Urinary flow dynamics – MRI-based computational modeling

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Cardiovascular Fluid Dynamics Laboratory

Introduction

- Benign prostate hyperplasia (BPH) affects a majority of men over the age of 60 in the United States.
- Along with BPH, lower urinary track symptoms (LUTS) and bladder dimension changes are a common development in this population.
- The complex biomechanics of the full male urogenital system and their effects on BPH symptom development are still not fully understood.
- Non-invasive analysis and diagnostic methods for prostate and bladder pathologies have previously been limited.
- Magnetic resonance imaging (MRI) has the potential to analyze many of these factors in a single imaging session.
- MRI based computational fluid dynamics (CFD) models could provide valuable information about the urinary flow dynamics

Purpose

To implement an MRI urodynamics protocol and to perform patient specific computational fluid dynamics (CFD) simulations of bladder voiding in healthy controls and BPH patients.

Materials and Methods

Patient Population

- 3 healthy controls and 3 BPH patients were recruited.
- MRI was performed on a clinical 3T scanner using a high-density flexible surface coil array.
- 3D 'Fast-spin echo' (FSE) T2-weighted acquisitions were performed immediately before and after voiding. A sagittal plane 2D spoiled gradient echo (SGRE) dynamic real-time imaging (RTI) acquisition was performed during voiding (Figure 1).

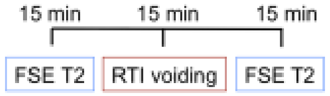

Figure 1: MRI urodynamics. Imaging protocol.

Image Processing

- The bladder and urethra were segmented from pre and post voiding 3D images, while bladder cross-sectional area change during voiding was calculated from the 2D RTI using a semiautomatic segmetation software mimics.

Acknowledgements

This work was funded by the National Institutes of Health Grant, 4K12-DK100022-04 (Dr. Roldan-Alzate).

Materials and Methods Continued

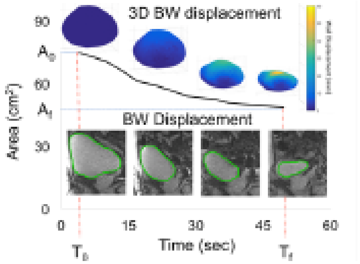

Figure 2: Real time imaging of voiding in a healthy volunteer. The curve shows the bladder emptying with respect to time following a sigmoidal behavior. 2D mid sagittal plane images show the bladder deformation at four different time points during the voiding event.

Computational Fluid Dynamics

- Measurements from both the 3D and 2D images were incorporated in a patient specific simulation of bladder voiding. For the CFD simulation.
- Bladder wall motion was estimated as from real time MRI segmentations and imposed to virtually drive voiding. The urethra was assumed to be rigid and its outlet was set to atmospheric pressure
- Figure 2. shows a schematic description of the MRI based modeling methodology implemented in this study.

Results

- The control subjects had large displacements at the bladder dome with little observed asymmetry.
- The men with BPH/LUTS had smaller displacements and unlike the controls did not exhibit a consistent displacement pattern.
- These qualitative observations from the displacement maps were confirmed looking at probability functions of the displacement and the left-right asymmetry (Fig 3 bottom).
- Overall the bladder walls of men with BPH/LUTS moved only 25%-50% as much as the control subjects. The control subjects had little left-right asymmetry (4%-14%) while the BPH patients had large left-right asymmetry (40%-160%)

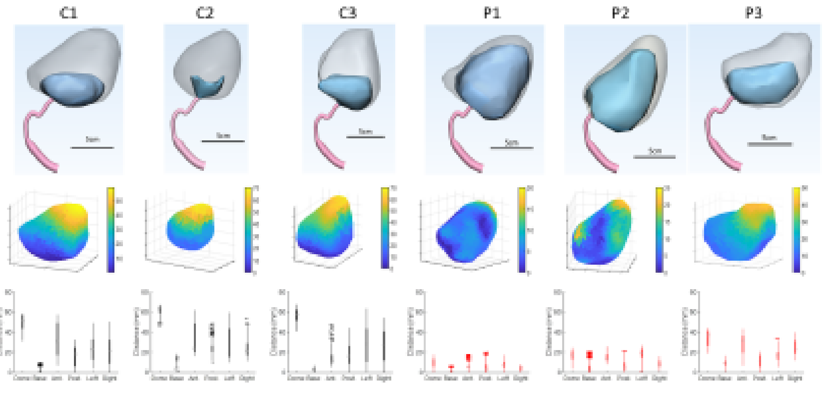

Figure 3: Top row: pre- and post-voiding bladder anatomies for each subject. Middle row: Bladder wall displacement maps (in mm) for each subject. Note that the legend scale is much smaller for the men with BPH/LUTS. Bottom row: Box plots showing regional displacement behavior for each subject (C: Control; P: Patient).

Results & Discussion

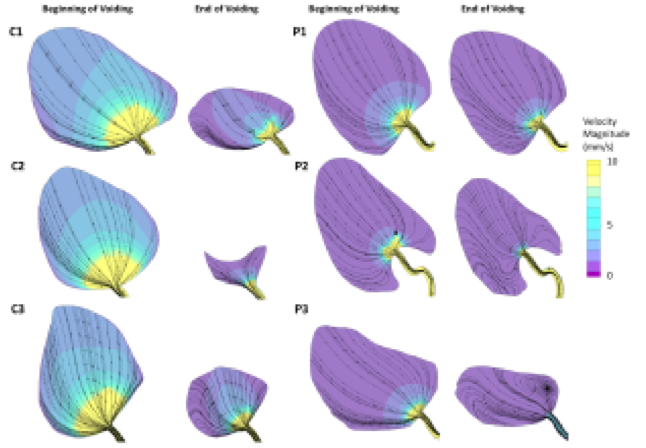

Figure 4: CFD results showing velocity contours and streamlines on a sagittal plane at the center of the bladder for each subject. Results are displayed for time frames from near both the initiation and termination voiding. Streamlines indicate the direction of urine flow and velocity magnitude is the magnitude of the velocity vector or the overall speed of urine flow

- Control subjects had higher urine velocities in the bladder than men with BPH/LUTS, that may be due to their greater bladder wall displacements.
- Near the initiation of voiding, streamlines (showing the direction of urine flow) for all three control subjects and two men with BPH/LUTS (P1 and P3) were directed toward the bladder neck and prostatic urethra.
- Towards the end of the voiding process, control subjects C1 and C3 had small recirculation regions by the anterior bladder wall while the streamlines for C2 were still all directed toward the bladder neck and prostatic urethra.
- Near the end of voiding patient P1 had a small posterior recirculation region, P2 had a large anterior recirculation region and P3 had large anterior and posterior recirculation regions
- Despite the men with BPH/LUTS having larger recirculation regions, they had lower average vorticity in the bladder due to their slower flow rates and smaller velocities.

Conclusion

In summary, this pilot study demonstrated the feasibility of MRI bladder voiding studies to non-invasively investigate bladder function. Results from displacement analysis suggested that men with BPH/LUTS have decreased and asymmetric bladder wall motion compared to healthy male controls and fluid dynamic analysis of voiding suggested that men with BPH/LUTS have larger recirculation regions in the bladder