A multi-scan MRI-based virtual cystoscopy

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ABSTRACT

Computed tomography (CT) based virtual cystoscopy (VC) has been studied as a potential tool for screening bladder cancer. It is accurate in localizing tumor of size larger than 1 cm and less expensive, as compared to fiberoptic cystoscopy. However, it is invasive and difficult to perform due to using Foley catheter for bladder insufflating with air. In a previous work, we investigated a magnetic resonance imaging (MRI) based VC scheme with urine as a natural contrast solution, in which a MRI acquisition protocol and an adaptive segmentation method were utilized. Both bladder lumen and wall were successfully delineated. To suppress motion artifact and insight pathological change on the bladder wall images, a multi-scan MRI scheme was presented in this study. One transverse and another coronal acquisitions of T1-weighted that cover the whole bladder were obtained twice, at one time the bladder is full of urine and at another time it is near the empty. Four bladder volumes extracted from those 4 datasets were registered first using a flexible three-dimensional (3D) registration algorithm. Then, associated 4 lumen surfaces were viewed simultaneously with the help of an interactive 3D visualization system. This MRI-based VC was tested on volunteers and demonstrated the feasibility to mass screening for bladder cancer.

Keywords: multi-scan MRI, virtual cystoscopy, and flexible registration.

1. INTRODUCTION

Bladder cancer is the fifth cause of cancer deaths in the United States. Over 50,000 new cases and more than 11,000 deaths were reported in 1995 [10]. A common test for bladder cancer is urine dipsticks or standard urinalysis, which can be tested at home. It has a sensitivity of less than 90% and specificity of approximately 70% [8]. However, the finding is usually at the very late stage and not able to provide the accurate location and size of the lesion. Cystoscopy, the main method of investigating bladder abnormalities at present, is more accurate. However, it is invasive, has limited field-of-view (FOV) and lacks an objective scale. Moreover, it is not indicative in patients with severe urethral strictures or active vesical bleeding.

In recent years, the feasibility studies of applying virtual endoscopy techniques for screening bladder cavity were reported [3,4,5,9]. This technology is called virtual cystoscopy. In those research reports, several CT-based VC schemes were tested on patients and some of the results were compared with the conventional cystoscopy. Since bladder wall could not be distinguished from the urine in the CT image, use of Foley catheter for bladder insufflating with air is necessary to obtain the contrast between the urine and the bladder wall in those studies. A similar conclusion was made in those reports that VC has the potential for screening bladder cancer while further improvement and test is highly desirable. On one hand, VC has not reached the quality of fiberoptic examination and remains restricted for use in some specific cases, for example, for patients with urethral strictures. On the other hand, using a Foley catheter to distend bladder with room air has been proved to be difficult in handling patient and is very uncomfortable for patient (sedation is required).

The tumor on the bladder is often developed gradually from the mucosa into the bladder muscle. Most urologists in the western hemisphere use the Jewett, Strong, Marshall system of classification [7] to describe the depth of penetration of the tumor into the bladder wall. It is desirable that the virtual cystoscopy could assist physician to detect the depth of the penetration. This requires that the image acquired can provide good contrast on bladder muscle and other tissues. In CT image, the bladder muscle has no contrast to other soft tissues. Hence, the CT-based VC can only detect the tumor based on geometry information. This limits the possibility of detection of the small tumor. In other words, the ability to detect the bladder carcinoma in early stage is weak for CT-based VC.

MRI-based VC is a potential alternative choice for early detection of bladder carcinoma. MRI has better tissue contrast and multi-spectral image data, though it has lower spatial resolution. In our previous work [6], a feasibility study on MRI-based VC was presented. Two in vivo MRI protocols were tested and a self-adaptive segmentation algorithm was utilized. Patient was asked to drink a cup of water half an hour prior to the MR scan. Both the bladder wall and lumen were successfully delineated. For VC, the idea quality of MR images for detection of bladder lesion is expected to distinguish both the

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pathological and morphological changes of the tissues on the bladder wall. However, patient’s breathing often creates motion artifact in the images. Moreover, the bladder wall may appear morphological differences when bladder lumen is in different states, for example, full of urine or near empty. In this study we present a multi-scan, MRI-based VC scheme aiming at overcoming those problems mentioned above. Both T1- and T2-weighted imaging protocols were tested. The segmentation algorithm and the associated visualization technique were developed and presented. The method was tested on two male healthy volunteers of age 34. The results were promising.

2. METHODS AND MATERIALS

2.1. Materials

Two male health volunteers of age 34 were recruited in this study with consent. At present, no patient or female volunteer has been solicited. Since we focus on the feasibility study of the technology, the limited subjects do not seriously influence the demonstration. Usually the thickness of the bladder muscle of male is much thicker than that of female. Whether this will cause some difficulty in delineating the bladder wall from female dataset will not be discussed in this study.

2.2. MRI protocols

All the MR images were acquired by a Picker 1.5 T Edge whole-body scanner. After testing and comparing on several protocols available in this machine, four of them were chosen in this study for acquiring T1- and T2-weighted images. The body coil was used as the transceiver.

The first protocol is KJELL FASTER for T1-weighted transverse imaging with parameter of 256x256 matrix size, 38 cm FOV, 1.5 mm slice thickness (no gap), 3 ms TE, 9 ms TR, 30 degree flip angle, and one-scan average. The second one is KJELL FASTER for T1-weighted coronal imaging with parameter of 256x256 matrix size, 38 cm FOV, 1.5 mm slice thickness (no gap), 3 ms TE, 9 ms TR, 30 degree flip angle, and two-scan average. The third one is AXIAL FSE T2 for T2-weighted transverse imaging with parameter of 256x256 matrix size, 38 cm FOV, 1.5 mm slice thickness (no gap), 96 ms TE, 12167 ms TR, 90 degree flip angle, and two-scan average. The fourth one is CORONAL FSE T2 for T2-weighted coronal imaging with parameter of 256x256 matrix size, 38 cm FOV, 1.5 mm slice thickness (no gap), 96 ms TE, 12167 ms TR, 90 degree flip angle, and two-scan average.

2.3. Multi-scan MRI scheme

The designed multi-scan MRI scheme consists of four T1-weighted acquisitions. These four acquisitions are sequentially implemented. Half an hour prior to these scans, the volunteer was asked to empty the bladder and drink a cup of water. The first and two acquisitions were one transverse and one coronal respectively. After these two scans, the volunteer went to restroom to empty the bladder. Then, additional two acquisitions of transverse and coronal were performed. For comparison, all volunteers were instructed to follow similar four scans of T2-weighted acquisition. Since the fat possesses similar intensity as that of urine in the T2-weighted images and the T2 protocol takes longer acquisition time, we recommend the T1 protocol for VC studies. In the following of this paper, we call the four scans according to the order of acquisition as scan 1, scan 2, scan 3, and scan 4. If no further statement, these four scans are of T1-weighted, where scans 1 and 3 are transverse slicing, scans 2 and 4 are coronal slicing.

Because of the long T1 relaxation of the urine, a significant contrast between the urine and bladder wall can be obtained (Fig. 1 a). A noticeable contrast can also appear between the bladder muscle and other surrounding tissues (Fig.1, b). However, the boundary between the bladder wall and the rectum wall may be vague (Fig. 1 b). When bladder is fully distended as in the scans 1 and 2, the bladder wall would be thinner. A physiologically altered location is expected to have a different thickness. When bladder is near empty in the scans 3 and 4, the wall would be thicker. For a thicker wall, it is more likely to obtain contrast between normal and physiologically altered tissues. The urine is much brighter than other tissue in T2-weighted image while the wall layer is difficult to be detected (Fig. 1. c).
It usually takes 2 to 5 minutes to acquire a single T1-weighted volume image depending on the height and weight of subject. During this period, the patient cannot hold a single breath. He is asked to relax and breathe smoothly. However, even the smoothly breathing may cause motion in abdomen, and this usually creates motion artifact strip along the direction of the spine. This kind artifact may frequently be seen in transverse slicing image. For overcoming this defect, another coronal slicing acquisition is introduced in the scheme. It is desirable that this transverse/coronal protocol will reduce the possibility of false positives on tumor detection.

2.4. Image processing

After the four-scan datasets were acquired, they were transferred to a laboratory computer workstation through local net in the hospital. The four datasets were processed one by one.

The first task was image segmentation. The method developed previously [1] was employed. In this method, a three-dimensional (3D) interpolation procedure was first applied to the datasets. The size of dataset were expended from 256x256xn to 512x512xm, where n was the number of slices of the original dataset and m was the number of slices of the interpolated dataset. The value of m was determined to ensure that the interpolated dataset has an equal scale in three coordinate directions, i.e. a cubic voxel array. The interpolation is similar to a low pass filtering. It can suppress noise and partial volume effect in the MR images. All the following processing steps were applied on the interpolated dataset.

A parallelepiped volume that covered the entire volume of bladder and its associated tissue was roughly extracted. This relative smaller volume of interest could be extracted manually by fixing the coordinates of top most and bottom most vertexes of the parallelepiped. The purpose was to reduce the computation burden by working on a dataset of smaller quantity. This smaller dataset was called the focused dataset.

The classification of those voxels in the focused dataset was based on their local intensity vectors. The intensities of the second order neighbors of a given voxel constituted the local intensity vector of that voxel (Fig 2). The collection of local vectors of all voxels in the focused dataset formed a series of local vectors. A series of feature vectors were then generated from the series of local vector by the principal component analysis. The feature vectors were clustered utilizing a vector quantization algorithm [1]. Using this algorithm, a maximum class number must be pre-set. Here we set it to be 5 based on numerical experiments and clinical consideration. Voxels in the focused dataset were then segmented according to the classification results of their associated feature vectors. The final segmentation result was represented as a stack of character format images where voxels were labeled with their class number.

Figure 2. The depiction of the neighbors of a voxel in 3D space. The given voxel is labeled with 0 and its neighbors are labeled with the number of neighbor orders.
Although the bladder lumen in T2-weighted images can be more easily delineated than in T1-weighted images, because there is always an area between the bladder wall and the rectum wall, where the segmentation algorithm identifies the walls correctly, we prefer working on the T1-weighted images for several other reasons mentioned above. In order to correctly identify the wall of bladder and rectum, a post-processing step is necessary. At present, we identify the walls manually. Other methods are under investigation. After the post-processing the wall and the lumen of bladder were in different classes. By manually choosing a seed point in the lumen, the lumen could be extracted by means of a region growing algorithm. Since the wall was distinguished from other tissues, it could be extracted by the same method. In the multi-scan scheme, there were four volumes of interest (VOIs) extracted from the four scans from a single volunteer. The user could choose the volume of either wall or lumen to be displayed by means of computer graphics technology. This will be discussed in the following.

The thickness of the bladder wall is useful information for detecting the location of the lesion. When volumes of both the lumen and the wall were extracted, voxels on the interior surface of the wall volume could be determined. These voxels were called boundary voxels. The Euclidean distance from the center of each boundary voxel to that of the nearest exterior voxel was then calculated, where the exterior voxel was not in both in wall and the lumen. The distance between the boundary voxel and the exterior voxel was defined as the thickness of the wall at that boundary voxel.

2.4. Flexible registration

To screen those four VOIs from the same volunteer, registration was necessary. Because the shape of the bladder varied greatly within the four scans, it has no practical meaning to register exactly on voxel between those four VOIs. In practice, the physician will focus on viewing a certain area of the bladder in all those four VOIs simultaneously after initial inspection. In other words, an exact registration is not necessary, since quantity analysis on the geometry structure is not clinical attractive. For navigation purpose, it is reasonable and feasible to register those VOIs in a flexible way.

For each VOI, the center of the volume was first determined by averaging three coordinates of all the voxels in the volume. A Cartesian coordinate system was then constructed with its origin at the center. The directions of those three axes were chosen as the same as those of the natural coordinate system of human body (Fig. 3). The unit length of the coordinate system was the same as the voxel size of the interpolated dataset. It is noted that the units of the four scan datasets were identical due to the same pixel spacing in imaging.

![Figure 3. The depiction of the directions of the natural human body coordinate system.](image)

2.5. Display modes

We have developed an interactive visualization system which has been successfully applied to virtual laryngoscopy and virtual surgery [2,11]. It was adapted to this work. The user could interactively navigate inside the lumen and view any area on the surface at any zooming scale. In general, the geometry structure of bladder is much simpler than that of larynx or inner ear. However in multi-scan virtual cystoscopy all those four volumes are desirable to be displayed simultaneously. Moreover, the focus of each view must aim at the same area on the surface of the lumen or wall. We included this characteristics into our visualization system based on our flexible registration result.

After registration, the four VOIs were associated to the natural coordinate system. A large main square display window was opened. The window was divided into four sub-square windows with equal size. In each sub-window one of the bladder lumen of the scans was displayed. The viewing points for all four volumes were at their own center and the viewing direction were identical within the natural coordinate system. When user interactively changes the viewing parameters, all the four views are changed simultaneously according to the same parameters associated to the natural coordinate system. If the user wants to inspect a specific spot on the surface in a certain area, he push the button of the area number in the given toolbox on the right side of the main window, then the whole display window will be covered by the view of that area. He can
interactively zoom in and out, shift the viewing point, and change the viewing angle. By pushing the reset button in the toolbox, the main window would return to the parallel multi-scan display.

The volume of the wall and the volume of the lumen are not displayed together. There is an option for user to choose which volume to be displayed. When the wall is displayed, a pop-up text window will be appeared. The wall thickness associated with those voxels located at the center of those area are listed in this text window.

3. RESULTS

Two healthy male volunteers were recruited the multi-scan MRI scheme for virtual cystoscopy. For research purpose, both T1- and T2-weighted protocols were utilized. For a single T1- or T2-weighted multi-scan scheme it took nearly half an hour. This period of time included the time to empty urine after those first two scans of full bladder with urine. Each volunteer was asked to drink a cup of water after emptying his bladder by half an hour prior to the scan.

All bladder lumens in T2-weighted images were successfully extracted by directly applying the segmentation algorithm. All the bladder lumens and walls in T1-weighted images was first extracted by the segmentation, and then were corrected manually at the boundaries between the bladder and the rectum. These extracted volumes were reviewed by the visualization system. All pictures presented in this paper came from one of the volunteer. The slice numbers for scan 1, 2, 3, and 4 were 80, 80, 50, and 50 respectively. The voxel size of both transverse and coronal imaging were $1.484375 \times 1.484375 \times 1.5 \text{ (mm)}^3$, thus the voxel was nearly a cubic volume. The interactive visualization was implemented nearly real time. Fig. 4 is the depiction of the multi-scan display with the natural coordinate system, where bladder lumen is displayed transparently. Fig. 5 demonstrates the multi-scan display of interior surface, where the viewing parameters for the four scans are identical. Fig. 6 shows a situation where some artifacts appear in the display of scan 1 while the artifacts disappears in the same location in the display of scan 2. This demonstrates the ability of the multi-scan scheme to eliminate false positive.

Figure 4. The bladder lumens from the four T1-weighted scans are registered to the natural coordinate system. The top panel are the scan 1 (left) and the scan 2 (right). The bottom panel are the scan 3 (left) and the scan 4(right).
MULTI-SCAN MRI SCHEME IS A NON-INVASIVE, EASY IMPLEMENTED, AND PATIENT COMFORTABLE PROCEDURE, WITH THE ABILITY OF CORRECTION OF THE BLURRING DUE TO MOTION AND SLICING. THE REASON OF CHOOSING T1, RATHER THAN T2 WEIGHTED IMAGING IS BECAUSE OF THE FACT THAT THE FAT TISSUES HAVE A SIMILAR DENSITY AS THE URINE IN T2-WEIGHTED IMAGE. FURTHERMORE, T1-WEIGHTED IMAGING TAKES LESS TIME. THE INTERACTIVE VISUALIZATION SYSTEM CONSIDERS ALL THE INFORMATION AVAILABLE IN THE FOUR DATASETS. THIS MRI-BASED VC IS NOVEL AND FEASIBLE FOR MASS SCREENING. THE FLEXIBLE REGISTRATION METHOD HAS THE POTENTIAL APPLICATION TO VIRTUAL ENDOSCOPY AND IS PROMISING FOR COMPUTER AIDED DETECTION/SCREENING OF TUMORS.

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