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FORMATION AND CHARACTERISTICS OF LAMINAR VORTICES IN MICROSCALE ENVIRONMENTS WITHIN AN OBSTRUCTED AND STENTED URETER: A COMPUTATIONAL STUDY

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ABSTRACT

Despite the widespread clinical usage of ureteric stents for the drainage of urine in impaired ureters (e.g. caused by ureteric stones, tumors) many complications are still associated with stent's implants. Encrusting and infective events, due to crystals' deposition and bacterial adhesion on the stent surface, usually lead to stent failure. In earlier experimental results we showed the presence of vortices in regions of the stent (e.g. side holes) which are thought to act as initial anchoring sites for encrusting deposits. In the current study we show computationally how the stent's design is a crucial factor for developing the vortices.

KEYWORDS: Ureteric stent, Micro-vortices, Urodynamics, Kidney stone

INTRODUCTION

Double-J stenting is a very common clinical method employed to restore the drainage of urine from kidney to urinary bladder, in the presence of an obstruction of the ureter [1]. After implant, stents allow for an instantaneous decrease of the pressure in the renal pelvis. However, their long-term usage is associated with encrusting or infective events, due to crystals' deposition and bacterial adhesion on the stent surface, respectively [2]. Urine flow field within stented ureters is thought to contribute significantly to the occurrence and progression of these events [3]. However, the role played by fluid dynamic parameters on stent's functionality is poorly understood, particularly in regions of the stent (i.e., side holes) which are thought to act as initial anchoring sites for encrusting deposits. In our previous work we developed an artificial model of the obstructed and stented ureter (Fig.1), and we analyzed the local fluid dynamics both experimentally and computationally [4].

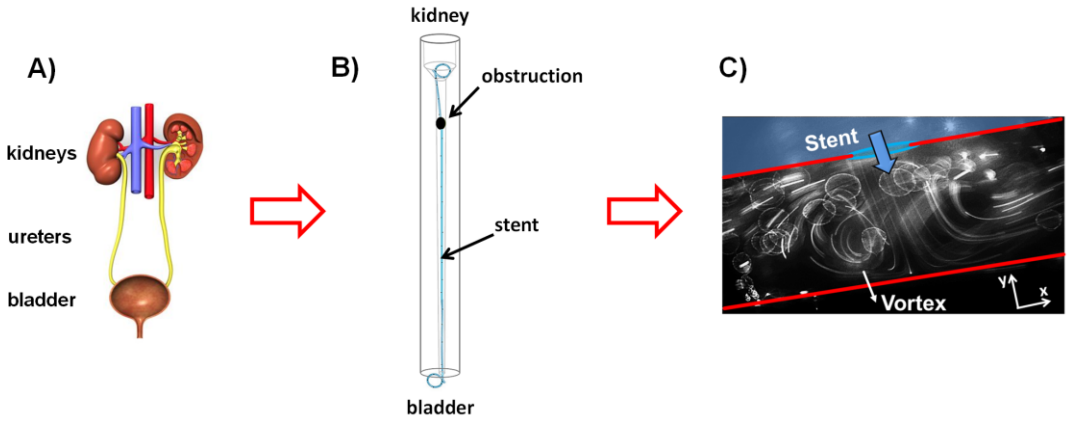


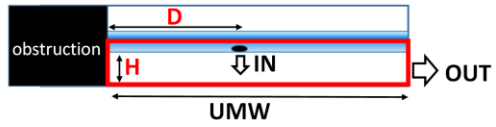
Figure 1: A) Schematic depiction of the urinary system, comprising of kidneys, ureters and bladder. B) Schematic representation of the developed ureter model, with highlighted the renal and bladder compartments, ureter lumen obstruction and a double-J stent [4]. C) Representative microscope image of 15 µm diameter fluorescent polystyrene beads in a region of the ureter model located between the obstruction and a side hole of the stent. The formation of laminar vortices can be appreciated [4].

Notably, we were the first to report on the formation of vortices in the microfluidic domain located between the ureteric obstruction and stent's side holes (Fig.1) [4]. Vortices may significantly impact on the long-term performance of the stent, as they could act as entrapment sites for flowing crystals and bacteria. This paper reports on the dependence of laminar vortices' formation and characteristics on (i) the distance (D) between ureteric obstruction and stent's side holes and (ii) the micro-gap (H) between the stent and the inner wall of the ureter.

MATERIALS AND METHODS

A two-dimensional (2D) numerical model was developed to investigate the fluid dynamics within a micro-confined region of the ureter lumen, located between the ureteric occlusion and a stent's side hole (Fig.2). COMSOL Multiphysics (Palo Alto, USA) was employed for construction and meshing of the two-dimensional model geometry. The geometry was meshed using triangular elements with maximum edge element size of 50 μm. Steady-state mass conservation and momentum conservation equations were solved over the computational flow domain, using a laminar model. The working fluid was assumed to be incompressible and Newtonian, with a density of 1000 kg/m^3 and a dynamic viscosity of 0.001 Pa·sec. A detailed description of the boundary conditions applied is reported in Figure 2. Furthermore, a discrete phase model was employed to obtain the positional information of calcium carbonate particles (diameter: 100 μm) exiting the side hole of the stent. A one-way coupling between discrete and continuous phases was applied.

A)



B)

Symbol	*Physical component*	*Length (mm)*	*Boundary condition*
Blue colour	Stent wall	10.8	Wall STATIONARY NO SLIP
UMW	Ureter Model Wall	10.8	Wall STATIONARY NO SLIP
IN	Inlet (stent side hole)	0.8	Velocity Inlet VELOCITY NORMAL TO BOUNDARY
OUT	Outlet	Variable: 0.5-1.5mm	Pressure outlet P = 0Pa

Figure 2: A) Schematic representation of the two-dimensional computational domain (red square). B) Summary of the geometrical characteristics of the computational domain, and boundary conditions applied to each individual edge. D is the distance between the obstruction and the stent's side hole, H is the gap between the stent and the inner wall of the ureter.

RESULTS AND DISCUSSION

Computational results show that both D and H can significantly influence the fluid dynamic field within the ureter lumen (Fig.3a and 3b). The number of vortices in this micro-confined region has been observed to increase with increasing D and with decreasing H, which in turn increases the number of potential entrapment sites. This is clinically relevant, and should be used to inform stent design, since (i) D can be varied by changing the number of side holes in the stent, and (ii) H can be varied by changing the stent's external diameter. Additionally, fluid velocity influences the trajectory of suspended particles (Fig.4), with higher velocities more likely to cause particles' entrapment within the vortices and interaction between flowing particles and the inner wall of the ureter. This suggests that designing for lower fluid velocities nearby the stent's side holes (i.e., by increasing the cross-sectional area of the side holes) may minimise the occurrence of entrapping events in the extra-luminal space of the stent.

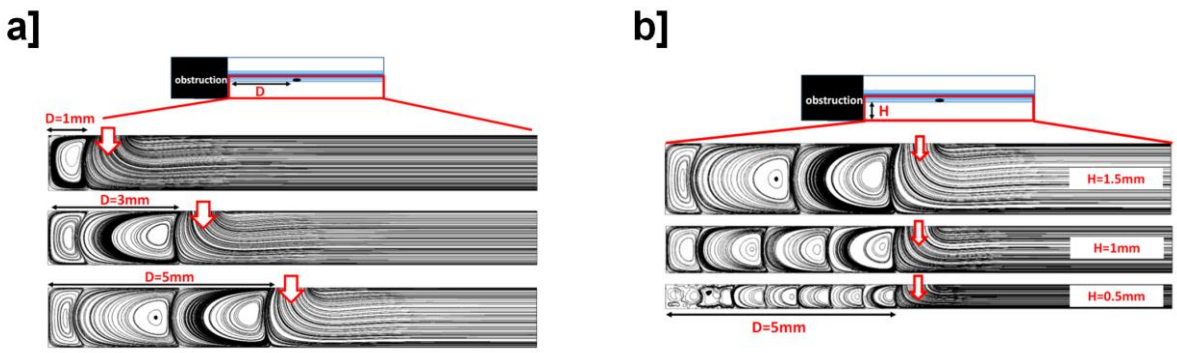


Figure 3: (a) Dependence of vortices formation on the distance (D) between the obstruction and the stent side hole. Fluid streamlines highlight the presence of laminar vortices. The number of vortices increases with increasing D (from top to bottom). H=1.5 mm. (b) Dependence of vortices formation on the gap (H) between the stent and the inner wall of the ureter. Fluid streamlines highlight the presence of laminar vortices. The number of vortices increases with decreasing H (from top to bottom). D=5.0 mm.

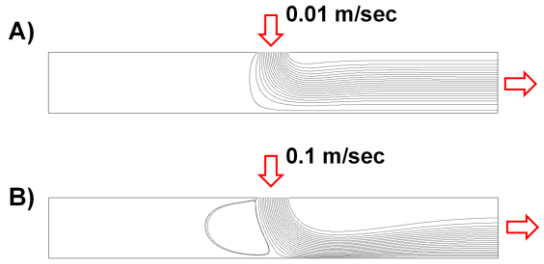


Figure 4: Trajectory of 100 μm diameter particles at different velocity of the fluid exiting the stent's side hole, namely 0.01 m/sec (A) and 0.1 m/sec (B). Red arrows indicate the flow direction. Particles trapping within the vortex can be appreciated at the higher fluid velocity. D=5.0 mm and H=1.5 mm.

CONCLUSION

The computational results shown in this study, coupled with our previous experimental results, provide unique insights regarding the possible role of the local fluid dynamics on ureteric stent functionality. After implantation stent side holes are generally considered the most prone regions to develop encrustation in a ureteric stent, and we found that they are also the regions where laminar vortices are present. It seems reasonable that a higher number of vortices leads to an increased risk of developing anchoring sites for encrusting deposits. We have shown that the stent design (with particular attention on the number of stent side holes and stent's external diameter) strongly affects the number of vortices formed in the region between the stent and the inner wall of the ureter. The results provided in this study may help improving the existing stent designs.

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