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Correlation between intravesical pressure and prostatic obstruction grade using computational fluid dynamics in benign prostatic hyperplasia

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Abstract: An urodynamic test which measures various physiologic variables during voiding is generally used for accurate diagnosis of a bladder outlet obstruction (BOO) resulting from benign prostatic hyperplasia (BPH). However, this method is difficult to directly apply to all patients because it is an invasive test and many patients suffer from anxiety and embarrassment during the test. Thus, other diagnosis methods such as uroflowmetry and prostatic symptom score are performed to measure the degree of BOO prior to the urodynamic test, and it is necessary to construct a quantitative relationship among the obstruction level, the intravesical pressure, and the uroflow rate. The aim of this paper is to analyse the variation of intravesical pressure as a function of the extent of the obstruction and the uroflow rate from given information on the size of the bladder and the urodynamic test using a computational fluid dynamics approach. In order to analyse the intravesical pressure, a two-dimensional axisymmetric model of the bladder including a narrowed region, i.e. the prostatic obstruction, is created. Then the variation of the intravesical pressure is quantitatively obtained as a function of the magnitude of the uroflow rate and the extent of the obstruction. It is shown that the intravesical pressure significantly increases even for small obstructions and that at large obstructions it can reach values higher than 100 cm H₂O, which is a dangerous value. It is shown that the intravesical pressure decreases as the uroflow rate decreases. This study can form the basis of a non-invasive test for the diagnosis of BHP.

Keywords: bladder, prostatic obstruction, computational fluid dynamics, urodynamics, intravesical pressure

1 INTRODUCTION

Benign prostatic hyperplasia (BPH) is a common benign neoplasm that can affect ageing men. Lower urinary tract symptoms (LUTS) for prostatic hyperplasia include enlargement of the prostate, bladder outlet obstruction (BOO), contractional disorders in the detrusor muscle, and an overactive detrusor muscle [1]. It is reported that BOO can lead to neurogenic detrusor overactivity, impaired detrusor contractility, polyuria, and changes in cellular metabolism [2].

The urodynamic test to measure various physiologic variables during voiding is generally used for accurate diagnosis of BOO resulting from BPH. Urodynamic investigation is performed with a 7 Fr dual-lumen urethral catheter and a 9 Fr rectal balloon catheter at a filling rate of 50 ml/min to measure the intravesical pressure (P ves) and the abdominal pressure (P abd), respectively (see Fig. 1). A pressure flow study is performed in a sitting position similar to cystometry. However, this method is difficult to directly apply to all patients

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because it is an invasive test and many patients suffer from anxiety and embarrassment during the test. Therefore, other diagnosis procedures (uroflowmetry and prostatic symptom score) are performed to measure the BOO degree prior to performing an urodynamic test. The international prostatatric symptom score is obtained through responses to a questionnaire, which can suffer from subjective responses that can lead to low accuracy.

The literature contains reports on non-invasive diagnosis procedures such as measurement of the bladder wall thickness, prostate size, and prostatic resistive index [3–5]. There has been a recent report on the use of an inflatable penile cuff [6]. This method requires measuring the uroflow rate and the cuff pressure required to interrupt flow. Measuring the bladder wall thickness using ultrasound visualization can be used to diagnose prostatic hyperplasia. This technique is based on the clinical observation that an increase in the size of the lower urinary tract obstruction results in detrusor muscle hypertrophy [7–9]. This method has the advantage of being quick and simple to apply; however, it can be highly inaccurate since the measured thickness depends on the location of the markers used in the measurement. The level of inaccuracy inherent in this measurement technique means that it can be difficult or even impossible to decide if an increased thickness value is due to a measurement error or is the result of BPH [8].

Presently, the most widely used non-invasive diagnosis method for LUTS is uroflowmetry. This technique is used in clinical practice to objectively measure the uroflow strength. It is performed in either a sitting or standing position to simulate the normal voiding situations. Its result consists of a maximum urinary flow and a flow pattern in the shape of a curve. It is reported that a maximum uroflow rate of less than 10 ml/s has an approximately 90 per cent chance of being the result of an obstruction (abnormal). A rate between 10 and 15 ml/s has a 65 per cent chance (equivocal), and a rate greater than 15 ml/s has a 30 per cent chance (normal). However, it has been reported in the literature that it is difficult to distinguish between a lower bladder obstruction and detrusor contractile dysfunction [10, 11].

Since the intravesical pressure is related to the prostatic obstruction, the constriction effect of the obstruction has to be analysed. Several studies have been performed in order to study the effect of a constricted tube on the characteristics of the flow

![Fig. 1 Typical recording taken in an urodynamics test on a healthy 35-year-old man](image-url)
and the pressure drop \[15, 16\]. Transrectal ultrasonography is a widely used method in clinical practice to measure the volume of the prostate. However, it is currently not possible to accurately measure the degree of obstruction using this technique \[17\]. Thus, it is necessary to develop a quantitative relationship between the extent of the obstruction, the intravesical pressure, and the uroflow rate using a mathematical model.

There are reports in the literature on attempts to develop a mathematical model of micturition based on urodynamic data \[18, 19\] and to analyse a urinary tract obstruction using the method of computational flow dynamics (CFD) \[20\]. In this study, the CFD method is used to generate a model of the bladder with various-sized prostatic obstructions and uroflow rates. The aim of this paper is to analyse the variation of intravesical pressure based on the extent of the obstruction and flowrate from given information on the bladder size and the urodynamic test for healthy men, and to construct a contour map of the intravesical pressure for the specific obstruction grade and uroflow rate based on the CFD results.

## 2 METHODS

Micturition occurs due to an increase in intravesical pressure created by contraction of the detrusor muscle. The intravesical pressure is defined by the head loss in the urinary tract during detrusor contraction. Figure 2 shows that the bladder can be considered as being a sphere whose radius decreases during voiding; in fact its volume decreases from 450 to 18 ml. In order to estimate the effective variation of the pressure, a model of a simplified bladder with an initial volume of 450 ml was created; this model is based on what would be expected for a healthy 35-year-old man (Fig. 3). The two-dimensional (2D) axisymmetric model consists of a bladder and a urinary tract including a narrowed region (prostatic urethra) and it was created using 61,340 fluid cells of the commercial CFD program, STAR-CD \[21\]. The axisymmetric model is an unrealistic representation of the human bladder; however, it is a reasonable starting point to report the correlation between the intravesical pressure and the obstruction grade. The initial bladder radius was set to a value of 47.54 mm which corresponds to the volume of 450 ml. Based on clinical information the length of the obstructed region was assumed to have a value of 5 mm and to be located at a distance of 20 mm from the point at which the bladder and urethra meet, see Fig. 3.

The rheological properties of the urine in the bladder were considered to be those of water which is a reasonable assumption since more than 90 wt% of urine is in fact water. The flow characteristics of urine in a urinary tract conform to the laws of mass conservation (equation (1)) and momentum conservation (equation (2)) for an unsteady incompressible flow

\[
\nabla u = 0
\]

\[
\rho \left( \frac{\partial u}{\partial t} + u \nabla u \right) = -\nabla p + \mu \left( \nabla u + \nabla u^T \right) + \rho g
\]

where \(u\) is the velocity vector in Cartesian coordinates and \(t, p,\) and \(\rho\) are time, pressure, and density, respectively. Also, \(\mu\) is the dynamic viscosity and \(g\) is the vector of gravitational force.
The motion implicit in shrinking the bladder during micturition was simulated using the subroutine ALE in STAR-CD which contains a movable mesh. The flowrate of the incompressible urine excreted via the urethra by contraction of the bladder was described using

\[ Q = \frac{\partial V}{\partial t} = \frac{\partial}{\partial t} \left( \frac{4}{3} \pi R^3 \right) = 4\pi R^2 \frac{\partial R}{\partial t} = 4\pi R^2 \frac{R_n - R_{n-1}}{\Delta t} \] (3)

where \( Q \) denotes the flowrate of the urine, \( V \) denotes the volume of the bladder, and \( R \) denotes the radius of the bladder. The radius at the current time step \( n \) is calculated from that of the previous time step \( n-1 \) using equation (4). Thus, the specific urinary flow rate is obtained by changing the bladder radius over time

\[ R_n = R_{n-1} + \frac{Q}{4\pi R_{n-1}^2} \Delta t \] (4)

The flow rate and the pressure obtained using the CFD model duplicate the clinical result, which shows a bell shape (rapidly increasing and then slowly decreasing) for the uroflow rate and the intravesical pressure during voiding (Fig. 1). Taking \( Q \) to be the urinary flowrate profile of a healthy person, it can be approximated as a fourth-order polynomial function (equation (5)) and when this function is substituted into equation (4) it is able to replicate the clinically obtained flowrate (Fig. 4)

\[ Q = 0.933 + 3.24t - 0.194t^2 + 0.00379t^3 - 0.0000244t^4 \] (5)

The other profiles of the flow rate shown in Fig. 4 are supplementary profiles to compare the effect of a lower flowrate than the normal flowrate. These profiles show different maximum values of the flowrate at the same total volume. Next, the diameter and the length of urinary tract were regulated to be in a range of reasonable values to agree

![Fig. 3 Model of a urinary system with BHP](image)

![Fig. 4 The profile of urinary flowrate for a healthy person and the various curves of urinary flowrate used in this study](image)
with the pressure profile of the clinical result shown in Fig. 1. The ratio of the area of the narrowed urethra to the actual urethral area \( A' \) was defined (equation (6)) and subsequently used to analyse the effect of the extent of the obstruction (1 - \( A' \)). This ratio was represented in eight steps between 1.0 and 0.3

\[
A' = \frac{A_{\text{obstruction}}}{A_{\text{urethra}}} \quad (6)
\]

Then, the variation of intravesical pressure was analysed for the magnitude of flowrate as a function of the extent of the obstruction. The result represents the intravesical pressure as a function of time and pressure at a distance from the point at which the bladder and urethra meet. The extent of the obstruction is between 0 (\( A' = 0 \)) and 70 percent (\( A' = 0.3 \)) and the flowrate is varied between 8 and 18 ml/s. The obtained results are plotted onto a contour map. In order to assess its accuracy and reliability, the results obtained using the proposed CFD model are compared with the results obtained in urodynamic tests to measure the intravesical pressure and the uroflow rate.

3 RESULTS

First, the intravesical pressure profile was obtained using the CFD model for the case where there was no obstruction; this was done in order to determine the radius and the length of the urethra. The pressure values for various radii were calculated in the model at a length of 100 mm (Fig. 5(a)). The results show that the intravesical pressure increases up to 13 s and then it decreases towards the end of voiding, which is similar to the flowrate shown in Fig. 4. In addition, as the radius decreases, the maximum value of the intravesical pressure increases due to an increase in head loss. This means that a smaller radius of the urethra created by an obstruction requires additional pressure during voiding. The length of the urethra is the main variable in the developed model. Thus, the pressures for various lengths were obtained at a fixed radius of 2.1 mm (Fig. 5(b)). As the length increases, the maximum pressure linearly increases due to the head loss in the inner surface of the duct. It can be seen from Fig. 5 that a length of 100 mm and a radius of 2.1 mm produce results that agree with the clinical result and these values were used in all subsequent simulations. The difference between the simulated and clinical results in the initial stages of micturition is a result of the fact that the diameter of the urethra instantaneously expands at the start of micturition. The length of the urethra is long enough that end effects can be ignored in the CFD simulations.

The pressure distribution in all regions of the bladder during voiding obtained using the proposed model is presented in Fig. 6. At the start of micturition, the pressure in the urethra immediately decreases due to a large head loss, and as the bladder shrinks, the gradient of the pressure along the urethra decreases. The maximum pressure is 25 cm H_2O for a healthy person (\( A' = 1 \)). Figure 6 also shows the pressure distribution as a function of the extent of the obstruction at the times of 5, 10, and 15 s. As the size of the obstruction increases the pressure gradient increases over time. Particularly, the
The narrowing of the urethra due to hypertrophied prostatic tissue induces voiding problems such as weak urinary stream, frequency, residual urine sensation, and so on [22]. Initially, men with BPH take medicine to resolve their voiding problems and most of them respond to this treatment option. However, in some cases this treatment is ineffective. For example, men with severe BPH may experience acute urinary retention during medication. These patients require surgical treatment to solve their voiding problems. Therefore, it is important to provide a method of assessment to avoid inappropriate medical surgery in men with severe BPH. The uroflowmetry test is the standard clinical method to evaluate the degree of obstruction created by BPH and the results of this test are used to inform the decision as to whether or not surgery is required.

It is clinically important to measure the intravesical pressure using an urodynamc test for the diagnosis of BPH because the intravesical pressure is used to define the degree of obstruction in terms of detrusor pressure and the flowrate [23]. Normally the standard maximum intravesical pressure would be between 40 and 60 cm H₂O during voiding. Treatment is normally considered when the value of the pressure is above 80–100 cm H₂O. Accurate information about the extent of the obstruction would help to inform the correct choice of treatment in clinical practice i.e. medicine or surgery. Figure 9 shows a contour map of the intravesical pressure as a function of the extent of the obstruction and the

4 DISCUSSION

Figure 7 shows the evolution of pressure during voiding as a function of the extent of the obstruction. As the prostatic hyperplasia becomes severe, the intravesical pressure is exponentially increased for \( A' < 0.7 \). At some point between \( A' = 0.3 \) and \( A' = 0.4 \) the intravesical pressure goes higher than 100 cm H₂O, which is a dangerous value. In fact at \( A' = 0.3 \) the intravesical pressure reaches its maximum value of 120 cm H₂O (Fig. 7(a)). This result shows that additional detrusor pressure for voiding is needed because of the increase in the intravesical pressure for the larger obstructions, which might impair the functioning of the bladder muscle. Also, as the size of the obstruction increases a large pressure gradient is developed in the urethra between the negative pressure in the region of the obstruction and the large pressure at the point at which the urethra attaches to the bladder (Fig. 7(b)). This pressure could cause a reverse circulation of urine into the endocrine organ which could result in an enlarged prostate.

Figure 8 shows the evolution of the intravesical pressure for \( A' = 0.5 \) as a function of the uroflow rate. If the flowrate decreases then the intravesical pressure also decreases because the head loss for the constant gradient is reduced. When the flowrate is reduced by 50 percent then the maximum pressure decreases from 45 to 16 cm H₂O (Fig. 8(a)). The value of the pressure above the obstruction is also decreased as the flowrate is reduced (Fig. 8(b)).
uroflow rate during voiding. This figure allows the intravesical pressure to be predicted from information on the obstruction and uroflow rate based on a healthy person. The $x$-coordinates in Fig. 9 are the resistance factor, which directly measures the extent of the obstruction. This result is similar to nomograms that have been previously used in standard assessment procedures [23–25]. The intravesical pressure during voiding has a specific profile because it depends on the extent of detrusor contractility. Thus, the urinary obstruction reduces the uroflow rate at a specific intravesical pressure. For instance, when the pressure has a value of 25 cm H$_2$O and the obstruction is 20 per cent, the flow rate is reduced by 10 per cent as shown in Fig. 9 (point A). Conversely, the contour map indicates the intravesical pressure as a function of the degree of obstruction and flow rate reduction. In addition, an obstruction of 40 per cent reduces the flow rate by 22 per cent (point B) and that of 60 per cent reduces it by 45 per cent for the same pressure (point C). Thus, the flow rate is sharply reduced as the extent of the obstruction increases and in turn this means that a large contraction of the detrusor muscle is required over a long time period in order to allow voiding in a severe BOO case.

This research could be used for better diagnosis of BPH by quantitatively considering the intravesical pressure.

Fig. 7  Evolution of the pressure as function of the extent of the obstruction (a) pressure profile during voiding as a function of time and (b) pressure profile as a function of the distance from the base of the bladder

Fig. 8  Evolution of the pressure as a function of flowrate (a) pressure profile during voiding as a function of time and (b) pressure profile as a function of the distance from the base of the bladder ($A^t = 0.5$)
pressure for benign prostatic enlargement and uroflow rate. However, there are some limitations for its clinical application. The data on pressure and urinary flow rate collected in the urodynamic test include an initial variation and the plot needs to be validated and improved using data taken in other urodynamic tests. Also, this method needs to incorporate the age of the patient using other non-invasive methods such as uroflowmetry. Although the presented results need to be generalized before its routine adoption in clinical practice it can still be used as a basis establish the relationship between intravesical pressure and the prostatic size for diagnosis of BPH.

5 CONCLUSIONS

This paper has presented an analysis of the variation of intravesical pressure in the presence of BPH using a CFD modelling approach. It has been shown that as the prostatic hyperplasia becomes severe then the intravesical pressure exponentially increases for $A' < 0.7$ and in fact at some point between $A' = 0.3$ and $A' = 0.4$ it goes higher than 100 cm H$_2$O, which is a dangerous value. Also, as BOO increases, the pressure gradient in the region of the obstruction in the urinary tract significantly increases. The variation of uroflow is relatively less affected by changes in the intravesical pressure for a given value of $A'$. The concepts proposed in this paper could be used to aid the diagnosis of BHP by studying the intravesical pressure changes created by benign prostatic enlargement and uroflow rate.

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