COMPARISON OF SOUND-BASED URINARY FLOW PREDICTION METHODS AND VALIDATION WITH A LARGE CLINICAL SAMPLE

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Uroflowmetry is a well-established and commonly conducted diagnostic test for Lower Urinary Tract Symptoms (LUTS), which assesses the severity of any blockage or obstruction by measuring the volumetric speed of urination. The urine flow is measured by a specially designed clinical scale called “uroflowmeter” while a patient urinates in a urology clinic. Recently, for at-home self-check of urinary flow to monitor full daily picture of voiding, several alternative uroflowmetry schemes with various modalities have been proposed, and sound-based models are regarded as a promising solution with its non-invasive and ease-of-use nature. These alternative acoustic-based approaches were developed and validated with the limited number of healthy human subjects, which is known to have a bell-shaped curve. However, the urine flow of patients shows various irregular patterns with low sound level and low signal-to-noise ratio, it is strongly needed to validate the prediction methods with various patients prior to utilizing new sound-based approaches as reliable medical applications. This study aims to validate existing acoustic-based urine flow prediction approaches with a large clinical sample including both normal subjects and patients. Uroflowmetry data and sound recordings of 137 subjects were collected in the urology clinic at a university hospital, and the performance of the existing prediction models was assessed with three key clinical urodynamic parameters including the maximum flow rate, voided volume and voiding time.

Keywords: sound based uroflowmetry, urine flow

1. Introduction

Uroflowmetry is a diagnostic test for Lower Urinary Tract Symptoms (LUTS) proposed by Drake in 1948 [1]. Uroflowmetry has been well-established for more than half-century and still commonly conducted to examine voiding pattern of a person in a urology clinic. The test measures voiding mass (ml) per unit time then calculates major parameters that are related to the LUTS diagnosis (see Fig. 1)
Although Uroflowmetry is the most accurate method to measure urine pattern of a patient, there are some limitations to perform the diagnostic test on a regular basis. First of all, voiding pattern of a person is generally irregular, cannot be performed at one’s will at in a timely manner. Furthermore, an unfamiliar environment – special equipped toilet installed located in a urology clinic – may affect one’s voiding pattern in an unnatural way. Therefore, there is a need for a new diagnostic method that can be used regularly in daily life.

There are various works that aim to use mobile devices to record voiding sound and analyze the voiding pattern. Sound level based analysis [2, 3, 4, 5], based on the prediction model from recordings [6], using multiple channels with selected frequency bands [7, 8]. On the other hand, using additional acoustic sensor is proposed [9].

In this study, Uroflowmetry data and sound recordings of 137 subjects were collected in the urology clinic at a university hospital. These data were used to validate voiding pattern prediction methods based on an acoustical analysis.

Among abovementioned four urine flow measurement methods based on sound analysis, two methods were selected to evaluate. Sonouroflowmetry (SUF) was chosen as the most advanced and validated scheme with two validation studies with 50 healthy male and female patients, one registered US patent and a prototype mobile application. The other is Uroflow Monitor (UFM) with a number of filed/registered patents and one FDA 510(k) clearance as a medical device. Both methods do not require specially designed hardware for recording and analysis, so can be easily built on smartphone or PC with the published information on their researches. SUF is based on the assumption that sound intensity in time domain highly correlated to flow rate, and UFM makes the assumption that urine flow has different spectrum characteristics across frequency subbands on top of the sound intensity.

2. Selected methods

2.1 Sonouroflowmetry (SUF)

Hitt et al. proposed Sonouroflowmetry (SUF) to predict the volumetric speed of urine from urinating sound recorded by mobile phone [2]. The underlying assumption is a direct correlation between urine flow rate and sound intensity of urinating sound at the air-water interface when the fluid hits the water surface. In the SUF method, signal-pressure level of the urinating sound is sampled, and its positive amplitude envelope is captured. Smoothing by a median convolutional filter is suggested to suppress acoustic artifact in time domain [3]. SUF assumes that this filtered signal would well represent the actual urine flow, which is typically measured by scale-based clinical uroflowmeter (Fig. 2). The methods were validated to show good correlation with uroflowmetry [3, 4].
We built an implementation of the SUF scheme as described above, following the information published in patents, papers and white papers. We also used a mobile application named *Uroflow Trace* developed and released by the SUF research team. To verify our version of the implementation of SUF, we recorded several urination events using both versions of implementation simultaneously. Figure 3 depicts predicted uroflows by *Uroflow Trace* mobile application and our implementation (simulation) from the same urination sound. We concluded that our implementation repeats the SUF scheme well and could be applied to predict uroflow retrospectively from the clinical data we collected instead of the SUF scheme and *Uroflow Trace* mobile application.

### 2.2 Urine Flow Monitor (UFM)

#### 2.2.1 Basic Idea

Urine Flow Monitor (UFM) is based on observations that certain frequency bands characterize the sound of the urine flow. The series of patents by Belotserkovsky propose that it is possible to measure the urine flow rate by detecting the intensity at selected acoustic frequency bands [7, 8]. The patents specify that the sound level within the range of 250-550Hz (called *Measurement channel*) strongly depends on a urine flow level, whereas the sound level in the frequency ranges of 1000-1200Hz, 2000-2200Hz, and 4400-4600Hz are significantly independent with the flow level (See Fig.7 in [7]). These independent frequency bands are called *Reference channels*. Belotserkovsky’s patents are based on the idea that by analyzing the difference or ratio between the measurement channel with one or more reference channels would determine the urine flow rate and other data.

#### 2.2.2 Calibration

The sound level of urine flows can be affected to device’s microphone characteristic and recording environment (e.g. distance to the source, background noise level). Therefore, the urine flow-monitoring device (sound recording device) should be calibrated before in use. In general, calibration using the total voided volume is practically applicable method. Let $D(t)$ be the difference between the measurement $M(t)$ and reference channel $R(t)$ (in decibel). Then $D(t) = M(t) - R(t)$ is proportional to the flow rate and the proportional constant $A$ and linear bias $B$ in Eq. (1) can be calculated if two distinct total voided volume is known for separate cases.
\[ V_o = \int_{t_1}^{t_2} (A \cdot D(t) + B) dt \] \hspace{1cm} (1)

3. Data acquisition

Outpatients who visited the urology clinic of Seoul National University Bundang Hospital were recruited. Research nurse explained the study and obtained informed consent from patients according to the standard consent process and procedure.

Clinicians and patients conducted usual uroflowmetry examination as prescribed by the investigators (certified urologists) in an examination room, and measured reference urine flow using clinical uroflowmeter (CubeFlowS; McubeTechnology Co. Ltd., Seoul, Republic of Korea). During the examination, the urination sound was recorded using built-in recording applications and microphone in iPod Touch with iOS (Apple, Inc., Cupertino, CA, USA) and Galaxy S8 (Samsung Electronics, Co. Ltd., Suwon, Republic of Korea) with Android operating system (Google, Inc., Mountain View, CA, USA) by researchers.

This clinical data acquisition study was approved by the Seoul National University Bundang Hospital institutional review board on September 7, 2017 (B-1709-423-301), and all participants provided written informed consent. The authors had full access to all deidentified data in the study and take responsibility for its integrity and the data analysis.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Male</th>
<th>Female</th>
</tr>
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<tbody>
<tr>
<td>PCC Qmax</td>
<td>0.38</td>
<td>0.78</td>
</tr>
<tr>
<td>PCC Voided Volume</td>
<td>0.68</td>
<td>0.60</td>
</tr>
<tr>
<td>PCC Voided Time</td>
<td>0.87</td>
<td>0.76</td>
</tr>
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</table>

4. Evaluation of selected methods

4.1 Sonouroflowmetry

4.1.1 Evaluation Measure

Sound data mixed with external noise and with Qmax lower than 5ml/s were excluded. After screening 9 males and 18 females data according to the criteria, data from 60 males and 50 females were selected for validation.

4.1.2 Results

Table 1 summarizes correlations between actual urine flow parameters and predicted parameters from the sound. Pearson Correlation Coefficient (PCC) of each voiding parameters between actual flow and SUF are cited from their validation works ([3, 4]). We repeated the evaluation of SUF with our own implementation (SUF-Sim) as described 2.1 and clinical data of outpatients. PCC of parameters in ‘SUF-Sim’ column in Table 1 was calculated between actual parameters captured from clinical uroflowmeter and predicted one by our implementation.

When SUF-Sim prediction applied to our male subjects, it shows good correlations of Qmax and voiding time (0.78 and 0.76, respectively) and a moderate correlation of voided volume (0.60). Qmax in this validation especially shows a significant rise in correlation, compared to the previous SUF validation study (0.38 to 0.78). It is supposed that difference in ethnicity, diversity of urine patterns, the severity of symptoms, study protocols and other unknown factors in subjects may cause the rise
in the correlation of Qmax. SUF validation used data collected from 25 healthy male subjects (ethniciy was not noted in the literature, but supposed to be Caucasian), and SUF-Sim used data from 60 male Asian subjects with no to severe level of symptoms and various voiding patterns.

Figure 4. Scatterplot representing the correlation between Qmax and Voided volume by uroflowmeter and corresponding data predicted by simulation.

For the female subjects, SUF-Sim prediction was documented to result moderate to low correlations of voiding parameters. For all three voiding parameters, significant drops in correlation were observed. Validation study of female subjects ([4]) doesn’t provide detailed information on prediction model, but it is supposed that SUF added some algorithms not known to us to optimize prediction performance for female subjects, while the same SUF-Sim prediction was applied to female subjects here.
4.2 Urine Flow Monitor (UFM)

Urine Flow Monitor (UFM) can be a distinctive approach compared to SUF or other methods based on sound pressure level change in the time domain because it is considering different response at selected frequency bands. It may be a unique solution based on the dynamic of the urine as it impacts the surface of the water in a toilet. The fundamental assumption of UFM is that the sound level of the measurement channel (250-550Hz) is proportional to the urine flow rate whereas reference channels (1000-1200Hz, 2000-2200Hz, and 4400-4600Hz) are independent of the urine flow rate. However, we could not verify the basic assumption with the clinical data.

![Figure 5](image)

Figure 5: (Left) Spectrogram of the recorded urine sound. (Right) Power spectral density of the selected bands

![Figure 6](image)

Figure 6: UFM prediction result

Figure 5 (right) shows the power spectral density (PSD) of the measurement channel and reference channels from one of the recordings from the clinical data. Power spectral density was calculated over a 0.1s temporal window with 50% overlap. From the spectrogram in Fig. 5 (left), we can see that urine started from 11s of the recording and PSD graphs in Fig. 5 (right) also clearly show this acoustic event. However, PSD of reference channels increase as urine start and follows the graph of the measurement channel; which contrasts to the basic assumption of UFM. Note that Figure 5 is based on the clinical data of a typical subject. Consequently, urine flow prediction using UFM does not work for any reference channels (Fig. 6).
5. Discussion

Based on our analysis (not published) of various sound features, urination of female subjects sounds differently from that of the male subjects, perhaps due to the difference in the anatomy of pelvic/lower urinary tract and posture during urination. We suppose a combination of those factors made different voiding sound of men and women, so a prediction scheme that worked with good correlation for the male could not work for the female. So far, most of the previous studies and patents focus on sound intensity and sound event at the air-water interface, which dominantly characterize male urination. Separate and dedicated models for female could be deliver better prediction and correlation result for female subjects.

The other integral factor to complete this technology as a clinically meaningful product is to offer predicted flow and parameters with guaranteed accuracy. The SUF method and SUF-Sim show moderate to good level of correlations in key voiding parameters, but it doesn’t guarantee accuracy in prediction. Uroflow Trace, a prototypical mobile application utilizing SUF method delivers relative predicted flow without an absolute prediction value of a flow rate. To be widely applied for clinically meaningful use including diagnosis of LUTS and at-home monitoring, further works on prediction value and accuracy validation beyond correlations analysis should be conducted.

6. Acknowledgment

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REFERENCES