Design of an Optical Uroflowmeter and Assessing Bladder Pressure Through Video Analysis of the Male Urine Stream

by

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Abstract

Voiding dysfunction, such as benign prostatic hyperplasia and impaired detrusor contractility, affects more than half of men over the age of 50. Uroflowmetry provides quantitative information of flow dysfunction by measuring the flow rate and total volume of urine expelled by the body. The majority of existing clinical uroflowmeters determine flow rate using a scale to measure increasing mass of urine expelled with time; however, they are expensive and typically found only in specialists’ offices, making it difficult for patients to receive testing. An opportunity therefore exists to develop a much more affordable device which would allow flow rate testing to become a part of routine care and to be conducted in a wider variety of environments such as General Practitioners’ offices and home monitoring. The high demand for digital cameras, particularly due to their extensive use in mobile devices, has resulted in their accelerated advancement and cost reduction. Therefore, a device based on this technology is investigated.

In addition to the development of this device, a study was conducted to investigate if information regarding bladder pressure may be obtained by analyzing digital images of the urine stream. Voiding dysfunction may result in abnormally high bladder pressure, caused by urinary obstruction, or low bladder pressure which may be caused by reduced detrusor contractility. The clinical implications and treatment for these two cases are very different; however, they present with similar low flow rate voiding patterns and cannot currently be distinguished non-invasively. It was postulated that increased inertia and turbulence may exist in high pressure flows, and may be identifiable in the digital images of the urine stream.
Preface

This thesis was prepared under the supervision and guidance of Dr. Sheldon Green and Dr. Dana Grecov who provided the research topic of designing a uroflowmeter based on image processing.

Dr. M.A. Lynn Stothers (Department of Urological Sciences, University of British Columbia Hospital) provided the research topic of determining if information regarding the pressure in the bladder can be obtained by analyzing digital images of the urine stream. Acquiring pathologic subjects was facilitated by Dr. M.A. Lynn Stothers, Jessica Galo, and Sabina Galay (Department of Urological Sciences, University of British Columbia Hospital). Ethics approval for this study was obtained from the UBC Clinical Research Ethics Board (Certificate Number: H11-03006).

For the optical uroflowmeter, the author designed and constructed the device and wrote the Matlab code to determine flow rate. For the Pressure Visualization study, the author recruited pathologic and control subjects, assembled the testing apparatus, and processed the digital images using Matlab.
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Glossary

**Binary image:** An image consisting of only ones (white) and zeros (black)

**Detrusor:** a layer of the urinary bladder made of smooth muscle fibers that forces urine out of the body as it contracts

**Detrusor instability/urge incontinence:** strong sudden need to void

**Detrusor overactivity:** involuntary detrusor contractions during filling

**Free Surface:** the surface of a fluid subject only to a perpendicular normal stress (gravity) and to no shear stress (the liquid-air boundary)

**Signs:** evidence observed by the physician to verify and quantify symptoms (i.e. leakage while coughing)

**Symptoms:** subjective and often qualitative indicators of pathology as perceived by the patient or care provider which may lead the individual to seek professional medical care

**Transurethral resection of the prostate:** surgery to treat benign prostatic hyperplasia in which prostate tissue is removed to eliminate or reduce obstruction

**Urethral stricture:** narrowing of the urethra due to injury or disease

**Urogenital System:** a grouping of the reproductive organs and the urinary system

**Urology:** the medical field focused on diseases and disorders affecting the urogenital system
List of Abbreviations

BCC  Bladder Care Centre at the University of British Columbia Hospital
BOO  bladder outlet obstruction
BPE  benign prostatic enlargement
BPH  benign prostatic hyperplasia
GP   general practitioner (family physician)
ICS  International Continence Society
IPSS international prostate symptom score
LUTD lower urinary tract dysfunction
LUTS lower urinary tract symptoms
P_{abd}  abdominal pressure
P_{det}  detrusor pressure
P_{d,max}  maximum detrusor pressure
P_{d,peak FR}  detrusor pressure at maximum flow rate
P_{d,mean}  mean detrusor pressure
P_{ves}  intravesical pressure
PFS  pressure-flow study
PVR  post void residual
Q_{ave}  average flow rate
Q_{max}  maximum flow rate
RMS  root mean square
UBC  University of British Columbia
UDS  urodynamic studies
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I would like to thank everyone whose help allowed me to complete this thesis. To my supervisors, Dr. Sheldon Green and Dr. Dana Grecov, for their insightful guidance and kind support. To Dr. M.A. Lynn Stothers for her insight and support, and to Jessica Galo and Sabina Galay for their assistance in recruiting pathologic subjects. To Markus Fengler, Glenn Jolly, and Sean Buxton for their expertise, willingness to help, and admirable patience. A special thanks to everyone who volunteered as subjects for this study. And finally, I am thankful for the love and support of my family and friends, without whom this work would not have been possible.
Chapter 1

Introduction

Lower urinary tract symptoms (LUTS) affect approximately two-thirds of men over the age of 40 [1]. Identifying the cause of LUTS is notoriously difficult as many present with similar symptoms. Urodynamic studies, in combination with patient history and examination, are used to identify the cause of dysfunction; however, these studies are invasive, expensive, and subject to clinical wait times.

1.1 Background

1.1.1 Relevant Anatomy and Physiology

The function of the lower urinary tract is to store and release urine in a controlled manner. Normal storage and release is dependent on a healthy and properly functioning bladder, urethra, urinary sphincters, and prostate as shown in Figure 1-1. Pathology affecting these structures leads to LUTS and voiding dysfunction.
Figure 1-1: Anatomy of the male lower urinary tract.

1.1.1.1 Bladder

The bladder is a highly distensible muscular organ with two functions: to store and release urine. The normally functioning bladder acts as a low pressure (< 40 cmH2O [2]) reservoir, and has an average capacity of 500 mL [3].

The bladder expels urine by contraction of the detrusor, a smooth muscle layer of the bladder wall. This contraction pulls the bladder neck open, forming a funnel though which urine is expelled. In normal voiding, pressure within the bladder does not exceed 10 mmHg [4], and no residual urine should remain [5].
The trigone is a triangular region within the bladder which connects the two ureteral orifices and the urethral orifice. This region contains stretch receptors which transmit signals to the brain signaling the need to void. The desire to urinate begins at a volume of approximately 150 mL [6].

The bladder neck, the most inferior portion of the bladder, lies directly on the prostate and is separated from the urethra by the internal urethral sphincter. Its function is to close the bladder outlet during storage.

1.1.1.2 Urethra

Urine leaves the body via the urethra which is separated from the bladder by the internal urethral sphincter. The total length of the male urethra is approximately 20 cm and is divided into four sections. The most superior section is the prostatic urethra, followed by the membranous, bulbar, and penile sections. It is 3-4 cm in length and is encircled by the prostate. The membranous urethra begins at the inferior apex of the prostate and is approximately 2 cm in length. The bulbar urethra is an enlarged section resembling a “bulb” and contains the bulbourethral gland. The penile urethra begins at the base of the penis and terminates at the external urethral meatus. The length of these two sections of the urethra vary from person to person.

1.1.1.3 Prostate

The normal prostate is a walnut sized (24 cm³) fibromuscular and glandular organ and lies directly inferior to the bladder. It weighs approximately 18 g and encircles the prostatic urethra. [3]

1.1.1.4 Urinary Sphincters

The urethra contains both an internal and external sphincter. The internal urethral sphincter is comprised of circular smooth muscle fibers from the detrusor and prevents urine from entering the urethra during storage. This sphincter is autonomously controlled by the parasympathetic nervous system. The external urethral sphincter is located inferior to the prostate and is made of skeletal muscle and is under voluntary control.
1.1.2 Relevant Pathology

LUTS are typically what cause patients to seek medical attention; however there is very little correlation between symptoms and their cause, as a variety of conditions may present with similar symptoms. For example, prostatectomy was historically conducted to relieve symptoms indicative of obstruction, but showed a cure rate of only 72%, low for an elective procedure of this nature [7]. LUTS may also indicate pathologies outside of the urogenital system, such as inflammation or carcinoma of surrounding structures, side effects of medication, and diet. Objective and quantifiable testing is therefore necessary.

Risk factors for voiding dysfunction include increasing age [8], weight gain in adulthood, especially around the mid-section [9] [10] [11], high alcohol consumption (≥75g/day), a history of hypertension [12] or diabetes [12] [13] [14], and consumption of red meat [15].

Factors associated with a decreased risk or severity of LUTS include vegetable consumption, especially those high in lycopene, vitamin E, and carotene [16] [17] [15], and increased physical activity [18] [19] [14].

1.1.2.1 Lower Urinary Tract Symptoms

LUTS are typically divided into three categories: storage, voiding, and post voiding symptoms. Details of these symptoms are provided in Table 1. These categories are not isolated, and it is common for abnormalities of the voiding phase to cause problems in the storage phase [20].
Table 1: Lower urinary tract symptoms as defined by the International Continence Society [21]

<table>
<thead>
<tr>
<th>Storage Phase Symptoms</th>
<th>Description</th>
</tr>
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<tr>
<td>Increased daytime frequency</td>
<td>Patient voids frequently during the day</td>
</tr>
<tr>
<td>Nocturia</td>
<td>Patient wakes one of more times at night to void</td>
</tr>
<tr>
<td>Urgency</td>
<td>Sudden and difficult to defer desire to pass urine</td>
</tr>
<tr>
<td>Urinary incontinence</td>
<td>Involuntary urine leakage</td>
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<table>
<thead>
<tr>
<th>Voiding Phase Symptoms</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>Slow stream</td>
<td>Perception of slow urine flow</td>
</tr>
<tr>
<td>Splitting or spraying</td>
<td>Urine stream splits into multiple streams or sprays</td>
</tr>
<tr>
<td>Intermittent stream</td>
<td>Urine flow stops and starts on one or more occasions</td>
</tr>
<tr>
<td>Hesitancy</td>
<td>Difficulty initiating a stream</td>
</tr>
<tr>
<td>Straining</td>
<td>Muscular effort used to initiate, maintain, or improve the stream</td>
</tr>
<tr>
<td>Terminal dribble</td>
<td>Flow slows to a trickle/dribble and the final part of voiding is prolonged</td>
</tr>
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<table>
<thead>
<tr>
<th>Post Voiding Symptoms</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeling of incomplete emptying</td>
<td>Sensation of urine remaining in the bladder</td>
</tr>
<tr>
<td>Post micturition dribble</td>
<td>Involuntary loss of urine immediately after finished voiding, usually after leaving the bathroom or rising from the toilet.</td>
</tr>
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</table>

1.1.2.2 Relevant Causes of Lower Urinary Tract Symptoms

In men, LUTS are typically the result of obstruction or impaired detrusor function. These conditions need not occur in isolation, and in fact, bladder outlet obstruction often occurs along with detrusor overactivity [22].

Obstruction is among the most important urologic disorders not only due to its high prevalence, but also as it often results in urinary tract infection and may lead to atrophy of the kidney.

The most common cause of obstruction is benign prostatic hyperplasia (BPH) [14], a condition in which the number of epithelial and stromal cells in the prostate increases. The growing prostate may impinge upon the urethra, resulting in obstruction. Voiding pressure in individuals with BPH is increased as the detrusor must overcome the increased resistance of the narrowed urethra, leading to hypertrophy of the detrusor. The prevalence of BPH increases with age affecting 25% of men between 40 to 49 years of age, 50% of men between 50 – 59 years of age,
and 80% of men between 70 to 79 years of age [23]. A comparison between a healthy lower urinary tract and one affected by BPH is shown in Figure 1-2.

![Figure 1-2: Depiction of a normal bladder and prostate (left), and enlarged prostate causing obstruction and hypertrophy of the detrusor and bladder neck. (Image reproduced from Smith’s General Urology [5].)](image)

Causes of urinary obstruction other than BPH include cancer or inflammation of the prostate or surrounding structures, calculus formation, urethral stricture, and anatomical abnormalities.

A second cause of LUTS is impaired detrusor function which includes detrusor instability, impaired contractility, and under-activity.

Detrusor instability is characterized by the involuntary and spontaneous contraction of the detrusor during storage, due to causes other than neurologic disease. Often the cause of this condition is unknown. Unlike other causes of dysfunction, a strong correlation between detrusor instability and LUTS urgency and urge incontinence has been observed [7] [24].

Impaired detrusor contractility involves reduced detrusor contraction strength and duration resulting in post-void residual urine volume. Other causes of LUTS include sphincter
incompetence, outpouching of the bladder or urethra (urethral or bladder diverticulum), damage to structures in surgery. Medications may also cause LUTS, with diuretics causing an increase in urinary frequency as an example.

When the strength and/or duration of detrusor contraction is reduced, detrusor underactivity is said to be present. This condition has a prevalence of 40% of elderly men, becoming more prevalent with age [25].

1.1.3 Patient Evaluation and Urodynamic Studies

Due to the unreliability of symptoms and their poor correlation to cause, urodynamic studies are key in obtaining quantifiable data regarding the health of the lower urinary tract. Urodynamic studies seek to reproduce symptomatic complaints in an environment in which measurements can be made to determine their cause.

Patient evaluation often begins by obtaining a detailed history, and possibly scoring symptoms using the International Prostate Symptom Score (IPSS). The IPSS is reproduced in Appendix A and consists of seven questions regarding frequency, nocturia, weak stream, hesitancy, intermittency, incomplete bladder emptying, and urgency. Each question is rated on a 5 point scale and the severity of symptoms is determined from the sum as mild (a score of 0 to 7), moderate (8 to 19), or severe (20 to 35).

There are a variety of other tools available to clinicians to assess the health of the urogenital system such as the following:

- A voiding journal recording voiding time and volume
- A rectal exam to assess the size, shape, and stiffness of the prostate
- X-ray of the abdomen and pelvis
- Urinalysis to test for urinary tract infections and to assess renal function.
- Urinary cytology to screen for carcinoma of the bladder
- Measurement of post-void residual volume (PVR)

Urodynamic studies include the following three tests: uroflowmetry, filling cystometry, and pressure-flow studies. Each of these tests are explained in detail in the sections below.
1.1.3.1 Uroflowmetry

Uroflowmetry is the measurement of urine flow rate, and is a non-invasive tool used to assess the functional state of the urinary tract. When this test is used in conjunction with invasive cystometry and pressure-flow studies, a definitive diagnosis of the cause of dysfunction can be determined.

Devices that measure urine flow rate are called uroflowmeters, and the parameters they measure are shown schematically in Figure 1-3. FDA regulation number 876.1800 lists uroflowmeters as a Class II device and are exempt from premarket notification procedures.

![Diagram of uroflowmetry parameters](image)

**Figure 1-3:** Schematic of a normal uroflow showing measured parameters with International Continence Society recommended terminology.

Normal flow patterns achieve a maximum flow rate of 15 mL/s or greater [26] within the first 5 seconds of flow [7], and have an average flow rate of approximately half the maximum flow rate [5]. In reduced flow patterns, the maximum flow rate does not exceed 10 mL/s [26]. Rates between 10 and 15 mL/s are difficult to interpret meaningfully as there is significant overlap between normal and symptomatic men in this range. Some urologists recommend using the average maximum flow rate of multiple tests, but this is difficult and expensive to conduct [27].

Three classic uroflow patterns are reproduced in Figure 1-4.

- Figure 1-4 (a) shows a classically normal bell shaped flow pattern in which the flow rate progresses relatively smoothly, reaching a maximum flow rate well above 15 mL/s.
- Figure 1-4 (b) shows an example of abdominal straining with detrusor activity. As this patient’s detrusor muscle does not contract, generating the pressure required to void, he must instead contract his abdominal muscles, allowing him to void in spurts with each abdominal contraction.

- Finally, Figure 1-4 (c) shows a classically obstructed flow pattern identifiable by the prolonged flow time and low flow rate. The fluctuations are due to attempts at improving flow by again squeezing the abdominal muscles; however, this is met with less success as the obstruction impairs flow.

**Figure 1-4:** Examples of uroflowmeter traces (a) a normal flow, (b) a flow indicative of abdominal straining, (c) a flow indicative of obstruction. The horizontal axis is time where each square is one second. (Images reproduced from Smith’s General Urology [5].)
Uroflowmeters are used in both seated and standing configurations as shown in Figure 1-5. A large funnel directs the flow into a collection container and flow rate is determined.

<table>
<thead>
<tr>
<th>Seated</th>
<th>Standing</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="a" alt="Image" /></td>
<td><img src="b" alt="Image" /></td>
</tr>
<tr>
<td><img src="c" alt="Image" /></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 1-5:** Uroflowmeters used in three configurations: (a) seated on a urodynamics exam table [28] (b) general seated configuration [29], and (c) standing configuration [28].

Several variations of the uroflowmeter have been investigated and are available commercially. The advantages and disadvantages of many of these designs are discussed in the following section.

### 1.1.4 Current and Prior Designs

The first attempt to measure urine flow was made by Rehfisch in 1897 in which a collection container was connected to Marey’s tambour and flow rate was recorded using a kymograph [30]. The modern uroflowmeter was invented by Willard M. Drake in 1948 [31]. His device provided an idea of maximum flow rate by directing urine into a container corresponding to a flow rate range. This principle and many other principles of operation have been investigated, as outlined in Table 2.
Table 2: Past and current investigations into uroflowmeter design

<table>
<thead>
<tr>
<th>Descriptive Title</th>
<th>Principle of Operation</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Gravimetric       | Accumulating weight [32] or pressure [33] is measured by a scale or pressure transducer and correlated to volume which is differentiated with time to get flow rate. | • Well established clinical use  
• Accuracy independent of site of stream impact  
• Easily adapts to a variety of collection containers | • Impulse measurement noise  
• Sensitive to changes in specific gravity  
• Expensive as requires scale or pressure transducer |
| Spinning Disk     | Urine is directed onto a disc rotated at a constant rotational velocity by a motor. The current required to maintain the disc spinning at the same rotational velocity is correlated to the urine flow rate. [34] [35] | • Well established clinical use in research applications  
• Accurate and highly responsive (typical time constant of 0.25 s) [36] | • Sensitive to the path of urine as it reaches the disc (If the stream hits different points on the disc or walls of the container, hills and valleys in the flow rate curve appear, especially at high flow rates.)  
• Low sensitivity at starting and ending stages of voiding [37]  
• Sensitive to changes in specific gravity  
• Cleaning is difficult  
• Noisy operation  
• Expensive as requires a motor and bearing system. |
| Capacitive Dipstick | The capacitance of a dipstick increases as urine accumulates is mounted in a collecting chamber. The change in capacitance is correlated to flow rate. [38] | • Inexpensive  
• No mechanical parts | • Sensitive to changes in specific gravity |
| Acoustic          | A microphone records the sounds of voiding which are analyzed using software reporting voiding strength and duration [39]. | • Useful in home monitoring applications  
• Inexpensive to implement | • Does not provide flow rate data but only flow rate intensity for the purpose of |
<table>
<thead>
<tr>
<th>Descriptive Title</th>
<th>Principle of Operation</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| **Inductive/Magnetic** | Urine passes through a magnetic field inducing a voltage in the urine proportional to its flow rate. The induced voltage is measured by two electrodes positioned at right angles to the flow. [40] [41] | • Collection container not required and can be positioned over a toilet | • Measuring signal is small  
• Electromagnet which is necessarily powerful is relatively expensive |
| **Cantilever** | The displacement of an elastic cantilever is detected by a displacement transducer and correlated to flow rate. [37] [42] [43] | • Simple design  
• Uses inexpensive, well known parts | • Measurement signal is small and must be amplified  
• Measurement signal is nonlinear  
• Cleaning is difficult |
| **Air Displacement** | The collection container contains a sealed column of air with a pressure transducer located at the uppermost portion. As the container fills, air is pushed upwards and the pressure in sealed container rises with increasing volume. [44] [45] | • Measuring transducer does not come into contact with urine. | • Measurement signal is small and must be amplified  
• Sensitive to ambient conditions  
• Must be airtight |
| **Drop Spectrometry** | Analyzes deviations in the break-up pattern of the urinary stream. [46] [47] | • Short time constant | • Requires expensive equipment |
| **Radioisotope uroflowmetry** | A scintillation counter is placed against the posterior aspect of the bladder and the diminishing level of radiation as the bladder empties is measured. | • None identified | • Administration of radioactive isotope  
• Time required for isotope to reach bladder  
• Expensive equipment required |
<table>
<thead>
<tr>
<th><strong>Descriptive Title</strong></th>
<th><strong>Principle of Operation</strong></th>
<th><strong>Advantages</strong></th>
<th><strong>Disadvantages</strong></th>
</tr>
</thead>
</table>
| Maximum flow rate threshold | Device provides information on the maximum flow rate but does not measure flow rate with time. This may be done with a container with a hole in the bottom and indication if the accumulating volume reaches a certain height [48] [49] [50] [51] | - Inexpensive  
- Simple to use  
- Useful for home use | - No flow rate trace obtained |
| Image Analysis | X-ray images of the bladder are analyzed and changes in bladder size are correlated with flow rate [36]. | - Not sensitive to funnel error or impact of stream | - Exposure to X-ray  
- Poor accuracy |
| Ultrasonic | Doppler ultrasound measurements are used to measure urine velocity [52]. | - Not sensitive to funnel error or impact of stream  
- Provides urethral cross-sectional area versus time | - Expensive equipment required |
| Float | The rise of a float as urine accumulates is sensed and correlated to volume which is differentiated to obtain flow rate [53]. | - None identified | - Cleaning is difficult  
- Consists of many parts |

### 1.1.4.1 Cystometry

Cystometry is done to assess how well the bladder is able to fill and store urine. Bladder capacity, compliance, urge sensation, pressure during filling and storage, fullness sensation, and the ability to inhibit and initiate voiding are determined. Analysis of detrusor pressure during this test provides information on detrusor overactivity or involuntary contractions.

Conventional cystometry normally take place in a urodynamics laboratory and involves a double lumen catheter being inserted through the urethra into the bladder, and a single lumen catheter inserted to the rectum as shown schematically in Figure 1-6. The bladder is artificially filled through one of the ports of the urethral catheter. The second port and the rectal catheter contain pressure transducers which measure the intravesical pressure (within the bladder) and abdominal
pressure respectively. The pressure caused by the detrusor may then be determined as the difference between the intravesical pressure and abdominal pressures. Analysis of detrusor pressure during this test provides information on detrusor overactivity or involuntary contractions.

Figure 1-6: Schematic of a cystometry procedure. (Image reproduced from Urodynamics Made Easy [54].)

1.1.4.2 Pressure-Flow Studies

The pressure-flow study (PFS) is conducted after cystometry and involves measuring the abdominal and intravesical pressure during voiding. PFS are the gold standard for determining the cause of LUTS, and are the most definitive test available to determine the cause of voiding dysfunction [55]. Since decreased urine flow rate can have multiple causes, the synchronous measurement of detrusor pressure and flow rate is necessary to determine the cause of dysfunction. PFS allow the physician to identify the following three fundamental states of the urogenital system:
Table 3: Functional States of the Urogenital System

<table>
<thead>
<tr>
<th>State</th>
<th>Detrusor Pressure</th>
<th>Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unobstructed</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Obstructed</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Poor detrusor contractility</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

Assignment to one category is not necessary and borderline and combination cases are common.

The International Continence Society (ICS) has created nomograms to standardize the diagnose obstruction and assess bladder contractility in men. These nomograms are reproduced in Figure 1-7 and Figure 1-8 below. As obstruction occurs gradually, patients may be truly equivocal.

Figure 1-7: ICS nomogram determining three cases: obstructed, equivocal, and unobstructed where $P_{det}$ is detrusor pressure and $Q_{max}$ is maximum flow rate. (Image reproduced from [55].)
Figure 1-8: Bladder contractility nomogram in which patients are categorized as having strong, normal, or weak contractility. (Image reproduced from [55].)

1.1.4.3 Alternatives to Standard Pressure-Flow Studies

The high economic expense, as well as patient discomfort, risk, and inconvenience, of PFS has led to the investigation of several non-invasive techniques. Currently, however, no alternative procedure has provided sufficient evidence to justify the replacement of invasive PFS [56]. Several of the techniques found in the literature are briefly discussed below and include near infrared spectroscopy (NIRS), external condom catheter, compression cuff, ultrasound-derived measurements, sound analysis, and prostate size measurements.

The NIRS method uses light to monitor changes in the concentration of oxygenated and deoxygenated blood. Research has shown that bladder outlet obstruction leads to haemodynamic changes in the bladder which may be detected and analyzed using this method.

In the external condom catheter technique, the patient voids into a modified incontinence condom capable of occluding the flow at the meatus. A pressure transducer located between the meatus and the occlusion measures the isovolumetric bladder pressure [57]. This pressure measurement should theoretically differentiate obstruction (high pressure) from impaired contractility (low pressure) given a low flow rate. Limitations of this technique include leakage and expansion of the condom.

Griffiths et al. investigated a similar technique inspired by blood pressure measurements [58]. A compression cuff is placed on the penis which is inflated to occlude the urethra. The cuff is then
rapidly deflated, resulting in a flow surge, \( Q_{\text{surg}} \), and subsequent steady state flow rate, \( Q_{\text{ss}} \). An index called the PCR index describes this change as a percentage according to the expression:

\[
PCR = \left( \frac{Q_{\text{surg}} - Q_{\text{ss}}}{Q_{\text{ss}}} \right) \times 100
\]

Obstruction or impaired contractility is assumed based on established PCR values. Many cycles of inflation and deflation may be repeated to get a sense of the pressure pattern with time. The pressure in the cuff at interruption is assumed to be the same as the pressure in the bladder plus a constant accounting for the high difference and abdominal pressure. Limitations include the assumption that the cuff pressure is transmitted the same in all patients (variability in tissues), the exact time of interruption is difficult to identify.

Drawbacks of these techniques include inhibited voiding, the lack of abdominal pressure measurements to assess abdominal straining, and lack of pre-void pressure measurements.

Ultrasound-derived measurements of bladder wall thickness offer another potential non-invasive alternative to PFS, but their diagnostic parameters are still under evaluation [56]. Doppler ultrasound during urethral flow is informative, but requires complex equipment and its clinical utility has yet to be established.

Sound analysis has also been investigated. The urine stream has a tendency to become turbulent as it passes through an obstruction, and the sound generated from this turbulence has been recorded and analyzed in a simplified polyvinyl alcohol cryogen model of the urethra. Differences in acoustic spectra related to the degree of obstruction were observed [59].

Assessing the size and shape of the prostate has been investigated and a poor correlation between prostate size and outlet obstruction was found [60]. There may be more hope in looking at the prostate shape, though few studies have been conducted [61] [62]. Transrectal ultrasound is the most frequency used imaging technique to assess the volume and shape of the prostate. Attempts have also been made to measure the amount of prostatic protrusion into the bladder [63]. This technique, however, has many problems as the degree of protrusion is a function of bladder volume and wall musculature, and was found to be no more effective than measuring post-void residual volume in diagnosing BOO [63].
1.2 Motivation

1.2.1 Optical Uroflowmeter

Uroflowmeters for home use provide a convenient way to obtain multiple flow traces, and prevent the inherent problems involved with clinic-based measurements. Currently, there is a gap between low cost devices designed for home use which often only provide max flow rate, and precise, expensive clinical devices [64]. A simple and inexpensive device could also be adopted in other medical environments such as in general practitioners’ offices and rural areas.

Due to the rapid advances in quality and decreases in cost of computer and camera technology, video recording and image processing techniques provide a possible solution in the design of a device capable of bridging this gap.

1.2.2 Flow Visualization Pressure Study

Currently only invasive techniques are used clinically to obtain information regarding the pressure in the bladder. An investigation was conducted to determine if clues as to the pressure in the bladder could be obtained from analyzing digital images of the urine stream.

1.3 Research Objectives

This thesis details the development of a novel uroflowmeter that uses image processing techniques to determine flow rate, and a human study conducted at the Bladder Care Centre at the UBC Hospital to determine if information regarding bladder pressure may be obtained from the appearance of the urine stream. The objectives of each of these projects are described below.

1.3.1 Optical Uroflowmeter

The following objectives were defined for the new uroflowmeter:

- Manufacture cost of a few hundred dollars or less
- Meet the ICS accuracy recommendation of ± 2.5 mL/s [57]
- Simple, durable, and easy to use.
1.3.2 Flow Visualization Pressure Study

The objective of this study was to determine if the external flow stream of a high pressure flow contains visible turbulence or other differences not present in lower pressure flows.

1.4 Thesis Outline

Chapter 2: Development of an Optical Uroflowmeter
Describes the design, testing, and results of an optical uroflowmeter that measures urine flow rate using image processing techniques.

Chapter 3: Flow Visualization Pressure Study
Describes a study conducted at the Bladder Care Centre at the UBC Hospital which investigated if any information regarding the pressure in the bladder may be obtained by the appearance of the urine stream.

Chapter 4: Conclusions and Future Work
Summarizes the goals, results, and contributions of the research, and improvements and future directions possible for the research presented in this thesis.
Chapter 2

Development of an Optical Uroflowmeter

2.1 Introduction
Uroflowmeters currently used in clinical practice provide high measurement accuracy (< 2.5 mL/s) but are prohibitively expensive to be used in a wider range of medical environments. More affordable devices designed for at-home or screening applications often only provide approximate maximum flow rate and total voided volume, falling short in their ability to provide diagnostic information [65]. An opportunity therefore exists to develop a low cost device that bridges this gap, bringing uroflowmetry to a wider variety of medical environments such as home monitoring and General Practitioners’ offices.

The high demand for digital cameras, particularly due to their extensive use in mobile devices, has resulted in their accelerated advancement and cost reduction. Therefore, a device based on this technology is investigated.

2.1.1 Design Requirements
The following functional requirements were identified for the uroflowmeter:

- Manufacture cost of a few hundred dollars
- Meet ICS uroflowmeter accuracy recommendation of ±2.5mL/s error
- Simple, durable, and easy to use with minimal instruction.

2.2 Methods

2.2.1 Voiding Simulation Apparatus
To test the accuracy of the optical uroflowmeter and to compare it to the performance of a currently used device, a voiding simulation apparatus capable of generating reproducible flow
patterns was constructed. A schematic of the apparatus is shown in Figure 2-1 and consists of a Micropump GJ-N23 gear pump controlled through a National Instruments PCI-6010 DAQ.

![Schematic of the apparatus](image)

**Figure 2-1:** Schematic of voiding simulation apparatus.

The flow rate generated by the pump is a function of an applied control voltage that ranges between 0 and 5 volts. The flow rate corresponding to the applied control voltage was calibrated, and the results are shown in Figure 2-2. Flow rate increases linearly with applied control voltage according to the expression shown in Figure 2-2. The error in the measured flow rate is represented by the error bars which were calculated using the root sum squared (RSS) technique as shown in Appendix B.

![Self-tested calibration curve](image)

**Figure 2-2:** Self-tested calibration curve for Micropump GJ-N23 gear pump.
Three different voiding patterns representing a spectrum of physiologically relevant flow frequencies and amplitudes were simulated. These patterns are shown in Figure 2-3 through Figure 2-5 and include a representation of the classically normal, obstructed, and abdominally strained patterns discussed in Section 1.1.3.1.

Figure 2-3: The top plot shows the flow pattern to be replicated to simulate a “normal” flow pattern. The bottom plot shows the simulated test flow pattern and contains a similar frequency and amplitude of the actual flow pattern. The voltage to be applied to the pump to simulate this flow pattern is shown on the right y-axis, and the corresponding output flow rate is shown on the left y-axis.
Figure 2-4: The top plot shows the flow pattern to be replicated to simulate an “obstructed” flow pattern. The bottom plot shows the simulated test flow pattern and contains a similar frequency and amplitude of the actual flow pattern. The voltage to be applied to the pump to simulate this flow pattern is shown on the right y-axis, and the corresponding output flow rate is shown on the left y-axis.

Figure 2-5: The top plot shows the flow pattern to be replicated to simulate an “abdominally strained” flow pattern. The bottom plot shows the simulated test flow pattern and contains a similar frequency and amplitude of the actual flow pattern. The voltage to be applied to the pump to simulate this flow pattern is shown on the right y-axis, and the corresponding output flow rate is shown on the left y-axis.
2.2.2 Optical Uroflowmeter

The designed optical uroflowmeter consists of a camera, filling container, and lighting source all of which are contained within an enclosure. To start the device recording, the user presses the video start button shown in Figure 2-6. The funnel directs the urine stream into the filling container located inside the device.

The camera, as shown in Figure 2-7, images the container as it fills. The acquired video file is analyzed against a calibration video and the volume in the container at each frame is determined using image processing techniques. Volume data is then differentiated to determine flow rate.

Figure 2-6: Exterior of the uroflowmeter showing the urine directing funnel and video start button.
Figure 2-7: Internal view of the uroflowmeter.

2.2.2.1 Camera and Video Recording

A JVC GZ-HM440AU camera was used to image the filling container. This camera has a 1/5.8 inch 1.5 megapixel CMOS sensor with a maximum resolution of 1280 x 1024 pixels, 24 Mbps bit rate recording, 29.97 FPS recording, a focal length of 2.9 to 116.0 mm, and F-stop of F1.8 - F6.3.

The camera was mounted vertically as the wide angle of the lens allowed the entire height of the filling container to be imaged while keeping the camera as close as possible to the filling container. Video was saved at a resolution of 720 x 480 pixels and analyzed using Matlab.

2.2.2.2 Filling Container

A carefully designed filling container was constructed to encourage smooth and repeatable fillings. The fluid is directed into a vertical channel within the filling container by the external funnel. The bottom 25 mm of the channel has several small holes of an approximate diameter of 1.5 mm drilled through it in order to reduce the horizontal velocity of the flow and minimize surface disturbances. A vertical barrier was also installed in the centre of the container to further decrease the momentum of the fluid.

To improve measurements at low volumes, an inverted cone was fixed to the bottom of the filling container, decreasing the volume of fluid necessary to fill the bottom of the container.
This allowed the surface of the fluid to begin rising smoothly at volumes above approximately 30 mL.

In order for the fluid to spread evenly at the interface with the container, it is desirable for the contact angle between the fluid and the container to be as close to 90° as possible. This will simultaneously increases the smoothness and repeatability of the appearance of the free surface of the fluid, and reduce the need to carefully dry the container between tests. As the contact angle between glass and water is approximately 67°, a FOGuard® TRI-CLEAR™ (ISTN Inc.) anti-fog film was installed on the imaged side of the container to increase this angle. The improvements resulting from this film are shown in Figure 2-8.

![Figure 2-8: Demonstration of the appearance of the glass-water interface (left) and the improved film-water interface (right).](image)

### 2.2.3 Video Processing

The video files were analyzed using Matlab. The camera generated .MTS files which were converted to .AVI in order to be read in Matlab.
Each frame of the video was analyzed to determine the height of the liquid surface in the container. Image subtraction between the frame of interest and a background frame isolated the fluid height from the rest of the image as demonstrated in Figure 2-9. The first frame was assigned as the background frame until flow began. Once flow began, it was important to continuously update the background frame to account for changes in overall image lighting as the container filled. This was done by assigning the background frame as the frame in which the fluid level was a defined number of pixels lower.

![Current Frame](image1.png) ![Background Frame](image2.png) ![Subtracted Image](image3.png)

**Figure 2-9:** Simplified depiction of how the subtracted image is obtained. The current frame to be analyzed is subtracted from its background frame and a threshold is applied resulting in the subtracted image.

As the shape of the free surface in contact with the container is expected to be quadratic, a second order polynomial was fit to the detected surface points. This reduced the effect of inaccurately detected points or problem areas caused by bubbles and other surface disturbances.

In practice, the liquid imaged is likely to be urine, water, or a mixture and may contain radio-opaque contrast agents. Thus the surface detection algorithm must be flexible and able to detect
a variety of fluid colors and opacities. Colored and partially opaque fluids are quite simple to analyze using image subtraction as a clear difference can be identified from the background as the container fills. Detection becomes more difficult when imaging clear fluids. In order to accurately image transparent fluids, the filling container was adapted to take advantage of the refraction of light as it passes through a fluid.

To make use of refraction in this device, lines of various colors were drawn at an angle of approximately 45° on the momentum reducing barrier. As the container fills, these drawn lines appear to bend, allowing the image processing program to identify the location of the fluid surface as demonstrated in Figure 2-10.

![Empty Container](image1.png)  ![Partially Filled Container](image2.png)

**Figure 2-10:** Depiction of refraction allowing clear fluids to be imaged. The image on the left shows the empty filling container while the image on the right shows it partially filled. The surface of the fluid can be identified visually despite the fact that the fluid is transparent.

A binary image isolating the fluid surface, as was shown in the rightmost image of Figure 2-9, was created from the subtracted image using a threshold established through trial-and-error. This threshold was tested for a variety of liquid colors and opacities ranging from clear water to darkly colored yellow and red.

The fluid height in each column of pixels was assigned as the top-most white pixel, as shown schematically in Figure 2-11. The volume corresponding to the height of the liquid was then determined from calibration data.
Calibration data was obtained by pumping water into the device at a known constant flow rate and applying the image processing algorithm discussed above to determine the height of the liquid surface in each frame. The total volume at the end of the test was measured and assigned to the last frame showing a change in column height. The volume at each previous frame was then calculated by subtracting the time, known from the frame rate of the camera, multiplied by the flow rate. For each frame, the fluid surface height in each column of the image was saved along with the calculated volume for that frame. A relationship between pixel height and volume was then determined by fitting a curve to each of these points for each column in the image. This provided a formula to calculate the volume based on the detected height for each pixel column of the image. The image processing algorithm therefore determines the volume in each column of the image. The average of these values was then assigned as the volume for the frame.

2.2.4 Labore Urocap III Traces

The optical uroflowmeter was compared to the standalone model Laborie Urocap III uroflowmeter currently being used at the Bladder Care Centre at the UBC Hospital. The Urocap III has a flow range between 0 and 50 mL/s, a volume range of 0 – 1000 mL, and produces a physical printout as shown in Figure 2-12. These traces were scanned to analyze them digitally.

Figure 2-11: A schematic representation of the detection of the topmost white pixel, represented by a 1 in the binary image, in each column of the image.
Figure 2-12: An example of one of the test flow pattern results from the Laborie Urocap III uroflowmeter.

Matlab was used to detect the dots visible on the flow rate trace and gridlines were drawn through them. The traces were then squared by rotating the images until the flow rate gridlines were aligned with the horizontal. The dots were then re-detected and the gridlines re-drawn. As the gridlines have known values of time and flow rate, the positions of the gridlines were recorded and correlated with the known time at flow rate. Values for time-per-pixel and flow rate-per-pixel were then calculated.

These values allowed the pump input and experimental curves to be superimposed on top of the Urocap III hospital traces for easy comparison. The Urocap III flow rate trace was isolated as shown in blue for the comparison analysis with the optical uroflowmeter.
Figure 2-13: Digitized flow rate pattern produced by the Urocap III showing the detected flow rate and time dots and isolated flow rate pattern (blue).

2.3 Results

Five trials for each of the simulated test flow patterns for both the optical uroflowmeter, labeled A-E, and Urocap III, labeled 1-5, are shown in Figure 2-14 through Figure 2-16.

Figure 2-14: Flow rate traces for the simulated “normal” flow pattern.
Figure 2-15: Flow rate traces for the simulated “abdominally strained” flow pattern.
Figure 2-16: Flow rate traces for the simulated “obstructed” flow pattern.

The measured volume, voiding time, maximum flow rate, time to maximum flow rate, and mean flow rate are provided in Table 4 on the following page.
Table 4: Comparison of the measured flow parameters to their expected values using the optical uroflowmeter.

<table>
<thead>
<tr>
<th>Test</th>
<th>Detected Volume [mL]</th>
<th>Expected Volume [mL]</th>
<th>% Diff</th>
<th>Detected Voiding Time</th>
<th>Expected Time</th>
<th>% Diff</th>
<th>Q_max</th>
<th>Expected Q_max</th>
<th>% Diff</th>
<th>Time to Max</th>
<th>Expected Time to Max</th>
<th>Mean FR</th>
<th>Expected Mean FR</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>NormA</td>
<td>432</td>
<td>430 ± 5</td>
<td>0.5%</td>
<td>28.9</td>
<td>32.0</td>
<td>9.6%</td>
<td>27.5</td>
<td>26.8</td>
<td>2.6%</td>
<td>12.9</td>
<td>16.0</td>
<td>14.7</td>
<td>13.4</td>
<td>9.7%</td>
</tr>
<tr>
<td>NormB</td>
<td>430</td>
<td>430 ± 5</td>
<td>0.0%</td>
<td>28.9</td>
<td>32.0</td>
<td>9.6%</td>
<td>27.3</td>
<td>26.8</td>
<td>1.9%</td>
<td>13.0</td>
<td>16.0</td>
<td>14.5</td>
<td>13.4</td>
<td>8.2%</td>
</tr>
<tr>
<td>NormC</td>
<td>431</td>
<td>430 ± 5</td>
<td>0.2%</td>
<td>29.7</td>
<td>32.0</td>
<td>7.3%</td>
<td>27.3</td>
<td>26.8</td>
<td>1.9%</td>
<td>12.6</td>
<td>16.0</td>
<td>14.1</td>
<td>13.4</td>
<td>5.2%</td>
</tr>
<tr>
<td>NormD</td>
<td>433</td>
<td>430 ± 5</td>
<td>0.7%</td>
<td>28.6</td>
<td>32.0</td>
<td>10.7%</td>
<td>27.0</td>
<td>26.8</td>
<td>0.7%</td>
<td>12.1</td>
<td>16.0</td>
<td>14.6</td>
<td>13.4</td>
<td>9.0%</td>
</tr>
<tr>
<td>NormE</td>
<td>431</td>
<td>430 ± 5</td>
<td>0.2%</td>
<td>27.8</td>
<td>32.0</td>
<td>13.1%</td>
<td>27.5</td>
<td>26.8</td>
<td>2.6%</td>
<td>11.7</td>
<td>16.0</td>
<td>14.7</td>
<td>13.4</td>
<td>9.7%</td>
</tr>
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</tr>
<tr>
<td>AbdoA</td>
<td>432</td>
<td>435 ± 5</td>
<td>0.7%</td>
<td>48.2</td>
<td>48.0</td>
<td>0.4%</td>
<td>17.8</td>
<td>17.3</td>
<td>2.9%</td>
<td>35.3</td>
<td>4.0</td>
<td>8.9</td>
<td>9.0</td>
<td>2.8%</td>
</tr>
<tr>
<td>AbdoB</td>
<td>431</td>
<td>435 ± 5</td>
<td>0.9%</td>
<td>47.9</td>
<td>48.0</td>
<td>0.2%</td>
<td>17.9</td>
<td>17.3</td>
<td>3.5%</td>
<td>26.9</td>
<td>4.0</td>
<td>8.9</td>
<td>9.0</td>
<td>1.8%</td>
</tr>
<tr>
<td>AbdoC</td>
<td>435</td>
<td>435 ± 5</td>
<td>0.0%</td>
<td>47.4</td>
<td>48.0</td>
<td>1.3%</td>
<td>17.2</td>
<td>17.3</td>
<td>0.6%</td>
<td>26.9</td>
<td>4.0</td>
<td>8.9</td>
<td>9.0</td>
<td>0.6%</td>
</tr>
<tr>
<td>AbdoD</td>
<td>436</td>
<td>435 ± 5</td>
<td>0.2%</td>
<td>47.4</td>
<td>48.0</td>
<td>1.3%</td>
<td>17.1</td>
<td>17.3</td>
<td>1.2%</td>
<td>10.8</td>
<td>4.0</td>
<td>9.0</td>
<td>9.0</td>
<td>0.1%</td>
</tr>
<tr>
<td>AbdoE</td>
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<td>435 ± 5</td>
<td>0.9%</td>
<td>47.5</td>
<td>48.0</td>
<td>1.0%</td>
<td>17.9</td>
<td>17.3</td>
<td>3.5%</td>
<td>35.1</td>
<td>4.0</td>
<td>9.1</td>
<td>9.0</td>
<td>0.7%</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>ObstA</td>
<td>657</td>
<td>660 ± 5</td>
<td>0.5%</td>
<td>132.8</td>
<td>133.0</td>
<td>0.1%</td>
<td>9.8</td>
<td>10.1</td>
<td>3.0%</td>
<td>8.8</td>
<td>5.6</td>
<td>5.0</td>
<td>4.9</td>
<td>1.5%</td>
</tr>
<tr>
<td>ObstB</td>
<td>661</td>
<td>660 ± 5</td>
<td>0.2%</td>
<td>133.4</td>
<td>133.0</td>
<td>0.3%</td>
<td>9.8</td>
<td>10.1</td>
<td>3.0%</td>
<td>8.3</td>
<td>5.6</td>
<td>4.9</td>
<td>4.9</td>
<td>1.0%</td>
</tr>
<tr>
<td>ObstC</td>
<td>658</td>
<td>660 ± 5</td>
<td>0.3%</td>
<td>131.2</td>
<td>133.0</td>
<td>1.3%</td>
<td>9.8</td>
<td>10.1</td>
<td>3.0%</td>
<td>8.3</td>
<td>5.6</td>
<td>4.9</td>
<td>4.9</td>
<td>2.9%</td>
</tr>
<tr>
<td>ObstD</td>
<td>658</td>
<td>660 ± 5</td>
<td>0.3%</td>
<td>133.4</td>
<td>133.0</td>
<td>0.3%</td>
<td>9.8</td>
<td>10.1</td>
<td>3.0%</td>
<td>8.3</td>
<td>5.6</td>
<td>4.9</td>
<td>4.9</td>
<td>0.7%</td>
</tr>
<tr>
<td>ObstE</td>
<td>656</td>
<td>660 ± 5</td>
<td>0.6%</td>
<td>133.4</td>
<td>133.0</td>
<td>0.3%</td>
<td>9.8</td>
<td>10.1</td>
<td>3.0%</td>
<td>8.2</td>
<td>5.6</td>
<td>4.9</td>
<td>4.9</td>
<td>0.7%</td>
</tr>
</tbody>
</table>
To assess the accuracy of the optical uroflowmeter, the difference between the pump input curve and the measured curve are plotted for each frame of data collected. The results are shown in Figure 2-7 through Figure 2-9. Note that the measurement accuracy for the “normal” flow pattern is very low initially though it does follow the Urocap III trace quite well in Figure 2-14. The reasons for this are described in the discussion. The initial 30 mL of fluid also shows poor accuracy for reasons explained in Section 2.2.2.2.

**Figure 2-17:** Accuracy of the optical uroflowmeter relative to the pump input curve for the “normal” test flow pattern.
**Figure 2-18:** Accuracy of the optical uroflowmeter relative to the pump input curve for the “abdominally strained” test flow pattern.

**Figure 2-19:** Accuracy of the optical uroflowmeter relative to the pump input curve for the “obstructed” test flow pattern.
2.3.1 Comparison with Gravimetric Uroflowmeter at the UBC Bladder Care Centre

To assess how similarly both devices perform, the minimum absolute sum of difference between each measured curve and the expected curve based on the input to the pump was computed.

To compute the sum of difference for the optical uroflowmeter, data points were obtained every 1/29.97 seconds corresponding to the frame rate of the camera. As a physical printout was obtained for each trial using the Urocap III, the printout was digitally scanned and the flow rate at each sequential time pixel was determined using image processing. Linear interpolation was then used to obtain the flow rate at the same time spacing as the optical uroflowmeter.

The initial 30 mL was removed from the theoretical curve for the comparison as the optical device is known to have poor accuracy over this range as discussed in Section 2.2.2.2, and it was desired to assess the accuracy of the optical uroflowmeter beyond this initial region. The modified theoretical curve was then incrementally shifted by 1/29.97 seconds along the curves for each device and the absolute sum of difference was computed resulting in Figure 2-20 through Figure 2-22. The minimum values for each trial are also tabulated in Table 5.

The root mean square (RMS) was then calculated at the minimum sum of difference, as follows:

\[ RMS = \sqrt{\frac{1}{n} (FR_{measured} - FR_{expected})^2} \]

Where \( FR_{measured} \) is the measured flow rate, \( FR_{expected} \) is the expected flow rate and \( n \) is the total number of points. The RMS values are provided in Table 5.
Figure 2-20: Sum of difference between uroflow trace and input signal for the simulated “Normal” flow pattern. The red lines show results for the Urocap III uroflowmeter and the black lines show results for the optical uroflowmeter.

Figure 2-21: Sum of difference between uroflow trace and input signal for the simulated “Abdominal Straining” flow pattern. The red lines show results for the Urocap III uroflowmeter and the black lines show results for the optical uroflowmeter.
Figure 2-22: Sum of difference between uroflow trace and input signal for the simulated “Obstructed” flow pattern. The red lines show results for the Urocap III uroflowmeter and the black lines show results for the optical uroflowmeter.
### Table 5: Comparison between the minimum sum of difference for the Urocap III and Optical uroflowmeters.

<table>
<thead>
<tr>
<th>Trial</th>
<th>UroCapIII SOD [mL/s]</th>
<th>RMS [mL/s]</th>
<th>Optical SOD [mL/s]</th>
<th>RMS [mL/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norm1</td>
<td>504</td>
<td>0.884</td>
<td>325</td>
<td>0.521</td>
</tr>
<tr>
<td>Norm2</td>
<td>553</td>
<td>0.994</td>
<td>271</td>
<td>0.464</td>
</tr>
<tr>
<td>Norm3</td>
<td>504</td>
<td>0.876</td>
<td>396</td>
<td>0.604</td>
</tr>
<tr>
<td>Norm4</td>
<td>554</td>
<td>0.929</td>
<td>370</td>
<td>0.643</td>
</tr>
<tr>
<td>Norm5</td>
<td>530</td>
<td>1.051</td>
<td>448</td>
<td>0.929</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>529</strong></td>
<td><strong>0.947</strong></td>
<td><strong>362</strong></td>
<td><strong>0.632</strong></td>
</tr>
</tbody>
</table>

| Standard Deviation | 25 | 0.075 | 68 | 0.180 |

| Abd1   | 722 | 0.670 | 938 | 1.116 |
| Abd2   | 727 | 0.678 | 643 | 0.714 |
| Abd3   | 807 | 0.758 | 616 | 0.656 |
| Abd4   | 632 | 0.589 | 692 | 0.617 |
| Abd5   | 817 | 0.771 | 669 | 0.679 |
| **Average** | **741** | **0.693** | **712** | **0.756** |

| Standard Deviation | 75 | 0.074 | 129 | 0.204 |

| Obs1   | 615 | 0.276 | 986 | 0.397 |
| Obs2   | 508 | 0.231 | 914 | 0.364 |
| Obs3   | 673 | 0.263 | 834 | 0.343 |
| Obs4   | 1240 | 0.387 | 767 | 0.281 |
| Obs5   | 773 | 0.286 | 767 | 0.281 |
| **Average** | **762** | **0.289** | **854** | **0.333** |

| Standard Deviation | 284 | 0.059 | 96 | 0.051 |

### 2.3.2 Sensitivity to Levelness

The accuracy of the optical uroflowmeter is expected to be sensitive to levelness relative to the calibration video. Trials were run on four non-level surfaces, representative of locations it is likely to be placed during use. Levelness was measured using a 12” Mastercraft 57-5319-0 toolbox level and are shown in Table 6.

### Table 6: Measured degree of levelness of four relevant surfaces

<table>
<thead>
<tr>
<th>Surface</th>
<th>Degrees from Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stool</td>
<td>4</td>
</tr>
<tr>
<td>Stool II</td>
<td>7</td>
</tr>
<tr>
<td>Counter</td>
<td>4</td>
</tr>
<tr>
<td>Desk</td>
<td>0</td>
</tr>
</tbody>
</table>
The greatest un-levelness measured was 7 degrees. The uroflowmeter was thus inclined by 7 degrees on all four sides (front, back, right, and left) and the resulting flow rate measurements were recorded and are shown in Figure 2-23.

**Figure 2-23:** Flow rate measurements for the inclined uroflowmeter.

The sum of difference between the expected and measured flow rate were computed and are provided in Table 7.

**Table 7:** Measured sum of difference for level sensitivity tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Sum of Difference [mL/s]</th>
<th>Normalized Sum of Difference [mL/s]</th>
<th>Voided Volume [mL]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>185</td>
<td>0.17</td>
<td>697</td>
</tr>
<tr>
<td>Inclined on the Left</td>
<td>144</td>
<td>0.13</td>
<td>703</td>
</tr>
<tr>
<td>Inclined on the Right</td>
<td>142</td>
<td>0.13</td>
<td>702</td>
</tr>
<tr>
<td>Inclined on the Front</td>
<td>220</td>
<td>0.2</td>
<td>695</td>
</tr>
<tr>
<td>Inclined on the Back</td>
<td>209</td>
<td>0.19</td>
<td>705</td>
</tr>
</tbody>
</table>
2.4 Discussion
An inexpensive uroflowmeter with comparable accuracy to the Urocap III has been designed.

A problem was identified with the pump used to simulate test flow patterns. Though it functions very accurately at constant flow rates as demonstrated in Figure 2-2, its response to a dynamic signal is was found to be somewhat less accurate, particularly in the case of the simulated normal flow pattern as shown below in Figure 2-24. This does limit the assessment of accuracy, as determined in Figure 2-17, of the designed device as the theoretical curve, particularly in the simulated normal test, is not precisely known.

![All Curves](image)

**Figure 2-24:** All simulated normal flows for each the Urocap III (shown in black) and the optical uroflowmeter (shown in red) plotted along with the theoretical curve (shown in green).

For the reasons discussed above, the overall accuracy of the optical uroflowmeter is best described by the “abdominally strained” and “obstructed” flow patterns. Based on Figure 2-17 through Figure 2-19, and understanding the limited knowledge of the actual flow rate curve
particularly in the “normal” test cases, the flow rate accuracy of the designed optical uroflowmeter may be said to be ±1.4 mL/s.

To compare the optical uroflowmeter and the Urocap III quantitatively, the sum of difference between the expected curve based on the input signal to the pump and the curves generated for each of these devices was calculated. As the pump input curve is expected to not completely describe the output, less attention should be paid to the actual numerical value of the sum of difference, and more attention should instead be directed to comparing the values between the two devices. For the simulated normal pattern, the optical device followed the slope of the theoretical curve more closely, particularly in the second half of the curve as shown in Figure 2-24, and is reflected by the lower average sum of difference. The sum of difference for the abdominally strained cases are much closer, as is the obstructed case if the standard deviation is taken into account.

The root mean square (RMS) was computed for each trial as shown in Table 5. The average RMS for the optical uroflowmeter was lower for the simulated normal flow pattern, but not significantly different for the other two patterns when standard deviation is taken into account. The RMS values were the lowest for the obstructed flow patterns as the pump was most accurately able to recreate this pattern.

As the optical uroflowmeter was expected to be sensitive to levelness relative to its calibration data, a test to assess the resulting inaccuracy was performed. The device was inclined 7° to the front, back, right, and left and a flow of constant rate was directed into the filling container. The video was analyzed against a calibration video taken when level. The resulting flow rate trace is not significantly different in any of these cases, to the trace when the device was level relative to the calibration video.

2.5 Conclusions

Though the current apparatus is too large and heavy for routine clinical use, it is sufficient for proof of concept and can be miniaturized and made more robust for practical use. Excluding the initial start-up, the device provides comparable accuracy to the Urocap III. The device has a measurement accuracy of approximately ±1.4 mL/s excluding the initial 30 mL, well within the ICS recommendation of measurement accuracy within 2.5 mL/s.
The device is simple in operation, and consists of few parts. It consists of a camera, a specially designed filling container, a light source, and an enclosure, all of which can be assembled for a few hundred dollars.
Chapter 3

Flow Visualization Pressure Study

3.1 Introduction
Urinary obstruction, as caused by BPH, causes abnormally high detrusor pressure during voiding and leads to LUTS, an increased rate of urinary tract infection, changes to the bladder muscle, and may lead to kidney damage. As such, determination of high detrusor pressure is important to patient health. The urodynamic study is the gold standard technique to assess bladder pressure and consists of a non-invasive uroflow, cystometry, and a pressure-flow study as discussed in Section 1.1.3.

Conventional urodynamics has many disadvantages and limitations. It is invasive and exposes patients to discomfort and risk. It also consumes $75 CND worth of disposables per patient, providing both an economic and environmental impact. Though small catheters are used, the presence of the catheter in the urethra during the pressure-flow study affects the flow. The following section details an experiment conducted to determine if information on bladder pressure may be obtained from the appearance of the external urine stream.

Two observable differences were postulated to exist between high and low pressure flows. The first is increased turbulence and surface roughness in high pressure flows. A urinary obstruction will cause the local velocity and Reynolds number to increase, encouraging flow separation and mixing. Both of these effects increase the likelihood of turbulence.

The second identifiable difference in a high pressure flow was thought to be the length of the initially continuous section of the urine stream. The typical urine stream has an initially continuous section that breaks up into droplets as shown in Figure 3-1. This initial continuous section may be longer in flows with a higher bladder pressure as the inertia of the stream is expected to be higher.
Figure 3-1: Outline of initial continuous section of urine stream followed by breakup into droplets.

3.2 Methods

Eleven pathologic and ten control subjects were recruited and tested at the Bladder Care Centre (BCC) at the UBC Hospital as per UBC Clinical Research Ethics Board approval.

Pathologic subjects were identified as men over the age of 19, free of urinary tract infection, and scheduled for urodynamic study at the Bladder Care Centre. Pathologic subjects completed their urodynamic study before participating in the experiment.

Control subjects were identified as men between the ages of 19 and 35 with no previous surgeries or conditions affecting the lower urinary tract and free of lower urinary tract symptoms or infection. Subjects were asked to record two voidings and complete an International Prostate Symptom Score (IPSS) questionnaire as evidence of normal functioning of their lower urinary tracts.
3.2.1 Urodynamic Study
The urodynamic study for each pathologic patient was conducted using Laborie Medical equipment. A small #8 French catheter was inserted in the urethra for the cystometrogram and pressure flow study. This double lumen catheter uses one port for filling and the other for bladder pressure measurement.

3.2.2 Video Analysis
The experimental setup used to record the urine stream is shown in Figure 3-2. A Phantom V611 high speed camera was used with a Navitar Zoom 7000 lens. Images were captured in greyscale at a resolution of 800 x 600 pixels, a frame rate of 24 frames per second, and an exposure time of 90 μs. A relatively low frame rate and resolution were chosen to ensure the camera would have adequate memory to capture images throughout the void.

![Figure 3-2: Experimental setup for video recording of the urine stream](image)

A stand was constructed and placed in front of the collection funnel to ensure subjects remained in the field of view of the camera, and provided a surface onto which subjects could support and stabilize themselves to reduce movement of the stream.
Subjects were asked to press a button initiating camera recording, and to then void into the collection funnel. A Laborie Urocap III uroflowmeter was used to record the uroflow.

3.3 Results
General observations of each voiding recording are provided in Appendix C.

3.3.1 Subject Information and Urodynamic Study Results
The age, uroflow results, and pressure measurements of each pathologic subject are provided in Table 8. Subject 5469 was only able to void a few drops and hence the column is greyed as little analysis was possible.

Table 8: Pathologic subject information and urodynamic study results

<table>
<thead>
<tr>
<th>Pathologic Subject ID</th>
<th>Years of Age</th>
<th>Peak Flow Rate [mL/s]</th>
<th>Mean Flow Rate [mL/s]</th>
<th>Voiding Time [s]</th>
<th>Flow Time [s]</th>
<th>Time to Peak Flow [s]</th>
<th>Voided Volume [mL]</th>
<th>Bladder Pressure [cm H2O]</th>
</tr>
</thead>
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<td>0975</td>
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<td>8</td>
<td>4</td>
<td>64</td>
<td>53</td>
<td>2</td>
<td>262</td>
<td>69.9 62.5 70.3</td>
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<tr>
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<td>6</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>38</td>
<td>31.6 41.3 30.4</td>
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<td>4</td>
<td>98</td>
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<td>79</td>
<td>254</td>
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<td>6</td>
<td>246</td>
<td>58.0 72.8 59.5</td>
</tr>
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<td>1</td>
<td>1</td>
<td>26</td>
<td>25</td>
<td>0</td>
<td>48</td>
<td>117.1 117.8 101.7</td>
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<td>10</td>
<td>4</td>
<td>76</td>
<td>44.1 125.8 53.6</td>
</tr>
</tbody>
</table>

The IPSS score and uroflow results of each control subject are provided in Table 9.
Table 9: Control subject information and urodynamic study results

<table>
<thead>
<tr>
<th>Control Subject ID</th>
<th>IPSS Score</th>
<th>Peak Flow Rate [mL/s]</th>
<th>Mean Flow Rate [mL/s]</th>
<th>Voiding Time [s]</th>
<th>Flow Time [s]</th>
<th>Time to Peak Flow [s]</th>
<th>Voided Volume [mL]</th>
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<td>11</td>
<td>13</td>
<td>13</td>
<td>8</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28</td>
<td>19</td>
<td>29</td>
<td>29</td>
<td>14</td>
<td>560</td>
</tr>
<tr>
<td>C6557</td>
<td>0</td>
<td>15</td>
<td>9</td>
<td>34</td>
<td>34</td>
<td>4</td>
<td>313</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>11</td>
<td>24</td>
<td>24</td>
<td>10</td>
<td>279</td>
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<tr>
<td>C7922</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>44</td>
<td>43</td>
<td>24</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>5</td>
<td>41</td>
<td>39</td>
<td>22</td>
<td>196</td>
</tr>
<tr>
<td>C8003</td>
<td>0</td>
<td>Subject unable to void for uroflow.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C8491</td>
<td>1</td>
<td>29</td>
<td>15</td>
<td>25</td>
<td>25</td>
<td>13</td>
<td>381</td>
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<td>30</td>
<td>28</td>
<td>14</td>
<td>602</td>
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<tr>
<td>C9157</td>
<td>2</td>
<td>23</td>
<td>12</td>
<td>35</td>
<td>35</td>
<td>7</td>
<td>443</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29</td>
<td>17</td>
<td>21</td>
<td>21</td>
<td>5</td>
<td>363</td>
</tr>
<tr>
<td>C9595</td>
<td>0</td>
<td>29</td>
<td>17</td>
<td>47</td>
<td>47</td>
<td>12</td>
<td>819</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27</td>
<td>17</td>
<td>39</td>
<td>39</td>
<td>12</td>
<td>693</td>
</tr>
</tbody>
</table>

3.3.2 Appearance and Surface Roughness of the Stream

The appearance of the urine streams of both normal and pathologic subjects were compared qualitatively. In the images below, an effort was made to capture the stream at maximum flow rate by multiplying the time to maximum flow rate by the frame rate and adding the number of frames until flow is observed to begin in the video. The images are shown in the order of decreasing pressure at maximum flow rate.

Note that the pressure shown on the images below are the pressures recorded at maximum flow rate during the pressure-flow study which the pathologic subjects completed before participating in the study. Pressure was not measured during video recording.
Subject: 9058
Flow Rate: 6 mL/s
$P_{dpk FR}$: 99.3 cmH20

Subject: 9575
Flow Rate: 8 mL/s
$P_{dpk FR}$: 93.8 cmH20

Subject: 0975
Flow Rate: 8 mL/s
$P_{dpk FR}$: 69.9 cmH20

Subject: 2785
Flow Rate: 13 mL/s
$P_{dpk FR}$: 58.0 cmH20
Subject: 1576
Flow Rate: 8 mL/s
$P_{d, pk FR}$: 55.4 cmH20

Subject: 8147
Flow Rate: 22 mL/s
$P_{d, pk FR}$: 52.6 cmH20

Subject: 9649
Flow Rate: 12 mL/s
$P_{d, pk FR}$: 44.1 cmH20

Subject: 9134
Flow Rate: 13 mL/s
$P_{d, pk FR}$: 41.0 cmH20
Figure 3-3: The appearance of the urine stream at maximum flow rate for pathologic participants in order of decreasing pressure at maximum flow rate.

For the purposes of comparison, the appearance of the urine stream at maximum flow rate for a selection of control subjects are shown below. The figures are grouped into three groups according to flow rate ranges. The first group shows three examples of high flow rate streams, the second intermediate flow rate streams, and the final low flow rate streams.
Figure 3-4: Appearance of control subject high flow rate urine streams at maximum flow rate.
Figure 3-5: Appearance of control subject intermediate flow rate urine streams at maximum flow rate.
Figure 3-6: Appearance of control subject low flow rate urine streams at maximum flow rate.

The surface roughness of each stream was quantified by fitting a smoothed line to the detected edge of the stream and computing the sum of squared difference between the two curves. These quantities were then normalized by the total number of points along the stream to allow comparison between videos. A minimum of fourteen frames per second of recorded data were analyzed and the results are shown in Figure 3-7 through Figure 3-9.
Figure 3-7: Surface roughness as the sum of squared difference versus the pressure at maximum flow rate.

Figure 3-8: Surface roughness as the sum of squared difference versus the maximum recorded pressure.
Figure 3-9: Surface roughness as the sum of squared difference versus mean pressure.

For the purposes of comparison, the surface roughness of the control subjects was assessed in the same manner. Surface roughness expressed as the sum of squared difference is shown in Figure 3-10.

Figure 3-10: Surface roughness as expressed by the sum of squared difference for control subjects.
3.3.3 Length of Inertia Stream

The length of the inertia stream as described in Section 3.1 was analyzed in a minimum of fourteen frames per second of data recorded. The length of the inertia stream when plotted against any of the three measured pressures showed no remarkable pattern, an example of which is shown in Figure 3-11.

![Pathologic Subjects: Length of Inertia Stream Versus Pressure at Maximum Flow Rate](image)

**Figure 3-11:** A plot of length of inertia stream versus pressure at maximum flow rate showing no observable pattern.

The time required for the inertia stream to either reach a steady value or extend beyond the field of view, and the time to reach maximum length when measurable was determined. An example of the length of the inertia stream for a flow in which the inertia stream does not extend beyond the field of view is shown in Figure 3-12, while one in which the inertia stream quickly extends beyond the field of view is shown in Figure 3-13.
**Figure 3-12:** The time for the inertia stream to reach a steady value is shown as by the vertical line, and time to reach maximum value as shown by the orange line.

**Figure 3-13:** The time for the inertia stream to extend beyond the field of view is shown as the vertical green line. Note in this case the time to maximum inertia stream length cannot be measured.
A possible pattern emerges when the time to maximum inertia stream length is plotted against pressure as shown in Figure 3-16.

**Figure 3-14:** A plot of the time to reach a steady inertia stream length versus pressure at maximum flow rate.

This same pattern is not observed when plotting time to maximum flow rate, as obtained by the uroflow, versus pressure as shown in Figure 3-15.
Figure 3-15: Time to maximum flow rate versus pressure at maximum flow rate showing no pattern.

However when the same is plotted for the control subjects, this possible pattern is lost as shown in Figure 3-16.
Figure 3-16: Plot of time to reach steady inertia stream length showing a possible correlation with pressure.

A plot of time to steady inertia stream as a percentage of total flow time is shown in Figure 3-17. Control subjects were plotted at a pressure of 10 cm H20.

Figure 3-17: Time to steady inertia stream as a percentage of total flow time.
3.4  Discussion

The potential benefits of this technique are numerous. It is non-invasive, does not require any disposables, and the images are easy to review as they are captured digitally and can be analysed in slow motion and in high detail. The technique is also very simple and could be easily reproduced in remote areas and other countries.

3.4.1  Appearance of the Urine Stream Measurement of Surface Roughness

The appearance of the urine streams of both normal and pathologic subjects were compared with no remarkable findings. Qualitatively, there is no observable difference in the streams in terms of diameter, trajectory, and appearance relative to pressure. Images were shown at maximum flow rate as this point may be identified in the same manner for all videos.

The surface roughness of the inertia stream was determined as the sum of squared difference between the detected stream edge points and a highly smoothed line fit to these points. There were no remarkable findings when roughness was plotted against any of the three measured pressure. The surface roughness of the control subjects was also found to vary greatly.

Both the appearance and surface roughness of the stream appear to be more a function of flow rate than pressure. The image of the highest pressure at maximum flow rate stream (topmost right image of Figure 3-3) appears very similar to the lowest flow rate streams observed in the control subjects (Figure 3-6).

3.4.2  Length of Inertia Stream

The length of the inertia stream as described in Section 3.1 was measured in a minimum of fourteen frames per second of recorded data. There were no remarkable findings when comparing the recorded pressure and length of the inertia stream.

Expressing the time to a steady inertia stream did provide a possible pattern; however, this pattern was lost when plotted along with the results for control subjects. A larger sample size, much more controlled patient positioning, and larger imaged field of view would be required to determine this result definitively.
3.4.3 Pathologic Subjects

Pathologic subject 5469 was only able to void a few of drops and thus surface roughness and inertia stream measurements were not made.

The sample size of the pathologic group is small, but is sufficient for a pilot study to qualitatively look for difference between high and low pressure urine streams. Unfortunately, only two of the pathologic participants had considerably elevated voiding pressures, and a much larger sample size would be required to obtain a group of subjects displaying a wide range of obstructed flow patterns.

There is a theoretical consideration in looking at the streams of participants after completing urodynamic testing caused by the prior insertion of the catheter into the urethra. As the stream imaging was performed after the completion of the urodynamic study, there is the possibility that the insertion of the catheter may traumatis the urethra. The effect of this is expected to be small as no hematuria was observed. Also, the results of uroflows conducted after completion of cystometrogram and pressure flow studies are accepted clinically.

3.4.4 Control Subjects

Control subjects were carefully screened by taking a detailed history and quantifying symptoms using the IPSS questionnaire. As their bladder pressure was not measured, there is a chance these individuals have pathology, however the chance of this is low. To support the claim that the control voidings represent “typical” voidings for these individuals, they were asked to record two voidings for comparison.

In all cases, the two voids completed by each control subject were found to be comparable visually and in terms of the uroflow results. Control subjects C0357 and C6557 had unusual voids. Subject C0357 voided at a remarkable rate of 55 mL/s in both voids. This is interesting as it provides an example of a high pressure flow with the absence of obstruction. Subject C6557 provides an example of the opposite. He was nervous and voided with a low flow rate of 10 mL/s. This provides an example of a low pressure flow likely in the absence of obstruction as evidenced by his history and IPSS score.
Control subject C8003 was unable to void in front of the camera and withdrew his participation in the experiment. Control subjects C6557 and C8491 did not record their first flows; however, their uroflow results are provided in darkened cells in the table for the purposes of comparison with the second void.

3.4.5 Limitations and Future Work
It is important to note that some individuals have difficulty voiding in front of the camera. One control subject, not presenting any known lower urinary tract symptoms, was unable to void in front of the camera. Thus a device of this type would be of little help assessing these patients.

It would be very interesting to look at individuals before and after transurethral resection of the prostate and observe the differences in the appearance of the urine streams. It would also be interesting to investigate a much larger group of pathologic patients and to study a range of normal subjects of varying age in recognition that bladder strength may reduce with age and may affect observations.

Obtaining imaging consistency when working with human subjects was difficult. Given the same instructions, patient interpretation can result in very different looking videos. A more constricting stand and improved instruction and supervision may combat these issues. It would also be useful to image with a larger field of view that would capture the entire length of the inertia stream for all subjects.

3.5 Conclusions
The flow visualization study did not produce any observable trends that might provide information on the lower urinary tract pressure during voiding. The small sample size may not be sufficient to observe trends within the pathologic group. A more detailed and in-depth study with a larger sample size may be able to produce some results to more definitively rule against this technique. The study as conducted provided no conclusive results either for nor against the possibility of future results in this area.
Chapter 4

Conclusions and Future Work

4.1 Contributions

4.1.1 Optical Uroflowmeter
A low-cost uroflowmeter meeting ICS accuracy recommendations has been proposed that would enable uroflowmetry to be conducted in a wide variety of medical environments, such as General Practitioner’s offices, home monitoring, and remote areas.

The device consists of a video camera, filling container, lighting system, and enclosure. It was discovered that an anti-fog (surfactant) coating on the wetted surface of the filling container provides greatly increased filling repeatability by reducing the contact angle between the fluid and glass, and acts to even out the rising water surface within the container. Additionally a method was developed, using the principal of refraction of light through water, which allowed for the detection of the free surface of transparent liquids within the container.

In the testing environment, the device functioned to within ±1.4 mL/s error. This is well below the ±2.5 mL/s maximum error recommended by the ICS.

4.1.2 Flow Visualization Pressure Study
For the flow visualization study, the objectives were to provide a method to obtain quality information for physicians without incurring the economic cost and patient discomfort of conventional urodynamic testing. The urine streams of eleven pathologic and nine control subjects were recorded and observed to attempt to determine if information regarding the pressure in the bladder many be obtained by analyzing the appearance of the urine stream. It was originally postulated that two observable differences may exist between these cases in terms of surface roughness or the length of the initially continuous section of the urine stream termed the inertia stream.
The video files were analyzed using computer vision techniques. The analysis of these videos is inconclusive, and shows no optically observable trend that may provide any information as to the pressure in the bladder while voiding.

4.2 Limitations & Future Work

4.2.1 Optical Flowmeter

The primary source of error for the uroflowmeter in its current state is the chaotic and non-repeatable way that the test liquid spreads to cover the bottom of the container at the beginning of the trial. In the current iteration of the device, the first 30mL of container filling are prone to errors for this reason.

Secondly, the device is currently in a prototyping stage and must be redesigned for practical use. In its current form, the device requires re-calibration every few trials for best results. The theory and physical principals the device operates on are sound, however a redesign of certain components within the device would increase repeatability and decrease amount of calibration required. Components to be redesigned could include the camera mounting system and the filling container mounting.

Finally, because this device is a proof-of-concept, there are still significant limitations in terms of user friendliness. While the device meets its objective of simplicity, in its current form it requires a number of manual steps, including transferring video files to a desktop PC and image processing in Matlab. Many of these steps could be automated to make the device suitable for at-home applications.

4.2.2 Flow Visualization Study

The flow visualization study did not produce any observable trends that might provide information on the lower urinary tract pressure during voiding. The small sample size may not be sufficient to observe trends within the control group. A more detailed and in-depth study with a larger sample size may be able to produce some results to more definitively rule against this technique. The study as conducted provided no conclusive results for, or against, the possibility of future findings in this area.
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Appendix A

International Prostate Symptom Score (IPSS) Questionnaire

The IPSS was developed in 1992 by the American Urological Association and consists of seven questions regarding frequency, nocturia, weak stream, hesitancy, intermittency, incomplete bladder emptying, and urgency. Each question is rated on a 5 point scale and the severity of symptoms is determined from the sum as mild (a score of 0 to 7), moderate (8 to 19), or severe (20 to 35). A copy of the questionnaire used to assess control subjects in the Pressure Visualization Study is reproduced on the following page.
<table>
<thead>
<tr>
<th>International Prostate Symptom Score</th>
<th>Not at all</th>
<th>Less than 1 time in 5</th>
<th>Less than half the time</th>
<th>About half the time</th>
<th>More than half the time</th>
<th>Almost always</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Over the past month, how often have you had a sensation of not emptying your bladder completely after you finished urinating?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2. Over the past month, how often have you had to urinate again less than 2 hours after you finished urinating?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3. Over the past month, how often have you found you stopped and started again several times when you urinated?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4. Over the past month, how often have you found it difficult to postpone urination?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5. Over the past month, how often have you had a weak urinary stream?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6. Over the past month, how often have you had to push or strain to begin urination?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>7. Over the past month, how many times did you most typically get up to urinate from the time you went to bed at night until the time you got up in the morning?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

(Circle the column that best represents the number of times you awake each night, on average.)

**Total Score: _____________**

**What Your Score Means:**

0-7 Points Symptoms are considered mild.

8-19 Points Symptoms are considered moderate.

20-35 Points Symptoms are considered severe.

Regardless of the score, if you are experiencing symptoms that interfere with your quality of life, you may wish to consult a urologist for further evaluation and additional information regarding this condition.

Source: American Urological Association
Appendix B

Root of Sum of Squares (RSS) for Pump Calibration Curve

The root of sum of squares calculation provides a measure of the overall error in a measurement. RSS is computed by the following expression:

\[ u_{Total} = \sqrt{u_1^2 + u_2^2 + \ldots + u_n^2} \]

Therefore, to determine the total uncertainty in the flow rate measurement, the following RSS calculation was made:

\[ Q = \frac{\Delta V}{\Delta t} \]

Where \( Q \) is the flow rate, \( V \) is the volume, and \( t \) is the time.

\[ u_Q = \sqrt{\left(\frac{1}{\Delta t} u_{\Delta V}\right)^2 + \left(\frac{\Delta V}{\Delta t^2} u_{\Delta t}\right)^2} \]

Where \( u_Q \) is the flow rate uncertainty, \( u_{\Delta V} \) is the uncertainty in the change in volume, and \( u_{\Delta t} \) is the uncertainty in the time.

A 1000 mL graduated cylinder with gradations every 10 mL was used for the volume measurements. The container was empty at the start of the flow rate trial and therefore no error is associated with the starting volume. The uncertainty in the volume measurement is taken as half of the distance between the gradations, and \( u_{\Delta V} \) is therefore 5 mL.
The filling time was measured with a stop watch, and the uncertainty in the start and stop times is approximated as 0.1 seconds resulting in the following $u_{\Delta t}$:

$$u_{\Delta t} = \sqrt{u_t + u_\tau} = 0.35 \text{ seconds}$$

**Table 10:** Calibration data for Micropump gear pump.

<table>
<thead>
<tr>
<th>Volts</th>
<th>Time [s]</th>
<th>Volume [mL]</th>
<th>FR [mL/s]</th>
<th>uFR [mL/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>430.4</td>
<td>600</td>
<td>1.39</td>
<td>0.007</td>
</tr>
<tr>
<td>0.5</td>
<td>459.9</td>
<td>650</td>
<td>1.41</td>
<td>0.007</td>
</tr>
<tr>
<td>0.5</td>
<td>473.4</td>
<td>700</td>
<td>1.48</td>
<td>0.007</td>
</tr>
<tr>
<td>1</td>
<td>220.8</td>
<td>1000</td>
<td>4.53</td>
<td>0.015</td>
</tr>
<tr>
<td>1</td>
<td>217.6</td>
<td>1000</td>
<td>4.60</td>
<td>0.015</td>
</tr>
<tr>
<td>1</td>
<td>217.9</td>
<td>1000</td>
<td>4.59</td>
<td>0.015</td>
</tr>
<tr>
<td>2</td>
<td>92.2</td>
<td>1000</td>
<td>10.85</td>
<td>0.038</td>
</tr>
<tr>
<td>2</td>
<td>91.7</td>
<td>1000</td>
<td>10.90</td>
<td>0.038</td>
</tr>
<tr>
<td>2</td>
<td>91.7</td>
<td>1000</td>
<td>10.91</td>
<td>0.038</td>
</tr>
<tr>
<td>3</td>
<td>58.1</td>
<td>1000</td>
<td>17.21</td>
<td>0.069</td>
</tr>
<tr>
<td>3</td>
<td>57.8</td>
<td>1000</td>
<td>17.30</td>
<td>0.069</td>
</tr>
<tr>
<td>3</td>
<td>58.0</td>
<td>1000</td>
<td>17.24</td>
<td>0.069</td>
</tr>
<tr>
<td>4</td>
<td>42.4</td>
<td>1000</td>
<td>23.59</td>
<td>0.108</td>
</tr>
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<td>4</td>
<td>42.1</td>
<td>1000</td>
<td>23.75</td>
<td>0.110</td>
</tr>
<tr>
<td>4</td>
<td>42.2</td>
<td>1000</td>
<td>23.70</td>
<td>0.109</td>
</tr>
<tr>
<td>4.5</td>
<td>37.4</td>
<td>1000</td>
<td>26.74</td>
<td>0.132</td>
</tr>
<tr>
<td>4.5</td>
<td>37.3</td>
<td>1000</td>
<td>26.81</td>
<td>0.132</td>
</tr>
<tr>
<td>4.5</td>
<td>37.3</td>
<td>1000</td>
<td>26.81</td>
<td>0.132</td>
</tr>
</tbody>
</table>
Appendix C

MATLAB Code for Volume Detection

Purpose: To determine the volume and flow rate of fluid filling a container
Inputs: Filling video
Outputs: Smoothed Volume (sVol) and Flow Rate (sFR)

```matlab
clear all; warning('off');

% Determine the volume of fluid in each frame and save into Volo

% Select video file for processing
filename = 'norm8.avi'; file = VideoReader(filename);
[Vol] = detVol(file)

% Smooth raw data and determine flow rate
[Vols, FR] = detFR(Vol)
```

Purpose: To determine the volume of fluid in a container in each frame
Inputs: Filling video (file)
Outputs: Volume in each frame (Vol)

```matlab
function [Vol] = detVol(file, crop)

% Obtain calibration data
[heightData volumes] = calibData();

% Build coefficient matrices
rc = size(heightData);
cols = rc(2)
for i=1:1:cols
    y = volumes;x = heightData(:,i);
    p = polyfit(x,y,3);
```
% Call polyval to use p to predict y, calling the result yfit:
yfit = polyval(p,x);

% Compute the residual values as a vector signed numbers:
yresid = y - yfit;

% Square the residuals and total them obtain the residual sum of squares:
SSresid = sum(yresid.^2);

% Compute the total sum of squares of y by multiplying the variance of y
% by the number of observations minus 1:
SStotal = (length(y)-1) * var(y);

% Compute R2 using the formula given in the introduction of this topic:
rsq = 1 - SSresid/SStotal;

coeff1(1,i)=p(1); coeff2(1,i)=p(2); coeff3(1,i)=p(3); coeff4(1,i)=p(4);
end

%% Misc pre-allocate/used
x1 = 180; x2 = 340; y1=1; midImage = 127;

% File details
Fps = file.FrameRate;
nFrames = file.NumberOfFrames;
H = fspecial('unsharp');

% Pre-Allocate Space and Misc
Vol = ones(1, nFrames) .* 0;
Vol(1) = 0;
frameVolM = [1:size(heightData,2)];
cols = [1:1:size(heightData,2)];

% Cycle through each frame
start=51;
BG = read(file, start-50);
BG = imrotate(BG, 270);
BG = BG(y1:end, x1:x2, :);
for frame=start:1:nFrames
    RF = read(file, frame);
    RF = imrotate(RF, 270); % rotate
    RF = RF(y1:end, x1:x2, :); % crop
    diff = abs(RF-BG).*6+abs(BG-RF).*6;
    bdiff = diff(:, :, 1)+diff(:, :, 2)+diff(:, :, 3);
    bdiff = wiener2(bdiff); % 2D noise removing filter
    bdiff = im2bw(bdiff, .8);
    % Retain only the largest area
    clear sizearea;
    [imlabel totalLabels] = bwlabel(bdiff,8);
    if totalLabels > 1
        for i=1:totalLabels
            sizearea(i) = length(find(imlabel==i));
        end
    end
end
end
[maxno largestAreaNo] = max(sizearea);
bdiff = zeros(size(diff));
bdiff(find(imlabel==largestAreaNo)) = 1;
bdiff = im2bw(bdiff, 0.1);
end

% Ignore below detected cols+10 from previous 
if Vol ~= 0
    for i=1:1:length(cols)
        bdiff(cols(i)+10, i) = 0;
    end
end

[sorted loc] = sort(bdiff, 'descend');
cols = loc(1, :);
midPt(frame) = cols(midImage);

% Update BG frame to frame where cols(midImage) is 10 pixels lower 
midPt(1)
if midPt(1) < 600
    for u = frame:-1:start
        if cols(midImage) ~=0 && midPt(u) - cols(midImage) > 10
            break;
        end
    end
end
BG = read(file, u);
BG = imrotate(BG, 270);
BG = BG(y1:end, x1:x2, :);
end

% Fit a second order polynomial to the detected height points
p = polyfit([1:1:length(cols)], cols, 2);
cols = polyval(p, [1:1:length(cols)]);
cols = abs(cols);

% Determine Vol based on callibration coefficients
Vols = coeff1 .* cols.^3 + coeff2 .* cols.^2 + coeff3 .* cols + coeff4;
Vol(1, frame) = mean(Vols);

% If any point is at top, make Vol =0
for k=1:1:length(cols)
    if cols(k) == 1
        Vol(1,frame) = 0;
        break;
    end
end

words = num2str(Vol(1, frame));

% Display current frame and detected fluid height
imshow(bdiff);
line([1:(x2-x1+1)], cols, 'color','g', 'linewdith', 1)
title ('[Vol:', words]);
end
% Remove extreme outliers
for i=length(Vol):-1:2
    if abs(Vol(i) - Vol(i-1)) > 30
        Vol(i-1) = Vol(i)
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Purpose: To determine the volume of fluid in a container in each frame
%%% Inputs: Volume in each frame (Vol)
%%% Outputs: Smoothed volume (sVol) and smoothed flow rate (sFR)

function [sVol, sFR] = detFR(Vol)

% Determine initial spike in detected volume data
for i=length(Vol):-1:1
    if Vol(i) < 2;
        initialSpike = i+1;
        break;
    end
end
Vol = Vol(initialSpike:end);

% Increment order until R^2 is sufficiently high (thresholded)
SV = Vol(2:150); SV=smooth([1:1:length(SV)], SV, .1, 'loess');

for order=1:1:20
    order
    % Use polyfit to compute a linear regression that predicts y from x:
    y = SV';x = [1:1:length(y)];
    p = polyfit(x,y,order);
    % Call polyval to use p to predict y, calling the result yfit:
    yfit = polyval(p,x);

    % Compute the residual values as a vector signed numbers:
    yresid = y - yfit;

    % Square the residuals and total them obtain the residual sum of squares:
    SSresid = sum(yresid.^2);

    % Compute the total sum of squares of y by multiplying the variance of y
    % by the number of observations minus 1:
    SStotal = (length(y)-1) * var(y);

    % Compute R2 using the formula given in the introduction of this topic:
    rsq = 1 - SSresid/SStotal
    % Plot fit data
plot(Vol, 'color', 'k'); hold on; grid on;
plot(x, yfit, 'color', 'm');
pause;
clf;
if rsq > .998 \%R^2 threshold
    break;
end
end

% Fill in initial section
for i=0:-1:-1000
    Vol = [0 Vol]
    Vol(1) = polyval(p,i);
    if Vol(1) <= 0 || (Vol(1) > Vol(2))
        break;
    end
end

% Determine appropriate amount of smoothing based on the number of peaks
wp=.5;x=[1:1:length(Vol)];shift = 30;
smoothed = smooth(x,Vol,wp,'sgolay',2);
for i=1:1:length(smoothed)-shift-1
    p = polyfit([1:1:shift], smoothed(1, i:(i+shift-1)),1)
    FR(i) = p(1) * 29.97;
end
pks = findpeaks(sVol)
wp = 0.3;
if length(pks) > 2
    wp = 0.1;
end
sVol = smooth(x,Vol,wp,'sgolay',2);
for v=1:1:length(sVol)-1
    if sVol(v+1) < sVol (v)
        sVol(v+1) = sVol(v);
    end
end

% Determine flow rate (linear)
shift = 30; cshift = num2str(shift); \%determine FR over 30 frame (1s) interval
for i=1:1:length(sVol)-shift-1
    p = polyfit([1:1:shift], sVol(1, i:(i+shift-1)),1);
    FR(i) = p(1) * 29.97;
end

% Set "small" or negative values to 0
for i=1:1:length(FR)
    if FR(i) < 1
        FR(i) = 0;
    end
end
FR = [zeros(1,100) FR zeros(1,100)];

% Spread out first three seconds (90 frames)
for i=1:length(FR)
    if FR(i) ~= 0
        break
    end
end

x = [0:1:size(FR,2)-1] ./ 29.97;
spread=2; cspread=num2str(spread); section=60; csection=num2str(section)
xm = x;
last = x(i+section); first = x(i);
xm(i:i+section-1) = [last-(section*spread-1)/29.97:spread/29.97:last];
xm(1:i-1) = x(1:i-1)-(first-xm(i));

cwFR = num2str(wFR);
wp = wFR/length(Vol);
sFR = smooth(xm,FR,wp,'loess');

% Plot results
ylim([0 30]); hold on; xlabel('Time [s]'); ylabel('Flow Rate [mL/s]');
set(gca,'ytick',[0:5:40]);
set(gca,'xtick',[-5:5:175]);
grid on; title([ 'File:' filename, ' wV:' cwV, ' wFR:' cwFR, ' Section',
csection, ' Spread' cspread]);
plot(xm, sFR, 'color', 'b')
FR = ytheo .* 4.4654 - 1.4758;
if norm == 1
    FR = ytheo .* 6.3509 - 1.776;
end
plot(ttheo+mov,FR, 'color', 'r'); grid on;