Detrusor Pressure Estimation from Single Channel Bladder Pressure Recordings

M. Abdelhady[1,2], J. Han[1,3], S.J.A. Majerus[2], L. Brody[4] and M. Damaser[1,2,3]

1. Dept. of Biomedical Engineering, Lerner Research Institute, Cleveland Clinic, Cleveland, OH
2. Advanced Platform Technology Center, Veterans Affairs Medical Center, Cleveland, OH, USA
3. Dept. of Biomedical Engineering, Case Western Reserve University, Cleveland, OH
4. SRS Medical, N. Billerica, MA, USA

{abdelhm2, damasem}@ccf.org, {jxh1247, sjm18}@case.edu, brody@srsmedical.com

Abstract*— Cystometry measures the behavior of the bladder and is frequently used to evaluate lower urinary tract abnormalities. Cystometry is conducted using two catheters, one in the bladder and the other in the vagina or rectum, which increases discomfort and complexity of the test. In this work we evaluated a method to estimate detrusor pressure (P_{DET}), the pressure generated by a bladder contraction, from only a single catheter measuring vesical pressure (P_{VES}). Using twenty urodynamic studies, we used statistical inference and wavelet multiresolution analysis to maximize the correlation coefficient (R) between estimated P_{DET} and calculated P_{DET} after detecting and eliminating artifacts. Moreover, the estimator design considered a prospective real-time implementation. Root main square (RMS) error and correlation coefficient were used to evaluate algorithm accuracy in estimating P_{DET}, while a statistical F-score evaluated the accuracy of artifact detection. The output of the proposed estimator compared with calculated P_{DET}, and overall estimation performance showed that $RMS = 10.7 \pm 2.1$ cmH$_2$O and $R = 0.88 \pm 0.6$ (N=20). Moreover, detection accuracy for cough and Valsalva events were 99.5% and 84.3%, respectively. We conclude that estimating P_{DET} from P_{VES} only is feasible making single channel cystometry a possibility.

Keywords*— Event-driven estimation, bladder pressure, discrete wavelet transform.

I. Introduction

The two functions of the urinary bladder are to store and evacuate urine. Cystometry (a type of urodynamics test) assesses reflex function of the bladder during the storage phase, providing information, e.g. on the absence or presence of detrusor instability and detrusor-sphincter coordination [1, 2]. Cystometry uses a rectal or vaginal catheter and a transurethral bladder catheter to measure abdominal (P_{ABD}) and vesical or bladder (P_{VES}) pressures, respectively (Fig. 1). P_{ABD} describes the forces exerted by abdominal musculature and the surrounding organs on the bladder. P_{VES} measures the pressure within the bladder, which is a summation of the pressure generated by the detrusor muscle (P_{DET}) superimposed on P_{ABD}. The detrusor pressure is then distinguished from abdominal induced changes by the simultaneous difference between vesical and abdominal pressure through the formula [2]:

$$P_{DET} = P_{VES} - P_{ABD} \quad (1)$$

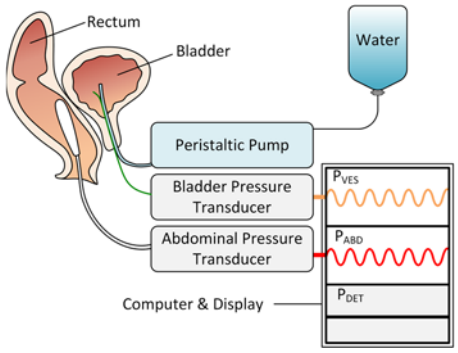

Figure 1. Urodynamic cystometry test using two catheters placed in the bladder and vagina.

In clinical practice, cystometry is restricted to a short length of time due to patient comfort and facility time. Ambulatory recordings of bladder pressure (ambulatory urodynamics) have also been demonstrated to provide new physiological insights. For example, Damaser et al. showed that the difference between full bladder pressure and almost empty bladder pressure can be used to estimate the detrusor pressure of a limited set of patients who undergo clean intermittent catheterization [3].

One challenge in urodynamic recordings (both stationary and ambulatory) is abdominal pressure artifacts due to the movement of the abdominal reference catheter. Only if the abdominal catheter perfectly measures P_{ABD} and P_{ABD} is exactly transmitted to P_{VES} is the P_{DET} estimated from (1) valid; artifacts in P_{ABD} instantly corrupt P_{DET}. Urodynamics therefore requires skill, patience, and experience to gather and interpret bladder pressure recordings.

As (1) indicates, a single measurement of P_{VES} contains both the signal of interest (P_{DET}) and the P_{ABD} signal. The goal of single-channel urodynamics is to measure only P_{VES}, then use signal processing to extract P_{DET} after removing the P_{ABD} signal. Besides the cost savings of a single catheter used for the test, this technique would increase comfort, reduce infection risk, and reduce the complexity of the clinical cystometry exam.

In this paper, we introduce a technique using discrete wavelet multiresolution analysis and statistical inference

analysis to estimate the detrusor pressure. The paper introduces the proposed framework, presents the signal processing methodologies, and discusses results from an initial analysis of pre-recorded urodynamic signals.

II. PROPOSED FRAMEWORK

Because P_{DET} is generated by detrusor smooth muscle, there are physiological limitations on the speed and force of muscle contraction. In other words, abdominal pressure data and detrusor events may be spectrally distinguished. Previous work in bladder event identification on single-channel recordings showed that wavelet-based algorithms can identify urologically meaningful events solely using P_{VES} with minimal false positives [5, 6].

However, prior work focused on event detection, not P_{DET} reconstruction [5, 6]. Estimating the underlying P_{DET} from a signal containing superimposed P_{ABD}, with few distinguishing frequency components, is challenging. Broadly, P_{VES} may be split into P_{DET} and P_{ABD} components with high- and low-pass filtering. Karam et al. demonstrated that by applying a discrete wavelet transformation (DWT) with Daubechies 4-tap wavelet, the signal may be separated into approximation and detail coefficients, where the detail coefficients tend to contain P_{ABD}, and the approximation coefficients tend to contain P_{DET} and may be used to detect voiding events [6].

Correlation analysis from 20 urodynamic (UDS) recordings demonstrated that P_{DET} and P_{VES} were consistently linear, indicating that P_{DET} is contained within P_{VES} (Fig. 2). As expected, the correlation of P_{DET} with P_{ABD} was low, indicating that P_{ABD} is independent of P_{DET} and should be removed from the estimate of P_{DET}. The proposed framework therefore uses P_{VES} to estimate P_{DET}.

The framework comprises three main stages: the prefilter stage, discrete multiresolution analyzer, and signal reconstruction (Fig. 3). The framework is intuitive from the perspective of an embedded system which would ease verification and troubleshooting in an embedded system implementation where P_{VES} is buffered, then pushed to the pipeline using the sliding

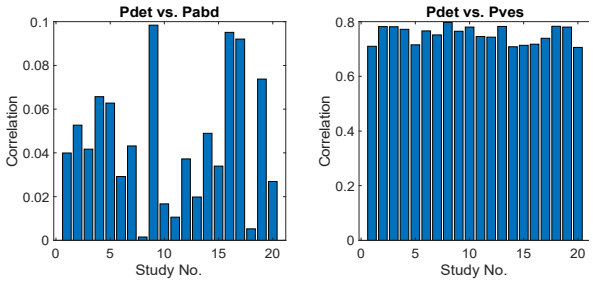

Figure 2. Correlation between P_{ABD} and P_{DET} (left) as well as P_{VES} and P_{DET} (right) from data from 20 human subjects.

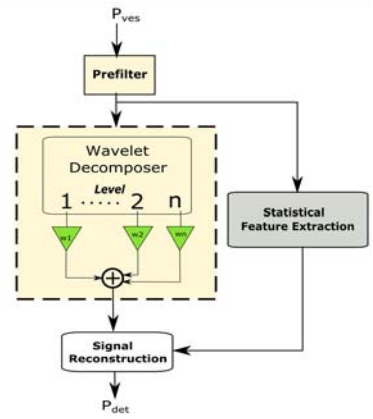

Figure 3. A block diagram shows the estimation process stages: filtration, wavelet decomposition, and signal reconstruction using the statistical features.

window/frame technique. The function of each stage is affected by the window size. Therefore, the size of the sliding window (W_{sz}) is crucial for estimation efficiency. Selecting the optimal size of the sliding window is outside the scope of this work and was considered as a fixed size (W_{sz}=32 sample).

III. METHODOLOGY

A. URODYNAMIC DATA

A total of 20 (7 male and 13 female) cystometry UDS recordings were collected using air-charged catheters with a CT3000Plus Complete Urodynamics system (SRS Medical, N. Billerica, MA) at a sampling rate of 10 Hz. Recordings consisted of multiple signals including volume voided (Volume), intravesical pressure (P_{VES}), intra-abdominal pressure as measured via a rectal catheter (P_{ABD}). A signal representing the simultaneous difference between these two pressure channels ($P_{DET} = P_{VES} - P_{ABD}$) was calculated. Data were manually annotated to denote relevant events such as cough, valsalva, position change, and voiding contraction during retrograde bladder filling and voiding.

B. PREFILTERING STAGE

The prefilter removes white noise and spike artifacts which arise from movement of catheters during cystometry. A two-stage filter was used. The first stage was a 10^{th} order finite impulse response band-pass filter with bandwidth of 0.02 - 5 Hz and stop band attenuation of 30 dB. The second stage was a 3^{rd} order Savitzky-Golay smoother which used convolutional linear least squares to fit successive adjacent data points with a low degree polynomial [7, 8]. Unlike simpler smoothing techniques, such as a moving average filter, the Savitzky-Golay smoother preserves data features such as peak width and height.

C. MULTIRESOLUTION WAVELET ANALYSIS

The filtered data were passed to a wavelet multiresolution analyzer (MRA) and decomposed into fundamental frequency components. The strength of MRA dwells in its ability to preserve time-domain and frequency-domain information using the DWT. The proposed MRA unit was augmented with a tunable weight vector W_i , where $i \in [1,2,\dots N]$ and $N = \log_2(W_{sz})$ was the wavelet resolution level. The weight vector provided a flexible method of estimating P_{DET} using a weighted sum. In this work we used Wsz=32. Since the sampling rate of UDS datasets was 10 Hz, it was possible to decompose the 32-sample frame into five frames representing the window component at 1, 2, 3, 5, and 10 Hz (32 sample in each resolution).

In addition to window size, sampling frequency, and weighting vector, selecting a mother wavelet for MRA played an important role in estimating P_{DET}. The output of the wavelet decomposer, $\tilde{P}$, can be described as:

$$\bar{P}(W,\psi,W_{sz}) = \sum_{i=1}^{N} \left(\frac{1}{\sqrt{2}}\right)^{i} W_i \psi_i \qquad (2)$$

where W_i is the window resolution at level i, $\psi(.)$ is the mother wavelet function, and $N = \log_2(W_{sz}) \in \mathbb{R}$ is the depth of decomposition. Usually, the vector W_{sz} is predefined and selected to capture the slowest event (e.g., Valsalva). Instead, we investigated varying the mother wavelet first with a unity weighted vector value. Then the W value was obtained with a static mother wavelet function via least mean square (LMS) fitting.

Reconstructing a 10 min cystometry signal from its MRA resolutions provided a test for wavelet function fidelity. The RMS error between the original and reconstructed signal called reconstruction error (RE) and the reconstruction computation time (RT) were used to evaluate the selected wavelet function though the reconstruction test. A set of popular symmetrical and orthogonal wavelet functions were selected to test as shown in Table 1. The Symlet wave function with four vanishing points (Sym4) was selected since it achieved the best balance between RT and RE.

In order to find the weight vector, LMS was used with P_{VES} as the input and P_{DET} as the output. With W_{sz}=32 and wavelet function Sym4, the P_{VES} was decomposed into 5 levels. The LMS results showed that the last level weight was significantly higher than the other weights when estimating the low-frequency P_{DET} signal (Fig. 4).

D. Event Detection and Elimination

Event detection improves the DWT estimate of P_{DET} because it allows an event-dependent selection of the reconstruction weights W_i. For example, if an abdominal event (containing high frequency elements) is detected, the weighting vector for windows during the event can de-emphasize initial scales of the DWT.

Table 1. The characteristic of reconstruction outcomes using different wavelet functions

	Haar	DB4	**Sym4**	Dmey	Coif4
RT (msec)	1.9	3.7	**3.4**	8.7	14
RE	1e-5	1e-12	**1e-12**	1e-12	1e-12

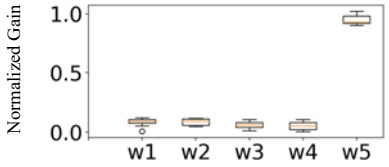

Figure 4. Gains in wavelet decomposition of 5-level wavelets resulting from LMS for the cystometry dataset and 32 sample window size.

Statistical features of the window serve as an alternative abstract representation of the window and a strong indicator of contraction onset and termination of each event. Previous work reported using an adaptive threshold that tracks the baseline pressure and detects when the P_{DET} estimate exceeds this plus a fixed threshold [9]. The most recent work has investigated the detection and classification of bladder events using wavelet analysis [5, 6].

However, while previous studies reported only detection of event onset, detecting the total span of an event is an important factor that has received less attention [7]. The span of the event is the time difference between the onset and termination time. The given UDS dataset showed that the average duration of coughs was 1.4±0.5 sec and the average duration of a Valsalva event was 2.5±0.5 sec. The fixed window size of 32 samples was sufficient to capture the slowest event with at most two consecutive windows.

Event detection used the previous observations to identify a vector of threshold values to identify the event onset and termination. For a sliding window, the kernel of the event detection algorithm was:

$$\Gamma(k) = \begin{cases} \mathbf{1} & F_g > T_m \; and \; f(v) > T_r \\ \mathbf{0} & otherwise \end{cases} \qquad (3)$$

where $v = [\mu, \sigma, \xi, \delta] \in \mathbb{R}^4$ is a vector, σ is the local window standard deviation, μ is the arithmetic mean, δ is the maximum value of local gradient, ξ is the rate of signal zero crossing, F_g is a flag set at onset and cleared at termination, and T_m and T_r are threshold values corresponding to the average duration of each event. In the presented work, $T_m$and T_r were empirically determined by manually identifying the lengths of valsalva and cough events.

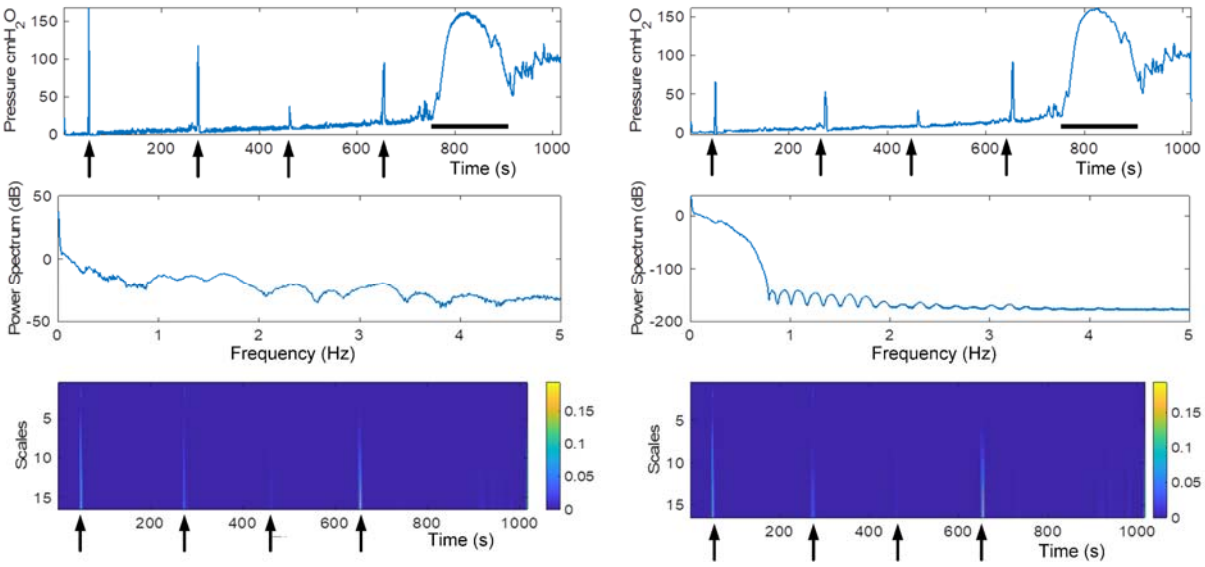

Figure 5. Frequency spectrum and scalogram of Pves before (left) and after (right) the two stage prefilter. Arrows indicate the locations of cough events, and the solid horizontal bar identifies the duration of the bladder voiding (emptying) phase.

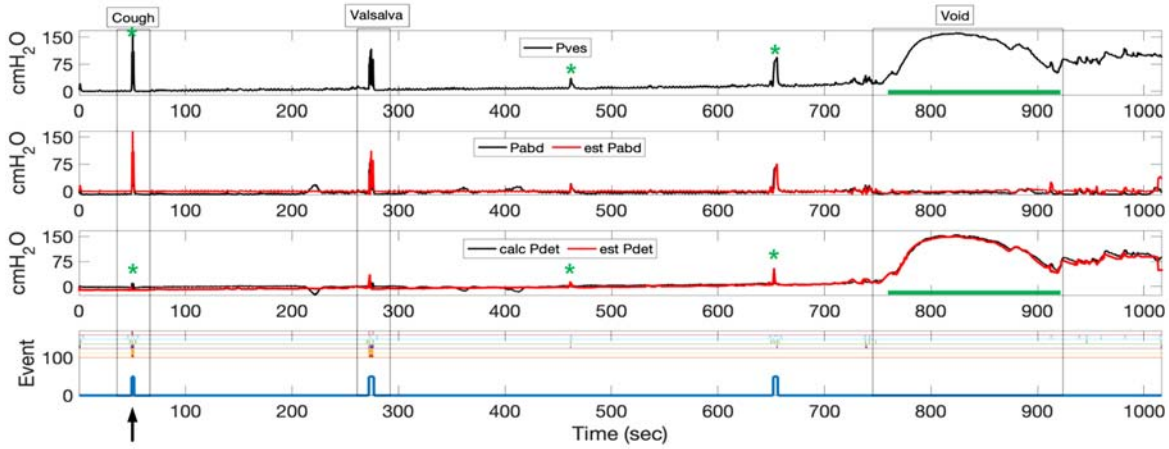

Figure 6. A urodynamic study with measured P_{VES} (1st row), measured P_{ABD} vs. estimated P_{ABD} (2nd row), estimated P_{DET} vs. calculated P_{DET} (3rd row), and event indicator (4th row). Cough events on PVES and passing to PDET are marked with asterisk (*) and the void event is denoted by a solid horizontal line indicating the start and end.

In general, the estimated P_{DET} was calculated by eliminating the detected events, i.e:

$$P_{DET}(W, W_{sz}, \mu, \sigma, \delta, \xi) = \begin{cases} \bar{P} & \Gamma(k) = 1 \\ \bar{P} - \mu & otherwise \end{cases} \quad (4)$$

This relatively simple technique was adopted due to the low computational overhead, which makes it more suitable for real-time implementation.

IV. Results and Conclusion

In addition to smoothing the P_{VES} signal, the 2-stage prefilter attenuated large amplitude, pressure spikes due to coughs (Fig. 5). Coughs should only appear in P_{ABD}, with no pressure in the P_{DET} estimation, because they are generated entirely by the abdominal muscles. Pairing the wavelet decomposer with the prefilter resulted in a 23% reduction in cough artifacts passing to the P_{DET} estimation instead of P_{ABD}.

The root main square (RMS) value and correlation coefficient R were used to evaluate algorithm accuracy. Furthermore, a statistical F-Score was used to evaluate the accuracy of artifact detection. The output of the estimator was compared with the calculated P_{DET}, and the overall estimation performance showed $RMS = 10.7 \pm 2.1\ cmH_2O$ and $R = 0.88 \pm 0.6$ (N=20). Moreover, detection accuracy for cough and valsalva were 99.5% and 84.3% respectively (Fig. 6). Detection accuracy was determined relative to clinical annotation of events for each cystometry recording.

In conclusion, we have developed a promising proof-of-concept of estimating P_{DET} using data from a single catheter. The single catheter estimator could mitigate the burden of using two catheters during cystometry.

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