VALIDATION OF PRESSURE MEASURING TECHNIQUE FOR UROFLOWMETRY

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ABSTRACT
Uroflowmetry is a non-invasive clinical test useful for screening benign prostatic hyperplasia (BPH) common in the aged men. The standard way to obtain the urinary flow rate is to continuously measure the urine weight proportional to volume over time. The present study proposed an alternative technique measuring pressure to overcome noise problems present in the standard weight measurement. Experiments were performed to simultaneously acquire both weight and pressure changes during urination in 9 normal men. Noise components were separated from volume signals converted from both weight and pressure signals. Signal-to-noise ratio was defined as the ratio of the signal to noise power in volume changes, which was 8.5 times larger in the pressure measuring technique, implying that cleaner signal could be obtained, more immune to noisy environments. When four important diagnostic parameters were estimated, excellent correlation coefficients higher than 0.99 were resulted with mean relative errors less than 5%. Therefore, the present pressure measurement seemed valid as an alternative technique for uroflowmetry.

KEY WORDS
Benign prostatic hyperplasia, Uroflowmetry, Pressure measurement, Signal-to-noise ratio, Diagnostic parameter estimation.

1. Introduction
The prostate is continuous with the base of the bladder and encloses prostatic urethra. Benign prostatic hyperplasia (BPH) is characterized by an increased prostate volume in the periurethral area, resulting in clinical symptoms of lower urinary tract. The severity of BPH, one of the most common disease among older men, significantly affects the health-related quality of life[1]. Uroflowmetry is a widely practiced non-invasive clinical test to evaluate voiding function for screening BPH. The standard way to obtain the urinary flow rate signal is continuously measuring the weight of urine over time by a load cell as shown in Fig. 1.

![Fig. 1. Uroflowmetry principle by weight measurement.](image)

The urine container is placed upon the load cell, which provides an electrical signal of the weight(W) proportional to volume(V) as in Eq. (1),

\[
W=mg=\rho gV
\]

where m, \( \rho \), and g are mass, density, and gravitational constant, respectively. Since urinary flow rate(F) is obtained by differentiating V with time(t) by definition,

\[
F=\frac{dV}{dt}=\frac{1}{\rho g} \frac{dW}{dt}
\]

Diagonal parameters, e. g., maximal and mean urinary flow rates, are easily calculated on F(t)[2]. Although weight measuring seems simple enough, undesired noises are introduced such that downward urination accelerates the stream of urine, applying significant impact against the bottom of the container in addition to its own weight. Also, the container with urine in needs to be well balanced upon the load cell, otherwise it is inclined in different directions depending on where the urine stream arrives. Both of these phenomena would occur in an unpredictable way, reducing the signal-to-noise ratio(SNR) in the weight signal, which may lead to noisy volume measurements.
To overcome these problems, the present study proposes an alternative technique which measures pressure near the bottom of the urine container as shown in Fig. 2.

Fig. 2. Uroflowmetry principle by pressure measurement. Pressure transducer with a catheter provides the pressure signal $(P)$ on the bottom proportional to volume $(V)$.

With a container of cylindrical shape, the pressure $(P)$ on the bottom is proportional to the depth below surface $(h)$, thus proportional to $V$ as in Eq. (3),

$$P = \rho gh = \frac{P_g g}{A} V$$

where $A$ is the cross-sectional area. $F$ is then calculated similarly to Eq. (2).

$$F = \frac{dV}{dt} = \frac{A}{\rho g} \frac{dP}{dt}$$

In our experience, this pressure measuring technique reduced noise to a significant degree, thus the present study performed experiments in normal men, simultaneously measuring both $W$ and $P$ signals, and quantitative comparison was made. SNR was evaluated in a polynomial signal model followed by estimation of diagnostic parameters.

2. Materials and methods

Experimental set-up. A cylindrical container was made with a diameter of 70mm and a height of 300mm. A side hole was made near the bottom, through which a catheter with a diameter of 3mm was inserted to measure $P$ by a differential pressure transducer (MPX10DP, Freescale, U.S.A.). A load cell (BCL-2L, CAS Corp. Korea) beneath the container simultaneously provided $W$ during urination. As shown in Fig. 3, both signals were digitized with 12 bits at 100Hz (P-400, PhysioLab, Korea), converted into volume unit, and stored in a personal computer for later analysis.

To minimize any possible noises including the aforementioned impact effect, dual funnel structure was specially made as shown in Fig. 4. The upper funnel collected urine toward the upside down surface of the lower funnel, which spread urine outward and guided flow to the side wall of the container. By this way, urine always flowed on the inner side surface, down to the bottom of the container.

Fig. 3. Block diagram of the experimental set-up. Both weight and pressure signals were simultaneously acquired, digitized, then stored in a personal computer (PC) for analysis.

Fig. 4. Dual funnel structure to minimize possible noises. Both collecting and guiding funnels guided the urinary stream in a desired way. Refer to text for detailed description.

Experimental procedure. Nine healthy males aged 20–30 years participated in the experiment. They drank 350mL of water right after lunch, waited for at least 2 hours, and voided on voluntary necessity. Voiding was made with standing position into the collecting funnel without particular attention.

Noise decomposition. For quantitative analysis of noise, $V$ acquired during the experiment was considered to be composed of true signal and measurement noise as

$$V = s + n$$

where $s$ and $n$ denoted the signal and the noise components, respectively. Since the signal component would slowly increase while voiding, 3rd order polynomial was introduced to represent $s$ as

$$s(t) = at^3 + bt^2 + ct + d$$

where $a$, $b$, $c$, and $d$ were constant coefficients. From Eqs. (5) and (6),

$$n(t) = V(t) - s(t)$$
Noise component introduced during the measurement keeps, in general, much higher frequency band than signal component, thus the constants, a, b, c, and d, were estimated by least squares fitting of V onto the 3rd order polynomial model in Eq. (6). Although V has both s and n components, high frequency components of noise are removed by least squares fitting as long as n shows random feature. The estimated constants, a, b, c, and d, formed s in Eq. (6) subtracted from V to decompose n by Eq. (7). Since the quality of a signal should be assessed by signal-to-noise power ratio (SNR) rather than the amplitude of noise and the power in a time signal is proportional to the squared amplitude[3, 4], SNR was defined as

\[
SNR = \frac{\int_{T_u}^{T_u+T_w} s^2 dt}{\int_{T_u}^{T_u+T_w} n^2 dt} = \frac{\int \left( a t^3 + b t^2 + c t + d \right)^2 dt}{\int \left( V(t) - \left( a t^3 + b t^2 + c t + d \right) \right)^2 dt}
\]

where integration was performed over voiding period. SNR was calculated for volume signals converted from both weight and pressure measurements in every subject. Paired student’s t-test was performed between the weight and pressure measurements in every subject. Paired student’s t-test was performed between the weight and pressure measurements in every subject. The very high correlation coefficient of 0.9996(P<0.0001) of the 4 parameters were estimated on both F_w and F_p, and compared between the two techniques by linear regression analysis with the weight signal parameters as independent variables, since the weight measurement is the current standard in clinical practice[5].

3. Results

**SNR comparison.** Figs. 6(a) and 6(b) show V_w and V_p signals, respectively, acquired in a typical subject. The magnitude of high frequency variation presumably reflecting the noise component seems significantly larger in V_w compared with V_p. Signal and noise components are separated in Figs. 6(c, d) and 6(e, f), respectively, clearly seen that the magnitude of noise in pressure measuring technique(Fig. 6(f)) is much smaller than that of weight measuring technique(Fig. 6(e)). When the averaged SNR was calculated for 9 subjects, the pressure measuring technique showed approximately 8.5 times higher value than the weight measuring technique. Paired student’s t-test established statistical significance(P<0.001), demonstrating that the pressure measuring technique, proposed by the present study, was superior in signal quality to the standard weight measuring technique.

**Diagnostic parameter estimation.** Following the SNR comparison described above, the volume signals obtained from weight and pressure measurements (denoted by V_w and V_p, respectively) were moving averaged over 11 data points(±50msec) and numerically differentiated to obtain the urinary flow rate signals (F_w and F_p, respectively). F_w and F_p were again moving averaged over 11 data points. Moving averaging was performed for both volume and flow to reduce noise as much as possible before parameter estimation. The weight and pressure measuring techniques to determine the less noisy technique.

**Diagnostic parameter comparison.** Linear regression results are depicted in Fig. 7 with the identity line for all 4 diagnostic parameters. In Fig. 7, the weight and pressure measuring techniques are denoted by the superscripts, “w” and “p”, respectively, on each parameter notations. The voiding duration, T_w was slightly longer in pressure measuring technique with relative errors<4% in Fig. 7(a). The urinated volume, V_w took a slightly but consistently larger values in the pressure measuring technique(Fig. 7(b)) by approximately 5%, however, demonstrated a very high correlation coefficient of 0.9996(P<0.0001). The maximal urinary flow rate, F_max, in Fig. 7(c) was somewhat larger in pressure measuring technique by a mean relative error of approximately 5% with the lowest correlation coefficient of 0.9931(P<0.0001) of the 4 parameters. The mean urinary flow rate, F_mean, in Fig. 7(d) showed similar values in both techniques with relative errors less than 3% with a correlation coefficient of 0.9973(P<0.0001). Although V_w and F_max were somewhat larger in pressure measuring technique compared to the standard weight measurement, the relative errors averaged for 9 subjects were no greater than 5% with excellent correlation coefficients higher than 0.99. T_w and F_mean demonstrated similar values in both techniques also with high enough correlation coefficients(0.9991 and 0.9973, respectively). Therefore, both weight and pressure

- The voiding duration(T_w) was first determined as the time taken to finish voiding. Urinated volume(V_u) was obtained by integrating F(t) over T_w. The maximal urinary flow rate(F_max) was read at the peak on F(t), and V_u was divided by T_w to get the mean urinary flow rate(F_mean). All four parameters were estimated on both F_w and F_p, and compared between the two techniques by linear regression analysis with the weight signal parameters as independent variables, since the weight measurement is the current standard in clinical practice[5].
measuring techniques were equivalent to each other in diagnostic parameter estimation capability.

Fig. 6. Volume signals (a, b) obtained from weight (a, c, e) and pressure (b, d, f) measurements in a typical subject. The subscripts “w” and “p” denote weight and pressure measurement techniques, respectively. s(c, d) and n(e, f) are decomposed signals and noises, respectively, from V(a, b).
Fig. 7. Linear regression results of 4 diagnostic parameters. (a), (b), (c), and (d) correspond to $T_u$, $V_u$, $F_{\text{max}}$, and $F_{\text{mean}}$, respectively. The straight and dashed lines represent the identity and the regression lines, respectively. The superscripts, “w” and “p” on each parameter abbreviations denote weight and pressure measuring techniques, respectively. R in each panel is the correlation coefficient.

4. Discussion

In the present study, the authors proposed an alternative technique of uroflowmetry, measuring pressure to reduce noises introduced in the standard weight measuring technique. Although weight and pressure are equivalent physical variables for volume measurement (Figs. 1 and 2), practical situation could be quite different. The subject voids down into the container, thus the urinary stream gets higher velocity due to gravity having more kinetic energy than flowing in horizontal direction. When it hits the bottom of the container or the surface of the load cell, impact noise inevitably occurs in addition to the urine weight itself. As pointed out earlier, unbalanced position of the load cell surface where urine arrives could cause another problem. More than single load cells could be used to average out the measurement noises, but not practical due to increased production cost. When pressure instead of weight is taken as a measurand, the balance in transducer position is of no interest, because fluid pressure transmits to every direction resulting in the same pressure level anywhere on the horizontal plane of a same depth below surface where the catheter end is placed. It is also free of impact noise, since the pressure at the catheter end is only related to the depth below surface. The urine stream falling down may cause wave generation on the surface, but only an averaged effect would be transmitted to the catheter end. The experimental result that SNR of volume signal was very much enhanced by an average of 8.5 times in pressure measurement well proves these advantages.

Dual funnel structure of Fig. 4 was applied to reduce noises as much as possible for all experiments, yet the weight measurement had a lot larger noise amplitude than pressure measurement (Fig. 6). Therefore, the present pressure measurement can be considered as a superior technique in nature, which provides a signal more immune to ill conditioned environments, requiring less post processing. To test this advantage, we poured 500mL of water at high flow rates directly on the bottom of the container without using the funnels. The pressure signal was not affected showing a gradual increase with a similar degree of noise, whereas the noise component got much larger almost hiding the signal component in the weight signal. Much longer ($\approx 1$sec) averaging had to be done on the weight signal to obtain the true volume changes.

Moving averaging for a duration of $\pm 50$msec was the shortest duration to remove high frequency noise in the weight signal, thus applied on both the weight and pressure signals. Numerical differentiation was performed by simply taking slopes of the two adjacent volume data points to obtain flow rate signal, then another moving average also for the same duration of $\pm 50$msec was
performed to remove noise caused by differentiation. These two step moving averages enabled almost the same flow shapes in both the weight and pressure measurements as shown in Fig. 8.

![Graph](image)

Fig. 8. Urinary flow rate signals obtained from weight(a) and pressure(b) measuring techniques in a typical subject. Note the similar wave shape in both signals.

When a shorter duration by a half was applied for averaging, the weight measurement resulted in significant noise amplitude in flow, while the pressure measurement still provided a clean flow signal (specific results not presented). In other words, the pressure measuring technique needs less post processing of the raw signal.

Eventual goal of uroflowmetry is to obtain the parameters useful for diagnosis in voiding function of a patient. The four parameters estimated in the present study can represent the flow pattern well enough in clinical practice[2, 5]. $V_u$ showed almost ideal correlation coefficient between the weight and pressure measurements(Fig. 7(b)), but $V_p$ was consistently larger than $V_u$ by about 5% in all subjects, probably due to a small difference or error in calibration factors converting weight or pressure into the corresponding volume data. The same amount of deviation regardless of the magnitude of $V_u$ supports this possibility. $T_u$ in Fig. 7(a) showed a slightly longer time, since the same level of threshold was applied to the volume data converted from both the weight and pressure signals to determine the time moment of significantly increased flow rate above zero.

Considering two different transducers(load cell and pressure transducer) were used for each techniques, slight difference in $T_u$ would not cause a practical problem since the correlation coefficient was high enough(0.9991) as well as statistically significant($P<0.0001$). $V_u$ and $T_u$ were slightly overestimated in the pressure measurement, thus the ratio of these two parameters, $F_{mean}$ became almost the same in both techniques(Fig. 7(d)). The peak value on the flow rate signal, $F_{max}$ was somewhat larger in the pressure measurement and showed the lowest correlation coefficient of 0.9931. Overestimation in volume conversion from pressure should have been also reflected on flow rate, resulting in larger $F_{max}$. Since $F_{max}$ is a parameter taken at the instant moment showing a peak flow, it is not surprising to observe a lower correlation coefficient than the other three parameters having average nature. Nevertheless, a high enough correlation coefficient of 0.9931 should not disqualify the present pressure measuring technique.

In summary, the present study proposed a new pressure measuring technique for uroflowmetry in purpose of minimizing measurement noises introduced in the current standard weight measuring technique. Appropriately defined SNR showed a much larger value implying that the pressure measurement would provide a cleaner raw signal more immune to noisy environments. When four diagnostic parameters were estimated and compared between the two techniques, the correlation coefficients were higher than 0.99 with mean relative errors smaller than 5%, validating the equivalence of the present pressure measurement to the standard weight measurement technique. Further clinical studies on patients are warranted.

References