and right-left axes (6,7) and that the AP movement is related to changes in the shape of the rectum (5,6,8,9). Finally, Van Herk et al (6) correlated prostate motion with the leg rotation of the patient in the supine position. They also found that both a “scissors” movement and left-right roll of the legs influence the rotation of the prostate around the craniocaudal axis (6).

McTavish et al (10) found that T2-weighted MR images obtained at 1.5 and 0.5 T are comparable and of good quality. At the higher field strength of 1.5 T, however, we are able to visualize the substructure of the gland, which facilitates separate analysis of the peripheral zone and central gland. There is an obvious difference between the shape of the prostate gland on the preoperative 1.5-T MR images (obtained with an endorectal coil) and that on the 0.5-T MR images obtained during MR imaging–guided brachytherapy (when a surface coil and an endorectal obturator are used) (2,3). There is also a difference between the extent of deformation of the peripheral zone and the central gland.

We performed this study to establish and document the prostate gland deformations that occur between pre- and intraoperative MR imaging. We report the change in shape by contouring the peripheral zone, central gland, and total gland. Three-dimensional (3D) models of the pre- and intraoperative data sets were created, and shape changes were established and quantified.

**MATERIALS AND METHODS**

**Patients and Imaging Protocol**

Imaging data from 10 sequential MR imaging–guided brachytherapy sessions in 10 patients were analyzed retrospectively. All patients enrolled in the program underwent preprocedural diagnostic MR imaging (at 1.5 T and with an endorectal coil). After giving informed consent, all eligible patients underwent MR imaging–guided brachytherapy (11). At our institution, all prostate brachytherapy procedures are performed with MR imaging guidance.

**Pretreatment imaging.**—Pretreatment 1.5-T MR imaging (Signa LX; GE Medical Systems, Milwaukee, Wis) was performed in all patients by using an endorectal coil integrated with a pelvic multicoil array. The endorectal coil (Mederad, Pittsburgh, Pa) is designed with a double latex balloon mounted on a flexible plastic shaft. Patients were placed in a supine position in the closed-bore magnet. The standard protocol was used, and axial, sagittal, and coronal T2-weighted fast spin-echo images were obtained. The imaging parameters were as follows: 5,000/102 (repetition time msec/echo time msec), 10-cm field of view, 3-mm-thick sections, no section gap, 256 × 192 matrix, and four signals acquired.

**Intraoperative imaging.**—Intraoperative MR imaging was performed in an open-configuration 0.5-T unit (Signa SP; GE Medical Systems), also referred to as the intraoperative MR imager (12). For intraoperative imaging, patients are placed in the lithotomy position to allow percutaneous iodine-125 seed insertion through a perineal template. After the induction of general anesthesia, the patient was prepared and draped in the standard fashion. A Foley catheter and rectal obturator (2 cm in diameter) were positioned (3). A red rubber catheter was inserted into a hollow tube through the obturator to prevent gas buildup in the rectum and possible rectal wall distention. On the basis of the MR imaging protocol, we performed T2-weighted fast spin-echo imaging with a flexible external pelvic wraparound surface (diaper) coil and the following parameters: two or three planes, axial and coronal views, 6,400/100, 24-cm field of view, 5-mm-thick sections, no section gap, 256 × 256 matrix, and two signals acquired.

**Dimension Measurements**

Two operators (M.H., A.B.) working together manually contoured the boundaries of the total gland, central gland, and peripheral zone by using our in-house image processing and visualization software, the 3D Slicer (www.slicer.org) (13), running on a UNIX workstation (Ultra10; Sun Microsystems, Mountain View, Calif). If any difficulties were encountered in image interpretation, a third operator (C.M.C.T.) more experienced in prostate imaging was consulted (Fig 1).

After contouring was performed, 3D models of the central gland and peripheral zone from each patient (based on pre- and intraoperative data sets) were created and interactively displayed and navigated with the 3D Slicer. The display facilitated comparisons between 3D models of pre- and intraoperative data for each case (Fig 2). On the basis of the 3D shape change, statistical hypotheses (see below) were tested by obtaining the following measurements: (a) AP dimension (in millimeters) in the midline of the total gland, central gland, and periph-
eral zone on the midaxial sections; (b) the greatest transverse dimension of the gland (in millimeters); and (c) volume (in milliliters) of the total gland, central gland, and peripheral zone. As an estimate of superoinferior height, the number of sections containing gland was counted and multiplied by the section thickness. A radiologist (C.M.C.T.) was consulted to minimize interpretation error due to partial volume averaging. We computed the volume of the total gland, central gland, and peripheral zone by segmenting the original images and counting the total number of the voxels in each section. We then converted the total number of voxels into volume by using the voxel dimensions. In cases in which an even number of sections represented the gland, we calculated the mean value of the dimensions noted earlier for the corresponding pair of sections.

Reproducibility Evaluation

As a measure of reproducibility, a single case was selected at random, and segmentation and measurement were performed five times.

Statistical Methods

Statistical analytical methods were used to address whether there were any changes in the AP dimension and volume of the total gland, peripheral zone, and central gland. The transverse dimension and superoinferior height were also analyzed.

Because of the high case-to-case variability, nonparametric Wilcoxon signed rank tests for paired (ie, pre- vs intraoperative) data (14) were performed to evaluate the statistical hypotheses. The null hypothesis indicated that the population medians of the underlying paired measurements were equivalent. Furthermore, one-sided statistical tests were performed when there was a clear directionality in the dimension change, with the resulting $P$ values reported.

In the repeated measurement experiment, summary statistics including the mean and standard deviation (SD) were computed, followed by the coefficient of variation (obtained by dividing the SD by the mean).

RESULTS

3D models of the central gland and peripheral zone from each patient (on the basis of pre- and intraoperative data sets) were created, interactively displayed, and navigated with the 3D Slicer (Fig 2). At visual inspection of each case, substantial changes were observed, including an apparent increase in the AP dimension of the gland and a decrease in the transverse dimension between pre- and intraoperative imaging.

The interval between the two examinations was 69–218 days (mean ± SD, 111.9 days ± 43.7). This delay was due to the variable time between pretreatment assessment, treatment decision making, and brachytherapy. At T2-weighted MR imaging, the signal intensity of the prostate exhibited a typical appearance—the central gland was hypointense and the peripheral zone was hyperintense to muscle (Fig 3). On the basis of the segmentation of the gland, quantitative measurements were obtained as described earlier (see Fig 1) for each of the 10 cases. Table I provides the median, range, median in percent, and range in percent of the changes in the following measurements of the prostate gland between pre- and intraoperative imaging: (a) AP dimension of the central gland, peripheral zone, and total gland; (b) transverse dimension; (c) superoinferior height; and (d) volume of the central gland, peripheral zone, and total gland.

The gland changed from having a flat posterior shape during the 1.5-T imaging study to having a round shape.
during the 0.5-T imaging study. Moreover, the peripheral zone at the midline went from being relatively thin during 1.5-T imaging to becoming relatively thick during 0.5-T imaging. The total gland AP dimension increased from 1.5 T to 0.5 T (median, 4.9 mm; mean ± SD, 4.1 mm ± 4.4; P = .02). Specifically, the AP dimensions of the central gland increased (median, 1.5 mm; mean ± SD, 1.8 mm ± 3.0; P = .03), as did those of the peripheral zone (median, 1.8 mm; mean ± SD, 2.3 mm ± 3.4; P = .05). The mean increase in the AP dimension of the peripheral zone was greater than that of the central gland (P = .02). Note that the ranges of AP dimension change (actual and percentage) for the peripheral zone were very wide. We illustrate an extreme case in which a large AP dimension change was noted between pre- and intraoperative imaging, especially in the peripheral zone (Fig 4).
The greatest transverse dimension of the prostate gland showed a significant decrease from 1.5-T to 0.5-T imaging (median, 4.5 mm; mean ± SD, 4.3 mm ± 3.1; \( P < .005 \)). However, no statistically significant changes in the various measures of volume changes or in the superoinferior height were observed (Table 1), nor were any consistent trends observed.

To assess reproducibility, we performed a series of repeated measurement experiments in which all of the coefficients of variation were within 1.5 SDs around the mean, which represents satisfactory reproducibility (Table 2).

**DISCUSSION**

Our results indicate that the prostate gland and its internal substructure underwent significant shape changes between the two imaging sessions. The preoperative (1.5-T) appearance of a relatively flat gland (with short AP dimension and wide transverse dimension) contrasts

**Table 1**

<table>
<thead>
<tr>
<th>Measurement Axis</th>
<th>Median</th>
<th>Range of Change</th>
<th>Median in Percent</th>
<th>Range of Percentage Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP dimension (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central gland*</td>
<td>1.5</td>
<td>−2.9, 7.5</td>
<td>5.8</td>
<td>−10.2, 33.6</td>
</tr>
<tr>
<td>Peripheral zone*</td>
<td>1.8</td>
<td>−1.6, 8.8</td>
<td>43.7</td>
<td>−28.0, 1503.4</td>
</tr>
<tr>
<td>Total gland*</td>
<td>4.9</td>
<td>−1.3, 10.8</td>
<td>15.4</td>
<td>−3.5, 41.8</td>
</tr>
<tr>
<td>Transverse dimension (mm)*</td>
<td>−4.5</td>
<td>−10.2, 0.9</td>
<td>−7.6</td>
<td>−19.1, 1.5</td>
</tr>
<tr>
<td>Superoinferior height (mm)</td>
<td>1.5</td>
<td>−16.0, 9.0</td>
<td>4.3</td>
<td>−18.6, 25.0</td>
</tr>
<tr>
<td>Volume (cm³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central gland</td>
<td>0.9</td>
<td>−7.9, 5.0</td>
<td>2.4</td>
<td>−18.0, 28.0</td>
</tr>
<tr>
<td>Peripheral zone</td>
<td>0.9</td>
<td>−3.3, 5.4</td>
<td>5.2</td>
<td>−19.3, 38.7</td>
</tr>
<tr>
<td>Total gland</td>
<td>2.0</td>
<td>−4.7, 6.9</td>
<td>4.3</td>
<td>−11.1, 19.3</td>
</tr>
</tbody>
</table>
|*Results of statistical hypothesis tests suggested that these changes were significant.

**Figure 4.** MR images obtained at (a) 1.5 T (5,000/102, 10-cm field of view, 3-mm-thick section, no section gap, 192 matrix, four signals acquired) and (b) 0.5 T (6,000/100, 24-cm field of view, 5-mm-thick section, no section gap, 256 matrix, two signals acquired) (zoomed to the same scale as in a) in the midaxial plane demonstrate an extremely large deformation in the peripheral zone. These images represent an extreme case.
Table 2  
Variability of Prostate Dimension Changes (from 1.5 T to 0.5 T) on Five Repeated Measurement Sets for One Case

<table>
<thead>
<tr>
<th>Measurement Axis</th>
<th>Mean ± SD</th>
<th>Coefficient of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP dimension (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central gland</td>
<td>1.4 ± 1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Peripheral zone</td>
<td>6.1 ± 1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Total gland</td>
<td>7.5 ± 0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Transverse dimension (mm)</td>
<td>−2.1 ± 2.3</td>
<td>−1.1</td>
</tr>
<tr>
<td>Volume (cm³)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central gland</td>
<td>1.4 ± 2.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Peripheral zone</td>
<td>3.5 ± 2.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Total gland</td>
<td>4.9 ± 0.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Note.—Repeated measurements were not obtained for supero-inferior height because the number of sections containing the gland were selected by an expert and used for later segmentation on which measurements were based.

with the more rounded shape observed at intraoperative (0.5-T) MR imaging. These deformations were verified with quantitative measurements. We demonstrated that the relative increase in AP dimension was greater for the peripheral zone than for the central gland. Despite case-to-case variability, satisfactory reproducibility was obtained with a repeated measurement experiment.

There are several possible causes of the observed changes in shape. Compression secondary to rectal wall pressure by the endorectal coil at 1.5-T imaging, against the posterior aspect of the gland, is the most plausible explanation. Another important factor may be the change in patient position from supine (preoperatively) to lithotomy. In addition, but less likely, imaging variables such as the different field strengths and imaging parameters may have had an effect on the measured variables.

With regard to compression, AP shortening of the gland is likely to occur once the endorectal coil balloon is inflated, which naturally increases pressure within the rectum. Although the obturator, which is fixed and made of Plexiglas, also compresses the rectal wall, it appears to cause less pressure than the endorectal coil. This may be explained by the fact that, after the obturator is placed in the rectum, some downward traction is applied to move the rectum posteriorly to facilitate perineal catheter insertion. This will likely stretch the gland in the AP dimension.

Other investigators have shown similar effects of rectal filling at AP translational movement of the entire prostate (5,6,8,9). Our study goes further to document the effects of rectal filling on internal zonal deformation of the prostate—a phenomenon supported by the fact that peripheral zone dimensions undergo greater changes than do central gland dimensions. This difference may occur because the peripheral zone is closer to the endorectal coil, thus transmitting more pressure to the peripheral zone than to the central gland. It may also be due, however, to differences in the tissue properties (ie, compressibility) of the substructures of the gland. The peripheral zone consists of glandular tissue with a high water content. The central gland, conversely, is a combination of the periurethral zone (transitional) and central zone (the site of benign prostatic hyperplasia) and contains stromal, muscular, and glandular tissue and even calcium. Thus, it is less likely to be compressible.

Changes in the shape of the prostate may also be due to changes in the position of the patient’s pelvis—supine in the case of 1.5-T MR imaging and lithotomy in the case of 0.5-T MR imaging. Van Herk et al (6) previously reported on prostatic movement caused by leg rotation with abduction and/or adduction, although their experiment was conducted only in the supine position.

The shape changes noted in this study have relevance to the possible integration of preoperative endorectal coil MR imaging for US-guided procedure planning. We expect similar shape changes to occur during US-guided procedures because transrectal US–guided brachytherapy is also performed in the lithotomy position (15) and a transrectal US probe is used. To plan a lithotomy-based implant procedure with US guidance, the patient is placed in the supine position and images are obtained with transrectal US. During implantation, the US probe is filled with water, which causes distention of the rectal wall and compression of the prostate. During MR imaging, the endorectal coil is filled with air. In both cases, the prostate gland is compressed. The compressive effects are likely very similar. The importance to treatment planning is in these effects on the prostate, its zones, and the proximity of the rectum. During a US-guided implant procedure, there is likely a greater degree of compression on the prostate than during an MR-guided implant procedure. In US, the rectal wall is in close contact with the prostate by the water bath in and around the transducer. After the implant (either MR imaging or US) is placed, all external forces are removed and only natural rectal pressures remain. These will require further study, as they will likely have an effect on the actual source-to-prostate and source-to-rectal wall relationship and, thus, ultimately the actual dosimetry.
In summary, we analyzed and compared the changes in shape and volume of the prostate from preoperative 1.5-T MR imaging to intraoperative 0.5-T MR imaging. Computerized 3D visualization of the gland and quantitative measurements have shown that (a) the prostate assumes a flatter shape at preoperative MR imaging and a more rounded shape at intraoperative MR imaging, (b) the shape change of the peripheral zone in the AP axis is greater than that of the central gland, and (c) the volume and superoinferior height of the prostate gland do not change in a consistent fashion. These findings will be helpful for future studies involving prostate image registration and segmentation.

When planning radiation doses for brachytherapy and other imaging-guided interventional procedures, it is clearly important, as the data suggest, to consider the influence of rectal filling and other factors (eg, patient position and subsequent glandular deformation). These findings show that the prostate can undergo substantial shape changes between imaging sessions. As efforts are made to integrate high-resolution preoperative images with intraoperative images, these potential changes must be anticipated. Our findings also suggest that, without careful integration of both data sets, the pretreatment images alone may not be reliable for accurate therapy planning.

REFERENCES


