Accurate Prostate Volume Estimation Using Multifeature Active Shape Models on T2-weighted MRI

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Rationale and Objectives: Accurate prostate volume estimation is useful for calculating prostate-specific antigen density and in evaluating posttreatment response. In the clinic, prostate volume estimation involves modeling the prostate as an ellipsoid or a spheroid from transrectal ultrasound, or T2-weighted magnetic resonance imaging (MRI). However, this requires some degree of manual intervention, and may not always yield accurate estimates. In this article, we present a multifeature active shape model (MFA) based segmentation scheme for estimating prostate volume from in vivo T2-weighted MRI.

Materials and Methods: We aim to automatically determine the location of the prostate boundary on in vivo T2-weighted MRI, and subsequently determine the area of the prostate on each slice. The resulting planimetric areas are aggregated to yield the volume of the prostate for a given patient. Using a set of training images, the MFA learns the most discriminating statistical texture descriptors of the prostate boundary via a forward feature selection algorithm. After identification of the optimal image features, the MFA is deformed to accurately fit the prostate border. An expert radiologist segmented the prostate boundary on each slice and the planimetric aggregation of the enclosed areas yielded the ground truth prostate volume estimate. The volume estimation obtained via the MFA was then compared against volume estimations obtained via the ellipsoidal, Myschetzky, and prolated spheroids models.

Results: We evaluated our MFA volume estimation method on a total 45 T2-weighted in vivo MRI studies, corresponding to both 1.5 Tesla and 3.0 Tesla field strengths. The results revealed that the ellipsoidal, Myschetzky, and prolate spheroid models overestimated prostate volumes, with volume fractions of 1.14, 1.53, and 1.96, respectively. By comparison, the MFA yielded a mean volume fraction of 1.05, evaluated using a fivefold cross-validation scheme. A correlation with the ground truth volume estimations showed that the MFA had an r^2 value of 0.82, whereas the clinical volume estimation schemes had a maximum value of 0.70.

Conclusions: Our MFA scheme involves minimal user intervention, is computationally efficient and results in volume estimations more accurate than state of the art clinical models.

Key Words: Prostate volume; active shape models; prostate cancer; MRI; texture; image processing.

Prostate volume has been shown to be a strong predictor of treatment outcome for patients with prostate cancer (1,2), especially when combined with a baseline prostate-specific antigen (PSA) level (3). Prostate volume has also been shown to be useful in determining PSA density (4). The most common method for estimating the prostate volume involves modeling the prostate as a simple geometric shape based on manually estimated measurements of the anteroposterior, transverse, and craniocaudal lengths of the prostate.

The most common models for approximating the prostate shape are the ellipsoid model (4,5,6–14) and the prolate spheroid model (4,6,9). It is important to note that the ellipsoidal model has been a clinical standard for comparisons from at least 1991 (7) to the present day (12,14). Some researchers have reported that in several cases the ellipsoid model underestimated the prostate volume (6,8,11,15). Tewari et al (11) and Eri et al (6) both found that the ellipsoid model underestimated the prostate volume by about 10%. Matthews et al (8) found that the ellipsoid model from transrectal ultrasound (TRUS) imagery underestimated the volume for large prostates (>50 mL), but overestimated the volume for small prostates (<30 mL). Myschetzky et al overcame this underestimation by proposing a new formula in which the ellipsoid volume estimation is multiplied by a factor of 1.34 (15). Additionally, methods involving manual intervention are typically subject to inter- and intraobserver variability (16,17) and these volume estimations are not highly reproducible.

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Although most prostate volume estimations are done using TRUS imagery, a strong correlation ($r^2 = 0.925$) has been shown between the volume estimations obtained using TRUS and from magnetic resonance imaging (MRI) (5). In addition, the ellipsoidal model was found to yield accurate volume estimations for T2-weighted MRI of the prostate, even when an endorectal coil was used (12). In previous work (13), it was found that the ellipsoidal volume estimations were more accurate than a planimetry-based approach (aggregating a series of measurements from each slice) when using a surface coil; in contrast to other work (12) in which planimetry estimates were found to yield more accurate volume estimations compared to the ellipsoidal model estimates when using an endorectal coil. In previous work (5), a planimetry based volume estimation was performed by measuring the areas from manual two-dimensional (2D) segmentations of the prostate on each slice.

Our prostate volume estimation method is related to the technique used by Hoffelt et al (5), in which the gland areas obtained by manual segmentation of the capsule were aggregated across multiple 2D sections. However, although Hoffelt et al (5) obtained the prostate areas manually, we aim to perform the capsule segmentations automatically via the use of a multifeature active shape model (MFA) (18).

Although active shape models (ASMs) are a popular segmentation technique, they sometimes fail to converge to the desired object boundary in the case of weak image gradients (19). ASMs essentially model the shape of an object a statistical variations in a set of anatomical landmarks the appearance of an object as a Gaussian distribution of intensities near each anatomical landmark. The appearance model typically uses the intensities of the image to learn a statistical appearance model. However, relying solely on the intensity information may not be sufficient for accurately detecting the correct boundary, especially if different regions of the image, or different regions within the desired object, have similar intensity values. This is particularly true of MRI in which strong bias field inhomogeneity artifacts can significantly obfuscate object boundaries (20).

In this work we present a new ASM that we call the MFA. We calculate the gray level statistics of each image by convolving a set of kernels with the intensity image. These include the Kirsch (21) and Sobel (22) kernels to better quantify the edges of the prostate border. Although traditional ASMs use neighboring intensity information, they are dependent on the normal to the shape at any given landmark point. By contrast, the Gaussian and mean kernels take neighboring information into account and yet do not depend on the normal of the shape. Additionally, the Cartesian x and y coordinates of each landmark point are included as additional "features." Further, because texture features of the prostate boundary are not always optimally modeled as a Gaussian, we describe the distributions as sums of multiple Gaussians (GMM) (23), allowing us to better characterize the feature distributions at each landmark on the prostate boundary. A forward feature selection scheme is employed to determine the best textural features in terms of discriminability between the prostate border and background. Only these features are then employed in conjunction with the MFA.

The MFA is employed to estimate the gland area on each slice, which is multiplied by the slice interval (distance between center of adjacent slices) to yield an estimation of the prostate volume. This estimation is compared to the ellipsoid (4), Myschetzky (15), and prolate spheroid (4) volume estimation techniques. All four methods were evaluated in terms of accuracy with respect to a ground truth estimate of the prostate volume obtained via expert radiologist derived segmentations of the prostate on individual 2D slices.

MATERIALS AND METHODS

Data Description and Notation

The datasets considered in this study comprised 19 1.5 Tesla (T) MRI studies obtained from the American College Of Radiology Imaging Network trial (24) and 26 3T T2-weighted MRI studies from the Beth Israel Medical Center in Boston, henceforth denoted as D_1 and D_2 respectively. A complete description of the 45 MRI datasets considered in this study is provided in Table 1. The volume estimation for the ellipsoid method is denoted as V_{Ell}, the Myschetzky method as V_{Mys}, and the prolate spheroid method as V_{Sph}. The MFA-based segmentation method yields a volume estimation V_{MFA} and the expertly determined volume estimation is referred to as V_{Ex}.

Ground Truth Estimations of Prostate Volume

The ground truth volume (V_{Ex}) for the prostate in each of the 45 studies was determined as follows. For each study C, an expert radiologist provided a manual segmentation of the prostate for all slices in which the prostate was visible. The set comprising the area estimates of the prostate from all M slices within a single three-dimensional (3D) study C, is denoted as $S_{Ex} = \{A_m, \mid m \in \{1, \ldots, M\}\}$ where A_m denotes the segmented area of 2D slice m. The estimated prostate areas (region contained within the manual delineations of the capsule) on all slices are integrated and multiplied by the slice interval T. This is similar to the approach presented elsewhere (5), in which planimetry area estimates were aggregated to estimate the prostate volume. The ground truth prostate volume (V_{Ex}) in C is then calculated as

$$V_{Ex} = T \cdot \sum_{m=1}^{M} A_m. \quad (1)$$

Clinically Employed Prostate Volume Estimation Models

For the ellipsoid, Myschetzky, and prolate spheroid models, an expert manually determined the transverse (D_1), craniocaudal