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TECHNICAL NOTE

ON THE FLOW THROUGH THE HUMAN FEMALE URETHRA

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Abstract—The flow characteristic for a human female urethra is determined by direct measurement of flow rate and pressure difference data. The measurements are made on a full-scale physical model of a urethra in its open state, which was created using dimensional information taken from video cystograms. The measured data therefore include viscous dissipation effects associated with developing flow, changes in cross-sectional area and changes in flow direction. These effects are often ignored in mathematical models of this system. The data may therefore assist in the development and testing of more realistic models for urine flow. The measured characteristic is compared with a mathematical model of the flow based on a straight tube of uniform diameter carrying fully developed turbulent flow. When the diameter of the model tube is chosen to be equal to the distal diameter of the urethra, it is observed that the predicted flow characteristic provides a good first approximation to the measured characteristic, despite the substantial differences in geometry and flow regime between the mathematical model and the actual system. © 1997 Elsevier Science Ltd

Keywords: Micturition; Urethra; Urethral resistance; Urine flow; Fluid dynamics.

INTRODUCTION

The relationship between intravesical pressure and urine flow has been the subject of several studies (Constantinou, 1982). The aim is to find an effective model relationship between the flow rate, pressure and anatomical features of the bladder and urethra, such that clinical measurements of flow parameters might then be used to detect and assist with the diagnosis of dysfunction. Models may be based on frictional resistance in a rigid tube (Smith, 1968; Walter *et al.*, 1993, 1994), or may utilise an elastic tube theory (Griffiths, 1971, 1977; Spangberg *et al.*, 1989). An adequate representation of the relationship between pressure and flow rate in the urethra is required for the general application of any model.

In most cases, the model is developed using the assumption that the urethra is a straight tube of uniform diameter carrying fully developed flow. The geometry of the actual urethra, however, is somewhat more complex. Furthermore, the urethra is far too short for the flow to become fully developed. The frictional pressure losses in developing flow are significantly higher than those in fully developed flow, and the presence of abrupt changes in cross-section and changes in flow direction will contribute to increased viscous losses. These effects are very difficult to quantify and include in a model without substantial complication to the model. It is therefore important to determine the relative importance of these factors, and to assess the accuracy with which the current simple models represent the true behaviour.

Tanagho and McCurry (1971) demonstrated the importance of abrupt changes in cross-section, and more recently Walter *et al.* (1994) accounted for entrance effects by making measurements of flow through short steel tubes. This permits the effect of the entry flow to be quantified, and represents an important advance. The actual urethra, however, consists of a series of relatively abrupt changes in cross-sectional area and changes in flow direction. In the current work we have created a full-sized physical model of a urethra using data taken from a video cystogram of a healthy subject. The actual relationship between pressure difference and flow rate in a realistic geometry has therefore been measured for the first time.

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MATERIALS AND METHODS

In a separate radiological study (unpublished data), sitting lateral micturating video cystograms in the resting, straining, and 'cutting-off' ('squeezing') positions have been used to determine a typical longitudinal cross-section of the open urethra in a healthy subject (Fig. 1). Co-ordinates taken from the video cystograms (Fig. 2) were used to program a numerically controlled machining centre to cut the desired shape from a block of epoxy, thereby producing a 'pattern' for the manufacture of the urethral tube. The pattern was then coated with several layers of silicone rubber. After removal of the pattern the silicone then forms a firm tube of the required shape, size and surface roughness. The surface of the actual urethra in the fully extended state is relatively smooth. The surface of the model urethra was finished to reflect this condition. Finally, the tube was mounted into a housing and attached to a fluid reservoir (Fig. 3).

The fluid level in the reservoir was adjusted to provide a range of effective intravesical pressures. The diameter of the reservoir is many times larger than that of the urethra. The flow could therefore be allowed to run for a considerable period of time without significant change in reservoir head. As a result, the tests were performed under the condition of constant flow rate. If the velocity in the reservoir is taken to be zero, the pressure difference across the urethra can be defined as $\Delta P = P_{ves} - P_0 = \rho g H$, where P_{ves} is the pressure at the base of the reservoir, P_0 is atmospheric pressure, H is the head above the entry to the urethra, ρ is the fluid density and g is the acceleration due to gravity. The pressure difference is divided into two components: $\Delta P = \Delta P_{dyn} + \Delta P_{frict}$, where ΔP_{dyn} is the dynamic pressure difference and ΔP_{frict} represents viscous dissipation and a small gravitational component. The dynamic pressure difference is defined as $\Delta P_{dyn} = (1/2)\rho V^2$, where V is the average velocity in fully developed flow at the urethral exit plane.

Measurements were made using water as the model fluid, having a kinematic viscosity of $0.01\ cm^2\,s^{-1}$ and density of $1000\ kg\,m^{-3}$. The flow rate was measured by collecting a quantity of the efflux over a specified period of time. During this period the change in level of the reservoir was negligible. The exit velocity can then be determined by making use of the urethral outlet diameter. Multiple measurements were made for heads up to 65 cm H_2O. The corresponding maximum flow rate for this urethra was $25\ cc\,s^{-1}$. These values fall within the range of data reported in the literature (Smith, 1968; Walter *et al.*, 1993).

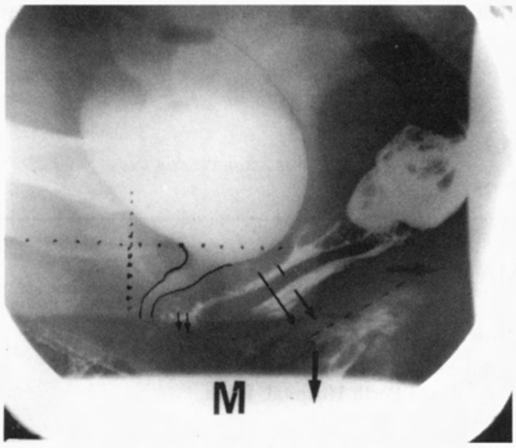

Fig. 1. Video cystogram of the bladder and urethra in a healthy subject during micturition. The diameters of various parts of the urethra during micturition were determined using the known external diameter of a No. 14 Foley catheter as a reference.

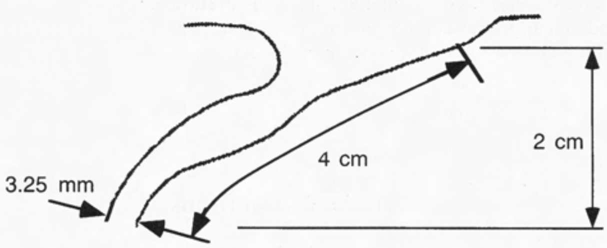

Fig. 2. Longitudinal profile of the model urethra adapted from the video cystogram (Fig. 1). The lateral cross-section is taken to be circular.

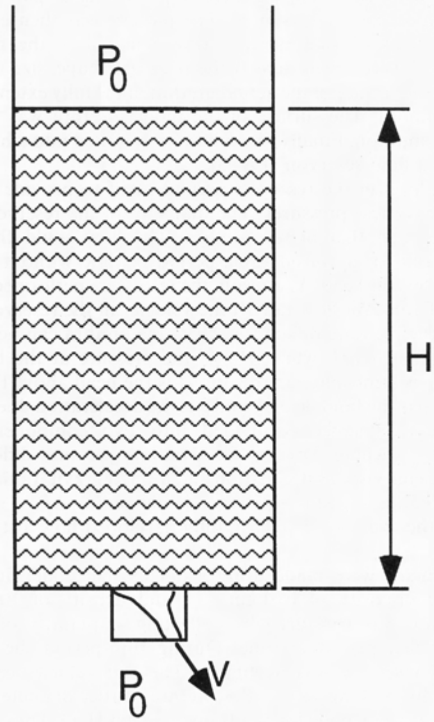

Fig. 3. Experimental apparatus showing the reservoir head, H, and the distal velocity, V. The atmospheric pressure is P_0. The apparatus permitted a maximum head of 65 cm H_2O to be applied to the urethra.

The measured results are compared with a model based on a straight tube of length, L, and uniform diameter, d, which is the form of model commonly used in the literature (Smith, 1968; Walter *et al.*, 1993, 1994). The tube length is taken to be $L = 4$ cm and the diameter of the tube is $d = 3.25$ mm (Fig. 2). By assuming the exit pressure to be the pressure of the surroundings, P_0, the following energy equation can be written:

$$\Delta P = P_{\text{ves}} - P_0 = \frac{8\rho Q^2 Lf}{\pi^2 d^5} + \frac{1}{2}\rho V^2 - \rho g \Delta h, \tag{1}$$

where Q is the volume flow rate, ρ is the fluid density, g is the acceleration due to gravity, f is the friction factor and Δh is the change in height from one end of the urethra to the other (approximately 2 cm).

The viscous losses depend on the wall roughness, the flow regime, the degree of flow development, entrance effects and flow rearrangement due to changes in tube cross section. The flow regime is characterised by the Reynolds number, which is defined as, $Re = Vd/\nu = 4Q/\pi d\nu$, where ν is the kinematic viscosity of the fluid. Turbulent flow will exist when the Reynolds number exceeds 2300. We use a constant tube diameter of 3.25 mm, which corresponds to the urethral exit diameter in the current subject. Under these conditions the flow in the tube is turbulent when the flow rate exceeds 5.9 cc s^{-1}. As the experimental flow rates are typically higher than this critical value, the model flow is assumed to be turbulent. The friction factor is in general a function of Reynolds number and wall roughness ratio, although for rough walled ducts it becomes a function only of the roughness ratio at high values of the Reynolds number (complete turbulence). The urethral wall is assumed to be smooth. In this case, the friction factor depends strongly on the Reynolds number. We have adopted here the Blasius correlation for friction factor in smooth walled tubes: $f = 0.316Re^{-1/4}$ (Gerhart *et al.*, 1992).

RESULTS

The measured flow characteristic (Fig. 4) shows remarkably good quantitative agreement with the model prediction. The dynamic component of the pressure difference was calculated from the data. The difference between this curve and the total pressure difference curve is the pressure loss due to viscous dissipation effects minus the gravitational effect, the latter being relatively trivial. The dynamic component of the pressure clearly represents a substantial part of the total pressure.

The results are quite sensitive to the urethra exit diameter. For example, the characteristic corresponding to an outlet diameter of 4 mm produces substantially more flow at a given pressure than the 3.25 mm tube (Fig. 4).

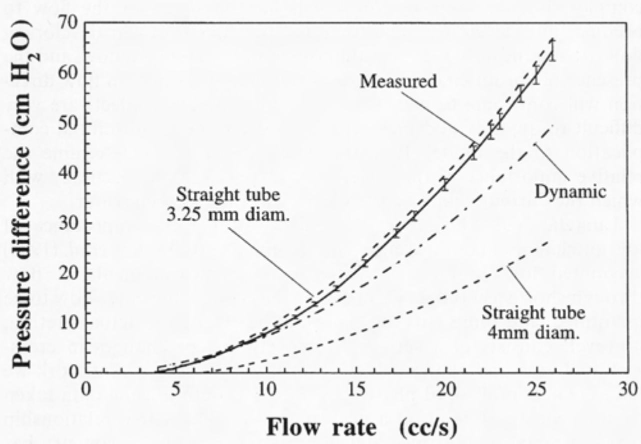

Fig. 4. The pressure vs flow rate characteristic. The measured relationship is shown in comparison with the dynamic pressure component and the total pressure predicted by a model based on a smooth, straight tube of length 4 cm and uniform diameter equal to the urethral exit diameter (3.25 mm). The difference between the curves corresponding to two diameters (3.25 mm and 4 mm) illustrates the high sensitivity of the flow to tube diameter.

DISCUSSION

The good quantitative comparison between the measured data and the model data is somewhat surprising, given the dramatic differences in geometry and nature of the flow between the two systems. Note that the wall friction contribution to the total pressure in the urethra will be at its maximum at the distal end, where the diameter is at a minimum. This represents a relatively short section of the total tube length. In the mathematical model the diameter is uniform throughout. Equal friction is therefore experienced along the whole length of the tube, thereby enhancing the contribution of the wall friction relative to the case of flow through the distal segment. The model, however, does not account for additional dissipation and wall friction associated with developing flow. The net result is that the model provides a good first approximation to the actual flow characteristic.

It is important to note that this work has been performed using a single urethral geometry. In practise the shape of the urethra will vary from subject to subject. The comparison between the flow characteristics for the 3.25 mm diameter tube and the 4 mm diameter tube (Fig. 4) illustrates the sensitivity of the flow behaviour to tube diameter. As a consequence, the exact pressure vs flow characteristic will also vary from one subject to the next, although the qualitative nature of the characteristic and the relative contributions of the various components to the total pressure are not expected to change significantly.

The experimental results presented in this report represent the flow rate vs pressure characteristic for steady flow through a particular urethral tube. As the effects of changes in cross-sectional area, changes in flow direction and the influence of developing flow are all present, the data can provide a reference for the development and testing of mathematical models.

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