

New valve-mechanical model of urinary tract function: the theory of biological dual valves

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KEY WORDS

new biological model ▶ peristalsis ▶ urinary tract physiology

ABSTRACT

Introduction. Until now, peristalsis has been the only known method of urine transport. The main objective of this paper was to study urinary tract function – especially the upper urinary tract, the ureter – from a new mechanical point of view. The physical (physical dual valves) and biological basis (biological dual valves) of a new functional model is presented based on previous observations and knowledge.

Methods. A review of the literature was performed, with special emphasis on ureter motility.

Results. After analyzing the anatomy and physiology of the urinary tract, complemented by basic physical observations, the authors have developed a new valve-mechanical model of urinary tract function. A comprehensive mechanical hypothesis is also presented, integrating the role of peristalsis.

Conclusions. The authors believe that the new theory enhances previous knowledge. From a structural point of view, the urinary tract may be considered to consist of dual-valves. The dual-valve mechanism combined with peristalsis allows better explanation of the function of the upper urinary tract in particular. The main conclusion is that the flow in the urinary tract must be studied integrally within the body. This new theory does not contradict well-known and acknowledged theories, and moreover, it may help solve certain medical problems.

INTRODUCTION

Until now, peristalsis has been the only known method of urine transport. Peristalsis has been studied *in vivo* and *in vitro*, but other factors, such as intra-abdominal pressure, respiration, and the pressure of adjacent structures among others, have received little attention.

1.1. The mechanism of peristalsis

Peristalsis is considered to be myogenic in origin, with neuro-hormonal factors playing only a modulatory role [1–4]. Three types of cells have been identified in the upper urinary tract: atypical and typical muscle cells and renal interstitial cells. The atypical smooth muscle cells, which are preferentially located in the proximal regions of the upper urinary tract, act as the essential pacemaker of pyeloureteric motility [5]. There is close contact between all types of cells [6–9]. Opinions on the function of the pacemaker cells are divided. It has been suggested that a urine flow-dependent mecha-

nism triggers ureteral peristalsis in the UPJ (uretero-pelvic junction) [10]. In contrast, according to Lang et al. the initiation and control of ureteral peristalsis is considered to be under the influence of, but not triggered by, the rate of urine flow, while the cyclic release of Ca^{2+} from internal stores acts as an essential mechanism underlying autorhythmicity in the upper urinary tract" [11].

1.2. The intra-abdominal pressure (IAP)

The intra-abdominal pressure is the pressure normally detected in the abdominal cavity, which is obviously above the atmospheric pressure (or is equal to it). The first observations on this were published by Marey (1863) and Heinricus (1890). Later on, IAP gained more importance in connection with the diagnosis of urinary and bowel disorders. In 1986 Graw and Bahl published an article about "An active artificial ureter with autonomous energy supply driven by the intra-abdominal pressure fluctuations caused by the respiratory movements" [12].

The effect of intra-abdominal pressure is very complex and our knowledge about it is very limited. What is known is that it exists according to the respiratory movements, and is therefore permanently changing. Hence, it influences all organ functions included in this integrated hydraulic system (thorax and abdomen), among them the cardiovascular system, the respiratory system, and the urine flow too.

The real significance of the IAP has only recently been recognized. First, anesthesiologists discovered the importance of the IAP in polytraumatic patients. Then an international organization was launched (The World Society of the Abdominal Compartment Syndrome-WSACS). Following the third WSACS congress, Malbrain et al. listed the cardiovascular and respiratory effects of elevated intra-abdominal pressure on 33 measurable parameters [13].

In this order of ideas this IAP, as a permanently changing pressure force, may act as a hydraulic pumping force on the urinary tract, which is situated in close contact with the abdomen. The value of the IAP plays a minor role in this process, while what is really important is the fluctuation of the pressure (at high or low level). Therefore, very high intra-abdominal pressures may not induce hydronephrosis, since they are variable (for example in case of ascites the IAP is high, but varies according to respiratory movements also.)

IAP can be measured in several ways. Indirect methods are preferred [14]. The normal IAP is 0–5 mmHg.

1.3. Physics

The physical point of view has been discussed in several published papers. Griffiths wrote: "One dimensional, *lubrication theory analysis* shows that peristalsis can pump urine from kidney into bladder only at relatively low mean rates of urine flow. At high flow rates the peristaltic contractions do not pump, but rather hinder the flow of urine through the ureter". According to Malbrain *the abdominal cavity and the organs behave according to Pascal's law*, as they are similar to fluids [15, 16]. This also means that the pressure measured at a specific location in the abdominal cavity reflects the IAP characteristics of the whole abdominal cavity;

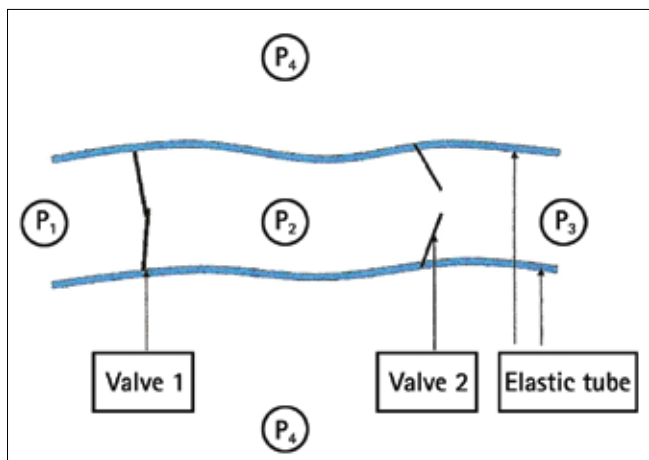


Fig. 1. The physical dual valves.

however, the fact that the abdominal organs do not behave absolutely as fluids has been proven by measurements that revealed a pressure gradient from the diaphragm to the pelvis. However, this fact does not contradict Malbrain's observation). Keulenaer and al. wrote the following in their review: *the abdomen truly behaves as a hydraulic system* [17].

The physical dual valves

The operating principles of the dual valves are simple. Dual valves actually mean two cascading rectifying valves (Fig. 1).

If these valves are placed in a flexible tube and the wall of the tube is put under pressure (P_4), the fluid can only flow in one direction. Provided the external pressure is high enough, valve 2 opens and lets the fluid flow out. Once the external pressure (P_4) ceases, the pressure between the two valves (P_2) also decreases and falls under the pressure of the adjacent segments (P_1 and P_3). At this point, the fluid can flow into the intervalvular segment of the tube, but only from one direction (from P_1). The repetition of the process presented above results in one-way flow (pumping).

The biological dual valves

Several examples can be found in the human body, for example the valves in the veins and lymphatic vessels. Two valves within a flexible vessel may work according to the principles of the physical dual valves. They prevent the backflow of blood or lymphatic fluid, and they pump blood towards the heart using the mechanical energy of the surrounding muscles (Fig. 2).

The biological valve structure

It is important that not only real valves but also valve-like anatomical structures and the special geometrical arrangement of certain structures can work as biological valves (biological valve structure). The terminal segment of the ureter is a good example, as – passing through the wall of the urinary bladder – it can be closed by increasing the intravesical pressure.

The biological valve function

In a wider sense, all anatomical structures that allow the flow of a certain fluid in only one direction (for example the renal–pelvic border or the mucous membrane of the bowel) work as biological rectifying valves.

METHODS

A literature search was performed, using the keywords „peristalsis“, „ureteral motility“, „upper urinary tract motility“, and „in-

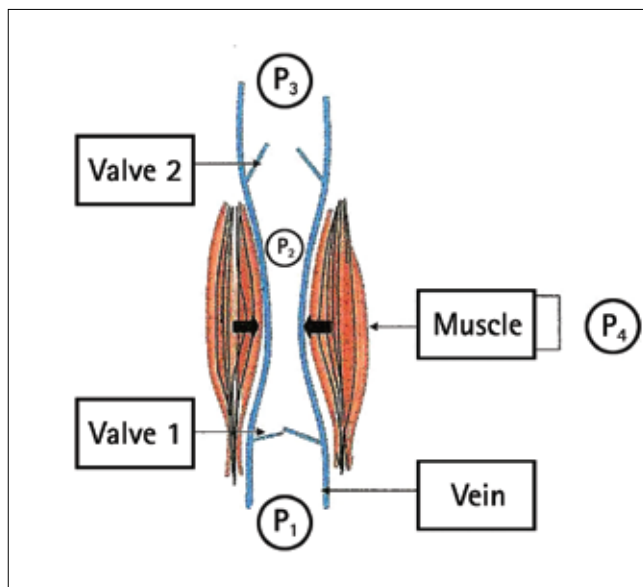


Fig. 2. The biological dual valves.

tra-abdominal pressure“. Special emphasis was given to physical aspects of ureter motility.

RESULTS

3.1. The valve–mechanical model of the urinary tract

Figure 3 presents two parallel images of the urinary tract, one showing the biological structure, the other introducing the urinary tract from a mechanical point of view.

The essentials of the new hypothesis are as follows: from a mechanical point of view, the urinary tract can be considered as a dual valve structure, in which two dual valves can be identified.

First biological dual valve

After entering the pylon, urine cannot flow back to the renal parenchyma, as the renal–pyelon border functions as a biological valve, comprising *the first valve*.

The second valve can be found at the junction between the ureter and the urinary bladder, that is, the ureterovesical junction (UVJ). Normal flow is also one-way at this point. The ureter is a flexible tube that connects the two valves. *The first biological dual*

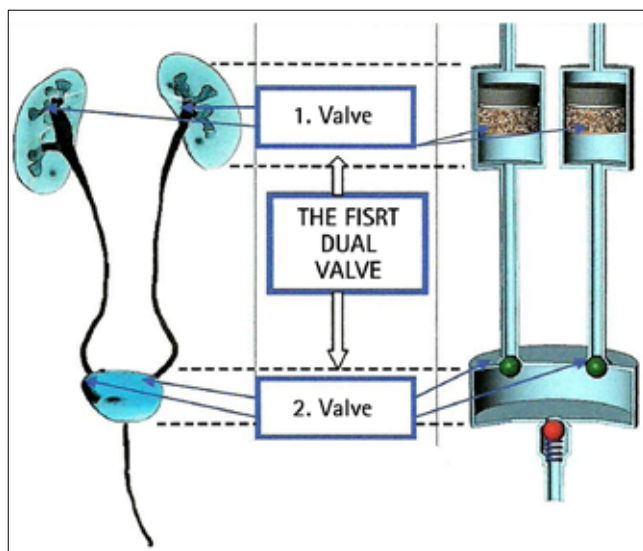


Fig. 3. Biological and mechanical representation of the urinary tract.

valve consists of the two rectifying valves and the connecting flexible tube, and this whole structure is equivalent to the upper urinary tract.

Second biological dual valve

The first valve is the UVJ mentioned above. The second valve is the sphincter urethras, which surrounds and closes the proximal part of the urethra. The flexible tube between these two valves is the urinary bladder. The second biological dual valve consists of these structures and is equivalent to the lower urinary tract (with the extrasphincteric part of the urethra).

The variable external pressure

From an anatomical point of view, the upper urinary tract lies on a hard posterior wall at the back of the abdominal cavity, adjacent to several blood vessels. Continuous movements and the ever-changing IAP are characteristics of the abdominal cavity. The front wall of the abdomen and the diaphragm move perpetually with respiration, and there is regular movement in the bowels and pulsation in the blood vessels. The IAP changes with these motions, which also affect the urinary tract directly due to its close connection with the intestines and blood vessels.

Therefore, all the conditions of an energy-saving one-way pump (i.e. urine transport) are provided in the upper urinary tract: the flexible tube (the ureter), the two rectifying valves (the renal-pylon border and the UVJ) and an external, variable positive pressure.

The new theory has less significance in the lower urinary tract. Here the pelvis forms a stiff external shell that diminishes the effects of the external pressure on IAP.

DISCUSSIONS

Supposing that the hypothesis of the dual valves is correct, an explanation is required to show how this hypothesis matches the role of peristalsis. In the development of a comprehensive model, the following two facts are useful:

- According to all observations made to date, *if the amount of urine secreted reaches a critical point, the urine flows as an unbroken fluid column.*

- We do not know exactly *how this fluid column moves*, although this is the situation that can be explained most easily and obviously via the mechanism of dual-valve pumping!

The following new definitions need to be introduced for better understanding of the comprehensive hypothesis, besides the definition of "bolus volume" – BV, which means the amount of urine (fluid) transported by one peristaltic (P) wave:

- *Minimum bolus volume (BVmin)* is the minimum amount of urine that is able to pass the P wave along the ureter.

- *Starter bolus volume (BVstart)* is the minimum amount of urine that is able to start a P wave, i.e. induce the minimal pressure in the pyelon that can be detected by the atypical cells. When the BVstart does not reach the BVmin, the P wave subsides in the pyelon or at the pyelo-urethral border.

- Above the *maximum bolus volume (BVmax)*, the urine boluses unite to form a fluid column.

- *Flow volume (FV)* is equal to or larger than BVmax, and this flow of urine forms a fluid column.

BVstart, -min, -max, and FV may differ in every human body, although normal ranges may be defined.

The comprehensive hypothesis states that both transport mechanisms are responsible for urine transport in the upper urinary tract and that they work at the same time. During the transport of small amounts of urine, peristalsis has the main role,

while at higher levels of secretion, urine is passed according to the mechanism of dual-valves. As the dual-valve structure and the IAP are constant, this type of transport is presumably constant as well, and thus it works in parallel with P. It is also probable that P does not subside above the BVmax, but helps with transport. P stops only above a certain FV, when the tightness of the ureter wall blocks the P wave.

The cooperation between P and dual-valve transport is probably regulated by the neuro-endocrine system (for example, it may adjust the two types of transport between BVmin and BVmax, or it may stop P at a certain FV by detecting the tightness of the ureter wall).

Dual-valve transport also occurs in the lower urinary tract, although the (stiff) bones of the pelvis restrict the significance of the hydraulic pump (the IAP).

The human body should be observed and explained as an integrated system. The abdomen, the chest, and the retroperitoneum do not exist and function separately, but comprise an integrated hydraulic system (the wall consisting of the chest and the internal organs behaving as a fluid), divided into two compartments by the diaphragm. This hydraulic system includes and regulates the flow processes of the body, such as blood and lymphatic flow, bowel movements, urine transport, and respiration. There is undoubtedly a strong link between the elements (circulation, respiration, and excretion) of this system. The question is how this system is regulated!

CONCLUSIONS

A new hypothesis based on a mechanical valve model of urinary tract function has been introduced above. This new hypothesis observes and explains the function of the urinary tract within the functioning of the whole body, which means the following:

- The urinary tract may be considered to consist of dual-valves from a structural point of view.

- The dual-valve mechanism combined with peristalsis allows better explanation of the function of the upper urinary tract in particular.

- The flow in the urinary tract must be studied integrally within the body.

- More accurate information on the characteristics (e.g. flexibility) and function of the upper urinary tract can be gained from the measurement of BVstart, -min, -max, and FV.

- Further experiments are necessary to judge the accuracy of the author's findings.

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